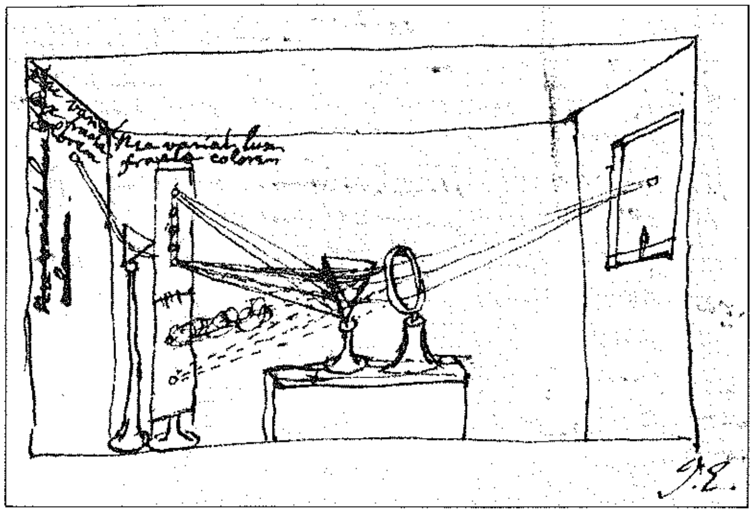

Isaac Newton's drawing of his experimentum crucis.

Four

EXPERIMENTUM CRUCIS: Newton's Decomposition of Sunlight with Prisms

IN JANUARY 1672, ISAAC NEWTON (1642–1727) SENT A short note to Henry Oldenburg, the secretary of a newly established group of eminent scientists (or "philosophers," as they were then known) called the Royal Society of London. The Society had admitted Newton just one week before, its members impressed by his invention of an ingenious new type of reflecting telescope. Newton made Oldenburg a brazen claim. I have made a "philosophical discovery," Newton said, which was "in my judgment the oddest, if not the most considerable detection, which hath hitherto been made in the operations of nature."[1] Oldenburg might have been forgiven for thinking this preposterous, an arrogant claim by an overambitious youngster. And indeed Newton was a difficult person—combative, hypersensitive, and obsessively secretive. But this was no hyperbole.

A few weeks later, Newton sent the members of the Royal Society the description of an experiment that decisively showed, he said, that sunlight, or white light, was not pure as previously thought, but composed of a mixture of rays of different colors. Newton referred to this as his *experimentum crucis,* or "crucial experiment." His decomposition of light was at once a landmark in the history of science and a sensational demonstration of the experimental method. This experiment, one of Newton's many biographers wrote, "was as beautiful in its simplicity as it was effective in encapsulating Newton's theory."[2]

ISAAC NEWTON WAS BORN in Lincolnshire, England, in 1642, the same year Galileo died. He came into the world, perhaps appositely, on Christmas Day. From 1661 until 1665, Newton studied at Trinity College at Cambridge University. His was, another biographer asserted, "the most remarkable undergraduate career in the history of university education,"[3] for Newton discovered and thoroughly mastered on his own, and in the seclusion of his private notebooks, the new philosophy, physics, and mathematics that was being slowly and arduously forged by the most advanced scientists in Europe. In 1665, when Newton had graduated but was staying on for further studies, the Great Plague hit England and Cambridge University shut its doors for two years, sending Newton back to Lincolnshire. This enforced idle time among the fields and orchards of his mother's estate was not a setback to his education, but an unexpected blessing. It allowed Newton, then in his scientific prime, to think without interruption on numerous scientific topics on which he was already working at the cutting edge. Historians call this period of Newton's life his *annus mirabilis,* or "year of miracles," for in it he laid the foundations of many of his seminal ideas: in physics, the idea of universal gravitation (the inspirational falling-apple story, which comes to us via Newton's half-niece and Voltaire, supposedly took place at this time); in astronomy, the laws of planetary motion; in mathematics, calculus. During this time, Newton also began work on a revolutionary set of experiments in optics.

