ROBERT AND MICHÈLE
ROOT-BERNSTEIN

SPARKS OF GENIUS

The Thirteen Thinking Tools of the World's Most Creative People

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Invention presupposes imagination but should not be confused with it. For the act of invention implies the necessity of a lucky find and of achieving full realization of this find. What we imagine does not necessarily take on a concrete form and may remain in a state of virtuality, whereas invention is not conceivable apart from its actually being worked out.

Thus, what concerns us here is not imagination in itself, but rather creative imagination: the faculty that helps us pass from the level of conception to the level of realization.

— Igor Stravinsky, *The Poetics of Music*

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Rethinking Thinking

EVERYONE THINKS. But not everyone thinks equally well. For real intellectual feasts we depend on master chefs who have learned to mix and blend and savor an entire range of mental ingredients. It's not that what they do in the kitchen is any different from what we do, they just do it better. We like to suppose master chefs were born that way, yet even the most promising individuals spend years in training. It follows that we, too, can learn the tools of the trade and thereby improve our own mental cooking. This process, however, requires us to rethink what gourmet intellection is all about. And rethinking shifts our educational focus from *what* to think to *how* to think in the most productive ways possible.

Our tour of mental cookery begins in the kitchen of the mind, where ideas are marinated, stewed, braised, beaten, baked, and whipped into shape. Just as real chefs surprise us by throwing in a pinch of this and a handful of something else, the kitchens of the creative imagination are full of unexpected practices. Great ideas arise in the strangest ways and are blended from the oddest ingredients.What goes into the recipes often bears no resemblance to the finished dish. Sometimes the master mental chef can't even explain how she knows that her dish will be tasty. She just has a gut feeling that this imagined mixture of ingredients will yield a delicious surprise.

Gut feelings don't make obvious sense. Consider, for example, the experience of young Barbara McClintock, who would later earn a Nobel Prize in genetics. One day in 1930 she stood with a group of scientists in the cornfields around Cornell University, pondering the results of a genetics experiment. The researchers had expected that half of the corn would produce sterile pollen, but less than a third of it actually had. The difference was significant, and McClintock was so disturbed that she left the cornfield and climbed the hill to her laboratory, where she could sit alone and think.

Half an hour later, she "jumped up and ran down to the field. At the top of the field (everyone else was down at the bottom) I shouted, 'Eureka, I have it! I have the answer! I know what this 30 percent sterility is.' " Her colleagues naturally said, "Prove it." Then she found she had no idea how to explain her insight. Many decades later, McClintock said, "When you suddenly see the problem, something happens that you have the answer — before you are able to put it into words. It is all done subconsciously. This has happened many times to me, and I know when to take it seriously. I'm so absolutely sure. I don't talk about it, I don't have to tell anybody about it, I'm just *sure* this is it."

This feeling of knowing without being able to say how one knows is common. The French philosopher and mathematician Blaise Pascal is famous for his aphorism "The heart has its reasons that reason cannot know." The great nineteenth-century mathematician Carl Friedrich Gauss admitted that intuition often led him to ideas he could not immediately prove. "I have had my results for a long time; but I do not yet know how I am to arrive at them." Claude Bernard, the founder of modern physiology, wrote that everything purposeful in scientific thinking began with feeling. "Feeling alone," he wrote, "guides the mind." Painter Pablo Picasso confessed to a friend, "I don't know in advance what I am going to put on canvas any more than I decide beforehand what colors I am going to use. . . . Each time I undertake to paint a picture I have a sensation of leaping into space. I never know whether I shall fall on my feet. It is only later that I begin to estimate more exactly the effect of my work." Composer Igor Stravinsky also found that imaginative activity began with some inexplicable appetite, some "intuitive grasp of an unknown entity already possessed but not yet intelligible." The Latin American novelist Isabel Allende has described a similarly vague sense propelling her work: "Somehow inside me — I can say this after having written five books — I know that I know where I am going. I know that I know the end of the book even though I don't know it. It's so difficult to explain."

Knowing in such ambiguous, inarticulate ways raises an important question. McClintock put it this way: "It had all been done fast. The answer came, and I'd run. Now I worked it out step by step — it was an intricate series of steps — and I came out with what it was. . . . It worked out exactly as I'd diagrammed it. Now, why did I know, without having done a thing on paper? Why was I so sure that I could tell them with such excitement and just say, 'Eureka, I solved it'?" McClintock's query strikes at the heart of understanding creative thinking, as do the experiences of Picasso and Gauss, of composers and physiologists. Where *do* sudden illuminations or insights come from? How can we know things that we cannot yet say, draw, or write? How do gut feelings and intuitions function in imaginative thinking? How do we translate from feeling to word, emotion to number? Lastly, can we understand this creative imagination and, understanding it, can we exercise, train, and educate it?

Philosophers and psychologists have pondered these and related questions for hundreds of years. Neurobiologists have sought the answers in the structures of the brain and the connections between nerve synapses. Full answers still elude us. But one source of insight into creative thinking has been greatly undervalued and underused: the reports of eminent thinkers, creators, and inventors themselves. Their introspective reports cannot answer all our questions about thinking, but they certainly provide important and surprising new avenues to explore. Above all, they tell us that conventional notions of thinking are at best incomplete, for they leave out nonlogical forms of thinking that can't be verbalized.

Take the testimony of physicist Albert Einstein, for instance. Most people would expect Einstein to have described himself as solving his physics problems using mathematical formulas, numbers, complex theories, and logic. In fact, a recent book by Harvard psychologist Howard Gardner, *Creating Minds,* portrays Einstein as the epitome of the "logico-mathematical mind." His peers, however, knew that Einstein was relatively weak in mathematics, often needing to collaborate with mathematicians to push his work forward. In fact, Einstein wrote to one correspondent, "Do not worry about your difficulties in mathematics. I can assure you that mine are still greater."

Einstein's mental strengths were quite different, as he revealed to his colleague Jacques Hadamard. "The words of the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be 'voluntarily' reproduced and combined. . . . The above mentioned elements are, in my case, of visual and some of muscular type." In a kind of thought experiment that could not be articulated, he pretended to be a photon moving at the speed of light, imagining what he saw and how he felt. Then he became a second photon and tried to imagine what he could experience of the first one. As Einstein explained to Max Wertheimer, a psychologist, he only vaguely understood where his visual and muscular thinking would take him. His "feeling of direction," he said, was "very hard to express."

McClintock, for her part, talked about developing a "feeling for the organism" quite like Einstein's feeling for a beam of light. She got to know every one of her corn plants so intimately that when she studied their chromosomes, she could truly identify *with* them: "I found that the more I worked with them the bigger and bigger [they] got, and when I was really working with them I wasn't outside, I was down there. I was part of the system. I even was able to see the internal parts of the chromosomes — actually everything was there. It surprised me because I actually felt as if I were right down there and these were my friends. . . . As you look at these things, they become part of you. And you forget yourself. The main thing about it is you forget yourself." A similar emotional involvement played a critical role in the prelogical scientific thinking of Claude Bernard, who wrote, "Just as in other human activities, feeling releases an act by putting forth the idea which gives a motive to action." For Wolfgang Pauli, a mathematical physicist, emotional response functioned in the place of ideas that had not yet been articulated. Within the "unconscious region of the human soul," he wrote, "the place of clear concepts is taken by images of powerful emotional content, which are not thought, but are seen pictorially, as it were, before the mind's eye."

Some scientists insist that thinking in feelings and mental images can be rationally manipulated. Einstein suggested "a certain connection" between "the psychical entities which seem to serve as elements in thought" and "relevant logical concepts." Mathematician Stanislaw Ulam made the argument even more strongly. He experienced abstract mathematical notions in *visual terms,* so the idea of "'an infinity of spheres or an infinity of sets'" became "a picture with such almost real objects, getting smaller, vanishing on some horizon." Such thinking is "not in terms of words or syllogisms or signs" but in terms of some "visual algorithm" having a "sort of meta- or super-logic with its own rules." For William Lipscomb, a Nobel laureate in chemistry and, not incidentally, a fine musician, this kind of thinking is a synthetic and aesthetic experience. In his research into the chemistry of boron he found himself thinking not only inductively and deductively but also intuitively. "I felt a focusing of intellect and emotions which was surely an aesthetic response," he wrote. "It was followed by a flood of predictions coming from my mind as if I were a bystander watching it happen. Only later was I able to begin to formulate a systematic theory of structure, bonding and reactions for these unusual molecules. . . . Was it science? Our later tests showed it was. But the processes that I used and the responses that I felt were more like those of an artist." Gut feelings, emotions, and imaginative images do make sense in science, but, like the meaning of a dance or a musical theme, that sense is felt rather than defined.

"Intuition or mathematics?" asks inventor and science fiction writer Arthur C. Clarke. "Do we use models to help us find the truth? Or do we know the truth first, and then develop the mathematics to explain it?" There is no doubt about the answer: gut feelings and intuitions, an "essential feature in productive thought," as Einstein put it, occur well before their meaning can be expressed in words or numbers. In his own work, mathematics and formal logic were *secondary* steps: "Conventional words or other signs [presumably mathematical ones] have to be sought for laboriously only in a secondary stage, when the associative play already referred to is sufficiently established and can be reproduced at will." To Wertheimer he explained, "No really productive man thinks in such a paper fashion. The way the two triple sets of axioms are contrasted in [Einstein's physics book with collaborator Leopold Infeld] is not at all the way things happened in the process of actual thinking. This was merely a later formulation of the subject matter, just a question of how the thing could best be written . . . but in this process they [the ideas] did not grow out of any manipulation of axioms." As he told Infeld, "No scientist thinks in formulae."

Scientists may not think in mathematical terms, but the need to express intuitive insight in a form comprehensible to others compels them, in McClintock's words, to "work with so-called scientific methods to put it into their frame *after* you know." Other scientists confirm the two-part process of intuitive, imaginative understanding followed, necessarily, by logical expression. Metallurgist Cyril Stanley Smith of the Massachusetts Institute of Technology (MIT) has said, "The stage of discovery was entirely sensual and mathematics was only necessary to be able to communicate with other people." Werner Heisenberg, who formulated the uncertainty principle, wrote that "mathematics . . . played only a subordinate, secondary role" in the revolution in physics he helped to create. "Mathematics is the form in which we express our understanding of nature; but it is not the content of that understanding." Nobel Prize–winning physicist Richard Feynman, who also saw and felt things intuitively, noted, "In certain problems that I have done, it was necessary to continue the development of the picture as the method, before the mathematics could really be done."

