THE WAR AGAINST BEAUTY

Appeals to aesthetics have no place in
public scientific argument, insists the iron rule.
This ban on beauty is also an attack on reason:
elegance often, if not always, points the way to truth.

BALANCE, BEAUTY, SYMMETRY. For all its dust, dirt, and motley ways of death, the universe has a good measure of these ethereal properties—a nobility of structure and an elegance in the fine texture, or so most of us would like to believe. There is a way in which, considered as an aesthetic whole, the world makes sense.

This hidden harmony is a key to a deeper understanding of things, many great thinkers both before and after the Scientific Revolution have supposed. Find the patterns governing nature's inner principles, and you can call on your sense of proportion, your eye for grace and elegance, to help discern the composition and the causal underpinnings of the universe. A good theory must explain the observable facts, but alongside explanatory power, beauty, too, shows the way to truth.

And yet, like philosophical and theological reasoning, aesthetic reasoning is eliminated entirely and indiscriminately from official scientific argument, from the journals and conference presentations, by the iron rule. It is a highly functional prohibition, an important part of the program of manipulation by which science molds ordinary human minds

into indefatigable empirical-testing machines. But is it reasonable? To answer that question, we need to know just how effective a guide to truth beauty has turned out to be. We should therefore consult the historical record.

THE CONSONANCE OF microcosm and macrocosm—that is the most ancient principle of universal harmony, and it was for a long time the most commanding. The human world reflects the physical world, proclaims this principle; further, the same patterns marshal the connections between things at every level of being: physical, chemical, biological, psychological, and theological; on earth as it is in heaven, among angels as it is among men.

A taste of this view's strange charm—a single pattern imposing itself at every level—still lingers today in the fascination with fractals. Many examples of these geometrical figures contain smaller embedded images of themselves, which then contain smaller embedded images still, and so on ad infinitum. Look into a well-known fractal, the triangle described by the Polish mathematician Waclaw Sierpinski in 1915 (Figure 10.1). You will see that within the outer triangular boundary, each of the three next largest triangles is an exact copy of the whole. Thus, the same triangular structure repeats itself at every scale, high and low, macro and micro. There is no smallest triangle: an infinity of ever more diminutive shapes is generated by simple three-sided iteration and miniaturization. It is a most elegant way to make a universe. Once upon a time, this was considered not merely a mathematical curiosity but the secret to all creation.

What is the master plan? One answer is provided by the venerable rule of four, a principle dating from antiquity that finds fourhood throughout God's creation. The world is made of four elements: fire, air, earth, and water. The human body is controlled by four vital flu-
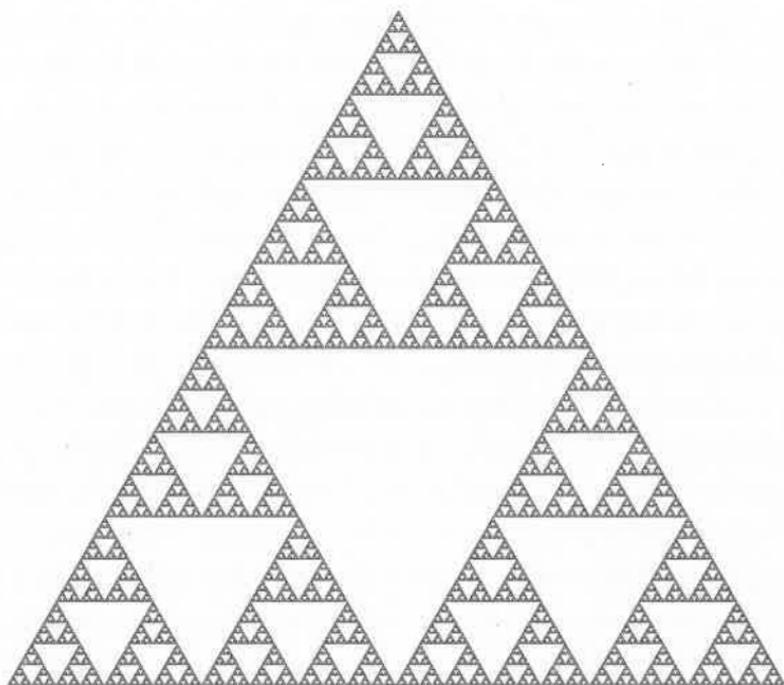
Figure 10.1. The Sierpinski triangle.

ids: blood, black bile, yellow bile, and phlegm. There are four cardinal virtues (justice, moderation, fortitude, and prudence), four evangelists, four letters in the name of god (in Latin, *Deus*), four seasons, four principal winds, four regions of the world, and four ages of man (childhood, adolescence, adulthood, old age). The same tetradic configuration is replicated at every level, from the grand structure of the cosmos through meteorological dynamics down to the physical and moral makeup of human beings and their spiritual history and destiny.

An even more fundamental fourhood underlies all of this. There are four physical attributes—hot and cold, moist and dry—that are found mixed in each of the substantive quartets. Fire is hot and dry, as are summer and adolescence; water is cold and moist, as are winter and old age.

This vision of universal fourfold harmony is dramatically expressed in the diagram with which the medieval English monk Byrhtferth (c. 970–c. 1020) concluded his treatise on the determination of the date of Easter (Figure 10.2). Looking deep into the diagram, you can unravel further implications of the scheme of four; for example, the initial letters of the four regions (Anathole, Disis, Arcton, Mesembrios), as Byrhtferth points out, spell Adam, the name of the first human and, for better and worse, the first inquirer after knowledge (or, more exactly, her assiduous assistant).

Similar organizing structures are strewn like spiky bouquets across the history of human thought, projecting their internal symmetry onto the sky above and the world around. The Swiss Renaissance thinker Paracelsus (1493–1541) saw a concordance of heavenly bodies with the parts of the human body: the sun, he thought, corresponds to the heart and to gold; the moon to the brain and to silver; the planet Venus to the kidneys and to copper; and so on for the other four known planets.

Isaac Newton eagerly consumed all the arcana of this sort that he could bring to light, his imagination seized by the idea of the world, its chemistry, its history, and its mythmaking as realizations of a great cosmic plan (Figure 10.3). The economist John Maynard Keynes, who purchased many of Newton's alchemical papers at a 1936 auction, vividly captured this aspect of Newton's worldview (alluding to Newton's concern with the *prisca sapientia*, the ancient wisdom):

