2 Robert Boyle

Chemistry and Experiment

Robert Boyle (1627–91) was a famous seventeenth-century chemist. His contemporary John Aubrey wrote of him: "His greatest delight is chemistry. He has at his sister's a noble laboratory and several servants (apprentices to him) to look [after] it. He is charitable to ingenious men that are in want, and foreign chymists have had large proof of his bounty, for he will not spare for cost to get any rare secret."* He certainly learned from others, notably the American alchemist George Starkey (1628–65), who was born in Bermuda, was educated at Harvard, spent some fifteen years in London, and died in the Great Plague. Although Boyle has often been referred to as the father of modern chemistry, his chemistry was not modern chemistry. He was an alchemist as much as a chemist. Modern chemistry rests in part on an idea of chemical elements developed in the late eighteenth and early nineteenth centuries, and Boyle by no means anticipated that idea. The origins of chemistry are too complex for any individual to be given sole credit. Boyle is, however, an important figure in the history of chemistry, and in two respects he deserves at least some credit as the founder of modern chemistry.

His major contributions were twofold. First, he convincingly championed chemistry as an important part of the new natural philosophy of the seventeenth century. More precisely, Boyle argued that chemical philosophy and corpuscular philosophy provided important support for one another. We will soon consider the nature of corpuscular philosophy. For now, it is enough to note that it offered mechanical explanations, based on the behavior of corpuscles. These corpuscles might be aggregations, groups, or clumps of atoms, which were in principle divisible. Alternatively, they might simply be individual atoms, which by definition were indivisible. Boyle made chemistry compatible with the new, fashionable, and dominant kind of scientific explanation. His second major contribution, partly borrowed from Starkey, was the development of an *experimental method* in chemistry that made it fit into the new

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*John Aubrey, *Brief Lives,* ed. R. Barber (London: The Folio Society, 1975), 55.

authoritative public practice of science championed by the Royal Society of London. It is a pleasing coincidence that his best-known chemical book, *The Sceptical Chymist,* was published in 1661, one year after the original foundation of the Royal Society.

Boyle was born in English-occupied Ireland, the seventh son of one of the richest men in the kingdom. When he was eleven years old, he went on a European tour, in what was to become a tradition for the sons of the wealthy. It is unfortunate that he was so young—too young to participate in the latest exciting philosophical debates. Paris at that time was the European center for corpuscular philosophy. Pierre Gassendi, an ordained priest, natural philosopher, atomist, and friend of Galileo and Kepler, was at the center of what was essentially an unofficial university for the study of mechanical and corpuscular philosophy. There a variety of different forms of atomism and mechanism jostled with one another. René Descartes invented his own brand of particle theory, in which space was considered to be completely filled with particles of different sizes. Boyle later learned much about these philosophies, and it is useful to say more about them now and about their origins.

In fifth century B.C., the Greek philosopher Leucippus invented a cosmology in which the world was described as made up of atoms moving in empty space. Democritus later took up and developed Leucippus's theory. He portrayed a world in which an infinite number of eternally unchanging atoms moved in a vacuum, and, through their chance combinations, produced all the different bodies in the world and accounted for their qualities. Aristotle, in the fourth century B.C., was extremely disturbed by such views. His reasons for being disturbed were good ones. For Aristotle, explanation was above all an account of the *causes* of things and of the *purposes* that governed them. In a world made up of atoms moving at random and governed only by chance, how could one talk of cause and purpose? How could one really explain anything? There were other problems too. Aristotle believed in continuity, whereas atoms moving in a vacuum inevitably introduced physical discontinuities. He did not dismiss all kinds of atomism. He believed in the existence of minute parts of matter which became known as *minima naturalia,* but these were in his view neither eternally unchanging nor existing in a vacuum, and in spite of being called *minima* (i.e., "least things"), they were not even indivisible. It was Democritus's doctrine of atoms and the void that Aristotle found philosophically intolerable, and he therefore rejected it.