So much for the myth that scientists *think* more logically than others. To think creatively is first to feel. The desire to understand must be whipped together with sensual and emotional feelings and blended with intellect to yield imaginative insight. Indeed, the intimate connections between thinking, emotions, and feelings are the subject of a startling book called *Descartes' Error* (1994), which revisits the famous philosopher's separation of mind (and thinking) from body (and being or feeling) more than three hundred years ago. The author, neurologist Antonio Damasio, finds that neurological patients whose emotional affect is grossly altered due to strokes, accidents, or tumors lose the ability to make rational plans. Because they are unable to become emotionally involved in their decisions, they fail to make good ones. Our feelings — our intuitions — are not impediments to rational thinking, they form its origin and bases. For Damasio, body and mind, emotion and intellect are inseparable. We agree. Not only do scientists feel their way toward logical ideas, but creative thinking and expression in every discipline are born of intuition and emotion.

For many people this may come as something of a surprise. Cognitive scientists such as Herb Simon and Noam Chomsky define thinking only as the logical procedures of induction and deduction or the rules of linguistics. Even Howard Gardner, who promotes the notion of more diverse ways of thinking in *Creating Minds* and *Frames of Mind,* argues that the thinking of creative people is best categorized by the one mode in which they express themselves. For Gardner and his colleagues, scientists such as Einstein, McClintock, and Feynman are logico-mathematical thinkers; poets and writers are characterized as highly verbal thinkers; dancers as kinesthetic thinkers; artists as mainly visual thinkers; psychologists as intrapersonal thinkers; and politicians as interpersonal thinkers. All of these characterizations seem to make sense, just as it seems to make sense that a baker will use yeast to make bread. But soda breads and flat breads are made without yeast, and yeast can be used to make many other foods, including beer and Grape-Nuts cereal. No single ingredient determines the outcome of a recipe, either in cooking or thinking. Characterizing individuals by a single element in their mental processes is as misleading as describing Einstein as — primarily — a logico-mathematical thinker.

Artists, for example, draw only partially upon visual stimuli. Emotions, kinesthetic feelings, philosophy, life itself, are other sources of artistic ideas. Painter Susan Rothenberg describes her process of painting as "really visceral. . . . I'm very aware of my body in space — shoulders, frontal positions. I have a body language that is difficult to explain. A lot of my work is about body orientation, both in the making of the work and in the sensing of space, comparing it to my own physical orientation." Sculptor Anne Truitt also feels her art in her body. In describing her apprenticeship, she writes:

> It was not my eyes or my mind that learned. It was my body. I fell in love with the process of art, and I've never fallen out of it. I even loved the discomforts. At first my arms ached and trembled for an hour or so after carving stone; I remember sitting on the bus on the way home and feeling them shake uncontrollably. My blouse size increased by one as my shoulders broadened with muscle. My whole center of gravity changed. I learned to move from a center of strength and balance just below my navel. From this place, I could lift stones and I could touch the surface of clay as lightly as a butterfly's wing.

Similarly, painter Bridget Riley describes her paintings as "intimate dialogue[s] between my total being and the visual agents which constitute the medium. . . . I have always tried to realize visual and emotional energies simultaneously from the medium. My paintings are, of course, concerned with generating visual sensations, but certainly not to the exclusion of emotion. One of my aims is that these two responses shall be experienced as *one and the same*."

Picasso, Gardner's prototype of the "visual thinker," clearly would have concurred. He believed that all sensation, all forms of knowing, are interconnected: "All the arts are the same: you can write a picture in words just as you can paint sensations in a poem. 'Blue' — what does 'blue' mean? There are thousands of sensations that we call 'blue.' You can speak of the blue of a packet of Gauloises and in that case you can talk of the Gauloise blue of eyes, or on the contrary, just as they do in a Paris restaurant, you can talk of a steak being blue when you mean red." Those who look at pictures and do not feel these (or other) associations miss the point. The mixture of feelings and sensations is what gives rise to the painting in the first place.

Because most artistic ideas begin nonvisually, artists also experience the process of translation that Einstein, McClintock, and others have described. Josef Albers may have expressed this process most succinctly when he wrote that art is "the discrepancy between physical fact and psychic effect . . . [a] visual formulation of our reaction to life." Sculptor Louise Bourgeois says, "I contemplate . . . for a long time. Then I try to express what I have to say, how I am going to translate what I have to say to it. I try to translate my problem into stone." Max Bill describes the object of art in similarly sweeping terms, as "the expression of the human spirit. . . . Abstract ideas which previously existed only in the mind are made visible in a concrete form." Paintings and drawings are "the instruments of this realization [by means of] color, space, light, movement." Georgia O'Keeffe wrote, "I long ago came to the conclusion that even if I could put down accurately the thing I saw and enjoyed, it would not give the observer the kind of feeling it gave me. I had to create an *equivalent* for what I felt about what I was looking at — not copy it." Thus the images of art are no more a direct reflection of the feelings, concepts, and sensations from which they arose than are a scientist's formulas direct expressions of his thoughts. All public languages are forms of translation.

Even those who express themselves in words find that they rarely think in words or generate their ideas in words. The poet e. e. cummings, for one, challenged the assumption that poets are essentially wordsmiths manipulating the rules of grammar, syntax, and semantics. "The artist," he wrote, "is not a man who describes but a man who FEELS." Gary Snyder, also a poet, has expanded on that theme, saying that to write he must "revisualize it all. . . . I'll replay the whole experience again in my mind. I'll forget all about what's on the page and get in contact with the preverbal level behind it, and then by an effort of reexperiencing, recall, visualization, revisualization, I'll live through the whole thing again and try to see it more clearly." Stephen Spender provided an almost identical description of his own creative process:

> The poet, above all else, is a person who never forgets certain sense-impressions, which he has experienced and which he can re-live again and again as though with all their original freshness. . . . It therefore is not surprising that although I have no memory for telephone numbers, addresses, faces and where I may have put this morning's correspondence, I have a perfect memory for the sensation of certain experiences which are crystallized for me around certain associations. I could demonstrate this from my own life by the overwhelming nature of associations which, suddenly aroused, have carried me back so completely into the past, particularly into my childhood, that I have lost all sense of the present time and place.

The crafting of imaginary worlds, in both cummings's and Spender's cases, took more than a mastery of language; it took an ability to relive sense impressions almost at will. Other writers have said much the same. Robert Frost called his poetry a process of "carrying out some intention more felt than thought. . . . I've often been quoted: 'No tears in the writer, no tears in the reader. No surprise in the writer, no surprise for the reader.'" The American novelist and short-story writer Dorothy Canfield Fisher also needed to experience what she wrote in order to write well. “I have,” she said, “intense visualizations of scenes. . . . Personally, although I never used as material any events in my own intimate life, I can write nothing if I cannot achieve these very definite, very complete visualizations of the scenes; which means that I can write nothing at all about places, people or phases of life which I do not intimately know, down to the last detail.” Isabel Allende, too, plans her books “in a very organic way. Books don’t happen in my mind, they happen somewhere in my belly. . . . I don’t know what I’m going to write about because it has not yet made the trip from the belly to the mind. It is somewhere hidden in a very somber and secret place where I don’t have any access yet. It is something that I’ve been feeling but which has no shape, no name, no tone, no voice.”

At first the impulse, the vision, the feeling, is unspoken. But in the end it must come to words. Once the poet or writer has relived inspiring or troubling images and feelings, the problem is the same one shared by scientists and artists: how to translate these internal feelings into an external language other people can experience. Fisher described her “presumption” in trying “to translate into words . . . sacred living human feeling.” T. S. Eliot, Howard Gardner’s exemplar of a “verbal thinker,” almost quoted O’Keeffe: “With a poem you can say, ‘I got my feeling into words for myself. I now have the *equivalent* in words for that much of what I have felt.’” Gary Snyder has stated, “The first step is the rhythmic measure, the second step is a set of preverbal visual images which move to the rhythmic measure, and the third step is embodying it in words.” William Goyen, a novelist, poet, and composer, characterized his writing process as “the business of taking it from the flesh state into the spiritual, the letter, the Word.”

Science-fiction writer Ursula LeGuin points out the irony in this translation process for writers of fiction: “The artist deals with what cannot be said in words. The artist whose medium is fiction does this in words,” which, she goes on to explain, “can be used thus paradoxically because they have, along with a semiotic usage, a symbolic or metaphoric usage.” Words are, in other words, both literal and figurative signs of interior feelings, but not their essence. They are, as Heisenberg said of mathematics, expressions of understanding, not its embodiment. So Stephen Spender defines the “terrifying challenge of poetry” as the attempt to express in words that which may not be verbally expressed but may be verbally suggested: “Can I think out the logic of images? How easy it is to explain here the poem that I would have liked to write! How difficult it would be to write it. For writing it would imply living my way through the imaged experience of all those ideas, which here are mere abstractions, and such an effort of imaginative experience requires a lifetime of patience and watching."

"Can I think out the logic of the images?" Relive "the imaged experience"? Create in words an effort of the imagination? The speaker could as easily be Einstein or McClintock as Spender. If this logic of images, of muscular movement, of feeling, is anything, it is not the mathematical logic or the formal linguistic logic that we study in school. Formal logic is used to prove the validity of preexisting propositions. This new "logic" — perhaps Ulam's term, "metalogic," is more appropriate — can prove nothing; rather, it *generates* novel ideas and conceptions, with no assurance of their validity or utility. This kind of thinking, as yet unstudied and unaccounted for by modern theories of mind, is nonverbal, nonmathematical, and nonsymbolic inasmuch as it does not belong to a formal language of communication. Nevertheless, our challenge here is to describe and understand this metalogic of feelings, images, and emotions. If Ulam is right, the result might be as revolutionary and as fundamental as the rules of symbolic logic codified by Aristotle thousands of years ago. Such a metalogic might, indeed, explain the creative origins and character of the articulated ideas to which Aristotle's logic can be applied.