He looked on the whole universe and all that is in it *as a riddle*, as a secret which could be read by applying pure thought to certain evidence, certain mystic clues which God had laid about the world to allow a sort of philosopher's treasure hunt to the esoteric brotherhood. He believed that these clues were to be found partly in the evidence of the heavens and in the constitution of elements . . . but also partly in certain papers and traditions handed down by the
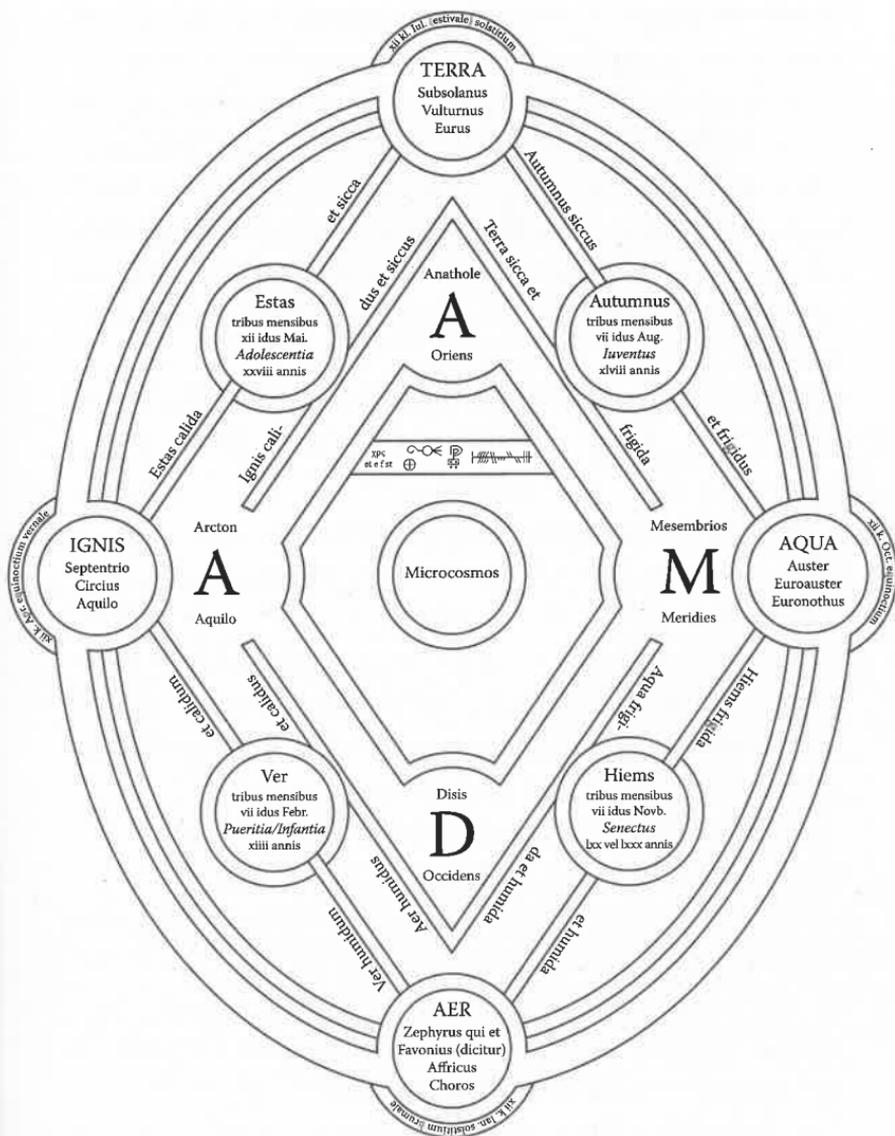
Figure 10.2. Byrhtferth's diagram. The four elements are *aer, ignis, terra,* and *aqua* (air, fire, earth, and water). The four seasons, which can be found in the circles between the elements, are *ver, estas, autumnus,* and *hiems* (spring, summer, fall, and winter). The four physical attributes (look along the sides of the diamonds) are *calidus, siccus, frigidus,* and *humidus* (hot, dry, cold, and moist).
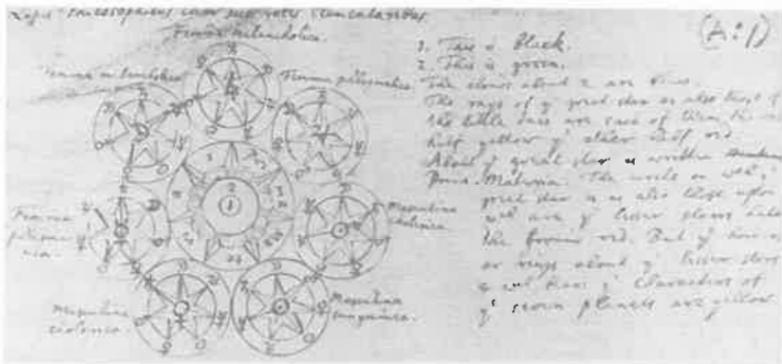
Figure 10.3. Newton's sketch (copied from an alchemical text) of the secrets of the philosophers' stone.

> brethren in an unbroken chain back to the original cryptic revelation in Babylonia. He regarded the universe as a cryptogram set by the Almighty.

It is a kind of magical thinking, a kind of religious thinking, a kind of mystical thinking, but it is also a kind of aesthetic thinking, using the sense of beauty and structure to decode the cosmos.

It is not, however, an effective kind of thinking. Byrhtferth's numerology is delightful, but not insightful. That the iron rule excludes such methods from scientific argument cannot, given what we have seen so far, be held against it.

This is, however, only a single example of aesthetic evaluation put to work as a technique of inquiry. Before generalizing about the merits of such methods, we must survey a few more cases.

In 1821, William Sharp Macleay, a British government official and a keen entomologist, published a study of insects in which he put forward a new framework for classifying life: the quinarian system. It took its name

from the Latin word for the number five, and in that number lay its structural essence. Every biological taxon—the birds, the beetles, the big cats—Macleay believed, consisted of five subgroups, and each of those subgroups of five more subgroups, and so on down to the level of individual species.

By arranging any five sister groups in a circle, as shown in the classification of birds in Figure 10.4, further structure became evident.
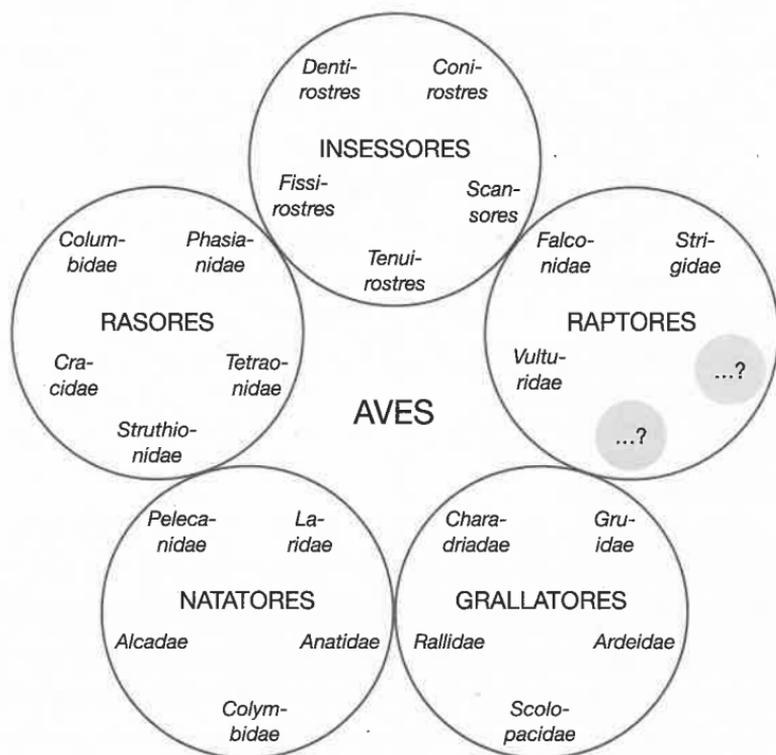

