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Rebecca Newberger Goldstein

What's in a Name?

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AMID THE DIVISIONS IN THOUGHT WHICH MARKED THE SCIENTIFIC REVOLUTION, THE FOUNDERS OF THE ROYAL SOCIETY INSISTED ON BINDING TOGETHER TWO CONTENDERS FOR THE BASIS OF NATURAL EXPLANATION. AS REBECCA GOLDSTEIN EXPLAINS, THERE WERE DEEP COMMITMENTS TO THE PRIMACY OF EXPERIMENTAL RESULTS, AND TO RECOGNISING UNDERLYING MATHEMATICAL PATTERNS. BUT THE REALLY POWERFUL TRICK, THEN AS NOW, LAY IN FINDING HOW TO BRING THEM TOGETHER.

After a lecture given by Christopher Wren, then the Gresham College Professor of Astronomy, twelve prominent gentlemen, deciding that they would meet weekly to discuss science and perform experiments, recorded their intention to form a 'Colledge for the Promoting of Physico-Mathematicall Experimentall Learning'.

It might not have been the most elegant of designations, but it did, in its very wordiness, portend great things. It gave notice to the hope – because it was still, in 1660, only a hope – that two distinct orientations, one mathematical, the other experimental, would be pounded together into one coherent scientific method. The hope paid off, and it was from

A colour engraving of Gresham College, home of the Royal Society from 1660 to 1710.

within the ranks of the Royal Society that the new compound emerged. Two cognitive stances that had seemed to have little to do with one another, except in their opposition to the system of natural philosophy dominant for centuries, were rendered equally necessary in the explanation of physical phenomena.

It was a time of epistemological urgency. A grandly unifying cathedral of thought was crumbling.[1] The all-inclusive view of the cosmos, laid down by Aristotle and buttressed by the medical theories of Galen, the astronomy of Ptolemy, and the theology of Christianity, had offered a way of explaining … absolutely everything. From the falling of objects to the rising of smoke; from generation and decay to the four basic personality types; from the relation between body and soul to the pathways of the planets; the supposed nature and reason for every aspect of the world could be extracted from an interlocking system that employed a homogeneous form of explanation throughout.

1 There were, of course, political and sociological dimensions to this process, since the grandly unifying system of thought was not only scientific (or proto-scientific) but also religious and political, making challenges to the system ipso facto religious and political challenges. I will focus on the scientific aspects of the process, but it is of course naïve to think that this constitutes the whole story. The history of ideas is hardly hermetically sealed against all but questions of validity and falsification.

The form of explanation had been purpose-driven, or teleological, and its scaffolding was the metaphor of human action. We explain human actions by citing the end state that the agent has in mind in undertaking it. The old system took this familiar model of explanation and expanded it to apply to the world at large. 'To be ignorant of motion is to be ignorant of nature,' Aristotle had written, but by motions he meant not just displacements of bodies but such processes as becoming a parent, gaining knowledge, growing older. All were subsumed under the same conception: a striving to actualise an end-state that was implicit in the motion and provided the explanation, the final cause, for the course that the motion took. The explanatory logic of human actions – based on intentions – was one with the explanatory logic of the cosmos.

The working hypothesis behind teleology was, of course, that all natural phenomena and processes do in fact have goals, allowing them to be viewed as potentialities on the way to being actualised. But every form of explanation makes use of some working hypotheses or other, ascribing to nature the features that allow such explanation to work. The mode of physical explanation that was to supplant teleology, making essential use of mathematics, also staked its claim on the world's being a certain way.

We are today understandably prepared to believe that the only reasons anyone might have had to cling to the old crumbling teleological cathedral, in light of the superior science battering it, were speciously theological; and, in fact, such reasons probably did motivate most of those who clung to the old system. Still, there was nothing a priori fallacious about the old system's assumptions about reality, just as there was nothing a priori true about the assumptions that would replace them.

The grand old system was crumbling, and it made for a capacious space into which genius could expand. When foundations fall, everything can and must be rethought. The exhilaration on display in the writings of the new scientists bears witness to how bracingly liberating such possibilities can be, at least for those with the intellectual imagination and bravado to

take advantage of them. 'You cannot help it, Signor Sarsi,' Galileo exults in *The Assayer*, written in the form of a letter to a friend, 'that it was granted to me alone to discover all the new phenomena in the sky and nothing to anybody else.'

Explanation Re-Explained

And what question is more foundational than the question of what counts as a good explanation? All the great men whom we now associate with the formation of modern science – Copernicus (1473–1543), William Gilbert (1544–1603), Francis Bacon (1561–1626), Galileo Galilei (1564–1642), Johannes Kepler (1571–1630), William Harvey (1578–1657), René Descartes (1596–1650) Robert Boyle (1627–1691), John Locke (1632–1704) and Isaac Newton (1643–1727) – were intensely involved with the question of what form explanation ought to take, if teleology was truly to be abandoned, and there was by no means a consensus among them. Two different orientations emerged: one rationalist, stressing abstract reason, the other empiricist, stressing experience.

