CHAPTER 8

THE SUPREMACY OF OBSERVATION

How the iron rule ejects everything from scientific debate but a theory's ability to explain observable phenomena—and how that came to be (the iron rule's fourth innovation)

ONLY EMPIRICAL TESTING COUNTS. Across the world of science, this thought is expressed over and over in some form or other. "Experiment is the sole judge of scientific truth" (physicist Richard Feynman). "Take nobody's word for it" (motto of the Royal Society). "To experience we refer, as the only ground of all physical enquiry" (nineteenth-century man of science John Herschel). "Observation is the generative act in scientific discovery" (biologist Peter Medawar). "All I'm concerned with is that the theory should predict the results of measurements" (physicist Stephen Hawking). Such words are an invocation and a celebration of modern science's fourth great innovation, its fourth great departure from the empirical inquiry of old: a prohibition on any form of persuasion, however well founded, however objective, that is not based on empirical testing.

To explain how the prohibition works and to get a sense of its novelty and peculiarity, we will visit Britain in the 1830s, where it is already at full operational capacity, shutting down any attempt to import phil-

osophical or religious thinking into scientific argument. From there we will travel more than a century further back in time, to catch the iron rule's censorious impulse at the moment that it takes control—thereby witnessing a critical moment in the creation of modern science and perhaps the most consequential invention in the history of thought.

William Whewell died after falling from his horse in 1866. He was 71 years old and left behind him a glittering trail of achievements. Born the son of a carpenter, he attended Trinity College at the University of Cambridge as a "subsizar," paying reduced fees in return for waiting on the tables at which the other students and the Fellows of the college took their meals. He won prizes for poetry and mathematics, became a Fellow at Trinity himself, was appointed a professor of mineralogy and then moral philosophy, and in 1841—29 years after he first entered Cambridge as a table-waiting scholarship student—he was elected Master of Trinity College.

Whewell's long-distance leap up the social ladder had its costs. Surrounded by his social "betters," he was sensitive and proud, quick to take offense. Moving from the local school for working-class children to a more elite grammar school, he soon found himself using his considerable physical size to fend off his bullying classmates; later on his friend John Herschel remarked that Whewell's "temper will never be good!"

Though master of a great college, he was socially awkward. According to the biographer Leslie Stephen:

> In early days he had little chance of acquiring social refinement; and, though he was anxious to be hospitable, his sense of the dignity of his position led to a formality which made the drawing-room of the lodge anything but a place of easy sociability.

What he lacked in charm, however, he made up for in industry.

At Trinity, he instituted a program of educational reform while writing about almost everything: the tides, astronomy, Gothic architecture, theology, mechanics, ethics, and the probability of life on other planets. He translated Goethe and Plato. He invented the self-registering anemometer, a device to determine wind speed. He descended a mine in Cornwall to measure the earth's gravitational field; he climbed mountains in Switzerland to contemplate the glory of God in the empyrean heights. And he coined a new word for the thinkers who had until his time been known as "men of science" or "natural philosophers": he proposed that they be called *scientists*.

Of all this prolific output, Whewell's greatest achievement was a three-volume history of the sciences, published in 1837, followed in 1840 by a two-volume philosophical study of their method, which as the title proclaimed was "founded upon their history"—a monumental pentalogy that makes Whewell one of the earliest and also one of the most distinguished historians and philosophers of modern science.

The last of the sciences to be considered in Whewell's history was the young discipline of geology. Whewell rather unconventionally included under the heading of geology the history of life, a story that had begun to emerge only in the previous 50 years in the layers of fossilized shells and bones uncovered by the Industrial Revolution's canal diggers and railway builders. The most startling chapter in this piecemeal chronicle revealed that long before the appearance of large mammals, the earth was dominated by dinosaurs and their kin. As the fossil-hunting doctor Gideon Mantell colorfully put it in "The Geological Age of Reptiles" (1831):

> There was a period when the earth was peopled by [egg-laying] quadrupeds of a most appalling magnitude, and . . . reptiles were the *Lords of the Creation*, before the existence of the human race!

Figure 8.1. England in the Age of Reptiles: George Nibbs's imaginative visualization of *The Ancient Weald of Sussex* (1838). At the center is an early and highly inaccurate reconstruction of the iguanodon, a dinosaur that Gideon Mantell was the first to describe.

That was only one of the epochs during which the planet had evidently been populated by wholly different life-forms; before the dinosaurs there were seas roiling with strange marine creatures—trilobites, ammonites, and primitive jawless fishes—and after the reptiles came pygmy horses and giant sloths.