That doctrine did, however, find some favor after Aristotle. Epicurus, another Greek philosopher, developed a philosophical system with cosmological and ethical components. The cosmology followed Democritus. The ethics found value in a world governed by chance, a godless world, in which pleasure was the only good. Epicurus's ideas survived into Roman times, when the poet and philosopher Lucretius wrote six books of verse called *On the Nature of Things* to popularize them. Lucretius, like Epicurus, saw atheism as a positive feature of atomism.

When Greek and Roman learning next surfaced in the Western world, it followed the same paths as alchemy had, by way of Alexandria into Arab civilization, which eventually extended into Spain. Following Spain's reconquest by Christian forces, its treasure house of Greek, Roman, and Arabic learning passed into the Christian West. Philosophical learning, including natural philosophy, became an avocation for churchmen, who pursued knowledge in the newly founded universities and in church establishments. Aristotle, suitably interpreted, was favored by them, and, since they did not have access to the works of the atomists, they did not have to wrestle with doctrines of atoms and the void.

Then came the Renaissance, a period of the recovery of ancient learning and of an unstoppable flow of new observations and new ideas, often emerging from or inspired by the old. Lucretius was rediscovered, and so was Epicurus. Greek atomism became fashionable at the French court. But just as Aristotle in the twelfth and thirteenth centuries had had to be interpreted and modified so as to be reconciled with Christianity, so too did atomism in the seventeenth century. Gassendi undertook the Christianization of atomism. Atoms, he explained, were not eternal but created by God. Their movement in the void was not random but the result of their God-given initial motions, which made them agents of divine purpose.

A work justifying atomism in ways very much like Gassendi's was also sought in England. A very unreadable but successful one appeared, written by Walter Charleton. By the time the Royal Society of London was founded, "mechanism" of one kind or another was the new orthodoxy, and both atoms and corpuscles were fitted into the world.

Boyle came to be an adherent of corpuscular philosophy. Aristotle's philosophy, with its four terrestrial elements occupying a plenum, was incompatible with a doctrine of atoms and the void, or of a universal matter. Boyle subjected Aristotle's theories, as far as they applied to chemistry, to serious criticism. He did the same to Paracelsus's theories, which were based upon three elements, the *tria prima*. Boyle's criticisms were both rational and experimental in character. They did not prevent him from pursuing alchemy as part of his chemistry. It is this unique combination of what were later separated into the twin pursuits of chemistry and alchemy, to the latter's disadvantage, that has led some historians to characterize Boyle's avocation as "chymistry," to distinguish it from what came before and after. I shall continue to use the spelling "chemistry" and the words *chemistry* and *alchemy*. It is, however, important to realize that Boyle's chemistry is very different from that of the late eighteenth century, just as that chemistry is very different from today's. The idea that alchemy involved metallic transformation while chemistry had other goals was not widely accepted until the very end of the seventeenth century. That acceptance was based on a mistake in historiography, which led to an incorrectly narrow interpretation of the range of alchemy. Chemistry at any given time is the product of a continuing history, subject both to evolution and on occasion to revolution.

A Christian Alchemist

When Aubrey wrote that Boyle spared no expense to learn rare secrets, he was referring especially to alchemical lore, which was frequently kept secret from all but adepts. Boyle's hostility toward Paracelsus's three-principle theory and toward Aristotle's four elements did not mean that he was against the philosophical theory of Sulfur and Mercury associated with Geber. Indeed, he believed that real, true, or philosophical Mercuries and Sulfurs could be isolated from metals. What he would not do was extend this idea to all substances. Nor did he accept the idea that the separated Mercuries and Sulfurs were elemental. He went so far as to believe that he had himself prepared the sulfur of gold and had been shown its mercury. He worked to animate mercury to produce more noble Mercuries, and he believed that he had succeeded in the alchemical degradation of gold to silver. If that was possible, so too was the reverse process, the transmutation of silver into gold.

Boyle had a lifelong interest in philosophical Mercury, which he thought would dissolve the metals into their constituents. He believed that the philosophers' stone existed and that it could serve as a universal medicine. He also believed that it was spiritually active and could facilitate communication with angels and rational spirits. Because God had created the world, seeking to understand the causes of natural phenomena was a path to the understanding of God's work. Natural philosophy, including Boyle's chemistry, was therefore a religious, indeed a Christian, activity. Boyle, by constructing a union of his religion with the fundamental ideas of gold making, showed how deeply he was committed to the enterprise.