In some sense, this cognitive split was nothing new. It had made itself felt in the ancient world, in the distinction between the Platonists and the Aristotelians. It is probably as old as thought itself, shadowing two distinct intellectual temperaments. But the new rationalist and empiricist orientations were not like the old. The rationalist orientation looked to mathematics to provide the new mode of explanation. The empiricists saw the new scientific method as emerging out of experimentation. In responding to the need for a new mode of explanation to take the place of teleology, they became epistemological rivals, offering competing models to take the place of the old system's final causes.

The men who met in Gresham College, London,[2] had given notice, in their self-baptism, that the mathematical and experimental approaches were not only compatible but collaborative; even, as it were, *one*. There is

Copernicus

Francis Bacon

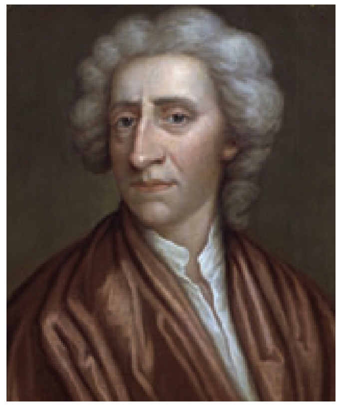
Galileo Galilei

Johannes Kepler

William Harvey

René Descartes

Robert Boyle



John Locke

Isaac Newton

an important epistemological claim implicit in their stated intention to promote 'physico-mathematicall experimentall learning', and the claim was by no means demonstrable in 1660. The thinkers whose work inspired them could be divided into those whose stance was slanted toward the new rationalist understanding of physical explanation – Copernicus, Kepler, Galileo, Descartes – and those who espoused the experimental understanding of physical explanation – Francis Bacon, William Gilbert, and William Harvey. This list suggests a geographical divide, with the rationalists on the Continent, the empiricists in England, which makes the ecumenicalism of the sources of inspiration all the more noteworthy.

The temperamental distinction between the mathematical rationalists and experimental empiricists could be, in fact, so marked that we can well wonder how these scientific founders made common cause with one another against the old system. How can such different scientific temperaments, proffering such different answers as to what a scientific explanation ought to look like, have conspired to hammer out the new methodology?

William Gilbert, for example, a luminary of the experimental approach, is acknowledged as the founder of the science of magnetism, and his experiments had been ingenious. He had carved out of a lodestone – a piece of naturally magnetic mineral – a scale model of the earth he called his terrella, or little earth, and with it he had been able to explain a phenomenon that had been known for centuries. A freely suspended compass needle pointed North, but later observations had revealed that the direction deviated somewhat from true North, and Robert Norman had published his finding in 1581 that the force on a magnetic needle was not horizontal but slanted into the earth. Passing a small compass over his terrella, Gilbert demonstrated that a horizontal compass would point towards the magnetic pole, while a dip needle, balanced on a horizontal axis perpendicular to the magnetic one, indicated the proper 'magnetic inclination' between the magnetic force and the horizontal direction. The experiments convinced him that the earth itself was a giant magnet. Galileo, his contemporary, commends his work, but criticises him for not being well-grounded in mathematics, especially geometry.

Galileo, for his part, could be high-handed in regard to experimentation, writing, for example, that it was only the need to convince his ignorant opponents that made him resort to 'a variety of experiments, though to satisfy his own mind alone he had never felt it necessary to make any'.[3] As one historian of science has written, 'If this was seriously meant, it was extremely important for the advance of science that Galileo had strong opponents, and in fact there are other passages in his works which show that his confident belief in the mathematical structure of the world emancipated him from the necessity of close dependence on experiment.'[4]

The two orientations, rationalist and empiricist, were partly defining themselves in opposition to one another, becoming far more adversarial now that the old system was crumbling. That system had blended together both a priori reason and empirical observation, conceiving both as co-dependently involved in scientific explanation. Aristotle had been a biologist, much given to observing the natural world, and the system that had grown up on Aristotelian foundations had always striven to take account of observable facts. So, for example, as more precise observations of the 'wandering' planets were made, a vast complexity of interacting celestial gears, the ever-more torturous epicycles and eccentrics, was sketched to accommodate them into the geocentric picture which was an essential part of the old system's teleology. In *Paradise Lost*, John Milton speaks of 'Sphere/With Centric and Eccentric scribbled o'er,/Cycle and Epicycle, Orb in Orb'. Such complexity was demanded because of ongoing observation. Aristotelians were not given to ignoring the observable facts. Quite the contrary: they observed processes so as to be able to read out of them the narratives of potentiality actualised.

Then again, Aristotle was also a logician, who had laid down the laws of the syllogism. According to Aristotle, logical demonstration, by way of the syllogism, was a necessary component of *epistêmê,* or scientific knowledge. In his *Posterior Analytics*, he says that scientific knowledge requires that we know the cause 'of why the thing is', and also know that it could not have been otherwise. In other words, scientific knowledge not only must discover causes but demonstrate that they are necessarily the causes, and it is the abstract science of the syllogism that is assigned the latter demonstrative role.