Optics, the study of light, was then of growing scientific importance. Since ancient times, thinkers had developed a basic knowledge of how light reflects and refracts (bends when passing through a transparent material). But prior to the seventeenth century, mirrors and lenses were of poor quality. Furthermore, their study was hampered by the prejudice that the images they produced were unworthy of serious examination because they were unnatural—how important could distorted and deceptive images be? But the invention of the telescope and microscope fueled the demand for better mirrors and lenses, which in turn increased interest in their manufacture and study. The new science, too, fostered the notion that optical distortions and transformations were not unnatural (like Aristotelian "violent" motions) but (again, like Galilean motion) just another arena governed by mechanical principles and mathematical laws that could be discovered through experimentation. Yet Descartes and other pioneers of optics in the seventeenth century still hewed to a view, found as far back as Aristotle, that white light is pure and homogeneous, with colors being a modification or "staining" of white light.

Cooped up on his mother's estate, while disease raged in the cities, Newton transformed one of her rooms into an optics laboratory, sealing it from light except for a tiny hole to the outside. There he spent day after day absorbed in experiments. Wrote one associate, "[T]o quicken his faculties and fix his attention [he] confined himself to a small quantity of bread, during all the time, with a little sack and water, of which, without any regulation, he took as he found a craving or failure of spirits." Newton's principal tool was a prism, a popular curiosity of the time highly regarded for its ability to transform white light into various colors. But Newton transformed the toy into a powerful instrument for scientific investigation in his study of light.

A common stereotype, inflicted on generations of schoolchildren, is that the scientific method is a robotic enterprise: forming, testing, and reforming hypotheses. A vaguer-sounding but more accurate account of what scientists do would be to say they "look at" a phenomenon—they examine it from different angles, understanding it by tweaking it this way and that to see what happens. In his converted laboratory, Newton "looked at" light, using various configurations of prisms and lenses, and eventually arrived at the conclusion that white light was not pure but a mixture of light of different colors. Newton would write later, "For the best and safest method of philosophising seems to be, first to inquire diligently into the properties of things, and establishing those properties by experiments and then to proceed more slowly to hypotheses for explanations of them."[4]

But for several years Newton told few people about this work. When he returned to Trinity College when it reopened in 1667, he attended lectures on optics delivered by Isaac Barrow, the first occupant of the Lucasian chair of mathematics at Cambridge (a famous chair, whose later occupants included Paul Dirac and Stephen Hawking), proofread Barrow's lecture notes, and in 1670 succeeded Barrow as Lucasian Professor. The post required him to wear a scarlet robe to indicate his elevated status over other faculty. It also required him to deliver a lecture to students at least once a week, in Latin, on some topic pertaining to mathematics. Newton chose optics, which allowed him to mix mathematics and experimental science and to "bring the principles of this science to a more strict examination." These lectures were sparsely attended. An associate remarked that "So few went to hear him, & fewer that understood

him, that oftimes he did in a manner, for want of hearers, 'read to the walls.' "[5] Literally read to the walls—not a single person attended his second lecture.

In 1671, Newton presented members of the Royal Society with a telescope he had invented based on his optical studies. The Royal Society had been established just over ten years earlier, as the Royal Society of London for Improving Natural Knowledge; its motto, inscribed on its coat of arms, was the Latin expression "*Nullius in verba*," which is traditionally translated as "Don't take anyone's word for it." The Royal Society met weekly, discussing and analyzing members' papers. This format was crucial to the stimulation of research and the professionalization of science, for it streamlined the process by which scientific information was disseminated and defended; one could focus on researching a specific topic and report one's results in a letter. These letters were published in what was initially called the Society's *Correspondence* and later the *Philosophical Transactions,* a forerunner of the modern scientific journal. When Newton joined, few members had heard of him. Nevertheless, his telescope was a sensation. Only six inches long, it was ingeniously designed and carefully built, and the equal of many much larger telescopes. Several members began trying to construct one for themselves, and they soon invited Newton into their ranks.

