Boyle on Fire: The Mechanical Revolution in Scientific Explanation

WILLIAM R. EATON

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continuum
LONDON • NEW YORK

Continuum
The Tower Building, 11 York Road, London SE1 7NX
15 East 26th Street, New York, NY 10010

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

ISBN: HB: 0–8264–7827–1

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress.

Typeset by Aarontype Limited, Easton, Bristol
Printed and bound in Great Britain by MPG Books Ltd, Bodmin, Cornwall

For
Anne Talbert
doctor maximus

ACKNOWLEDGEMENTS

I would like to thank the following people for their help with this project: Philip de Bary, Andrew Black, James Fieser, Robert Hahn, Helen Hattab, Robert Higgerson, Michael Hunter, Ronald Karl, Barbara King, Charles Littleton, Ernan McMullin, Patsy Mandfredi, Christina Martin, Andrew Mikolajski, Liz O'Donnell, James Powell, Leigh Proctor, George Schedler, Gerard Smith, and Anya Wilson. Without their help it could not have been completed.

Special thanks to James Powell and everyone at Pickering & Chatto for all their help and for permission to quote extensively from their fourteen-volume edition of *The Works of Robert Boyle*.

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INTRODUCTION

For some time it has been recognized that early modern philosophy has not only historical value, but philosophical value as well. Discoveries and debates in the seventeenth century have relevance to contemporary philosophical problems. This book is about the mechanical philosophy of Robert Boyle (1627–91) and its relevance to current issues in the philosophy of science. What is the nature of scientific explanation? What role does mechanical explanation play in scientific practice? Are mechanical explanations epistemologically superior to non-mechanical explanations?

Robert Boyle's approach to such questions is one of the many events that would become the scientific revolution. This intellectual movement is one of the causes that led to the modern, technological world in which we now live. Boyle led a complex life, and recent historical discoveries have established that many of his activities, such as his devotion to transmutation, cannot be accurately described as modern. But when you look at Boyle from the point of view of philosophy, particularly from the point of view of epistemology and the philosophy of science, there is a legitimate and important sense in which he was modern, and in which his investigations directly led to the development of the modern world. Specifically, Boyle established one of the primary explanatory models that has been employed by science from his time until ours.

Boyle was not the only mechanical philosopher, and by his own reckoning was not even the first. However, he did coin the term 'mechanical philosophy' and used it to categorize the theories of a wide range of philosophers including Descartes, Basso, Gassendi, Lucretius, Epicurus, Democritus, Leucippus, and Anaxagoras (even though many of these philosophers believed their theories to be directly opposed to each other). This brings up an interesting point that should be recognized throughout this study. The mechanical philosophy of the seventeenth century has become synonymous with atomism. This is an over-simplification. While it is true that atomism is very conducive to a mechanical approach to natural philosophy, it is not necessary to it, and was even rejected by many philosophers who described themselves as mechanical.

Although many philosophers can be described as mechanical philosophers, it is Boyle who most emphasizes the epistemological significance of the mechanical approach to the study of nature. And it is this emphasis that makes Boyle's work of more than historic value, being applicable to some very interesting questions in the philosophy of science today.

1

Boyle and the Philosophy of Science

Elemental theories and the scientific revolution

The mechanical philosophy of Robert Boyle ushered in an important new explanatory model for science. Although the main ingredient of this theory, often described by Boyle as the corpuscular hypothesis, ultimately failed, this failure does not entail the failure of the explanatory model of which it was an instance. Boyle often spoke of the mechanical model exclusively in terms of its epistemological significance. In this regard he saw the importance of *contrivance* to mechanical explanation. This aspect of Boyle's mechanical philosophy had enormous importance to the scientific revolution and the development of the modern world. Recent criticisms of Boyle's role in the scientific revolution attack many problems with his mechanical philosophy. But these attacks often focus on the limitations of his crude corpuscular variation of the mechanical philosophy, rather than the epistemological value of its model of explanation. Such objections miss the point. One goal of this study is to show that Boyle's role in the scientific revolution was more than merely offering another natural philosophy based on matter and motion, he also developed one of the primary models of explanation on which science has been based ever since.

One of the key features of the scientific revolution has been traditionally thought to be a shift away from Aristotelian philosophy. This happened in several areas. For example, in cosmology the heliocentric cosmos replaced the geocentric model. In medicine the theory of the four humours, advanced by Galen and loosely Aristotelian, was criticized and eventually abandoned. In natural philosophy the use of the four elements in explaining the properties and composition of compound substances was gradually replaced by a new mechanical philosophy which sought to account for nature in terms of the mechanical properties of material particles in motion. Robert Boyle was at the front of this latter movement, and in works such as *The Sceptical Chymist* (1661), *The Origine of Formes and Qualities* (1666), and 'The mechanical origin of heat and cold' (1675) he attacks the explanatory power of elemental theories of scientific explanation.

Boyle thought that such mechanical theories offered a refreshing alternative to the more traditional elemental theories of natural philosophy that were prevalent at the time. Now there were several elemental theories competing for supremacy by the seventeenth century, and each had a similar account of what qualified as a successful scientific explanation. Aristotelians, such as Francisco Suarez and Thomas Erastus, had long accounted for the properties of terrestrial substances by appealing to the four elements: Earth, Air, Fire, and Water.[1] Many of the followers of the sixteenth-century alchemist Paracelsus (1493–1541), also known as Philippus Aureolus Theophrastus Bombastus von Hohenheim, explained the properties of mixed bodies by appealing instead to three chemical principles: Salt, Sulphur, and Mercury. Still others used combinations of both elements and principles or different elements altogether.[2]

Aristotle himself thought that all terrestrial substances were combinations of form and matter.[3] Each of the four material elements (Earth, Air, Fire, and Water) had a combination of two out of four total *primary* qualities (Hot, Cold, Moist, and Dry).[4] Thus, Earth was both cold and dry. Air was hot and moist. Fire was hot and dry. And Water was cold and moist. When the elements combined to form substances the combination and proportion of the elements allowed for more complex properties. For example, wine is moist, and the moistness was thought to be due to a predominance of the element Water, but the more complex qualities of wine (for example, its colour) were due to the presence and proportion of the other three elements. Furthermore, each of the four elements had a natural place in the universe and a corresponding disposition for natural motion in the direction of that place. For instance, a rock was thought to fall to the ground when dropped because the natural place of the element Earth is the centre of the universe. Fire, on the other hand, rises upward because its natural place is a region of the sky below the heavenly bodies.

The Aristotelians illustrated their claim that all terrestrial substances were composed of the four elements by a common experiment called *analysis by fire*. The burning of a piece of freshly cut wood was said to illustrate the substance's separation into its primary elements. As Boyle describes it in *The Sceptical Chymist* through the Aristotelian character Themistius:

> For if You but consider a piece of green-Wood burning in a Chimney, You will readily discern in the disbanded parts of it the four Elements, of which we teach It and other mixt bodies to be compos'd. The fire discovers it self in the flame by its own light; the smoke by ascending to the top of the chimney, and there readily vanishes into air, like a River loosing it self in the sea, sufficiently manifests to what Element it belongs and gladly returns. The water in its own form boyling and hissing at the ends of the burning Wood betrayes it self to more then one of our senses; and the ashes by their weight, their firmness, and their dryness, puts it past doubt that they belong to the Element/of Earth.[5]

In a similar way, Paracelsians used the same method of analysis to support their three-principle theory. One notable example is the theory of Jean Beguin. In his *Tyrocinium Chymicum* of 1669 he describes the results of burning a green stick:

> This gives a certain wateriness which is mercury, that acid, permeable, penetrable, aethereal, and most pure liquor, whence is

> all nutrition, sense, motion, virtues, colours, and the retardation of very hasty age; an oleaginous substance, which is sulpher, a sweet oleaginous, and viscid balsom, conserving the native heat of the parts, the instruments of all vegetation, increase and transmutation, and the fountain and original of all odours grateful and ungrateful. It is assimilated to fire, by reason of the flame which it easily conceives; and the ashes give a salt, which is a dry body, saline and defending mixt things from putrefaction, endowed with wonderful faculties of dissolving, determination, taste and other infinite virtues.[6]

In this passage we can see an example of the number of properties that elemental theorists attempted to account for by appealing to primary qualities. However, some substances had such unusual properties that by Boyle's time Aristotelians and Paracelsians alike had adopted occult qualities to explain them. Magnets, drugs such as opium, and even healing amulets were said to have such mysterious powers that they could not be adequately explained by the traditional Aristotelian primary qualities. The status of occult qualities was a hotly debated topic among natural philosophers of the seventeenth century, and the search for their explanation was one of the driving forces behind the scientific revolution. This being the case, it is useful to look at the issue of occult qualities in more detail.

Occult explanations

Peter Alexander in his 1985 book *Ideas Qualities and Corpuscles* interprets Boyle's definition of an occult quality in the following way.

> For [Boyle] something is occult if, first, it is unobservable and the only ground for postulating it is that it 'explains' a particular phenomenon or property and there is no alternative method

> of confirming its presence and, second, if no intelligible description of it which is independent of what is claimed to explain can be given.[7]

Let's suppose that I find a rock that emits a mysterious sound. I claim that the sound is caused by the singing of a jinni living inside the rock. The jinni is an occult quality of the rock if: (1) the only evidence I can give for the presence of the jinni is the sound coming from the rock, (2) no other explanation depends upon the presence of the jinni, and (3) I cannot describe the jinni or I can only describe it as the cause of the sound emitted from the rock.

Recently Peter Anstey has raised a significant point that seems to run counter to Alexander's interpretation. Anstey claims that Boyle did not have a problem with occult qualities, *per se*, but with the Aristotelian and Paracelsian explanations of those qualities. As Anstey puts it:

> Boyle accepts the occult/manifest distinction and even includes notes about the occult qualities magnetism and electricity in his *Mechanical Qualities*. He frequently speaks of occult qualities without any critical or polemical intent, as if they're a natural phenomenon that must be addressed by the corpuscular philosophy. In fact, Boyle thinks that he most likely has the explanatory resources to give mechanical explanations for occult qualities. He tells us that he considers 'these three doctrines of effluvia, or pores and figures, and of unheeded motions, as the three principal keys to the philosophy of occult qualities' (*Effluviums*, *Works* III, p. 660). Therefore, Boyle's doctrine of the qualities is not an all-out assault on occult qualities, as Keith Hutchinson (1982) has shown. Boyle accepts occult qualities, but he rejects the Aristotelian account of them.[8]

Anstey is claiming that Alexander, among others, is wrong in thinking that Boyle directly rejected occult qualities. He accepted them. What he rejected were the explanations of the occult qualities advanced by the Aristotelians and Paracelsians of his time. Anstey's point is noteworthy, but a mere modification of Alexander's interpretation is all that is needed to understand Boyle's actual position.[9] To be safe let's just say that Boyle rejected occult explanations rather than occult qualities. Placing the focus on *explanations* rather than *qualities* should satisfy Anstey's point that Boyle accepted the existence of occult qualities but also concede the thrust of Alexander's interpretation that Boyle found elemental theories of scientific explanation lacking in explanatory value. It is also compatible with my thesis that Boyle's mechanical philosophy was not just the acceptance of the metaphysical corpuscular hypothesis but an epistemological theory as well.

More importantly, such an interpretation is supported by the fact that Boyle considered explanations employing Aristotle's traditional primary qualities (Hot, Cold, Moist, and Dry) to be just as occult as the more traditional occult qualities of magnetism or opium or the alleged healing power of magic amulets. Consider his attitude towards the primary quality Heat when he writes:

> If you ask a Vulgar Philosopher the cause of the fire burning, he will presently answer you, that the fire burns by the quality of heat that is most eminent in it: but if you further ask him what that heat is, and how it enables the fire . . . to performe the various effects we dayly see produced by fire; he will if he *be* ingenous, confesse to you in plain terms that he cannot tell, and though he *be not*, he will but in a confused & unintelligible Discourse give you cause to conclude as much.[10]

Boyle also wrote an entire treatise dealing with the primary quality Cold. In the preface he writes:

> I shall represent, that notwithstanding Cold's being so important a subject, it has hitherto been almost totally neglected.

> For I remember not that any of the Classick Authors, I am acquainted with, hath said any thing of it that is considerably. They do indeed generally treat of it, as one of the four first Qualities. But that which they are wont to say, amounts to little more, then that 'tis *a Quality that does congregate both things like, and things of unlike nature* . . . And having given us this inconsiderate Description of Cold, they commonly take leave of the subject, as if it deserved no further handling . . .[11]

Since Boyle rejected explanations that appealed to the Aristotelian primary qualities as well as the traditional occult qualities, his attack is an attack on occult explanations in general. Boyle thought that the mechanical philosophy was explanatorily and philosophically superior to elemental theories because those theories offered only occult explanations. And traditionally Boyle has been thought to play a significant role in the scientific revolution because the mechanical philosophy offered a method of scientific explanation that was not occult, and thus had more explanatory strength. It was a more legitimate form of explanation because it provided a describable mechanism rather than a mere label.

Therefore, for Boyle an explanation is occult if it appeals to a quality that is unobservable, the only grounds for postulating that quality is that it 'explains' a particular phenomenon or property, there are no alternative methods of confirming its presence, and no intelligible description of it which is independent of what is claimed to be explained can be given.

Consider this example. Wine is wet. If you asked a seventeenth-century Aristotelian why this was so, he might reply that wine had a predominance of the element Water. But this raises the further question 'why is water wet?' To this the Aristotelian could only claim that water is wet because one of the primary qualities of water is wetness. But here the explanation stops. Occult explanations did no more than label the very property in need of explanation.[12] Another famous example: why does opium put one to sleep? A seventeenth-century chemist might answer, 'Because it has dormative powers.' The mechanical philosophy is purported to be explanatorily superior because it offered a describable mechanism that could explain exactly how the relevant property was produced. Boyle is very confident of the role of mechanism in successful scientific explanations. In *The Origine of Formes and Qualities* he writes:

> That, then which I chiefly aime at is to make it Probable to you by / Experiments (which I Think hath not yet been done:) That almost all sorts of Qualities, most of which have been by the Schools either left Unexplicated, or Generally referr'd to I know not what Incomprehensible Substantiall Formes, *may* be produced Mechanically, I mean by such Corporeall agents, as do not appear, either to Work otherwise, then by vertue of the Motion, Size, Figure, and Contrivance of their own Parts, (which Attributes I call the Mechanical Affections of Matter, because to Them men willingly Referre the various Operations of Mechanical Engines:) or to Produce the new Qualities exhibited by those Bodies their Action changes, by any other way, then by changing the *Texture*, or *Motion*, or some other *Mechanical Affection* of the Body wrought upon. And if I can in any Passable measure do, though but in a generall way, in some or other of each of these Three Sorts, into which the Peripateticks are wont to Divide the Qualities of Bodies, I hope I shall have/ done no uselesse Piece of Service to Natural Philosophy, *Partly* by exciting You and Your Learned Friends, to Enquire after more Intelligible and Satisfactory wayes of explicating Qualities, and *Partly by Beginning* such a Collection of Materials towards the *History* of Qualities, that I shall the most largely Insist on, as Heat, Colours, Fluidity, and Firmnesse, as may invite You and other Ingenious Men to contribute also their Experiments, and Observations to so Useful a Work, and

> thereby lay a foundation, whereon You, and perhaps I, may superstruct a more Distinct and Explicite Theory of Qualities, then I shall at present adventure at.[13]

The traditional view of Boyle's role in the scientific revolution that I wish in part to defend developed alongside the general development of Boyle scholarship. So let's take a moment to look at the development of Boyle scholarship over the years as well as its current condition.

The status of Boyle scholarship

Boyle scholarship began shortly after his death in 1691 and has developed steadily ever since, falling roughly into four categories: biographical, historical, philosophical, and sociological. Biographical materials on Boyle began with his own account of his early life and education at Eton entitled in *An Account of Philaretus*. Soon Thomas Birch, who edited the first comprehensive collection of Boyle's work, wrote a detailed if glorified biography. This was the definitive account of Boyle's life until R. E. W. Maddison's massive *The Life of the Honourable Robert Boyle* in 1969. Maddison is also responsible for numerous articles concerning Boyle's life including 'Robert Boyle and some of his foreign visitors' (1951 and 1954) and 'The earliest published writings of Robert Boyle' (1961). Significant biographical work on Boyle was completed by Marie Boas-Hall in *Robert Boyle and Seventeenth-Century Chemistry* (1958) and *Robert Boyle on Natural Philosophy* (1965) and more recently by M. A. Stewart in the informative introduction to his *Selected Philosophical Papers of Robert Boyle* (Boyle 1991b). A new book is forthcoming from the great Boyle scholar Michael Hunter and promises to be the new standard biography of Robert Boyle.

The historical category is made up of the substantial amount of scholarship on Boyle that can be best described as the history of science. I shall mention only a few outstanding examples. The work of Marie Boas-Hall, Allen G. Debus, and R. P. Multhauf are the most detailed and significant of early work in this area, but recent work in this area by outstanding scholars such as Michael Hunter and Lawrence Principe have made Boyle a hot topic. Important work on Boyle was completed in the 1950s and 1960s by A. J. Ihde, with articles such as 'Antecedents to the Boyle concept of the element' (1956) and 'Alchemy in reverse: Robert Boyle and the degradation of gold' (1964), and Douglas McKie, with articles such as 'Fire and the flamma vitalis: Boyle, Hooke, and Mayow' (1953). In the 1970s, historical scholarship on Boyle continued with articles like K. D. Keele's 'The Sydenham-Boyle theory of morbific particles' (1974). Besides that of Hunter and Principe, recent scholarship in the history of science concerning Robert Boyle can be found in the work of D. T. Burns, Antonio Clericuzio, and Helene Metzger.

The philosophical scholarship on Boyle is diverse as well. Important work in the twentieth century includes P. P. Wiener's 1932 article 'The experimental philosophy of Robert Boyle (1626–91)'. Marie Boas-Hall and Lynn Thorndike also made significant contributions in this area. A renewed interest in Boyle's philosophy began in the late 1970s. Some great examples of this are *This Great Automaton, the World* a Ph.D. thesis by Mary Elizabeth Connor Bowen in 1976, and 'Boyle's atomism and the restoration assault on pagan naturalism' by J. R. Jacob in 1978. Then came a great deal of philosophical research on Boyle in the 1980s. In 1980 Yvette Conry wrote 'Robert Boyle et la doctrine cartésienne des animaux-machines'. Peter Alexander wrote a great book in 1985 entitled *Ideas, Qualities and Corpuscles: Locke and Boyle on the External World*. Then came Norma Emerton's *The Scientific Reinterpretation of Forms* and John Henry's 'Occult qualities and the experimental philosophy' in 1986. Michael Stewart, Michael Hunter, and Antonio Clericuzio dominated Boyle philosophical scholarship in the 1990s. And in 2000 Peter Anstey published the first comprehensive account of Boyle's philosophical system in *The Philosophy of Robert Boyle*.

The traditional view that Boyle's mechanical philosophy is explanatorily superior to Aristotelian natural philosophy developed in the biographical, historical, and philosophical areas of Boyle scholarship. This view was first expressed in detail in Marie Boas-Hall's *Robert Boyle on Natural Philosophy* (1965). An important revision of this tradition appears in Peter Alexander's book (1985). William Brock presented his version in *The Chemical Tree* (1992), and current examples of this interpretation can be found in Brian Silver's *The Ascent of Science* (1998) and Arthur Greenberg's fascinating *A Chemical History Tour* (2000).

Finally, I use the term sociological to describe the category that includes recent scholarship that interprets Boyle's role in the scientific revolution in light of its social context. This area of Boyle scholarship is generally critical of the traditional view and suggests that the scientific revolution had social and political causes, rather than any objective philosophical superiority of the mechanical philosophy. An early example of work in this area is Robert Markley's 'Objectivity as ideology: Boyle, Newton, and the languages of science' (1983). But this area of research really got off the ground with the work of Steven Shapin. His work includes: 'Pump and circumstance: Robert Boyle's literary technology' (1984), *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (with Simon Schaffer, 1985), 'The house of experiment in seventeenth-century England' (1988a), 'Robert Boyle and mathematics: reality, representation, and experimental practice' (1988b), *A Social History of Truth* (1994), and *A Scientific Revolution* (1996). But Shapin merely got the ball rolling and his work inspired a large amount of scholarship including articles such as Jan Golinski's 'Robert Boyle: scepticism and authority in seventeenth-century discourse' (1987), Young Sik Kim's 'Another look at Robert Boyle's acceptance of the mechanical philosophy: its limits and its chemical and social contexts' (1991), and Jan

Wojcik's *Robert Boyle and the Limits of Reason: A Study in the Relationship between Science and Religion in Seventeenth Century England* (1997), to name only a few. The work in this area most relevant to my project is Alan Gabbey's 'The mechanical philosophy and its problems: mechanical explanations, impenetrability, and perpetual motion' (1985), Alan Chalmers' 'The lack of excellency of Boyle's mechanical philosophy' (1993) and Steven Shapin's *The Scientific Revolution* (1996).

It should be noted that these distinctions are only rough groupings and there is certainly overlap between them all. But it is also surprising that there is a general lack of attempts to make connections between some of the different research points of view. Furthermore, interesting questions emerge when one considers some of the historical research (for example: what is Boyle's developed theory of combustion?), in terms of its philosophical significance (for example: does this theory of combustion, when applied to the fire-analysis experiments, avoid the problems associated with elemental theories?).

Currently, ground-breaking Boyle research is being conducted around the world. Peter Anstey is investigating the relationship and mutual influence between Boyle and John Locke. Iordan Avramov of the Bulgarian Academy of Sciences is completing work on Boyle's correspondence with Henry Oldenberg. Christiana Christopoulou of the University of Athens is working on Boyle's theory of cold. Brian Dean is writing a Ph.D. dissertation at the University of Illinois at Chicago regarding the dispute between Boyle and Henry More. Furthermore, the current tools for Boyle research are better now than ever before with the publication of the new, fourteen-volume edition of *The Works of Robert Boyle*, edited by Michael Hunter and Edward Davis, published by Pickering & Chatto (1999 and 2000), as well as the new on-line availability of Boyle's work diaries, thanks to the tireless work of Charles Littleton.

Challenges to the tradition

As mentioned before, recently the explanatory superiority of the mechanical philosophy has been challenged by a wave of scholars, including Alan Gabbey, Alan Chalmers, and Steven Shapin. These philosophers claim that the mechanical philosophy ran into just as many problems as the elemental theories when it came to successful explanations of natural phenomena. For example, Shapin recently has gone so far as to imply that mechanical explanations were just as occult as Aristotelian or Paracelsian theories when he writes, 'modern natural philosophers actually reintroduced occult qualities while claiming to reject them'.[14] Gabbey goes into more detail in his article 'The mechanical philosophy and its problems'. He argues that mechanical explanations were far from ideal:

> In general terms, the explanatory structures in the latter case were specified in such a way that they bore a correspondence, or exhibited a congruity, which fitted them to be causes of the explananda. Between the explanans and the explanandum there was posited a relation of adequation (or inadequation, where appropriate). In other and simpler words, the phenomena to be explained were caused by entities whose structures were such that they caused the phenomena. Previously, opium sent you to sleep because it had a dormative quality: now it sent you to sleep because it had a particular corpuscular micro-structure that acted on your physiological structures in such a way that it sent you to sleep.[15]

But notice that the mere words *corpuscular micro-structure* do not, in themselves, constitute a mechanical explanation. If all I said about the mysterious rock was that the sound emitted from the rock was due to its corpuscular microstructure, and left it at that, my explanation would indeed be just as occult as the explanation that appealed to the jinni. But it is relatively easy to come up with an actual description of a mechanism that might account for the dormative quality of opium. For example, I could hypothesize that the inner workings of the brain are similar to the gears of a clock. Opium, perhaps, due to the shape and size of the corpuscles that make it up, clogs up the gears in such a way that some of them slow down. The dormative quality is thus reducible to the slower rotation of brain gears. Is this explanation completely explanatorily successful? Most probably not! But as Gabbey himself points out, 'the issue here is explanatory legitimacy, not total explanatory success'.[16] As unsuccessful as my primitive mechanical explanation may turn out to be, it does give a description of how the quality might be produced that goes beyond merely labelling it as either an occult quality or as Gabbey's vague, undescribed corpuscular microstructure. Furthermore, my explanation has a better chance of being empirically tested, and can also be evaluated efficiently against other mechanical explanations.[17]

Shapin and Gabbey also question the success of the mechanical philosophy in dealing with colour sensations and the relation between the will and the body. Gabbey puts the issue in the following way:

> Less successful were the mechanists' explanations of those phenomena (notably sensations) for which they could provide explanatory structures – nothing was easier – but which could not be represented in any respect by means of an isomorphic macroscopic mechanism. For example, there is very little, if anything, in our experience that suggests a possible mechanical operation that would itself, qua isomorphic explanatory mechanism, produce in us the sensations of this or that color, this or that smell, this or that taste, or more significantly, would reproduce an action of the will on the body. Not surprisingly, the explanations the mechanists did provide for the phenomena of this kind were

> either extensions to the micro-world of the traditional Peripatetic qualities, or they were simply tautologous, a defect they shared with the corresponding Peripatetic explanations.[18]

It is unclear exactly what Gabbey is claiming in this passage. It could be one of at least two things. Perhaps Gabbey is claiming that the mechanical philosophy cannot account for the actual qualitative, conscious colour experiences that we have, nor can it explain how a non-physical *will* could influence a physical body. If this is the case then Gabbey is merely stating that the mechanical philosophy failed to solve the mind/body problem. To this I agree. The mind/body problem seems intractable, and it's difficult to see how Boyle's mechanical philosophy could help. But this doesn't damage the importance of its role in the scientific revolution. Alternatively, Gabbey could be claiming that the mechanical philosophy failed to provide a mechanism that could explain the physical differences in the colour spectrum. If this is what he is claiming then he is simply mistaken. And his mistake is that he oversimplifies the relationship between Boyle's mechanical philosophy and the corpuscular hypothesis. It is true that the corpuscular hypothesis was ill equipped to deal with the complexities of light-wavelength analysis. But there is still a mechanical explanation for how different colours are produced: the differences are caused by differences in the length of light waves, specifically distances between the peaks of each wave of electromagnetic radiation. Although the corpuscular hypothesis has long since been rejected, part of Boyle's mechanical philosophy, specifically his criteria for what counts as legitimate scientific explanation, has survived. The great philosopher of science Wesley Salmon expresses a view similar to my own when he writes about later versions of the mechanical philosophy.

> The difficulty with this late nineteenth-century version of the mechanical philosophy lies not in the fundamental philosophical perspective, but, rather, in its misconception of the basic

> mechanisms that actually operate in the physical world. We realize today that the mechanical properties of such material objects as springs and gears require explanation in terms of the fine structure of macroscopic objects. We recognize, for example, that electromagnetic forces play a crucial part in explaining such structures. Because of Maxwell's electromagnetic theory and Einstein's special theory of relativity, we now believe that the electromagnetic field has fundamental physical reality. Electromagnetic phenomena are not to be explained in terms of the behavior of a mechanical medium. The situation is just the reverse. The mechanical properties of the macroscopic objects used by Lord Kelvin to make his models are to be explained in terms of the properties of fields and of the waves that propagate through such fields . . . The propagation of such waves through these fields is a fundamental causal mechanism in our universe. We have to change our mechanistic view from the crude atomism that recognizes only the motion of material particles in the void to a conception that admits such nonmaterial entities as fields, but for all that, it is still a mechanistic worldview. Materialism is untenable, but the mechanical philosophy, I believe, remains viable.[19]

Such a view is supported by the fact that contemporary scientists describe their theories in mechanical terms. This point will be discussed in detail in Chapter 7, but for now consider a few examples. Natural selection has long been described as a mechanical process.[20] Medical researchers have described their work as the search for genetic mechanisms that trigger viruses. And for some time cognitive scientists have drawn important mechanical analogies between computers and the human brain that bear a striking similarity to the early modern mechanical analogies between the universe and the inner workings of a clock. The mechanical model of explanation is an indispensable tool in contemporary science.

Let's now reconsider the passage from Boyle's *The Origine of Formes and Qualities*. Boyle is confident, and perhaps excessively optimistic, that mechanical explanations which appeal exclusively to the geometric properties of corpuscles can adequately explain qualities such as heat, colour, firmness, and fluidity. But he also has the foresight to mention the possibility that *learned friends* and *ingenious men* might discover other, more successful, mechanical affections. Boyle's mechanical philosophy cannot be completely separated from the corpuscular hypothesis, but part of this mechanical philosophy is an epistemological theory about what counts as legitimate scientific explanation. In order to successfully explain a quality, a describable mechanism that demonstrates just how the quality is produced is required.

In order to demonstrate this we need to look at Boyle's mechanical philosophy in more detail. The next chapter considers the various positions that have been held regarding the intelligibility of mechanical explanations. Boyle's own position is examined in detail followed by the interpretations raised by the historical, philosophical, and sociological Boyle scholarship. The next two chapters focus on a specific group of mechanical explanations that Boyle endorsed throughout the course of his work: the mechanical interpretation of fire analysis. The third chapter presents a detailed account of several objections that Boyle employs against elemental interpretations of fire analysis. The first section of this chapter deals with the proper identification of Boyle's philosophical targets. As we shall see, the common belief that Boyle is primarily attacking Aristotelian and Paracelsian theories is an oversimplification. Boyle's main philosophical target in *The Sceptical Chymist* is actually represented by the character Elutherius, who advocates a complex hybrid system employing five chemical principles: Salt, Sulphur, Mercury, Earth, and Phlegm. I argue that Elutherius was intended to represent Nicaise LeFevre, a famous French alchemist active in England during the 1660s. With the primary target of *The Sceptical Chymist* identified, the model of explanation that underlies all elemental theories is revealed. Inspired by Peter Alexander's *Ideas, Qualities and Corpuscles*, I then present a detailed analysis of the eight major objections against elemental interpretations of fire analysis that Boyle raises in *The Sceptical Chymist*.

Chapter 4 considers Boyle's corpuscular interpretations of fire analysis and compares them to *The Sceptical Chymist* objections. In order to do this I consider how Boyle's theory of combustion developed over the course of his work. Thus, we take a look at several interesting sources spanning Boyle's scientific career, including works such as *The Sceptical Chymist*, 'The dialogue on heat and flame', 'Absolute rest in bodies', *The Origine of Formes and Qualities*, and 'The mechanical origin of heat and cold'. His interpretation begins with the theory, presented in *The Sceptical Chymist*, that heat is reducible to corpuscular agitation. This theory is little different from the simple atomistic theory of heat advanced by Lucretius and rediscovered in the sixteenth century. But this simple theory of combustion develops over the course of Boyle's work, becoming a sophisticated theory that explains combustion in terms of specific mechanical modifications of corpuscles and that provides a detailed account of the diverse phenomena observed in the fire-analysis experiments.

Chapter 5 explores the nature of mechanical explanation and the aspects of Boyle's mechanical philosophy that survive the death of the corpuscular hypothesis. Drawing on the work completed in the previous chapters, we examine each of Boyle's mechanical affections and how these mechanical affections are employed in scientific explanations.

Chapter 6 presents a more detailed analysis of the most important member of Boyle's list of mechanical affections: the contrivance of parts. This mechanical affection and its relationship to similar concepts such as order, position, and arrangement are explored, as well as the use of such concepts in the theories of mechanical philosophers such as Descartes and Galileo. Then the important relationship between mechanical explanations and the related concepts of the capacity for prediction and the mathematization of nature are explored.

The final chapter demonstrates the presence of the mechanical model of explanation in contemporary science. Several examples of contemporary mechanical explanations are presented including natural selection, DNA, plate tectonics, and the formation of arms in spiral galaxies. The application of the mechanical characteristics presented in Chapters 5 and 6 are identified and explored.

In order to identify these mechanical characteristics we must begin by identifying Boyle's criteria for legitimate scientific explanation. We will ultimately have to consider the objections that he raises against elemental interpretations of fire analysis. But we must begin by understanding the importance of intelligibility to the mechanical model of explanation, and how the views regarding its importance have been developed over time. The next chapter is devoted to this endeavour.

Notes

1. It should be noted that throughout this book the term 'element' is being used in the early sense of a primitive or simple body out of which a compound body is composed and not in the modern sense of a chemical entity that remains unchanged through a chemical reaction. Also, by 'elemental theory' I mean a theory that employs entities of this kind (whether referred to as elements or principles) in explaining the properties or composition of compound bodies.
2. Examples include Joseph Duchesne, Daniel Sennert, and Nicaise LeFevre.
3. See, for instance, Aristotle (1941), *Metaphysics*, in Richard McKeon (ed.), *The Basic Works of Aristotle*. New York: Random House, 791–802 (1032a–1037b).
4. See Aristotle (1941), *On Generation and Corruption*, in Richard McKeon (ed.), *The Basic Works of Aristotle*. New York: Random House, 511–12 (330a–331a).

5. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 222.
6. Beguin, Jean (1669), *Tyrocinium Chymicum*. London, 19–24.
7. Alexander, Peter (1985), *Ideas, Qualities and Corpuscles: Locke and Boyle on the External World*. Cambridge: Cambridge University Press, 17.
8. Anstey, Peter (2000), *The Philosophy of Robert Boyle*. London: Routledge, 24.
9. It is also interesting that Boyle recognizes the discovery of occult qualities as part of the scientific process. You observe a strange phenomenon, label it as an occult quality and then try to explain it mechanically. Kenneth Stikkers has pointed out that this is similar to the discovery of black holes. Physicists first labelled the anomalous phenomena and then examined different mechanisms to explain it.
10. See Boas-Hall, Marie (1965), *Robert Boyle on Natural Philosophy*. Bloomington, IN: Indiana University Press, 59.
11. Boyle, Robert (1999), 'New experiments and observations touching cold', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 4, 208–9.
12. It is important to note that even occult explanations had some strengths. For example, Aristotelian primary qualities were part of a comprehensive and internally consistent cosmology.
13. Boyle, Robert (1999), *The Origine of Formes and Qualities*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 5, 302.
14. Shapin, Steven (1996), *The Scientific Revolution*. Chicago, IL: University of Chicago Press, 42 (see footnote 11).
15. Gabbey, Alan (1985), 'The mechanical philosophy and its problems: mechanical explanations, impenetrability, and perpetual motion', in Joseph Pitt (ed.), *Change and Progress in Modern Science*. Dordrecht: D. Reidel, 12.
16. Gabbey, Alan (1985), 'The mechanical philosophy and its problems: mechanical explanations, impenetrability, and perpetual motion', in Joseph Pitt (ed.), *Change and Progress in Modern Science*. Dordrecht: D. Reidel, 11.
17. One might be tempted to object that the jinni can be empirically tested as well by opening the rock to see if an imp-like creature is inside. But remember, one of the features of my jinni explanation was that the jinni could only be described as the cause of the rock's mysterious sound.

18. Gabbey, Alan (1985), 'The mechanical philosophy and its problems: mechanical explanations, impenetrability, and perpetual motion', in Joseph Pitt (ed.), *Change and Progress in Modern Science*. Dordrecht: D. Reidel, 12.
19. Salmon, Wesley (1984), *Scientific Explanation and the Causal Structure of the World*. Princeton, NJ: Princeton University Press, 241.
20. See Dennett, Daniel (1995), *Darwin's Dangerous Idea*. New York: Simon & Schuster.