Boyle accepted the possibility of transmutation, and he distinguished between transmutation performed with the philosophers' stone and other modes of transmutation. The philosophers' stone could transmute any metal into gold, and it could indefinitely, perhaps endlessly, multiply itself and the gold that it produced. Transmutation could also be explained simply by the rearrangement of the corpuscles that made up a particular body, and it did not work on most metals. Use of the philosophers' stone could legitimately be reserved for initiates, and secrecy could be justified in its pursuit and practice. In contrast, other aspects of Boyle's chemistry needed to be open to scrutiny and criticism. Boyle sought to reconcile his science with the new and respectable corpuscular philosophy, on which he based his careful construction of a new experimental method.

The Philosophy of Experiment

Boyle devoted his life to developing details of a new way of knowing. He called this way the experimental philosophy. His experimental philosophy was his own, but he built it on foundations established by others. He did not see as far as his young friend Isaac Newton, but he could have said, as Newton did, that if he saw further than other men had, it was by standing on the shoulders of giants.

Like many of his contemporaries, Boyle found experimentalism a satisfying alternative to the sterility of Aristotelian learning. The fiercest and most influential critic of that learning in England in the generation before Boyle's was Francis Bacon (1561–1626), lawyer, statesman, and philosopher. Bacon wanted to found his theories on reliable information rather than on speculation or tradition. He believed that systematic and comprehensive natural histories—bodies of information about nature derived from experience rather than from the authority of ancient books—would provide the proper foundation. One did not understand what happened in nature by witnessing a single event or performing a single experiment. Knowledge needed lots of information as its foundation, and phenomena first needed to be observed before one worried about their causes.

Bacon was a lawyer, and experimentation for him was a way of putting nature on trial and making it reveal its hidden workings, the causes of phenomena. Judge and jury in a court of law needed a body of evidence to decide where the truth lay, and they needed experience and common sense in judging that evidence. Bacon argued that the natural philosopher worked in the same way, requiring lots of information to reach a conclusion. Bacon, like Boyle after him, was interested in searching out "the more subtle changes of form in the parts of coarser substances." In experiments, the natural philosopher, like the lawyer, should use his sense "only to judge of the experiment, and . . . the experiment itself shall judge of the thing." The point of collecting data and organizing them into systematic data banks, or natural histories, was "to give light to the discovery of causes."* Philosophers were to use experiment and sense to analyze and dissect nature. Chemical analysis offered one way of dissecting nature.

Boyle followed Bacon's approach closely here. He saw chemistry as a tool for probing nature, and he argued that other natural philosophers (including the chemists whose theories he criticized) had made improper use of empirical evidence. They had arrived at general conclusions and theories by reasoning with insufficient data. Sometimes they were so unwise as to derive a theory from just one experiment. Boyle, like Bacon, wanted his database to be complete. That was a huge enterprise, one that even if ultimately achievable would at best be out of reach for a very long time. Conclusions reached in the meantime were therefore necessarily tentative; they were hypotheses, which could be overthrown if counterevidence later came to light.

Boyle was a great admirer of those who showed the most ingenuity and rigor in their experiments. Remember that experiments were not merely a matter of observing; they were a way of putting nature on trial, in order to understand its causes and inner workings. Boyle particularly admired Galileo as an experimenter. Freely falling bodies were hard to observe, so Galileo had hit on the strategy of slowing them by letting them roll down inclined planes and then reasoning about what he observed. Boyle thought that chemists too needed to show how experiments were done, to bring experiments "out of their dark and smoky laboratories" into the light of informed public scrutiny.†

Distinguishing between observation and experiment, Boyle believed that chemists made observations "of what nature does, without being over-ruled by the power and skill of man." These observations were building blocks in the database of natural history. Experiment, in contrast, involved intervention, "when nature is guided, and as it were, mastered by art."‡ He realized that experiments went beyond the outward appearance of things. They depended on some prior theoretical knowledge, which was itself based on an interpretation of the history of nature. Theory and experiment therefore relied on one another.