To Whewell, the lesson taught by the rocks was plain. "The species of plants and animals which are found imbedded in the strata of the earth," he wrote, "are . . . different from any now existing on the face of the earth. . . . They imply . . . that the whole organic creation has been renewed, and that this renewal has taken place several times." How, Whewell asked himself, were these episodes of renewal—such as the replacement of the dinosaurs by mammals—brought about? New forms of life, he answered, are created by "other powers than those to which we refer natural events," or in other words, by the Christian God.

When Whewell's history was published in 1837, such an explanation was both reasonable and conventional. Charles Darwin was only 28 years old, freshly returned from his voyage around the world on the HMS *Beagle*. His masterwork, *On the Origin of Species*, would not emerge for another 20 years. There was little reason, then, for Whewell and his contemporaries to doubt that, just as the Bible said, "out of the ground the Lord God formed every beast of the field and every fowl of the air" (Genesis 2:19).

What was new was incontrovertible evidence that God had had more than one go at it. The creation of life had happened not only in some unknowable moment at the very beginning of time, but again and again, with the contours of each iteration impressed unmistakably in the fossil record.

That opened up an extraordinary opportunity to pursue two grand projects. First, knowledge of patterns in the rocks corresponding to episodes of renewed creation, available to anyone with a trained eye and a geologist's hammer, could cast light on God's mind, on his intentions and plans in fashioning this planetary receptacle for his supreme invention, the human race. And second, knowledge of God's intentions and plans, available to anyone with access to the holy scripture and a theological turn of mind, could cast light on the natural history of the world, on the marching order of life's grand parade.

As to the first project, some thinkers might have recoiled at the impiety, or at any rate the sheer temerity, of using scientific knowledge to plumb the divine intellect. Not Whewell. When the eighth Earl of Bridgewater, a clergyman, naturalist, and antiquarian, set aside a bequest to sponsor the publication of works devoted to finding signs of God's plan in nature, Whewell eagerly signed on. In 1833, he contributed a volume to what became known as the Bridgewater Treatises, in which he contended that "every advance in our knowledge of the universe harmonizes with the belief of a most wise and good God." From the configuration of

the planets, the arrangement of the earth's surface, and the sophisticated design of living things, we can see—according to Whewell—that "the wise and benevolent Creator of the physical world" is also the "just and holy" "Governor of the moral world" and thus the "Judge of men."

Writing his history and philosophy of the sciences in the late 1830s, then, Whewell would seem to be the ideal man also to lead the second project, which at that moment in time exhibited such promise: the integration of geological and theological knowledge to give a complete account of the history of life on earth. He had the empirical expertise, the religious motivation, and a preeminent position in the world of science.

But he did not do it. Indeed, in his *History of the Inductive Sciences*, he is adamant that no one should do it and more generally that science should take no account whatsoever of theology, which "must never be allowed to influence our physics or our geology." Biologists and geologists should attend only to "the ordinary evidence of science"—that is, to the outcomes of empirical observations—and should go only as far as that evidence can carry them. Theology, meanwhile, can use its proprietary resources, such as philosophical reasoning about the nature of God and scriptural interpretation, to make its own inferences about life's creation. When both endeavors conclude their investigations, their findings can be merged to provide a complete picture of the history of life—but not before.

Whewell's embargo on the second grand project, the importation of theology into geology, was not prompted by concerns about theology's irrelevance or impracticality. As best he could determine, the project was feasible and likely fruitful. The geologist's goal was to set out the course and the causes of the unfolding history of life, and in Whewell's view, the most important turning points in that history were effected by the hand of God. Without the assistance of theology there would be, at each of these pivotal moments, an empty space in the scientific annals of the earth's past. Further, Whewell believed that theology was able to fill these blanks: in the course of his Bridgewater Treatise he argued

that God's nature and plans manifested themselves in every aspect of the natural world. He repudiated the project all the same.

It is a conundrum. There is a need, the means to satisfy that need—yet in Whewell's prescription of methodological apartheid, a stern injunction against doing so.

The injunction makes no cultural sense: in the 1830s and 1840s, virtually every scientist was a believer, attributing the existence of the universe and all its marvelous peculiarities to the machinations of the Creator. As the Bridgewater enterprise shows, the zeitgeist made ample room for a merging of natural history and religion.