Newton's first formal submission to the Society was the letter that fulfilled his bold promise to Oldenburg to relay news of the "oddest" philosophical discovery yet made about nature's operations. This paper is often cited as a masterpiece of scientific literature and a model of scientific writing. It provides an excellent description not only of the crucial experiment itself but also of the thought process that led up to it—and a sharp reader will notice, between the lines, the sheer joy that Newton took in his investigations. The paper begins as follows:[6]

> To perform my late promise to you, I shall without further ceremony acquaint you, that in the year 1666 . . . I procured me a Triangular glass-Prisme, to try [to test] therewith the celebrated *Phenomena of Colors.* And in order thereto having darkened my chamber, and made a small hole in my window-shuts, to let in a convenient quantity of the Suns light, I placed my Prisme at its entrance, that it might be thereby refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colors produced thereby.

Others might have fallen into the temptation to pay attention only to the beguiling rainbow-like play of colors. But Newton was looking at what was happening from as many angles as possible. He saw beyond the colors to the shape they were assuming. "I became surprised to see them in an *oblong* form; which, according to the received laws of Refraction, I expected should have been *circular.*"

Why was Newton surprised? In the prevailing view of Descartes and others, prisms somehow modified or stained white light to produce the spectrum. If so, a pencil-thin beam should emerge from the prism with the same circular outline that it had when it entered. Instead, Newton saw, the image was shaped like a racetrack, with semicircular curves at the top and bottom connected by straight sections (Figure 4.1); the colors were arranged in horizontal bands, with blue at one end and red at the other. Newton also noticed a second puzzling feature: While the straight sections of the image were crisp, the curves at either end—blue or red—were blurred. This, plus the "extravagant" discrepancy between the length and the width—the former was about five times longer than the latter—"excited me to a more than ordinary curiosity of examining, from whence it might proceed."

Newton next describes his attempts to determine why the image

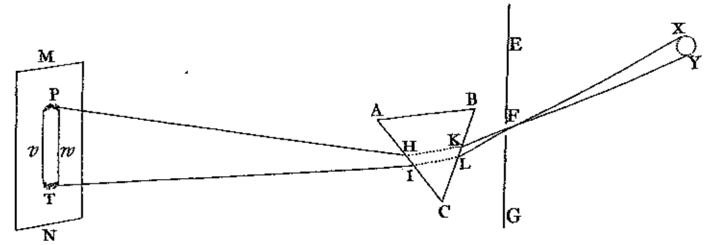

Figure 4.1. Newton's diagram of the oblong shape produced by a beam of sunlight after passing through a prism.

had acquired such an unexpected outline simply after passing through the prism. Trying to see if he could affect the shape of this outline, he tried using prisms of different thicknesses, and tried passing light through different parts of the prism. He rocked the prism back and forth on its axis. He changed the size of the hole in the window, and tried putting the prism outside in the sunlight so that the beam came through the prism before passing through the hole in the window. He checked to see if imperfections in the glass of the prism might be responsible. None of this affected the shape of the outline. Its puzzling oblong shape remained, and each color was always refracted—sent off at an angle while passing through the prism—in the same way.

Newton remembered times when he had seen "a tennis-ball, struck with an oblique racket," following an arc through the air. Maybe, he began to suspect, the shape of the spot could be explained if the prism somehow caused the light rays to travel in curved paths in the vertical direction. Thus drove him to another set of experiments.

> The gradual removal of these suspicions at length led me to the *Experimentum Crucis,* which was this: I took two boards, and placed one of them close behind the Prisme at

> the window, so that the light might pass through a small hole, made in it for that purpose, and fall on the other board, which I placed at about 12 foot distance, having first made a small hole in it also, for some of the Incident light to pass through. Then I placed another Prisme behind this second board, so that the light, trajected through both the boards, might pass through that also, and be again refracted before it arrived at the wall. This done, I took the first Prisme in my hand, and turned it to and fro slowly about in Axis, so much as to make the several parts of the Image, cast on the second board, successively pass through the hole in it, that I might observe in what places on the wall the second Prisme would refract them. And I saw by the variation of those places, that the light, tending to that end of the Image, towards which the refraction of this first Prisme was made, did in the second Prisme suffer a Refraction considerably greater than the light tending to the other end.