To succeed, experiments needed to be reproducible, both by the chemist who originated them and by other natural philosophers. Boyle gave careful at-

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*Quotations in this paragraph are from Bacon's works, as quoted by Rose-Mary Sargent, *The Diffident Naturalist: Robert Boyle and the Philosophy of Experiment* (Chicago: University of Chicago Press, 1995), 51.

†Boyle quoted in Sargent, *The Diffident Naturalist,* 71.

‡Ibid., 71, 137.

tention to the circumstances that could frustrate that need. One of the most important considerations was that chemists had to work with pure substances, and tests were required to ensure that purity. Impurities could come from the original source, for example, in complex minerals. They could be introduced deliberately, by fraud. They could creep in over time, as in the process whereby wine turns to vinegar. And there were lots of practical considerations. The scale on which an experiment was carried out could be a problem. Consider that fire would not work uniformly throughout a large sample but would work evenly in a small sample. Instrument quality was crucial. For example, if the connections between vessels were inadequately luted (sealed), reactants would escape. Even if such leakage did not change the process being investigated, it meant that precise quantitative measurement was impossible; and quantification was something that Boyle was keen on.

Chemistry and the rest of natural philosophy offered a way of learning about God's activity in the world and were therefore religious activities. Boyle was confident that God would gradually reveal all knowledge, including the knowledge of nature, to good Christians in heaven. But meanwhile, Boyle had to consider imperfect knowledge and imperfections in earthly apparatus. He had to control leakage of gases from lutes or from air pumps, control the different heats produced by furnaces, develop more accurate thermometers, and generally occupy himself with the operation and improvement of instruments.

Besides distinguishing between experiment and observation, Boyle divided experiment into two groups, "probatory" and "exploratory." Probatory experiments were designed not to test theoretical knowledge but to use such knowledge to test the reliability of the conditions surrounding an experiment. Those conditions included the purity or impurity of substances used and the adequacy of apparatus. Boyle made use of chemical indicators to test the progress of some reactions, so that, for example, he could decide whether a sample of spirit of salt (hydrochloric acid) was pure or contaminated.

Exploratory experiments could test hypotheses, see whether popular beliefs were well founded, or involve the invention of instruments, which could produce new phenomena by "reducing nature to alter her course." The same experimental procedures in different contexts could be either exploratory or probatory; distillation, for example, could determine whether a drug was pure or could be used to discover the drug's chemical constituents.

Not the least important of Boyle's practices concerning experiment was his habit of reporting experimental failures and disappointments. Failed experiments could suggest new lines of research or improvements in technique. Also valuable was his insistence on avoiding imprecise and arbitrary language in reporting the results of experiments or in framing hypotheses. Because Salt and Mercury simply had too many different meanings for Paracelsians, even when the experimental practice was good, the accounts of experiments and the reasoning from them were flawed.

Who Believes in Elements?

For Boyle, chemical observation and experiment could contribute significantly to natural philosophy by probing nature, exploring the inward parts of matter, and inquiring into causes. He pursued a program of "associating Chymical Experiments to Philosophical Notions."* He wanted to convince natural philosophers that chemistry could assist them, and part of his strategy for doing this was to show the congruence between chemical understanding and the mechanical philosophy. He wanted "to beget a good understanding betwixt the Chymists and the Mechanical Philosophers, who have hitherto been too little acquainted with one another's Learning."† He was, however, confronted with serious problems when it came to claiming that chemistry was a respectable part of the new natural philosophy of the seventeenth century. What were Boyle's colleagues in the recently founded Royal Society of London to make of proliferating and competing theories of the elements, textbooks that listed unreliable and unconfirmed observations, alchemical cheats and frauds, and the association of chemistry with secrecy, magic, unintelligibility, and downright dishonesty? Although there were a lot of chemist-alchemists in the Royal Society, such abuses would scarcely encourage philosophers to take chemistry seriously. Boyle had to establish a clear distinction between chemistry pursued according to the canons of his experimental philosophy, and the wrong-headed kinds of chemistry that had given the subject a bad name.