At present, the closest concept we have to such a metalogic is the vague one of intuition. Einstein said, "Only intuition, resting on sympathetic understanding, can lead to [insight]; . . . the daily effort comes from no deliberate intention or program, but straight from the heart." His colleague Henri Poincaré, perhaps the greatest mathematician of the late nineteenth century, wrote in *Science and Method,* "It is by logic that we prove, but by intuition that we discover. . . . Logic teaches us that on such and such a road we are sure of not meeting an obstacle; it does not tell us which is the road that leads to the desired end. For this it is necessary to see the end from afar, and the faculty that teaches us to see is intuition. Without it, the geometrician would be like a writer well up in grammar but destitute of ideas." Physicist Max Planck put it even more simply: the "scientist needs an *artistically* creative imagination." Indeed, scientist and artist are kin, for their insights begin in the same realm of feeling and intuition and emerge into consciousness through the same creative process.

And that is the point. It is too easy to look at the diverse things people produce and to describe their differences. Obviously a poem is not a mathematical formula, and a novel is not an experiment in genetics. Composers clearly use a different language from that of visual artists, and chemists combine very different things than do playwrights. But neither is all scientific thinking monolithic (physics is not biology) or all art the same (a sculpture is not a collage or a photograph). To characterize people by the different things they make is to miss the universality of how they create. For at the level of the creative process, scientists, artists, mathematicians, composers, writers, and sculptors use a common set of what we call "tools for thinking," including emotional feelings, visual images, bodily sensations, reproducible patterns, and analogies. And all imaginative thinkers learn to translate ideas generated by these subjective thinking tools into public languages to express their insights, which can then give rise to new ideas in others' minds.

A good many scientists and artists have noticed the universality of creativity. At the Sixteenth Nobel Conference, held in 1980, scientists, musicians, and philosophers all agreed, to quote Freeman Dyson, that "the analogies between science and art are very good as long as you are talking about the creation and the performance. The creation is certainly very analogous. The aesthetic pleasure of the craftsmanship of performance is also very strong in science." A few years later, at another multidisciplinary conference, physicist Murray Gell-Mann found that "everybody agrees on [where ideas come from]. We had a seminar here [the Aspen Physics Center in Colorado], about ten years ago, including several painters, a poet, a couple of writers, and the physicists. Everybody agrees on how it works. All of these people, whether they are doing artistic work or scientific work, are trying to solve a problem."

As one musician put it, the "absolute similarities" between the thinking processes of scientist and artist are true not only individually but on a social level, too. What the scientist perceives as common problem solving, the artist understands as shared inspiration — but the "answer" springs from the same creative act. As Nobel Prize–winning immunologist and writer Charles Nicolle put it, "[t]he disclosure of a new fact, the leap forward, the conquest over yesterday's ignorance, is an act not of reason but of imagination, of intuition. It is an act closely related to that of the artist and of the poet; a dream that becomes reality; a dream which seems to create." French physician Armand Trousseau agreed: "All science touches on art; all art has its scientific side. The worst scientist is he who is not an artist; the worst artist is he who is no scientist." Similarly, the constructivist sculptor Naum Gabo once wrote that "every great scientist has experienced a moment when the artist in him saved the scientist. 'We are poets,' said Pythagoras, and in the sense that a mathematician is a creator he was right." Stravinsky believed this too. "The way composers think — the way I think," he wrote, "is . . . not very different from mathematical thinking." No matter how expressed, the perspectives of Gell-Mann and Gabo, Stravinsky and Nicolle converge on the same point, aptly made by Arthur Koestler in his seminal book *The Act of Creation:* "Newton's apple and Cezanne's apple are discoveries more closely related than they seem." Both require reperceiving and reimagining the world from basic perceptual feelings and sensations.

While the universality of the creative process has been noticed, it has not been noticed universally. Not enough people recognize the preverbal, premathematical elements of the creative process. Not enough recognize the cross-disciplinary nature of intuitive tools for thinking. Such a myopic view of cognition is shared not only by philosophers and psychologists but, in consequence, by educators, too. Just look at how the curriculum, at every educational level from kindergarten to graduate school, is divided into disciplines defined by products rather than processes. From the outset, students are given separate classes in literature, in mathematics, in science, in history, in music, in art, as if each of these disciplines were distinct and exclusive. Despite the current lip service paid to "integrating the curriculum," truly interdisciplinary courses are rare, and transdisciplinary curricula that span the breadth of human knowledge are almost unknown. Moreover, at the level of creative process, where it really counts, the intuitive tools for thinking that tie one discipline to another are entirely ignored. Mathematicians are supposed to think only "in mathematics," writers only "in words," musicians only "in notes," and so forth. Our schools and universities insist on cooking with only half the necessary ingredients. By half-understanding the nature of thinking, teachers only half-understand how to teach, and students only half-understand how to learn.

This kind of half-baked education harms us more than we know. In our own experiences in school (and we both completed graduate school) no one ever even hinted that one could think about problems in any way but verbally or mathematically. It never occurred to us, and no one suggested that it might be possible, to formulate a math or physics problem as a set of images and feelings stewed in our minds or to plot a book or a poem as a series of images and emotions brewed in our bellies. No one ever mentioned that the stage of inventing an idea or solving a problem might be distinct from the stage of translating it into a disciplinary language. No one ever suggested, as this book will do, that the way we learned one subject or came to one insight might be the key to learning how to have insights in other fields.

If, however, the creative thinkers quoted in this chapter have accurately portrayed the manner in which they work — and we will argue that they have — it is obvious that education based solely on separate disciplines and public languages leaves out huge chunks of the creative process. Teachers work to hone students' mathematical and syntactical logic, but they ignore the metalogics of feelings and intuition. We are taught and tested with words and numbers, and it is assumed that we think in words and numbers. No schooling could be more misconceived. As William Lipscomb has said of current scientific education, "If one actually set out to give as little help as possible to both aesthetics and originality in science, one could hardly devise a better plan than our educational system. . . . One rarely hears about what we do not understand in science, and least of all how to prepare for creative ideas." The same can be said for training in the arts, humanities, and technologies. We master the languages of translation but neglect our mother tongue. Feasts are set before us that we do not taste. We honor chefs and refuse to emulate them.

Nothing could be more important, therefore, than recognizing and describing the intuitive "dialects" of creative thinking. As important as words and numbers are to the communication of insight, that insight is born of emotions and images of many sorts conjured within the imagination. Feeling as thinking must, therefore, become part of the educational curriculum. Students must learn how to pay attention to what they feel in their bones, to develop and use it. This is not pie in the sky. Various professions, including medicine, are beginning to recognize intuition as a necessary part of disciplinary thinking. Geri Berg, an art historian and social worker, formerly at Johns Hopkins University, believes that "emotional awareness, like observation and critical enquiry skills, is an important part of providing good health care." Dr. John Burnside, chief of internal medicine at the Hershey Medical Center in Pennsylvania, has argued this even more forcefully. "One of our educational failures," he writes, "is a lack of serious recognition and attention towards the 'gut feeling' or inclination of common sense. Perhaps because this inclination is non-numerical it is glossed over as the 'art of medicine,' implying instinct, passion, or the primeval. But I believe it can be defined and should be taught."

Whether we are attempting to understand ourselves, other people, or some aspect of nature, or simply provide excellent medical care, it is imperative that we learn to use the feelings, emotions, and intuitions that are the bases of the creative imagination. That is the whole point of gourmet thinking and education.

2

Schooling the Imagination

In *The Phantom Tollbooth* (1961), a classic fantasy by the architect and designer Norton Juster, a boy named Milo takes on an impossible quest. He seeks to reunite the kingdoms of words and numbers, which have been divided by what C. P. Snow called "the two cultures" problem, the inability of those in the sciences and those in arts and letters to communicate. In the course of his adventure, Milo journeys through the Forest of Sight on his way to the city of Reality, when suddenly he sees magnificent buildings towering in the distance. His guide, Alec Bings, informs him they are only a mirage: the city of Illusions. "How can you see something that isn't there?" grumbles the Humbug, one of Milo's companions. "Sometimes," replies Alec, "it's much simpler than seeing things that are. . . . For instance, if something is there, you can only see it with your eyes open, but if it isn't there, you can see it just as well with your eyes closed. That's why imaginary things are often easier to see than real ones." Then where, Milo and his companions ask, is the city of Reality? "Right here," says Alec, pointing. "You're standing in the middle of Main Street." But, says Milo, "I don't see any city."

Milo's ability to perceive Illusions but not Reality may seem like an artificial literary device, but we discovered many years ago that our educational system actually fosters this odd talent. The lesson was brought home in a particularly memorable way when we were undergraduates. We had a friend — we'll call him John — who was considered one of the most brilliant students in the history of our college. He completed unheard-of amounts of work, acing class after class. This was no mean intellectual feat, though John's feet, like those of many a mere mortal, turned out to be made of clay.

We made the disheartening discovery on the way out of the physics building, just a few weeks after a series of lectures on mechanics. John was a rather tall, lanky young man — no athlete, but no ninety-pound weakling either. Nevertheless, try as he might, he could not open one of the very heavy oak doors of the old lecture hall. One of us reached for the doorknob and gave the door a shove that swung it cleanly open.

"How did you do that so easily?" John asked.

"You're kidding, right?" we responded. "We just studied the physical principles that relate to doors a couple of weeks ago." John had mastered the relevant equations so thoroughly that he got one of the highest scores ever recorded on the midterm exam, but nevertheless he appeared puzzled. "No. Really. I don't understand," he said.

We gave him a clue. "You were pushing at the center of the door rather than the edge."

"So?"

"Well, why are doorknobs usually put at the edges of doors rather than in the middle?"

"It's easier to make the latching mechanism, I suppose," John essayed.

"Sure. But what *physical* principle is involved?" John shrugged his shoulders. He really hadn't the slightest idea. For all his genius, he wasn't putting us on. "Torque, John, torque!" we cried.

Torque is a rotational force. Most of us have a kinesthetic understanding of torque that we develop from opening and closing doors or using a wrench. We have learned by experience that the closer to the *unhinged* edge of the door we push, the easier it is to move; that the longer the wrench, the less force we need to exert to loosen a bolt. The principle is akin to that of the lever. Give me a fulcrum, a lever long enough, and a place to stand and I will move the world, Archimedes is supposed to have said. For torque, one might say, give me a wrench long enough and I'll loosen any bolt. Or, in terms of John's problem, let me push as far from the hinges as possible and I'll open any door.