Newton's own diagram for his *experimentum crucis,* which he drew on a piece of paper in his first lectures on optics, is shown in Figure 4.2. A pencil-like beam of light coming in through a hole in the window passed through a first prism and fanned out against a board a dozen feet away. In fanning, it threw out a rainbow-like display of colors—oblong in the vertical dimension, but with horizontal bands of color from red to blue. Anyone who had played with prisms had seen this, though not necessarily realizing the significance of the shape. But what Newton did next was novel: He added a second prism and board. He drilled a hole in the board, passed part of the oblong band of light through it to another prism on the other side, and then directed that beam against *another* board. By swiveling the first prism, he could maneuver the oblong band up and down

so that light of different colors would pass through the hole, through the second prism to the second board. He then looked carefully at what happened.

Newton noticed that blue light, which was greatly refracted by the first prism, was also greatly refracted by the second prism as well; similarly, red light, less refracted by the first prism, was less refracted by the second. He also noticed that *how* these were refracted did not depend on the angle of incidence (the angle at which they struck the surface of the prism). Newton concluded that the degree by which the rays were refracted—their "refrangibility," after the Latin word *refrangere,* "to break off"—was a property of the rays themselves and not of the prism. The rays kept their refrangibility while passing through the two prisms. The prisms did not modify the light rays but only sifted them according to their refrangibility.

Newton now held the answer to his initial question. The rainbow image was shaped like a racetrack because the prism spreads out the beam of light in a way dictated by the behavior of its individual component colors. If the axis of the prism is horizontal, the prism maintains the beam at the same width but spread it out vertically. The vertical tips of the oblong shape are blurry because there are fewer rays at the extreme top and bottom. Newton wrote: "And

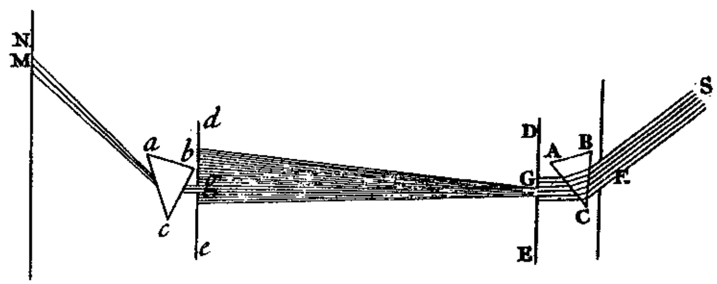

Figure 4.2. Newton's diagram of his experimentum crucis, *from his lectures on optics.*

so the true cause of the length of that Image [the oblong shape] was detected to be no other, than that *Light* consists of Rays differently refrangible, which, without any respect to a difference in their incidence, were, according to their degree of refrangibility, transmitted towards divers parts of the wall."

What was so crucial about this experiment, out of the hundreds that Newton had performed, many of which showed him similar effects? His own confidence in his conclusions about this experiment was based, not on it alone, but on all of his other attempts to look at light with prisms and lenses. But Newton saw no reason to insist that his colleagues follow his own extensive path of inquiry. All it should take to set his colleagues on the right track would be a single one. Thus there was a certain theatricality to the *experimentum crucis;* it was a demonstration or recapitulation of what by now he had already learned how to do. The purpose of the demonstration was to persuade colleagues, so it needed to be simple, with readily available instruments, and show the result cleanly and vividly to maximize the impact. As he would write later to someone struggling to recreate his experiments, "Instead of a multitude of things try only the Experimentum Crucis. For it is not [the] number of Expts, but [their] weight [is] to be regarded; & where one will do, what need of many?"[7]