However both rationalism and empiricism, as they emerged in the seventeenth century, were of an entirely different kind from their counterparts in the old system. The scientific rationalism of Copernicus, Galileo, Kepler, and Descartes had little use for the Aristotelian syllogism, which, so they argued, cannot expand our knowledge but merely rearrange it to set off implicit logical relations. Logic may be perfect, but it is also perfectly inert, incapable of moving substantive discovery forward. For the new scientific rationalists, it is not syllogistic logic but rather mathematics that holds an incomparable active power, capable of generating new knowledge. 'We do not learn to demonstrate from the manuals of logic,' Galileo wrote, 'but from the books which are full of demonstrations, which are mathematical, not logical.' A priori reason in the form of mathematics provides a methodology for discovery. As Galileo was to put it ringingly in *The Assayer*:

Philosophy is written in this vast book, which continuously lies upon before our eyes (I mean the universe). But it cannot be understood unless you have first learned to understand the language and recognise the characters in which it is written. It is written in the language of mathematics, and the characters are triangles, circles, and other geometrical figures. Without such means, it is impossible for us humans to understand a word of it, and

3 *The Scientific Works of Galileo* (Singer, Vol. II, p.252).

4 E.A. Burtt, *The Metaphysical Foundations of Modern Physical Science* (NY, Prometheus Books, 1999, p.76). Galileo's rationalist attitude has been echoed by various modern physicists. Paul Dirac, for example, said: 'It is more important to have beauty in one's equations than to have them fit experiments,' and Einstein, too, made such remarks, for example telling Hans Reichenbach that he had been convinced before the 1919 solar eclipse gave confirming evidence that his theory of general relativity was true because of its mathematical beauty. In our day, the hegemony of mathematics has been claimed most insistently by champions of string theory, which has as yet been unable to produce any testable predictions. 'I don't think it's ever happened that a theory that has the kind of mathematical appeal that string theory has has turned out to be entirely wrong,' Nobel laureate Steven Weinberg has said. 'There have been theories that turned out to be right in a different context than the context for which they were invented. But I would find it hard to believe that that much elegance and mathematical beauty would simply be wasted.' (Quoted on *Nova, The Elegant Universe*. http://www.pbs.org/wgbh/nova/elegant/view-weinberg.html.) String theory has been criticised, by more empirically inclined physicists, some going so far as to claim the theory does not even qualify as scientific. Thus the schism between scientific rationalists and empiricists continues into our own day.

Copernicus with the sphere of the solar system in his hand.

to be without them is to wander around in vain through a dark labyrinth.

It was, more than anything else, the new mathematical conception of the physical universe that had hastened the crumbling of the old explanatory system. Copernicus had urged his heliocentric model of the solar system not on the basis of its empirical superiority – both the geocentric and the heliocentric pictures could accommodate the data – but on the basis of its mathematical superiority:

> Nor do I doubt that skilled and scholarly mathematicians will agree with me if, what philosophy requires from the beginning, they will examine and judge, not casually but deeply, what I have gathered together in this book to prove these things … Mathematics is written for mathematicians, to whom these my labours, if I am not mistaken, will appear to contribute something.[5]

Under Galileo, the mathematical conceptualising of nature was radically advanced. He took the concept of motion, agreeing with Aristotle that it is the object of scientific explanation, and he reconfigured it into terms that can be expressed precisely in numbers. Distance travelled is quantifiable, as is time elapsed; and, from Galileo onward, motion is conceived of as a comparison between these two factors, the change of distance and the passing of time. Once motion itself had been reconfigured as a mathematical concept, other concepts, which are functions of motion, can be mathematically defined, so that, by developing the equations between the various functions of mathematical motions, new properties can be uncovered. The mathematical expression of the physical allows for what logic could never accomplish: the generation of new descriptions, going beyond the observable. It is the relations between these mathematical properties which, expressed as equations, remain constant between instances, yielding universal laws of nature. And it is these laws that supplant teleology in the new conception of explanation.

A priori mathematics, according to Galileo, does not entirely obviate the need for observation (only the most extreme of rationalists, Spinoza and Leibniz, were to argue the expendability, at least in principle, of all empirical knowledge, claiming that all could be a priori deduced from first principles[6]); but mathematics *does* allow us to deduce unobservable properties and thus to penetrate into the structure of nature.