Nor does it make logical sense. Two projects working toward the same end should always be open to collaboration. Imagine two children searching for a lost dog. One goes from house to house, knocking on doors and asking if there have been any sightings. The other roams the streets, parks, and junkyards calling the dog's name. They must separate in order to pursue their distinct strategies. But it is clearly in their interests to check in with one another from time to time: if the dog has been seen on the east side of town, better to explore the parks on the east side than the west side. What Whewell's separation of theology and geology required, however, was two completely disconnected searches.

Finally, intellectual partition makes, for Whewell, no emotional or psychological sense. It is contrary to his synthesizing spirit, captured delightfully in his words to a friend about a forthcoming visit to the English Lake District:

> You have no idea of the variety of different uses to which I shall turn a mountain. After perhaps sketching it from the bottom I shall climb to the top and measure its height by the barometer, knock off a piece of rock with a geological hammer to see what it is made of, and then evolve some quotation from Wordsworth into the still air above it.

Whewell believed that thought and action were to be woven through the world from multifarious directions but with a single thread. The exclusion of God from geology was, however, a proposal to cut the thread, indeed, to tear up the tapestry into motley, ragged patches of knowledge.

No emotional sense, no cultural sense, no logical sense. Yet what Whewell prescribed is a straightforward application of the iron rule—more exactly, of that aspect of the rule that says *only empirical testing counts*. When Whewell insisted on admitting to geology only empirical considerations, only rocks, fossils, clues chiseled out of the earth, he was doing what the iron rule, already firmly entrenched in scientific practice, told him to do. When his fellow scientists accepted his proposal without outrage, concern, or even vigorous comment, considering the exclusion of religious thinking from geology to be as congenial and conventional as would any twenty-first-century scientist, they, too, were guided by the rule.

Many contemporary scientists believe that religion has little or nothing that is useful to say about the history of life on this planet. Whewell and his peers, by contrast, took their religious knowledge to be both trustworthy and biologically revealing. That is why it is so illuminating to see the iron rule at work in 1837, why I have made the effort to take you back to Whewell's time rather than merely examining the practice of science in our own day. Whewell did not invent the iron rule—he was born far too late for that—but in his efforts to reconcile his scientific research with his religious belief, he casts its strictures in stark relief.

Under this revealing light, it is apparent that the iron rule excludes from scientific argument more than just "subjective" reasons. It excludes every nonempirical consideration, no matter how persuasive or well founded. To Whewell, the existence of the Christian God was as clear and certain as any observable fact. Yet he accepts that theological considerations ought nevertheless to be disbarred from official scientific dispute in accordance with the rule—not because they are bad reasons, not because they

are purely personal reasons, not because of any perceived logical defect, but simply because they are the wrong kinds of reasons for doing science.

The iron rule, then, legislates a distinction between scientific and unscientific reasons that is not at all the same as the distinction between objective and subjective reasons, or between strong and weak reasons, or between good and bad reasons. Scientific reasons to endorse a theory are supposed to be objective, strong, and good, but that is not enough: even the most powerful argument is excluded from science unless it is empirical, that is, grounded in a theory's ability to explain observed fact.

Whewell's case illustrates something else about "only empirical testing counts" that is central to the iron rule's operation: it applies to public scientific argument but not to private scientific reasoning, and even then only to argument in science's institutionally sanctioned venues for debate. The rule in no way prevented Whewell from musing to himself about the biological significance of his religion. It merely prevented him from exploring it in scholarly publications whose primary purpose was scientific communication. In his Bridgewater Treatise, then, a piece of popular theological writing, Whewell was quite free to speculate about God's part in the history of life.

Informal outlets for scientifically inspired religious expression have not vanished. Kelvin kept God out of his official publications about the age of the earth, but in an 1889 talk to the Christian Evidence Society, he felt free to follow Whewell in discerning, in the scientific world picture, clear evidence for the existence of a creator. And Francis Collins, the leader of the Human Genome Project, maintained the tradition in his 2006 book *The Language of God: A Scientist Presents Evidence for Belief.*

The iron rule ignores all such productions—it ignores anything outside science's anointed journals and conference proceedings—because they do not constitute moves in the game of modern science. To regulate that game is the rule's sole concern. Its first three great innovations—shallow explanation, the demand for objectivity, and the distinction

between reasoning and official argument—work together to ensure that all scientists share an understanding of what makes for an empirical move in the game. The fourth and final innovation, the "only" in "only empirical testing counts," insists that every move be empirical and in so doing transforms the game's players into observational and experimental prodigies, into extractors of evidence par excellence.