Insight visibly dawned in John's face, and he proceeded to calculate — in his head, mind you — that if the mass of the door was x, and the distance from the axis of rotation to the point at which the force was applied was y (and so forth), then, indeed, it would take significantly less force to move the door if that force was applied at the outer edge rather than at the center. The problem was that John made no connection between this intellectual work and his personal experience of the physical world around him. Torque problems were posed by a physics professor and solved using mathematics during a test. John could see what one might characterize as the "illusions" of torque equations before his mind's eye as clearly as Milo and his companions could see the city of Illusions in the Forest of Sight. But it had never occurred to John that such mathematical problems existed in real life. He could not relate his incredible store of academic knowledge and his fantastic facility with numbers to everyday activity. His Illusions failed to connect with Reality.

Unfortunately, many good students experience the same disjunction between academic work and real life. Albert Einstein certainly believed this to be true for his eldest son. When he took Hans Albert sailing, for instance, he expected the boy to apply his school knowledge of physics to the challenge of harnessing the wind and was disappointed when he did not. The case is all the more interesting because Einstein himself had been discouraged from tying experience to academic studies when he had attended the gymnasium (or technical high school). Although rote memorization and thinking in words and numbers formed the bulk of gymnasium studies, Einstein had found it difficult to ignore his senses and intuition. He blossomed only after transferring to a high school in Arrau, Switzerland, run according to the principles of Johann Heinrich Pestalozzi, an educational reformer who placed nonverbal, nonmathematical forms of thinking at the center of education. Students at the Kanton Schule focused not on communication skills but on learning how to imagine what it felt like to be inside a physical system. They learned to draw, create models, pay attention to their intuition, see and feel things in their minds. Later, as a patent examiner, Einstein practiced these skills further. He carried them into his physics and into his daily life.

When Einstein went sailing he *felt* the forces at work on his boat through the lines and the hull. He became, as his daughter Margot explained, "a little piece of nature" — a physical embodiment of his understanding. He could also interpret these feelings as expressions of well-known physical laws. As far as he was concerned, an expert sailor was an applied physicist, and a physicist was someone who could act upon his understanding in real life situations. Whenever Hans Albert made a sailing error, Einstein perceived it as a failure on his son's part to connect book work with experience of the world. "Every time his son made what he thought was a mistake in the sailing of the boat," Einstein's friend Chaim Tschernowitz recounted, "Einstein would burst out about the educational system of the gymnasia — how inefficient it was, and how it was responsible for all the mistakes men make in later life."

At about the same time J. J. Thomson, winner of a Nobel Prize in physics for his discovery of the electron, found similar failings in physics training at Cambridge University. To reach students like our friend John, Thomson larded his courses with physical demonstrations of physical laws and theorems. "The demonstrations brought to light some interesting points," he noted in 1937. "We found many cases where men could solve the most complicated problems about lenses, yet when given a lens and asked to find the image of a candle flame, would not know on which side of the lens to look for the image. But perhaps the most interesting point was their intense surprise when any mathematical formula gave the right result. They did not seem to realise it [mathematics] was anything but something for which they had to write out proofs in examination papers." Henri Poincaré found the same to be true in France. "There is one thing that strikes me, and that is, how far young people who have received a secondary education are from applying the mechanical laws they have been taught to the real world. . . . For them the world of science and that of reality are shut off in water-tight compartments."

The same disconnection between academic knowledge and physical experience continues to plague education today. "I am told," Harvard psychologist Leon Eisenberg told a symposium on creativity during the 1970s, "that in so distinguished an institution as MIT, a student can have mastered calculus to the satisfaction of the teacher by having solved the problem set on the final examination. On entering the physics course he cannot see how to apply the calculus to the solution of problems in physics. There is something very much wrong about what has been learned when the skills are not transferable." No less a scientist than Richard Feynman, whose work revolutionizing quantum physics earned him a Nobel Prize, confirmed Eisenberg's observation. In *Surely You're Joking, Mr. Feynman!* (1985), he told of students in a mechanical drawing class at MIT who didn't know how to describe the French curve mathematically. They were sure that the plastic tool they used for drawing smooth curves had to have "some special formula." For Feynman their ignorance was a joke and so was his response. "The French curve," he told them, "is made so that at the lowest point on each curve, no matter how you turn it, the tangent is horizontal."

> All the guys in the class were holding their French curve up at different angles holding their pencil up to it at the lowest point and laying it along, and discovering, sure enough, the tangent is horizontal. They were all excited by this "discovery" — even though they had already gone through a certain amount of calculus and had already "learned" that the derivative (tangent) of the minimum (lowest point) of *any* curve is zero (horizontal). They didn't put two and two together. They didn't even know what they "knew."

Indeed, professors at MIT and the California Institute of Technology (Caltech) as well as research directors at major engineering firms have long realized that what eventually separates successful scientists and engineers from the rest of the students in their classes is the ability to *feel* or *see* what the equations mean. Every student in their physics classes has the mathematical ability to solve Einstein's equations describing relativity theory, but only a few can bring the equations to life. Only a few can translate back and forth between their mathematical and their physical understanding as Einstein, Feynman, Pauli, Cyril Smith, and so many other great physical thinkers have been able to do. Having learned mathematics as a language of communication without also learning what mathematics communicates, too many students are like those observed by J. J. Thomson and Henri Poincaré, like our friend John. As brilliant as they are, they are only half-educated.

The problem of living in Illusions rather than in Reality is not limited to the sciences. Verbal schooling received in the humanities also fails in an analogous way by teaching students communication and analysis without exercising feeling, observing, empathizing, and other ways of knowing reality directly. The result can be crippling to the artist or writer. The writer Virginia Woolf explored an all-too-perfect example of this failing in her father. Sir Leslie Stephen, eminent man of letters and editor of the impressive *Dictionary of National Biography,* yearned to be a great literary figure, though he produced no more than dry, analytical criticism. According to Woolf, her father was "conscious of his failure as a philosopher, as a writer," telling her at least once that despite his high academic credentials, he had "only a good second class mind." After her father's death, Woolf took a long hard look at the "disparity . . . between [Stephen's] critical and his creative powers. . . . Give him a thought to analyse, the thought of Mill, Bentham, Hobbes," she wrote, "and his [writing] is . . . acute, clear, concise: an admirable model of the Cambridge analy[tical spirit]. But give him life, a character, and he is so crude, so elementary, so conventional, that a child with a box of coloured chalks is as subtle a portrait painter as he is."

Woolf blamed her father's education, just as Einstein, Thomson, and Feynman attributed the failings of their students and colleagues to an incomplete schooling. "One would have to discuss the crippling effect of Cambridge," Woolf wrote, "and its one-sided education; . . . and the crippling effect of intensive brain work; and to illustrate that by his lack of any distracting interests — music, art, the theatre, travel; and one would have to discover how much of this intensification and narrowness was natural; how much imposed by circumstances." The highly competitive nature of the honors examinations at Cambridge and other British universities in the mid-nineteenth century certainly had something to do with Stephen's narrow analytical powers. These tests, known as the triposes, relied heavily on memorization of material and speed of regurgitation. Stephen "crammed" well in both mathematics and linguistics, taking twentieth place in the math exam out of a particularly brilliant group of 143 students. And when he himself became a Cambridge tutor, he advised his students "to stick to your triposes, grind at your mill and don't set the universe in order until you have taken your bachelor's degree."

Such constant intellectual overwork left Stephen little time or inclination for the arts, a consequence his daughter deplored. Aside from his professional concern with literary criticism, Stephen ignored painting, music, theater, and opera, calling himself in this regard a "Philistine" — literally, a person hostile to aesthetic refinement. He even seems to have viewed artistic endeavor in the literary field with outright suspicion. "The imaginative writer," he declared, "is bound to be emotional and personal; he has to work up his innermost emotions for exhibition, and is thin-skinned and self-conscious. . . . Let us hope he has his reward in the raptures of creation, and be thankful we are spared his temptations."

Stephen certainly spared himself. Woolf noted that "at the age of sixty-five he was almost completely isolated, imprisoned. Whole tracts of his sensibility had atrophied. He had so ignored, or refused to face, or disguised his own feelings, that not only had he no conception of what he himself did and said; he had no idea what other people felt." Unable or unwilling to take his own emotions and feelings seriously, he was unable to perceive the impact of his ideas on others or to invent work that could move others in the ways literature or poetry must do. In contrast, his daughter achieved literary fame not only for her stylistic excellence but for her many literary innovations. Where her father was "limited" and "conventional," Woolf was as adventurous and inventive as any writer ever has been. She may have fretted when her father refused to send her to university, but in later years she realized that her self-schooling had been invaluable.

Woolf learned at home in an eclectic but also synthetic manner. From an early age she listened to her father read from Sir Walter Scott's Waverly novels, as well as from Jane Austen, Shakespeare, and classics of history. She spent time in "the mechanical part" of the South Kensington Museum and "the insect room" of the Natural History Museum. Along with her siblings, she made up stories in bed, imitating the tales her mother made up and wrote down for them. She contributed avidly to a family newpaper. In all this, her experience of learning, like Einstein's, seems to have been somatic. She developed almost total recall for her sensations; she had an ability to empathize with characters in books she was reading and tended to disappear into their worlds, forgetting herself. She took in so much that her father recognized by the time she was eleven that she "will really be an author in time." From about the age of fifteen, she became an autodidact, reading essays, history, biography, travel and adventure, poetry, novels. In German lessons with her father, as well as in math, she failed miserably, but she did study bookbinding with a teacher who came to the house and took private lessons in Greek and Latin. She discussed literature with her brother Thoby whenever he was home from his university, for "I don't get anyone to argue with me now, and feel the want." She learned to write by mimicking the best literary models and watching her sister explore the making of art. In complete contrast to her father, Woolf learned not only the "what" of literature but the "how" as well. Novels were not just to be read; they were to be *made.*

Woolf was fortunate to have escaped the educational separation of "what" and "how." To look at a novel or a sculpture or to listen to a piece of music as if it were simply an object — a "what" to be analyzed — is to perceive only the Illusion. Reality can be experienced only when we understand how the art emerges from and relates to life itself. More than sixty years ago the educational philosopher John Dewey argued in his classic *Art as Experience* that conventional art education fails in exactly the same way science education fails — by concealing rather than revealing the links between theory and practice. For Dewey, the more we consider artistic objects distinct from the original experience that formed them, the more we cut art off into a separate realm and threaten it with irrelevance. The "refined and intensified forms of experience that are works of art" are thus disconnected from "the everyday events, doings, and sufferings that are universally recognized to constitute experience."