In 1661 Boyle published *The Sceptical Chymist,* which demolished what he regarded as either fallacious reasoning or incompetent experiment or both. It was above all an attack on theories of the elements devised by those seduced more by theory than by experimental evidence. We have already encountered the principal element theories that Boyle attacked. Aristotelians had their four elements, earth, air, fire, and water. Paracelsians had three, the *tria prima* of Mercury, Sulfur, and Salt, which were not the same as the common mercury, sulfur, and salt of the laboratory, apothecary's shop, or even (in the case of table salt) the kitchen. Van Helmont had either one or two, depending on how you interpreted him: water, or, taking the biblical account literally, water and air,

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*Boyle quoted in Lawrence M. Principe, *The Aspiring Adept: Robert Boyle and His Alchemical Quest* (Princeton: Princeton University Press, 1998), 181.

†Ibid., 183.

which came before earth and were therefore in a sense primary. But then one had to remember the confusing circumstance that water, even if an original substance and so after a fashion elementary, nevertheless contained its own mercury and sulfur; and air was not regarded as a chemical species at all, although it might contain chemical substances in, for example, particles of smoke. The preceding sentences only make sense if the reader knows what meaning to attach to the words *element, mercury, sulfur,* and the rest. Using the same words with a variety of meanings was something that had offended Bacon and similarly offended Boyle, at least in those areas that he believed should be public science. There were regions of chemistry that he thought were best reserved for adepts and where secrecy was therefore acceptable, even desirable. But Boyle's *Sceptical Chymist* deals with public science, where theories are on trial, experiments have to be repeatable, and evidence needs to be confirmed by reliable witnesses.

Boyle took the various element theories literally, subjecting them to rational criticism and comparing their predictions with his own experiments and observations and with those of others. Heat was one of the keys to chemistry. It was common knowledge that heat was produced in most chemical reactions. A variety of fuels and furnaces had been developed over the centuries, giving the chemist control over the temperatures of *his* reactants and over the length of time they were heated.* In 1556 Agricola had written an encyclopedic treatise on metals which contained a great deal of information about the use and construction of furnaces. Such information, along with what we know about the traditional practices of alchemy, meant that chemists and alchemists knew how to use fire. They used fire to make alloys, to make charcoal, and in almost every operation of chemical and alchemical art.

We have seen that one of Boyle's major concerns was to reveal the inner workings of nature and that he considered chemical analysis to be one way to pursue this goal. Fire provided the commonest means of analysis, and Boyle was determined to show that, when applied to the various element theories of his day, it failed singularly to provide support for any of them. If one burned wood, ash and soot were produced, and so was smoke. This was not helpful

for any of the element theories. If one subjected recently cut green logs or branches of wood to destructive distillation, then things looked more promising. With distillation, one of the products was charcoal, which being solid might correspond to earth. Various liquid fractions were produced and could be condensed. Boyle characterized these as oil, vinegar, and water, which might correspond to the element water. Something that was hard to contain, which Boyle called spirit, also emerged during the distillation, and this might be related to air or water. When the distillation was carried out at a hot-enough temperature, the wood or charcoal would catch fire. Here perhaps was the element of fire. So it was just possible to claim that four elements were released from wood by fire, as long as one carried out the analysis under the right conditions. Merely burning the wood would not reveal so many elements.

There was a problem, though, which Boyle pointed out, taking his objection from Van Helmont: How do we know that what is produced by our analysis was previously present in the substance being analyzed? Analysis on its own

Renaissance Metalworking

Refining metals was important for alchemy but also for industry. The most famous manual of Renaissance metallurgy was by Georgius Agricola (1494–1555), who wrote a detailed account of mining technology. In the tenth chapter of this work, he explained how precious metals were separated from base metals and from one another. The techniques that he discussed often involved the use of acids, as in the separation of silver from gold. They also involved furnaces.

In this engraving, *A* is the furnace; note that there are several furnaces, since heating was the principal tool for metallurgists, just as it was for alchemists. *E* is the draught hole underneath the furnace, *C* indicates the air holes, and *B* the round hole in which a crucible (*F*) or distillation apparatus (*G* and *H*) could be placed. *K* marks the flasks in which the distilled substance could be condensed and collected.