Figure 10.4. The top level of a quinarian classification of birds (Aves) by Nicholas Aylward Vigors. Affinities are found between neighbors within a circle (for example, Conirostres and Scansores in the top circle) and where distinct circles touch (for example, Scansores and Falconidae). In the circle of the Raptores only three positions are filled; this indicated the existence of two undiscovered taxa with appropriate affinities to the Strigidae, Vulturidae, and Gruidae (that is, owls, vultures, and cranes).
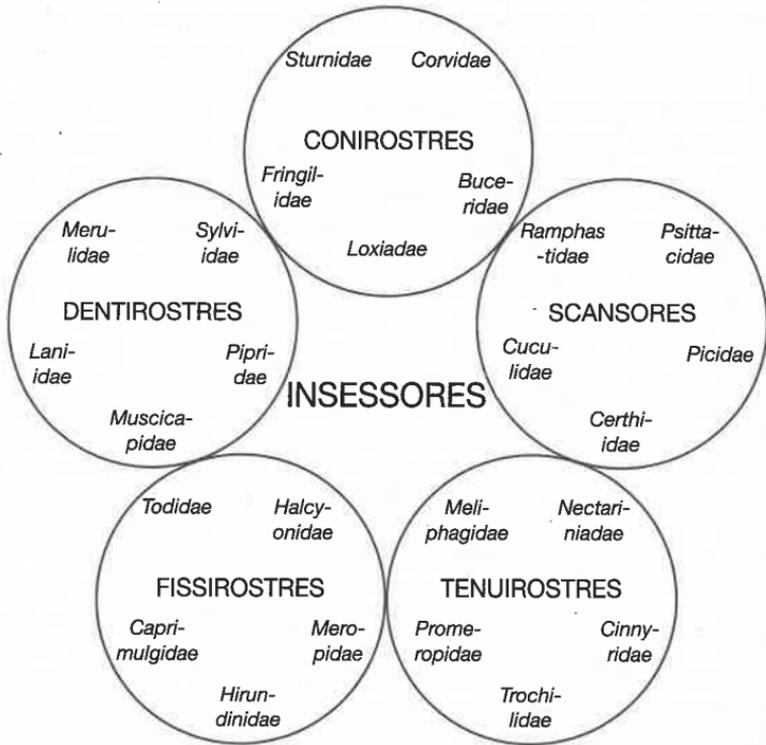
Figure 10.5. Vigors's quinarian classification of the Insessores, the group that appears at the top of the diagram in Figure 10.4. This figure shows the finer, deeper structure of the top circle in that diagram.

A group shared "affinities" with its immediate neighbors inside its circle, making for many important resemblances, and where the circles themselves touched, there were affinities between members of the groups on either side of the meeting point. In cases where a group appeared to contain fewer than five subgroups, such as the Raptores at the upper right of Figure 10.4, quinarians made a bold prediction: new taxa with the corresponding affinities would eventually be found.

The iteration of the quinarian principle creates a fractal-like geometry. Examine, for example, the diagram in Figure 10.5, which shows
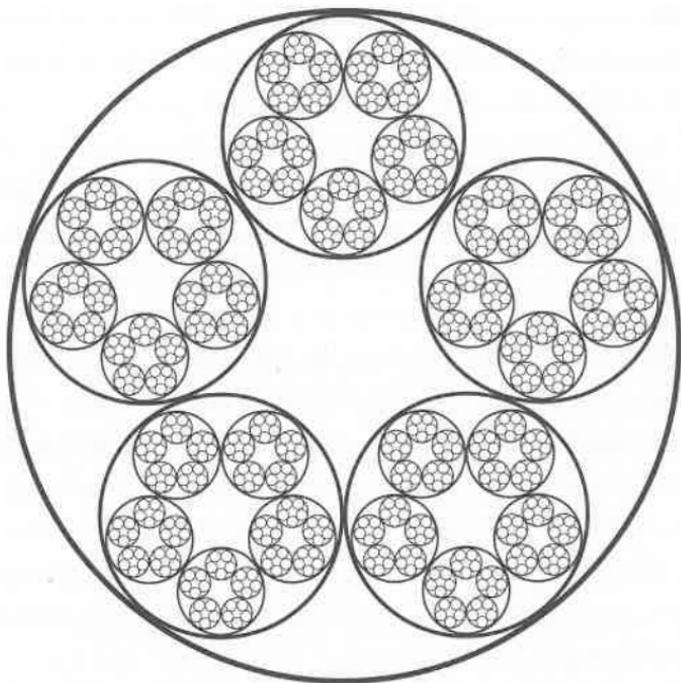
Figure 10.6. The nested structure of the quinarian system, shown schematically. Compare with Figure 10.1.

the Insessores from the top of Figure 10.4 in more detail. Not only do you see the five subgroups shown in the larger-scale figure; you see that each of these subgroups is itself divided into five more subgroups. As a consequence of this five-way nesting, life has the grand design shown in Figure 10.6, reminiscent of Figure 10.1's Sierpinski triangle.

The quinarian geometry and the affinities of neighboring groups were explained by Macleay as the consequence of a kind of branching process that generates life:

Nature appeared to me to have branched out in the animal kingdom . . . in a most beautiful and regular though intricate manner,

that might be compared to those zoophytes which ramify in every direction, but of which the extreme fibers form by their connexion the most delicate circular reticulations.

Zoophytes are plantlike animals, such as corals or sea lilies; Macleay was imagining the quinarian pattern, then, as a cross section through a treelike growth that over and over branched five ways. He did not think of the branching as a historical event; it was rather an abstract mathematical template to which the living world was compelled to conform.

What discloses the existence of Macleay's supposed template, and so reveals a fundamental principle governing the biological world, is the human sense of beauty, drawn ineluctably to the fivefold symmetry that the quinarians discerned in the panoply of life. Is the iron rule, by ignoring the judgments of this aesthetic sense, thereby crippling our powers of discovery?

For a time Macleay's quinarian system was immensely popular in Britain. Many naturalists in the late 1820s and early 1830s looked for the characteristic iterated five-way structure in their own taxonomical bailiwicks. One such follower was the young Charles Darwin, who wrote over 80 pages in his "transmutation notebooks" attempting to reconcile quinarianism with his notion of evolutionary change. The branching structure effected by Darwin's "descent with modification" would naturally give rise to something with the nested, circular aspect of Figure 10.6, as Macleay had observed, but Darwin was stumped by the rigid law of five. Why would branching always take place in five directions, rather than, say, four or six? He made a brave attempt to extract fivehood from the process of environmental adaptation, but eventually gave up, writing in his notes, "Number five in each group absurd."

By then it was the spring of 1838, and quinarianism was fast falling out of favor. A more careful examination of many quinarian efforts at classification showed that the five-way structure was often forced by promoting or demoting groups to levels at which they did not genuinely belong, along with other forms of Procrustean taxonomical violence. Denouncing quinarianism, the influential naturalist Hugh Edwin Strickland urged his colleagues

> to study Nature simply as she exists—to follow her through the wild luxuriance of her ramifications, instead of pruning and distorting the tree of organic affinities into the formal symmetry of a clipped yew-tree.