The problem with divorcing what and how in education is that *knowing* about things is not the same as *understanding* them. Feynman made the point when he said, apropos of the French curve, "I don't know what's the matter with people: they don't learn by understanding: they learn some other way — by rote or something. Their knowledge is so fragile!" John, a brilliant student, *knew* a great deal of physics, just as Leslie Stephen *knew* a great deal about literature. When it came right down to it, however, neither one *understood* his subject — how to use it practically, how to make with it or create something new. Their knowledge was, indeed, fragile and useless —

the result of an educational failure that all too often clothes itself in the garb of academic success.

An opposite kind of educational failure, in which Reality is perceived in the absence of Illusions, has also attracted attention over the years. Two decades ago, for instance, educational psychologist Jeanne Bamberger embarked on a study of children in Cambridge, Massachusetts, who did poorly in school despite their "virtuoso" ability to build and fix things in their everyday world. Very early on in her Laboratory for Making Things, Bamberger realized that these young students, like Einstein, had trouble learning disembodied principles of physics but understood them at a practical level very well. In the course of building mobiles, for example, they placed weights at appropriate distances from the fulcrum, even though they could not articulate any of the physical concepts involved. One student explained that he "just knew. . . . I had a feeling of it, like on a teeter-totter." His lack of Illusions, of theoretical knowledge, represented a "failure to perform" in an academic sense because he could not explain to others what he had accomplished or how. But he understood the Reality of the situation in the same sense that the scientists and artists quoted in Chapter 1 knew they had achieved some basic insight or arrived at some seminal idea but did not yet know how to express it. Bamberger concluded that this boy and children like him had a "hand knowledge" acquired through experience that was, in its own way, as powerful as the "symbolic knowledge" taught in school.

Experience-based understanding represents a "poorly understood, but well recognized phenomenon," in Bamberger's words, that has counterparts throughout the annals of innovative art and science. Many creative individuals — including Einstein and the graphic designer M. C. Escher — perform poorly in conventional schools. "In high school in Arnhem," Escher wrote, "I was a particularly poor student in arithmetic and algebra because I had, and still have, great trouble with the abstractions of numbers and letters. Things went a little better in geometry when I was called upon to use my imagination, but I never excelled in this subject while in school." Mathematics nevertheless played a role in his later design of artistic patterns. "Although I lack theoretical knowledge," he observed, "the mathematicians, and in particular the crystallographers, have had considerable influence on my work." The influence was mutual. Escher's intuitive grasp of tilings, dimensions, and symmetries proved so profound that academicians have used his art to illustrate many mathematical and physical concepts. Who could have predicted his achievement based on such an inauspicious beginning? Despite his poor performance in school, Escher *understood* mathematics, though in a way his teachers did not expect or appreciate.

This is precisely what Bamberger found in her Laboratory for Making Things. When the young boy spoke of a "feeling of it, like on a teeter-totter," his teachers did not understand the validity of his experience-based explanation. As Bamberger explains, "They had, of course, learned the formula of 'weight times distance' [for balancing different weights], but what they had been taught and what they had learned to *say* seemed disconnected from what they could directly see and feel. . . . The teachers themselves, like most adults, were used to keeping neatly separate their school knowledge and their everyday knowledge." Indeed, Bamberger found that many teachers in her project could not build the mobiles or other constructions that they assigned to their students. They knew the theory but could not apply it in the real world. Illusions and Reality were just as separate for them as for their students, but for a different reason.

We can see now what was wrong with the schooling of Leslie Stephen and our friend John. Both men excelled in "cramming" the thought of others in science, philosophy, literature, or history. Both men exhibited a complete lack of interest in practicing the arts, whether fine or mechanical. They had no hobbies; they did not build or fashion things with their hands or their minds. In short, they lacked imagination, that capacity to link mind and body, intellect and intuition. No one insisted that they learn by doing and making; no one encouraged them to meld "hand knowledge" and "symbolic knowledge"; no one pressed them to make connections between practice and analysis, or image and object. They acquired facts but could not imagine their meanings. Their brilliant minds — and the minds of so many like them — were blinkered by pedagogies that separated knowing and understanding, Illusions and Reality.

The result was a serious handicap. As we will show in subsequent chapters of this book, if you can't imagine, you can't invent. "Illusion," as Pulitzer Prize–winning author and artist Paul Horgan has written, "is first of all needed to find the powers of which the self is capable." If you can't conceive of things that don't exist, you can't create anything new. If you can't dream up worlds that might be, then you are limited to the worlds other people describe. You see reality through their eyes, not your own. Worse, having failed to develop your own illusory but insightful "eyes of the mind," the eyes in your head will not show you much of anything at all.

In *The Phantom Tollbooth,* Milo realizes this when he finds that the city of Reality is home to a great many people rushing in and out of buildings and up and down streets they — and Milo — do not see. "Hasn't anyone told them?" the boy asks, alarmed by the thought of people inhabiting a phantom reality, as blind to its existence as John and Stephen were to the realities they encountered. Alec replies matter-of-factly that telling does no good, "for they can never see what they are in too much of a hurry to look for." "Why don't they just live in Illusions," quips the Humbug, for then they might at least exist in a city they can "see." "Many of them do," Alec responds, "but it's just as bad to live in a place where what you see isn't there as it is to live in one where what you don't see is."

The trick, Milo finally figures out, is to live in Illusions and Reality at the same time. Fantasy and imagination suggest how the world might be; knowledge and experience limit the possibilities; melding the two begets understanding. Without the illusions of the mind, a clear grasp of reality is impossible, and vice versa.

The best scientists have always realized this, arguing, as so many do, that their Illusions must constantly be tempered with Reality. Theory is always tested by experiment and observation. Artists, writers, and professionals in the humanities say much the same thing, although the paradox of that interaction is, for them, never quite resolved. "Fiction writers, at least in their braver moments, do desire the truth: to know it, speak it, serve it," writes Ursula LeGuin. "But they go about it in a peculiar and devious way, which consists in inventing persons, places, and events which never did and never will exist or occur, and telling about these fictions in detail and at length and with a great deal of emotion, and then when they are done writing down this pack of lies, they say, There! That's the truth!"

LeGuin argues further that the writer's "tissue of lies" is credibly supported by all kinds of facts, a "weight of verifiable place-event-phenomenon-behavior." As the perceptual psychologist Richard Gregory points out, "It is a mistake to equate 'fiction' with 'false.'" By checking and crosschecking fiction with fact, experience with knowledge, by creating each in the image of the other, the writer ever more closely approximates recognized truths. Ultimately, however, the imagined fictions matter far more than the facts, for they fuel the creative process — not just in art but in science, too. "The illusions of the experimenter," wrote Louis Pasteur, inventor of the germ theory of disease, the first vaccines, and pasteurization, "form the greater part of his power." And Einstein stated categorically, "In creative work, imagination is more important than knowledge."

For the scientist, experimentation keeps imagination from going astray; for the artist, it is a dialectical dilemma. When LeGuin insists, "Distrust everything I say. I am telling the truth," she might just as easily say, Consider carefully what this fictive lens lets you see. Our perceptions of Reality depend upon the kind and quality of Illusions we conjure. This is what Picasso meant when he said, "Art is a lie that makes us realize the truth." Like so many artists and scientists, he understood that imagination does not simply discover truth, it shapes it. A wonderful anecdote concerning the painter illustrates the point. One day, Picasso took a train trip and, as happens on such occasions, engaged in conversation with the gentleman seated next to him. When the man learned to whom he was speaking, he began grumbling about the ways in which modern art distorts reality. According to one account, "Picasso demanded to know what *was* a faithful representation of reality. The man produced a wallet-sized photo and said, 'There! That's a real picture — that's what my wife really looks like.' Picasso looked at it carefully from several angles, turning it up and down and sideways, and said, 'She's awfully small. And flat.'"

Without imagination all the world is, indeed, as flat and small as the portrait Picasso examined. This was Leslie Stephen's problem, and John's. What we sense directly — a door, the sun and moon rising and setting, a photograph or drawing, the scribbled marks we call letters on a piece of paper — these things are not real at all or, rather, they are not real to us in and of themselves. We must interpret what we sense in terms of imagination to create understanding. All of science and all of art are demonstrations of this fact. The door is not just a piece of wood hung on hinges; it is also an example of torque and of mass; it is also a marriage of materials, manual skill, and utilitarian purpose; a work of artistic design; an exit, an entry. To think of it in these different ways requires us to perceive it in these different ways, as our friend John found out the hard way. Despite appearances, the earth turns, not the sun, and thus the sun, not the earth, is the center of the solar system. The photograph, the drawing, writing itself — these are nothing but paper with some ink or silver stains on it. What we make of each occurs in our minds in accord with our skill at recreating the sensory, emotional, and experiential feelings that they are meant to symbolize. Their meanings are invented fictions that have a ring of truth only if we carry the truth around inside ourselves. Productive thought occurs when internal imagination and external experience coincide.

This being the case, the task for educators, self-learners, and parents is simply put: to reunite the two. And the world's most creative people tell us how in their own words and deeds; in their own explorations of their own minds at work. What they find as individuals, when taken as a whole, is a common set of thinking tools at the heart of creative understanding. These tools include (but are not necessarily limited to) *observing, imaging, abstracting, recognizing patterns, forming patterns, analogizing, body thinking, empathizing, dimensional thinking, modeling, playing, transforming,* and *synthesizing.*

Initially, all knowledge about the world is acquired through *observing,* paying attention to what is seen, heard, touched, smelled, tasted, or felt within the body. The ability to recall or imagine these feelings and sensations is also an important tool called *imaging.* Just as observations can be made using any sense, so images can be recalled or created for any sense or sensation. Indeed, scientists, artists, and musicians alike report "seeing" in the mind pictures of things they have never actually seen, "hearing" sounds and songs that have not yet been made, and "feeling" the sensual properties of things they have never truly touched. Because sense experience and sense imagery are rich and complex, creative people in all disciplines also use *abstracting* as an essential tool. And whether one is an artist like Picasso, a scientist like Einstein, or a writer like Hemingway, the process of paring down complicated things to simple principles is the same.

Simplifying often works in tandem with patterning, a tool with two parts. *Recognizing patterns* is involved in the discovery of nature's laws and the structure of mathematics, but also the rhymes and rhythms of language, dance, music, and the formal intentions of the painter. Recognizing patterns is also the first step toward creating new ones. Novel *pattern forming,* whether in music, art, engineering, or dance, almost always begins with combining simple elements in unexpected ways. Even more interesting, there are patterns to pattern forming itself. Moreover, recognizing patterns in patterns leads directly to *analogizing.* The realization that two apparently different things share important properties or functions lies at the heart of the world's greatest works of art and literature and the most enduring scientific theories and engineering inventions.