Whewell believed that theology was an essential source of knowledge about the natural world. Nevertheless, he wanted to play the game. Theology, therefore, and all the insight that from his point of view stood to come with it, was abandoned on the sidelines.

The pain caused by that desertion shattered Whewell's customary clarity of thought. Arguing against any effort to unite theological and geological reasoning, he wrote that to attempt such a synthesis would be to assume

> that reason, whether finite or infinite, must be consistent with itself; and that, therefore, the finite must be able to comprehend the infinite, to travel from any one province of the moral and material universe to any other, to trace their bearing, and to connect their boundaries.

Perhaps this struck some of his readers as profound. To my philosophical ear, it is pure gobbledygook. Unable to reconcile the iron rule's directives with his intellectual conscience, Whewell was floundering; he was back in the schoolyard, trying to brazen his way out of trouble by sheer bluster.

Whewell's suffering is a clue to a crucial fact: for an intellect open to every respectable reason, to every relevant consideration, to every good argument, the now familiar doctrine that "only empirical testing counts" is, in its illiberality, quite alien. That unsettling doctrine was already firmly in place when Whewell embarked on his scientific career. How

did it come to govern all deliberation about the structure of the natural world? What was the origin of this most striking and important aspect of the iron rule? To find the answer, we can stay right where we are, in Trinity College, Cambridge, but we must turn back the clock another 150 years.

ARRIVING IN THE LATE SPRING of 1681, you might, with some agility and a certain disregard for the regulations, find your way into a private, walled garden to the right of the Great Gate at Trinity College. Suppose you do it.

In the garden you come upon a wooden structure built against a wall, and in that structure a well-provisioned laboratory. A notebook sits on the lab bench. Opening it at random, you read the following curious formulation:

> Neptune with his trident leads the Philosopher into the sophic garden.

There is no trident to be seen, and certainly no sea god—just furnaces, crucibles, alembics, and a welter of nameless substances. About the identity of the Philosopher, however, there can be no doubt, for you are standing in the laboratory of Isaac Newton, inventor of the calculus, discoverer of the laws of motion and gravity, analyzer of light—and one of the greatest alchemists of his age.

Deciphering page after page of Newton's densely written text in the waning light of the afternoon, you find a tantalizing description of the celebrated "green lion":

> Concerning Magnesia or the Green Lion. It is called Prometheus & the Chameleon. Also Androgyne, and virgin verdant earth in

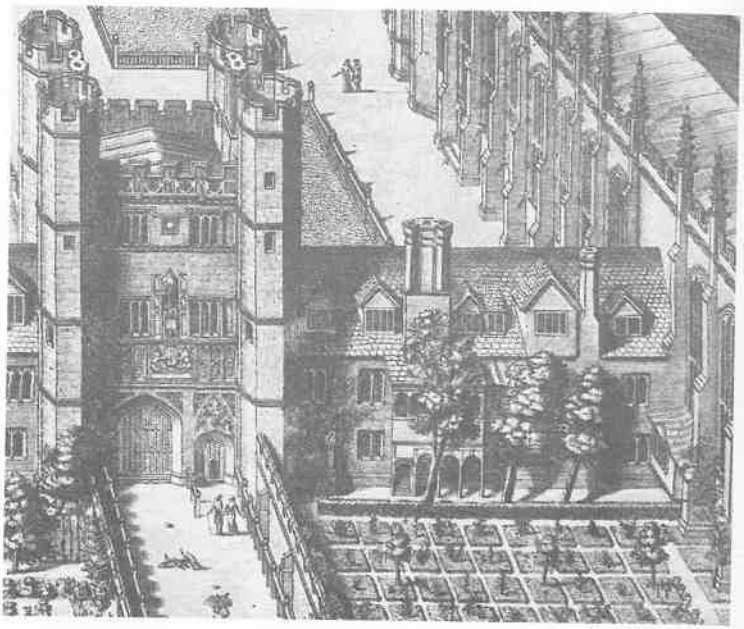

Figure 8.2. Newton's laboratory at Trinity College, Cambridge, was located somewhere within his private garden (bottom right), reached by a covered staircase from his chamber on the middle level just to the viewer's right of Trinity's Great Gate. Newton lived in this chamber from 1673 until he left Trinity in 1696. From a 1690 engraving by David Loggan.

> which the Sun has never cast its rays although he is its father and the moon its mother.

You turn to the end of the notebook. There lies recorded an astonishing discovery:

> May 10, 1681. I understood that the morning star is Venus and that she is daughter of Saturn and one of the doves . . . May 14. I understood the trident. May 18. I perfected the ideal solution . . . the eagle carries Jupiter up.