Of course, this meant that not all of the processes conceived of as motions by Aristotle were Galilean motions. Only motions susceptible to mathematical translation came under the purview of science; the rest were expelled from the possibility of physical explanation. Even more than this, Galileo, and those who followed him, defined physical nature itself in terms of mathematics. It was Galileo who first drew the distinction between primary and secondary qualities. If all aspects of physical reality are mathematically expressible, and if not all aspects of our experience are susceptible to mathematical treatment, the implication is that

5 From his Letter to Pope Paul III, in the De Revolutionibus.
6 See footnote on page [##].

not all aspects of our experience are physically real. Our minds contribute to what we seem to see out there in the world. Our experience is not transparent; there is a gauzy veil of subjectivity hung between us and the objective physical world of mathematical bodies, compounded out of mathematically arranged mathematical constituents, mathematically moving through mathematical space over the course of mathematical time. All those aspects of our experience that can be rendered in mathematical language are 'primary' and correlated with what is out there; the rest are 'secondary' qualities, features of our subjective experience, caused by the interaction between the primary qualities out there and our own sensory organs. This distinction was widely accepted, not only by rationalists like Galileo and Descartes, but empiricists like John Locke. The portions of *res cogitans* lurking in our cerebral hemispheres provide a sanctuary for the otherwise inexplicable flotsam and jetsam of perception.

Scientific rationalism, then, as it emerged to challenge the old system, placed its hopes not in logic but in mathematics. Whereas the old system's working hypothesis had been that all physical processes are striving toward an end they seek to accomplish, the working hypothesis of the new rationalists was that all physical processes have a quantitative structure, and it is this abstract structure that distils the laws of nature that provide their explanation. As the über-rationalist Spinoza was to express it:

> Thus the prejudice developed into superstitions, and took deep root in the human mind; and for this reason everyone strove most zealously to understand and explain the final causes of things; but in their endeavour to show that nature does nothing in vain, i.e. nothing which is useless to man, they only seem to have demonstrated that nature, the gods, and men are all mad together … Such a doctrine might well have sufficed to conceal the truth from the human race for all eternity if mathematics had not furnished another standard of verity in considering solely the essence and properties of figures without regard to their final causes.[7]

But what of the new empiricism? How was it in opposition to the old system? Aristotle may not himself have thought much of mathematics, but he was himself an empiricist, who took observation, most especially of biological organisms, very seriously; it was his mathematical-maniacal teacher, Plato, who dismissed sense data (and many of those in the Copernicus–Kepler–Galileo camp were neo-Platonists). But Aristotle and the grand cathedral of thought that was erected around him advocated a passive form of observation. Nature, working always with its own ends in view, the very ends which provide the explanation in terms of final causes, was not to be interfered with. Teleology trumped technology. The very windingness of the roads of Europe's medieval cities testifies to the old system's hands-off approach toward nature. These roads were laid out on paths the rain took as it rolled down inclines. To transpose our own pathways over nature's choices was a violation of the fundamental assumption of the old system. One must respectfully observe the motions of nature, since their course had been plotted by their implicit end states, and it is in the hands-off observation that the explanation emerges.

The new empiricism, in seeking its non-teleological form of explanation, took an aggressively interventionist attitude toward observation. In doing so it not only asserted its rejection of Aristotelianism, of the teleology that dictated passive observation; its new active observation, in the form of experimentalism, claimed to present a new science, a scientia operativa, that could supplant the old.

7 *The Ethics*, I, Appendix. Some of the new rationalists, such as Descartes, Spinoza, and Leibniz, argued that what was generative in mathematical reasoning need not be confined to the quantitative, but could range beyond, and thus give us a form of explanation so powerful as to obviate any need for observation at all. This belief caused them to attribute unlimited potency to a priori reason, and explains why they are now more characteristically classified as philosophers rather than scientists. But in their day there was no segregation between the two types of thinkers, philosophers all, and they all saw themselves as engaged in the same project of finding the mode of explanation to supplant teleology. A rationalist extremist like Spinoza was as engaged as any in the scientific project; indeed, he was in close communication with the Fellows of the Royal Society, through his communications with the indefatigably gregarious first secretary, Henry Oldenburg, and even offered, through Oldenburg, his critique of some of Boyle's ideas, in several instances not finding them sufficiently scientific. So, for example, in *De Fluditate* 19, Boyle wrote of animals that 'Nature has designed them both for flying and swimming,' which provoked from Spinoza the response, 'He seeks the cause from purpose' (*causam a fine petit*), which is, of course, a relapse to the old system.

The empiricist Bacon, just like the rationalist Galileo, believed that the experience we are presented with does not reflect nature as it is: 'For the mind of man is far from the nature of a clear and equal glass, wherein the beams of things should reflect according to their true incidence; nay, it is rather like an enchanted glass, full of superstition and imposture, if it be not delivered and reduced. For this purpose, let us consider the false appearance that are imposed upon us by the general nature of the mind …'

Bacon's solution to how to circumvent these false appearances, which he called the 'idols of the cave', lay in his empirical activism. We are not to stand passively by as submissive observers of what nature might offer of itself, but assert ourselves in the gathering of facts through experiment. This assertion is what transforms sense-data, subject to illusion, into facts. The keen but passive gazing that makes sense under the assumptions of teleology made no sense to Francis Bacon.