This experiment gave Newton not only an answer to his initial question about why the shape of the colors is oblong, but opened other possibilities and raised new questions. He had been busy grinding lenses for telescopes, but saw that this prism discovery implied an important limitation on the quality of telescopes made from lenses. "When I understood this," he wrote, "I left off my aforesaid Glass-works; for I saw, that the perfection of Telescopes was hitherto limited," not by imperfections in the glass, but because of the fact "that Light it self is a *Heterogeneous mixture of differently refrangible Rays.*" Lenses focus by bending or refracting light; but because different kinds of light refract by different amounts, even a perfect lens could not collect all the rays at one point. A more effective way to focus light for a telescope, Newton realized, would be to use mirrors rather than lenses, since when mirrors bounce or reflect light to focus it, the angle at which different kinds of light reflect is always the same. Newton said that he promptly set out to build a telescope that used mirrors, but his telescope making was interrupted by the plague. In 1671, he finally built one he was confident in and proud of—proud enough that he was able to overcome his usual obsessive secretiveness and show it to the Royal Society.

Newton laid all this out in the first half of the paper. In the second half, he discussed several implications of his discovery. A first was that the refrangibility of light was not a property caused by the prism through some form of modification, as Descartes and most other authors on the subject believed: "Colours are not *Qualifications of Light,* derived from Refractions, or Reflections of natural Bodies (as 'tis generally believed,), but *Original* and *connate properties,* which in divers Rays are divers. . . ." A second implication was that "To the same degree of refrangibility ever belongs the same colour, and to the same colour belongs the same degree of refrangibility." A third was that the refrangibility or color of a ray is unaffected by the substance it passes through. Newton had looked at this point very carefully:

> The species of colour, and degree of Refrangibility proper to any particular sort of Rays, is not mutable by Refraction, nor by Reflection from natural bodies, nor by any other cause, that I could yet observe. When any one sort of Rays hath been well parted from those of other kinds, it hath afterwards obstinately retained its colour, notwithstanding my utmost endeavours to change it. I have refracted it with prisms, and reflected it with bodies, which in day-light were

> of other colours; I have intercepted it with the coloured film of air, interceding two compressed plates of glass; transmitted it through coloured mediums, and through mediums irradiated with other sorts of rays, and diversly terminated it; and yet could never produce any new colour out of it.

Newton comes to the remarkable conclusion that white light is not original but compound, a fact that he had confirmed in some of his experiments by using additional prisms and lenses to recombine light that he had earlier separated:

> But the most surprising and wonderful composition was that of Whiteness. There is no one sort of Rays which alone can exhibit this. 'Tis ever compounded and to its composition are requisite all the aforesaid primary Colours, mixed in a due proportion. I have often with admiration beheld, that all the colours of the prism being made to converge, and thereby to be again mixed, as they were in the light before it was incodent upon the prism, reproduced light entirely and perfectly White. . . . Hence, therefore, it comes to pass, that Whiteness is the usual colour of light; for light is a confused aggregate of rays indued with all sorts of colours, as they were promiscuously darted from the various parts of luminous bodies.

Newton's "surprising and wonderful" discovery ignited new insights into what had been deep mysteries. In the rest of the article he addresses some of these one by one, solving with ease puzzles that had baffled his colleagues. How do prisms work, and how do they make the oblong shape of the spot they produce? They do not transform, but instead sift light, separating it into bands of like refrangibility. Imagine (this is not Newton's image) a pack of runners,

each of which is able to turn a corner at a different angle. Though they keep together when moving in a straight line, at the first sharp corner they will fan out into a band. How do rainbows form? Newton explains this as raindrops acting like a cloud of tiny prisms, refracting the light of the sun behind them. What about those "odd phenomena" involving colored glass and other materials in which the same stuff gives off different colors? These are "no longer riddles," Newton says, for they are materials that reflect and transmit different kinds of light in different conditions.

Newton accounted for an "unexpected experiment" made by Robert Hooke, the Royal Society's Curator of Experiments. Hooke had shined light through a jar of red liquid and a jar of blue liquid. Each one let light through—but when he tried to shine light through both jars together, they blocked all light. Hooke had not been able to explain this: Why, if each individual jar allowed light to pass through, would the combination block all light? Hooke's puzzlement, Newton said, was evidently due to the assumption that light was a uniform substance; instead, light was composed of many types of rays. The blue jar let through one type but blocked all others; the red jar let through a second type, and blocked all others. Because the two jars did not allow the same type of light to pass, "no rays could pass through both."