There were many types of furnaces and of distillation apparatus, but every piece of apparatus shown in this sixteenth-century illustration could have been found in earlier medieval laboratories or in laboratories as late as the eighteenth century. Alchemical, chemical, and metallurgical laboratories were relatively unchanged for hundreds of years.

- From Georgius Agricola, *De re metallica* (Basel, 1556), book 10, figure 1.

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*I have italicized the word *his* to make the point that the early Fellows of the Royal Society, as well as physicians, surgeons, metallurgists, and mining chemists, makers of gunpowder, and even, in the main, apothecaries and alchemists were almost all men. There are a few exceptions, like Maria the Jewess, an alchemist in Alexandrian times, and Margaret Cavendish, Duchess of Newcastle, a corpuscular philosopher of the seventeenth century who is often referred to as Mad Meg. There are more women associated with chemistry in the eighteenth and nineteenth centuries. But it was not until the nineteenth century changed into the twentieth that women began to practice chemistry in significant numbers.

does not tell us what substances preexisted in the compound substance being analyzed. But if we do not worry about that problem (and we *should* worry about it), maybe we can claim that the destructive analysis of wood shows that wood is composed of four elements. Boyle would not allow this. Fire analysis, he insisted, when applied to wood gives us not elements but "mixed bodies, disguised into other shapes: the *Flame* seems to be but the sulfurous part of the body kindled; the *water* boyling out at the ends is far from being elementary water, holding much of the salt and vertu of the concrete. . . . The *smoake* is so far from being *aire,* that it is as yet a very mixt body, by distillation yielding an oile, which leaves an earthe behind it; that it abounds in salt, may appear by its aptness to fertilise land, and by its bitterness, and by its making the eyes water."*

Fire analysis falls apart completely in the case of gold; no matter how much we heat it, we are left with the same metal that we started with. To make things worse, if we heat gold and silver together, we get an intimate mixture of the two metals, a kind of alloy. We can separate them again by using *aqua fortis* (concentrated nitric acid). Fire analysis gives us absolutely no basis to argue that gold is composed of four, or three, or for that matter of any other number of elements greater than one. Blood, in contrast, appears to give five products of analysis: phlegm, spirit, oil, salt, and earth. Are these five substances elementary? By means of such arguments, Boyle arrived at the conclusion that we have no good reason to adopt any element theory that claims there are universal elements present in all bodies. Fire analysis yields different answers for different substances and for the same substance under different conditions. So much for Aristotle and Paracelsus.

Boyle is, however, more impressed by Van Helmont, whom he regarded as a good experimentalist and whose results were generally reproducible. He was inclined to look favorably on Van Helmont for a variety of reasons, including his biblical literalism and his publication of the results of weighing reactants and products. Boyle took Van Helmont's willow tree experiment (see Chapter 1) a step further. If water was the source of the growth of the sapling and of the resulting increase in its weight, then there was no need to grow the plant in earth. So Boyle grew seedlings in water and confirmed that they increased in weight. He would not, however, accept water as the universal element. Since Van Helmont had specified that "elementary" water contained its own sulfur and mercury, he was not arguing for water as an element in the purest sense. In any case, Van Helmont's theory, like all the other element theories that Boyle criticized, could not be demonstrated universally. Water was therefore no more a universal element than the *tria prima.*

One other important point about Boyle's attack on element theory is that he did think it was important for chemists to pursue their analyses as far as possible, so as to break the substances down into the simplest constituents that could be reached in the laboratory. A century later, Boyle's simplest products of analysis were to become the building blocks of a new system of chemistry.

Wonderful Atoms

Corpuscles might well be divisible, but atoms by definition were not. Today, we associate atoms with chemical elements. Boyle definitely did not do so. That made for difficulties in relating theory to laboratory practice, for reasons we shall soon see.