2

On the Intelligibility of Mechanical Explanations

Before we compare Boyle's mechanical interpretation of fire analysis to the objections advanced in *The Sceptical Chymist* it will be helpful to consider the various positions that have been held regarding one of the most important purported strengths of the mechanical model of explanation: its superior intelligibility. In the previous chapter we were exposed to a general overview of the development and diversity of Boyle scholarship, but now we must consider how that scholarship addresses the specific topic of intelligibility. Attitudes about the intelligibility of mechanical explanations can be found in all the areas of Boyle research discussed in the previous chapter, and provide a method of identifying important trends in the scholarship. For example, the traditional view that categorizes Boyle as *modern* generally acknowledges the superior intelligibility of mechanical explanations. On the other hand, much of what I have described as the sociological research calls its superior intelligibility into question. The purpose of this chapter is to map out the various positions regarding the intelligibility of Boyle's mechanical philosophy.

We begin by considering Boyle's own position regarding the strengths of mechanical explanations. Interest in the intelligibility of mechanical explanations began with his earliest work in natural philosophy and lasted throughout his philosophical career. The next section of the chapter focuses on the views concerning the intelligibility of the mechanical philosophy expressed in the historical scholarship. It is this area of research that gives rise to the traditional interpretation of Boyle's role in the scientific revolution. This is an interpretation that I wish, at least in part, to defend.

However, it is important to note that some recent historical research rejects this traditional interpretation.[1] Next we consider positions on the intelligibility of mechanical explanations raised in the philosophical scholarship. This area generally accepts and elaborates on the traditional view. Finally we consider the sociological scholarship. Recent work in this area rejects the superior intelligibility of mechanical explanations, criticizes Boyle's role in the scientific revolution, and sometimes questions even the existence of the scientific revolution itself.[2]

It is important to keep in mind that I am approaching this issue from the point of view of a philosopher, rather than a sociologist or even a historian of science. That is, I am primarily interested in the nature of scientific explanation and what Boyle's philosophy has to say about it. I am also interested in the ways in which scientific theories develop and change. Much of the biographical, historical, and sociological research has a bearing on these issues. Obviously, Boyle's own philosophical convictions have a bearing on issues in sociology and the history of science. Research concerning the intelligibility of mechanical explanations is found in each area of Boyle scholarship, and it's important to recognize the diversity of approaches to this topic.

Boyle on the intelligibility of mechanical explanations

According to Boyle, one of the major strengths or advantages of the mechanical philosophy is the inherent intelligibility of mechanical explanations. He considered this to be a major epistemological benefit. Where he criticized the elemental model for the vacuous nature of its occult explanations, he praised the mechanical philosophy for its explanatory power. He believed that the mechanical model offered explanations that were easier both to comprehend and to clearly express. It offered the possibility of mathematical description. It also allowed efficient theory evaluation through prediction and experimentation.[3] Boyle refers throughout his career to the significance of the mechanical philosophy's superior intelligibility. It is a belief that develops very early in his scientific work and a belief that he never abandons.

Recently, Lawrence Principe has made a valid point attacking scholars holding the traditional view who have used scraps of unrelated passages from Boyle's vast corpus to support the interpretation of Boyle as a modern, while ignoring the vast time and effort he devoted to such non-modern pursuits as alchemy. But this is not the case with Boyle's position on the intelligibility of mechanical explanations. As we shall see, Boyle develops this position from his earliest scientific writings, and his interest in the issue continues steadily throughout his scientific career. Furthermore, Boyle's position regarding the intelligibility of mechanical explanations is completely compatible with his alchemical pursuits. This will be explored in more detail in the section of this chapter on historical scholarship below.

The essay 'Of the study of the booke of nature' was written before 1655 and perhaps as early as 1649, shortly after the construction of Boyle's first laboratory at Stalbridge, and is generally considered to be his earliest work on natural philosophy.[4] It contains Boyle's first mention of the scope and limitations of mechanical explanations. Boyle, like other mechanical philosophers of the period such as Descartes, believed that mechanical hypotheses were sufficient to explain natural phenomena, but he realized that the actual mechanism employed in nature, as well as the cause of that mechanism's creation, might be different than that of the hypothesis being advanced. These natural philosophers believed that God's omnipotence allows for the possibility that the same phenomenon might be caused by a different mechanism than the one described in even a successful explanation, success here being described in terms of clarity, prediction, and experimental corroboration. In other words, mechanical explanations are useful in a Baconian sense because they can provide efficient theory evaluation through prediction and experiment, but their use is limited nevertheless due to the possibility that the actual mechanism employed by God to produce the phenomenon might be different (even vastly different) than the mechanism described in a mechanical explanation. Thus mechanical explanations are sufficient but not necessary – an alternative mechanism that explains the same phenomenon just as successfully might be conceivable. In the following passage Boyle begins his treatment of this issue by claiming that mechanical affections such as size, figure, and contrivance can explain natural phenomena without supporting atheism. Boyle writes:

> 'Tis not the Knowing too much, but not knowing enuf that makes the Naturalists Atheists. Nor would I desire better sport then to meet with one of these confident Assertors; that deny God made the World because they thinke they can assigne the true Causes of all Effects in it, tho the Supreme Cause be left out. For the suttlest Filosopher in the World shall never be able to assigne the true & immediate Cause of the outward shape & Bulke, the Inward Contrivance of the Parts, & the Instincts & Sympathys of any one Animall, the Primitive formes & seminall Energys of things depending wholly upon the Will of the First Creator.[5]

Another important early source for Boyle's view concerning the intelligibility of mechanical explanations is the unfinished essay 'The requisites of a good hypothesis breefely consider'd in a dialogue between Carneades, Elutherius, Themistius, & Zosimus'. This work was most likely written in the late 1650s and was later developed into 'About the excellency and grounds of the mechanical hypothesis', published in 1674. In this early work, Boyle describes intelligibility as a necessary condition for successful scientific explanation. He writes:

> To convince men that an *Hypothesis* cannot be a good one without being an intelligible one there needs no other argument then to consider the very scope or design for which *hypotheses* have been framd. For an hypothesis is a *supposition* (whether true or fals) that men have pitched upon, or devis'd, as a Principle, by whose help phaenomenon wherto it is to be applyd may be *explicated*, that is clearly deducd from causes understood, And from this nature & scope of an hypothesis, tis obvious to infer, that it ought to be more clear & known than the *phenomena* it is to explain & if it be not intelligible when proposed, it cannot but be useless when applyd, And to go about to illustrate the obscure transactions of nature, by an obscure hypothesis, is as improper as to attempt to shew a man his way in the dark with an unlighted torch.[6]

Boyle goes on to criticize concepts employed by Aristotelians and chemists such as *entelechia*, *gass*, and *blass*. He describes these concepts, as well as the hypotheses that employ them, as obscure and unintelligible. Unfortunately the surviving fragment of the essay ends abruptly at this point.[7]

In both of these early passages we see that the issues regarding natural philosophy grow out of Boyle's broader theological and ethical concerns. Boyle is eager to distance himself from the atheistic atomism of Epicurus, and demonstrate the compatibility of the mechanical philosophy with Christianity. It is also interesting to note that in 'Of the study of the booke of nature' Boyle employs the infamous mechanical analogy of the watch in his presentation of an early teleological argument for the existence of God (long before William Paley's use of the same argument). Boyle also mentions the contrivance of parts. Both the use of mechanical analogies as well as the contrivance of parts are essential components of the mechanical philosophy and are discussed in greater detail in later chapters.

In his famous work *Of The Usefulness of Natural Philosophy*, first published in 1663, Boyle proclaims that the mechanical philosophy is sufficient to explain natural phenomena without appeal to any supernatural cause other than God, the designer of the mechanism's structure. This claim is very progressive considering its social and historical context. The primary target of this attack is, of course, occult qualities as well as concepts such as entelechies, substantial forms, and natural motions, all of which Boyle took to be occult. Consider the following passage:

> . . . All the things that appear in the World, may, and must be perform'd by merely corporeal Agents; or if you please, That all Natures *phaenomena* may be produc'd by the parcels of the great Mass of Universal Matter, variously shaped, connected, and mov'd. As a Man that sees a screw'd Gun shot off, though he may not be able to describe the number, bigness, shape, and coaptation of all the Pieces of the Lock, Stock, and Barrel, yet he may readily conceive that the Effects of the Gun, how wonderful soever they may seem, may be performed by certain pieces of Steel or Iron, and some parcels of Wood, of Gunpowder, and of Lead, all fashioned and put together according to the exigency of the Engine, and will not doubt, but that they are produc'd by the power of some such Mechanical Contrivance of things purely Corporeal, without the assistance of spiritual or super-natural Agents.[8]

It is very interesting to note that here Boyle claims that the existence of a mechanism can be inferred without direct observation of the mechanism itself. Likewise, Boyle believed that the mechanisms involved in natural phenomena were often unobservable directly. It also should be noted that in the essay the passage above is first presented as an objection, but Boyle goes on to say that he agrees with its illustration and even supports the sentiment with another example, this time the famous clock at Strasbourg. Here he writes:

> Though a skillful Artist, admitted to examine and consider it, both without and within, may very well discern that such Wheels, Springs, Weights, and other Pieces of which the Engine consists, being put together in such a coaptation, are sufficient to produce such and such Motions, and such other Effects as the Clock is celebrated for, yet the more he discerns the aptness and sufficiency of the parts to produce the Effects emergent from them, the less he will be apt to suspect that so curious an engine was produc'd by any causal concurrence of the Parts it consists of, and not rather the skill of an intelligent and ingenious Contriver.[9]

Boyle was, of course, ignorant of the mechanism of natural selection, and thus was unaware that such unintelligent features of nature as self-replication, mutation, and the finite nature of environmental resources can over time provide the illusion of intelligent design. Natural selection as an example of the mechanical explanation in contemporary science will be discussed in detail below in Chapter 7. For now it is important only to note that by 1663 Boyle was thoroughly convinced of the superior intelligibility of the mechanical model. Once a person examines a gun, clock, similar mechanism, or by extension a natural phenomenon, they can learn how the mechanism produces its effects or can infer that such a mechanism exists even if it cannot be directly observed. Thus, there is no need to posit occult or supernatural causes (other than God).

Although we cannot always examine the internal mechanism of a natural phenomenon, as the skilled artist in the passage examined the clock, we can justifiably infer the presence of a mechanism, just as the person who sees a gun shot off from a distance can infer the presence of a mechanism without directly observing the mechanism itself. To modernize the example, imagine that a person, without taking it apart, examines a modern, ornamental gun, the trigger mechanism of which is concealed in a decorative box. Boyle believed that such a person, even if they had never seen a gun before, would be justified in inferring the presence of an internal mechanism that causes the gun to produce its dramatic effects. Also controlled experimentation on the gun could yield important information about the nature of the mechanism without the aid of its direct observation. For example, the person might observe the shape and contrivance of the bullets that the gun fires, and be justified in inferring that the mechanism contains some kind of pin that strikes the bullet in a consistent and distinct way.

Boyle once again praises the intelligibility of the mechanical model a year later in the controversial book *Experiments and Considerations Touching Colours*. Here he claims that mechanical affections such as position, texture, and shape are both intelligible and fertile in the explanation of such natural phenomena as light and the operations of the eye. Boyle considers a common example advanced by seventeenth-century chemists: the black colour of sulphur that has undergone torefaction. In this process the sulphur is subjected to a scorching heat in order to drive off volatile ingredients, resulting in a black colour. This substance is not only black, but can cause other substances to turn black upon contact. Boyle seeks a mechanical explanation of this phenomenon in the following passage:

> When we are told that torrify'd Sulphur makes bodies Black, I desire to be told also, why Torefaction makes Sulphur itself Black. Nor will there be any Satisfactory Reason assigned of these Quaries, without taking in those Fertile as well as Intelligible Mechanical Principles of the Position and Texture of the Minute parts of the body in reference to the Light and the Eye . . . To be short, those I reason with, do concerning Blackness,

> what the Chymists are wont also to do concerning the other Qualities, namely to content themselves to tell us, in what Ingredient of a Mixt Body, the Quality enquir'd after, does reside, instead of explicating the Nature of it, which (to borrow a comparison from their own Laboratories) is much as if in an enquiry after the cause of Salivation, they should think it enough to tell us, that the several Kinds of Praecipitates of Gold and *Mercury*, as likewise of Quick-silver and Silver (for I know that make and use of such Praecipitates also) do Salivate upon the account of the *Mercury*, which though Disguis'd abounds in them, whereas the Difficulty is as much to know upon what account *Mercury*, itself, rather than other Bodies, has that power of working by Salivation. Which I say not, as though it were not *something* (and often the most we can arrive at) to discover in which of the/Ingredients of a Compounded Body, the Quality, whose Nature is sought, resides, but because, though the Discovery itself may pass for *something*, and is oftentimes more than what is taught us about the same subjects in the Schools, yet we ought not to think it *enough*, when more Clear and Particular accounts are to be had.[10]

In this lengthy, rambling passage we see several very interesting components of Boyle's philosophy. He once again proclaims the superiority of the mechanical philosophy, describing its principles as both fertile and intelligible. We also see a specific example of what he saw as a fundamental flaw in the elemental model of explanation. Here, the property of blackness is explained in terms of the existence and proportion of elements or chemical principles without ever explaining how the property is produced. On the other hand, explanations that appeal to properties such as position and texture have more empirical content, are not vacuous, and lend themselves to mathematical description and efficient evaluation through prediction and experiment.

In the essay 'An introduction to the history of particular qualities' Boyle reasserts the advantages of the mechanical philosophy over the elemental model. Here he describes the mechanical model of explanation as being both more fertile and more comprehensive than the elemental model. He writes:

> ... The foure Peripatetick Elements, and the three Chymical Principles are so insufficient to give a good account of anything near all the differing Phaenomena of Nature, that we must seek for some more Catholick Principles; and that those of the Corpuscular Philosophy have a great advantage over the other/in being far more fertile, & comprehensive then they.[11]

This is perhaps the clearest example of Boyle's position on the intelligibility of mechanical explanations. Boyle goes on to support this position by citing mechanical interpretations of several natural observations new to his time such as the shape and figure of lunar mountains, the existence of sunspots, and the then recently observed difference between the colours of the planets. Boyle claims that such phenomena cannot be accounted for by appealing to the four elements or their mixtures, nor those of the three Paracelsian principles, both of which are confined to sublunary explanations. Although he doesn't go into detail, Boyle goes on to list more potential sources of support for the mechanical model including solar eclipses, lunar eclipses, the satellites of Jupiter, the acceleration of descent in heavy bodies, the strange properties of magnets, and the ebbing and flowing of the sea.

In the essay 'The usefulness of mechanical disciplines to natural philosophy', first published in 1671, Boyle takes a somewhat different approach to the issue of intelligibility. Here he praises the study of mechanics for providing both concepts and mechanical analogies that can be used as tools for natural philosophy. This provides interesting information as to why he found the mechanical model superior in intelligibility. Boyle begins by offering a broad definition of mechanics. He writes:

> To prevent the danger of Stumbling (as they speak) at the Threshold, I shall begin this Discourse with advertising you, that I do not here take the Term *Mechanicks* in that stricter and more proper sense, wherein tis wont to be taken, when tis us'd onely to signifie the Doctrine about Moving Powers (as the Beam, Leaver, the Screws, and the Wedg,) and of framining Engines to multiply Force; but I here understand the word *Mechanicks* in a larger sense, for those Disciplines that consist of the Applications of pure Mathematicks to produce or modifie Motion in inferior Bodies: so that in this sense they comprise not onely the vulgar Staticks, but divers other Disciplines, such as Centrobarricks, Hydraulicks, Pneumaticks, Hydrostaticks, Balisticks, &c. the Etymologie of whose names may inform you about what Subjects they are conversant.[12]

This broad definition of mechanics suggests that Boyle saw a common feature among these disciplines. One important common feature is that all of the disciplines listed above employ explanations that appeal exclusively to mechanical affections such as size, shape, motion, and the contrivance of parts, all of which will be discussed in Chapter 5. Boyle goes on to claim that mechanics provides the natural philosopher with explanatory tools that are capable of providing accounts of everyday phenomena that have greater clarity than those of the elemental model. Consider the following passage:

> The Mechanical Disciplines help me to devise and judg of such *Hypotheses*, as relate to those Subjects wherein the Notions and Theorems of Mechanicks either ought necessarily to be consider'd, or may usefully be so. Of this we have Instances, not onely in those Engines that are Artificial, and are lookt upon as purely

> Mechanical, as the Screw, the Crane, the Balance, &ct. but in many familiar *Phaenomena*, in which the Theorems of the Mechanicks are not wont to be taken notice of to have an Interest: As *in* the carrying a Pike or Musket on one's shoulder, *in* the force of Stroaks with a longer or shorter Sword or other instrument, *the* taking up and the holding a Pike or Sword at Armes-length, and the power that a Rudder has to steer a Ship; *in* rowing with Boats, *in* breaking of Sticks against one's Knee, and in a multitude of other familiar Instances, of which the Naturalist's skill in Mechanicks will enable him to give a far more clear and solid Account, than the Ancient School-men or the Learned'st Physitians that are unacquainted with the Nature and Properties of the Center of Gravity, and the several kinds of Leavers, the Wedges, &c.[13]

In the above passage Boyle cites several examples of concepts borrowed from mechanics that are employed in the mechanical explanation of *familiar* phenomena. It is important to note that Boyle acknowledges not only the concepts of mechanics but also the use of analogies drawn from mechanics as important tools in the production of mechanical explanations. For example, it is easier to break a stick over one's knees if the position of the knee is placed in the centre of the stick. Boyle does not mention just how an Aristotelian or 'learned physician' would explain this phenomenon. Rather, he simply claims that it can be more clearly understood by employing mechanical concepts and analogies. The ability of a small rudder to steer a great ship can be clearly explained exclusively in terms of matter and local motion without appealing to mysterious properties inherent in either the water or the wood and metal out of which the ship and rudder are made.

Boyle goes on to claim that this method of investigation is also useful in the study of nature. Consider this from an epistemological point of view. Once you draw this mechanical analogy, and start looking at the world as if it was an intentionally designed mechanism, you begin to see mechanisms in the natural world. The ideas developed from the viewpoint of this explanatory model can be efficiently evaluated through the use of prediction and controlled experimentation. They can also account for phenomena not easily reconciled with elemental theories. Boyle writes:

> Nay there are several Doctrines about Physical things, that cannot be well explicated, and some of them not perhaps so much as understood without Mechanicks. That which emboldens me to propose a thing that seems so Paradoxical is, That there are many *Phaenomena* of Nature, whereof though the Physical Causes belong to the Consideration of the Naturalist, and may be render'd by him; yet he cannot rightly & skilfully give them without taking in the Causes *Statical*, Hydrostatical &c. (if I may so name them) of those *Phaenomena*, i.e. such Instances as depend upon the knowledg of Mechanical Principles and Disciplines.[14]

Boyle then cites the interesting example of the ability of wood to float in water. The Aristotelians, he claims, account for this phenomenon by appealing to the element Air, out of which the wood is partially composed. Since air is lighter than water and has a natural upward motion, the wood does not sink. But Boyle claims that such an explanation will not satisfy a naturalist well versed in the study of hydrostatics. Rather than having a positive quality of levity, the wood's ability to float is proportional to the density of the liquid. He writes 'when wood is not heavier than so much water, as is equal to it in bulk, it will swim; yet in case it be heavier than so much water it will sink'.[15] He then points out that some liquids can even cause stones or iron to float, substances that admittedly have a small, if any, amount of the element Air.

In the *Excellency of Theology Compared with the Natural Philosophy* of 1674 Boyle clearly states the foremost goal of the mechanical philosophy: to explain all natural phenomena in terms of matter and local motion. This is a common feature of the theories of several mechanical philosophers of the seventeenth century including Galileo, Descartes, and Gassendi. Boyle was committed to the union of the mechanical philosophy with the corpuscular hypothesis, but was unaware of the limits of this creative but crude atomism. The natural world is more complex. Its phenomena cannot be exhaustively accounted for by appealing to the local motion of corpuscles. The nature of matter is fundamentally different than what Boyle imagined. Nevertheless, the explanatory model on which the corpuscular hypothesis was based has remained one of the primary models of science. In the following passage Boyle explains the relationship between the mechanical philosophy and other sources of knowledge as well as its place in our overall understanding of the universe, arguing for its compatibility with God's divine plan and what he believed to be the revealed truth of the Bible:

> The Gospel comprises indeed, and unfolds the whole Mystery of Man's Redemption, as far forth as 'tis necessary to be known for our Salvation: And the *Corpuscularian* or Mechanical Philosophy, strives to deduce all the *Phaenomena* of Nature from Adiaphorus Matter, and Local Motion. But neither the Fundamental Doctrine of Christianity, nor that of the Powers and Effects of Matter and Motion, seems to be more than an Epicycle (if I may so call it) of the Great and Universal System of God's Contrivances, and makes but a part of the more general Theory of things, knowable by the Light of Nature, improv'd by the information of the Scriptures: So that both of these Doctrines, though very general, in respect of the subordinate parts of Theology and Philosophy, seem to be but members of the Universal Hypothesis, whose Objects, I conceive, to be *the Nature, Counsels, and Works of God, as far as they are discovered by us (for I say not to us) in this Life*.[16]

This passage expresses both the limitations of the mechanical philosophy as well as the limitations of human understanding in general. Boyle thought that the mechanical philosophy complemented Christianity and allowed an understanding of the physical aspects of God's clockwork creation. But the knowledge obtained by this model as well as the knowledge obtained from the Bible comprises only a portion of God's divine plan.

Boyle published another important work in 1674: 'About the excellency and grounds of the mechanical hypothesis'. Here he once again points to intelligibility as a great strength of the mechanical philosophy. This essay is a great source for understanding the reasons that Boyle held mechanical explanations to be more intelligible than the explanations based on the elemental model. He begins by covering a lot of the same ground covered in the 'The requisites of a good hypothesis'; the elemental model appeals to concepts that are vague, obscure, and vacuous, while the mechanical model appeals to concepts that are clear and easily comprehended. Boyle writes:

> The *first* thing that I shall mention to this purpose is the Intelligibleness or Clearness of Mechanical Principles and Explications. I need not tell you, that among the *Peripateticks*, the Disputes are many and intricate about *Matter*, *Privation*, *Substantial Forms*, and the *Eduction*, &c. And the *Chymists* are sufficiently puzzled, (as I have elsewhere shown,) to give such definitions and accounts of their Hypostatical Principles, as are reconcileable to one another, and even to some obvious *Phaenomena*. And much more dark and intricate are their Doctrines about the *Archeus*, *Astral Beings*, *Gas*, *Blass*, and other odd Notions, which perhaps have in part occasion'd the darkness and ambiguity of their expressions, that could not be very clear, when their Conceptions were far from being so. And if the principles of the *Aristotelians* and *Spagyrists* are thus obscure, 'tis not to be expected, the Explications that are made by the help onely of

> such Principles should be clear. And indeed many of them are either so general and slight, or otherwise so unsatisfactory, that granting/their Principles, 'tis very hard to understand or admit their applications of them to particular *Phaenomena*. And even in some of the more ingenious and subtle of the *Perapatetick* Discourses upon their superficial and narrow Theories, me thinks, the Authors have better plaid the part of *Painters* than *Philosophers*, and have onely had the skill, like Drawers of Landskips, to make men fancy, that they see Castles and Towns, and other Structures that appear solid and magnificent, and to reach to a large extent, when the whole Piece is superficial, and made up of Colours and Art, and compris'd within a Frame perhaps scarce a yard long. But to come now to the *Corpuscular* Philosophy, men do so easily understand one anothers meaning, when they talk of *Local Motion*, *Rest*, *Bigness*, *Shape*, *Order*, *Situation*, and *Contexture* of Material Substances; and these Principles do afford such clear accounts of those things, that are rightly deduc'd from them onely, that even those *Peripatetics* or *Chymists*, that maintain other Principles, acquiesce in the Explications made by these, when they/can be had, and seek not any further, though perhaps the effect be so admirable, as would make it pass for that of a hidden Form, or Occult Quality.[17]

Explanations of what we would describe as macro-phenomena that appeal to mechanical principles such as size, shape, and local motion are easy to understand. Boyle believed that the properties of matter did not change at the micro-level. Thus mechanical explanations of natural phenomena, even if the mechanisms were too small to be directly observed, were more intelligible, clear, and understandable than explanations based on the elemental model. In typical Boyle fashion, he goes on to support such claims by appealing to several examples: the belief of the *East-Indians* that lunar eclipses are caused by the moon losing consciousness, from which it must be roused, or the ghost-like image of a man thought to be caused by witchcraft, which is, in reality, caused by the light reflected by a concave spherical glass. Boyle claims that mechanical explanations of such phenomena are sufficient in both clarity and intelligibility to dispel the superstitions of anyone who takes the time to listen to the arguments.

He then claims that the major obstacle to the mechanical philosophy as a tool for the naturalist is not that the explanations lack clarity, but that Aristotelians and Paracelsians mistakenly believe that such explanations can be only seldom applied, and cannot provide a basis for the overall investigation of nature. Boyle writes:

> The Corpuscular Principles have been declin'd by Philosophers of different Sects, not because they think not our Explications clear, if not much more so, than their own; but because they imagine, that the applications of them can be made to but a few things, and consequently are insufficient.[18]

Boyle then launches a discussion of the nature of matter and motion, arguing that God, rather than mysterious properties inherent in the nature of matter, causes the motion of material bodies. Furthermore, matter and motion are the most basic, clear, and simple concepts that the naturalist can employ, neither being resoluble into the other. Again, Boyle was ignorant of the true complexity of matter, as well as the contemporary view that matter and energy are ultimately identical. Still, Boyle correctly praises the potential of a few simple and intelligible mechanical affections such as motion, figure, size, order, and texture to account for a wide variety of natural phenomena.

In the revealing essay 'Experiments, notes, &c. about the mechanical origin or production of divers particular qualities', published between 1675 and 1676, Boyle goes into a lengthy discussion of the scope and limitations of mechanical explanations. Boyle begins by restating his earlier view that though mechanical explanations are more intelligible than explanations based on the elemental model, such explanations are only sufficient rather than necessary in the investigation of natural phenomena. Boyle writes:

> If I took upon me to demonstrate, that the Qualities of bodies *cannot* proceed from (what the Schools call) *Substantial Forms*, or from any other Causes but Mechanical, it might be reasonably enough expected, that my Argument should directly exclude them all. But since, in my Explications of Qualities, I pretend only, that they *may* be explicated by *Mechanical Principles*, without enquiring, whether they are explicable by any other; that which I need to prove, is,/not that Mechanical Principles are *necessary* and *onely* things whereby Qualities may be explain'd, but that probably they will be found *sufficient* for their explication. And since *these* are confessedly more manifest and more intelligible than *Substantial Forms* and other Scholastic Entities (if I may so call them) 'tis obvious, what the consequences will be of our not being oblig'd to have recourse to things, whose existence is very disputable, and their nature very obscure.[19]

Here Boyle is essentially claiming that mechanical explanations are more parsimonious than explanations based on the elemental model. Since it is at least possible that qualities are caused by entities such as substantial forms, mechanical explanations are not necessary explanations. However, if a quality can be clearly and intelligibly explained by appealing exclusively to mechanical principles, such explanations are sufficient and the postulation of obscure, occult entities is not warranted. It should once again be noted that in this section my goal is merely to report Boyle's position on the intelligibility of mechanical explanations, not to defend this position or its representation of Aristotelian philosophy. Critics of this representation, such as Helen Hettab, have argued that in some passages Boyle oversimplifies Aristotle's philosophy. Such criticisms have some merit.

Another passage in this essay is very interesting. It also makes the point that mechanical explanations can be more intelligible than elemental explanations without being true by necessity. More importantly, it indicates that future investigations into natural phenomena might yield better and more accurate mechanical explanations. This progressive view is important because it shows Boyle's acknowledgement of the limitations of his own corpuscular theories as well as his belief that such limitations are compatible with the success of the underlying model of explanation behind his theories. Any particular mechanical explanation might eventually be rejected and replaced, but Boyle was confident that it would be replaced by another mechanical explanation. This suggests that the epistemological benefits of the mechanical philosophy were more important to Boyle than the metaphysical commitments of his particular variation of it. He writes:

> I do not undertake, that all of the following Accounts of Particular Qualities would prove to be the very true ones, nor every Explication the best that can be devis'd. For besides that the difficulty of the Subject, and Incompleatness of the History we yet have of Qualities, may well deterre a man less diffident of his own abilities than I justly am, from assuming so much to himself, it is not absolutely necessary to my present Design. For, Mechanical Explications of natural Phaenomena do give so much more satisfaction to ingenious minds, than those that must employ *Substantial Forms*, *Sympathy*, *Antipathy*, &c. that the more judicious of the vulgar Philosophers themselves prefer them before all others, when they can be had; (as is elsewhere shewn/at large) but then they look upon them either as confined to Mechanical Engines, or at least but as reaching to very few of Nature's *Phaenomena*, and, for that reason unfit to be received as Physical Principles. To remove therefore this grand Prejudice and Objection, which seems to be the chief thing that has kept off Rational Inquirers from closing with the Mechanical

Philosophy, it may be very conductive, if not sufficient, to propose such Mechanical accounts of Particular Qualities themselves, as are intelligible and possible, and are agreeable to the *Phaenomena* whereto they are applied. And to this it is no more necessary that the account propos'd should be the truest and best that can possibly be given, than it is proving that a Clock is not acted by a vital Principle (as those *Chineses* thought, who took the first, that was brought them out of *Europe*, for an *Animal*,) but acts as an Engine, to do more than assign a Mechanical Structure made up of Wheels, a Spring, a Hammer, and other Mechanical pieces, that will regularly shew and strike the hour, whether this Contrivance be or be not the very same with that of the Particular Clock propos'd; which may indeed be made to move either with Springs or Weights, and may consist of a greater or lesser number of/ Wheels, and those differingly scituated and connected; but for all this variety 'twill still be an Engine. I intend not therefore by proposing the Theories and Conjectures venture'd at in the following Papers, to debar my self of the Liberty either of altering them, or of substituting others in their places, in case a further progress in the History of Qualities shall suggest better *Hypotheses* or Explications. And 'twas agreeable to this Intention of mine, that I should, as I have done, on divers occasions in the following Notes, imploy the word *Or*, and express my self somewhat doubtingly, mentioning more than one Cause of a *Phaenomenon*, or Reason of an opinion, without dogmatically declaring for either; since my purpose in these Notes was rather to shew, it was not necessary to betake our selves to the Scholastic or Chymical Doctrine about Qualities, than to act the Umpire between the differing *Hypotheses* of the *Corpuscularians*; and, provided I kept my self within the bounds of Mechanical Philosophy, my design allowed me a great latitude in making explications of the *Phaenomena*, I had occasion to take notice of.[20]

The importance of this passage cannot be overstated. Many important issues concerning the intelligibility of the mechanical model are discussed. First, Boyle claims that mechanical explanations are so clear and intelligible that even the advocates of the elemental model prefer them when they can be had. Boyle again argues that the main obstacle to the acceptance of the mechanical model in natural philosophy is not its intelligibility, but rather the mistaken view that its application is very limited, containing the capacity to explain only mechanical engines and a few natural phenomena, but not broad enough to be the basis of an explanatory model. Here, Boyle is not clear about who it is that accepts the limited use of mechanical explanations. Furthermore he fails to explain why the clarity and intelligibility of the mechanical explanations of natural phenomena such as heat, cold, dryness, and moistness do not convince those that accept mechanical explanations of the workings of macroscopic artificial engines.

Nevertheless, the above passage offers an interesting mechanical analogy that seems to show that Boyle valued the explanatory model behind the mechanical philosophy more than any particular mechanical explanation or theory. This is a point that will be discussed in more detail in Chapter 6. Boyle points again to the common mechanical metaphor of the clock. He argues that one might be justified in inferring the presence of an internal mechanism that produces the effects of the clock without direct observation of this mechanism. He further claims that the mechanical model retains its superior intelligibility even if the actual mechanism advanced in the explanation is mistaken. Imagine a mysterious stranger who observes the actions of a clock and claims that they are produced by an internal mechanism. When asked to elaborate, he claims that the mechanism involves a precise contrivance of wheels, gears, and springs. The outer covering of the clock is then removed and it turns out that his explanation was incorrect both in terms of the number of gears and in terms of the source of the clock's energy. The gears are moved by weights rather than springs. Here the particular explanation was wrong, but the explanatory model was correct. According to Boyle, the stranger's explanation, though mistaken, was still superior in clarity and intelligibility to an explanation based on the elemental model, and might even have been a sufficient explanation in terms of prediction and experimentation.

A final point concerning this passage is Boyle's progressive confidence in the mechanical model. Boyle was a devout corpuscularian, but he also had the foresight to realize that future work in natural philosophy might replace his explanations with other mechanical theories. Boyle speaks of 'further progress in the history of qualities', and places this progress 'within the bounds of the mechanical philosophy'. This again shows that Boyle valued the epistemological strength of the mechanical philosophy as a model of explanation, rather than merely a metaphysical doctrine about the corpuscular nature of the world. It also suggests, and this point will be developed later in more detail, that recent criticisms of Boyle's mechanical philosophy miss the point and come close to attacking a straw man by rejecting the mechanical philosophy solely because of the limitations of Boyle's crude corpuscularianism. Boyle's corpuscular hypothesis is wedded to the mechanical philosophy, but its main strength is an epistemological position on the nature of scientific explanation that transcends the limitations of the simple atomic explanations that he advanced.

Boyle falls back into the habit of speaking of the corpuscular hypothesis and the mechanical philosophy as synonymous in an essay entitled 'Experiments and notes about the producibleness of chymicall principles', first published in 1680. This essay was originally intended to be an appendix to *The Sceptical Chymist*. That Boyle often conflates the two is not surprising once we understand that Boyle believed the corpuscular hypothesis to be a tool in the production of mechanical explanations that had an almost limitless flexibility. He was devoted to the idea that an appeal to a few simple mechanical properties such as size, shape, motion and contrivance of small material corpuscles could produce an endless variety of phenomena. But even given this devotion, he was committed more deeply to the mechanical model of explanation that underlies it. In an interesting passage towards the beginning of the essay Boyle once again praises the intelligibility of the mechanical philosophy. But here he also claims that he is open to the possibility of alternatives, should sufficient evidence be produced. The discussion here is focused on the claims of some of his contemporary alchemists to have produced chemical principles. Recent work by Lawrence Principe has demonstrated that Boyle had a long and profound interest, bordering on obsession, with alchemy in general and transmutation in particular.[21] This interest is shown in the following passage. Here Boyle writes:

> . . . If there be such adept *Philosophers* as some speak of (which I thinke not Incredible) and if they have (which supposing there be such I think not unlikely) among other rare things some *Alkahestical* or other ordinary potent *Menstruum*, or way of penetrating and working upon mixt bodies; they may for ought I know be able to obtaine such substances from them, as may induce me, and perhaps the Chymists too, to entertaine other thoughts about the constitution of compounded bodies (as they are wont to be call'd) than either I or they now have. And therefore though as to Naturall *Philosophy* in general I do not expect to see any Principles propos'd more comprehensive and intelligible than the *Corpuscularian* or Mechanical;/yet as to the subordinate Theory of mixt bodies in particular, I that have disputed only against the vulgar Hypothesis of the *Chymists* can easily retain a disposition to receive further light in this matter, when those that are the best able to afford it us, and from whom it will be no disparagement for much greater proficients than I, to learn, shall think fit to oblige us by doing so.[22]

Boyle was interested in the possibility of transmutation as well as the possibility that chemical substances could be produced by artificial means. But as important as his interest in alchemical pursuits is, it should also be noted that Boyle believed that such phenomena could be explained, as any other natural phenomena, by exclusively mechanical principles. Nevertheless, it seems that Boyle did not want to be a dogmatic supporter of the mechanical philosophy. He interpreted the strength of mechanical explanations in terms of intelligibility and comprehension, but if another theory offered superior intelligibility and comprehension he seems willing to have accepted it. This line of reasoning, even if mere rhetoric, does seem consistent with his criticisms of the elemental model.