Newton was now also able to explain the color of natural bodies—they reflect "one sort of light in greater plenty than another"—and he described his own experiments in a darkened room, in which he cast light of different colors on various objects, finding "by that means any body may be made to appear of any color." Are there colors in the dark, and is color a property of objects? No—color is a property of the light that shines on them.

Newton ended the letter with some suggestions for experiments his colleagues could make, though he warns that these experiments, like the *experimentum crucis,* are highly sensitive. The prism has to be of high quality or the light reaching the second prism will be impure, and the room must be absolutely dark lest light mix with the colors and confuse the issue. This latter feature makes the *experimentum crucis* more difficult to re-create than it may seem for high school science-education classes, however temptingly accessible and vividly instructive it might appear. Newton concluded:

> This I conceive is enough for introduction to experiments of this kind; which if any of the Royal Society shall be so curious as to prosecute, I shall be very glad to be informed with what success: that if any thing seem to be defective, or to thwart this relation, I may have an opportunity of giving further direction about it; or of acknowledging my errors, if I have committed any.

Newton's letter reached Oldenburg on February 8. As luck would have it, Oldenburg was preparing for a Royal Society meeting later that day and was able to put it on the agenda. Those present first sat through a letter on the possible influence of the moon on barometric readings, then another on the effects of a tarantula's sting, before hearing Newton's contribution. The Society was greatly impressed. Oldenburg reported that "[T]he reading of your discourse concerning Light and Colours was almost their only entertainment for that time. I can assure your, Sir, that it there mett both with a singular attention and an uncommon applause."[8] Oldenburg also mentioned that the members had directed him to publish it as soon as possible in the *Philosophical Transactions*, and it appeared in the next issue later that month.

NOT ONLY WAS NEWTON'S *experimentum crucis* a beautiful experiment, and his letter about it in the *Philosophical Transactions* the very model of a scientific paper, but it also spawned what is surely the first "journal controversy," in which scientists argue heatedly back and forth about an issue. Newton's experiment, challenging as it did the orthodoxy of the time, according to which prisms created colors by modifying white light, created a stir in the Royal Society and among other scientists, especially in France.

Without trying to replicate the *experimentum crucis*, Robert Hooke had dismissed Newton's letter a week after reading it with some rash and incorrect criticisms about the hypotheses Newton seemed to be making. Newton rose to the occasion, brilliantly displaying his combative talents in the exchange of letters that followed, recapitulating and elaborating his arguments, which included one of the most sarcastic put-downs in history. This made use of the fact that Hooke was so short and hunched (partly exacerbated by the type of exacting bench work that he did) that he resembled a dwarf. In one letter that fairly dripped with false flattery, Newton praised Hooke's contributions to his own work with the words, "If I have seen further it is by standing on [the] shoulders of Giants."[9] This famous remark is now often cited as gallant and humble when in fact it nastily ridiculed Hooke.

Scientists in France took longer to convert. One was an elderly professor at the College of English Jesuits at Liège named Francis Hall, though he called himself Linus in correspondence. In the fall of 1674, Linus—who was pushing eighty—wrote to Oldenburg claiming that, in experiments with prisms that he had conducted thirty years earlier, he never observed an elongated outline on sunny days, claiming the elongation of the image that Newton saw was due to the effects of clouds. Newton, who considered Linus incompetent, did not deign to answer. Oldenburg, however, ordered Hooke to stage a demonstration of Newton's *experimentum crucis* at a Royal Society meeting in March 1675. The weather, alas, did not cooperate, and in view of Linus's remarks it was thought pointless to carry out the experiment on a cloudy day. Linus died in the fall of that year, but his cause was honored by a devout pupil who expressed confidence that his master would be vindicated the next time the Royal Society tried the experiment on a sunny day.