The Lord Chancellor's metaphors are telling. Nature should be looked on as an uncooperative witness in a courtroom, who must be interrogated and even tortured in order that the information be extracted. Nature should be treated as a slave who must be 'constrained' and 'moulded' and compelled to serve man. We must 'shake her to her foundations'. In short, we force the sense-data to yield up the factual data that nature is actively keeping from us by asserting our own active power over nature in controlled experiments.[8] (Although sometimes these experiments end in nature asserting its power over us: the legend is that Francis Bacon died after contracting pneumonia while undertaking some experiments in the dead of winter on the preservation of meat by freezing.)

Thus for both the new rationalists and the new empiricists there was a veil of subjectivity separating the observer from the observed. In this way the two orientations, no matter how distinct their intellectual temperaments, shared a central attitude that went beyond their mere opposition to the old system and explains why they were, even if rivals, also potential allies. Both insisted, against the old system, on more assertiveness. Mathematics, as opposed to inert logic, inserted a generative power into physical description. Experiments, as opposed to passive observation, allow us to wrest the physical facts from illusory experience.

The old system had seen nature as eminently readable by us. The form of explanation spread throughout the cosmos was one which was familiar and natural to us; after all, it was an essentially human form of explanation, taking the sort of explication that applies to human actions and generalising it. The old system saw us as *of* the universe. There was no reason to suspect our experience, and Aristotle was an unguarded empiricist, an observer who never seemed to worry about what his own mind might be contributing to perception. But not so the post-teleology Baconian empiricist, no more than the post-teleology Galilean rationalist. For both, the experience we have of the world has to be subjected to special treatment in order for reliable information to be extracted.

Of Ends and Means

The activist empiricism of Bacon was correlated with a practical stance toward scientific knowledge, which blazed forth into utopian zeal:

> I humbly pray … that knowledge being now discharged of that venom which the serpent infused into it, and which makes the mind of man to swell, we may not be wise above measure and sobriety, but cultivate truth in charity … Lastly, I would address one general admonition to all; that they consider what are the true ends of knowledge, and that they seek it not either for pleasure of the mind, or for contention, or for superiority to others, or for profit, or fame, or power, or any of these inferior things; but for the benefit and use of life; and that they perfect and govern it in charity. For it was from the lust of power that the angels fell, from lust of knowledge that

8 The metaphors of Francis Bacon are a feasting ground for feminist readings of the history of science.

man fell; but of charity there can be no excess, neither did angel or man ever come in danger by it.[9]

Here, too, on this question of the 'true end of knowledge' a temperamental difference parts the new rationalists and empiricists. A Galileo or Descartes would not have been as inclined to archly dismiss 'pleasure of the mind' or 'lust of knowledge' as Bacon had been. Though the scientific rationalists and scientific empiricists might share the belief that experience must be subjected to special treatment to be rendered profitable for science, they had differing views on the profit of science. The experimental/empiricists (Gilbert, Harvey) tended to agree with Bacon's practical goals. As men must experimentally assert their power over nature, so, too, the value of possessing nature's secrets was that they be utilised for the practical improvement of men's lives. For the mathematical/rationalists the knowledge was sufficient unto itself, a thing deserving to be desired, whether it yielded practical improvements or not.

By 1660, the mathematical understanding of physical explanation could not be ignored, not with the work of people like Copernicus, Galileo, and Descartes; and the men who came together to form a Colledge for the Promoting of Physico-Mathematicall Experimentall Learning acknowledged the mathematical conception of the physical in their self-designation. Nevertheless by temperament these early men of the Royal Society were more allied with Bacon, Gilbert, and Harvey than with Galileo and Descartes. It was the 'experimentall learning' that most engaged them, and so, too, they were inclined to embrace the practical humanitarian goals of science that Bacon had linked with his experimentalism.

Christopher Wren gave the inaugural lecture at Gresham College, after the Royal Society had been officially formed in 1662, and in his address he spoke passionately of the manner in which the new thinking had thrown off the tyranny of the old system of thought, bringing in its stead the freedom of scientific investigation. In the course of his celebratory advocacy he extolled William Gilbert (chastised by Galileo for his lack of geometry) as the very embodiment of the new science:

> Among the honourable Assertors of this Liberty, I must reckon *Gilbert*, who having found an admirable Correspondence between his *Terrela*, and the great *Magnet* of the Earth, thought, this Way, to determine this great Question, and spent his studies and Estate upon this Enquiry; by which *obiter,* he found out many admirable magnetical Experiments: This Man would I have adored, not only as the sole Inventor of Magneticks, a new Science to be added to the Bulk of Learning, but as the Father of the new Philosophy.

But if any thinker hovered as a guiding spirit over the group it was the thoroughly empiricist Francis Bacon. Bacon had dreamed of a science that would operate in the way of a collaboration, a 'Fellowship' to take the place of individual geniuses working in isolation; it was all of a piece with his utopian ambitions for the new knowledge, and the members of the Royal Society called themselves 'Fellows' in homage to the Lord Chancellor's vision.