As we have seen, Boyle's position on the intelligibility of the mechanical philosophy developed over the course of his philosophical career. In the beginning, he recognized the importance of intelligibility in the formulation of successful scientific hypotheses, but was sceptical about the scope of mechanical explanations, claiming that such a model could produce only sufficient rather than necessary explanations. As his interest in natural philosophy grew he became more confident in the strength of the mechanical model, eventually claiming that its goal was to explain all natural phenomena in terms of matter and local motion. But this enthusiasm was gradually replaced by a more cautious and mature approach in his later writings. Boyle's criterion of intelligibility is still present, as well as his confidence in the mechanical philosophy. But towards the end of his career Boyle also seems open to the possibility that other models of explanation might provide even more intelligible accounts of natural phenomena than the mechanical philosophy. This, mixed with his lifelong theistic wonder at the nature of the universe, produced a more humble attitude towards the success of scientific endeavours. It can be seen very clearly in the book *A Free Enquiry* *into the Vulgarly Receiv'd Notion of Nature* first published in 1686. Boyle writes:

> . . . Though Mechanical Principles could not be *satisfactorily* imploy'd for explaining the *Phaenomena* of our World; we must not therefore necessarily recur to, and acquiesce in, that Principle, that Men call *Nature*, since neither will That intelligibly explain Them: But in that Case, we should ingeniously confess, That we are yet at a loss, *how* they are perform'd; and that this Ignorance proceeds, rather/from the Natural Imperfection of our Understanding, than from our not preferring *Nature* (in the Vulgar Notion of It,) to the Mechanical Principles, in the Explication of the *Phaeomena* of the Universe. For whereas *Monsieur Des Cartes*, and other acute Men, confidently teach, that there are scarce any of these *Phaenomena*, that have been truly and intelligibly deduc'd from the Principles peculiar to the *Aristotelians* and *School-Philosophers*; it will scarce be deny'd by any that is acquainted with Physico-Mathematical Disciplines, such as Opticks, Astronomy, Hydrostaticks, and Mechanicks, more strictly so call'd, but that very many Effects (whereof Some have been handled in this present Tract,) are clearly explicable by Mechanical Principles; which, for that Reason, *Aristotle* himself often imploys in his *Questiones Mechanicae* and elsewhere. So that, if because the Corpuscularian Principles, cannot be *satisfactorily* made/Use of to account for all that happens among Things Corporeal, we must refuse to acquiesce in them; it is but just, that, since a Recourse to what is call'd *Nature* is yet more dark and insufficient, at least, we must reject as well the Later as the Former *Hypothesis*, and endeavor to find some Other preferable to Both.[23]

In this passage Boyle admits that there might be natural phenomena for which the mechanical philosophy cannot provide a clear and intelligible explanation. But he claims that this is due to a natural limitation of human understanding rather than a failure of the mechanical model of explanation. He also claims that this limitation of the mechanical philosophy does not warrant a return to the elemental model of explanation, which he still takes to be epistemologically inferior. It should also be noted that Michael Hunter has pointed out that the work *Questiones Mechanicae* is spuriously attributed to Aristotle. It is possible that Boyle's pessimism about natural philosophy is due to his commitment to exclusive corpuscularian mechanisms in his own scientific explanations. As we have seen, Boyle acknowledged the possibility that other mechanical affections might exist. But he does not speculate about their nature. Perhaps this shows that Boyle was becoming aware of the limitations of the corpuscular hypothesis while retaining a confidence in the mechanical model of explanation. In any case, it is clear that Boyle remains committed to his criterion that successful investigations in natural philosophy require explanations that are both clear and intelligible.

The best way to conclude this section on Boyle's own position concerning the intelligibility of mechanical explanations is to consider two interesting passages from 'An appendix to the first part of *The Christian Virtuoso*', published posthumously in 1744 from notes written in the late 1680s and early 1690s. In the first passage Boyle clarifies his use of terms such as 'unintelligible', 'inconceivable' and 'incomprehensible'. He writes:

> By the word therefore inconceivable or unintelligible, may be understood such a thing, as we cannot frame an idea or conception of, that is not either self-destructive (as having one part inconsistent with another); or else clearly repugnant to some manifest and acknowledged truth, whether taught us by mere reason, or by natural reason assisted by revelation. By incomprehensible may be meant such a thing, as,/though we may frame symmetrical ideas of it (i.e.) such as are consistent within themselves, and not repugnant to any known truth; do not yet contain or involve divers things, that we are not able thoroughly to

penetrate, and perfectly to understand. And by incredible things, may be understood those, which, whether or no they belong to either of the former sorts, are not accompanied with such evidence of reason, as either do not probably, or at least do not sufficiently prove their truth, notwithstanding the objections, that seem to make them altogether unfit to be assented to.[24]

In this fascinating passage Boyle draws a distinction between the seemingly synonymous concepts of unintelligibility and incomprehensibleness. Here he describes as unintelligible ideas that are either inconsistent or contradict other true ideas, while he describes as incomprehensible ideas that cannot be clearly understood. This seems at odds with many passages in which he describes as unintelligible explanations he finds to be empty and vacuous. Perhaps explanations based on the elemental model that he so often criticizes contain hidden contradictions and inconsistencies. But this is not his general objection. What he finds most objectionable in the elemental model is the vacuous and empty explanations that it advances, explanations that label a phenomenon without clearly describing how it is produced, or explain a phenomenon by the mere presence of an ingredient without describing exactly how its presence produces the relevant effects.

How is this inconsistent usage to be explained? Perhaps it cannot be explained. Boyle often employed terms inconsistently. For example, because of their intimate relationship in Boyle's eyes, he often uses the phrases 'corpuscular hypothesis' and 'mechanical philosophy' interchangeably when a detailed analysis clearly shows that the mechanical philosophy refers to a broader set of philosophical commitments that extends beyond the interaction of corpuscles. Perhaps this inconsistent usage of the term 'unintelligible' can be explained in a similar way. Such a view may be supported by the observation that in the above passage he uses the term 'unintelligible' as a modification of the term 'inconceivable'. This term is more or less employed by Boyle in the way described.

An idea that is 'inconceivable' is either inconsistent or contradicts an acknowledged truth. Perhaps 'unintelligible' would have been better used as a modification of 'incomprehensible'. Such a modification more accurately reflects the most common usage of the term 'unintelligible' in Boyle's vast corpus.

The second interesting passage in 'An appendix to the first part of *The Christian Virtuoso*' restates Boyle's conviction that the mechanical philosophy can produce sufficient explanations of natural phenomena, but that such explanations are not necessarily true due to the possibility of other mechanisms and origins of production. This has been a common theme in Boyle's writing on the subject and stems from a desire to appreciate God's omnipotence. Here Boyle writes:

> Though a skilful mechanical philosopher may plausibly explicate many of these difficult phaenomena in a general way, so as to shew, that they may be possibly produced, according to mechanical principles; yet the particular modus continues in the dark; and even the general explications suppose some fabrick of the world, and such an origin, and such laws of motion, as involve difficulties, that confound our weak understanding.[25]

Both of these passages must be interpreted in light of the context in which they were written. In this part of the appendix to *The Christian Virtuoso*, Boyle is defending Christianity against potential objections that could be raised from the standpoint of an atheistic natural philosophy. Boyle admits that his faith encourages a belief in articles that 'surpass our reason'. If this is the case, and intelligibility is a necessary condition of successful explanation, then it follows that many articles of faith cannot be successfully explained. It is in this context that Boyle describes the difference between concepts such as inconceivability and incomprehensibility. It is also in this context that Boyle indicates the scope and limitations of the mechanical philosophy. The mechanical model is an incredibly useful tool in the scientific investigation of nature. But it is not a method of discovering necessary truth. Even a mechanical explanation that is successful in terms of intelligibility, prediction, and experimental corroboration might inaccurately describe the actual mechanism that produces the phenomenon and/or the origin of the mechanism itself. This goes to show that Boyle was not a blind advocate of the truth of the mechanical philosophy. He was very confident of its application as a tool in the investigation of nature, and could find no other model of explanation that was its superior in terms of clarity and intelligibility. But he also recognized the inherent limitations of such a model and of the scientific endeavour itself.

As we have seen in the many passages concerning the intelligibility of the mechanical philosophy that occur throughout his scientific writing, Boyle sincerely believed that the mechanical model offered explanations that were superior to the elemental model in terms of clarity and intelligibility. But it is also true that Boyle did a lot to advertise the advantages of the mechanical model. At times he seems almost desperate to portray himself as a modern and to distinguish his activities and investigations from his predecessors (and even contemporaries). This had a significant influence on the views about the mechanical philosophy's intelligibility that have developed since Boyle's death. The most direct impact is on what I have described as the historical research. The alleged inherent intelligibility of mechanical explanations was compatible with the interpretation of Boyle as a modern, and helped develop the traditional view of Boyle's role in the scientific revolution. In the next section we can see this development as well as the reaction against it.

Historical views on the intelligibility of mechanical explanations

As we saw in the previous chapter, Boyle scholarship in the area of the history of science is both developed and quite diverse. For the purpose of this chapter I want to focus on the important work of a few outstanding historians: Rupert Hall, Marie Boas-Hall, Richard Westfall, Michael Hunter, and Lawrence Principe. These notable historians can be divided into two general groups, Hall, Boas-Hall and Westfall falling into a traditional group, and Hunter and Principe forming a more contemporary group.

Rupert Hall set the stage for the traditional interpretation of the scientific revolution in his comprehensive book *The Revolution in Science: 1500–1750*, first published in 1954. Hall generally follows Boyle's position on the intelligibility of the mechanical philosophy. Early in the work he criticizes the elemental model of explanation in words reminiscent of both Boyle and Descartes, writing:

> We can as little apprehend the pigment of a flower by naming it yellow as the nature of a star by calling it twinkling. The world of direct sense experience is, almost universally, a texture of deceptions for physical reality is totally different and cannot possibly be described in the language of sensations.[26]

Here Hall is pointing out a general limitation of both the Aristotelian and Paracelsian theories. A quality cannot be explained by merely labelling it. The mechanical model is superior in terms of clarity and intelligibility because it offers a mechanism that attempts to describe how the quality is produced.

But Hall does not blindly follow Boyle's position. While he recognizes that the mechanical model was valued by the seventeenth-century philosophers chiefly for its intelligibility and simplicity, he claims that its greatest strength is the capacity of its explanations to be quantified and accurately measured. Hall continues:

> What is the point of this claim, apart from making the observer humble and sceptical about his sensations? Perhaps to us the chief advantage of the rejection of qualities is that shape, size,

> number, and motion can all be measured, where subjective sensations cannot; but the early tradition emphasized rather the intellectual simplicity of materialism: all substances could in principle be reconstructed from a small group of postulates, typically of the form: matter is composed of particles varying in size, shape, and motion; and further each property is capable of modification.[27]

Another interesting divergence is that while Hall accepts the explanatory superiority of Boyle's mechanical explanations, he interprets the mechanical philosophy's importance to the scientific revolution more in terms of quantification and experimentation rather than epistemology and intelligibility. For example, a lengthy discussion of Boyle focuses almost exclusively on his experimentation, its innovations and shortcomings, while generally ignoring his epistemological achievements.[28] Nevertheless, Hall accepts the intelligibility of mechanical explanations and sees the scientific revolution as a radical shift away from magic and occult explanations in favour of a genuinely modern approach to science. At one point he writes, 'What did happen was that about 1640 mathematical, mechanical, and experimental science became quite strong enough to need no magical or other esoteric prop'.[29] As we shall see shortly, contemporary historians of science, most notably Lawrence Principe, call such a radical shift into question.

Perhaps the greatest Boyle scholar of all time, with the possible exception of Michael Hunter, is the historian of science Marie Boas-Hall. In the late 1950s and early 1960s she dominated the study of Robert Boyle with two influential books, *Robert Boyle and Seventeenth-Century Chemistry* and *Robert Boyle on Natural Philosophy*. While her work has been recently criticized for glorifying Boyle's achievements and downplaying his shortcomings, the scope and detailed quality of her work cannot be ignored. She advocates Boyle's position on the intelligibility of the mechanical model and interprets this, I think correctly, as a major contribution to the scientific revolution. Boas-Hall is so impressed with the intelligibility of mechanical explanations that on her account, Boyle's mechanical philosophy is not only explanatorily superior to the elemental model of explanation, but also superior to the mechanical philosophies advanced by Descartes and Gassendi.[30]

In her first book, *Robert Boyle and Seventeenth-Century Chemistry*, Boas-Hall begins by claiming that Boyle's mechanical philosophy could explain nature without appealing to occult qualities. She writes:

> [Boyle] was much influenced by Cartesian mechanism (he even began, at one time, a discussion of the Cartesian view of animals as non-sentient 'engines'), and he particularly welcomed the concept of a world governed and explicable by the principles of mechanics, that is to say by matter and motion. This was a world from which all occult properties had been banished, yet which left explicit room for a Divine Creator, ruling the world through divinely devised immutable laws, so that mechanism and religion were combined in a truly English compromise.[31]

Boas-Hall claims that the mechanical philosophy was theoretically different from the Aristotelians and that this theoretical aspect is the greatest legacy of the mechanical philosophy. In this work Boas-Hall does tend to put Boyle on a pedestal. She sees Boyle completely as a modern, and ignores or downplays the many activities pursued by Boyle that could not be described as modern, or she describes these activities with a positive spin. According to Principe, this interpretation of Boyle is one of the elements that led to the popularity of the uncritical traditional interpretation of Boyle's role in the scientific revolution.

Principe's work will be discussed in more detail shortly, but for now I just want to point out that Principe's remarks are correct in a general sense, but when you consider some of the specific passages, while Boas-Hall exaggerates Boyle's modernity, she is also on the right track. For example, Boas-Hall claims that Boyle's application of the mechanical model to chemistry helped make it a truly modern natural philosophy. She writes:

> [Boyle] spent a great deal of time on purely chemical explanations, as will be apparent from the discussion of contemporary chemical theory; but he always tried to add the physical explanation, which he found not only to be more exalting, as Lemery thought it, but ultimately both more true and more interesting. To a certain extent this helped him; in other ways it hindered him. At least it kept him in the straight and narrow path of mechanical, rational explanations, and helped him to banish occult explanations from chemistry so that it could, as he longed to have it do, be regarded by both chemists and physicists as true natural philosophy.[32]

As Principe has demonstrated, the practice of alchemy had, by the seventeenth century, become sophisticated enough, even in terms of important scientific issues such as quantification, to be considered a true natural philosophy in the sense that Boas-Hall is using. But she is on the right track emphasizing the importance of Boyle's application of the mechanical model of explanation to chemistry.

Boas-Hall's next book is an excellent collection of previously unavailable Boyle essays entitled *Robert Boyle and Natural Philosophy: An Essay with Selections From His Writings.* In the substantial introduction to this material, Boas-Hall reaffirms her devotion to the superior intelligibility of mechanical explanations, valuing their importance to science more than even Boyle himself. Here she claims that mechanical explanations are uniquely intelligible due to their appeal to coherent concepts such as matter and local motion. Furthermore she claims that the success of such explanations implies that the world is inherently explicable, sometimes claiming that there is nothing that the mechanical philosophy cannot, in principle, explain. Consider the following passage:

> The Corpuscular philosophy could explain each and every property, merely by using facts of matter and motion, without recourse to imaginary occult forces or undetectable principles, like elements, spirits, attractions, and so on. Matter and motion are facts, experimentally detectable; they are intelligible, and their use to explain the properties of bodies makes the world intelligible as well, and the power of the creator even more wonderful.[33]

Another important passage is the following:

> There was, in fact, nothing, according to Boyle's view, that the corpuscular philosophy could not illuminate, make plain, or explicate. This was its great glory, that it did so much without being dogmatic, and with the aid of experiment. Whatever has been occult before became rational and reasonable when understood in the light of corpuscular philosophy.[34]

In many passages Boas-Hall agrees with what she claims to be Boyle's position on the intelligibility of mechanical explanations. She claims that Boyle not only supported the view that the mechanical model was explanatorily superior to the elemental model, but also believed that the world was inherently explicable and that there was nothing that the mechanical model could not explain. As we have seen in the last section, this is an exaggeration of Boyle's mature position. Boyle does hold that the mechanical philosophy is inherently superior to the elemental model due to its greater intelligibility. But Boyle's religious convictions led him to reject the idea that the world was completely explicable. God's ways are mysterious. He has revealed information about the human condition, according to Boyle, and he has given us a useful tool in the study of nature. But there could be information about the world that falls outside the scope of these two groups, information that might be beyond the finite minds of humans. We have also seen that Boyle recognized that the specific mechanism posited in even a successful mechanical explanation might be mistaken. This is certainly not compatible with the view ascribed to Boyle by Boas-Hall.

Still, Boas-Hall's study of the remarkable material in *Robert Boyle on Natural Philosophy* does have merit. She is the first I have found to discuss Boyle's philosophy in terms of explanatory models. She describes his position on occult qualities accurately, and even sets the discussion in terms of occult explanations, which I find attractive. Finally, she recognizes, if exaggerates, the importance of the mechanical model of explanation to modern science, and gives Boyle more *philosophical* credit than other historians of science, such as Rupert Hall, allow.

The final historian of science representing the traditional approach to be considered in this chapter is Richard Westfall. His book *The Construction of Modern Science: Mechanisms and Mechanics* was first published in 1971, and at the time was a ground-breaking study in the importance of mechanical explanation to the scientific revolution. Westfall recognizes that the mechanical philosophy was created to overcome the explanatory problems with occult qualities, and supports the traditional interpretation that seventeenth-century science comprised a 'fresh start', breaking with the scientific practices of the past. Westfall goes on to claim that the mechanical philosophers of the seventeenth century wanted to reveal the true cause of every natural phenomenon, believing that there was nothing in nature that the mechanical philosophy could not explain.

But there are also parts of Westfall's work that do not toe the traditional Hall/Boas-Hall line. For example, according to Westfall, it is Descartes who provides the most influential philosophical foundation of the mechanical philosophy. While this claim has some merit, Westfall fails to acknowledge the important philosophical contributions, specifically in the area of epistemology, made by Boyle. In fact, in his discussion of the philosophical underpinnings of the mechanical philosophy, Boyle is not even mentioned. Westfall writes:

> No one man created the mechanical philosophy. Throughout the scientific circles of western Europe during the first half of the 17th century we can observe what appears to be a spontaneous movement toward a mechanical conception of nature in reaction against Renaissance Naturalism. Suggested in Galileo and Kepler, it assumed full proportions in the writing of such men as Mersenne, Gassendi, and Hobbes, not to mention less well known philosophers. Nevertheless, René Descartes (1596–1650) exerted a greater influence toward a mechanical philosophy of nature than any other man, and for all his excesses, he gave to its statement a degree of philosophic rigor it sorely needed and obtained nowhere else.[35]

Westfall indeed makes a strong case for the importance of Descartes to the conceptual framework of the mechanical philosophy, but as we shall see, Boyle's contribution to working out the explanatory function of the mechanical philosophy to scientific practice is significant, and arguably even more important to the formation of modern science than Descartes' impressive metaphysical work.

More importantly, Westfall also strays from the traditional interpretation of the intelligibility of mechanical explanations by claiming that the mechanical model not only had problems, but also actually held back scientific progress. He argues that the dogmatic search and production of imaginary mechanisms stifled scientific creativity when other strategies would have been more productive. This is an attitude quite different from that of other traditional historians of science such as Marie Boas-Hall. Consider the following passage:

> In the 17th century, the mechanical philosophy defined the framework in which nearly all creative scientific work was conducted. In its language questions were formulated; in its language answers were given. Since the mechanisms of 17th century thought were relatively crude, areas of science to which they were inappropriate were probably frustrated more than encouraged by its influence. The search for ultimate mechanisms, or perhaps the presumption to imagine them, diverted attention continually from potentially fruitful enquiries and hampered the acceptance of more than one discovery. Above all, the demand for mechanical explanations stood in the way of the other fundamental current of 17th century science, the Pythagorean conviction that nature can be described in exact mathematical terms. Despite its rejection of a qualitative philosophy of nature, the mechanical philosophy in its original form was an obstacle to the full mathematization of nature, and the incompatibility of the two themes of 17th century science was not resolved before the work of Isaac Newton. Meanwhile, virtually no scientific work in the 17th century stood clear of its influence, and most of the work cannot be understood apart from it.[36]

Westfall is certainly correct to point out the crude nature of seventeenth-century mechanisms, and his thoughts on the relationship between the mechanical philosophy and the mathematization of nature foreshadow discussions in the later work of Steven Shapin. But Westfall fails to appreciate the importance of the new explanatory model that the mechanical philosophy supplied, a model that not only allowed the mathematization of nature but also encouraged mathematization as it matured. The relationship between the mechanical model of explanation and the mathematization of nature will be explored in more detail in Chapter 6. For now, let us note the legitimate existence of tension between the two, in the early stages of the mechanical philosophy, and move on to consider the views of two recent historians of science who have dominated contemporary historical research on Boyle.

The first contemporary interpretation of the intelligibility of mechanical explanations in the historical scholarship comes from the work of Michael Hunter, second, in my opinion, only to Marie Boas-Hall in the ranks of Boyle scholars. Hunter's mission in recent years has been to expand our understanding of Boyle through the exploration of his religious interests and a detailed analysis of how this influence affected Boyle as a scientist. This project is apparent throughout Hunter's work, but can be seen most directly in his two books: *Robert Boyle by Himself and His Friends* and *Robert Boyle: Scrupulosity and Science*.

However, the most important sources for his view concerning the intelligibility of mechanical explanations is the substantial introduction to the 1996 Cambridge edition of Boyle's *A Free Enquiry into the Vulgarly Received Notion of Nature*, edited by Michael Hunter along with Edward B. Davis. Here Hunter approaches Boyle's view on the intelligibility of mechanical explanations from the perspective of his religious motivations. Hunter claims that Boyle did indeed view mechanical explanations as inherently more intelligible than explanations that placed mysterious powers in nature itself. But according to Hunter, this stance is, in part, motivated by Boyle's desire to preserve the sovereignty of God. Thus the mechanical philosophy was not only *explanatorily* superior to Aristotelian natural philosophy, but also *theologically* superior because it placed the direct cause of natural phenomena in the hands of God rather than in nature. Hunter writes:

> Only the mechanical philosophy, in Boyle's view, banished all chimeras of an intelligent nature, and this seemed to him a powerful argument in its favour. In his opinion, it had two main advantages. First, by giving a more coherent and intelligible explanation of natural phenomena, it held out the possibility of genuine progress in the medical and mechanical arts,

> potentially fulfilling the utopian vision of Bacon that was never far from Boyle's thoughts. Second, by removing intermediaries between God and the world, the mechanical philosophy benefited theology by underscoring divine sovereignty and fighting against the paganistic tendencies of Neoplatonism and related ideas.[37]

According to Hunter, the mechanical philosophy was therefore a very attractive alternative to other forms of natural philosophy practised in the seventeenth century, including materialist versions of the mechanical philosophy rejected by Boyle on theological grounds. In another interesting passage, Hunter gives a more direct account of the traditional interpretation of Boyle's view of the intelligibility of mechanical explanations. He writes:

> Mechanical philosophers . . . did not hesitate to invent invisible mechanisms of unseen particles to explain such phenomena as gravitation and magnetism. They believed that they were giving more plausible explanations than the scholastics, not because they had made the causes more visible but because they had made them more intelligible and, in a few important cases such as atmospheric pressure, more directly testable. Mechanical explanations, they thought, are automatically more intelligible than explanations in terms of forms and qualities: what could be easier to understand than the working of a clock or an automaton? When Boyle invoked such analogies, as he frequently did in [*A Free Enquiry into the Vulgarly Received Notion of Nature*], he was appealing to the intuitions and experiences of an increasingly technical culture.[38]

In this passage Hunter claims that Boyle, along with other mechanical philosophers of the seventeenth century, appealed to the inherently superior intelligibility of mechanical explanations over explanations that employ forms and qualities. He also mentions the importance of the use of mechanical analogies to such explanations, as well as their experimental testability. But unlike Boas-Hall, Hunter implies, along the same lines as Westfall, that mechanisms were often hastily invented by mechanical philosophers, and were not always empirically verifiable.

The last interpretation by a historian of science that we will consider is the important recent work of Lawrence Principe. In two great books, *The Aspiring Adept: Robert Boyle and his Alchemical Quest* and *Alchemy Tried in the Fire: Starkey, Boyle, and the Fate of Helmontian Chymistry* (with William Newman), Principe has contributed immensely to our understanding of Boyle. In both works he criticizes various historians of science who distort the evidence to support the view of Boyle as a modern, while ignoring the vast amount of time and effort that Boyle devoted to such non-modern pursuits as alchemy. In *The Aspiring Adept*, Principe persuasively argues that Boyle had a lifelong interest in such alchemical topics as transmutation and the search for the philosopher's stone. Furthermore, his approach to this pursuit had much in common with traditional alchemy, including the application of secrecy to guard alchemical recipes from the wrong hands. This work shows a side of Boyle that historians such as Boas-Hall chose to de-emphasize and ignore. In *Alchemy Tried in the Fire*, Principe, along with Newman, demonstrates the debt Boyle owes to the American alchemist George Starkey for his chemical education. The work also explores the many parallels and similarities between the chemistry of Boyle and Van Helmont.

Concerning the issue of mechanical explanations, Principe has some interesting things to say. In *The Aspiring Adept*, he points out that Boyle did not exclusively present mechanical explanations, but sometimes presented both mechanical and non-mechanical explanations, side by side. To focus only on the mechanical explanations, as many scholars have, according to Principe, is to paint an overly modern picture of Boyle. Principe writes:

> Boyle's attempts to explain the action of his *menstruum peracutum* bring up the much larger issue of how historians treat Boyle and his texts. Boyle's first explanation, which is based upon the extractability of "Tinging parts," comes directly from traditional alchemical sources that posited the color of gold in its Sulphur. But Boyle subjoins a second explanation ... Now this explanation seems more "modern" and is in accord with the attribution of color to the texture of bodies that Boyle makes elsewhere. But it is important to note that both explanations – one based upon the alchemically informed concept of the extractability of "Tinging parts" and the other upon the effects of texture – exist side by side in Boyle's text. It is Boyle's intentional ambiguity, or rather his hesitancy to commit to a single, exclusive explanation of observable phenomena, that has contributed to selective readings of his writings. In a corpus as prolix and as diverse as Boyle's it is quite possible to pick and choose scraps to support almost any model, but this practice requires the simultaneous dismissal or neglect of points and opinions as valid to their author as those we choose to take up. Historians wishing to emphasize Boyle's commitment to the "mechanical philosophy" can readily take up the texture explanation and neglect the "Tinging parts" explanation. Such selectivity would then show Boyle as more "modern" and more assertive about explanatory models than he himself was willing to be.[39]

In this passage Principe makes a valid point, and supports it with a specific example. He goes on to provide further evidence of parallel explanations in the form of Boyle's treatment of the function of compasses. On several occasions Boyle did offer multiple alternative explanations of phenomena, rather than dogmatically advocating mechanical explanations. We have also seen that Boyle thought there were inherent limitations within the mechanical model. Furthermore, Principe is correct to point out that Boyle's alchemical interest was pursued in a way that was traditional to that field, although it should also be noted that Boyle suspected many traditional alchemical phenomena, such as transmutation, could be explained mechanically. Finally, Principe is accurate in his condemnation of the approach by traditional historians of science that go to great lengths to maintain the view of Boyle as a modern.

But it should also be pointed out that Boyle's faith in the mechanical model lasted throughout his scientific career, from his earliest scientific writing to his last publications, and this includes the large portion of his career in which he pursued alchemy. If anything, his avoidance of dogmatism is a testament to his open mind on the subject of scientific explanation, as we have seen in his willingness to accept non-mechanical explanations should such explanations prove to be more intelligible. It should also be emphasized that one of the goals of this study is to determine what aspects of Boyle's philosophy *have survived* in contemporary science. This justifies, and even necessitates, a focus on his treatment of mechanical explanations. Such a focus can be permitted so long as we respect the fact, expertly documented by Principe, that there are many ways in which Boyle was not a modern scientist.

Philosophical views on the intelligibility of mechanical explanations

In the previous section of this chapter we considered how several historians of science interpreted the intelligibility of mechanical explanations. Generally the goal of such scholars is to accurately depict the people, positions, and events that make up the history of science. Thus, the historical literature on the intelligibility of mechanical explanations seeks to accurately present Boyle's view on the subject rather than to pronounce judgement on that view. This of course is easier said than done, and the diversity of the historical scholarship on this subject bears this out.

What I have termed the philosophical and sociological scholarship seeks to subject Boyle's view to critical analysis. This requires an accurate account of Boyle's view, but goes beyond mere reporting to try to determine if Boyle's view is actually correct. Are mechanical explanations inherently more intelligible than elemental or occult explanations? In this section we consider the views of three philosophers concerning Boyle's claims about the intelligibility of mechanical explanations: Peter Alexander, Steven Nadler, and Peter Anstey.

Peter Alexander's book *Ideas, Qualities and Corpuscles: Locke and Boyle on the External World* has been a great influence on my work, and generally supports the traditional view of Boyle's role in the scientific revolution represented by Hall, Boas-Hall, and, to some extent, Hunter in the historical literature. Basically, Alexander agrees with Boyle that mechanical explanations are more intelligible than elemental explanations, have greater clarity, and more empirical content. Alexander writes:

> Boyle's greatest importance perhaps lay in the fact that he attempted to develop chemical theory on a basis of empirical investigation. He found, especially among the chemists, empirical methods that were confused and imprecise and from which large unjustified inferences were made and, especially among the peripatetics, a great interest in theories but little interest in their empirical confirmation. He also found, in both camps, 'explanations' that were unintelligible or circular and so failed to be explanatory. He was primarily interested in giving clear and confirmable accounts of natural phenomena and he saw that this must begin with accurate descriptions of them. In this he was following Francis Bacon and espousing a fundamental aim of the Royal Society (founded 1662–3). Explanations of the phenomena must make clear how they happened. Explanations require general theories; theories to be plausible must be based upon and checked against the results of observation and

> experiment; and it must be clearly stated how the theory is linked to the observed phenomena in every particular case.[40]

Alexander goes on to further describe the strengths of Boyle's approach in the following passage:

> [Boyle's] aim was to replace principles, elements, forms, and real qualities by inner structures which could be clearly described in terms drawn from experience and which would allow the precise descriptions of mechanisms. These descriptions, even though they would be unobservable structures, would have empirical content and would allow real explanations . . . It was hoped that inferences would be possible from the nature of what was observed, if it was observed in sufficient detail, to the unobserved underlying structures and mechanisms and that descriptions of them in terms we understand could be given. This would allow the intelligible description of the connections between the phenomena and these structures which would have real explanatory power. It also implied that the more careful and detailed the observations and experiments, the more likely they were to reveal and distinguish between the hidden mechanisms.[41]

In these two passages we see the traditional view advanced by other Boyle scholars such as Marie Boas-Hall. Elemental explanations are unintelligible and circular, and not really explanations at all. On the other hand, mechanical explanations are inherently more intelligible because they provide more empirical content and clearer descriptions of how the phenomena are produced. It is interesting to note that Alexander not only claims that mechanical explanations are more intelligible than elemental explanations, but also goes further, describing mechanical explanations as 'real' explanations and elemental explanations as failing to be explanatory.

In the very informative article 'Doctrines of explanation in late scholasticism and in the mechanical philosophy', Steven Nadler goes into more detail regarding the intelligibility of mechanical explanations. He agrees that mechanical philosophers of the seventeenth century generally found the explanations of the neo-Aristotelians to be unsatisfactory, barren, circular, and trivial. The mechanical philosophy, on the other hand, was based on concepts such as matter and motion that exhibited a superior clarity. Nadler also points out Boyle's three requirements for successful explanations. First, the explanation has to be intelligible. It must be clear and understandable, avoiding obscurity. Second, the explanation must be 'primary' and 'simple'. The elements in the *explanans* cannot be further reducible into more fundamental principles. Finally, and most importantly according to Nadler, a successful explanation must not simply identify the agent that causes the phenomenon, but must describe *how* the phenomenon is produced.

However, Nadler also points out some important limitations of mechanical explanations. First, such explanations are inherently hypothetical due to the unobservable and insensible nature of the mechanisms that are posited. Nadler writes:

> Because, however, the structures employed in mechanical explanations are inaccessible to observation, given the minute and insensible size of their constituent entities, any account of the mechanical cause of a phenomenon must necessarily be more or less hypothetical. The *de facto* unobservability of the causal mechanism itself and the in-principle unobservability of its causal efficacy mean that the best one can do is postulate its existence and composition, demonstrate its initial plausibility, and then show why it is preferable to (i.e., more likely than) any other possible explanation.[42]

As we shall see in Chapter 7, mechanical explanations are not always unobservable; many current mechanical theories in contemporary science involve macroscopic, observable phenomena. It is true that the explanations of natural phenomena advanced by the mechanical philosophers of the seventeenth century did posit the existence of unobservable mechanisms. But it should be noted that the unobservability of a mechanism does not necessarily entail that hypotheses concerning the mechanisms cannot be corroborated or falsified. Recall the example of the ornamental gun, the trigger mechanism of which was contained in a decorative box. Although the mechanism was unobservable, the presence of a firing pin could be experimentally corroborated. As we have seen, Boyle regarded such experimental corroboration, as well as the capacity for successful prediction, as examples of the strength of the mechanical philosophy.

A second limitation of mechanical explanation that Nadler identifies is that it assumes uniformity between macroscopic and microscopic worlds. Such uniformity was assumed to exist both in terms of ontological material and qualitative properties. The mechanical explanations of the seventeenth century appealed to qualities such as size, shape, and motion that the atomic and corpuscular entities that they posited possessed, and both atoms or corpuscles and macroscopic objects such as tables and chairs were made of the same material. The superior intelligibility claimed by the mechanical philosophers was due to the fact that the mechanisms employed in their explanations of natural phenomena appealed to the same qualities as those found in the macroscopic mechanisms observed in their everyday lives. This connection between the microscopic and macroscopic worlds also allowed the use of mechanical analogies, such as Boyle's famous analogy of the clock. Nadler writes:

> Two assumptions about the physical world underlie mechanical explanations. First, it is assumed that nature is completely homogeneous in material: In Boyle's words, 'there is one catholic or universal matter common to all bodies', whether at the

> microscopic or macroscopic level. The insensible particles are not materially different from the larger bodies which they compose (in fact, this must necessarily be the case, since the larger bodies are nothing more than collections of particles). Second, nature is uniform in its operations. The same operations characterize, and the same laws govern the observable behavior of complex bodies. This ontological and nomological uniformity allowed mechanists to employ models from the macroscopic world to represent the microscopic, insensible structures and operations constituting their explanations.[43]

It is interesting to note that we now know the microscopic level of reality is radically different than the macroscopic level. Such crude explanations as those advanced by the mechanical philosophers of the seventeenth century are not sophisticated enough to account for the diverse properties of matter. Nadler's focus is undoubtedly the mechanical explanations of the seventeenth century. However, he writes as if all mechanical explanations assume this uniformity. Once again, we shall see in Chapter 7 that this is not the case. Successful contemporary mechanical explanations exist that do not make this assumption. For example, contemporary theories of chemistry employ mechanical explanations yet do not depend on the uniformity of qualities between the microscopic and macroscopic levels of reality.