Tools for thinking are preverbal and presymbolic, and none more so than *body thinking* — thinking that occurs through the sensations and awareness of muscle, sinew, and skin. Well before they have found the words or the formulas to express themselves, many creative people "feel" ideas emerging. Bodily sensations, muscular movements, and emotions act as springboards for more formal thought. Athletes and musicians imagine the feel of their movements; physicists and artists feel in their bodies the tensions and movements of trees and electrons, instruments and tools. *Empathizing* is related to body thinking. Many creative people describe "losing" themselves in the things they study, integrating "I" and "it." Actors learn to make the character they play a part of themselves. Scientists, doctors, and artists play-act "becoming" another person or an animal, plant, electron, or star. Yet another tool, this one rooted in the experience of space, is *dimensional thinking,* the imaginative ability to take a thing mentally from a flat plane into three dimensions or more, from earth into outer space, through time, even to alternate worlds. One of the least recognized of our thinking tools, dimensional thinking is essential to engineering, sculpture, visual art, medicine, mathematics, and astronomy — indeed, any activity that involves interpreting "pictures" in one set of dimensions as objects in another set.

Up to this point, the thinking tools we have outlined are what might be called primary tools. None is absolutely independent of any of the others. Body thinking cannot be separated absolutely from imaging; analogizing relies on pattern recognition and pattern forming; and patterning relies in turn on observing. Nonetheless, one can learn and practice each of these tools somewhat independently of the others. Our last four, however, are clearly higher-order tools that integrate and rely upon the primary tools. *Modeling* objects and concepts often requires some combination of dimensional thinking, abstracting, analogizing, and manipulative or body skill. Poets and writers pattern genres on the exemplars of earlier writers; artists make small sketches and maquettes in preparation for their masterpieces; dancers model their choreography on real people; doctors learn procedures by trying them out on specialized mannequins; engineers test their ideas on working models. *Playing,* another integrative tool, particularly builds upon body thinking, empathizing and play-acting, and modeling. Playing involves a childlike joy in the endeavor at hand, an irreverence for conventional procedure, purpose, or the "rules of the game." Playfully challenging the limitations of a science, an art, or a technology just to see what happens is one of the most common ways in which novel ideas are born.

Transforming, another integrative tool, is the process of translating between one tool for thinking and another and between imaginative tools and formal languages of communication. In real life we become aware of problems through feelings of mental or bodily discomfort, but we must express the solution logically in words, movements, or equations or as an invention. To move from feelings to communication always requires a series of steps: translating the problem into images or models, searching for patterns through careful observation or experiment, abstracting out the most important material from the patterns and modeling it, then playing around with various solutions using empathizing or play-acting, and finally searching for the language that can best express one's insight. Transformational thinking weaves the rest of the tools together into a functional whole, correlating each skill with the others in a workable fashion.

Finally, and most important, *synthesizing* completes the imagination's tool kit, for understanding is always synthetic, combining many ways of experiencing. There are two fundamental components to synthetic thinking. One is *synesthesia,* a neurological and artistic term for experiencing sensations in multiple ways at once. A sound may provoke colors; a taste may call up tactile sensations or memories. Synthesizing also supposes an integration of knowledge in which observing, imaging, empathizing, and the other tools all work together organically — not serially, as in transformational thinking, but simultaneously, such that everything — memory, knowledge, imagination, feeling — is understood in a holistic, somatic way. The equations that describe torque become one with the feeling of torque when opening a door. We call this unified understanding linking mind and body, sense and sensibility, *synosia,* and it is the ultimate goal of a tools-for-thinking education.

Six important points must be made about these thirteen tools. First, we emphasize that we have relied upon creative individuals to describe their own thinking. Artist Brent Collins is typical of the introspective individual who clearly understands his creative process in terms of these imaginative tools. In working to transform mathematical models of equations into sculptural allegories, he says, "I made [2-dimensional] templates exactly to scale. . . . The entire mathematical logic of the sculpture is inherently readable from the template. There are, however, many aesthetic choices. . . . The template serves as a guide for a spatial logic I somehow intuitively know to follow. Using common woodworking tools and proceeding kinesthetically, I am able to gradually feel and envision its visual implications. . . . The linear patterns issue as abstractions." Dimensional thinking, modeling, body thinking, visual imaging, abstracting, synthetic thinking — he uses all of these tools to imagine and to create, as do the many other individuals we cite and discuss on the following pages.

Second, we acknowledge that we are not the first to take note of some of these imaginative skills. A century ago Francis Galton undertook many studies of what he called "genius." He observed that many of his eminent contemporaries tended to visualize things, to think with their bodies, and to transform ideas such as numerical patterns into visual ones. His work, and that of many psychologists building upon his ideas, has provided valuable insights into certain aspects of creative thinking. In studying the creative individuals of our own and times past, we are expanding upon Galton's original conception of the creative imagination. The tools described in this book are what creative people themselves say they use and, equally important, what studies of their creative processes show that they use.

Third, we argue that these tools for thinking promise to bridge the gap between Illusions and Reality to create synthetic understanding. Metallurgist Cyril Stanley Smith, also a humanist and artist, understands that tools for thinking, by their very nature, forge abiding connections between what is real, what is imagined, and what is created. Visual imaging, pattern recognizing, and pattern forming, based as they are in the sensory input of the external world, compel us to channel our sense-making capacities toward what Smith calls the "shared duality" of mind and matter. "The principles of pattern formation, aggregation, and transformation," he has written, "seem to be the same in matter and in the human brain, and if properly formulated they may provide a kind of visual metaphor that will serve to join and mutually illuminate physics on the one hand and geological, biological, and social history on the other — with art in between." The concept of tools for thinking is clearly a unifying one.

Fourth, we are not making any claims of cognitive significance for our tools. These tools are not to be taken for distinct forms of inheritable "intelligence" to be used as educational tracking devices or for cognitive "domains" representing specialized brain functions. Nor are they meant to be localized in some anatomical region of the brain or some set of neuronal connections. Rather, tools for thinking are exactly what we have called them: tools. They are just like whisks, knives, graters, spatulas, mixers, and blenders — equipment available to anyone. With practice and determination anyone can learn to use them with some degree of skill. We fully expect them to be used with other analytical tools, such as logic, and with communication tools, such as words and equations. Our tools complement but do not replace other cognitive skills.

Fifth, just as mastery of kitchen utensils does not guarantee innovation in cooking, mastery of tools for thinking does not guarantee innovation in science, art, or any other endeavor. There are no easy recipes for originality. Nevertheless, neither the chef nor the thinker can be creative without thorough practice and exercise of his or her equipment. Thinking tools are necessary to creativity, but, like the tools of any trade, they must be used with individual, even idiosyncratic, vision to yield innovative results.

Finally, though people can use these tools in the workplace or the home, their most important role may be in education. Our educational system is the embodiment of our cognitive and creative understanding of ourselves. If we fail to understand creative thinking, we cannot hope to have an educational system that will produce creative individuals. Conversely, a society that understands the nature of creativity will be able to foster it in the classroom. Indeed, we intend that these tools be used to cultivate imagination along with intellect, to reintegrate knowledge of mind with knowledge of body, to reveal in glorious detail the ways in which artists, scientists, dancers, engineers, musicians, and inventors think and create, so that the most unexpected surprises may illuminate all our lives.

An impossible and quixotic task? Perhaps. Knowledge is fragmenting at ever-increasing speed; understanding becomes ever more rare. C. P. Snow's two cultures have now multiplied to hundreds of noncommunicating cultures. Technology feeds reliance on the mysterious and even magical workings of "black boxes." Even as more and more information becomes available, we understand and use less and less of it. If society cannot find ways to make integrated understanding accessible to large numbers of people, then the information revolution is not only useless but a threat to humane civilization.

The only failure is not to try, as Milo learns in *The Phantom Tollbooth*. Surviving numerous scrapes with the Demons of Ignorance, in the end he reunites Dictionopolis, the capital of Words, and Digitopolis, the capital of Numbers, within the Kingdom of Wisdom by returning to them the banished Princesses of Rhyme and Reason. In terms that Milo would understand, we, too, can try to unite Illusions and Reality into Understanding through the medium of Tools for Thinking. Our goal is no less lofty than Milo's, and certainly as difficult. But if we push on the door in the right place, it will swing open.

3

Observing

All knowledge begins in observation. We must be able to perceive our world accurately to be able to discern patterns of action, abstract their principles, make analogies between properties of things, create models of behaviors, and innovate fruitfully. Before you read this chapter, therefore, we'd like you to test your observational skills. Turn on the television and describe what you observe about it. We're not looking for details such as who is saying what to whom in which program, but rather the characteristics of a working television itself. Try to get beyond the obvious aspects such as its glass screen, plastic case, and push-button switches to its intimate properties. Make notes and sketches about your observations. Then read this chapter and see how you could have gone about your task differently.

Most people equate observing with visual perception, which, although myopic, is as good a place to begin as any. So what do you see in the photograph below? At first glance you might think it a nondescript scene of dried-up grass. But look carefully. This photograph appeared as an illustration in a groundbreaking book about visual phenomena, Gerald Thayer's *Concealing-Coloration in the Animal Kingdom: An Exposition of the Laws of Disguise Through Color and Pattern: Being a Summary of Abbott H. Thayer's Discoveries* (1909). As the book title suggests, the picture shows something camouflaged. A small dark blob in the upper left corner might be an eye. The black patch toward the lower right could be the shadow of a tail. Above and to the left of this shadow, an area of somewhat different texture is evident. When these elements converge, you recognize a bird — specifically a ptarmigan, a type of grouse.

Fig. 3-1. An example of animal camouflage.

Now, why didn't you see the bird right away? The fact that it is camouflaged is no excuse. You see it perfectly well after you have spotted it, so observing must involve more than just looking. The truly remarkable thing is that although people have looked at camouflaged animals since the dawn of history, no one recognized the existence of a general concept. It took the keen mind of Gerald Thayer's father, Abbott Thayer, a painter of angels and women and a dabbler in natural history, to understand the meaning of camouflage. Thayer's contribution to evolutionary theory was significant enough to earn him a place alongside Charles Darwin and Alfred Russel Wallace (the codiscoverer of natural selection) and Henry Bates and Fritz Müller (the two men who characterized mimicry) in the pantheon of those who have elucidated basic mechanisms of natural selection. Thayer also invented military camouflage.