And yet intimations of a union between the 'physico-mathematicall' and 'experimentall' there had no doubt been. It is in the chemist Robert Boyle, the most important scientist among the twelve original Fellows, that we can see the two approaches groping somewhat dazedly toward one another. Boyle was certainly, in many ways, a disciple of Bacon – but not in all ways. He preserved an interest in the practical control of nature through knowledge of cases, which had been such a prominent feature in Francis Bacon, and which both men regarded as closely related to the empirical method; and yet he also had been touched by the Galilean spirit. Though not himself a profound mathematician, Boyle was keenly aware that astronomy and mechanics had outstripped chemistry. He was eager to carry chemistry forward by allying it with an atomistic interpretation of

9 From his Letter to Pope Paul III, in the *De Revolutionibus*

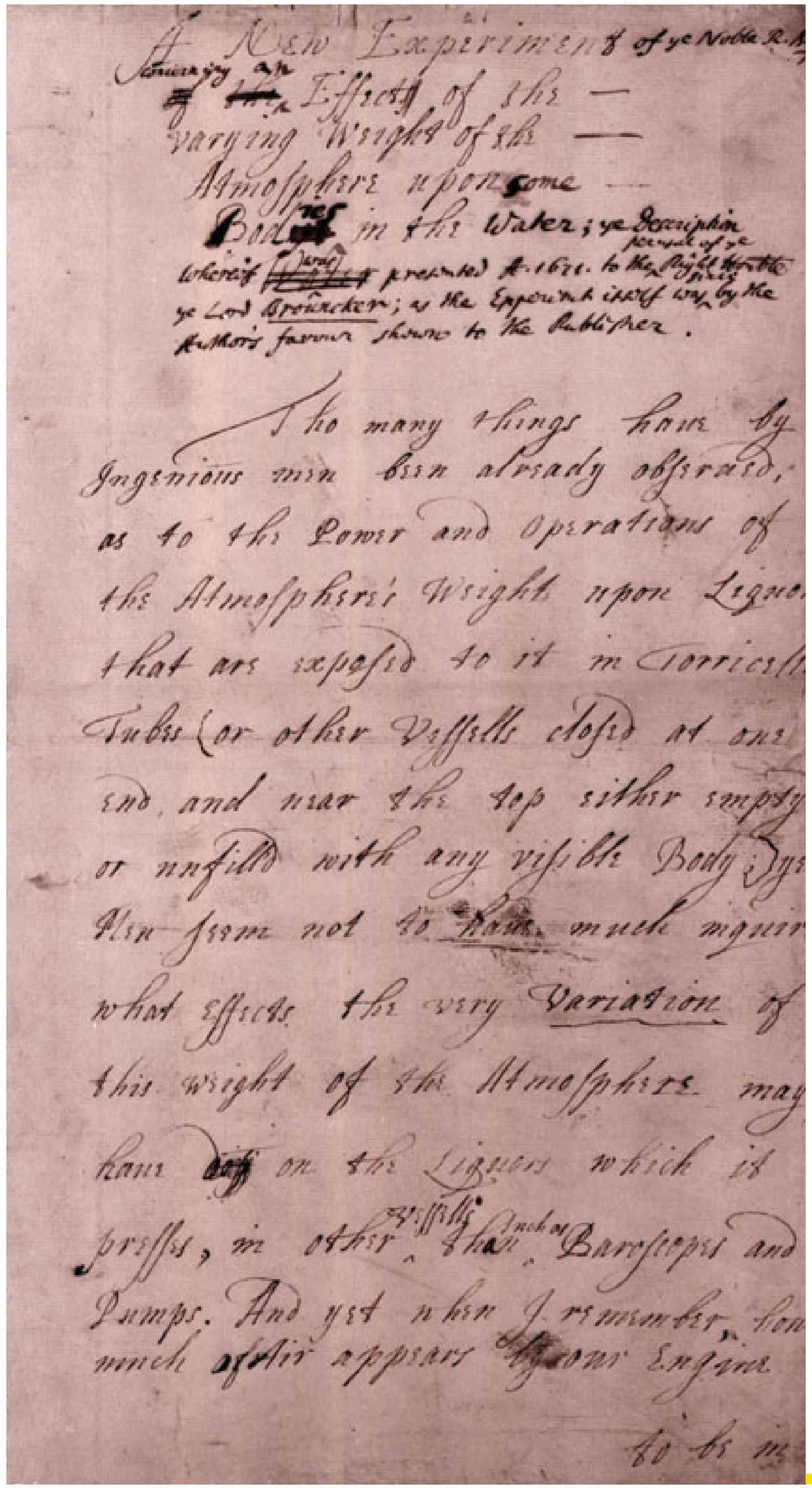
matter, and he recognised that mathematics was integral to the atomistic interpretation of physical phenomena.