In another interesting section of the article, Nadler points out three problems with mechanical explanations that were raised by philosophers of the seventeenth century. First, Nadler points out that even before Leibniz and Newton, philosophers criticized the mechanical philosophy for its failure to satisfactorily explain mental phenomena. Nadler writes:

> One critical issue concerns the limits of mechanical explanation and the identification of those phenomena which cannot be explained mechanically. Descartes, in his claim that 'there is

> no phenomenon of nature' which he has failed to explicate in accordance with his principles, includes not just properties and operations of physical bodies among themselves, but also their effects in the human mind in particular, sensations . . . There is a problem, however, in any attempt at a mechanical causal explanation of mental events. As explained earlier, any such explanation must be framed entirely in terms of matter and motion, with local contact serving as the *sine qua non* of interaction. Since the mind is immaterial and unextended, it cannot come into local contact with an extended material body. This would seem to rule out any kind of causal interaction of a *mechanical* nature between mind and body.[44]

Nadler goes on to cite Princess Elizabeth of Bohemia as an advocate of this concern. Of course, Nadler has in mind the dualism of Descartes when discussing this matter. If reductive materialism is true, then there is no problem with mechanical explanations of the mental. Furthermore, even if dualism is true for some mental phenomena such as consciousness, there are many mental phenomena (cognition, intelligence, memory) that can be explained mechanically. Finally, and this point will be discussed in more detail later, if structure or arrangement is the most important feature of mechanical explanation, then the existence of purely non-physical, mental mechanisms cannot be rejected out of hand because the phenomenal features of our mental states have both structure and arrangement. Of course seventeenth-century critics of the mechanical philosophy were not aware of these points and Nadler is limiting himself to a presentation of their objections. But it is important to point out that even on these matters the mechanical model of explanation is more dynamic than often acknowledged.

According to Nadler, a second problem with the mechanical philosophy that was recognized in the seventeenth century was that many physical phenomena couldn't be explained. Philosophers such as Henry More and Leibniz advanced this criticism, pointing to phenomena such as magnetism, gravity, and elasticity. This led many philosophers to postulate the existence of *plastic powers*, forces, and Leibniz's famous rehabilitation of substantial forms. Nadler writes:

> A second line of criticism came from those who felt that mechanistic principles fail to explain even those natural phenomena that involve bodies alone. Henry More, for example, was skeptical about the success and comprehensiveness of mechanistic explanation boasted of by Descartes. For More, the limits of mechanism are particularly represented by a whole class of physical phenomena which appear to be inexplicable in terms of the 'mere Mechanical powers of matter and motion.' What is needed in such cases is some immanent, active 'immaterial principle' to guide and check the motion of matter.[45]

The mechanical philosophers of the seventeenth century did have trouble explaining properties such as electricity, magnetism, elasticity, and gravity. Boyle may have been aware of this problem because there are a few passages in which he refers to plastic powers, although his general corpuscular theory rejects their existence. But such phenomena, with the possible exception of gravity, were eventually explained by science and these explanations were mechanical explanations.

A final problem that Nadler identifies concerns biology. Many philosophers of the seventeenth century failed to see how the mechanical philosophy could account for several problems concerning life, particularly conception. If animals are merely complex machines, then biological processes such as conception should be explainable mechanically. Nadler writes:

> Besides the kinds of problems in physics picked out by More and Leibniz, the mechanical philosophy faced rather critical difficulties in biology. For example, it was unclear how a

> mechanical explanation could be provided for the origin of life in conception. How could lifeless particles of matter in motion give rise to a living being such as an embryo. That there must be something more to a living creature besides being a mere material machine, however complex, is suggested by Bernard de Fontenelle: 'You say that animals are machines just as much as watches? However, if you put a dog-machine and bitch-machine beside each other, a third little machine may result. But two watches may be next to each other all their lives, without ever producing a third watch.'[46]

This criticism of the mechanical philosophy is simply due to ignorance in the seventeenth century of the actual mechanisms responsible for life. Once genetic mechanisms are understood, it is clearly and intelligibly easy to see how it is that dogs can mechanically produce other dogs, while watches cannot produce other watches. And despite the counter-intuitiveness that Fontenelle found, this difference is largely due to a difference in the complexity of the mechanisms involved.

The best way to conclude this section on the philosophical scholarship is to consider the recent work of Peter Anstey. Anstey's book *The Philosophy of Robert Boyle* is the first work to provide a systematic and detailed analysis of Boyle's philosophy. As we have seen, there are many works on Boyle, but this is the first to look at Boyle exclusively as a philosopher. Early on, Anstey admits that he is primarily concerned with Boyle's metaphysics, and nearly ignores his epistemology and philosophy of science. However, there are a few interesting passages in which he discusses mechanical explanations.

First, Anstey points out that Boyle's explanatory scheme is reductive. Natural phenomena are explained mechanically by reducing them to the products of the size, shape, texture, arrangement, and interaction of corpuscles. Consider the following passage:

> One of Boyle's points of departure from Aristotelianism is the familiar one about explanatory circularity, the point of Molière's famous ridicule that opium puts one to sleep because it has a dormative virtue. Boyle's response is to seek an account of the powers of bodies that offers more explanatory power and more parsimony than the Aristotelian theory. There are a number of strands to his attempts to furnish his readers with a more adequate theory of power-like qualities. But the one that he seems to adhere to most consistently is the principle that *all power-like qualities are reducible to, or in some sense dependent on, the mechanical affections of matter*. Again Boyle was nowhere explicit that this was a reductive principle as such. But most of his treatments of powers are attempts at a reduction of powers to either the primary qualities or relations between corpuscles which themselves are only characterised by the primaries.[47]

The connection between reduction, explanatory power, and mechanical affections that Anstey raises is interesting. He goes on to explain that Boyle focuses on the mechanical affections rather than the similar primary qualities adopted by Locke, because it is the mechanical affections that provide the explanatory power behind his mechanical explanations. Furthermore, these mechanical affections function as reductive principles. Anstey writes:

> Over and over again his accounts of such phenomena as magnetism, chemical reactions, gravity, sensible qualities, etc. are in terms of these 'mechanical affections' of corpuscles. They are the fundamental resources of the mechanical hypothesis. And this furnishes us with at least part of the answer to the question as to why not all the primary qualities of universal matter are included in Boyle's list of primaries. Why are such qualities as divisibility, impenetrability and extension not primaries? At least part of Boyle's answer is that they are not 'mechanical' affections of matter. In Boyle's view they make little or no contribution to the explanatory power of the theory.[48]

Anstey concludes his examination of mechanical explanations with the identification of two necessary conditions for mechanical explanations on Boyle's theory. According to Anstey, these conditions are the source of the explanatory superiority of mechanical explanations. The first condition is that a mechanical explanation must be structural. He points out, in a manner similar to Nadler, Shapin, and Gabbey, that mechanical explanations are types of structural explanation. This draws on the important work in philosophy of science conducted by Ernan McMullin and will be discussed in more detail in Chapter 6. In the meantime, Anstey's point is to acknowledge that a true mechanical explanation must appeal to structure in its description of the phenomenon to be explained. He writes:

> Clearly Boyle's emphasis on the role of the texture of corpuscles enables us to classify many of his explanations of the qualities of bodies as structural, such as his explanation of salts as being composed of stiff and sharp particles. To be sure, sometimes he goes beyond textual considerations and appeals to the shape and motion of atomic corpuscles. But in most, if not all, of these cases it is not incorrect to claim that it is the *structure* of the individual atomic corpuscles that is the *explanans*. Likewise when we turn to Boyle's use of the clock metaphor and allied mechanical metaphors, it is invariably the structure of the components of the machine that are referred to as analogous to the kinds of explanations that the corpuscular hypothesis gives.[49]

The second condition for mechanical explanations that Anstey identifies is what he describes as the familiarity condition. For Boyle, the superior clarity of mechanical explanations derives, at least in part, from its ability to describe the production of the phenomenon in question in familiar, easily understandable terms. By avoiding obscure and unclear concepts and relying on terms that are plain and recognizable, the explanation attains a higher level of intelligibility. Anstey writes:

> The second necessary condition of a reductive explanation for Boyle is that it reduces unfamiliar phenomena, or phenomena that are difficult to understand, to ones that are familiar and easily understood . . . It is the explanation that enables one to 'easily understand one another's meaning' which counts as an adequate one. As Boyle says in the *Forms and Qualities*, 'to explicate a phenomenon being to deduce it from something else in nature more known to us than the thing to be explained by.' He also accepts the contrapositive that phenomena that are inexplicable are those that cannot be understood by things that are familiar to us.[50]

This condition for mechanical explanations creates some interesting problems according to Anstey. One problem is that many of the explanations in contemporary physics, particularly those that postulate the existence of new and bizarre entities, do not seem to meet the familiarity condition. One example that Anstey uses to illustrate a point drawn from M. Friedman is the property of *charm* that is ascribed to quarks. This is an interesting problem but it is not detrimental to my thesis. In Chapter 7 I will demonstrate that the mechanical philosophy is alive and well. There are countless examples of mechanical explanations in contemporary science. But I do not defend the claim that *all* explanations in contemporary science are mechanical explanations, nor that the mechanical model of explanation is the only explanatory model that science employs. Thus in my view it is not problematic that there are some explanations in contemporary science that are not mechanical. Another problem with the familiarity condition that Anstey raises is a variation of Plato's Learner's Paradox found in the *Meno*. Anstey writes:

> The privileged epistemic status of the *explanans* in the familiarity view is that it must already be known. But if scientific knowledge is only acquired through scientific explanation, and the

> only phenomena that can explain are familiar, then one can never know anything unfamiliar. If one knows nothing, then one can never learn, for there is nothing familiar to function as the *explanans*![51]

Here Anstey is dangerously close to attacking a straw man. Boyle's point is that an explanation that depends on concepts that are obscure and unclear is not a coherent explanation at all. Boyle's mechanical explanations appeal to properties that are understandable because they are encountered in our everyday, macroscopic world. Consider an example. Many mechanical philosophers of the seventeenth century, including Boyle, explained heat in terms of atomic or corpuscular agitation. One can understand the concept of agitation but be unaware that heat is reducible to agitation. The knowledge of the one does not entail the knowledge of the other. In other words, knowledge of the *explanans* does not presuppose knowledge of the *explanandum*. But familiarity with the concept of physical agitation makes the mechanical explanation of heat both clear and intelligible.

Sociological views on the intelligibility of mechanical explanations

The last area of Boyle scholarship on the intelligibility of mechanical explanation to be considered is what I have termed the sociological research. This area of research has a lot in common with philosophical scholarship, offering criticism rather than mere description of Boyle's views. I have included it as a separate area due to the underlying similarity in approach to the issue: each of the scholars to be considered, Steven Shapin, Alan Gabbey, and Alan Chalmers, approach the topic from what can be described as a social constructionist point of view. They argue, in one form or another, that the scientific revolution had social/political rather than philosophical causes, and that the alleged superior intelligibility of mechanical explanations amounted to a biased social agreement to count such explanations as intelligible. Another reason I have put them into a separate group is that they represent the primary target of my project.

The most persuasive version of this position comes from the work of Steven Shapin, briefly described in the previous chapter. According to Shapin, there was not a scientific revolution at all.[52] In fact, he claims that historians of science have disputed each feature of the phrase 'the scientific revolution'. He writes:

> As our understanding of science in the seventeenth century has changed in recent years, so historians have become increasingly uneasy with the very idea of "the Scientific Revolution." Even the legitimacy of each word making up that phrase has been individually contested. Many historians are now no longer satisfied that there was any singular event, localized in time and space, that can be pointed to as "the" Scientific Revolution. Such historians now reject even the notion that there was any single coherent cultural entity called "science" in the seventeenth century to undergo revolutionary change. There was, rather, a diverse array of cultural practices aimed at understanding, explaining, and controlling the natural world, each with different characteristics and each experiencing different modes of change.[53]

Shapin's sympathy to this new historical interpretation is understandable. The successes of Newton, Boyle, Descartes, and Galileo have been glorified while their failures, limitations, weaknesses, and occult interests have been downplayed and ignored. Nevertheless, there was a pursuit in the early modern period that could be described as science. Natural philosophy was a recognized branch of philosophy whose importance was steadily increasing. This branch of philosophy was dominated by the theories of Aristotle and Paracelsus, which shared an identifiable explanatory model. This explanatory model was replaced in the seventeenth century with a different model that has become an important feature of science ever since. This gradual but steady rejection of the elemental model of explanation, and its replacement with the mechanical model, is a historically identifiable phenomenon that can be used to justify belief in the scientific revolution.

Shapin is also sceptical of the alleged explanatory superiority of the mechanical philosophy. He claims that the mechanical philosophy was just as occult as the philosophy it attacked. Shapin is also critical of mechanical explanations when he writes:

> Some critically minded historians and philosophers have even wondered whether the claimed global intelligibility of mechanical explanations was more than just practitioners' *agreement* that such explanations would count as more intelligible than alternatives.[54]

Thus, in Shapin's view the superior intelligibility of mechanical explanations was, in reality, a social convention in which mechanical explanations were accepted over non-mechanical explanations for reasons apart from objective, philosophical grounds. He goes on to make the stronger claim that the adoption of the mechanical philosophy over Aristotelian and Paracelsian theories had *exclusively* social and political causes. And this is a point that I find particularly interesting. Shapin is claiming that the 'scientific revolution' did not have any objective, philosophical legitimacy, but was purely a social and political phenomenon. He expresses this position very clearly when he writes:

> The superior intelligibility, and therefore the explanatory power, of the mechanical philosophy was more limited than its proponents claimed. Adherents' conviction that mechanical

> accounts were globally superior to alternatives, and more intelligible, has to be explained in historical rather than abstractly philosophical terms.[55]

Shapin primarily relies on the important work of Alan Gabbey to support these claims. As we saw previously, Gabbey thinks that mechanical explanations were, in many cases, no more intelligible than Aristotelian or Paracelsian theories. Gabbey does recognize that the mechanical philosophy had limited success in dealing with phenomena such as heat. Incidentally, this is one of the reasons I chose to focus on Boyle's mechanical interpretation of fire analysis to uncover the successful traits of the mechanical model. But despite such limited success, Gabbey believed that the mechanical philosophy was inherently flawed. He writes:

> Of the numerous conceptual burdens the Mechanical Philosophy had to bear, the two or three I shall examine were not examples of forgetfulness or loose thinking in the protagonists, or obstacles that we might have expected such a progressive philosophy of nature to remove as a normal part of its brief. They illustrate rather conceptual difficulties that seem inherent in the mechanical program . . .[56]

Gabbey finds three intrinsic problems with the mechanical philosophy: mechanical explanations in general, the failure of the mechanical philosophy to adequately deal with the problem of impenetrability, and the consequence, recognized by Leibniz, that the mechanical philosophies of those such as Boyle and Descartes entailed the physical possibility of perpetual motion. For the purposes of this chapter Gabbey's critique of mechanical explanations is the most important.

As we saw in Chapter 1, Gabbey believes that mechanical explanations are not inherently more intelligible or simpler, and are often no more intelligible than Aristotelian explanations. The mechanical explanations advanced in the seventeenth century often suffered from the similar problems of circularity and obscurity. Mechanical explanations merely claimed that the phenomenon to be explained was caused by entities the structures of which were such that they caused the phenomenon.

As mentioned earlier, this is a valid point concerning many of the mechanical explanations, particularly those regarding conscious sensations, advanced in the seventeenth century. But it does not apply to all mechanical explanations put forward during this period, as we shall see in the following chapters. Furthermore it is a criticism directed exclusively at the crude atomism and corpuscularianism associated with most of the mechanical explanations of the period, and thus does not apply directly to the underlying explanatory model on which these explanations are based.

The last scholar to be considered on the issue of the intelligibility of mechanical explanations is Alan Chalmers. In his interesting article 'The lack of excellency of Boyle's mechanical philosophy', he argues along lines similar to Shapin and Gabbey. Many of the mechanical explanations advanced by Boyle were far from intelligible and simple. Chalmers supports this by citing Boyle's failed attempts to provide clear and intelligible mechanisms for such natural phenomena as impenetrability, gravity, elasticity, and cohesion (although I, personally, find his theory of cohesion easy to understand). Also, mechanical philosophers in general could not guarantee that their explanations penetrated deep enough to describe the ultimate cause of the phenomenon in question. Chalmers writes:

> Good theories, then, enable us to explain a wide variety of phenomena, described in terms of a variety of qualities, by appeal to a few fundamental qualities, the primary ones. We need

> to characterize and understand the causal mechanisms that underlie and give rise to the world of appearances. Insofar as Boyle was able to argue that his opponents failed to do this whilst he strived to do so he certainly had a point. But the argument so far does not yet bring us to the mechanical philosophy. It does not establish that the primary qualities must be the mechanical ones identified by Boyle, nor does it establish that the primary qualities figuring in an explanation need to be ultimate ones, not subject to explanation at a deeper level.[57]

Chalmers, for the most part, agrees with Boyle's negative attack on occult explanations, but does not think that Boyle's mechanical philosophy fared any better. Part of my project is an attempt to show that this, at least in one very important example, is not the case. The next two chapters are dedicated to this endeavour; by comparing Boyle's developed mechanical theory of heat and fire to the objections he raises against occult explanations we can see if the mechanical model has more explanatory legitimacy than the elemental model, and, if it does, discover what aspects of the mechanical model contribute to this superiority.

In the next chapter we will consider, in detail, several of the objections that Boyle raises against the elemental model of explanation. These objections are found in Boyle's most famous work, *The Sceptical Chymist*. Although Boyle's own mechanical theory had not fully matured by the time of its publication, this difficult work remains essential for an accurate understanding of Boyle's philosophy. He worked on this venture for several years, both at Stalbridge and later at Oxford, and it illustrates his concern for the need of both clarity and intelligibility in scientific explanation. With Boyle's complex view concerning the intelligibility of mechanical explanations understood, as well as the interpretations and criticisms of this view by various Boyle scholars explored, we are now ready to move on to an investigation of Boyle's criticism of the elemental interpretations of fire analysis.

Notes

1. See, for example, Principe, Lawrence (1998), *The Aspiring Adept: Robert Boyle and His Alchemical Quest*. Princeton, NJ: Princeton University Press.
2. See Shapin, Steven (1996), *The Scientific Revolution*. Chicago, IL: University of Chicago Press.
3. This is discussed in more detail in Chapter 6.
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3

Boyle's Attack on Elemental Interpretations of Fire Analysis

Philosophical targets of the *Sceptical Chymist*

In order to understand the role of mechanical explanation in science, as well as Boyle's contribution to the scientific revolution, we now need to consider, in detail, his objections to elemental interpretations of fire analysis. These objections are given their most thorough presentation in *The Sceptical Chymist*, although many of the ideas there presented occur in earlier work. The *Sceptical Chymist* is a dialogue that is set in the garden of Carneades, a sceptic sympathetic to atomism. Carneades is hosting a philosophical conference in his garden with Themistius, an Aristotelian, and Philoponus, a Paracelsian. The famous atomist Leucippus is expected, but never actually arrives. And Elutherius, a guest of Carneades, attends the conference with his friend, Boyle himself.

It has been traditionally held that *The Sceptical Chymist* is an attack against Aristotelian and Paracelsian theories of mixed bodies. Consequently, commentators usually dismiss the character Elutherius as largely unimportant. For example, Peter Alexander describes Elutherius as 'a common man'.[1] William H. Brock, in the otherwise-informative book *The Chemical Tree: A History of Chemistry*, describes him simply as 'neutral'.[2]

But this view is an over-simplification at best. As Robert Multhauf demonstrates, the dialogue is largely directed against a complex five-element system advanced by the character Elutherius. In his article 'Some non-existent chemists of the seventeenth century: remarks on the use of the dialogue in scientific writing' he writes:

> Consider the case of Boyle, whose *Sceptical Chymist* was formerly altogether, and is still largely, viewed as a critique of the system of the four elements of the Aristotelians and the three-element system of the Paracelsians. One who pays attention to this work as a dialogue will observe that *Themistius*, the Aristotelian, is disposed of in short order, and that the dialogue is principally among the working chemists. But then the Paracelsian, *Philoponus*, is dispatched even more speedily. Some time before the end of the dialogue one or both of them is incidentally mentioned as no longer present. How, then, can *The Sceptical Chymist* be a critique of Aristotelians and Paracelsians? In the main, it is not. *Elutherius*, who asks almost all of the questions, is inclined to believe in a system of elements which purports to derive the elements in bodies by *actual analysis*, which is accomplished by their destructive distillation, with the collection of the "elements" as fractions. This school found that they always got neither more nor less than five parts. One of the less ambiguous members[3] was to call them mercury or spirit, sulfur or oil, salt, phlegm, and earth, thus hopefully reconciling the system with those of both Aristotelians and the Paracelsians. In such a situation, Elutherius is enabled to shift from one system to another as he is pursued by the relentless *Carneades*, but he is also saddled, as the wily sceptic recognized, with the defects of them all ... Thus it is not *untrue* to describe Boyle's book as a critique of the Aristotelians and Paracelsians, but it oversimplifies circumstances which are not inconsequential. It obscures something for which there is other evidence, namely that Aristotelian and Paracelsian ideas about elements were anachronistic in Boyle's time.[4]

If Multhauf is correct and the five-element theory of Elutherius is the primary philosophical target of *The Sceptical Chymist* then it is important to identify who it is that Elutherius represents. As an Aristotelian, the character Themistius might represent a number of philosophers, Thomas Erastus, Francisco Suarez, or even Thomas Aquinas to name a few, and there are important differences among their philosophies to be sure. But there is also a general similarity between them, especially when it comes to issues in natural philosophy such as the composition of terrestrial substances. Likewise, the identification of Philoponus, the Paracelsian character, poses no insurmountable difficulty. A great many Paracelsians, such as Jean Beguin and Paracelsus himself, have significant philosophical differences, but the general elemental aspects of their theories are very similar. However, the identification of Elutherius is more difficult. Little seems to be known of this more sophisticated five-element theory, at least by philosophers. Scholars in the history of chemistry can fill in some of the pieces here, and this has important consequences for interpreting what Boyle was up to, philosophically, in *The Sceptical Chymist*.

In other words, we want to learn if Boyle's mechanical philosophy has more explanatory legitimacy than the elemental theories. Boyle thought that the theory of Elutherius was the most sophisticated representative of the elemental theories because it was flexible; it had the advantages of both the Aristotelian and Paracelsian theories, and could account for the largest number of observed phenomena. But who is Boyle talking about? Who advocated such a theory? Who does the character Elutherius represent?

There were several natural philosophers who advocated a five-element system in the seventeenth century. According to R. Hooykaas, the French Paracelsian Joseph Dushesne (1544–1609), also known as Quercetannus, was the first to advance the theory of five chemical principles.[5] Perhaps Elutherius is Quercetannus. But there are other candidates. For example, he also could be the seventeenth-century chemist Nicholas Lemery. There are even similarities between Elutherius and Van Helmont and Daniel Sennert, but these candidates are less likely philosophically and most of them can be ruled out completely by the fact that in *The Sceptical Chymist* Carneades deals with Quercetannus, Van Helmont, and

Sennert by name (a rarity, given Boyle's famous, though elusive, gentlemanly style).[6] As for Lemery, his presentation of the five-element theory was not published until 1675, fourteen years after *The Sceptical Chymist*, which makes him an unlikely candidate.

My own candidate for Elutherius is the French chemist Nicaise LeFevre (1610–69). There are several factors that make him a good choice. First, their theories are identical. LeFevre advocated the same five elements advanced by Elutherius: Salt, Sulphur, Mercury, Earth, and Phlegm. Furthermore, he endorsed analysis by fire as the method of their identification. Second, LeFevre was active in England in 1660, prior to the publication of *The Sceptical Chymist*. His work was known and discussed throughout the Invisible College (Boyle's intellectual circle prior to the formal formation of the Royal Society). Third, earlier versions of *The Sceptical Chymist* do not focus on the five-element theory (already in existence) but focus instead, exclusively, on the four-element theory of Aristotle and the three-element theory of Paracelsus. It is only after the success of LeFevre's work that Boyle applies his ideas to the five-element account of mixed bodies.

These claims, of course, require support. Let's begin by looking at the similarities between the elemental theory advocated by the character Elutherius and that of LeFevre. Elutherius most clearly presents the elemental theory in which he is inclined to believe in the fifth part of *The Sceptical Chymist*:

> But suppose (sayes *Elutherius*) that you should meet with Chymists, who would allow you to take in Earth and Water into the number of principles of Mixt Bodies; and being also content to change the Ambiguous Name of Mercury for that more intelligible one of spirit, should consequently make the principles of Compound Bodies to be Five; would you not think it something hard to reject so plausible an Opinion, only because the Five substances into which the Fire divides mixt Bodies are not exactly pure, and Homogeneous? For my part/(continues

> *Elutherius*) I cannot but think it somewhat strange, in case this Opinion be not true, that it should fall out so luckily, that so great a Variety of Bodies should be Analyz'd by the Fire into just five Distinct substances; which so little differing from the Bodies that bear those names, may so Plausibly be call'd Oyle, Spirit, Salt, Water,[7] and Earth.[8]

LeFevre proposes the same elemental theory in his work *Traicte' de la Chymie*, originally published in Paris in 1660. In the first section of Chapter 2 in the 1670 English translation he describes his theory. Note the number of principles as well as their method of analysis:

> For as the anatomist doth make use of razors and other sharp tools in his dissections, to separate the better the several parts of the human body, which is his chief object: The same doth the chymical artist, fetching his instruction from nature it self, to attain his end, which is nothing else but to joyn *homogeneal* and separate *heterogeneal* things by means of heat; for he doth nothing else but contribute his care and labour, to regulate the first according to the exigency in their several substances, which he separates and purifies afterwards; for the fire never relents or slackens its action, but rather drives it on and encreaseth it, untill he finds no *heterogeneity* or *Dissimilar* parts left in the compound. After that the artist hath performed the chymical resolution of bodies, he doth find last of all five kinds of substances, which chymistry admits for the principles and elements of natural bodies, whereupon are laid the grounds of its doctrine, because in these five substances is found no heterogeneity; these are, the phlegmatick or waterish part, the Spirit or Mercury, the Sulpher or Oil, the Salt, and the Earth.[9]

Here we see that analysis by fire is described as the method for separating compound bodies into their primary elements. And that the five substances LeFevre discovered through such analysis are identical to the five advanced by Elutherius. But there are more reasons to suppose that Elutherius is LeFevre than the similarities between their chemical theories. LeFevre was a celebrated scientist in France, eventually becoming the royal chemist.[10] His fame soon spread to England. Members of the Oxford Group such as Richard Jones and Henry Oldenburg knew LeFevre's work.[11] According to Maddison, LeFevre visited England in 1660, prior to the publication of *The Sceptical Chymist*, and was appointed to royal apothecary and professor of chemistry by Charles II.[12] LeFevre and Boyle even served together as members of the Royal Society's Chymical Committee during 1663 and 1664.[13] No doubt, LeFevre's five-element theory was a familiar topic in Boyle's intellectual community.

But perhaps the most compelling support for the identification of Elutherius with LeFevre comes from textual evidence in the form of the revisions Boyle made to his work in this area. In 1954 Marie Boas-Hall, in the journal *Isis*, published an early, rediscovered version of *The Sceptical Chymist*. Written between 1651 and 1658 (most likely in 1654) during Boyle's Stalbridge period, and copied down by Henry Oldenberg, 'Reflections on the experiments vulgarly alleged to evince the four peripatetic elements and the three chymical principles' was a valuable find for Boyle scholars because, not intended for publication, it is written in a very straightforward style that presents Boyle's ideas very clearly. It lacks the repetitive, over-detailed, and often tedious style in which *The Sceptical Chymist* was written. But it also lacks something else: a focus on, or even recognition of, the five-principle theory. This early version only recognizes the four-element theories of the Aristotelians and the three-principle theories of the Paracelsians. In fact, in this essay Boyle uses the observation that wood analysed by fire seems to result in the production of five different substances as a counter-example, to discredit the number of elements advocated by the Aristotelian and Paracelsian theories. It is only after Boyle moves to Oxford and becomes aware of LeFevre's theory (as well as its popularity) that he applies his arguments to the five-element theory. Consequently, and I think this is important, he is forced to apply his objections to elemental theories in general, and to question the explanatory model upon which all elemental theories are based.

In a recent email correspondence, Michael Hunter has expressed scepticism that Elutherius represents LeFevre or any person in particular. Rather he believes that Elutherius is more likely a general character that represents all advocates of the five-principle theory, of which there were many in the seventeenth century. Hunter makes a good point. But my theory is not completely far-fetched. For one thing, Boyle had a habit of attacking philosophers indirectly and an aversion to directly naming his philosophical targets. He believed this to be a civil way of focusing on the position itself while avoiding insult to the party in question. Furthermore, Boyle's professional relationship with LeFevre does not make it inconceivable that he had someone specific in mind. It is true that my theory is based on the assumption that Elutherius represents a specific individual. But once such an assumption is made, LeFevre seems a likely candidate. Furthermore, if the social/political context in which Boyle worked is important, as scholars such as Steven Shapin claim it is, then the identification of Boyle's philosophical targets is an important inquiry. For example, if Elutherius is LeFevre, then it is interesting to note that at least some of Boyle's philosophical adversaries also had social/political clout in the scientific community of seventeenth-century England.

With Elutherius potentially identified we are almost ready to consider Boyle's objections against elemental interpretations of fire analysis. But first we must examine the experiments upon which they are based.

The experiments

The bulk of the fire analysis experiments discussed in *The Sceptical Chymist* were conducted before Boyle settled at Oxford. At the young age of eighteen, he had finished his educational travels on the continent and had gone to live at his family's estate at Stalbridge in Dorset. He lived there for several years, building his first laboratory by1649, but perhaps as early as 1646.[14] While not up to the standards of his later Oxford laboratory, this early laboratory had state-of-the-art equipment including a vast array of iron and steel tools, expensive glass vessels and eventually a furnace. Boyle apparently had some difficulty obtaining this last item, complaining in a letter to his sister Katherine:

> That great earthen furnace, whose conveying hither has taken up so much of my care, and concerning which I made bold very lately to trouble you, since I last did so, has been brought to my hands crumbled into as many pieces, as we into sects; and all the fine experiments, and castles in the air, I had built upon its safe arrival, have felt the fate of their foundation. Well, I see I am not designed to the finding out the philosophers stone, I have been so unlucky in my first attempts at chemistry. My limbecks, recipients, and other glasses have escaped indeed the misfortune of their incendiary, but are not, through the miscarriage of that grand implement of Vulcan, as useless to me, as good parts to salvation without the fire of zeal. Seriously, madam, after all the pains I have taken, and the precautions I have used, to prevent this furnace from the disaster of its predecessors, to have it transported a thousand miles by land, that I may after all this receive it broken, is a defeat, that nothing could recompense but that rare lesson it teaches me, how brittle happiness is, that we build upon earth.[15]

Boyle used a wide variety of tools in the experiments he conducted for *The Sceptical Chymist*. These included iron and glass retorts, silver spoons, and even an iron skillet. The furnace was coated with a special, heat-resistant lute Boyle had learnt about from the American alchemist George Starky. It is interesting to note its complex production. In a work diary dated January 1650 he writes:

> The lute I line those furnaces with, which are to endures the highest violence of the fire, is made of equall parts of common-mortar; tobacco-pipe-clay; (or in lieu thereof scrap't chalke) rye-flower, horsedung made up into a very stiffe mortar by beating extreame[ly] well beaten together, with a little flockes or haire as little water, beare or butter-milke, as possibly will [suf]fise.[16]

The fire analysis experiments that are most important to *The Sceptical Chymist* were conducted, primarily, on Gaujacum wood, a type of wood found in the West Indies and Central America known in the seventeenth century for its medicinal value. But Boyle also applies analysis by fire to a wide variety of other materials including, but not limited to, amber, gold, lead, camphor, brimstone, and even human blood. The exact method of analysis varies as well: sometimes the material is burnt in an open chimney, but it is also distilled in a retort and sometimes heated gently in a bath. Boyle, along with Van Helmont and Jean Beguin, was a pioneer in his attention to qualitative detail when conducting experiments. He recorded the type of material, the exact method of analysis, and the specific results. The only major ingredient missing in his work that is part of the scientific experiment as we know it today is an attention to quantitative measurements of the amount of the materials used, something included in the work of Van Helmont, but not adequately emphasized until Lavisior.[17]

Early on in *The Sceptical Chymist*, the sceptical chemist Carneades rattles off several fire-analysis experiments.[18] Several more are cited throughout the course of the dialogue, but these are the most important. The first involves simply burning a piece of Gaujacum wood, applying it directly to the fire, in an open chimney. He notices that the solid part remaining consists of two distinct substances: ashes and soot. Next Gaujacum wood is distilled in a retort. The result is five distinct substances: oil, spirit, vinegar, water, and charcoal. In the third experiment amber is kindled in the furnace while a silver spoon is held, concave side up, over the smoke. The result Carneades records is that the spoon collects 'an unusual soot' which has an unexpected smell. The same process is applied to camphire and the soot collected has a different smell than the camphire smoke. Next camphire is enclosed in a glass vessel and then exposed to a gentle heat. This results in the material being sublimed, that is, changed directly from a solid state to what we would describe as a gaseous state.

Another experiment that Carneades mentions involves brimstone being placed in a special iron subliming pot and exposed to a moderate fire. The result is a dry, almost tasteless flour (although I don't think you'd want to eat much of it). Next brimstone is analysed by exposing it to a naked flame. This time the result is a saline and fretting liquor. Another experiment involves heating unfermented blood in a mild bath. The material seems to separate into two substances, phlegm and a *caput mortum*. But when unfettered blood is exposed to a good fire in a retort the resulting number of substances increases to a spirit, two oils, *caput mortum*, and a volatile salt. Carneades also notes that when impure lead and silver are exposed in a moderate fire together they are 'colliquated' into one mass. But when impure silver is exposed to a hotter fire, lead and the other base metals are separated.

The range of experiments Boyle conducted at Stalbridge is a reflection of the status of fire as the primary tool employed in chemical analysis during the seventeenth century. Fire analysis was so popular that some chemists, such as Peter Severinus, advocated it as the only way to arrive at a knowledge of things and their properties. With knowledge of the variety of fire-analysis experiments

Boyle conducted, we are at last ready to consider his objections against elemental theories.

The objections

Peter Alexander identifies eight major objections to elemental interpretations of fire analysis in *The Sceptical Chymist* and it's important to look at each in detail. The objections seem to fall roughly into three types, with some objections applying to more than one type. The first type of objection attacks the notion that fire analysis is a universal method of separating any substance into its primary elements. As we have seen, this was a view held by both Aristotelians and Paracelsians. The second type of objection is directed against the number of elements proposed by Aristotelian and Paracelsian theories. The third type of objection attacks a specific element proposed by the Aristotelian or Paracelsian theories.