The difference between passively looking and actively observing continues to yield surprises in the hands of modern artists. The objects Jasper Johns paints — everyday things such as flashlights, light bulbs, and American flags — are chosen precisely because it is so hard to *see* them. "What interested me was this," Johns says. "At a certain point I realized that certain things that were around me were things that I did not look at, but recognized. And recognized without looking at. So you recognize a flag is a flag, and it's very rare that you actually look at the surface of it to see what it is. This aspect of things interested me and I began to work with it, to see how I could look at things that I was accustomed to looking at, but not seeing." Johns's American flag series consists of various ghostlike apparitions and highly textured surfaces. By reiterating and altering an object we know so well, he forces us to look again, to think about what we see.

As Johns suggests, even artists have to learn how to observe, and many can recall a key moment when they learned the difference between looking and seeing. For the artist Georgia O'Keeffe, this moment occurred when an art teacher, during her second year of high school, brought to class a stunning purple jack-in-the-pulpit.

> Holding a Jack-in-the-pulpit high, she [the teacher] pointed out the strange shapes and variations in color — from the deep, and black earthy violet through all the greens, from the pale whitish green in the flower through the heavy green of the leaves. She held up the purplish hood and showed us the Jack inside. I had seen many Jacks before, but this was the first time I remember examining a flower. . . . She started me looking at things — looking very carefully at details. It was certainly the first time my attention was called to the outline and color of any growing thing with the idea of drawing or painting it.

The lesson was so powerful that O'Keeffe went on to see jacks, as well as other flowers, skulls, landscapes, and even skyscrapers in ways that no one had ever seen them before. Near the end of her life she distilled what she had learned about observing into a few sentences: "Still — in a way — nobody sees a flower — really — it is so small — we haven't the time — and to see takes time, like to have a friend takes time."

O'Keeffe's words are appropriate for observing in any field, for as the poet and arts advocate Herbert Read has written, observing "is almost entirely an acquired skill. It is true that certain individuals are born with an aptitude for concentrated attention, and for the eye-and-hand co-ordination involved in the act of recording what is observed. But in most cases the eye (and the other organs of sensation) have to be trained, both in observation (directed

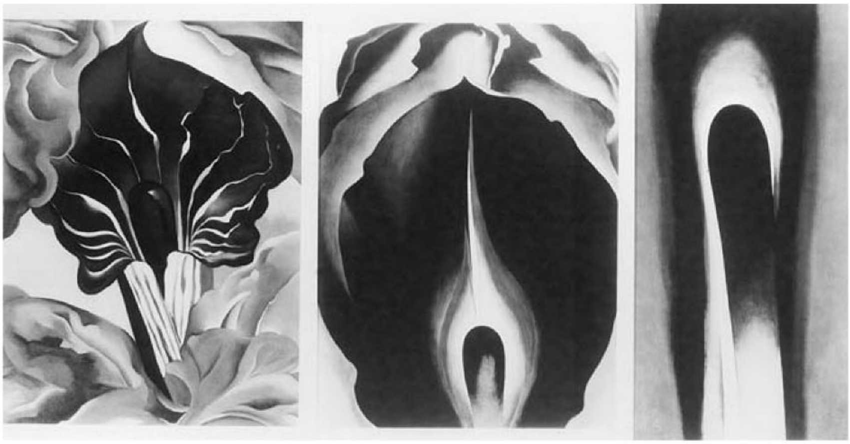


Fig. 3-2. *Left to right: Jack-in-the-Pulpit, No. 2; Jack-in-the Pulpit, No. 4;* and *Jack-in-the-Pulpit, No. 6* by Georgia O'Keeffe, 1930.

perception) and in notation." Such training takes what biologist Konrad Lorenz called "the patience of a yogi."

The patience to look and look again is therefore a trait that characterizes great artists. Pablo Picasso, renowned for his artistic abstractions, first learned as a young boy to draw realistically what he observed meticulously. "I recall my father saying to me, 'I am quite willing for you to become a painter, but you must not begin to paint until you are able to draw well, and that is very difficult.' Then he gave me a pigeon's foot to practise on. He came around later to look at my work and criticize it." The father, an art teacher who specialized in drawing pigeons, made his son draw the foot over and over. "At last the day came," Picasso continued, "when he gave me permission to go ahead and draw whatever I liked. . . . By the time I was fifteen I could do faces and figures and very large compositions — often without models — because, simply by practising on pigeons' feet, I had learned how to capture the mystery of lines, even of nudes." Having learned to observe one thing, he had learned the keys to observing and describing everything.

Artists past and present understand that manual facility is inextricably bound to observational prowess — and vice versa. In fact, many believe that what the hand cannot draw, the eye cannot see. This point was made by Henri Matisse, who taught himself to draw people in motion on the streets of Paris. He and a friend would sit outside and in just a few seconds try "to draw the silhouettes of passers-by, to discipline our line. We were forcing ourselves to discover quickly what was characteristic in a gesture, in an attitude." As Matisse knew well, observational facility was prized by his teacher, Eugène Delacroix. "If you are not skillful enough to sketch a man falling out of a window, during the time it takes him to get from the fifth storey to the ground," Delacroix is supposed to have said, "you will never be able to produce monumental work." Vincent van Gogh's goal, similarly, was to be able to draw "in such a way that it goes as easily as writing something down . . . to see in such a way that one can reproduce at will what one sees on a larger or smaller scale." The fact that van Gogh was able to produce some of his masterpieces within the space of a single afternoon demonstrates the acuity and facility he developed.

Writing also requires acute observational skills. e. e. cummings once characterized himself as a "wily observer of everything-under-the-sun," and, according to John Dos Passos, as the two men walked about town "he [cummings] would be noting down groups of words or scribbly sketches on bits of paper." Novelist W. Somerset Maugham believed similarly that "it is essential for a writer unceasingly to study men," and he meant not only their physical appearance but their conversation and their behavior. "You must be ready to listen for hours to the retailing of second-hand information," he advised, "in order at last to catch the hint or the casual remark that betrays." Indeed, according to writer Louise Morgan, Maugham was a "hunter" of human characters, interacting with people in much the way a scientist does experiments, to obtain more precise information. He was "winningly polite and attentive, but in an altogether impersonal way. . . . It is the sense of his catholic human interest that reconciles one to the scrutiny of his ruthless intelligence."

The importance of such observational powers in a writer should not surprise us. The development of a "true-seeming" plot depends upon a wide knowledge of how others respond to words, gestures, and deeds. The stimulation of sensation in the reader also depends upon an awareness of sensation in oneself. The writer not only lives experiences, he or she observes and analyzes them, too. The novelist Daphne Du Maurier once described a disturbing conversation she had in her teens when she suddenly realized she was operating on two planes of consciousness, one conversational and the other observational:

> Somewhere, buried in the unconscious of the eighteen-year-old, must have been the embryo writer observing, watching, herself un-

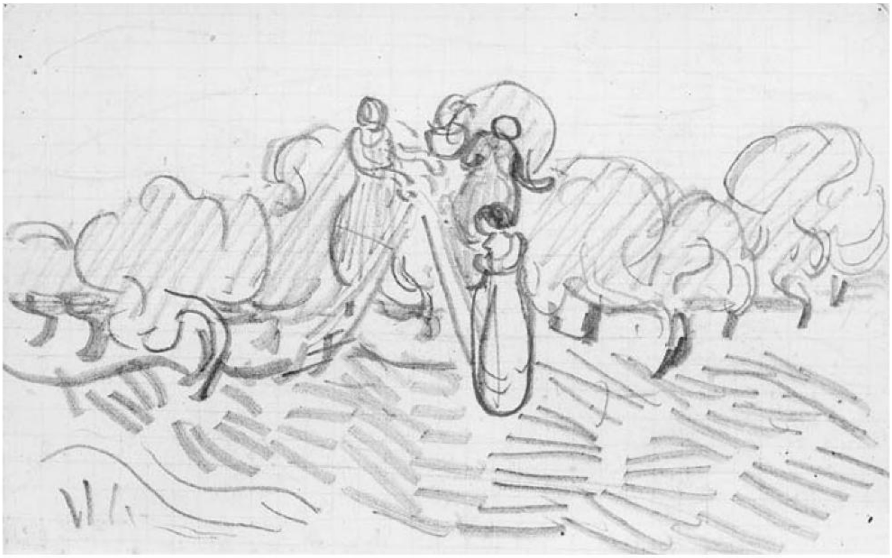


Fig. 3-3. *Women Picking Olives* by Vincent van Gogh.

> moved, noting the changing moods of a woman [her schoolmistress] dissatisfied with her mode of life and temporarily bored by her young companion. The seed of an idea, sorting itself from others, might take some five and twenty years or more to germinate and come to the surface, fusing with later observations, these observations in turn blending with characters from long-forgotten books, but finally a story or a novel would emerge.

Du Maurier's autobiographical volumes are, in fact, filled with events that she witnessed, stored away in memory, and later transformed into the details of her novels. A teenage crush on the much older Sir Basil Rathbone, for example, was worked into *Rebecca;* her homes, Ferryside and Menabilly, became the Manderley of that novel, and a real-life ship disaster that occurred nearby provided the flavor and some of the details of the plot.

Observation is equally the bedrock of the sciences. And, like Georgia O'Keeffe, many scientists believe that the secret to it lies in time and patience. Karl von Frisch, who decoded the dance language of bees, wrote that his ability to observe came from simply lying "for hours between the cliffs, motionless, watching living things I could see on and between the slimy green stones just below the surface of the water. I discovered that miraculous worlds may reveal themselves to a patient observer where the casual passer-by sees nothing at all." Konrad Lorenz, whose studies of geese, fish, and other animals revealed their hidden worlds, also commented on the need to indulge one's love of looking. "It is a pleasant urge. Those who have it want to look at animals, want to own them, to breed them. To really understand animals and their behavior you must have an esthetic appreciation of an animal's beauty. This endows you with the patience to look at them long enough to see something." Other scientists, such as geologist Nathaniel Shaler, at Harvard, were given exercises, much as Picasso was, that forced them to look at a specimen over and over until inobvious facts, for example, that in some fish the scale pattern differs on the two sides, became obvious.