After Darwin's *On the Origin of Species* was published in 1859, the reason for this "wild luxuriance" became clear: new kinds of organisms evolve not to realize some universal mathematical imperative but to take advantage of local environmental opportunities or to evade local environmental threats. William Whewell's friend, the scientist John Herschel, somewhat derisively called natural selection the "law of higgledy-piggledy." He was right: natural selection's tinkering, its jury-rigging in the face of immediate circumstances, achieves marvelous transformations yet builds what is from the geometrical point of view a rather disorderly, if beguilingly organic, tree of life (Figure 10.7).

The quinarian system was, like Byrhtferth's rule of four, a metaphysical fantasy. It might look also to be a fable with a methodological moral: *Do not be seduced by formal beauty; in natural science, be guided only by observed fact.* Another victory, then, for the rationality of the iron rule and its spurning of aesthetics? For the value of strictly empirical thinking, for eyes trained on the raw data just as it lies and nothing beyond
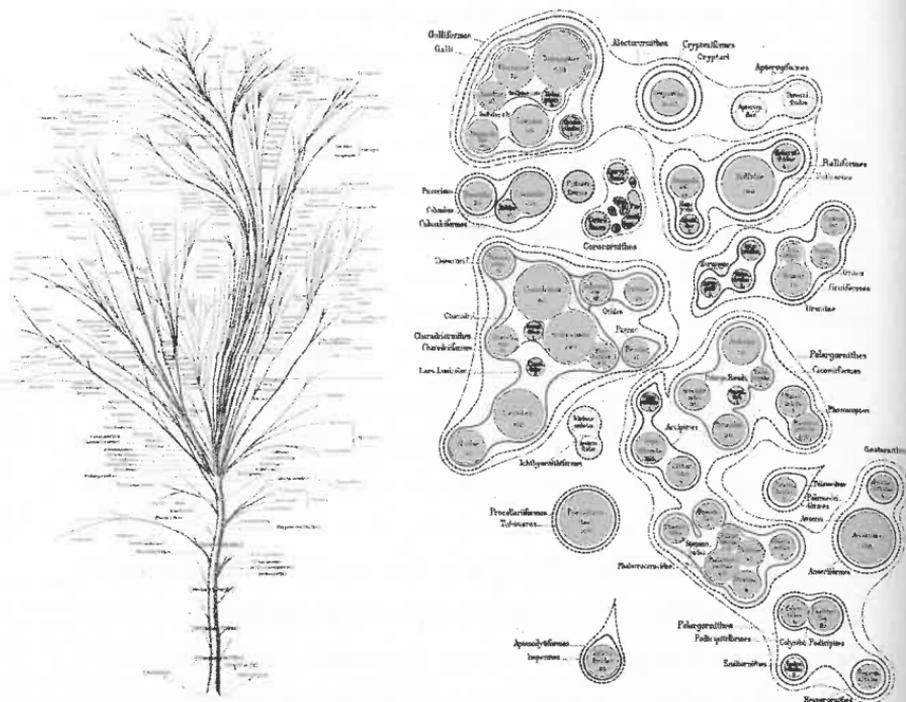
Figure 10.7. The tree of life after Darwin. Max Fürbringer's 1888 classification of birds shows none of the fixed five-way branching characteristic of the quinarian system. On the left, a view of the entire tree; on the right, a cross section whose irregularity can be compared with the symmetry of Figure 10.6.

or above? It is still too soon to reach a conclusion; we have seen only one side of the story. As some tales of success will reveal, there is in fact much to be gained in the study of nature if you keep your eyes open to the right sort of harmony and form.

THE SCOTTISH NATURALIST Sir D'Arcy Wentworth Thompson (1860–1948) laid down this credo:

I know that in the study of material things, number, order and
position are the threefold clue to exact knowledge; that these three,
in the mathematician's hands, furnish the first outlines for a sketch
of the Universe.

"Material things," for Thompson, included plants and animals, all of
which reproduce and grow by way of physical mechanisms. Diverse bio-
logical forms are frequently generated by the same underlying causal
process; in such cases there will be a hidden mathematical unity to be
found in the diversity—so Thompson argued in his 1917 magnum opus
On Growth and Form.

A study of the forms taken by soap bubbles and snowflakes, for
example, revealed the physical basis of the multifarious and intricate
skeletal structures of many kinds of radiolarians, single-celled organ-
isms that make up a large proportion of oceanic plankton. Likewise, the
same physical principles that determine the radial splash pattern made
by a pebble falling into a glass of milk play a role, Thompson wrote, in
the growth of the ring of tentacles that surround the mouths of polyps in
the class Hydrozoa (some of which are the branching "zoophytes" that
inspired the quinarian Macleay).

In his final and most famous chapter, Thompson introduced a
technique of great elegance—an aesthetic power move, as it were—to
uncover profound affinities between apparently distinct animal body
types. The physical form of the fish *Polyprion* can be subjected to simple
geometrical transformations, he showed, that as if by some mathemati-
cal magic turn it into each of three related species (Figure 10.8).

In an even more spectacular demonstration, Thompson used a sim-
ple stretching operation to morph the ordinary looking puffer fish into
the biologically related but physiologically quite dissimilar and rather
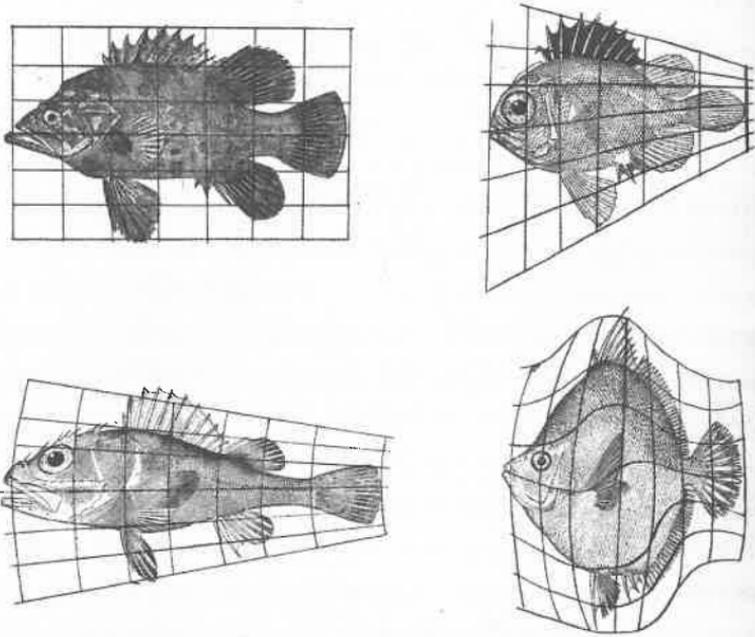exotic sunfish (Figure 10.9). Of this latter case Thompson wrote:

Figure 10.8. *Polyprion* (top left) transformed into three other kinds of fish. The transformations are simple stretchings of the square grid superimposed on *Polyprion*; imagine *Polyprion* drawn on a rubber sheet that is then deformed by being pulled in one or more different places and directions.

It accounts, by one single integral transformation, . . . for the new and striking contour in all its essential details, of rounded body, exaggerated dorsal and ventral fins, and truncated tail.