The first objection is simply that many substances cannot be separated into elements by fire analysis. Some examples of this are the cases of gold and silver. Carneades expresses this in the following passage:

> For Fire can no more with the Assistance of Water than without it Separate any of the Three Principles, either from Gold, Silver, Mercury, or some Others of the Concretes named Above. Hence We may Inferre, That Fire is not an Universal Analyzer of all Mixt Bodies, since of Metals and Minerals, wherein Chymists have most Exercis'd Themselves, there Appear scarce Any which they are able to Analyze by Fire,/ Nay, from which they can Unquestionably Separate so much as One of their Hypostatical Principles; Which may well Appear no small Disparagement as well to their *Hypothesis* as to their Pretensions.[19]

Boyle expresses the same point when he writes:

> . . . There are some mixt Bodies from which it has not been yet made appear, that any degree of Fire can separate either Salt or Sulphur or Mercury, much less all the Three. The most obvious Instance of this Truth is Gold, which is a Body so fix'd, and wherein the Elementary/Ingredients (if it have any) are so firmly united to each other, that we finde not in the operations wherein Gold is expos'd to the Fire, how violent soever, that it does dicernably so much as lose of its fixednesse or weight, so far is it from being dissipated into those Principles, whereof one at least is acknowledged to be Fugitive enough, and so justly did the Spagyricall Poet somewhere exclaim, *Cunda adeo miris illic compagibus haerent*.[20]

Boyle puts the objection most eloquently when he applies it to the Aristotelian theory in the earlier 'Reflections on the experiments vulgarly alleged to evince the four peripatetic elements and the three chymical principles'. He writes:

> Then I say, that out of some bodies four elements cannot be extracted, as gold, out of which not so much as any of them hath been hitherto. The like may be said of silver, calcined talke, and divers other fixed bodies, which to reduce into four heterogeneal substances, is a task too hard for Vulcan.[21]

This objection is interesting in several respects. Notice first that it is an empirical objection. It appeals to the testimony of experience. The claim that fire is a universal method of separating bodies into elemental ingredients is empirically falsified through the use of observed counter-examples. But Boyle fails to consider some possibilities that are not inconsequential. For instance, it is conceivable that all bodies are made of the four elements but that there is something in the nature of fire or the nature of wood, perhaps due to a specific substantial form, that enables fire to separate wood, and wood alone, into its elements through burning. A similar possibility can be conceived employing the three principles. Consider an analogy from contemporary chemistry: electrons can be separated only from the atoms of some elements, but from this it does not follow that other atoms do not have electrons. Likewise, just because fire lacks the ability to extract the four elements from gold, it does not follow that gold is not composed of the four elements.

The second objection that Alexander identifies in *The Sceptical Chymist* is that although all parties agree that elements must be homogeneous, there are methods other than fire of separating substances into homogeneous parts. Methods include distillation, freezing, and the use of some solvents. Why shouldn't these parts be equally classified as elements? In the words of Carneades:

> . . . It will be very hard to/prove, that there can be no other Body or way be given which will as well as the Fire divide Concretes into several homogeneous Substances, which may consequently be call'd their Elements or Principles, as well as those separated or produc'd by the Fire. For since we have lately seen, that Nature can successfully employ other Instruments than Fire to separate distinct Substances from mixt Bodies, how know we, but that Nature has made, or Art may make, some such Substances as may be a fit Instrument to Analyze mixt Bodies or that some such method may be found by Humane Industry or Luck, by whose means compound Bodies may be resolv'd into other Substances, than such as they are wont to be divided into by the Fire. And why the Products of such an *Analysis* may not as justly be call'd the component Principles of the Bodies that afford them, it will not be easy to shew, especially since I shall hereafter make it evident, that the Substances which Chymists are wont to call the Salts, Sulphurs, and Mercuries of Bodies, are not so pure and Elementary as they presume, and as their *Hypothesis* requires.[22]

One important example of an alternative method of separating bodies into homogeneous parts that Boyle provides is the freezing of beer, which separates the alcohol from the beer. This is a phenomenon that fascinated Boyle throughout his scientific career. In *The Sceptical Chymist* he describes the process:

> I might confirm the Dutchmen's Relation, by what happen'd a while since to a neere Friend of mine who complained to me, that having Brew'd some Beer or Ale for his own drinking in *Holland* (where he then dwelt) the Keenness of the late bitter Winter froze the Drink so as to reduce it into Ice, and a small Proportion of a very Strong and Spirituous Liquor.[23]

Notice that this second objection also appeals to empirical evidence. If there are alternative ways of producing homogenous substances, then it seems that the burden is on the elemental theorist to explain why such substances do not also count as elements. But a crafty elemental theorist might have room to reply. For example, a proponent of the four-element theory might respond by simply denying that the resulting substance is truly homogeneous. He might claim that the alcohol that is separated from the beer by the process of freezing can be further separated into Water, Fire, and Air through fire analysis due to alcohol's combustible nature.

The third major objection against elemental interpretations of fire analysis that Alexander identifies in *The Sceptical Chymist* is that the fire used in analysis might be changing the nature of the substance rather than separating it into its primary constituents. Boyle writes:

> The Fire even when it divides a Body into Substances of divers Consistencies, does not most commonly analyze it into Hypostatical Principles, but only disposes its parts into new Textures, and thereby produces Concretes of a new indeed, but yet of a compound Nature.[24]

Again we have an empirical objection. But here Boyle offers an alternative interpretation that seems to be consistent with the observed phenomena. What evidence exists that the separated parts are constituent ingredients of the substance and not new substances? It is also interesting to note that although this is a legitimate difficulty for elemental interpretations, it does not seem applicable to a corpuscular interpretation of fire analysis. As we will see in the next chapter, a mechanical interpretation can be provided for either alternative. Only the elemental model of explanation requires that the separated substances be constituent parts.

Another objection that is important is Boyle's claim that the products of fire analysis can be further broken down into other parts. If this is the case then they must be further compound substances. As a result, they cannot be considered elements. One passage in which he expresses this point is the following:

> And that the Fire doth oftentimes divide Bodies, upon the account that some/of their Parts are more Fixt, and some more Volatile, how far soever either of these Two may be from a pure Elementary Nature, is Obvious enough, if Men would but heed it in the Burning of Wood, which the Fire Dissipates into Smoake and Ashes: For not only the latter of these is Confessedly made up of two such Differing Bodies as Earth and Salt; but the Former being condens'd of that Soot which adheres to our Chimneys, Discovers it self to contain both Salt and Oyl, and Spirit and Earth, (and some Portion of Phlegme too) which being, all almost, Equally Volatile to that Degree of Fire which Forces them up . . .[25]

This objection seems to adequately refute the Aristotelian and Paracelsian elemental theories. If wood can be separated into more than four homogeneous parts, then it is difficult to explain how the wood could be composed of only four elements or three principles. But notice that this objection does not refute elemental theories in general or the elemental model of explanation. For example, LeFevre's five-element theory seems to have the resources to account for the additional homogeneous parts produced in Boyle's example.

The next objection that Alexander identifies in *The Sceptical Chymist* is that many admittedly compound substances can be sublimed, that is, vaporized and condensed back into a solid without passing through a fluid state. This can be performed over and over again without any sign of disintegration or separation. One example that Boyle presents is brimstone. He writes:

> . . . Common Sulphur (if it be pure and freed from its Vinager) being leasurely sublime'd in close Vessels, rises into dry Flowers, which may be presently melted into a Bodie of the same Nature with that which afforded them. Though if Brimstone be burnt in the open Air it gives, you know, a penetrating Fume, which being caught in a Glass-Bell condenses into that acid Liquor called Oyl of Sulphur *per Campanam*. The use I would make of these Experiments collated with what I lately told you out of *Agricola* is this, That even among the Bodies that are not fixt, there are divers of such a Texture, that it will be hard to make it appear, how the Fire, as Chymists are wont to imploy it, can resolve them into Elementary Substances.[26]

The strength of this objection is similar to the first one. It does successfully contest fire as a universal method of separating compound substances into elements. But it does not acknowledge the possibility that fire has the unique ability to separate wood, and wood alone, into its primary constituents. Perhaps more importantly, the lack of disintegration after repeated sublimation attacks the proportional aspect of elemental explanations. In other words, the release of a gas, on the elemental model, is explained as the separation of the element Air from a substance. But this would require a diminution of the whole. If the gas can be turned back into a solid without any sign of disintegration, then such a diminution clearly has not taken place. The only alternative explanation on the elemental model seems to be that the substance has transmuted back and forth into different elements. But if this is the case then neither can be considered a true element.

The sixth objection Alexander identifies is that heating can sometimes produce more than three or four homogeneous parts. If this is true, then the Aristotelian and Paracelsian theories of explanation are incomplete accounts of the composition of compound substances. One example that Boyle cites is the distillation of raisins, which yields an alkali, phlegm, earth, oil, and a spirit different from wine. He writes:

> It seems questionable enough, whether from Grapes variously order'd there may not be drawn more distinct Substance by the help of the Fire, then from most other mixt Bodies. For the/ Grapes themselves being dryed into Raysins and distill'd, will (besides *Alcali*, Phlegm, and Earth) yield a considerable quantity of an Empyreumatical Oyle, and a Spirit of a very different nature from that of Wine. Also the unfermented Juice of Grapes affords other distil'd Liquors then Wine doth. The Juice of Grapes after fermentation will yield a *Spiritus Ardens*; which if competently rectifyed will all burn away without leaving any thing remaining. The same fermented Juice degenerating into Vinager, yields an acid and corroding Spirit. The same Juice tunned up, armes it self with Tartar; out of which may be separated, as out of other Bodies, Phlegm, Spirit, Oyle, Salt, and Earth: not to mention what Substances may be drawn from the Vine it self, probably differing from those which are separated from Tartar, which is a body by it self, that has few resemblers in the World. And I will further consider that what force soever you will allow this instance, to envince that there are some Bodies that yield more Elements then others, it can scarce be deny'd but that the Major part of bodies that are divisible into

> Elements,/yield more then three. For, besides those which the Chymists are pleased to name Hypostatical, most bodies contain two others, Phlegme and Earth, which concurring as well as the rest to the constitution of Mixts, and being as generally, if not more, found in their *Analysis*, I see no sufficient cause why they should be excluded from the number of Elements.[27]

This objection, like the others, is largely empirical, referring to observations of experiments conducted by Boyle. But it is important to notice that here Boyle also resorts to unsupported speculation in his prediction that the grapevine will produce substances that differ from the raisins and the grape juice when analysed by fire. Nevertheless, this objection does successfully refute three- and four-element theories, but once again it does not refute elemental theories in general. LeFevre's theory seems to have the resources to overcome this objection.

An important objection that Boyle mentions repeatedly throughout *The Sceptical Chymist* is that fire analysis actually unites some substances rather than separating them into elements. Boyle is fond of three examples of this kind of unification, citing each repeatedly. They include the production of metallic alloys, types of glass, and even soap. Alexander cites the following passage:

> Moreover, the Fire sometimes does not Separate, so much as Unite, Bodies of a differing Nature; provided they be of an almost resembling Fixedness, and have in the Figure of their Parts an Aptness to Coalition, as we see in the making of many Plaisters, Oyntments, &c. And in such Metalline Mixtures as that made by Melting together two parts of clean Brass with one of pure Copper, or which some Ingenious Trades-men cast such curious Patterns (for Gold and Silver Works)/as I have sometimes taken great Pleasure to Look upon ... And sometimes too the Fire does not only not Sever the Differing Elements of a Body, but Combine them so firmly, that Nature her self does very seldom, if ever, make Unions less Disoluble.

> For the Fire meeting with some Bodies exceedingly and almost equally Fixt, instead of making a Separation, makes a Union so strict, that it self, alone, is unable to Dissolve it; As we see, when an Alcalizate/Salt and the Terrestrial Residue of the Ashes are Incorporated with pure Sand, and by Vitrification made one permanent Body, (I mean the course or greenish sort of Glass) that mocks the greatest Violence of the Fire, which though able to Marry the Ingredients of it, yet is not able to Divorce them.[28]

This objection strikes the fatal blow to the Severinus dream of fire as a universal method of separating compound bodies into their primary elements. This is similar to the problem that arises from the inability of fire to separate substances such as gold, but in this case it is even more severe, resulting in the very opposite of the unique function that fire is claimed to perform. Furthermore, this objection strikes at the very heart of the Aristotelian definition of the primary quality of Heat as a separating force. This will be discussed in more detail in the next chapter.

The last objection Alexander cites is that, according to Boyle, many of the alleged elements can be produced *de novo*. If they are true elements this should not be possible. Here, Boyle draws on the famous experiment originally performed by Van Helmont in which water alone seemed to produce an abundant amount of plant matter. Van Helmont dried two hundred pounds of earth in a furnace and then planted in it a small willow tree weighing five pounds. He grew the tree for five years applying only water, and then took precise measurements of the earth and the plant matter, including the leaves that had fallen over the course of the experiment. Knowing nothing of the process of photosynthesis, Van Helmont concluded that the extra material (composed of all of the alleged elements) was produced by water alone. According to the Aristotelians and the Paracelsians this should be impossible. It is very important to note that, despite his experimental innovation, Van Helmont's own interpretation of the experiment was still grounded in the elemental model of explanation. He simply concluded that Water was the only true element, having the capacity to produce the others. Boyle offers a mechanical interpretation of this experiment that will be discussed in the next chapter.

In *The Sceptical Chymist* Boyle offers an array of objections against elemental interpretations of fire analysis with varied degrees of effectiveness. Considered as a whole, they put the elemental model into question. But if Boyle's mechanical philosophy offers a superior explanatory model then his corpuscular interpretation of fire analysis should avoid these objections. At the time *The Sceptical Chymist* was written Boyle's mechanical philosophy, specifically the development of a group of explanatory tools called *mechanical affections*, had not yet matured. Over the course of the next twenty years Boyle developed mechanical explanations for the various phenomena observed in the fire analysis experiments. The next chapter reconstructs Boyle's mechanical interpretation of the fire-analysis experiments and then applies the *Sceptical Chymist* objections to this interpretation.

Notes

1. See Alexander, Peter (1985), *Ideas, Qualities and Corpuscles: Locke and Boyle on the External World*. Cambridge: Cambridge University Press, 21.
2. See Brock, William (1992), *The Chemical Tree: A History of Chemistry*. New York: Norton, 56.
3. Nicholas Lemery.
4. Multhauf, R. P. (1966), 'Some non-existent chemists of the seventeenth century: remarks on the use of the dialogue in scientific writing', in A. G. Debus and R. P. Multhauf (eds), *Alchemy and Chemistry in the Seventeenth Century*. Los Angeles, CA: Andrews Clark Memorial Library, 41–2.
5. See Hooykaas, Reijer (1937), 'Die elementenlehre der iatrochemiker', *Janus*, 41, 26–8.

6. Interestingly, although Quercetannus advanced the five-element theory, in *The Sceptical Chymist* Boyle presents him as an advocate of the *Tria Prima*. See for example, Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 282.
7. In other passages Elutherius refers to this element as Phlegm. See, for example, Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 262.
8. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 322.
9. LeFevre, Nicaise (1670), *A Compleat Body of Chymistry*, London: J. Wright, 20–1.
10. See Boyle, Robert (1999), Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 3, 407 (see footnote a).
11. See Boyle, Robert (1999), Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 3, 407 (see footnote a).
12. See Maddison, R. E. W. (1969), *The Life of the Honourable Robert Boyle*. London: Taylor & Francis, 170.
13. See Maddison, R. E. W. (1969), *The Life of the Honourable Robert Boyle*. London: Taylor & Francis, 113.
14. See Maddison, R. E. W. (1969), *The Life of the Honourable Robert Boyle*. London: Taylor & Francis, 70–1.
15. See Maddison, R. E. W. (1969), *The Life of the Honourable Robert Boyle*. London: Taylor & Francis, 70–1.
16. Boyle, Robert (2002), 'Work diary VI (memorialls philosophicall beginning this newyears day 1649/50)', in Charles Littleton and Michael Hunter (eds), 'The work diaries of Robert Boyle (electronic edition)', ⟨http://www.perseus.tufts.edu/cgi-bin/perscoll?collection=Boyle⟩. Accessed January 26, 2005.
17. For the traditional account of the origins of quantitative chemistry, see William Brock (1992), *The Chemical Tree: A History of Chemistry* (New York: W. W. Norton & Co., 87–127. For an alternative account, see Principe, Lawrence (2002), with William R. Newman, *Alchemy Tried in the Fire: Starkey, Boyle, and the Fate of Helmontian Chymistry*. Chicago, IL: University of Chicago Press.

18. See Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 234–6.
19. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 246.
20. Thus all its properties cling together there in wonderful bonds.' Hunter and Davis point out that Boyle is here quoting Giovanni Aurelio Aurgurello's *Chrysopoeia* (1515). Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 236.
21. Hall, Marie Boas- (1954), 'An early version of Boyle's Sceptical Chymist', *Isis*, 45, 158.
22. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 243.
23. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 252.
24. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 242.
25. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 248.
26. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 239.
27. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 285.
28. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 248–9. For an example of a passage concerning the unification that results in the production of soap, see Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 235.

4

Boyle's Mechanical Theory of Heat and Fire

In the last chapter we looked at Boyle's objections against elemental interpretations of fire analysis. Now we will consider whether or not Boyle's developed mechanical philosophy offers an interpretation of fire analysis that overcomes these objections. If the mechanical philosophy cannot offer such an interpretation, then it seems that the recent social-constructionist criticisms of Boyle's role in the scientific revolution have some merit.[1] In other words, if Boyle's own theory cannot overcome the objections set forth in *The Sceptical Chymist*, then it's hard to see how the mechanical philosophy can be an objectively superior alternative to elemental theories of scientific explanation. Furthermore, if Boyle's interpretation does not have more explanatory legitimacy than the more traditional elemental theories, it's easier to be persuaded by the claim that the shift towards mechanical explanations in the seventeenth century, at least in this area of natural philosophy, had exclusively social/political rather than philosophical causes, as philosophers such as Shapin have maintained.

In order to do this we need to understand the development of Boyle's mechanical theory of heat and fire and how this theory can be applied to the fire-analysis experiments. Then, by comparing the objections to these mechanical interpretations of fire analysis, we can determine what aspects of the explanations are superior to the elemental theories, determine what aspects of the explanations survive the death of the corpuscular hypothesis, determine what aspects of the explanations are present in contemporary science, and, consequently, come to a more robust understanding of Boyle's role in the scientific revolution.

Against Aristotelian definitions

Boyle was sympathetic to the atomism endorsed by Lucretius in *De rerum natura*, but wanted to distance himself from the stigma of atheism, with which, by the seventeenth century, it was associated. This sympathy can be seen in his adoption of the view that heat is reducible to atomic agitation. Like Descartes and other mechanical philosophers of the period, Boyle was not satisfied with many of the obscure Aristotelian definitions of qualities such as heat and motion. For example, according to Aristotle part of the very definition of heat was the ability to separate things of unlike nature and unite things of the same nature.[2] As we saw in the last chapter, Boyle discovered through experiment that this was not always the case, and that in some substances heat failed to separate constituent parts and sometimes even united different substances, as in the production of metallic alloys, soap, and certain types of glass. Boyle saw in Lucretius an account of heat that was more intelligible, an account that seemed to agree with a wider variety of observations, and an account that could be developed into a mechanical explanation.

But Boyle was not alone in his dissatisfaction with the obscurity of some Aristotelian definitions. Consider Descartes's view of the Aristotelian definition of motion. In his famous *Le Monde* Descartes writes:

> [The Aristotelians] admit themselves that the nature of their motion is very little understood. To render it in some way intelligible they have not yet been able to explain it more clearly than in these terms: *Motus est actus entis in potentia, prout in potentia est*. For me these words are so obscure that I am compelled to leave them in Latin because I cannot interpret them. (And in fact the sentence 'Motion is the actuality of a potential being in so far as it is potential' is no clearer for being translated.) . . . For my part, I am not acquainted with any motion except that

which is easier to conceive than the lines of the geometers – the motion which makes bodies pass from one place to another and successively occupy all the spaces which exist in between.[3]

In a similar way, Boyle is dissatisfied with the very definition of heat advanced by the Aristotelians. In *The Sceptical Chymist* he writes:

> . . . It is the very Definition of Heat given by *Aristotle*, and Generally Received, *Congregare Homogenea & Heterogenea Segregare*, to Assemble Things of a Resemebling, and Disjoyn those of a Differing Nature. To this I answer, That this Effect is far from being so Essential to Heat, as 'tis Generally Imagin'd; for it rather Seems, that the True and Genuine Property of Heat is, to set a Moving, and thereby to Dissociate the parts of Bodies, and Subdivide them into Minute Particles, without regard to their being Homogeneous or Hetrogeneous, as is apparent in the Boyling of Water, the Distillation of Quicksilver, or the Exposing of Bodies to the action of Fire, whose Parts/either Are not (at least in that Degree of Heat Appear not) Dissimilar, where all that the Fire can do, is Divide the Body into very Minute Parts which are the same Nature with one another, and with their *Totum*, as their Reduction by Condensation Envinces.[4]

Descartes advocates a similar theory of heat that he expresses in *Le Monde* when he writes:

> When the flame burns wood or some other similar material, we can see with the naked eye that it sets the minute parts of the wood in motion and separates them from one another, thus transforming the finer parts into fire, air, and smoke, and leaving the coarser parts as ash. Others may, if they wish, imagine the form of fire, the quality of heat, and the process of burning to

> be completely different things in the wood. For my part, I am afraid of mistakenly supposing there is anything more in the wood than what I see must necessarily be in it, and so I am content to limit my conception to the motion of its parts.[5]

It is clear that Boyle was at least sympathetic to the atomic agitation theory of heat at least by 1655, and perhaps as early as 1649. But it is not until his 'Of the mechanical origine of heat and cold' that he develops the theory into a detailed mechanical account of heat. Let's now consider this account in more detail.

Heat as corpuscular agitation

One of the examples that Boyle is fond of citing as evidence for the claim that heat is reducible to the local motion of corpuscles is the boiling of water. Here he goes against the anecdotal wisdom that a watched pot never boils, for that is exactly what he does. And the results of this observation seem to support a theory of heat based on motion and agitation. When water is heated, its nature seems to slowly change. At first nothing happens. But soon very tiny bubbles begin to form around the bottom of the container. Eventually these bubbles grow in size until they break from the container and rise to the surface, and as more such bubbles are produced the water begins to agitate rapidly and to release steam. Boyle saw this as dramatic evidence for the agitation theory of heat. Boyle writes:

> Thus we see that the particles of water in its natural (or usual) state, move so calmly, that we do not feel it warm at all, though it could not be a liquor unless they were in it a restless motion; but when water comes to be actually hot, the motion does manifestly and proportionably appear more vehement, since it does not onley briskly strike our organs of feeling, but ordinarily produces store of very small bubbles, and will melt butter or coagulated

> oyl, cast upon it, and will afford vapours, that, by the agitation they suffer, will be made to ascend into the air. And if the degree of Heat be such as to make the water boil, then the agitation becomes much more manifest by the confus'd motions, and waves, and noise, and bubbles, that are excited, and by other / obvious effects and Phaenomena of the vehement and tumultuous motion, which is able to throw up visibly into the air great store of Corpuscles, in the form of vapours or smoak.[6]

This example does seem to provide empirical evidence for a theory that accounts for heat as the agitation of particles. The bubbles begin as tiny entities, almost imperceptible, and grow in size and agitation as the temperature of the applied heat increases. But at this level of observation there also seem to be problems with the theory. For example, I can take a container of water at room temperature and manually agitate the water to a similar degree with my hand without causing the slightest increase in the temperature of the water. If heat is simply reducible to agitation, it seems to follow that my manual agitation should cause a similar production of heat.

Boyle would respond to such an objection by claiming that in the case of true heat the agitation first occurs at the insensible corpuscular level. In other words, in the manual agitation of water the water is only agitated at the larger, macroscopic level, where in the case of true heat the original agitation is microscopic. Observational evidence for this is that the first bubbles to appear in the heated water are so tiny that they can be only barely perceived by the naked eye. Boyle cites the similar example of the lack of heat in a whirlwind of dust. Here you have the agitation of relatively small particles without heat, but such particles are not agitated at the microscopic level. Boyle writes:

> For though a heap of dust it self were vehemently and confusedly agitated by a whirlwind, the bulk of/the grains or

> Corpuscles, would keep their agitation from being properly Heat, though by their numerous strokes upon a man's face, and the brisk commotion of the spirits and other small particles that may thence ensue, they may perchance occasion the production of that Quality.[7]

This is an interesting response, and it seems to satisfactorily explain why manually agitated water would not produce heat. But now we are left with the question of why manual agitation sometimes does produce heat. For example, if I rub my hands together, the friction produces warmth. And the production of fire by manual friction, through two sticks rubbed together or the more sophisticated method of a bow spinning a wooden rod on a wooden block, is an example well known before the rise of the earliest civilizations. Normally, such examples would provide useful evidence for an agitation account of heat. But if such agitation must begin at the corpuscular level, Boyle is left to explain why the manual agitation of flesh or wood produces such corpuscular agitation while the manual agitation of water does not.

Such considerations lead Boyle to develop three requirements for the production of heat according to his mechanical theory. And it is these three conditions that mark the beginning of his developed theory of combustion and separate it from the cruder versions of the agitation theory found in Lucretius, Descartes, Galileo, and Boyle's own earlier work.

Conditions for the mechanical production of heat

According to Boyle the production of heat requires more than mere agitation. Specifically, three conditions must obtain. First, particles must be agitated. Again, Boyle is endorsing an agitation theory of heat that has its roots in ancient atomism. Second, the directions of the local motion of the individual particles must be numerous and varied. Such variation in the direction of agitation helps to account for phenomena such as the observation that the sensible quality of heat can travel, for example, from fire to an iron rod, and then from one end of the rod to the other. Finally, the agitation must be at the insensible corpuscular level. This explains why water manually agitated can be sensibly cooler than water that is heated, but not to the point of boiling. In addition to these three conditions we also must keep in mind the fact that Boyle held that all mechanical explanations must appeal exclusively to the mechanical affections of the phenomena (size, figure, local motion, and the contrivance of parts) rather than appealing to what Boyle took to be occult entities such as the Aristotelian primary qualities, occult qualities, or substantial forms.

With this in mind, let's at last consider Boyle's mechanical explanation of the common fire-analysis experiment involving freshly cut wood burnt in an open chimney. First notice that on Boyle's account, the explanation is mechanical and not occult because it appeals only to the mechanical affections. These mechanical affections are similar to what mechanical philosophers such as Descartes and Galileo describe as the geometrical properties or modes of matter, and include local motion, figure, size, and the contrivance of parts, and will be discussed in more detail in the next chapter. Heat is reducible to the mechanical modification of the local motion of corpuscles. All three of the conditions for the mechanical production of heat are met in the burning of wood. It is important to note that Boyle believed that the corpuscles of freshly cut wood are already in some degree of agitation. For example, he believed that the *seasoning* of wood is the same kind of mechanical process as burning but at a lesser or slower degree of agitation. Here the wood gets harder and more compact as the more fluid corpuscles of the wood that are in a higher degree of agitation (the sap) move away (evaporate) from the central corpuscular mass.

In the case of fire the same mechanical process occurs faster and produces several effects. First, in the presence of the flames, the extreme corpuscular agitation has spilt over into the sensible level. Boyle believed that flames are actually types of fluid.[8] There is fast agitation of sensible particles in varied directions, accompanied by intense heat. This agitation spreads to other parts of the wood which themselves become agitated. It is interesting to note that Boyle believed that some of the specific mechanical properties of flames varied according to the type of fuel used in the fire. These mechanical variations accounted for differences in the properties of the flames such as colour and even the ability to penetrate glass. He expresses these sentiments in an unusual essay entitled 'Tract about flame', most likely written sometime during the 1670s.[9] Boyle writes:

> The first circumstance I shall mention by which the operations of fire can be modified is the fuel with which the fire is fed. This, I know, seems a paradox, since it is generally presumed that all fires are of one and the same nature, whatever the substances were before they were ignited. But I have elsewhere shown that even the flames themselves can differ greatly one from another, for different reasons, but also because some of the corpuscles of which they are composed are able to retain distinct and particular qualities at the same time as constituting the parts of a real flame. But if this is so, it will not be difficult to conceive of those solid and indestructible corpuscles, while they are violently tossed about by the rapid motion of the subtler and ethereal substance in which they swim, as making such strong impacts on the bodies into whose pores they insinuate themselves/that at lest a few of them firmly stick there, and thus become material parts of those harmful [?] products which are confidently assumed to proceed from fire merely from its being a very hot agent. And since I have found out through many experiments that some of these fiery corpuscles are so subtle that, with the help of other,

> more subtle parts of the flame and the rapid motion into which they are driven, they can even enter the glass itself and increase the weight of the bodies enclosed in it, it will be more likely that when fire happens to act upon bodies that are exposed to it without the obstruction of any glass, which acts as a defense or protection whereby the denser parts do not enter, the addition of matter contributed by the fire may be greater and may also vary according to the different fuels of such a fire.[10]

In this interesting passage Boyle claims that the corpuscles of which a flame is composed can, at least in some instances, retain qualities of the substance fueling the fire. But this is not due to a mysterious substantial form. Rather, it's due to retention of the mechanical affections of the corpuscles in agitation. Boyle goes on to cite the example of flames produced by burning liquid sulphur. According to Boyle, such flames have properties that differ from the flames produced by other fuels including a blue colour, more intense heat, and a capacity to penetrate and loosen the parts of a thin sheet of silver.

But the mechanical affections of the flames are only one component of Boyle's mechanical interpretation of the burning of freshly cut wood. For example, the smoke is composed of the extremely fine corpuscles of the wood that have become so agitated that they ascend into the air. Boyle considered smoke also to be fluid in nature.[11] Furthermore, in some passages he points out that the smoke can be composed of multiple heterogeneous parts.[12]

The hissing of the sap is the liquid part of the wood becoming even more agitated by the fire, boiling at the sensible level and turning into steam. Finally, the remaining ashes consist of the corpuscles of the wood whose size and figure most resisted agitation. Boyle describes the nature of ashes when he writes:

> Whye may we not then ascribe the incombustibleness of ashes not barely to their being destitute of sulphur but to this, that by the demolishing of the texture of the concrete those particles are

> collected together which though in a convenient texture they might help to constitute a combustible ⟨body⟩ are yet by their particular bulk ⟨or weight or⟩ shape ⟨or two of all of these⟩ unfitt to be soe violently agitate[d] by the small particles of a flame as to imitate their motion.[13]

Notice that in this passage Boyle attributes the incombustibleness of the remaining ash to the mechanical affections of the corpuscles that make it up. Boyle is not specific about which affections account for this resistance to agitation, but offers bulk, weight, and shape as possible candidates. Furthermore, these corpuscles are not members of a homogeneous element because they can be further separated through distillation. Similar mechanical explanations can be provided for the variety of different fire-analysis experiments that Boyle performed.

One might be tempted to think that this interpretation of the fire analysis of wood is essentially the same as the Aristotelian interpretation: the fire separates the wood into flames, smoke, water, and ash. But there are also important differences. On Boyle's account, the separated parts are not interpreted as elements but are viewed as all being composed of the same thing: material corpuscles. Second, Boyle can account for the various phenomena by appealing exclusively to mechanical affections rather than positing primary qualities, substantial forms, or the Aristotelian conception of natural motion.

With this mechanical interpretation of the most basic fire-analysis experiment understood, let's begin the comparison of Boyle's mechanical philosophy to the *Sceptical Chymist* objections. Recall Boyle's objection that fire cannot separate some substances into either four elements or three principles or into heterogeneous substances. One example was the case of gold, a substance that could not be separated with any amount of fire. This phenomenon can be explained by appealing to Boyle's mechanical affections. The fire has no mysterious capacity to separate objects into elements. It consists, rather, in the rapid agitation of corpuscles. In substances such as wood the corpuscles, due to their size, figure, and contrivance, are packed loosely together, and the separation of these corpuscles can be accomplished relatively easily by the rapid agitation of fire corpuscles. This also explains why rotten wood burns faster than hard, fresh wood or seasoned wood. In other substances the figure and contrivance of corpuscles is such that they resist the finite agitation caused by the fire. In the case of gold, the corpuscles are packed together in such a way that fire will agitate them to the point of liquidity, but not to the point of actual separation.

One might object that this is not different than claiming that the four elements are present in the gold but resist separation from the fire. But the difference is that the resistance involved in Boyle's account can be explained by appealing exclusively to mechanical affections: 1) the insufficient speed of the local motion of agitated fire corpuscles; 2) the figure or shape of the corpuscles of the gold; 3) the arrangement of the gold corpuscles; and 4) the overall density of the gold's corpuscular mass. Claiming that the four elements are present in the gold but resist agitation raises the question of why they resist agitation. This can be explained either by appealing to an occult quality of the gold or to the mechanical affections. Boyle believed that the mechanical account was ultimately more intelligible.

Let's consider another objection that is raised in *The Sceptical Chymist*. Boyle objected that there are other ways of separating substances into homogeneous parts. Why aren't these homogeneous parts also considered to be elements? Examples of such separation that Boyle is fond of citing are freezing and distillation. Boyle's answer to this question is simply that the homogeneous substances produced in such separations are not additional elements because they are all made of the same thing of which every material substance is made: corpuscles. The separation into homogeneous parts is explained mechanically by appealing to mechanical affections. The freezing of beer yields ice and a vehement liquid, the freezing of wine yields vehement liquor and a *caput mortum*.

Boyle cites several occasions where such experiments are performed, although I cannot find a passage in which he describes a specific mechanical explanation of this phenomenon. The closest he comes is when he describes an experiment in which beer was left outside during winter in order to freeze. Boyle and some friends waited until four in the morning for the beer to freeze and found that the strong liquor that remained tasted better than the beer from which it was produced, which, incidentally, they had been drinking while they waited. This is an interesting observation, but not quite a mechanical explanation or even, as Principe would agree, a modern scientific experiment.

Nevertheless, an account of the phenomenon that appeals exclusively to mechanical affections can easily be constructed. Some corpuscles of beer at room temperature are in more rapid agitation than others. Evidence for this might be the carbonation visible at the sensible level. When beer is frozen some of the corpuscles remain in an agitated state while others do not, perhaps due to their shape or arrangement with other corpuscles. Boyle might hold that in principle even the corpuscular agitation found in this remaining fluid might slow to the point that the local motion comes to rest or is so slow that it is no longer in a visible fluid state. An interesting aspect of Boyle's theory is that heat and cold are not separate positive qualities as the Aristotelians maintained, but rather a simple mechanical difference in the degree of agitation. Even though the agitation in the hottest flame is not sufficient to separate the corpuscles of gold beyond a fluid state, it is possible in principle that they could be agitated to the point at which separation occurs. Likewise, the winter night might not be sufficient to slow the agitation of alcohol beyond a fluid state, but a temperature might be cold enough in principle to stop the local motion of these corpuscles.

The third objection is a problem only for elemental theories, in particular to the claim that substances are composed of primary elements. This objection identifies a possible alternative interpretation of fire-analysis experiments by pointing out that the fire may be changing the substance into another substance or changing its ingredients rather than merely separating them. Thus there is no guarantee that the products of fire analysis are original ingredients of the substance. Alexander cites two of Boyle's examples. First, heating many vegetables produces glass. Second, glass can be produced by heating the salt and earth remaining in the ashes of burnt plants. This glass resists intense heat without disintegration. In Boyle's own words 'the fire meeting with some bodies exceedingly and almost equally fixt, instead of making a separation, makes a union so strict, that it self, alone, is unable to divorce it'.[14] In fact, Boyle was interested in phenomena associated with glass throughout his philosophical career, no doubt for reasons including its complex properties, its relation to the problem of Descartes' subtle matter, and its vital role in the implementation of many of his experiments.

As mentioned previously, this objection from *The Sceptical Chymist* raises a problem that is effectively avoided by the mechanical model of explanation. Notice that whether the products of fire analysis are considered constituent parts or new substances is a problem that can be settled by mechanical explanation. Boyle believed that the texture of glass was related to the motion of its corpuscles: different textures (sometimes due to flaws or the inclusion of foreign matter in its production) produced variations in the local motion of its corpuscles resulting in increased fragility or fractures.[15] Perhaps when substances such as vegetable matter and sand are heated the rapid agitation of the fire corpuscles alters the figure of the corpuscles of these substances in such a way that when they collide they interlock. Once interlocked, they resist separation from heat.