What had Newton found out?

Perhaps the answer lies in an undated note describing the extraction of something extraordinary from the veins of the green lion:

> Dissolve volatile green lion in the central salt of Venus and distill. This spirit is . . . the blood of the green lion Venus, the Babylonian Dragon that kills everything with its poison.

Other notes identify the blood of the green lion with "vivified mercury," a substance capable of destroying even gold—"the green lion devouring the sun."

As to the nature of vivified mercury, we are in the dark. (It is not to be confused with the ordinary element.) Likewise, although "the trident" appears to be a kind of chemical process, we have little idea how it might work. Newton's fantastic language is a kind of alchemical code inspired by the language of other alchemists, in which "green lion" refers to stibnite, or antimony ore, "Venus" refers to copper, and "doves of Diana" means silver. His writings cannot, however, be fully understood in terms of these conventional meanings. Clearly, the Babylonian dragon is a more arcane quarry than antimony ore or ordinary mercury—but because Newton did not explain the purpose of his experiments or supply a key to his system, we have no idea what, precisely, he supposed he had discovered in the middle of May 1681.

Whatever were the goals of his alchemical research, Newton pursued them relentlessly: he alchemized for decades after being appointed the Lucasian Professor of Mathematics at Cambridge, writing "well over a million words" on the topic. He kept it all to himself, publishing nothing.

Why was Newton so interested in alchemy? The answer is simple, though it sits uneasily with the public image of Newton as a purely scientific intellect, a harbinger of the Enlightenment. Newton, like Whewell,

was interested in *everything*—everything, that is, that might possibly reveal the secret powers underlying the workings of the universe. Thus, he studied the motions of the planets, which disclose the principles of universal gravitation. He conducted alchemical experiments "to liberate the spirit or active virtue of bodies from its encumbering feces." And he followed paths of inquiry that involved no experimentation or observation at all, but simply reading and thinking.

Among these nonempirical pursuits was the philosophical investigation of the nature of space, matter, and motion. To this end, Newton studied the works of the preeminent English metaphysicians of his day—the Cambridge Platonists—and penned a treatise (like the alchemy, never published) to refute Descartes's contention that there can be no empty space. In later writings he denounced another Cartesian idea, that all changes in motion are caused by collision. Bouncing molecules, thought Newton, cannot account for substances such as oil and water failing to mix; their tendency to segregate must rather be explained by a "secret principle of unsociableness." In the same vein, he attempted an account of the vital spirit, the spark of life, apparently the cause of all motion:

> The vital agent diffused through everything in the earth is one and the same. And it is a mercurial spirit, extremely subtle and supremely volatile.

Other unpublished writings from the same period—roughly, the 1670s, after Newton had made many of his discoveries in mathematics and physics—display an intense interest in the proper interpretation of scripture and in biblical prophecy. Newton worked hard to find historical events that corresponded to events foretold in the Bible, he attempted to reconstruct the exact plan of the great Jewish temple in Jerusalem, and he used his biblical chronology along with the words of the prophets to

predict a date for the Second Coming, which was apparently to occur some time in the late nineteenth century. As he labored, he found himself drawn ineluctably to the heretical Arian doctrine that Jesus Christ was created by, rather than identical to, the Christian God. Though it endangered his position at Cambridge, he never renounced this belief.

Some historians have, in the light of these endeavors, attributed to Newton a belief in the *prisca sapientia*, or ancient wisdom—a profound knowledge of the nature of things supposedly grasped by sages in ancient times and passed on allusively and allegorically by figures such as Pythagoras and Plato. To decode the wisdom takes the sensibility not only of a physicist but also of a philosopher and a poet. The ancient story in which the god Vulcan surprises his wife Venus in the embrace of Mars and captures the couple in a golden net is, according to Newton and other alchemists, to be understood as a recipe for a fecund substance called "the net," a "hermaphrodite" that combines "the male seed of Mars with the female principle of Venus." Only an investigator equally dextrous with analogy and alembics, a rigorous experimenter and a metaphorical scrutineer, could fully exploit such clues. Newton's writings on physics, philosophy, alchemy, and scriptural interpretation indeed seem like fingers reaching for the *prisca sapientia* in any and every possible way.

Francis Bacon, decades earlier, warned about the corruption of scientific inquiry by "superstition and a dash of theology," in which the understanding is seduced by "fantastic, high-blown, semi-poetical philosophy." "Lofty, high-minded characters," he thought, are especially susceptible to these "idols of the theater," which stage entrancing theoretical, even mystical, tableaux that distract the mind from the plain speech of the observable facts. Breaking into Newton's laboratory, we have caught him in flagrante, engaged in the most un-Baconian behavior imaginable.