But he also contended that chemistry, in its vigorous experimentalism, had something to teach the fields of astronomy and mechanics that had been so transformed by its mathematical reconfiguration. These latter endeavours 'have hitherto presented us rather a mathematical hypothesis of the universe than a physical, having been careful to show us the magnitudes, situations, and motions of the great globes, without being solicitous to declare what simpler bodies, and what compounded ones, the terrestrial globe we inhabit does or may consist in'.[10]

Boyle's suggestion is that the new science, as understood by Galileo et al, is all very well and good, but that, in its overly abstract mathematical demonstrations and idealised formulations, it had travelled too far in the direction of apriorism. Robert Boyle is proposing that chemistry, though lagging behind on the theoretical side, might yet have something to offer the fledgling methodology in the way of getting one's hands stained with the stuff of 'the terrestrial globe we inhabit'. His distinction between mathematical and physical hypotheses is important, and we shall see it again. It reveals Boyle's intuition that there was still something missing in the systems of Galileo and Descartes, no matter how impressive they were.

It is relevant that Boyle was a chemist. The example of the alchemists, though they strayed too near to mysticism and magic for Boyle's taste, was not purely negative, for they had defied the old system's passivity toward nature. (Bacon, too, had praised alchemy as a scientia operativa.)

But though Boyle seemed to have sensed the presence of a unified methodology binding together the activist approaches of the new rationalism and new empiricism, he does not manage to bring it forth, perhaps because he himself lacked mathematical muscle.[11] The best that he can offer is a reconciliation wrought by relativism: if what one is after is knowledge of nature then quantitative deductions on the model of Galileo and Cartesianism will yield satisfaction; but if one's aim is control of nature in


A New Experiment of ye Noble R.B. concerning ye Effects of the varying Weights of the Atmosphere upon some Bodies in the Water; ye Description whereof presented A. 1671 to the Royall Society by ye Lord Brouncker; & the Experiment itself by the Authors favour shown to the Publisher.

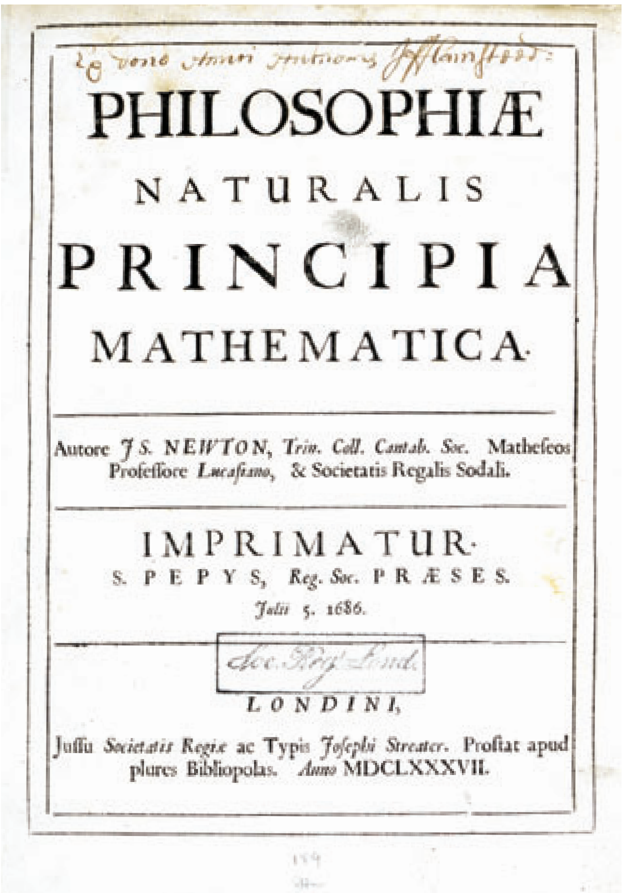
Tho many things have by Ingenious men been already observed, as to the Power and Operations of the Atmosphere's Weight upon Liquors that are exposed to it in Torricellian Tubes (or other Vessells closed at one end, and near the top either empty or unfilled with any visible Body) yet there seem not to have been much inquiry what effects the very Variation of this weight of the Atmosphere may have on the Liquors which it presses, in other vessells than Baroscopes and Pumps. And yet when I remember how much of the air appears in our Engine

An undated example of Robert Boyle's writing on chemistry – "… the Effects of the varying Weights of the Atmosphere upon some bodies in the Water…".

10 Robert Boyle, *The Works of The Honourable Robert Boyle*, ed. Thomas Birch (6 vols, London, 1672), vol. I, p. 356.
11 Newton

the interest of particular ends, the necessary relations can often be discovered between qualities immediately experienced or drawn forth from experiments. It all depends on what one wants out of one's science, he writes, although the implication is that true knowledge, if that's what one wants, will require something more deductive than experimental.

The true blending of the two rivals for replacing the teleological understanding of explanation finally arrived in a work whose very title is telling: *Philosophiæ Naturalis Principia Mathematica*, The Mathematical Principles of Natural Philosophy. With Isaac Newton, a scientist who saw mathematics as essential to physical understanding had entered the ranks of the Royal Society. And yet the experimental aspect is also of fundamental importance to his methodology.