This explanation may seem a bit far-fetched, but it avoids the objection because it does not have to claim that the fire has a special capacity to separate substances into primary, unchangeable elements. The examples cited in the objection can be explained by appealing to Boyle's mechanical affections.

The fourth objection raised against Aristotelian and Paracelsian interpretations of fire analysis is also avoided by the corpuscular hypothesis. Recall that Boyle claims that the products of fire analysis can sometimes be further broken down and thus shown to be compound by methods such as distillation. So even if it is conceded that the products of fire analysis are original ingredients they cannot be primary elements. Boyle's theory rejects the position that the products of fire analysis are elements; instead they are corpuscles with different mechanical affections. Therefore, the fact that they can be further broken down is unproblematic.

It is important to remember that the elemental model of explanation can also avoid this objection by simply positing the existence of additional elements or principles. This is exactly the strategy that Nicaise LeFevre employs in his five-principle theory. LeFevre correctly thought that the traditional three-principle theory had to be abandoned. The theory was inadequate because there was empirical evidence for more than three homogeneous chemical principles. However, he thought that the way to fix it was to posit more principles. For LeFevre, the explanatory model of Paracelsus could be saved. On his account, Paracelsus had the correct explanatory model, but was simply wrong about the number of principles.

Boyle, however, believed that the phenomena of distillation directly supported the mechanical philosophy. During the late 1670s and early 1680s Boyle conducted a variety of distillation experiments, notably distilling oil of aniseed in glass, tin, and iron retorts. The results of these experiments, he believed, supported the mechanical philosophy over the elemental theories. These results are presented in 'A chymical paradox' (1680), a section of a larger work entitled *New Experiments and Observations Made Upon the Icy Noctiluca* (1682), although it was originally intended to accompany *Experiments and Notes About the Producibleness of Chymicall Principles* (1680). This support for Boyle's corpuscular hypothesis centres on experiments in which Boyle distilled oil of aniseed some thirty-six times after witnessing similar distillations performed by a now unknown chemist. This early chemist discovered that distillation of oil of aniseed produced a black, pitch-like *caput mortum*. When the same substance was distilled more of the substance was produced. This happened consistently after several distillations, sometimes producing more of the substance and sometimes less. Boyle reasoned that if the elemental theories were true, then the process of distillation was separating elements or principles from the oil, leaving a purer fluid with fewer impurities. But if this is the case the amount of *caput mortum* remaining should be less and less with each additional distillation. But instead the additional distillations frequently produced more of the substance. This led Boyle to conclude that rather than elements being separated by the fire, a new compound substance was being produced. He offers two possible mechanical explanations for this effect. First, it is possible that subtle corpuscles of fire are penetrating the retort and directly combining with the oil corpuscles to produce the *caput mortum*. Alternatively, different types of oil corpuscles, mechanically modified by the agitation produced by the fire, might be combining to form the substance. Boyle believed that both mechanical interpretations were superior to the elemental theories because they could account for the fact that some additional distillations produced more *caput mortum* than others.[16]

Recall that the fifth objection raised in *The Sceptical Chymist* was particularly problematic for elemental theories of chemical explanation. Boyle cites cases in which repeated sublimation occurs without any observable disintegration. Once again, sublimation is the process of using the applied heat from fire to make a substance change from a solid to a gaseous state without going through a liquid phase. Boyle cites several examples including the quicksilver obtained from cinnabar and the sulphur obtained from iron pyrites. This is problematic for the elemental theorist because the gas should represent the separation of one of several elements or principles of which the substance was composed. Thus, the gas must be a fraction rather than a whole. If no disintegration took place then the substance would have to be both wholly composed of the element Earth at the solid stage and then wholly composed of the element Air at the gaseous stage. But this is impossible on the elemental model.

According to the mechanical interpretation of such sublimations, the lack of disintegration is unproblematic. The sublimation is straightforwardly explained by appealing to mechanical affections. The corpuscles of some substances, perhaps due to their figure, are so susceptible to the agitation caused by the fire that the speed of their local motion increases at an extremely fast rate, skipping a liquid state altogether. The lack of disintegration might be caused by the uniform figure of the corpuscles of that particular substance. The similar shape might cause the increase of agitation at a rapid but uniform rate. In this case, none of the corpuscles of the substance become agitated at different rates, as is the case with wood, where some corpuscles pass through a fluid state while others resist agitation altogether. Thus, the mechanical philosopher can provide an interpretation of the phenomenon without appealing to an elemental separation.

The six objection raised in *The Sceptical Chymist* was that heat sometimes produces more than three or even four homogeneous parts, so an Aristotelian or Paracelsian account of the elements is incomplete. It was acknowledged in the previous chapter that this problem was not insurmountable for the elemental model of scientific explanation. All that is required is the addition of elements or principles to account for the relevant experiments. For example, LeFevre's five-principle theory can account for the five homogeneous parts produced by the distillation of raisins.

Perhaps the phenomena can be more eloquently explained by appealing to Boyle's mechanical affections. The different substances might be interpreted as the result of variations in resistance to corpuscular agitations due to differences in figure or contrivance. Furthermore, the addition of extra elements or principles by the elemental model seems to be somewhat *ad hoc*. But one might reply that the addition of mechanical affections is equally *ad hoc*. But to this Boyle can once again appeal to the claim that the mechanical model is supported by distillation on the objective grounds mentioned in 'A chymical paradox'.

The seventh objection seems to be more straightforwardly problematic for the elemental model. Both Paracelsians and Aristotelians believed that fire had a special capacity to separate substances into constituent parts. As we have seen, the capacity to separate compound substances was even part of the very definition of Heat for the Aristotelians. But fire sometimes unites substances, as in the production of metallic alloys, glass, and soap. As we have seen in the mechanical interpretation of the phenomena associated in the third objection, the mechanical philosopher can provide an interpretation that appeals exclusively to mechanical affections such as size, figure, local motion, and the contrivance of parts.

Recall that the final objection raised against the elemental interpretations of fire analysis was that the alleged elements could be produced *de novo*, whereas it should be impossible to make elements. Boyle cites the willow-tree experiment originally conducted by Van Helmont in which water alone seems to produce all four of the Aristotelian elements.

Peter Alexander does an excellent job of describing Boyle's mechanical interpretation. He writes:

> Water is corpuscular and changes in the tree could be explained not by the mere absorption of water which then remained unchanged but by the rearrangements of the corpuscles of the water to produce other substances. Some other substances

> might have done as well; the corpuscles of air could be similarly rearranged. Boyle connected this with his experiments on the burning of plants to obtain what were alleged to be elements or principles so van Helmont's experiments appeared to show that they were all capable of being transmuted into water or *vice versa*, which, according to many peripatetics and chemists, was impossible. Boyle's hypothesis allowed him to say that if this did indeed happen it could give an intelligible mechanical explanation; transmutation of one substance into another, whether or not it was claimed to be elementary, could be explained by the rearrangements of the corpuscles of the first substance into the structure peculiar to the second.[17]

Because the material produced by the addition of water to the tree is not elemental in nature it is not problematic for the mechanical model. And this is itself an interesting point. Although Principe and Newman are to be commended for their dedicated work demonstrating Boyle's great debt to Helmontian chemistry, there is a clear and important difference between the two, and it is an epistemological difference in the use of explanatory models. Despite its sophistication in method, Van Helmont's theory is still based in the elemental model of explanation. Van Helmont's willow-tree experiment strikes a devastating blow to Aristotelian and even traditional Paracelsian theories due to the implausibility that a true element could be produced from another element. But Van Helmont's conclusion is that Water must be the only element capable of producing the other alleged elements *de novo*. This explanation, despite Van Helmont's experimental innovations, is still firmly based in the elemental model of explanation. Boyle's interpretation of the experiment is more radical because it is based on a new mechanical model of explanation, and accounts for the extra plant material by appealing to mechanical affections rather than the primary qualities or substantial form of a mysterious element.

In this chapter we considered Boyle's developed theory of heat and fire and then compared it to the objections he raises against elemental interpretations of fire analysis in *The Sceptical Chymist*. As we have seen, Boyle's mechanical theory either completely avoids these objections or fares just as well as the most sophisticated of the elemental theories. This alone does not demonstrate that the mechanical model of explanation is superior to the elemental model. But it does warrant an investigation of what aspects of the mechanical model contribute to its success against these objections. In the next chapter we consider the mechanical model of explanation in more detail, and determine if it is indeed superior to the elemental model.

Notes

1. For example, Shapin's claim that the mechanical philosophy was just as occult as the elemental theories.
2. See Aristotle (1941), *On Generation and Corruption*, in Richard McKeon (ed.), *The Basic Works of Aristotle*. New York: Random House, 510 (329b).
3. Descartes, René (1991), *The World*, in John Cottingham, Robert Stoothoff, Dugald Murdoch, and Anthony Kenny (eds), *The Philosophical Writings of Descartes*. Cambridge: Cambridge University Press, vol. 1, 93–4.
4. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 247.
5. Descartes, René (1991), *The World*, in John Cottingham, Robert Stoothoff, Dugald Murdoch, and Anthony Kenny (eds), *The Philosophical Writings of Descartes*. Cambridge: Cambridge University Press, vol. 1, 83.
6. Boyle, Robert (2000), 'Of the mechanical origine of heat and cold', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 8, 342.
7. Boyle, Robert (2000), 'Of the mechanical origine of heat and cold', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 8, 343.

8. See, for example, Boyle, Robert (2000), Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 8, xlii–xliii.
9. See Boyle, Robert (2000), Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 14, xv.
10. Boyle, Robert (2000), 'Material relating to mechanical origin of qualities: tract about flame,' in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 14, 59–60.
11. See Boyle, Robert (1999), *Certain Physiological Essays and Other Tracts*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 121.
12. See Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 298.
13. Boyle, Robert (2000), 'Dialogues concerning flame and heat,' in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 13, 267.
14. Boyle, Robert (1999), *The Sceptical Chymist*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 249.
15. See Boyle, Robert (1999), 'Of absolute rest in bodies', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 6, 208–10.
16. See Boyle, Robert (2000), 'A chymical paradox', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 9, 352–4.
17. Alexander, Peter (1985), *Ideas, Qualities and Corpuscles: Locke and Boyle on the External World*. Cambridge: Cambridge University Press, 31.

5

Boyle's Mechanical Epistemology

Reactions to Shapin and the social constructionists

We no longer explain natural phenomena such as fire through the arrangement and movement of marble-like corpuscles. Heat is, in fact, reducible to agitation, but this agitation takes place at the molecular level, a world radically unlike the divinely guided clockwork that Boyle imagined. Nevertheless, there are very important aspects of the mechanical philosophy that survive the death of Boyle's crude corpuscular theory. In the last chapter we examined Boyle's mechanical theories of heat and fire, how these theories could be developed into mechanical interpretations of the different fire analysis experiments, and also how these interpretations fared against the most important objections that Boyle raises against elemental theories in *The Sceptical Chymist*. The purpose of this comparison was to determine whether or not these mechanical interpretations are explanatorily superior to the elemental interpretations and, if they are superior, establish which features of the interpretations are responsible for this explanatory superiority.

It has been my general goal to build a defence of the mechanical philosophy against recent attacks raised against it by scholars such as Steven Shapin. Recall that according to Shapin, the scientific revolution in general, and the acceptance of mechanical explanations in particular, had *exclusively* social and political causes rather than any objective philosophical superiority of mechanical explanations. Shapin and other social constructionists have made us reassess the scientific revolution in light of the complex social and political conditions of seventeenth-century England. In this regard Shapin's work has been influential, but it has also generated controversy.

According to Principe, for example, Shapin's work is valuable because it identifies overlooked aspects of Boyle's life and work, but it also has problems. For instance, Principe believes that Shapin overemphasizes the social aspects of Boyle's work while ignoring important facts concerning the origins of seventeenth-century science. More importantly, Principe claims that Shapin is basing his sociological critique on an outdated model of the development of science and an essentially traditional view of Boyle himself. Principe writes:

> The sociological program also assumes an older view of the development of science. It implicitly assumes, as did earlier historiography, that the origins of modern science lie in a seventeenth century revolution with the Royal Society of the Restoration at its center. Having (perhaps unconsciously) made this assumption, when adherents of the sociological approach seek for sociological factors responsible for the emergence or "reification" of unique aspects of modern science, they focus on that time and place and subsequently on its chief figure – Boyle. But if, as more broadly based studies show, the Royal Society is not the sole (or perhaps even chief) template of modern science practice, then the assumption that its social space and strategies are somehow straightforwardly explanatory on their own, or of the rise of modern science culture and practice, is undermined. Perhaps more critically, such studies selectively delineate the Royal Society itself, centering on its "modern" and successful affairs – much in the tradition of the Halls. I might add that finding sociological explanations too frequently becomes, as Karl Popper might say, like finding Marxist or psychoanalytical ones: they are almost always discoverable when sought, but rarely verifiable as causes. Rather

> more troubling is the apparent assertion by some supporters of social constructivism that the historical background is relatively unimportant; one supportive reviewer writes in regard to *Leviathan and the Air Pump* that "it mattered little whether the portraits of Hobbes, or, especially, of Boyle were historically accurate." The troubling ramifications of such an utterance need not be insisted upon.[1]

According to Principe, the shortcomings of the social constructionist approach are many. It is the product of an outdated view of Boyle and the history of science. Its explanations and causes are not verifiable. Furthermore, it does not consider causes outside the social world of seventeenth-century English science. One area of historical background particularly ignored, that Principe finds essential to an accurate understanding of Boyle, is the development of alchemy, interpreted in a traditionally inaccurate way by Shapin.

Now it should be noted that at first glance some of these same charges seem applicable to my project. It looks as if it is based on the assumption that there was a scientific revolution in seventeenth-century England with Boyle at its centre. My study also primarily focuses on the aspects of Boyle's work that can be described as modern, ignoring important, nay vital, aspects of his life and work that are not modern. But on such charges, I am perhaps in a better position to defend myself than Shapin and the social constructionists. For one thing, I do not claim that Boyle was the only important figure of the scientific revolution or that historical background is unimportant. For another, my focus on Boyle is justified by his important work in epistemology and philosophy of science, an aspect of the scientific revolution that has not been adequately explored. Finally, my focus on the modern-like features of Boyle's mechanical philosophy is justified because I am interested in the theoretical elements of his philosophy that have survived in contemporary science.

Michael Hunter is also critical of Shapin's work. While Hunter admits that Shapin's interpretation isn't necessarily incompatible with his own, he does suggest that Boyle was more politically strategic than was actually the case. Rather than a shrewd manipulator, Hunter argues that Boyle was something closer to an accidental beneficiary of the social conditions upon which Shapin focuses. Hunter writes:

> In addition I would argue that Shapin and Schaffer make a more conscious strategist out of Boyle than is warranted by the evidence. Claims for 'literary technology' on Boyle's part are rather undercut by study of the manuscript versions of his writings, which suggests that the evolution both of his prose and of the structure of his books was more haphazard than such claims would imply. It could also be argued that Boyle was a more accidental beneficiary of a broader shift in contemporary culture towards an anti-dogmatic and empirical stance than *Leviathan and the Air-pump* implies. In some of his statements Boyle seems genuinely surprised at the acclaim that his books achieved, and it is worth stressing that the appeal to 'matters of fact' – however important for Boyle – was not unique to him and his Royal Society colleagues, but was almost a cliché of Restoration intellectual life.[2,3]

Hunter is particularly concerned that Shapin's focus on the political aspects of Boyle's work downplays the importance of his religious interests. For Hunter, it is Boyle's religious beliefs that are the primary motivation behind his scientific endeavours. Though they seem suspicious when interpreting his work from the point of view of social and political strategic self-interest, for Boyle these religious interests were both sincere and sometimes troubling. Hunter writes:

> Finally Boyle is made to seem too secular-minded in his motivation, too concerned about the political threat and the legacy of

> the Civil War, when in fact his concerns were dominated by religion to an extent that may seem implausible to late twentieth-century commentators but which must be understood if we are to do justice to him ... Some of the same problems apply to Steven Shapin's more recent *A Social History of Truth* (1994), in which Boyle plays a central role. Again, there is a strange inability to take seriously the religion that was so central to Boyle's personality ... Throughout, there is a distressing insensitivity to the evangelical Christianity by which Boyle was so powerfully imbued, and which is clearly crucial to any attempt properly to understand him. Clearly, this may require a conscious effort on the part of secular-minded commentators from the late twentieth century, but that does not make it less imperative if we wish to understand the preoccupations of a thinker like Boyle.[4]

The traditional interpretation of Boyle's philosophy glorified and oversimplified a complex social phenomenon, but the recent social constructionist interpretations have overstated the importance of this social dimension, downplaying or ignoring important philosophical features. In these past three chapters I intend to show that the pendulum needs to swing back in the other direction. The scientific achievements of the seventeenth-century mechanical philosophers have been, in the past, exaggerated. Nevertheless, a legitimate change in scientific theory did occur, and this change can be accurately described as revolutionary. The elemental model of explanation was forever abandoned. A new model was adopted and has lasted in science ever since. The problems with early versions of the mechanical philosophy were not problems inherent in the mechanical programme. Specific mechanical theories, including Boyle's, were rejected, but they were replaced by *other mechanical theories* based on the same model of explanation. Consequently, the mechanical philosophy did not share the same fate as the corpuscular hypothesis. In fact, it is alive and well. Other explanatory models exist in science to be sure, but the mechanical model is frequently (almost constantly) employed in scientific theoretical endeavours. In this chapter we will consider the primary explanatory tools of Boyle's mechanical philosophy: the mechanical affections of matter. The next chapter presents a detailed examination of the contrivance of parts, the mechanical affection most important to contemporary science. The final chapter demonstrates the presence of mechanical explanations in contemporary science.

To see this we need to look first at the features of Boyle's mechanical interpretation of fire analysis that helped it to overcome the *Sceptical Chymist* objections. Many of the traits that allowed its success in this area of natural philosophy are the traits that were retained in scientific practice after the simplistic forms of seventeenth-century atomism were rejected.

The mechanical affections of matter

According to Boyle, a mechanical explanation is superior to an occult explanation because it describes how the phenomenon was produced by appealing exclusively to intelligible mechanical affections rather than merely labelling the phenomenon to be explained or appealing to obscure occult entities such as substantial forms. These mechanical affections are somewhat similar to the primary qualities of Locke and Galileo, or the geometric modes of extension postulated by Descartes. They include properties such as size, figure, texture, local motion, and the contrivance of parts. However, some primary qualities commonly accepted by the mechanical philosophers of the seventeenth century are left out of Boyle's list of mechanical affections. These include important properties such as extension, divisibility, and impenetrability. Anstey claims that the reason for this omission is epistemological. He writes:

> Over and over again [Boyle's] accounts of such phenomena as magnetism, chemical reactions, gravity, sensible qualities, etc. are in terms of these 'mechanical affections' of corpuscles. They are the fundamental resources of the mechanical hypothesis. And this furnishes us with at least part of an answer to the question as to why not all the qualities of universal matter are included in Boyle's list of primaries. Why are such qualities as divisibility, impenetrability, and extension not primaries? At least part of the answer is that they are not 'mechanical' affections of matter. In Boyle's view they make little or no contribution to the explanatory power of the theory.[5]

Boyle uses the mechanical affections primarily as epistemological tools. Some primary properties of matter, such as extension, had little explanatory power for Boyle so they are not included as mechanical affections. It is important to note that these mechanical affections were the same properties by which most of the macroscopic machines of Boyle's time operated. This machine analogy itself was very important to the development of the mechanical philosophy and will be discussed shortly. Right now, I would like to examine the most common mechanical affections used in Boyle's explanations.

Boyle believed that all the properties of the physical world could be explained in terms of the interaction of microscopic material particles he called corpuscles. The most important mechanical affections are motion, size, shape, and contrivance. But in the essay 'An introduction to the history of particular qualities', included as a preface to *Tracts Written by the Honourable Robert Boyle*, first published in 1670, Boyle presents a more detailed and comprehensive list of the mechanical affections.[6] In the third chapter of the essay, Boyle is responding to the objection against the mechanical philosophy that the diverse phenomena of nature cannot be explained by the mere operations and modifications of matter and motion. Responding to this objection, Boyle appeals to the famous analogy presented by Lucretius in *De rerum natura*. Lucretius points out that a relatively limited number of letters can produce a wide variety of words and sentences.[7] In a similar way, the finite modifications of matter and motion can produce the great diversity of nature's phenomena. According to Boyle, the shape, size, motion, and contrivance of corpuscles can be developed into at least eleven total mechanical affections that in turn can be combined to produce the great diversity of phenomena that we see in nature. This extended list of mechanical affections includes motion, rest, effluviums, size, shape, pores, posture, order, texture, mixture, and what Boyle describes as the *universal fabric of things*. There are obvious similarities between these affections and some seem to have only a conceptual difference, but all are modifications of matter and motion and, according to Boyle, equally intelligible properties. These mechanical affections do the bulk of the explanatory work in Boyle's mechanical philosophy, so let's consider each in detail.

Local motion, in the Cartesian sense defined above, is one of the most important of the mechanical affections. For one thing, it is the primary cause of the capacity for corpuscles to act on one another. Boyle often describes motion as the 'grand instrument of change'. It can take a surprisingly diverse variety of forms, as Boyle describes in the following passage:

> So likewise, Motion, which seems so simple a Principle, especially in simple Bodies, may even in them be very much diversifyed. For it may be more ore lesse swift, and that in an almost infinite diversity of degrees: It may be simple or compounded, Uniforme, or Difforme, & the greater Celerity may precede or follow: The Body may move in a streight Line, or in a Circular, or in some other curve Line: as Ellipticall, Hyperbolicall, Parabolicall, &c. of which Geometricians have describ'd severall, but of which there may be in all I know not how many more; or else the Bodies motion may be varied according to the

> scituation, or nature of the Bodie it hits against, as that is capable, of reflecting it, or refracting it, or both, and that after severall manners. The Body may also have an undulating motion, and that with smaller or greater waves; or may have a Rotation about its own middle parts; or may have both a Progressive motion,/and a Rotation, and the one either equall to the other, or swifter then it, in almost infinite Proportions. As to the Determination of motion, the Body may move directly upwards, or downwards, decliningly, or Horizontally, East, West, North, or South &c. according to the scituation of the Impellent Body.[8]

This dynamic variety of motion gives it almost unsurpassed explanatory power. According to Boyle, motion is responsible for many of the qualities considered to be primary and irreducible by the Aristotelians. We have seen that the heat and cold are reducible to the motion of corpuscles, but Boyle also claims that motion is an important ingredient in the production of qualities such as firmness and fluidity.[9] Motion also has the ability to widen the pores of corpuscles.[10] More importantly, motion has the ability to produce other mechanical affections.[11] Finally, local motion is a property that is particularly intelligible and is a causal feature of most, if not all, of the macroscopic machines of Boyle's time, including clocks, levers, guns, waterwheels, and locks.

In his comprehensive list, Boyle also includes *rest* as a mechanical affection in its own right. Boyle defines rest essentially as the absence of motion. In his essay 'Of absolute rest in bodies', first published in 1669, he claims that many macroscopic objects that appear to be at rest (glass, iron, lead, wood, bodies of water, etc.) are composed of corpuscles that are actually in various degrees of motion.[12] But in 'An introduction to the history of particular qualities' he considers the possibility that the corpuscles themselves can sometime be at rest, although other passages suggest that such corpuscles are never at rest for very long. He writes:

> And since all the parts of the Universall Matter are not allwaies in motion, some of them being arrested by their mutual Implication, or having transferred (as far as our sense informe us) all that they had to other Bodies, the consequence will be, that some of these portions of the common matter will be, in a state of *Rest* (taking the word in the popular sence of it).[13]

Although rest is simply the absence of motion, it still counts as a mechanical affection in its own right due to its explanatory power. It is a property of bodies that is intelligible and easy to understand, and it plays an important, sometimes vital, role in the proper function of many machines. Consider Boyle's favourite example, the clock. It is the property of rest, at specific intervals between the motions of the gears, which allows the accurate measurement of time.

Another member of Boyle's extended list of mechanical affections is also related to motion: effluviums. He describes effluviums as subtle particle emanations that are emitted from larger corpuscular structures. Boyle writes:

> . . . Very many Bodies having Particles, which by their smallness, or their loose adherence to the bigger, or more stable parts of the Bodies they belong unto, are more easily agitated and separated from the rest by heat and other Agents; therefore there will be great store of Bodies that will emit those subtle Emanations that are commonly called *Effluviums*.[14]

Effluviums, while not a type of motion or the absence of motion, are intimately related to motion due to a natural disposition to become separated from corpuscular structures and set into motion, most often through the bombardment of other corpuscles. These effluviums, in turn, not only have the capacity to bombard other corpuscular structures, but also can penetrate such structures, as will be discussed shortly. Notice that this disposition to separate and move is unlike Aristotelian natural motion in that it is reducible to mechanical properties such as size and figure, rather than a mysterious tendency to return to some primal location in the universe. It is also interesting to point out that in the case of effluviums the analogy to macroscopic machines is more difficult. Clocks and levers don't, under normal circumstances, emit particles. But consider a sawmill of the type common in the seventeenth century. Using such a mechanical apparatus to cut wood causes the by-production of sawdust. These particles seem roughly analogous to the effluviums to which Boyle appeals.

Another important explanatory property of a corpuscle is its size or bulk. Boyle believed that corpuscles varied in size but that, properly speaking, they were so small that they were insensible. However, it is important to note that he sometimes uses the term 'corpuscle' loosely, referring to insensible corpuscular clusters or even very tiny visible particles, such as the grains of dust in a whirlwind. Generally, Boyle accepted the argument raised by Lucretius that our tactical sensation of a blowing wind provides empirical evidence that invisible particles exist. Boyle, along with Lucretius, reasoned that their invisibility was due to their very small size.

Throughout Boyle's career the microscope gained popularity as a useful scientific instrument. Boyle's laboratory assistant, Robert Hooke, an important philosopher in his own right, conducted many notable experiments with microscopes on flies, pieces of cork, and essentially any suitable sample on which he could get his hands. It was in fact Hooke who coined the term 'cell'. Boyle was aware of the fact that his corpuscles were not found under the microscope. But although the microscope was not able to verify his theories, Boyle believed that it did provide indirect support for the plausibility of his view. Here, for example, a machine allowed one to see that a fly had many eyes. This was a fact about nature that was, hitherto, invisible to humans, but true nevertheless. Likewise, macroscopic phenomena such as heat and combustion might be explained in terms of the interaction of insensible particles rather than primary qualities, substantial forms, or the proportions of elemental ingredients. Furthermore, and I think this is important, the objects uncovered by the microscope had the very mechanical affections that Boyle predicted: size, figure, local motion, and contrivance. Boyle saw no reason to doubt that objects at an even smaller level had the same properties. For example, in the essay 'About the excellency and grounds of the mechanical hypothesis' he writes:

> Both the Mechanical affections of Matter are to be found, and the Laws of Motion take place, not onely in the great Masses, and the middle-siz'd lumps, but in the smallest Fragments of Matter; and a lesser portion of it, being as well a Body as a greater, must, as necessarily as it, have its determinate Bulk and Figure: and he that looks upon Sand in a good Microscope, will easily perceive, that each minute Grain of it has as well its own size and shape, as a Rock or Mountain.[15]

This leads us to perhaps a more important mechanical affection than size: the shape or figure of a corpuscle. This affection is related to a further affection that Boyle describes as 'contrivance', and will be discussed in detail shortly. The figure of various corpuscles played an important role in several mechanical explanations. The shape of a corpuscle might be highly susceptible or highly resistant to agitation. It might allow it to interlock and become united with other corpuscles and corpuscular clusters. Figure might also allow a corpuscle to penetrate a porous object that appeared impenetrable at the sensible level, a quality relevant to issues concerning the possibility of a void or vacuum in nature. Figure might also determine the direction in which the corpuscle moves.

A mechanical affection in Boyle's extended list that is a variation of shape or figure is the porous quality of some corpuscles. The pores of a corpuscle are reducible to variations in shape, and Boyle often appealed to pores in his explanations. For example, in the essay 'Of the great efficacy of effluviums' he argues that the insensible pores of rope can be penetrated by water. He writes:

> ... We must not for the most part look upon Effluviums as swarms of Corpuscles, that only beat against the outside of Bodies they invade, but as Corpuscles, which by reason of their great and frequently recruited numbers, and by the Extreme smallness of their Parts, insinuate themselves in multitudes into the minute pores of the bodies they invade, and often penetrate to the innermost of them; so that, though each single Corpuscle, and its distinct action, be inconsiderable, in respect of the multitude of parts that compose/the body to be wrought on; yet a vast multitude of these little Agents working together upon a correspondent number of small parts of the body they pervade, they may well be able to have powerful effects upon the Body, that those parts constitute, as, in the case mentioned in the former Chapter, the Rope would not probably have been enabled to raise so great a weight, though a vehement Wind had blown against it, to make it lose its perpendicular straightness, but a vast multitude of Watery Particles, getting by degrees into the pores of the Rope, might, like an innumerable company of little wedges, so widen the pores as to make the thrids or splinters of Hemp, the Rope was made up of, swell, and that so forcibly, that the depending weight could not hinder the shortening of the Rope, and therefore must of necessity be rais'd thereby.[16]

In this explanation we can see how the mechanical affections of corpuscles work together to form a mechanical explanation. I cited this passage to illustrate Boyle's use of pores, but in this example we also see how the presence of these pores is combined with the local motion of effluviums of very small size to explain the increased strength of the rope. Boyle thought that such mechanical objections could be combined to produce intelligible explanations of natural phenomena.

The remaining affections in Boyle's extended list all relate to the more primary mechanical affection Boyle often describes as the contrivance of parts, although he also uses terms such as 'arrangement', 'structure', 'order', 'coaptation', and 'contexture'. This mechanical affection is particularly important to the history of science, and the next chapter is devoted to a more detailed analysis of this affection. For now, let's examine the remaining members of Boyle's extended list and how they are related to contrivance. First Boyle identifies posture as a mechanical affection. The position of a corpuscle in relation to its neighbouring corpuscles is a property that can supply explanatory power. Boyle writes:

> Moreover (then) not only the greater fragments of Matter, but those lesser ones, which we therefore call *Corpuscles* or *Particles* have certaine Locall respects to other Bodies, & to those *scituations* which we denominate from the Horizon; so that each of these minute Fragments may have a particular *Posture*, or Position (as erect, inclining, horizontal &c.) . . .[17]

Furthermore, it's an intelligible property that has clear examples at the level of macroscopic machines. A good example is a lock and key. Properties such as shape, size, and motion are essential to the proper function of a lock and key, but the posture or position of the serrations of a key in relation to the pins of the lock is equally important.

The next three mechanical affections are order, texture, and mixture. These concepts are closely related, and Boyle seems to use the terms 'texture' and 'mixture' as different varieties of order. By order or consecution, Boyle means the specific arrangement in which the corpuscles can be found, in relation to one another. He often uses the term 'texture' when the structure is composed of homogenous parts, and the term 'mixture' when the structure is composed of heterogeneous parts. Boyle writes:

> . . . There may belong to [the corpuscles] a certain *Order* or Consecution, upon whose score we say one is before, or behind another, and many of these fragments being associated into one Mass or Body, have a certain manner of existing together, which we call *Texture*, or by a word more comprehensive, *Modification* . . . And as those conventions of the simple Corpuscles that are so fitted to adhere to, or be complicated with one another, constitute those durable and uneasily disoluble Clusters of Particles that they may be call'd the Primary Concretions or Elements of things: so these themselves may be mingled with one another, and so constitute Compound Bodies, and ev'n those Resulting Bodies may by being mingled with other/Compounds, prove the Ingredients of decompounded Bodies; and so afford a way whereby Nature varies Matter, which we may call *Mixture*, or Composition, not that the Name is so proper as to the Primary Concretions of Corpuscles; but because it belongs to a Multitude of Associations, and seems to differ from *Texture* (with which it hath so much Affinity as perhaps to be reducible to it,) in this, That alwaies in Mixtures, but not still in Textures, there is a required Heterogeneity of the Component Parts.[18]

Although on a certain common-sense level the concept of texture seems to be closer to a variation or pattern in the shape of a single corpuscle, Boyle uses the term as a property of the arrangement or structure of several corpuscles, so that the cluster taken as a whole has a pattern. Anstey has a lot to say about Boyle's use of texture, and interprets it as one of four primary qualities at the *molecular* level of corpuscles in which individual corpuscles make up larger corpuscular structures. Anstey writes:

> Texture is a structural property of particle aggregates and, like the determinates size, shape, and motion, is an accidental property. It is derived from the shape, size, motion, and posture of

> the atomic corpuscles, where posture is defined as the position of a corpuscle relative to other corpuscles. As the motion and especially the posture of the atomic corpuscles change, so too does the texture of the cluster of particles. But more importantly, texture is an essential property of molecular corpuscles. So here again we have the application of an essentiality criterion, only this time it applies to corpuscles at the molecular level. Texture is not essential at the atomic level because, by definition, no atomic corpuscles have it. But at the molecular level it is 'physically impossible' for a corpuscle to lack it.[19]

Anstey seems to be using the term 'texture' in a broader sense, coming closer to what I have described as the *contrivance of parts*. Anstey draws on textual support from Boyle's *The Origine of Formes and Qualities*, citing a passage in which Boyle writes:

> . . . When many Corpuscles do convene together as to compose any distinct Body, then from their Accidents (or Modes) . . . there doth emerge a certain Disposition or Contrivance of Parts in the whole, which we may call the *Texture* of it.[20]

Anstey concedes that this is merely a semantic issue about the use of the terms and whether we describe it as texture or contrivance, whether we count it as a primary quality or a mechanical affection, matters little. All the same, a few things should be taken into consideration. First, Anstey is following the traditional literature in describing Boyle's mechanical affections as primary qualities (in the Lockeian sense), although he is sensitive to the distinction. This seems appropriate as Anstey is particularly concerned with Boyle's metaphysics; the debate in which he is involved is whether or not to count texture as a primary quality. Second, one of the ways he supports this interpretation is by claiming that Boyle implies that *texture* should be considered primary when he writes, in his 'Essay on nitre', 'motion, figure, and disposition of parts, and such like primary and mechanical affections'.[21] But here it seems that 'disposition of parts' is closer to the 'contrivance of parts' than it is to 'texture'. Third, Anstey's interpretation does not seem to do proper justice to the subtle distinction between texture and mixture that Boyle raises in 'An introduction to the history of particular qualities' cited above. In that essay it seems that Boyle is listing both 'texture' and 'mixture' as types of 'order'. This, combined with his frequent use of the term 'contrivance', leads me to interpret it, rather than texture, as one of the primary mechanical affections. Finally, it should be noted that, on either interpretation, texture is a very important property, playing a vital role in a wide range of Boyle's mechanical explanations, from fluidity to cohesion. Contrivance, order, and arrangement also have parallels in the world of macroscopic machines. Boyle's favourite example is the gears of a clock, which function properly due to their specific arrangement.