The rationale for our unauthorized incursion was to seek out the

source of the iron rule's decree that only empirical testing counts and thus the origin of the most important tenet of modern science. We seem to have discovered, however, that Newton was in this respect not one of the first scientists but—as the great economist John Maynard Keynes wrote—"the last of the magicians." Have we traveled too far back in time or to the wrong place? Not at all. Take a closer look at Newton's researches and you will see that this particular magician enacted his enchantments in a rather unusual way.

On the one hand, Newton's interests were as broad as those of any Renaissance wizard. But on the other, the methods he used to pursue those interests were kept quite separate. Undertaking the investigation of the physics of motion, light, and gravity, the sole basis of his reasoning was mathematics, astronomical observation, and experiment. In his studies of "chymistry," or alchemy, experiment was again paramount, but it was now blended with allegorical thinking and an entirely new suite of hypotheses about vital agents, mercurial spirits, and the like. In his metaphysical disputes with Descartes about the nature of matter and space, his method was pure thought, that is, philosophical argumentation. And in his theological investigations of the nature of God and God's plan for the human race, accounting for aspects of history that gravity and vital sparks alone could not explain, Newton's methods were scriptural interpretation—for which he laid down 15 rules—and textual criticism. Throughout, Newton made little or no attempt to bring his conclusions in one area to bear on any other. His intellect operated, in short, as if in accordance with some "secret principle of unsociableness" that prevented his different investigations, in spite of their overlapping subject matter, from coming together to share their secrets.

Thanks to this sequestration of methods, as congenial to Newton as it was repellent to Whewell, the work that made Newton famous—his physics of gravity and light—was pursued entirely in accordance with the iron rule's edict that "only empirical testing counts." Alchemy,

theology, and the *prisca sapientia* played no role in these investigations. Newton judged physical theories solely with respect to the observable phenomena that they were able to explain.

Yet he was not following the iron rule. He was not following any methodological doctrine at all. What drove him was pure instinct, a quirk of his psychology that made him, quite unlike his seventeenth-century peers, a natural intellectual compartmentalizer.

When he entered the alchemy lab, he not only put on the alchemist's robe; he also assumed the alchemist's persona, taking on their allusive language, their allegorical style of thought, and their conception of matter and the principles of chemical interactions. In his beliefs, his behavior, and his words, he became the alchemist.

Figure 8.3. The alchemist, as imagined by Joseph Wright of Derby.

Figure 8.4. The mathematical physicist, as envisioned by William Blake in the person of Newton himself.

When he left the lab at daybreak and went back to his investigations of gravity, the robe was left hanging among the phials, funnels, and retorts. He was now wholly the physicist, intent on using the geometrical method to explain patterns of motion and concerned exclusively with the question of which trajectories can be derived from what mathematical laws.

Like a great actor, Newton gave each of his characters full rein, inhabiting rather than overpowering them, pushing their distinctive concerns, obsessions, assumptions, and modes of reasoning to the limit, playing them for all the knowledge they were worth. And so method for Newton was always multifarious: a cabinet of masks, a repertoire of dramatic roles. Each line of investigation took place in a different set-

ting following a different script: alchemy in the laboratory; gravity in the observatory; theology in the hermit's cave; philosophy—of course—in the sophic garden.

In keeping religion and philosophy out of empirical inquiry, Whewell was following the iron rule, by his time a social code recognized and respected by all serious scientists. Newton, by contrast, did not need a rule to tell him that in physics, only empirical testing counts. That kind of narrowness was built directly into his channels of thought.

Or at least, such was the case for the Newton who lived and worked at Trinity College, Cambridge, from 1667 to 1696. Years later, he evidently came to see how much his success had depended on his compartmentalizing ways, and at the age of 70, having served for almost two decades as Warden and then Master of the Royal Mint in London, he formulated his instinctive mental habit as a methodological principle, broadcasting it to the world in the postscript to the second edition of the *Principia* (1713):

> Whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses . . . have no place in experimental philosophy.