Thompson proposed that the fish transformations, in their simplicity and beauty, suggested deep truths about development and growth, pointing to a single underlying physical mechanism at work in the related species—not Darwin's natural selection, but a mechanism that is prior to and that can be exploited by natural selection. Indeed, the transformations constituted a "proof" that

a comprehensive "law of growth" has pervaded the whole structure
in its integrity, and that some more or less simple and recognizable
system of forces has been in control.

The same was true, Thompson believed, of the mathematically related
physical forms that he found within groups of crustaceans, crocodiles,
ungulates, and many other animals.

In contrast with his ideas about radiolarians and hydrozoans, he
did not suggest any particular physical mechanism as the foundation
of these laws of growth. His views did, however, enable him to make
specific predictions. He correctly forecast that the human precursors
known at the time—such as *Homo erectus* and the Neanderthals—
would not form a "straight line of descent," but would rather be found
on a complex tree of which humans were just a single branch (albeit
the only branch still existing). He determined the likely form of tran-
sitional fossils linking one of the first birds, *Archaeopteryx*, with a later
descendant, and he was able to use his mathematical methods to pre-
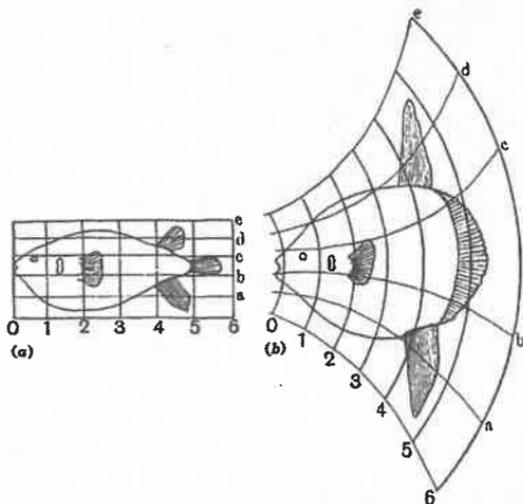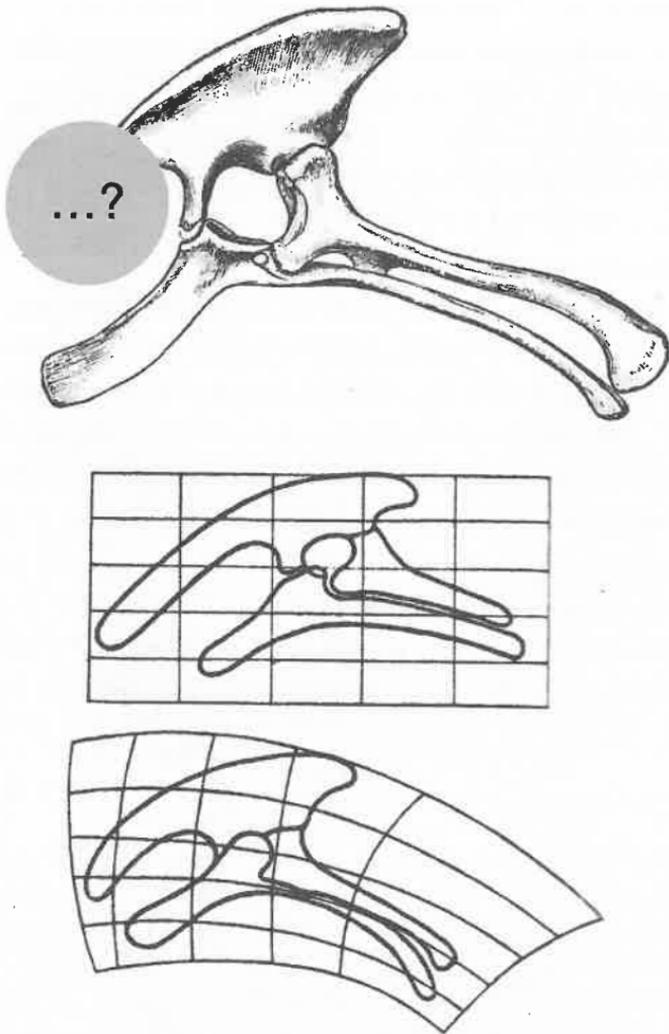

Figure 10.9. The puffer fish (left) transformed into a sunfish (right).

dict the shape of a missing part of the dinosaur *Camptosaurus*'s ilium bone (the upper pelvis) by extrapolating, using one of his mathematical transformations, from the known form of the dinosaur *Stegosaurus*'s ilium (Figure 10.10).

Figure 10.10. The reconstruction of the *Camptosaurus dispar* ilium bone. *Top left*: the fossilized ilium bone analyzed by O. C. Marsh, missing its front part. *Top right*: Marsh's reconstruction, in which the bone receives a sharp, toothy completion. *Bottom left*: Thompson's reconstruction (lower grid), based on a mathematical transformation of the same bone in *Stegosaurus* (upper grid). *Bottom right*: a more complete *Camptosaurus dispar* ilium, showing the superiority of Thompson's reconstruction to Marsh's.

We now know that the laws of growth are not, as Thompson supposed, simple physical principles, but are rather consequences of the convoluted mechanisms of developmental genetics. Even within this modern framework, however, Thompson's transformations are consid-

ered by many biologists to be part of the solution to one of the greatest explanatory puzzles raised by the evolution of complex life.

How does a body plan as unusual as that of the sunfish (Figure 10.9) evolve? This much we know. Beginning with an ancestor looking not unlike the puffer fish, natural selection must have adjusted many large-scale traits at the same time to achieve the sunfish's distinctive physique (and size—mature sunfish can weigh up to 2½ tons). If each of those traits were determined by a separate set of genes, such a coordinated adjustment would be extremely difficult, if not impossible: since natural selection acts on chance variations, it would have to wait for a happy coincidence of many independent mutations to produce even a single step along the way to the final product.

Thompson's discoveries suggest a more satisfying story, according to which strikingly different physiological layouts, such as the body plans of the puffer fish and the sunfish, are the consequence of small genetic differences that, in effect, control the knobs on the control panel of growth, imposing a "fun house mirror" effect on the finished product. Just one or a few mutations, then, might be sufficient to turn the dial ever so slightly toward the "sunfish" setting. A series of such events, in an environment that favors the sunfish way of life, provides a path to the evolution of these huge, strange creatures that is not so difficult for natural selection to follow.

More generally, the capacity to effect radical physiological change through minor genetic tweaks enables natural selection to easily explore numerous alternatives to a species' standard body plan, alternatives that are often weird yet occasionally highly advantageous. Had the capacity not existed, many evolutionary developmental biologists believe, complex life-forms could not have evolved. The earth would have had to rest content with its radiolarians and its polyps or perhaps something simpler still.

Thompson's insights were built, as he was proud to acknowledge, on his high regard for beauty and form. Cultivated in the right way and

in the right place, then, a concern for mathematical simplicity and elegance is after all quite capable of illuminating the higgledy-piggledy world of biology.

Score one for beauty. To tip the argument decisively toward the truth-finding power of the aesthetic sense, however—and therefore to firmly establish the irrationality of the iron rule's scorn for beauty, the logical ugliness that made modern science so difficult to embrace—we should look to physics.