The final mechanical affection that Boyle includes in his comprehensive list is what he describes as the 'universal fabric of things'. This is by far the most unusual of the affections he lists and seems to be intimately connected with the natural laws of motion. Boyle describes the affection in the following way:

> . . . every distinct portion of Matter, whether it be a Corpuscle or a Primary Concretion, or a Body of the first, or of any other order of Mixts, is to be considered not as if it were placed *in vacuo*, nor as if it had Relation only to its neighboring Bodies, but as *being plac'd in the Vniverse, constituted as it is*, amongst an Innumerable company of other Bodies, whereof some are near it, and others very remote, and some are great and some small, some particular and some Catholick Agents, and all of them governed as well by *The Vniversal fabric of things, as by, the Laws of Motion* established by the Author of Nature in the World.[22]

This member is unique among the extended list of mechanical affections. Each corpuscle in the universe is related to every other corpuscle in the universe, and this relationship is subordinate to the laws of motion set by God. While this affection, like the others, seems straightforwardly intelligible, unlike the others it does not seem to correspond to the macroscopic machines of Boyle's time. It is true that every gear of a clock bears a spatial relation to every other gear, and these gears obey the laws of motion, but Boyle is saying something more radical. He is claiming that no particle of the universe can be completely understood in isolation, that every physical part of the universe is connected. This is particularly interesting given Boyle's belief in the existence of a vacuum in nature. It straightforwardly follows from Descartes' rejection of the void, for instance, that every body in the universe is connected to every other body. But Boyle's recognition of the spatial relationship between each particle of matter in the universe, despite the existence of empty space, is fascinating.

The mechanical affections of fire analysis

Each of the primary mechanical affections and several of the general mechanical affections listed above are present in Boyle's interpretation of the fire-analysis experiments, and it is the use of these intelligible affections that makes his interpretation explanatorily superior to the elemental interpretations. We can see this by considering the role of each. First, the concept of local motion plays a fundamental part in Boyle's mechanical interpretation. Recall once more that the burning of green wood in an open chimney, the heat of the fire, the fluidity of the flames and smoke, and the movement of the fire as it consumes the wood are all reducible to the varied motions of agitated corpuscles. The rapid, penetrating motion of corpuscles also produces the heat appealed to in other forms of fire analysis, such as distillation. Rest, to a relative degree, also plays an important part, as the ashes constitute the corpuscles that have most strongly resisted agitation.

Size is also an important factor in his interpretation for several reasons. First, true heat results from agitation that takes place at a level in which the particles are so small they are insensible. Second, the size of the corpuscles has a bearing on which become separated from the corpuscular mass, as well as the degree of agitation required for this separation to take place. The same is true for the shape of figure of the corpuscles, which can be prone to agitation in the case of smoke, or resistant to agitation in the case of ash.

Finally, the contrivance of parts plays a role in the mechanical interpretation of fire analysis in the form of texture. For example, texture, shape, and size combine to explain why ashes resist agitation while other parts of the wood do not. In the 'Dialogues concerning flame and heat', Boyle writes:

> For if it appeare ⟨that⟩ what flyes away from a flaming concrete is not barely the kindled sulphur of it, but consists of divers other Corpuscles which are hurried along by it and with [it] whye may it not be sayd that the incombustibleness of the remaining part of the concrete may be ascribed not barely to the consumption of the Sulphur but to that change of texture which necessarily followes upon the accolation of soe many ⟨& various⟩ parts as fly away, & which would perhaps follow upon the bare recesse of the Sulphureous ingredient . . . Whye may we not then ascribe the incombustibleness of ashes not barely to their being destitute of sulphur but to this, that by the demolishing of the texture of the concrete of those particles are collected together which though in a convenient texture they might help to constitute a combustible ⟨body⟩ are yet by their bulk or ⟨weight or⟩ shape ⟨or two or all of these⟩ unfit to be soe violently agitate[d] by the small particles of a flame as to imitate their motion.[23]

In this passage we see that Boyle's interpretation appeals to each of the primary mechanical affections, combining to form an intelligible interpretation of why ashes resist agitation. The concept of effluviums also plays a role represented by those corpuscles that are most prone to separation due to the bombardment of the agitated corpuscles.

Furthermore, the appeal to these mechanical affections allows Boyle to provide an intelligible response to the objections he raises against the elemental interpretations of fire analysis. Fire lacks the ability to separate some substances, such as gold, into constituent parts. This can be explained by appealing to the shape, position, and texture of the gold corpuscles. The finite motion of the fire can put these corpuscles into a liquid state, but cannot separate them.

The fact that substances can be separated into homogenous parts by other means than fire is a legitimate problem for the elemental theorist because they must explain why such parts do not also count as elements. But the corpuscular hypothesis can explain this phenomenon by appealing to the mechanical affections of figure and arrangement. The fact that the products of fire analysis can be further broken down into more than three or four different substances can be explained mechanically in a similar way.

It should be noted that such explanations are hypothetical. Boyle does not tell us what specific shape and arrangement are responsible for the ability of gold to resist separation. But the explanation is explanatorily superior because it appeals to intelligible properties that are easy to understand, rather than occult qualities of a substantial form that allows gold to resist agitation. The mechanical model also allows us to appeal to macroscopic analogies. Consider a man attempting to break an iron chain by throwing stones at it. The links of the chain resist separation because their size, shape, and arrangement are stronger than the limited force of the thrown stones. However, the links are separable, in principle, if the force applied is greater, say a projectile shot from a cannon. Likewise, the texture of the gold corpuscles resists separation from the limited force of the bombardment of fire corpuscles, but might be still separable in principle.

However, it must be noted that part of my thesis is that the mechanical philosophy has survived in contemporary science. Although contemporary science abounds in mechanical explanations, these explanations do not always appeal to the size, shape, and motion of material particles. By far the most important of Boyle's mechanical affections for the history of science is contrivance. To show this we must first come to an understanding of the relationship between the concepts of *contrivance* and *structure*, and of the role of structural explanation in science.

Notes

1. Principe, Lawrence (1998), *The Aspiring Adept: Robert Boyle and His Alchemical Quest*. Princeton, NJ: Princeton University Press, 24–5.
2. Hunter, Michael (2000), *Robert Boyle: Scrupulosity and Science*. Woodbridge: Boydell Press, 9.
3. Here the phrase 'matters of fact' refers to the experimental production of facts concerning the observations of Boyle's air-pump experiments, a major focus of Shapin's work. See Shapin, Steven (1985), with Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life*. Princeton, NJ: Princeton University Press, 22–79.
4. Hunter, Michael (2000), *Robert Boyle: Scrupulosity and Science*. Woodbridge: Boydell Press, 9–11.
5. Anstey, Peter (2000), *The Philosophy of Robert Boyle*. London: Routledge, 54.
6. It should be noted that in this essay Boyle describes motion, size, shape, and rest as the most primary affections, the other affections following from them. I have included contrivance as one of the primary affections because (1) many members of the extended list are directly related to contrivance and (2) Boyle often describes it as a mechanical affection in its own right. A more detailed discussion of this affection and its importance to Boyle's philosophy can be found in the next chapter.
7. Lucretius writes: 'These then must be composed of varied shapes; smells enter the body in ways that color can't; color and taste have each their special paths to the senses hence, in basic shape, they differ. Dissimilar shapes, then, gather into one conglomerate, and things are of mixed

seed. Why, yes! In the very verse I write, you see dozens of letters shared by dozens of words, and yet you must admit that words and verses consist, now of these letters, now of those; not that few letters rarely run through all, or that not two have letters all alike, but that in general all do not match all.' See Lucretius (1977), Frank O. Copley (trans.), *The Nature of Things*. New York: Norton & Company, 44–5.

8. Boyle, Robert (1999), 'An introduction to the history of particular qualities', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 6, 277.
9. See, for instance, Boyle, Robert (1999), *Certain Physiological Essays and Other Tracts*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 2, 187–201.
10. See Boyle, Robert (2000), 'Miscellaneous scientific papers', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 14, 84.
11. See Boyle, Robert (1999), 'An introduction to the history of particular qualities', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 6, 274–8.
12. See Boyle, Robert (1999), 'Of absolute rest in bodies', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 6, 195–9.
13. Boyle, Robert (1999), 'An introduction to the history of particular qualities', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 6, 274.
14. Boyle, Robert (1999), 'An introduction to the history of particular qualities', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 6, 274.
15. Boyle, Robert (2000), 'About the excellency and grounds of the mechanical hypothesis', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 8, 107.
16. Boyle, Robert (1999), 'Of the great efficacy of effluviums', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 7, 261.
17. Boyle, Robert (1999), 'An introduction to the history of particular qualities', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 6, 274.
18. Boyle, Robert (1999), 'An introduction to the history of particular qualities', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 6, 274–5.

19. Anstey, Peter (2000), *The Philosophy of Robert Boyle*. London: Routledge, 48.
20. Boyle, Robert (1999), *The Origine of Formes and Qualities*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 5, 316.
21. Anstey, Peter (2000), *The Philosophy of Robert Boyle*. London: Routledge, 49.
22. Boyle, Robert (1999), 'An introduction to the history of particular qualities', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 6, 275.
23. Boyle, Robert (2000), 'Dialogues concerning flame and heat', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 13, 266–7.

6

The Contrivance of Parts

Mechanism, structure, and arrangement

Several scholars, including Gabbey, Shapin, Anstey, and Nadler, classify the mechanical explanations of the seventeenth century as types of structural explanation. In doing so, they draw on the important work in the philosophy of science conducted by Ernan McMullin, who claims that an explanation is structural if it explains the properties or behaviour of a complex entity by appealing to its structure. Structure is here defined as a set of constituent entities or processes and the relationships between them. McMullin describes this in the following passage:

> When the properties or behavior of a complex entity are explained by alluding to the structure of an entity, the resultant explanation may be called a *structural* one. The term "structure" here refers to a set of constituent entities or processes and the relationships between them. Such explanations are causal, since the structure invoked to explain can also be called the *cause* of the feature being explained.[1]

McMullin emphasizes the causal nature of structural explanations. They are causal explanations because the structures described therein are claimed to cause the phenomenon to be explained. Such explanations may be contrasted with nomothetic explanations, which appeal to a natural law and cite the phenomenon to be explained as an instance of that law, and genetic explanations, which provide a description of the origin of the structure or behaviour of the phenomenon to be explained.

McMullin goes on to claim that structural explanations can be divided into two types. Direct or categorical structural explanations are those in which the structure is directly observable. McMullin uses the example of a clock. When explaining why it is that the large hand of a clock moves exactly twelve times faster than the small hand, the structure of the gears, to which the explanation appeals, can be directly observed. Most of Boyle's mechanical explanations represent a second type of structural explanation that McMullin describes as 'hypothetico-structural explanations'. In these explanations the structure to which the explanation appeals is hidden or inaccessible to direct observation. He also points out that such explanations are inherently hypothetical and explain the phenomenon by starting with the effect and working back to the cause.

According to McMullin, hypothetico-structural explanations have two chief advantages over nomothetic explanations. First, in the case of nomothetic explanations, the explanation does not directly come from a natural law, but from the manner in which the phenomenon to be explained has been found to be reproducible. It is such experimental reproducibility that illustrates its co-occurrence with a natural law. Structural explanations, on the other hand, go beyond such co-occurrence to describe a structure that would account for the co-occurrence. McMullin claims that such an account is simply beyond the scope of nomothetic explanations. What I have described as occult explanations McMullin considers to be very simplistic nomothetic explanations. For example, McMullin cites the case of the dormative power of opium, about which, along with other examples, he writes, 'these latter are nomothetic explanations, but it is obvious that they are weak in explanatory force from the scientific point of view'.[2]

A second advantage of structural explanations over nomothetic explanations is their retroductive nature. McMullin writes:

> There is a second reason why structural explanation is more powerful than is nomothetic explanation. The two involve

> different types of inference, retroduction and induction, respectively, using Peirce's terminology. Induction goes from the particular to the general; the "leap" involved is one of extension only. Retroduction introduces conceptual novelty, thus refuting Hume's assertion that scientific ideas must be "copies" of sense-impressions. The leap involved is a much greater one, therefore, and one more basic to progress in science. The justification for it is the explanatory success of the hypothesis (in this case, the structural hypothesis).[3]

As examples of structural explanations in the above sense, Gabbey believes that the mechanical theories of Descartes, Gassendi, Boyle, Newton, and Galileo attempt to explain natural phenomena by referring to sets of constituent entities and their relationships to one another. Gabbey writes:

> Clearly, explanations in the Mechanical Philosophy are typical examples of structural explanations. The salient features of structural explanations, as outlined by McMullin, hold for the mechanical explanations of a Galileo, a Descartes, a Gassendi, a Boyle or a Newton. Natural phenomena are given causal explanations by retroductively linking them to bodies with position and motion structured in an appropriate way, and (except in the case of the simplest mechanical effects) it is the *structure*, together perhaps with the nomothetic causal relationships, that causes the phenomena, rather than any individual body, motion or disposition. Since the number of possible structures is unlimited, even for a small number of component bodies, as Boyle noted, mechanical explanations promise a potentially large range of new explanatory tasks, and offer the hope of deductive testing and new predictive domains.[4]

Gabbey, along with Shapin, Anstey, and Nadler, is essentially correct in describing Boyle's mechanical explanations as structural. However, it is important to note that McMullin's definition of structure, which of course is the essential aspect of his definition of structural explanation, might be too broad to be completely accurate. If a structure is defined only as the relationship between constituent entities or processes, then many problematic types of explanations also seem to count as structural. For example, consider Aristotle's explanation of the properties of terrestrial substances. Primary qualities such as Heat and Cold are certainly entities in Aristotle's philosophy. And it is their relationships, including their presence and proportion, which are employed to explain the natural phenomena. Thus, this should count, according to McMullin's definition, as a type of structural explanation, but this seems counter-intuitive. In fact, McMullin explicitly denies that the Aristotelian elemental theory is structural.[5]

McMullin's definition might even allow explanations in which natural phenomena are explained in terms of the volitions of angry gods to be counted as structural. For example, a volcanic eruption might be explained in terms of powerful gods quarrelling with each other. Gods, their volitions, and their actions are certainly constituent entities in this crude explanatory scheme, and the phenomenon to be explained is explained in terms of the relationships between these entities.

McMullin is not convinced that this is a serious problem. In a recent email correspondence he claims that the essential feature of the concept of structure involved in retroduction is causality, so that a structure is causally responsible for the phenomenon being explained. McMullin goes on to claim that this definition of structure is not satisfied by the Aristotelian counter-example. I am not sure that this completely avoids the problem. For example, on the Aristotelian account the predominance of the element Water is the cause of the moistness of wine.

Nevertheless, I am not claiming that all structural explanations are exclusively mechanical explanations, or that the two are synonymous. Rather, I agree with McMullin and Gabbey that mechanical explanations are types of structural explanations, and that structural explanation is to be defined as an explanation that appeals to the structure of the phenomenon to be explained. But I question McMullin's definition of structure. A structure might be more than just any type of relationship between entities. It could be a particular kind of relationship. Perhaps it is a relationship that concerns the *arrangement* of the constituent entities. Such arrangements are present in the mechanical explanations of the seventeenth century, but lacking in elemental explanations. A focus on arrangement also allows the types of explanations that McMullin has in mind, including many of the explanations advanced in contemporary science, to count as structural explanations.[6] For example, the explanations that I cited from Wesley Salmon in Chapter 1 that explain natural phenomena in terms of waves in an electromagnetic field would count as structural in just this sense.

On the other hand, if McMullin's broader definition of structure is correct, and a structure is any causally relevant relationship between constituent entities, then perhaps the relationship of *arrangement* is what distinguishes mechanical explanations from other types of structural explanations. A mechanical explanation is thus a categorical or hypothetical structural explanation in which the structure involved is based on the arrangement of constituent parts. McMullin is sympathetic to this definition of mechanical explanation, agreeing that Boyle's mechanical explanations appealed to arrangement in this sense, citing the example of Boyle's mechanical explanation of the barometer. Although he questions whether Newton's dynamical explanation of motion would count as mechanical in this sense.

Boyle's inclusion of the contrivance of parts in his list of mechanical affections is a direct acknowledgement of the importance of both structure and arrangement to mechanical explanation. While the explanations advanced by other mechanical philosophers were indeed mechanical, Boyle is the first to adequately emphasize the importance of structure and arrangement to mechanical explanations.

Descartes, for example, often writes of the size, shape, and local motion of bodies, and employs structures to mechanically explain a variety of phenomena, but seldom directly acknowledges the importance of structure, arrangement, or contrivance in scientific explanation. One notable exception occurs in *Le Monde*. Descartes writes:

> If you find it strange that in explaining these elements I do not use the qualities called 'heat', 'cold', 'moisture', and 'dryness' – as the philosophers do I shall say to you that these qualities themselves seem to need explanation. Indeed, unless I am mistaken, not only these four qualities but all others as well, including the forms of inanimate bodies, can be explained without the need to suppose anything in their matter other than the motion, size, shape, and arrangement of its parts.[7]

Galileo also seldom mentions the concept of arrangement, an exception occurring in *The Assayer*, but he does not include it among his primary qualities or generally emphasize its importance to mechanical explanation. In fact, his use of the conception in *The Assayer* is particularly curious. Although it appears in his discussion of the primary qualities of matter (size, shape, and motion), Galileo uses the concept of arrangement only regarding the placement of the nose and tongue on the human face. In an interesting passage, he writes:

> It is remarkable how providently the tongue and nasal passages are situated and disposed, the former stretched beneath to receive the ingression of descending particles, and the latter so arranged as to receive those which ascend. The arrangement whereby the sense of taste is excited in us is perhaps analogous to the way in which fluids descend through the air, and the

> stimulation of the sense of smell may be compared to the manner in which flames ascend in it.[8]

Boyle, however, primarily through the concept of contrivance, both acknowledges the importance of arrangement to scientific explanation, and includes it among his mechanical affections. Also it is this emphasis on arrangement, perhaps more than any other feature of the seventeenth-century mechanical philosophies, that has survived in modern scientific practice.

But it is important to note that arrangement, while essential, is not the only aspect of Boyle's conception of contrivance. Boyle believed that every corpuscular arrangement was guided by divine intentionality. For Boyle, this aspect of contrivance had equal, if not more, importance than arrangement. That creation was intentionally designed was known by revelation according to Boyle. It was this intentionality that justified the search for the mechanisms underlying natural phenomena.

In the previous chapter we explored Boyle's mechanical affections, the primary epistemological tools of his mechanical philosophy. The next and final chapter demonstrates the presence of the mechanical philosophy in contemporary science, but to fully understand its importance we need to first consider the contrivance of parts in more detail. It is Boyle's focus on contrivance that encouraged the eventual scientific emphasis on structural explanation, and it is this focus on structure that fuels the search for mechanisms in the natural world.

Boyle's use of contrivance

There are two distinct but essential properties involved in Boyle's conception of contrivance: intentionality and arrangement. We can see the importance of each by considering some of the passages in which Boyle discusses contrivance. It should once again be kept in mind that Boyle used a variety of terms and phrases to signify this concept including, but not limited to, the contrivance of parts, the disposition of parts, the coaptation of parts, contexture, order, arrangement, and structure. We have seen in the previous chapter that Boyle also uses terms such as 'texture' and 'mixture' in a similar way; with subtle distinctions he sometimes raises and sometimes ignores. One interesting passage in which he employs the term 'contrivance' occurs at the very beginning of Boyle's scientific career and adequately illustrates the connection he saw between theology and natural philosophy. In the essay 'Of the study of the book of nature', he indicates that organisms contain a contrivance of parts, the immediate causes of which are known only to God. This passage was discussed in Chapter 2 but is worthy of consideration in this context. Boyle writes:

> For the suttlest Filosofer in the World shall never be able to assigne the true & immediate Cause of the outward shape & Bulke, the Inward Contrivance of the Parts, & the Instincts & Sympathys of any one Animall, the Primitive formes & seminall Energys of things depending wholly upon the Will of the First Creator.[9]

Here Boyle is expressing contempt toward atheistic natural philosophers who attempt to explain the world without appealing to a divine creator. But we also see in this early passage the two essential components of Boyle's conception of contrivance. He implies that the outward shape, size, and form of the animal are dependent upon an internal structure or arrangement of material parts, and that furthermore God intentionally designed this structure. Boyle goes on to appeal to the subtle contrivance of parts of a watch as an analogy to the intentionally designed arrangement of the world.

Boyle mentions contrivance again in *Of The Usefulness of Natural Philosophy*. Here he argues that God intentionally designed the universe in such a way as to be intelligible to man, though he was under no obligation to do so. Boyle writes:

> For not content to have provided him all that was requisite either to Support or Accommodate him here, [God] hath been pleas'd to contrive the World so, that (if Man be not wanting to himself) it may afford him not onely Necessaries and Delights, but Instructions too; For each Page in the great Volume of Nature is full of real Hieroglyphicks, where (by an inverted way of Expression) Things stand for Words, and their Qualities for Letters.[10]

Here Boyle's use of contrivance focuses more on the intentional aspect of God's creation, but the analogy to letters implies the importance of arrangement or structure in God's creative acts. Later in the essay, Boyle compares the world created by God, whom he describes as the *divine contriver*, to lesser, though admirable, human contrivances such as the operations of firearms and the famous clock at Strasbourg, a machine in which he emphasizes the wonderful *coaptation* of pieces. Throughout the essay we see Boyle's employment of the properties of both intentionality and arrangement, united in the concept of the contrivance of parts.

Another important source for Boyle's conception of contrivance is the famous essay *The Origine of Formes and Qualities*. In the preface, we see Boyle give his most explicit inclusion of the contrivance of parts as one of the primary mechanical affections. He writes:

> That then, which I chiefly aime at, is to make it Probable to you by/experiments (which I think hath not yet beene done:) That almost all sorts of Qualities, most of which have been by the Schooles either left Unexplicated, or Generally referr'd, to I know not what Incomprehensible Substantiall Formes; *may* be produced Mechanically, I mean by such Corporeal Agents, as

> do not appear, either to Work otherwise, then by the vertue of the Motion, Size, Figure, and Contrivance of their own Parts, (which Attributes I call the Mechanical Affections of Matter, because to Them men willingly Referre the various Operations of Mechanical Engines:) . . .[11]

In this passage, Boyle includes the contrivance of parts among the primary mechanical affections, although it should also be noted that, according to Hunter, in the Latin version of the essay the phrase 'contrivance of parts' is followed by the phrase 'and various changes of texture and motion'.[12] Nevertheless, this passage directly indicates the importance of *arrangement* to Boyle's conception of contrivance. Boyle goes on to employ the concept of contrivance in an interesting discussion about locks and keys. Here he notes that the proper function of the lock and key go beyond shape, size, and motion to involve an intentional arrangement or contrivance of parts that functions mechanically, without requiring mysterious powers or faculties. Boyle writes:

> We may consider then, that when *Tubal-Cain*,[13] or whoever else were the Smith, that Invented *Locks* and *Keyes*, has made his first Lock, (for we may Reasonably suppose him to have made that before the *Key*, though the Comparison / may be made use of without that Supposition,) That was onely a Piece of Iron, contriv'd into such a Shape; and when afterwards he made a Key to that Lock, That also in it self Consider'd, was nothing but a Piece of Iron of such a Determinate Figure: but in Regard that these two Pieces of Iron might now be Applied to one another after a Certain manner, and that there was a Congruitie betwixt the Wards of the Lock and those of the Key, the Lock and the Key did each of them now Obtain a new Capacity and it became a Main part of the Notion and Description of a Lock, that it was capable of being made to Lock or Unlock by that Piece of Iron we call a Key, and it was Lookd upon as a Peculiar

> Faculty and Power in the Key, that it was Fitted to Open and Shut the Lock, and yet by these new Attributes there was not added any Real or Physical Entity, either to the Lock, or to the / Key, each of them remaining indeed nothing, but the same Piece of Iron, just so Shap'd as it was before . . . To carrie this Comparison a little Further, let me adde, that though one that would have Defin'd the First Lock, and the First Key, would have Given them distinct Definitions with Reference to each other; and yet (as I was saying) these Definitions being given but upon the Score of Certain respects, which the Defin'd Bodies had One to Another, would not/infer, that these two Iron Instruments did Physically differ otherwise then in the Figure, Size, or Contrivement of the Iron, whereof each of them consisted.[14]

This is an important passage for several reasons. It illustrates both components of Boyle's conception of contrivance, intentionality and arrangement. Boyle claims that the shape, size, and motion of the lock and key must be organized in a certain specific way for the mechanism to function. This intentional structure gives the lock and key new capacities that are actually reducible to shape, size, and motion. Boyle goes on to point out that the intentional arrangement of the lock and key become essential features of both their notion and description, thus emphasizing its explanatory importance as a mechanical affection. Shortly afterwards in the essay, Boyle describes texture as a type of contrivance, writing:

> And when many Corpuscles do so convene together as to compose any distinct Body, as a Stone, or a Mettal, then from their other Accidents (or Modes,) and from these two last mention'd,[15] there doth emerge a certain Disposition or Contrivance of Parts in the whole, which we may call the *Texture* of it.[16]

Once again we see that the relationship between contrivance and texture is vague, but the work as a whole is a good illustration of the importance that intentional arrangement played in Boyle's explanatory scheme. A final source is useful when examining Boyle's use of contrivance. In 'About the excellency and grounds of the mechanical hypothesis', Boyle claims that God not only put matter into motion, but also contrived matter into structures and mechanical affections. Boyle writes:

> . . . I plead onely for such a Philosophy, as reaches but to things purely Corporeal, and distinguishing between/the first *original* of *things*; and the subsequent *course of Nature*, teaches, concerning the *former*, not onely that God gave Motion to Matter, but that in the beginning He so guided the various Motions of the parts of it, as to contrive them into the World he design'd they should compose, (furnish'd with the *Seminal* Principles and Structures or Models of Living Creatures,) and establish'd those *Rules of Motion*, and that order amongst things Corporeal, which we are wont to call the *Laws of Nature*. And having told this as to the *former*, it may be allowed as to the *latter* to teach, That the Universe being once fram'd by God, and the Laws of Motion being setled and all upheld by His incessant concourse and general Providence; the Phaenomena of the World thus constituted, are Physically produc'd by the Mechanical affections of the parts of Matter, and what they operate upon one another according to Mechanical Laws.[17]

Here again we see the two essential components of Boyle's conception of contrivance come into play. Corporeal particles are intentionally arranged and put into moving structures, according to divine laws that, in turn, mechanically produce the natural phenomena that we observe in the world. A few pages later Boyle claims that God's contrivances, such as the human body, are incomparably superior in structure to the rarest and most impressive man-made objects.

There are many other passages in which Boyle writes of the importance of contrivance to the mechanical philosophy. But these examples are sufficient to illustrate his use of the term as well as his focus on the underlying concepts of both intentionality and arrangement. Particularly, Boyle's emphasis on arrangement, whether through the use of the term contrivance, order, structure, or texture, demonstrates an awareness of the importance of structure to mechanical explanations that is emphasized by Boyle perhaps more than any other mechanical philosopher of his time.

Part of my project is to demonstrate that the mechanical philosophy has survived the death of corpuscularianism, and is an active part of contemporary science. I have argued that Boyle's focus on contrivance has played an important role in this legacy. But the mechanical explanations in contemporary science do not often appeal to divine intentional design (as we will see in the next chapter). If such intentionality is an essential feature of Boyle's conception of contrivance, how can the concept of contrivance play such an important role in contemporary scientific explanation? The answer to this, I think, is that modern mechanical explanations often illicitly appeal to the apparent intentionality that is caused by natural processes, such as natural selection, of which Boyle was unaware. Scientists in fact look for organized structures in natural phenomena and often find them. What motivated this search for Boyle was the belief that such structures were divinely designed to be understood by man's investigation of nature. Although contemporary science functions without such appeals to intentional design, the idea that mechanisms exist in nature undoubtedly has its origin in such speculations.

The appeal to arrangement and structure made by mechanical explanations also directly leads to epistemological advantages such as the capacity for both mathematization and accurate prediction. These are features of the mechanical philosophy that are often cited by the traditional interpretation of the scientific revolution, but they are also controversial. So let's take a moment to examine each.

Mechanism, mathematics, and prediction

Shapin criticizes the traditional view of the relationship between mathematics and the mechanical philosophy. He describes this view in the following passage:

> It is sometimes said that the mechanical picture of a matter-and-motion universe "implied" a mathematical conception of nature. Certainly a mechanical view of the world was in principle amenable to mathematization, and a number of mechanical philosophers vigorously insisted on the central role of mathematics in the understanding of nature. Boyle, for example, accepted that a natural world whose corpuscles were conceived to be variously sized, shaped, arranged, and moved called out, in principle, for mathematical treatment.[18]

But Shapin argues that in practice such mathematization was next to impossible, and did not play an important role for the specific mechanical explanations advanced in the seventeenth century. He writes:

> Despite widespread contemporary professions of a natural "fit" between mechanism and mathematically framed accounts, however, very little of the mechanical philosophy was actually mathematized, and the ability to represent mathematically expressed physical regularities or laws did not depend on belief in their mechanical causes. That is to say, although the mathematization of natural philosophy was certainly an important feature of seventeenth century practice, professions of a

> constitutive relation between mechanism and mathematics remain problematic.[19]

Shapin even points out that philosophers such as Bacon and Boyle were aware of this problem. He writes:

> Such practitioners as Bacon and Boyle said that mathematical accounts worked very well when nature was considered abstractly, and less well when it was addressed in its concrete particularities.[20]

Shapin raises an interesting point. And such contemporary claims about the natural fit between mathematics and the mechanical philosophies of the seventeenth century might be premature or at least oversimplified. But let us consider this relationship between the mechanical model of explanation and the capacity of mathematization.

Consider the simple example of an ordinary doorknob. The knob is attached to a spindle of a specific shape that fits exactly into a hole in the latch mechanism. When the knob is turned the spindle is rotated, drawing the latch out of the latch hole in the doorframe and into the interior of the door, allowing the door to open. This mechanism can be described in very precise mathematical terms, but such a description is not a necessary condition of a successful mechanical explanation of the doorknob, a description of the structure of the mechanism is sufficient. Mechanical explanations are conducive to mathematical description, and the more complex the mechanism the more helpful such a description will be. But mechanical explanations and mathematical descriptions are conceptually distinct. It is possible for a successful mechanical explanation to exist without a mathematical description, just as it is possible for a mathematical description to exist without a mechanical explanation.

Such a state holds true for Boyle's mechanical interpretation of the fire-analysis experiments. If fire is composed of the local motion of agitated corpuscles, then it should be possible, in principle, to provide a precise mathematical description of the size, shape, and motion of each individual corpuscle. But a successful mechanical explanation of fire does not require such a description, and can even be corroborated empirically in its absence.

Now let us consider the similar relationship between mechanical explanations and the capacity for accurate prediction. Consider our example of the doorknob. Knowing certain mechanical affections of the door, the doorknob, the doorframe, the hinges, and similar facts about the immediate environment, I can make generally accurate predictions about what will happen when the doorknob is turned and then pulled. But how is this capacity for prediction related to mechanical explanation?

First, it's important to note that the capacity for prediction can exist, in principle, without the presence of mechanical explanation. Consider a possible world in which a rabbit mysteriously and consistently appears every time the words *abra kadabra* are uttered in the presence of a hat. In such a world it would be possible to predict the appearance of a rabbit, under certain conditions, with perfect accuracy. But it is also possible that in such a world no mechanical explanation of this strange phenomenon could be provided. Here we have the presence of an infallible capacity for prediction without the presence of mechanical explanation.

Although the capacity for accurate prediction does not require mechanical explanation, a successful mechanical explanation produces this capacity. The correct understanding of the mechanism yields a capacity for at least generally accurate prediction. The capacity can even be used as a measurement for the success of a mechanical explanation. This use of prediction to evaluate alternative explanations is a product of the mechanical model's focus on structure. Once the explanation of a natural phenomenon is based on the mechanical model it can compete efficiently with other mechanical explanations in terms evaluated by the capacity for prediction.

It is important to note that Shapin convincingly demonstrates that such evaluations are social practices, and that these evaluations can become biased. For example, evaluation in terms of prediction in the seventeenth century involved the *selection* of experiments to be recognized in the evaluation process. Boyle sometimes dismissed mechanical theories of significant predictive value. Shapin cites the example of Boyle's famous air-pump experiments, and his rejection of Hobbes' alternative interpretations.[21] Nevertheless, the capacity for prediction is still an important ingredient in the mechanical model, and an ingredient that has remained a part of science, even if a fallible part, ever since the adoption of the mechanical model of explanation.

Mechanical explanations are structural explanations that appeal exclusively to what Boyle described as the mechanical affections, the most important of which was the contrivance of parts. Boyle's concept of contrivance appeals to the notions of both arrangement and intentionality. This model of explanation has been an active feature of the scientific endeavour from Boyle's time up to the present day. In the next chapter we will consider some important examples that demonstrate that the mechanical philosophy is alive and well.

Notes

1. McMullin, Ernan (1978), 'Structural explanation', *American Philosophical Quarterly*, 15, 139.
2. McMullin, Ernan (1978), 'Structural explanation', *American Philosophical Quarterly*, 15, 144.
3. McMullin, Ernan (1978), 'Structural explanation', *American Philosophical Quarterly*, 15, 145.

4. Gabbey, Alan (1985), 'The mechanical philosophy and its problems: mechanical explanations, impenetrability, and perpetual motion', in Joseph Pitt (ed.), *Change and Progress in Modern Science*. Dordrecht: D. Reidel, 10.
5. See McMullin, Ernan (1978), 'Structural explanation', *American Philosophical Quarterly*, 15, 140.
6. McMullin claims that structural explanation has become the dominant form of explanation in science. See McMullin, Ernan (1978), 'Structural explanation', *American Philosophical Quarterly*, 15, 140.
7. Descartes, René (1991), *The World*, in John Cottingham, Robert Stoothoff, Dugald Murdoch, and Anthony Kenny (eds), *The Philosophical Writings of Descartes*. Cambridge: Cambridge University Press, vol. 1, 89.
8. See Matthews, Michael R. (ed.) (1989), *The Scientific Background to Modern Philosophy*. Indianapolis, IN: Hackett Publishing Company, 58.
9. Boyle, Robert (2000), 'Of the study of the book of nature', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 13, 157.
10. Boyle, Robert (1999), *Of The Usefulness of Natural Philosophy*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 3, 232.
11. Boyle, Robert (1999), *The Origine of Formes and Qualities*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 5, 302.
12. See Boyle, Robert (1999), *The Origine of Formes and Qualities*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 5, 302.
13. Hunter notes that this is a biblical reference, referring to Genesis, Chapter 4, Verse 22.
14. Boyle, Robert (1999), *The Origine of Formes and Qualities*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 5, 309–10.
15. Here Boyle is referring to *Order* and *Position*.
16. Boyle, Robert (1999), *The Origine of Formes and Qualities*, in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 5, 316.
17. Boyle, Robert (2000), 'About the excellency and grounds of the mechanical hypothesis', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 8, 104.

18. Shapin, Steven (1996), *The Scientific Revolution*. Chicago, IL: University of Chicago Press, 57–8.
19. Shapin, Steven (1996), *The Scientific Revolution*. Chicago, IL: University of Chicago Press, 58.
20. Shapin, Steven (1996), *The Scientific Revolution*. Chicago, IL: University of Chicago Press, 59.
21. See Shapin, Steven (1985), with Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life*. Princeton, NJ: Princeton University Press.

7

Mechanical Explanation in Contemporary Science

In the previous chapter we examined Boyle's concept of the contrivance of parts, and how his focus on this particular mechanical affection showed an acknowledgement of the structural nature of mechanical explanation. Throughout this work I have claimed that the mechanical philosophy survived the ultimate failure of Boyle's corpuscular hypothesis, and that while Boyle's general metaphysics was eventually rejected, the most essential feature of his epistemology, what I have described as the mechanical model of explanation, remains an important part of contemporary science. It is now time to support this claim.