With these words, he wrought a great half-truth. As a summary of the methods of Newton the man, what he said was pure myth. In his alchemy he sought to read mystical symbols, and in his inquiry into space and time he philosophized vigorously with Descartes's ghost. But as a summary of the method of Newton the mathematical physicist—a dramatic persona rather than a living person, but nonetheless the true author of the *Principia*—what he said was quite accurate. The insights of that extraordinary work were achieved through a process that we would now recognize as an embodiment of the iron rule and in particular of its injunction to attend to no other virtues of a theory than its ability to

explain the phenomena. So in the *Principia*'s postscript, Newton gave his successors, and the world, the prohibition on religious, philosophical, and other nonempirical argument in science that constitutes the iron rule's fourth great innovation.

That prohibition, like the iron rule's more positive aspect—the definition of empirical testing in terms of shallow causal explanation—shimmered and sparkled with the Newtonian aura. It was seen by the thinkers who came after Newton as the vital spirit of empirical discovery. Adherence to both aspects of the rule swept across Europe, precipitating a revolution—the Scientific Revolution—that turned the creaking, antique apparatus of natural philosophy into the sleek knowledge-making machinery that is modern science.

NEWTON DID NOT FIGHT the Scientific Revolution single-handed: a number of other leading figures of seventeenth-century natural philosophy helped to prepare the way for the adoption of the iron rule. Although it was Newton's influence that was decisive, these lieutenants deserve a place in any account of the revolution's success. I will pause to read a few names from the roll of honor.

Something approximating the iron rule's prohibition on subjectivity and nonempirical argument can be found, as intimated above, in Bacon's prospectus for science, with its rejection of the "idols" of human nature, language, and culture in favor of the probative power of simple observation. Bacon also anticipated the shallow notion of explanation, criticizing earlier natural philosophers in characteristically unsparing terms:

> It is no less of a problem that in their philosophies and observations they waste their efforts on investigating and treating the principles of things and the ultimate causes of nature, since all utility and opportunity for application lies in the intermediate causes.

Bacon's rationale for shallow explanation is, unlike Newton's, facile in a moral as well as a metaphysical sense: once you have a good set of causal principles, he seems to be saying, your learning the underlying mechanisms by which they operate won't make you any richer. Nevertheless, he must receive a share of the credit for articulating both sides of the iron rule.

The extraordinarily precise naked-eye astronomical measurements of the Danish astronomer Tycho Brahe (1546–1601) were crucial in helping his assistant Johannes Kepler (1571–1630) to formulate his laws of planetary motion, physical principles that were in turn explained by Newton's gravitational theory. Kepler's use of Tycho's observations demonstrated early on the scientific value of minute details of no intrinsic philosophical interest—the immense importance of the digits far to the right of the decimal point celebrated by the Tychonic principle for which I have appropriated Tycho's name.

Robert Boyle (1627–1691), who investigated the properties of gases and numerous other phenomena, proclaimed the virtues of making observations independently of any theoretical conjecture:

> To keep my judgement as unprepossessed as might be with any of the modern theories of philosophy, till I were provided of experiments to help me to judge of them, I had purposely refrained from acquainting myself thoroughly with the entire system of either the Atomical, or the Cartesian, or any other whether new or revived philosophy.

Boyle claims, then, to have proceeded straight to the lab without reading any of the great natural philosophers of the age; when he came to advocate the atomic hypothesis, as he does in the essay from which the preceding passage is taken, it is supposedly on the basis of raw data alone. This theoretical agnosticism is too extreme to serve as a general recipe

for science, and in any case modern historians doubt that Boyle's account of his method is accurate. Still, like Bacon in the *New Organon*, he articulated an ideal in roughly the spirit of the iron rule.

Among Galileo Galilei's (1564–1642) many contributions to the modern world picture were his efforts to write down mathematical formulas describing the principles of physics and to derive from them the motions of particular kinds of objects. In *Two New Sciences* (1638), for example, he uses his physical principles to calculate the trajectories of cannonballs and the like, showing that such projectiles will follow a classical mathematical curve—the parabola. This mathematical systematization was central to demonstrating the power of shallow explanation in physics (although, I should add, shallow explanation need not be mathematical). The Dutch thinker Christiaan Huygens (1629–1695) continued the tradition, formulating a physics of collisions and deriving the mathematics describing the motion of a pendulum.

The last scientific revolutionary to be commended here is not a person but an organization: England's Royal Society (founded in 1660 and still thriving), which devised the idea of an objective register of empirical observation, the scientific journal in its embryonic form.