"IT IS MORE IMPORTANT to have beauty in one's equations than to have them fit experiment," wrote the English theoretical physicist Paul Dirac—the beauty being a sign that the theory was on the right track and that the discrepancy with experiment was likely "due to minor features . . . that will get cleared up with further developments." Beauty is the beacon; truth is what it marks. Einstein, according to the physicist Eugene Wigner, thought along the same lines: "The only physical theories which we are willing to accept are the beautiful ones." You needn't look far to find similar sentiments behind many doors in the corridors of theoretical physics or in the popular writing of physicists such as Subrahmanyan Chandrasekhar, David Deutsch, and Frank Wilczek.

The historical record suggests that they are onto something important. Newton's sense of beauty, it is clear, not only drew him to the mysteries of the *prisca sapientia*, the ancient knowledge, but also pointed him to the simple mathematics that lay behind the curves traced by cannonballs, planets, and comets, thereby unveiling the secrets of universal gravitation. Before him, Copernicus and Galileo were among science's beautiful thinkers, and after him, many more were to come. Indeed, there are too many cases of successful aesthetic reasoning in the annals of the physical sciences to list even in passing, so I will confine myself to a single momentous episode from the recent history of particle physics.

That will cement the case in favor of beauty and therefore against the rationality of the iron rule.

The story begins in 1931, when James Chadwick confirmed the existence of the neutron. With that discovery, the nature of the basic building blocks of matter seemed to have been settled. Atoms were made of central clusters of protons and neutrons surrounded by electrons, and electromagnetic radiation was made of photons, adding up to four fundamental particles in all. Byrhtferth the monk would have been gratified to see the rule of four making a smooth transition from ancient and medieval metaphysics to twentieth-century physics.

Or not entirely smooth: there were two additional particles that had been hypothesized but not yet seen: the pion, whose busywork was supposed to help keep the atomic nucleus together, and the neutrino, a small and mysterious particle emitted during a certain kind of radioactive decay. Still, even Aristotle had added a fifth element—the quintessence, of which he supposed the heavenly bodies were made—so why not six?

Had only the count stopped there. In the 1930s and 1940s, particle physicists headed for the alpine peaks of the Americas and Europe. Their aim was to get as close as possible to high-energy radiation pummeling the earth's upper atmosphere from unknown sources in outer space, so-called cosmic rays. There a bewildering spectacle lay in wait. When cosmic rays collided with air molecules, they created things that no one had ever seen before: entirely new particles, such as the muon, the kaon, and the mysterious lambda.

Then, with the development of sophisticated particle accelerators, such as the Cosmotron at Brookhaven National Laboratory, 60 miles east of New York City, the mountains became superfluous: weird particles could be generated in the outer suburbs of Long Island. Meanwhile, ever more sensitive detectors—notably, the bubble chamber invented in 1952 by Donald Glaser—made them easier to see. And new kinds kept

appearing: the xi, the sigma, the delta, new kinds of pion and kaon, the eta meson. . . .

The variety was as dazzling as it was disconcerting, more reminiscent of the exuberance of a tropical rainforest than of the supposed bedrock of the universe. It was as though the biological law of higgledy-piggledy went all the way down—making for, as Robert Oppenheimer put it, a veritable "zoo" of particles. Would a bill of lading for the fundamental units of reality turn out to look more like a modern biological taxonomy—like the tree of birds shown in Figure 10.7—than like Byrhtferth's realization of the power of four? Or would someone find hidden order and simplicity in the zoo?

Murray Gell-Mann grew up in straitened circumstances in New York City, the child of immigrants from Eastern Europe who never quite secured their hold on the American dream. He was early on declared to be a prodigy, skipping grade after grade at school and entering Yale as an undergraduate at the age of 15. It was 1944, and much of the Yale campus had been co-opted for military training. Archaeology and linguistics were Gell-Mann's principal interests at the time, but his difficult and demanding father insisted he study something practical—if not engineering, then at least physics. As everyone around him was absorbed into the armed forces, the 15-year-old immersed himself in the subtle harmonies of the natural world.

A constellation of far-reaching discoveries lay waiting: thanks to his eye for underlying beauty, Gell-Mann would become one of the most important physicists of the twentieth century. He earned his doctoral degree in 1951, even as the gates of the particle zoo were swinging open and subjecting physicists to a stampede of new and peculiar forms of matter. Soon after, he conceived of a novel property of matter that he called "strangeness." Just as a particle can have a certain electric charge, it can have a certain quantity of strangeness, positive or negative. Pro-

tons and neutrons have no strangeness at all—or more exactly, they have a "strangeness number" of 0. But some of the new particles, beginning with the lambda, were truly strange. (The "strangeness number" of the lambda particle is -1.) When particles collide or decay, turning into other particles, strangeness is "approximately conserved": the sum of their strangeness numbers has a strong tendency to remain the same, before and after, as though any collection of matter contains a fixed quantity of strangeness that can easily be moved around but increased or decreased only with the greatest effort.

The postulation of strangeness brought some discipline to the zoo in the shape of a formula linking particles' strangeness to their electric charge and some of their other known properties. It also explained the mysteriously long time that it took the lambda particle to decay: it turned out that the decay can't happen without changing the amount of strangeness in the world. That doesn't prevent it, but it does throw on the brakes, allowing the lambda to linger for a few extra fractions of a nanosecond before disintegration.

Strangeness was just the first of Gell-Mann's insights into the structure of matter. In 1961, he published a geometrical organization of the hadrons, a class of particles that includes protons and neutrons and most of the other particles in the zoo. This scheme arranged the hadrons into several different groups according to what Gell-Mann called the "eightfold way."

You can think of the eightfold way as organizing a given set of eight particles—an "octet"—into a table, with rows corresponding to the particles' strangeness number and columns corresponding to their electric charge (Figure 10.11). There is a profound symmetry to octets that cannot be captured in such a figure—for that you need many more than two spatial dimensions—but which is mathematically encoded in what is called the SU(3) symmetry group. Suffice it to say that these arrangements of particles carried, in the eyes of Gell-Mann and other theoret-

ical physicists, a kind of formal beauty, a mathematical rightness, that is fully the equal of the order on display in the quinarian system or in Byrhtferth's diagram.