There were several versions of corpuscular philosophy in Boyle's day. Boyle focused on the shared aspects of different corpuscular and mechanical systems, including that of Descartes, and argued for their strengths when compared with Aristotelian and other nonmechanical doctrines. It is therefore not necessary here to explore the variety of mechanical and corpuscular systems available in the mid-seventeenth century, but it will be useful to note the principal ones. Gassendi had produced a version of Epicurus that was increasingly acceptable to Christians. Descartes had come up with the remarkable notion that spatial extension was equivalent to matter, so there could be no vacuum. There were other versions of atomism that left no room for God or for spirit, but such atheistic views were very unpopular. Isaac Newton had his own version of atomism, in which atoms coexisted with spirit and were ruled by God's agents; that is where gravitation and other forces came in, and they operated throughout all space. Boyle's corpuscular theory was, like Gassendi's and Newton's different brands of atomism, compatible with God and spirits.

As an older contemporary of Newton, Boyle did not have the advantage of Newton's speculations that chemistry might be handled by a system of short-range forces operating on atoms. He believed in atoms moving in space. Some of his most widely reported experiments were those carried out with an air pump. He explained that it was possible in the jar of the pump to produce a vacuum, where that meant simply a space altogether or at least almost entirely devoid of air. Boyle, unlike Descartes, believed in the possibility of a vacuum or void, a space empty of matter. He thought that all material bodies were made up corpuscles, which were in turn made up of atoms combined in different ways. It was from these different combinations of atoms that the qualities of bodies arose.

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*Boyle quoted in W. H. Brock, *The Norton History of Chemistry* (New York: Norton, 1993), 57 (emphasis in original).

Gassendi adopted the medieval idea of "seminal virtues" which fitted atoms together and shaped them uniformly. Boyle carried out a very large number of experiments, on acids, alkalis, metals, crystals, and other substances, and concluded that each specifically different substance had its own particular internal form or virtue. That accounted for the uniformity of properties or qualities associated with and indeed essential to each distinct substance. The smallest atoms formed aggregates, which came together to form more complex aggregates. All the substances handled by an experimental chemist were compounded of simpler atoms, and their distinct properties arose from four properties of the corpuscles, their *bulk, texture, shape,* and *motion.* Bulk, shape, and motion are straightforward for us. We can understand an explanation of the sweetness of sugars in terms of the roundness of their particles and of the sharp taste and corrosive nature of acids by the geometrical sharpness of their constituent particles. Texture is a little more complicated. The word has the same root as the word *textile* and means the weave of bodies. The texture of particles helps to determine the way that they are woven together into bodies within the reach of our senses. Velcro fasteners are an obvious twentieth-century instance of texture or structure affecting the way bodies fit and stay together.

Boyle now had the foundations for his explanations of chemical change and material transformation. When a fertilized hen's egg produces a chick, there has been a transformation and reorganization of the egg-stuff into chick-stuff. The transformation is produced by a seed, and it is mechanical (rearrangement) and vital. Mechanical chemistry and a kind of vital chemistry, a chemistry of life, are both at work. Again, if a farmer with an orchard grafts a pear shoot onto a plum tree and the graft takes, then the same tree will produce both pears and plums. Here, clearly, the same substance is feeding the growth of both fruits on the same tree, and an explanation in terms of corpuscular rearrangement is one that Boyle found satisfying. Mechanical explanations, he argued, are simply so much more satisfying than explanations based on Aristotle's philosophy. They can account for anything, at least in principle. That is their strength—and also their weakness, as we can see, even if Boyle could not. An explanation that claims to cover everything really explains nothing, since it cannot be tested or refuted. Boyle had no way to prove the correctness of a particular mechanical or corpuscular explanation. He just had a conviction that this was the right *kind* of explanation. He could classify substances according to their qualities, as he did using indicators to discriminate among acids, base or alkaline substances, and neutral substances. But he could not use corpuscular explanations to make firm predictions, and he could not relate his laboratory classifications to any definite account of constituent atoms. If a theory has no predictive value and no firm correlation with practically derived classifications of substances, then it cannot take us very far.

Boyle's contributions to chemistry were numerous and significant. He advanced chemical classification a long way, and his category of neutral substances was valuable for an understanding of the chemistry of salts. Making chemistry a respectable part of natural philosophy was of great importance. The experimental method that Boyle devised, with its emphasis on evidence, repeatability, public verification, quantification, and the use of pure materials, was of even greater importance. His mechanical explanations, however, were ultimately sterile.