Bacon's prescriptions; the exacting measurements of Tycho Brahe; Robert Boyle's celebration of experiment over theory; Kepler's mathematical astronomy and Galileo's and Huygens's mathematical mechanics; the publications of the Royal Society: all of these contributed to the conception of purely observation-based inquiry codified by the iron rule. The script for playing the empirical scientist, and in particular the mathematical physicist, had by Newton's time been drafted already by Bacon and the rest. None of these thinkers, however, inhabited the role like Newton. He needed no direction. Simply by following his compartmentalizing heart, he acted out the iron rule more stringently, more perfectly, than anyone who came before.

I HAVE DISMANTLED the iron rule, over the last few chapters, to analyze each of its four innovations. Now I need to reassemble the parts, showing how the innovations work together to power and steer the knowledge machine.

The iron rule demands that scientific arguments consider only the explanatory power of contending theories. The positive core of the rule is a shallow, permissive conception of explanatory power, on which a phenomenon is explained by deriving it from a theory's causal principles. The principles need not pass any philosophical test or even be fully understood—thus, Newton considered himself to have explained the motions of the planets and the tides using his theory of gravity, although he offered no explanation of the causes of gravity itself.

The negative side of the rule forbids scientists, when making their case in official venues such as scientific journals, to assess theories using anything other than explanatory power. Philosophical and religious arguments in particular are out of bounds, no matter how compelling they may seem to scientists and to society at large. Likewise, scientists may not bring personal or cultural or other parochial considerations to bear in making their case; the iron rule requires that everything subjective be removed from scientific argument.

The Scientific Revolution, then, accomplished by way of the iron rule both a shallowing and a narrowing of the old forms of deliberation: post-Revolutionary argument is shallower in its conception of explanatory power, and it is narrower in its range of reasons for accepting and rejecting hypotheses and theories. Although such constrictions have little intuitive appeal, they have turned out to provide the superstructure for an extraordinarily effective engine of inquiry.

We live in a Tychonic world—a world in which great competing stories about the underlying nature of things can be distinguished by, and only by, scrutinizing subtle intricacies and minute differences. Humans

in their natural state are not much disposed to attend to such trifles. But they love to win. The procedural consensus imposed by the iron rule creates a dramatic contest within which the trifles acquire an unnatural luster, becoming, for their tactical worth, objects of fierce desire. The rule in this way redirects great quantities of energy that might have gone toward philosophical or other forms of argument into empirical testing. Modern science's human raw material is molded into a strike force of unnervingly single-minded observers, measurers, and experimenters, generating a vast, detailed, varied, discriminating stock of evidence.

At the same time, the iron rule preserves this evidence, maintaining a craft tradition of "sterilization" that archives observed phenomena in a form that is distorted as little as possible by interpretation and other consequences of plausibility rankings.

The thinking of each generation of scientists is, and is permitted by the iron rule to be, essentially subjective. But that subjectivity does not matter in the long run. As thinkers come and go, observations accrue, revealing in time which theories are better explainers and which are worse. The eventual consequence is Baconian convergence on the truth: informed opinion increasingly favors the one theory, the correct theory, that accounts for every aspect of the accumulated evidence.

Science, then, is built up like a coral reef. Individual scientists are the polyps, secreting a shelly carapace that they bequeath to the reef upon their departure. That carapace is the sterilized public record of their research, a compilation of observation or experimentation and the explanatory derivation, where possible, of the data from known theories and auxiliary assumptions. The scientist, like a polyp, is a complete living thing, all too human in just the ways that the historians and sociologists of science have described. When the organism goes, however, its humanity goes with it. What is left is the evidential exoskeleton of a scientific career. You can see the bare bones laid down by Eddington's eclipse expedition, for example, in the black-and-white rows of numbers

that represent stars' photographed positions and the mathematical calculations that yield the sun's implied bending of starlight (Figures 2.3 and 7.4).

The intellectual edifice that is scientific knowledge is composed largely of these exoskeletal remains. It is held together, like a reef, not by living things, but by the evidence and argument that living things produce, assembled according to a strict architectural plan ordained by the iron rule.

Look at science's theater of inquiry, and you see life. You see the surface of the reef, where the polyps still thrive: you see working scientists going about their investigations guided by hunches, intuitions, ambitions, temperament, circumstance, culture. If you were to suppose that this was science in its entirety, you would conclude it was subjective through and through. That is the characteristic mistake, I think, of those radical subjectivists who infer from the day-to-day contextuality of scientific activity a long-term epoch-to-epoch contextuality. Neither the reef nor science is as lively, as soft, as transient as it appears. Both are built deep down from simpler stuff that outlasts the passing of the organic profusion on the periphery, forming a grand, stony, and severe structure upon which rests their success.