In this chapter we will consider several important examples of mechanical explanation in contemporary science. I have chosen samples both for their clarity and their obvious appeal to the mechanical model of explanation, but the list of examples I present is far from exhaustive. One simply does not have to look very far to find evidence of the continued influence and use of the mechanical philosophy in science. Among other things, the presentations in this chapter make it plausible that the acceptance of mechanical explanations in the seventeenth century had more than social and political causes. Instead, the mechanical model came to be accepted, at least in part, for objective philosophical reasons, including its explanatory superiority to the elemental model of scientific explanation.

Before exploring the contemporary examples, let's begin by considering the use of mechanical analogies in science. The application of such analogies has its origins in the dawn of scientific enquiry, but their use can still be found in science today. Next we will look at several examples of mechanical explanations in contemporary science. These include explanations involving natural selection, genetics, plate tectonics, and the formation of arms in spiral galaxies. Each of these examples make a direct appeal to the mechanical affection of arrangement or structure, and several appeal to many of Boyle's other mechanical affections, including size, shape, and motion.

The machine analogy

Analogies between nature and machines played an important role in the mechanical philosophies of the seventeenth century and Boyle's philosophy is no exception. Boyle saw the universe as a divine machine analogous to the sophisticated clocks that had become common in his time. It is interesting to note that earlier clocks often had their mechanisms exposed. By Boyle's time the clock-making industry had advanced to the point where the internal mechanisms responsible for the motion of observable features, such as the hands, were often hidden, sometimes in dramatically artistic ways. Likewise, Boyle and the other mechanical philosophers reasoned that the universe is a vast machine whose internal mechanisms are hidden due to their small size. But although the mechanisms of nature are hidden, scientific investigation may reveal them just as the workings of a clock are revealed once the casing is removed.

One of Boyle's favourite examples was the clock at the cathedral in Strasbourg. This enormous machine was the peak of technological sophistication in Boyle's day. It not only indicated the time but also calculated solar cycles, lunar cycles, eclipses, and had a variety of ingenious automata. Explanations of the workings of such clocks are mechanical explanations, describing how the various functions of the clock are caused by the structure and motion of its parts. As we discovered in Chapter 2, Boyle found such explanations particularly intelligible. They inspired him to search for similar explanations of natural phenomena.

As previously noted, the clock is not the only mechanical analogy that Boyle employs in his vast corpus. He also makes analogies involving many different machines including firearms, levers, pulleys, locks, and keys. The popularity of the clock metaphor is due, no doubt, to a combination of the clock's complexity, evident intentionality, and the significance of the arrangement and local motion of its parts.

This important analogy between man-made machines and natural phenomena can be found in contemporary science. Consider the important analogy between the computer and the human brain. The analogy between the functions of the brain and the functions of computers has proved to be very constructive and informative. Although the analogy is controversial and has run into significant problems in explaining mental phenomena, such as the nature of consciousness and the intentionality of mental states, it has helped a great deal in formulating theories about such important mental properties as perception, imagination, learning, memory, and information-processing. Furthermore, the analogy between the computer and the brain has been an invaluable tool to the new science of artificial intelligence.

The mechanical analogy is an important explanatory tool in the mechanical philosophy, but it was not a development new to the seventeenth century. As early as the fifth century BCE philosophers have employed such analogies. For example, Anaximander made a mechanical analogy between the cosmos and the wheel of a chariot. During the Han dynasty, the ancient Chinese philosopher Zhang Heng appealed to this same mechanical analogy. The metaphor also became compatible with the later cosmological model advanced by Ptolemy. While the mechanism of the chariot wheel is quite simple, its use is very significant to the history of science, and often neglected due to the common emphasis on organic cosmological models, such as the egg. This early use shows that mechanical analogies are far from unique to the seventeenth century. Rather, their presence can be seen from the very origins of science to the present day. The contemporary use of mechanical analogies in science is sufficient to show that the mechanical philosophy survived the death of Boyle's corpuscular hypothesis, but the consideration of recent scientific mechanical explanations puts the matter beyond any reasonable doubt. Let's consider some important examples.

Natural selection as mechanism

Consider the theory of natural selection in evolutionary biology. Basically, the sexual reproduction of organisms in the natural world is restricted by the finite availability of natural resources. Because natural resources are limited, only a finite amount of organisms survive long enough to reproduce. Some organisms possess traits that help them obtain the natural resources needed to survive long enough to reproduce. When these organisms reproduce they pass these traits on to their offspring. Organisms that do not survive long enough to reproduce consequently are not able to pass on their traits. Over time this process leads to incredible diversity and adaptation to the environment. It should be noted that natural selection is only a metaphor for this process. Adaptation and diversity arise without any conscious selection at all, and natural selection has proven to be a fundamental explanatory tool in modern biology, the value of which cannot be overstated.

Charles Darwin laid the foundations for this incredible explanatory theory, variations of which are nearly universally accepted today by the scientific community. In the introduction to his famous book *On the Origin of Species*, Darwin speculates that the great diversity of species in the world had not been individually created. But Darwin is quick to point out that such speculation is insufficient without an explanatory description of exactly how the species of the world developed. In words strikingly similar to Boyle, Darwin writes:

> In considering the origin of species, it is quite conceivable that a naturalist, reflecting on the mutual affinities of organic beings, on their embryological relations, their geographical distribution, geological succession, and other such facts, might come to the conclusion that each species had not been independently created, but had descended, like varieties, from other species. Nevertheless, such a conclusion, even if well founded, would be unsatisfactory, until it could be shown how the innumerable species inhabiting this world have been modified, so as to acquire that perfection of structure and coadaptation which most justly excites our admiration.[1]

In this passage Darwin is calling for a description capable of explaining the exact process by which the diversity of species in the world could have developed without independent design and creation. Darwin describes the mechanism by which this takes place as natural selection. He writes:

> As more individuals of each species are born than can possibly survive; and as, consequently, there is a frequently recurring struggle for existence, it follows that any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected. From the strong principle of inheritance, any selected variety will tend to propagate its new and modified form.[2]

This process of natural selection is a mechanical process because it appeals to no qualities or powers other than the arrangement of an organism's traits in relation to the abundance of its local environmental resources. In his recent book, *Darwin's Dangerous Idea*, Daniel Dennett acknowledges the relationship between *mechanism* and natural selection. Dennett writes:

> If I were to give an award for the single best idea anyone has ever had, I'd give it to Darwin, ahead of Newton and Einstein and everyone else. In a single stroke, the idea of evolution by natural selection unifies the realm of life, meaning, and purpose with the realm of space and time, cause and effect, mechanism and physical law.[3]

This view of evolution as a natural mechanism is a major theme throughout the course of Dennett's informative book. But Dennett is not the first to interpret natural selection as a mechanism. Manfred Eigen describes evolution in a similar way. In his book *Steps Toward Life* he writes:

> [Natural] selection is more like a particularly subtle demon that has operated on the different steps up to life, and operates today at the different levels of life, with a set of highly original tricks. Above all, it is highly active, driven by an internal feedback mechanism that searches in a very discriminating manner for the best route to optimal performance, not because it possesses an inherent drive towards any predestined goal, but simply by virtue of its inherent non-linear mechanism, which gives the appearance of goal-directedness.[4]

Mechanism is an appropriate description of the process of natural selection. It is a process that creates diversity and adaptation through mechanical affections such as structure and arrangment. In other words, natural selection is a process that works through the arrangement and interactions of constituent entities such as organisms, food, water, climate, cover, and other natural resources.

The mechanics of DNA

It is interesting to note that while Darwin was able to mechanically describe how it was that species could develop and change through natural selection, he was, nevertheless, ignorant of the deeper mechanisms by which the traits of an organism were passed on to its offspring in the process of reproduction. On the surface, this might seem a bit surprising. Mechanical explanations have been touted as explanatorily superior to occult explanations due to their greater intelligibility. How can a mechanical explanation be clear and intelligible if it appeals to deeper mechanisms that are unknown, as in the case of Darwin's explanation of natural selection? The answer is that every explanation, even every mechanical explanation, comes to an end at some point. But this is not particularly problematic because the value of an explanation depends on the phenomena one seeks to explain.

Consider Boyle's frequent clock analogies. The motions of the hands of the clock can be described mechanically, but these macro-level mechanisms, according to Boyle, ultimately rely on the micro-level mechanisms of the insensible corpuscles of which the clock is made. Even if one was unaware of such insensible mechanisms, a successful and intelligible mechanical explanation might be produced of why it is that the large hand moves exactly twelve times faster than the small hand.

The traits passed on to successive generations through the process of natural selection rely on molecular mechanisms that occur in the cells of organisms. A complex molecule called deoxyribonucleic acid or DNA, usually located on chromosomes in the nucleus of the cell, determines the traits of all organisms, as well as most viruses. Basically, a molecule of DNA is composed of two strands or chains that are arranged in the form of a winding staircase called a double helix. These strands are composed of chemical compounds called nucleotides, and are arranged like a ladder. Each nucleotide consists of a sugar molecule, a phosphate group, and one of four nitrogen compounds that are called bases. Each rung of the ladder is formed by a combination of two of the nitrogen compounds. It is this arrangement of bases that determines the traits of the cell, and consequently the traits of an organism.

The structure and significance of the DNA molecule was discovered in 1953 by James Watson and Francis Crick, and directly lead to the development of the new science of genetics. Watson describes the discovery in his recent book *DNA: The Secret of Life*:

> DNA, as Crick and I appreciated, holds the very key to the nature of living things. It stores the information that is passed on from one generation to the next, and it orchestrates the incredibly complex world of the cell ... By the mid-sixties, we had worked out the basic mechanics of the cell, and we knew how, via the "genetic code," the four-letter alphabet of DNA sequence is translated into the twenty-letter alphabet of the proteins.[5]

Watson uses the term 'mechanics' in his description of DNA, and this use is appropriate. The genetic explanation of the development and transfer of an organism's traits is a mechanical explanation that appeals primarily to the precise arrangement of nitrogen-containing compounds. Such arrangements become incredibly complex, but the explanations developed from such arrangements are intelligible in *exactly the respect that Boyle anticipated*. The concept of the arrangement of four component parts is both clear and understandable, and the incredible diversity such an arrangement can manifest is reminiscent of Lucretius' alphabet analogy concerning the infinite mechanical modifications of atoms. Furthermore, Watson's use of the mechanical analogies such as chains and ladders is equally intelligible. DNA molecules and, by extension, explanations that appeal to these molecules, are extremely complex structures, but these structures are composed of a straightforward and intelligible arrangement of four constituent parts. Consider an analogy from mathematics. Extremely complicated mathematical explanations can be based on a series of self-evident steps. Likewise, genetic explanations retain an inherent intelligibility despite the complexity of the structure because the explanation appeals to clear and intelligible mechanical affections and analogies.

Continental drift as mechanism

Why do the shapes of the continents seem to fit together? How do mountains form? What causes earthquakes to occur? The theory of continental drift provides answers to these questions, and these answers take the form of mechanical explanations. The continents, as well as every other feature of the earth's crust, rest on gigantic plates that, in turn, rest on a semi-fluid layer of the earth, allowing them to move. The arrangement and motion of these plates cause earthquakes, the formation of mountains and the apparent fit of the separate continents, which were once united. In the excellent article 'From continental drift to plate tectonics', Naomi Oreskes describes the development of this invaluable explanatory geological theory. She writes:

> Since the 16th century, cartographers have noticed the jigsaw-puzzle fit of the continental edges. Since the 19th century, geologists have known that some fossil plants and animals are extraordinarily similar across the globe, and some sequences of rock formations in distant continents are also strikingly similar. At the turn of the 20th century, Austrian geologist Eduard Suess proposed the theory of Gondwanaland to account for these similarities: that a giant supercontinent had once covered most or all of the earth's surface before breaking apart to form continents and ocean basins. A few years later, German meteorologist Alfred Wegener suggested an alternative explanation:

> continental drift. The paleontological patterns and jigsaw-puzzle fit could be explained if the continents had migrated across the earth's surface, sometimes joining together, sometimes breaking apart. Wegener argued that for several hundred million years during the late Paleozoic and Mesozoic eras (200 million to 300 million years ago), the continents were united into a supercontinent that he labeled *Pangea* – all Earth. Continental drift would also explain paleoclimate change, as continents drifted through different climate zones and ocean circulation was altered by the changing distribution of land and sea, while the interaction of rifting and drifting land masses provided a mechanism for the origins of mountains, volcanoes, and earthquakes.[6]

The theory of continental drift explains geological features by straightforwardly appealing to Boyle's mechanical affections. This example of the presence of mechanical explanation in science is particularly interesting because it appeals not only to the arrangement of continent parts, in this case tectonic plates, but also to other mechanical affections such as size, shape, posture, and local motion. When tectonic plates collide over the course of many years, mountains such as the Himalayas are formed. This is a mechanical process because it is the mechanical interaction of the tectonic plates that causes the phenomenon. Similar modifications of the plates cause other natural phenomena. Although the structures involved are massive rather than the microscopic corpuscles on which Boyle focused, the very same mechanical affections are applied producing explanations with the high level of intelligibility that Boyle championed.

The mechanical explanation of continental drift is also interesting because, like natural selection, it relies on another underlying mechanical explanation. In fact, the theory of continental drift was not generally accepted until a further mechanism was found to explain the motion of the tectonic plates.[7] The mechanism advanced to explain plate motion is the presence of convection currents within the earth's mantle.[8] Convection is a mechanical process by which circular motion is produced in a fluid body due to the warmer portions rising, while the cooler portions sink. Such circular motion in the earth's mantle is believed to cause the motion of tectonic plates.

Another interesting point concerning the theory of continental drift is that, like many mechanical explanations in the history of science, it became accepted by gradually replacing another mechanical theory. For example, at one time the formation of mountains was explained by a mechanical process called *contraction*. According to the theory of contraction, the earth was, at one time in the distant past, very hot, and has been gradually cooling over the years. As the earth cooled, the surface contracted like a drying apple, causing the formation of geological features such as mountains. Oreskes describes the theory in the following way:

> One of the central scientific questions of 19th-century geology was the origin of mountains. How were they formed? What process squeezed and folded rocks like putty? What made the earth's surface move? Most theories involved terrestrial contraction as a causal force. It was widely believed that Earth had formed as a hot, incandescent body, and had been steadily cooling since the beginning of geological time. Because most materials contract as they cool, it seemed logical to assume that Earth had been contracting as it cooled, too. As it did, its surface would have deformed, producing mountains.[9]

But despite an appeal to mechanical affections such as shape, size and motion, as well as an initial plausibility, the explanation of mountain formation in terms of contraction was not without its problems. One of the problems that led to its downfall, and the acceptance of the theory of continental drift, came from advances in the detailed mapping of mountain ranges. Oreskey writes:

> Nineteenth-century geologists had worked in great detail to determine the structure of mountain belts, particularly the Swiss Alps and the North American Appalachians. When they mapped the folded sequences of rocks in these regions, they found the folds to be so extensive that if one could unfold them the rock layers would extend for hundreds of miles. Impossibly huge amounts of terrestrial contraction would have to be involved. Geologists began to doubt contraction theory as an explanation for the origins of mountains.[10]

Thus, contraction theory, though based on the mechanical model of explanation and clearly intelligible, gave way to alternative explanatory theories such as continental drift. This illustrates one of the strengths of the mechanical model of explanation. Mechanical theories compete with other mechanical theories, the mechanisms of which offer better explanations of the phenomenon in question. Just as Boyle's corpuscular hypothesis was eventually rejected and replaced with other mechanical theories of matter, contraction theory was rejected and replaced by a theory that appealed to the mechanism of tectonic-plate motion to better explain the formation of mountain belts. Similar theoretical replacement can be seen in the explanatory theories of galaxy formation.

The mechanics of spiral-galaxy formation

One common type of astronomical phenomenon is the presence of spiral galaxies in the known universe, accounting for approximately 65 per cent of the brightest galaxies observable from earth. There are several types of spiral galaxy, but a frequent type is the recognizable *Grand Design* spiral galaxy, of which our galaxy, the Milky Way, is an instance. Such galaxies are composed of several visible arms that rotate around the galactic centre. For many years the presence and formation of these arms were explained in the following way. Galaxies are composed, for the most part, of stars. The arms of a spiral galaxy were thought to be very dense clusters of stars, which, through their gravitational rotation around the galactic centre, gave the arms an appearance of rotation in a pattern similar to the rotation of the planets around the sun due to Kepler's laws.

Such an explanation is clearly mechanical, appealing not only to the arrangement of stars in a galaxy, but also to mechanical affections such as size, shape, and local motion. But this mechanical explanation was eventually rejected. In the influential book *Galaxies: Structure and Evolution*, Roger Taylor explains this rejection in the following way:

> Although the differential rotation of galaxies can be understood . . . in just the same way that there is a very distinct differential rotation of planets in the solar system described by Kepler's law, it raises serious problems when we consider the spiral structure of galaxies. Suppose that at some time a galaxy has the somewhat idealized spiral pattern . . . Suppose also that the galaxy has a rotation curve of the type which I have described in which the angular velocity near the centre of the galaxy is very much greater than that near the edge. Now follow the evolution of the galaxy for a time during which the central regions rotate several times but the outer regions do not complete a single rotation . . . The spiral structure is rapidly *stretched* and *wound up* and the relatively simple spiral structure is rapidly destroyed. For rotation curves of the type which are observed, very substantial winding up would occur in a time of order 10^9 years compared with an estimated age of most galaxies of order 10^{10} years or more. Because there is a very substantial number of regular spiral galaxies, it appears that the spiral structure is a long-lived phenomenon which must be preserved against modifications apparently produced by different rotation.[11]

Taylor points out that if the arms were simply composed of stars that always remain in the arm, then in only a few rotations the arms would wind up and the spiral structure would be destroyed. The frequency of *grand design* spiral galaxies in the universe suggests that the spiral structure is stable, lasting through many rotations, so a new explanation of the presence and formation of spiral arms must be found. The explanation of spiral arm formation that is currently preferred is called *Density Wave Theory*. According to this theory, the arms of a spiral galaxy are formed of rotating density waves. Stars, rotating at a different speed than the arms, move in and out of these density waves. Taylor argues that such density waves are the result of new star formation. He writes:

> This has led to the idea that the spiral structure cannot contain the same material at all times . . . It has instead been suggested that the spiral pattern is a density wave. Where the density of matter is enhanced at the crest of the wave, there is supposed to be enhanced star formation so that both luminous stars and gas show a spiral pattern. In this case, although the spiral arm is always present, the material in the pattern is continuously changing; this is a similar situation to any other wave such as, for example, a water wave.[12]

Taylor continues the discussion later in the book, writing:

> The evidence that star formation is associated with spiral structure and that this is a wave pattern is qualitatively very good. In the first instance massive main sequence stars which are unambiguously young are mainly situated in the spiral regions both in our own Galaxy and in other spiral galaxies. This observation is most easily made for nearby bright spirals where the whole spiral structure can be observed. We have no reason to believe that high and low mass stars are produced by distinct processes. If they are not, the observation that young massive stars are concentrated in spiral arms indicates that the spiral arms are

> the main site of star formation. I have explained that the spiral wave is believed to move around the galaxy so that star formation can occur at all parts of the galactic disk in turn. The most massive stars have such a short lifetime that, by the time they have ceased to be luminous, the spiral pattern has hardly changed its position. They should therefore only be found in spiral regions. Slightly less massive stars are luminous for a fraction of the rotation period of spiral waves. Stars of this type should be visible not only in the spiral region but also in regions just behind the spiral patterns which were fairly recent sites of star formation. Stars of lower mass, such as the Sun, have a main sequence lifetime which is equal to many rotation periods of the pattern. Such stars should therefore be observed throughout the disk with no significant correlation with the present position of the spiral arms. The observations of the distribution of stars of different spectral types and hence lifetimes are in good general agreement with these predictions, especially when it is recognized that the compression of gas in spiral waves is probably not the only cause of star formation.[13]

In this passage we can clearly see that wave-density theory offers an explanation of spiral-arm formation based on the mechanical model of explanation. The theory directly appeals to several of Boyle's mechanical affections including arrangement, size, shape, and motion. We also see theory rejection and replacement occurring within the same mechanical model of explanation. Another interesting point, identified by Taylor, is the relationship between the mechanical explanation of spiral-arm formation advanced by wave-density theory and the capacity for accurate prediction, here in the form of galactic star disbursement, arranged according to age.

In this chapter we have considered only a few examples of mechanical explanation in modern science. These examples have been chosen for both their clarity and their direct appeal to Boyle's mechanical affections. But other examples in contemporary science abound. While the mechanical model of explanation is certainly not the only explanatory model to be found in science, its use as a theoretical epistemological tool is indisputable.

In order to understand the importance of the mechanical model of explanation in science it is helpful to consider the following. Imagine, for a moment, the status of scientific inquiry if the mechanical model, perhaps due to a government decree, could not be employed. Virologists could no longer discuss the mechanisms of viral RNA synthesis. Psychologists could no longer describe dissociative or psychogenetic amnesia as a defence mechanism. The Center for Disease Control and Prevention could no longer consider the movements of people around the globe through systems of mass transit as a mechanical explanation for the spread of diseases such as SARS. Would the discipline of science collapse without the ability to appeal to the mechanical model of explanation? This would be an exaggeration. But the efficient and steady progress of science since the seventeenth century owes a considerable debt to the interpretation of nature as a mechanism, and Boyle's work in epistemology and the philosophy of science was influential in bringing about this point of view.

What does this all show? Does it conclusively demonstrate that mechanical explanations are superior to occult explanations? I think such a view is plausible. Occult explanations identify phenomena in need of explanation, an important endeavour to be sure, but mechanical explanations attempt to tell an intelligible story about how underlying properties or entities and their arrangement and interaction cause the phenomena. It is one thing to claim that moistness is a primary quality of water. It is quite another to explain how the arrangement and structure of hydrogen and oxygen atoms and their relationship to environmental temperature causes liquidity.

The mechanical model of explanation that was developed in the seventeenth century started an emphasis on structure that has lasted in science ever since. This new emphasis can correctly be described as revolutionary. The fact that such a model has been almost permanently adopted by science might not prove that it is objectively superior to earlier models of explanation. As the social constructionists correctly point out, the adoption of explanatory models by a scientific community is a social phenomenon. But the continued employment of mechanical explanation in science does suggest that there was a scientific revolution that took place throughout the seventeenth century and that Robert Boyle played an important role in bringing this revolution about.

Notes

1. Darwin, Charles (2003), Joseph Carroll (ed.), *On the Origin of Species*. New York: Broadview Press, 96.
2. Darwin, Charles (2003), Joseph Carroll (ed.), *On the Origin of Species*. New York: Broadview Press, 97.
3. Dennett, Daniel (1995), *Darwin's Dangerous Idea*. New York: Simon & Schuster, 21.
4. Eigen, Manfred (1992), *Steps Toward Life*. Oxford: Oxford University Press, 123.
5. Watson, James (2003), *DNA: The Secret of Life*. New York: Alfred A. Knopf, xi–xiii.
6. Oreskes, Naomi (2001), 'From continental drift to plate tectonics', in Naomi Oreskes and Homer Le Grand (eds), *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Oxford: Westview Press, 3.
7. It should be noted that there were several other factors involved in the acceptance of continental drift. For an excellent account of the eventual acceptance of the theory, see Oreskes, Naomi (2001), 'From continental drift to plate tectonics', in Naomi Oreskes and Homer Le Grand (eds), *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Oxford: Westview Press.
8. Oreskes, Naomi (2001), 'From continental drift to plate tectonics', in Naomi Oreskes and Homer Le Grand (eds), *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Oxford: Westview Press, 7.

9. Oreskes, Naomi (2001), 'From continental drift to plate tectonics', in Naomi Oreskes and Homer Le Grand (eds), *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Oxford: Westview Press, 4.
10. Oreskes, Naomi (2001), 'From continental drift to plate tectonics', in Naomi Oreskes and Homer Le Grand (eds), *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Oxford: Westview Press, 6.
11. Taylor, R. J. (1996), *Galaxies: Structure and Evolution*. Cambridge: Cambridge University Press, 68.
12. Taylor, R. J. (1996), *Galaxies: Structure and Evolution*. Cambridge: Cambridge University Press, 68.
13. Taylor, R. J. (1996), *Galaxies: Structure and Evolution*. Cambridge: Cambridge University Press, 144–5.

Conclusion

Boyle's Role in the Scientific Revolution

I have argued that the scientific revolution marked a change in the model of explanation. Boyle played an important role in bringing this change about in several respects. He looked for a common thread in the different mechanical philosophies of his time. He was among the first to claim that the mechanical philosophy was more intelligible than the elemental theories. And he was the first to sufficiently emphasize the role of structure in mechanical explanation.

Boyle considered a vast assortment of individuals to be mechanical philosophers, including Anaxagoras, Descartes, Democritus, Epicurus, Galileo, Gassendi, Leucippus, and Lucretius. He believed these philosophers were similar in their appeal to mechanical affections. Boyle believed that mechanical philosophers could be divided into three classes. In a postscript intended to accompany his 1686 work entitled *Notion of Nature and Final Causes* he writes:

> . . . I thinke there are three differing sorts of Mechanical Philosophers as that appellation comprizes all those that make use of ⟨the⟩ Mechanical affections of Matter to explain the Phaenomena of Nature. The first sort of these consists of the ⟨Epicurean & such like⟩ Attomists who ⟨after Leucippus & Democritus⟩ ascribe not only the particular effects produc'd in the world but the first formation of the world it selfe to ⟨the casual concourse of indivisible Corpuscles of⟩ Uncreated Matter moveing

from all Eternity in an infinite empty space without taking in any Diety or other incorporeal substances to set these atoms a moveing or regulate their Motions. The second sort of Mechanical Philosophers consists of those that acknowledge God to have been the Author of ⟨both⟩ Matter & Motion, but teach that ⟨He⟩ having impress'd such a quality of Motion upon the universall Matter & establisht some Rules or Lawes according to which the parts of this Matter shall communicate or transfer their Motions one to another without lessening or augementing the original quantity of Motion impress'd on the whole Mass ⟨tho⟩ God ⟨left⟩ the Matter ⟨to it selfe yett⟩ by ⟨the⟩ various occursions or justleings of the parts they ⟨were able⟩ by degrees to worke themselves into such Bodys as we call ⟨the⟩ Sun Moon ⟨fix'd⟩ stars, Planetts ⟨Aire⟩ Earth Water ⟨Vegetables⟩ Minerals Animals &c whose ⟨orderly⟩ Agragate or systeme we call the World. But tho these two sorts of Mechanical Philosophers be the only that the learned Men I have been speaking of are pleas'd to take Notice of and for their sakes to pass severe censures upon Mechanical Philosophers in generall yett I must take leave to affirme that there is a third sort of them who employ minute Corpuscles of differing ⟨sizes⟩ & variously shap'd ⟨& mov'd⟩ to explicate the particular phenomena that they meet with in the world as 'tis now constituted but tho these may be call'd Mechanical Philosophers because in the explication of such particular Phaenomena they prefer the Mechanical principles newly mentioned to the substantiall formes real qualitys & ⟨those⟩ other principles of the vulgar Philosophy which they take to be unintelligible precarious or Needless yett are ⟨they⟩ far from thinkeing the Mechanicall affections of matter sufficient to have brought the parts of it into so goodly & admirably artificiall a frame as ⟨that of⟩ our world without the direction of a Most Wise & powerful Agent that is in one word, God.[1]

Boyle believed that although the theories of these philosophers are very different, they are radically unlike elemental theories in their adoption of a model of explanation that appeals to mechanical affections rather than primary qualities or substantial forms. As we have seen, he believed that this model offered explanations that were more intelligible than elemental theories. Boyle's advancement of the mechanical model of explanation was a significant step in the scientific revolution.

Boyle was also the first mechanical philosopher to adequately emphasize the importance of structure and arrangement in mechanical explanation. This can be seen in his adoption and emphasis of the contrivance of parts as a mechanical affection, as well as his frequent use of various mechanical analogies. There has been an important emphasis on the structure of natural phenomena in science ever since, and this new emphasis on structure was an essential aspect of the scientific revolution.

Mechanism, magnetism, and the mind/body problem

Boyle's mechanical model of explanation based on mechanical affections is well illustrated by his interpretation of the fire-analysis experiments. Gabbey, among others, is correct to point out many of the flaws in his specific corpuscular explanations. For instance, Boyle was never able to deal satisfactorily with problems concerning impenetrability and the nature of elasticity. Even his contemporaries recognized these limitations. Gabbey also might be correct in claiming that there are problems inherent in the mechanical philosophy. One problem might be the lack of a describable structure in Boyle's philosophy that would explain the nature of subjective conscious experiences. But if he is correct he is pointing to a problem with structural explanations in general. Therefore his claim does not provide the support that Shapin desires to justify the position that there was no scientific revolution, no event or series of related events that forever changed science as a practice. There *was* a scientific revolution. And Boyle played a crucial role in it. Boyle advanced the adoption of a new model of explanation and a new emphasis on the structure of natural phenomena.

With this said, I would like to conclude with some suggestions about future research in this and related areas. As far as Boyle scholarship is concerned there are at least two related future projects that are important. First, more work needs to be done on Boyle's mechanical interpretations of electricity and magnetism. Electricity and magnetism were very important concerns of the seventeenth-century mechanical philosophers. Up until this time they were considered occult qualities. Their mechanical explanation was an important goal of Boyle, Descartes, and Gassendi. Furthermore, it is the eventual scientific explanation of these phenomena that directly led to the contemporary theories of physics and the postulation of an electromagnetic field as a fundamental feature of reality. Understanding Boyle's work in this area may lead to important insights into the nature of these theoretical developments.

A second area in Boyle research that deserves attention is his view of subtle matter, corpuscles so small that they can penetrate the glass and make a vacuum physically impossible. Descartes was a mechanical philosopher who defined matter exclusively in terms of extension and thus believed a void was impossible. It is well known that Boyle disagreed with Descartes and Hobbes on this issue. But there are some passages that suggest that Boyle acknowledged the possible existence of subtle corpuscles with the capacity to penetrate glass. Flushing out his position on this issue will foster a better understanding of the relationship between his theory and the theories of other mechanical philosophers of this period.

Another related area of research that should be pursued is in contemporary philosophy of mind. A recent goal of many philosophers is to develop a science of consciousness. Such a science was long assumed to be necessarily materialistic in nature. But recent philosophers, sympathetic to forms of dualism, such as David Chalmers, have advocated a position which holds consciousness to be a natural phenomenon explainable in terms of phenomenal laws. Viewing this goal from the point of view of the mechanical model of explanation we can see that such a science of consciousness might require an explanation of consciousness in terms of phenomenal mechanisms. If phenomenal mechanisms are conceivable then a science of consciousness might be developed. If, on the other hand, such phenomenal mechanisms are not possible then the mind/body problem might be intractable, as philosophers such as Thomas Nagel and Ned Block have suggested. If arrangement is a key feature of mechanical explanation, as I have argued, then such phenomenal mechanisms cannot be rejected out of hand. Our phenomenal conscious experiences are ordered and arranged in very specific ways. The existence of phenomenal or non-physical mechanisms might be a real possibility.

Recognizing the essential epistemological aspects of Boyle's mechanical philosophy increases our understanding of the subtlety and importance of the philosophical work in the seventeenth century. But it also provides a new way to look at the scientific enterprise. It suggests an important interpretation of the nature and development of scientific explanation that, despite important advances in our understanding of the social aspects of the history of science, should not be ignored.

Note

1. Boyle, Robert (2000), 'Suppressed or discarded sections of Notion of Nature: postscript', in Michael Hunter and Edward Davis (eds), *The Works of Robert Boyle*. London: Pickering & Chatto, vol. 14, 148.

Robert Boyle Chronology

1627	Born at Lismore, Ireland, January 25.
1635–8	Attends Eton College.
1639–44	Travels throughout Europe.
1645	Settles at Stalbridge, Dorset.
1646–9	Establishes laboratory and begins conducting fire-analysis experiments.
1654	Possibly writes 'Reflections on the experiments vulgarly alleged to evince the four peripatetic elements and the three chymical principles'.
1655	Settles at Oxford.
1655–60	Conducts famous vacuum-pump experiments.
1660	Attends formal formation of Royal Society, November 28.
1661	Publishes *The Sceptical Chymist*.
1666	Publishes *The Origine of Formes and Qualities*.
1668	Settles in London.
1690	Publishes *The Christian Virtuoso*.
1691	Dies, December 31.

Glossary of Technical Terms

Air: one of the four Aristotelian elements of which all terrestrial substances were alleged to be composed. Air was said to have two primary qualities: hot and moist.

Alchemy: a medieval chemical art whose objectives included the transmutation of base metals into gold, an elixir for immortality, and a chemical explanation of the cosmos and its origin.

Atomism: the doctrine, originally developed by Leucippus and Democritus, that the universe is composed of indivisible material particles in an empty void.

Caput mortum: a residual byproduct of distillation.

Corpuscular hypothesis: the doctrine, advanced by Robert Boyle, that all matter consists of microscopic mechanical particles called corpuscles, which move and interact throughout an empty vacuum.

Distillation: a chemical process in which a substance is evaporated and then condensed, chiefly for purification.

Earth: one of the four Aristotelian elements of which all terrestrial substances were alleged to be composed. Earth was said to have two primary qualities: cold and dry.

Element: a primitive or simple body out of which a compound body is said to be composed.

Elemental theory: a chemical theory that holds that the properties of a compound substance are determined by the presence and proportion of primitive or simple bodies out of which the substance is said to be composed.

Fire: one of the four Aristotelian elements of which all terrestrial substances were alleged to be composed. Fire was said to have two primary qualities: hot and dry.

Fire analysis: an early method of chemical investigation in which a substance was exposed to fire or heat in order to separate it into its elemental ingredients.

Iatrochemistry: an early branch of chemistry primarily devoted to the discovery and production of medicines.

Mechanical affections: a set of epistemological principles including size, shape, motion, and arrangement, valued by Boyle for their intelligibility and employed in his mechanical explanations.

Mechanical explanation: a scientific explanation that appeals exclusively to mechanical analogies or mechanical affections.

Mercury: one of the three Paracelsian principles of which all terrestrial substances were alleged to be composed.

Nomothetic explanation: an explanation that posits a natural law and explains a phenomenon by citing it as an instance of that law.

Occult explanation: an explanation that appeals to a quality that is unobservable, the only ground for postulating it is that it 'explains' a particular phenomenon or property, there are no alternative methods of confirming its presence, and no intelligible description of it that is independent of what is claimed to be explained can be given.

Occult quality: a quality that is unobservable, the only ground for postulating it is that it 'explains' a particular phenomenon or property, there are no alternative methods of confirming its presence, and no intelligible description of it that is independent of what is claimed to be explained can be given.

Paracelsian: a follower of the sixteenth-century alchemist Paracelsus (1493–1541), also known as Philippus Aureolus Theophrastus Bombastus von Hohenheim.

Peripatetic: an Aristotelian.

Primary quality: unless otherwise noted, any of the four fundamental properties of Aristotelian elements, including hot, cold, moist, and dry. Aristotle believed that each element contained a combination of two of these properties that in turn produced the observable traits of terrestrial substances.

Salt: one of the three Paracelsian principles of which all terrestrial substances were alleged to be composed.

Spagyrist: an alchemist.

Sublimation: a chemical process in which a substance changes from a solid to a gaseous state, without going through a liquid phase.

Sulphur: one of the three Paracelsian principles of which all terrestrial substances were alleged to be composed.

Torefaction: a chemical process in which a substance is subjected to heat in order to drive off volatile ingredients, often resulting in a black colour.

Water: one of the four Aristotelian elements of which all terrestrial substances were alleged to be composed. Water was said to have two primary qualities: cold and moist.

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