Gell-Mann went on within a couple of years to reason that his octets, together with a "decuplet" of 10 more exotic particles, pointed to a deeper organizing principle in nature. In the same way that the complicated structure of Byrhtferth's diagram is generated by a quartet— hot, dry, moist, and cold—and the quinarians' structures are generated by an iterated fivefold symmetry, so the octets and decuplets were, to those with mathematical eyes to see their SU(3) symmetry, generated by
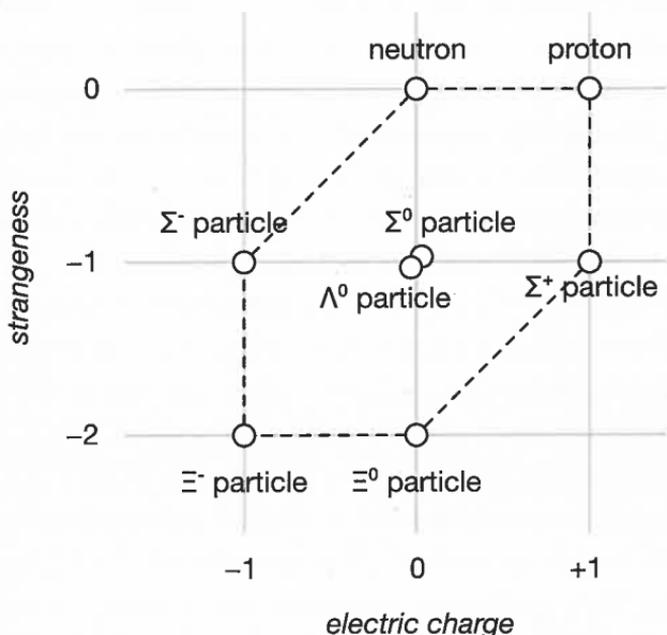

Figure 10.11. The Gell-Mann octet containing the proton and the neutron. Rows share the same value for strangeness; columns share the same value for charge. At the center is the lambda particle, labeled Λ^0.

a principle of three, a triplet called the "fundamental representation" of SU(3). Gell-Mann seized on this three-ness, hypothesizing that all the particles in his octets and decuplets were built from more fundamental particles, the quarks, of which there were three kinds: up, down, and strange (along with their "antiparticles"). A proton, for example, is made of two "up" quarks and a "down" quark, while a positive pion is made of one up quark and one down antiquark. The once sui generis lambda particle turns out to be nothing more than a coalition of an up quark, a down quark, and (of course) a strange quark.

The pursuit of beauty had led to truth: almost all contemporary scientists accept the reality of quarks (of which it now turns out there are six: Gell-Mann's three and then three more far larger ones). In 1961, however, Gell-Mann could not argue for the eightfold way on the basis of its charismatic symmetry, its gratification of the aesthetic sense. Hard evidence was needed. A part of that evidence was the theory's ability to explain the observed properties of the numerous particles known to belong to the zoo; far more glorious still would be a novel prediction subsequently vindicated by observation. From the empirical as opposed the aesthetic point of view, that would be the mark of truth.

In July 1962, at a conference at CERN, in Switzerland, the discoveries of two new xi particles were announced: the Ξ^{*-} and the Ξ^{*0}. Gell-Mann, sitting in the audience that day, realized that the new particles, along with 7 that were previously known, would fill all but a single space in a potential decuplet of 10 particles, shown in Figure 10.12. Like the quinarians positing additional families of Raptores to complete their elegant five-way taxonomic circles (Figure 10.4) or D'Arcy Thompson inferring the structure of the missing part of the *Camptosaurus* hip bone to preserve the simplicity and continuity of his geometrical transformations (Figure 10.10), Gell-Mann reasoned that this additional particle must exist in order to uphold the beauty of the eightfold way. During a discussion period, he sauntered to the chalkboard, drew the decuplet

with its suggestive gap, and then filled the gap by boldly predicting the existence of a new particle with a certain charge, strangeness, and mass, the omega-minus—so-called because omega, the last letter of the Greek alphabet, signaled the structure's consummation.

The missing particle turned up on Long Island in 1964, thrust into existence by the Alternating Gradient Synchrotron and observed in a big new bubble chamber at the Brookhaven National Lab. It was exactly what the iron rule demanded: an empirical test. Gell-Mann had predicted the omega-minus, and sure enough it—or rather its distinctive bubble-chamber signature, shown in Figure 10.13—had been observed. Murray Gell-Mann had secured his Nobel Prize.
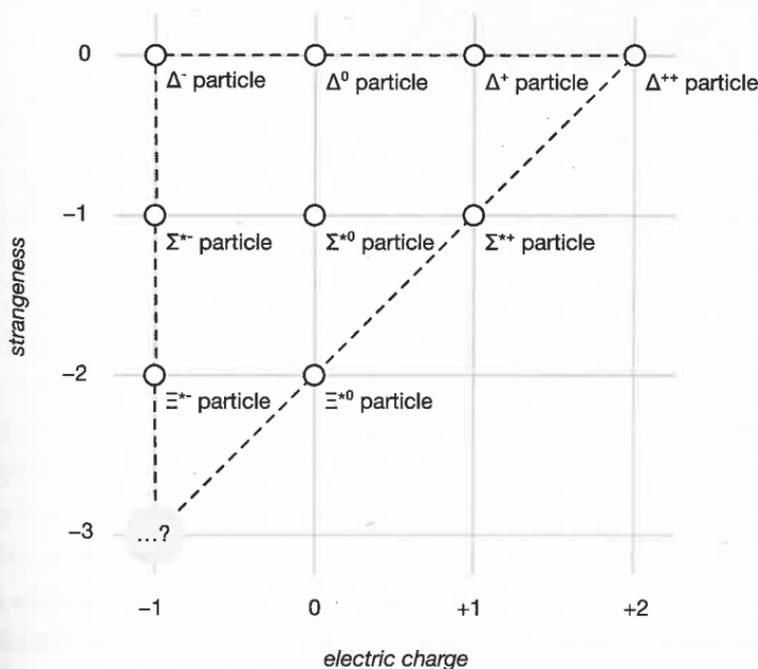

Figure 10.12. A decuplet that would be completed by a particle filling the gray zone at the bottom left, that is, a negatively charged particle with a strangeness number of –3. Gell-Mann predicted the existence of such a particle: the omega-minus.
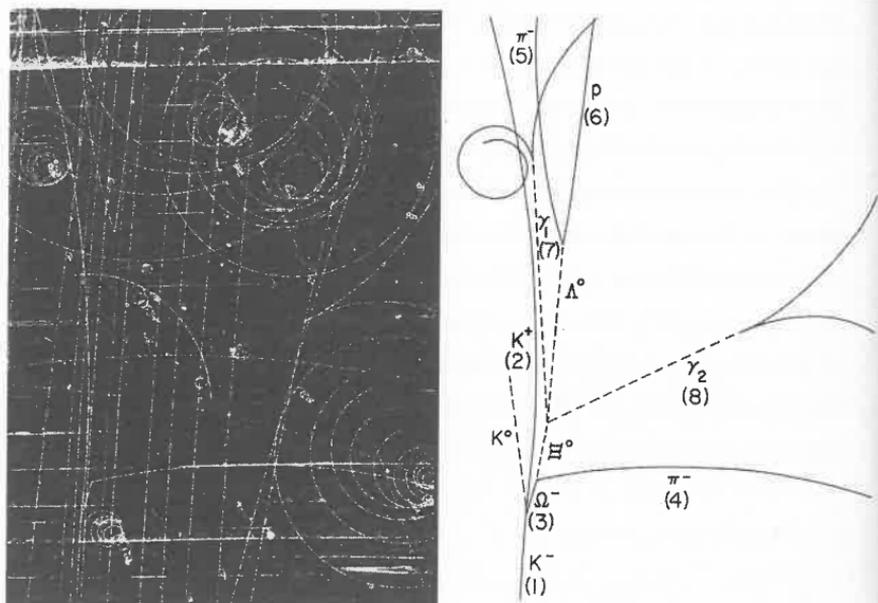
Figure 10.13. What counts in scientific argument: the telltale signature of the omega-minus particle. On the left is a photograph of the bubble-chamber tracks recording the trajectories of various particles created by the collision of a proton with a kaon. Only electrically charged particles show up in a bubble chamber; neutral particles are invisible and so their trajectories must be inferred. On the right is a schematic of the crucial elements of the image (with the inferred trajectories of neutral particles shown as dashed lines). The kaon (K⁻, numbered 1 in the schematic) enters at the bottom. The omega-minus itself (Ω^-, numbered 3) exists only for a short time before decaying into an inferred xi particle (Ξ^0) and a negative pion (π^-, numbered 4).