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore JS. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

The title page of 'Principia', the inscription is written by John Flamsteed noting that the book is a gift from the author – Newton.

Newton observes in his preface to the *Principia* that 'all the difficulty of philosophy seem to consist in this – from the phenomena of motions to investigate the forces of nature, and then from these forces to demonstrate the other phenomena'.

The phrase to 'demonstrate the other phenomena' reiterates the message of the work's title: the fundamental place of mathematics in Newton's method:

> We offer this work as mathematical principles of philosophy. By the propositions mathematically demonstrated in the first book, we then derive from the celestial phenomena the forces of gravity with which bodies tend to the sun and the several planets. Then, from these forces, by other propositions which are also mathematical, we deduce the motions of the planets, the comets, the moon, and the sea.

As it was for Aristotle, so it was for Newton: to investigate nature is to investigate motions. Only, of course, Newton has inherited Galileo's transformed conception of motion, reconfigured by, and restricted to, mathematical expression. The mathematical imagination of Newton, surpassing that of Galileo or Descartes, made possible the mathematical absorption of far vaster reaches of physical phenomena. The language of the Book of Nature is not confined to geometry, as it been according to Galileo and Descartes; rather it is analysis that becomes the more important means of expressing what is physically relevant. His invention of fluxional calculus afforded him a powerful tool whose operations could not be fully represented geometrically. On the question of mathematical type, Newton is pragmatically flexible, writing in his Preface to the *Principia,* 'For you may assume any quantities by the help whereof it is possible to come to equations; only taking this care, that you obtain as many equations from them as you assume quantities really unknown.'

But Newton follows as much in the footsteps of Bacon, Gilbert, and

Harvey, as in those of Copernicus, Kepler, Galileo and Descartes. This is most sharply brought home by his reiterated denunciation of 'hypotheses'. By hypothesis, Newton means empirically unattached claims about reality, and by his emphatic rejection of 'hypotheses', he is emphasising the necessity of tying scientific statements down to experience. Unlike Galileo or Descartes, Newton distinguishes between mathematical truth and physical truth (echoing the intuition in Boyle's complaint against the rationalists). That the resistance of bodies is in the ratio of the velocity, 'is more a mathematical hypothesis than a physical one', he says in *Principia* II, 9, and makes similar statements in connection with his discussion of fluids (*Principia,* II, 62). A mathematical truth that has not been made manifest in experience has not advanced to a physical truth. And experience must be experimentally manipulated in order for the mathematical truth to be made manifest in it. Galileo and Descartes were right that the mathematical structure that is latent in physical processes provides their explanation; but Bacon, too, had been right that nature requires prodding by way of experimentation in order for the mathematical and the physical to rendered one.

In fact – and here is where the two anti-Aristotelian strains are finally brought together – it is precisely because ultimate explanation is mathematical, and this mathematical structure is not immediately given up in passively observed nature, that experimentation is necessary. The explanation of the motion is to be found in uncovering the mathematical structure within it; but experience as such does not readily give up the latent mathematical structure. Experiments are necessary to tease out the implicit mathematics, whose consequences can then be mathematically drawn, leading to further mathematical conclusions that must again by tied down to experience by way of experiment.

Newton's work on optics is as instructive as his mechanics, demonstrating both the fundamental place of mathematics and the necessity for experiment. His eagerness to reduce yet another sphere of phenomena to mathematical formulae results in a science of colours. And yet mere observation could not have given Newton the phenomena that would yield to mathematical formulae. His famous interventions – for example, placing two prisms within the path of a light beam, one that would split white light into the spectrum, the other that would reconstruct white light out of the spectrum – were as essential to the science as the resultant mathematical equations. To paraphrase Immanuel Kant (who was three years old when Newton died in 1727): Experimentation without mathematical explanation is blind; mathematical explanation without experimentation is empty.

Unreasonable Effectiveness

Looking back now, there seems something almost accidental about the emergence of both the new rationalism and the new empiricism as coevals, each offering a rival substitute for the disputed teleology of the old system, each appealing to different sorts of intellects, tending toward divergent opinions as regards the ultimate worth and purpose of knowledge. All these centuries later, the methodological amalgamation can still call forth our wonder – most memorably expressed by the late physicist and Nobel laureate Eugene Wigner, in the phrase 'the unreasonable effectiveness of mathematics in the physical sciences'.

It is appropriate to be amazed. Who could have hoped that both the new rationalism and the new empiricism could be joined together in the most successful experiment in human thought to date? Here is a means of exploring nature which, though embedded in the empiricism of experimentation, is also capable of challenging (by way of the theory of relativity) our psychological sense of time, or (by way of quantum mechanics) our notions of causality, two linchpins of common-sense experience.

Who could have hoped? To that question, at least, we have an answer: the men who formed a Colledge for the Promoting of Physico-Mathematicall Experimentall Learning.