Hooke again made plans for a demonstration at the Royal Society, and what Newton referred to as "ye Experiment in controversy" was rescheduled for 27 April 1676 (a sunny day, as it turned out). Although Newton was not present—he generally shunned such public occasions—it was a landmark in the dawn of modern science, for it was the first experiment planned and executed by a scientific society to obtain the decisive answer to a pressing controversy. The official records of the Royal Society state:

> The experiment of Mr. NEWTON, which had been contested by Mr. Linus and his fellows at Liege, was tried before the Society, according to Mr. NEWTON's directions, and succeeded, as he all along had asserted it would do: and it was ordered, that Mr. OLDENBURG should signify this success to those of Liege, who had formerly certified, that if the experiment were made before the Society, and succeeded according to Mr. NEWTON's assertions, they would acquiesce.[10]

Some French critics held out a few years longer. A French Jesuit named Anthony Lucas tried the *experimentum crucis* but found red rays among the purple; another found red and yellow among the violet. Newton stopped responding, writing that "[t]his is to be decided not by discourse, but new Tryall of ye experiment."[11] He had already delivered warnings about what could go wrong with the experiment. Like any complexly performing device, an experiment can be arranged incorrectly—but when done right, it shows what

went wrong in the incorrect trials; it provides its own criteria of success.

NEWTON'S *EXPERIMENTUM CRUCIS* provided the world with many things at once: a piece of information, a set of tools and techniques, even a moral lesson. It owes its beauty to each of these. Newton's experiment disclosed a piece of truth about the world with astounding simplicity and ingenuity: Who would have thought, after using a prism to split a beam of white light into a rainbow, to pick a portion of that and send it through *another* prism? With that configuration, no further manipulations were necessary to show Newton's colleagues that white light is composed of rays of different colors with different degrees of refraction.

The experiment allowed us to understand many puzzling phenomena of light, and gave us techniques for separating light of different colors and of building better telescopes. Newton's insight erupted like a firecracker, shooting connections in many different directions.

Finally, Newton's *experimentum crucis* was a moral lesson for scientists. It said, in effect: "This is the way to go about understanding a puzzling phenomenon. Experiment long and hard. Then pick out the most economical and vivid demonstration you can find, point out the ways it can go wrong, and show what new connections it makes possible."

Thus its beauty has nothing to do with the prettiness of the colors themselves; Newton, like Eratosthenes with his shadows, looked beyond the colors to what was making them behave the way that they do. But like Galileo's inclined-plane experiment, Newton's *experimentum crucis* revealed something about the nature of experimentation itself. What's distinctive about the *experimentum crucis* is that it has a kind of moral beauty.

By 1721, when a second French edition of Newton's *Opticks* was scheduled to be published in Paris (the first having appeared in 1704), its French publisher, Varignon, wrote to Newton, "I have read the Opticks with the greatest delight, and all the more so because your new system of colours is firmly established by the most beautiful experiments." Varignon asked Newton for a drawing to put at the top of the first page that might symbolize the contents.

Newton chose a drawing of the *experimentum crucis* with a laconic caption: "Light does not change color when it is refracted." It was an elegant symbol of what, in Newton's hands, became the science of optics itself.

Interlude

DOES SCIENCE DESTROY BEAUTY?

When I heard the learn'd astronomer,
When the proofs, the figures, were ranged in columns before me,
When I was shown the charts and diagrams, to add, divide, and measure them,
When I sitting heard the astronomer where he lectured with much applause in the lecture-room,
How soon unaccountable I became tired and sick,
Till rising and gliding out I wander'd off by myself,
In the mystical moist night-air, and from time to time,
Look'd up in perfect silence at the stars.

—WALT WHITMAN

TO LOVERS OF BEAUTY, Newton brought not peace but a sword.

Early philosophers, poets, and artists viewed light as having a special status among all the world's phenomena. Plato compared the sun and its rays to the Good—the highest form—for it not only nurtured but illuminated everything. Followers in the Platonic tradition, including St. Augustine, Dante, Grossteste, and St. Bonaventure, saw a special tie between light and beauty or being; light was the principle of all visible and sensuous beauty, and beautiful in itself. It