I want to direct your attention past this glorious pageant of discovery to something rather peculiar going on in the background. On a number of occasions, Gell-Mann declared his allegiance to the Platonic precept that truth and beauty are entangled, saying in an informal talk, for example, that beauty, simplicity, and elegance are "a chief criterion for the selection of the correct hypothesis." Yet he made no appeal to

this criterion in his official publications on the eightfold way. Nor do his physicist colleagues. Flip through the pages of the journals *Physical Review* or *Physics Letters*; you will find no invocations of beauty, no arguments grounded on a theory's grace or charm, though the authors might covertly hope that readers' tastes will resonate with their own. The reason is the iron rule's edict that only empirical testing counts.

The cosmologist Brian Greene sums up this consequence of the iron rule's tunnel vision succinctly in his book *The Elegant Universe*. Although physicists "make choices and exercise judgments about the research direction in which to take [a] partially completed theory" that are sometimes "founded upon an aesthetic sense—a sense of which theories have an elegance and beauty of structure on par with the world we experience," nevertheless,

> aesthetic judgments do not arbitrate scientific discourse. Ultimately, theories are judged by how they fare when faced with . . . hard experimental facts.

That is an acute characterization of an elegance-loving scientist's awkward existence under the iron rule: in your private thinking, let a theory's grace and beauty convince you of its truth, but say nothing whatsoever of these qualities when you go to persuade others. Like Whewell, deprived of his right to reason theologically in his scientific work, the aestheticizing scientist cannot publicly—or at least cannot officially— call on their most cherished springs of insight.

DOES IT MAKE SENSE? From a practical point of view, certainly: the injunction against aesthetic disputation forces all scientists, no matter how enamored with beauty, to put their energy if not their passion into the prediction and generation of empirical detail. But does scien-

tific argument conducted according to such a precept respect the rules of logic? Not if it constitutes a categorical rejection of useful information. The question, then, is how valuable, on balance, aesthetic considerations tend to be.

To reckon the score, look at the history. On the one hand, the idea that the microcosm mirrors the macrocosm was a thesis that went nowhere. It was not a ludicrous notion: for all that anyone knew in 1600, God might have taken great pleasure in recapitulating his creation according to the same plan at every scale. Newton cannot be criticized for hedging his bets between experimentation and interpretation. But in the end, the beauty of fractals aside, there turned out to be meager profit in searching for profound parallels between the great and the small. The same is true for the Pythagorean approach of the quinarians. In the wake of Darwin, it became clear that there would be no universal formal structure in the organization of species, but only Herschel's law of higgledy-piggledy.

On the other hand, there are the successes: D'Arcy Thompson's mathematical transformations of body type, Gell-Mann's eightfold way and his system of quarks, and before them, a string of insights in mathematical physics, chemistry, and other sciences. The failures are on an epic scale, yet the successes are too important, too frequent, and too dazzling to ignore.

Scientific inquiry should therefore take an open-minded attitude toward aesthetic considerations. It should permit beauty in all its forms to provide guidance in concert with the observable facts. As more is learned, a scorebook should be maintained, ranking different styles of aesthetic thinking according to their successes and failures in the various domains of scientific inquiry. Striking symmetries, it might emerge, are tremendously important in fundamental physics, sometimes revelatory in physiology, but almost worthless in biological taxonomy. A fixation on simple arithmetic—as manifested in the ancient law of four depicted

in Byrhtferth's diagram or the law of five underlying the quinarian system—might turn out to be useless everywhere. The creator of the universe, it seems, is not that sort of mathematician. With time, science could learn to distinguish the dangerously grandiose numerology of the quinarian system and its like from the subtle and fruitful attention to order and symmetry that brought us the theory of quarks.

The iron rule does not take this reasonable path. It is painfully simple-minded, uninterested in making sophisticated distinctions; it shuts down aesthetic deliberation altogether, rejecting the good along with the bad.

Suppose you are handed an envelope. You know that it is more than likely to contain information that is valuable, even crucial, to realizing your goals. Surely you open it? When the envelope is packed with aesthetic guidance, the iron rule throws it away. That is illogical, unreasonable, irrational.

A SCIENTIFIC RATIONALIST like Popper might regard the iron rule, with its exaltation of empirical testing, as a gleaming instrument of reason, paring away meddlesome theology, feckless philosophy, and a sentimental weakness for beauty—not painlessly, perhaps, but with an inexorable logic that no one could justly resist. I have said by contrast that the rule's ham-fisted surgery violates the principles of rationality. Some of what it removes we are well to be rid of, but it goes too far, and goes too far in an especially simplistic and thoughtless way: it imposes a wholesale prohibition on all forms of nonempirical thinking, no matter how judicious, no matter what their track record, no matter how well they synergize with empirical observation. The iron rule takes to human thought not with a logical scalpel but with a cleaver.

The progress enabled by this butchery cannot be denied. The iron rule may impose irrationality on scientific argument, but it is a strategically brilliant irrationality, manipulating its human subjects into the

vehement engagement with empirical detail that makes modern science so formidable a knowledge-making machine.

The first time I read Kuhn's *Structure of Scientific Revolutions*, I paid too much attention to the titular revolutions and missed what in the book was truly revolutionary: the suggestion that science, humanity's supreme rational achievement, is driven by a kind of narrowness or blindness. It was during my second reading—on a train somewhere between Philadelphia and New York City, I still remember—that I looked out the coach window and saw the book in an entirely new way.

Kuhn was wrong about paradigms. Scientists' private thinking is not locked down, not limited, in the manner he supposes. What is severely limited is scientists' official speech—deprived of philosophy, religion, and beauty—and those limits, irrationally narrow in their own way, have the same ultimate effect that Kuhn attributed to the paradigm: to launch a fiercer, more tenacious, and more exacting search of the space of possible explanations than would have been attainable, given the foibles of our psychology, by any other means. That is, all in one, a fabulous paradox, a lesson in humility, and a reminder that humans are very interesting people.

An apparently impenetrable logical barrier once stood between those people and modern science. The iron rule, science's first commandment, looked perverse; perceiving its perversity, if they considered it at all, knowledge seekers had no reason to put it into practice; not seeing it at work, they could have no notion of its power. If the human race was going to get its vaccines, its electric motors, its wireless communicators—the wellsprings of health, the armatures of industry, the filaments of human connectivity—something out of the ordinary had to shatter the barrier. Newton's unusual psyche, his instinctive urge to compartmentalize, was the right kind of eccentricity. But he could not have broken through on his own; there is a larger story to tell about a sudden change of hearts and minds in seventeenth-century Western Europe.