However, simply looking, even patiently, is not sufficient. Part of seeing, as the camouflaged ptarmigan demonstrates, is knowing what to look at or for. Thus the real skill in hunting for fossils, according to paleontologist Elwyn Simons, is prompt and penetrating visual discrimination: "It's seeing order in a random background. . . . In the Egyptian desert where we hunt fossils, the desert surface is all covered with stones of all sorts and colours that have survived from wind erosion. It's called desert pavement or *serir* in Arabic . . . and if there's a bone with a tooth in it in that background it's not easy to see that in the pattern. I guess it's kind of comparable to some people who, if they're given a book in which some word occurs only once, can flip through and find it." Biologist Jared Diamond, an expert on tropical birds, believes that anyone who wishes to do fieldwork must "learn to . . . detect a bird just as a quick bit of motion that's different from the motion of a leaf in the treetops." Anyone who has gone bird watching in the woods, insect collecting through the fields, or fossil hunting on banks of shale will understand the point that he and Simons are making. Like Delacroix, Matisse, and van Gogh, scientific observers must learn to see the essence of things in an instant.

But observation, scientific and otherwise, goes well beyond the visual. As a scientist, Diamond depends greatly upon aural observation, too. "In the jungle in New Guinea, you hear most birds, you don't see them, and so you have to be good at identifying birds by sound. Since I'm musical, it happens that I have a good ear for bird sounds. . . . One morning I took [two colleagues] out into the rainforest. . . . We got out there before dawn, and by 7:30 A.M., I had identified fifty-seven bird species for them, but we had not yet seen a single bird." If this feat seems hard to believe, consider that composer Olivier Messiaen, who incorporated bird song into his music, could recognize at first hearing some 50 species of birds in his native France and another 550 species from around the world after a bit of reflection and consultation with his manuals. Most people learn to distinguish by sound at least fifty-seven different types of musical instruments and can identify all of their friends merely by their voice on the telephone. Professional musicians can even identify the "voices" of different examples of the same type of instrument. People who are deprived of sight — as Diamond was by the very density of the jungle — often do even better. The eighteenth-century novelist Henry Fielding had a sightless half-brother named John who, as a magistrate in London, was said to be able to identify more than three thousand criminals by their voices alone.

Being deprived of one sense can indeed sharpen our reliance on others, though not their actual acuity. We learn to use sensory stimuli that we usually ignore, and sometimes such heightened attention results in original insights. Biologist Geerat Vermeij's entire career is testimony to this fact. When Vermeij lost his sight as a very young boy, he was forced to rely upon his remaining senses. "The information they conveyed now meant something," he has written, "whereas previously I could afford to ignore it. My world was not black and hopeless. It sparkled as it did before, but now with sounds, odors, shapes, and textures. . . . Indeed, it is all these sensations that together provide a vivid, if nonvisual, picture of the world around me." Encouraged in his hobbies by family and teachers, Vermeij became particularly enamored of seashells and decided to become a professional conchologist. Now a professor of biology at the University of California at Davis, he makes frequent forays to the beaches of Africa, South America, and the South Pacific and is known worldwide for his evolutionary studies.

From the outset, Vermeij realized that his choice of profession required strong observational skills. "Much can be learned from books," he has noted, "but the knowledge thus gained is inevitably filtered through someone else's faculties. There simply is no substitute for making one's own observations in the wild." Vermeij replaced visual observation with tactile. "Observation by hand is particularly well suited to objects the size of most shells," he has noted, and it often leads to insights that can't be gained visually.

Vermeij's colleague Alfred Fischer remembers the day when Princeton professor Robert MacArthur was illustrating a lecture with the preserved skins of two birds. The birds looked virtually identical to sighted people, although one was from America and the other from Africa — an example of what evolutionary biologists call convergence. Vermeij, however, had no difficulty distinguishing them by touch. One of his secondary-school teachers had "felt strongly that we should know the shapes and characteristics of ducks, swans, owls, eagles, herons, gulls and other birds" by means of a collection of stuffed animals. "I don't find any resemblance," Vermeij said of MacArthur's specimens. "The beak and the feet are entirely different, and the very texture of the plumage sets them apart." So much for the objectivity of vision.

Vermeij has found that seashells hold secrets that only tactile observation can reveal. A sighted person will immediately observe that tropical shells tend to have bright coloration and intricate patterns, whereas shells from cold waters tend to be drab and unadorned. Vermeij, however, observes that tropical shells are chalky in texture while their cold-water cousins are hard and smooth. Why? he wonders. As Fischer says, Vermeij actually experiences shells differently from the rest of us: "Our eyes see mainly in two dimensions. Gary experiences form palpably in three dimensions, which provides him with a different, often advantageous perspective." Examples such as this should warn us against relying on any single sense as a basis for observation.

Fortunately, many disciplines train nonvisual observation skills. The nineteenth-century composer Robert Schumann believed that the ear's sensitivity to sound could be cultivated not only by musical training but by listening to everyday sounds. "Endeavor," he wrote to prospective students of music, "to distinguish tones and keys. The bell, the window pane, the cuckoo — seek to discover what tones they produce." Just as everyday visual observation can be useful to the artist, so aural observation can supply the musician with new musical ideas. Composer Georg Philipp Telemann recommended studying the improvisations of folk musicians, since "an observant person could pick up enough ideas from them in a week to last a lifetime." Many composers, including Zoltán Kodály, Béla Bartók, George Gershwin, Aaron Copland, and Darius Milhaud, not only observed folk musicians but perceived musical potentials in their themes that even their originators did not. Thus, Stravinsky argued that music itself, and modern music in particular, forces us to distinguish between hearing and listening in much the same way that modern art makes us look rather than simply see. "It obliges the *hearer* to become a *listener,* summons him to active relations with music." The hearing mind, like the seeing mind, must participate actively in observing.

Not surprisingly, looking and seeing, hearing and listening, have their equivalent in the distinction between passive movement and active motion in dance and other performing arts. Modern dance pioneer Doris Humphrey argued that the choreographer must be "a keen observer of physical and emotional behavior" and must have "a good eye and a sensitive ear" in order to create physical "images gleaned from close observation." "A dancer's art," agreed Martha Graham, "is built on an attitude of listening, with his whole being." Nor is this a skill to be practiced only in the studio, says dancer-choreographer Alwin Nikolais:

> In the final analysis the dancer is a specialist in the sensitivity to, the perception and the skilled execution of motion. Not movement but rather the qualified itinerary en route. The difference may be made even clearer by giving the example of two men walking from Hunter College to 42nd and Broadway [in New York]. One man may accomplish it totally unaware of and imperceptive to the trip, having his mind solely on the arrival. He has simply moved from one location to another. The other may, bright-eyed and bright-brained, observe and sense all thru which he passes. He has more than moved — he is in motion.

Actor-directors Konstantin Stanislavsky and Richard Boleslavsky argued similarly that the student of theater must, in Boleslavsky's words, learn "to notice everything unusual and out of the ordinary in every-day life. It builds . . . his sensory and muscular memory. . . . The only thing which can stimulate inspiration in an actor is constant and keen observation every day of his life."

Even smell and taste can have important roles in observation, as is clear in the cases of perfumers, aromatherapists, wine tasters, brewmasters, and chefs. Many other professionals also use these senses. Any baker can identify the pleasing smell of baker's yeast. It is less obvious that, as bacteriologist John Cairns admits, one of the attractions of his vocation is the smell of the bacterial colonies: "It is a rather nice smell. When you come into the laboratory in the morning there's this homely smell greeting you." In fact, many microorganisms can be identified by smell alone. One French microbiologist is famous among his colleagues for characterizing unknown cultures "by smell, sniffing at the culture tubes." You've done this sort of sleuthing yourself if you recognize the musty odor of mildew and the nauseating scent of rotten eggs. Chemists such as Primo Levi use their nose to identify chemicals, too. "I'm very glad that I educated my nose," Levi quipped once. Ecologist Tom Eisner agrees, having made dozens of discoveries by sniffing out the sometimes attractive, sometimes pungent chemical communication and defense systems of insects. "I'm essentially a nose with a human being attached," he jokes, noting that his father was a perfumer who taught him the importance of olfactory observation in their "redolent basement." Eisner even admits that as a child he would sniff strangers on meeting them, a habit some physicians, such as those at the Monell Chemical Senses Center in Philadelphia, also use for diagnostic purposes. Odors are clues to medical conditions as various as stress, which increases body odor; yeast infections; diabetic ketosis, in which the breath smells like acetone; and kidney disease, in which a person's breath may smell fishy from the buildup of ammonia-like compounds. We ignore such information at our peril.

Taste, too, can be diagnostic. Ancient physicians made a practice of tasting patients' pus and urine, which led to the discovery thousands of years ago that the urine of diabetics is sweet. Doctors nowadays verify this symptom with simple chemical tests, but as bacteriologist W. E. B. Beveridge recounted in *The Art of Scientific Investigation,* the old way still works: "A Manchester physician, while teaching a ward class of students, took a sample of diabetic urine and dipped a finger in it to taste it. He then asked all the students to repeat his action. This they reluctantly did, making grimaces, but agreeing that it tasted sweet. 'I did this,' said the physician with a smile, 'to teach you the importance of observing detail. If you had watched me carefully you would have noticed that I put my first finger in the urine but licked my second finger!'"

Of course, no physician today would dare put a body fluid of another individual in his or her mouth for diagnostic purposes, but taste is still sometimes used, purposefully or accidentally, in the laboratory and out in the field. One archeologist claims to be able to "date any Roman aqueduct by the flavor on her tongue of its crumbling masonry — she had tasted them all." Chemists discovered both saccharin and aspartame when they accidentally splashed these substances into their mouth or licked their fingers and realized how sweet their work really was.

The keenest observers make use of every kind of sensory information. In fact, the greatest insights often come to individuals who are able to appreciate the "sublimity of the mundane," the deeply surprising and meaningful beauty in everyday things. How many times have you gotten into the bathtub without really seeing that the water level rises? It took Archimedes to notice and connect the displacement of water with the density of objects. How many times have you hammered on something without really hearing the sound it makes? It took Pythagoras listening to blacksmiths at work to recognize the connection between the length of an object and its pitch, whether the material is an iron bar, the wooden bar of a marimba, or the string on a cello. And how many times have you looked at the sky and wondered why it is blue? This question led the eighteenth-century physicist John Tyndall to discover that the color of the sky is caused by light scattering caused by dust and other particles. He developed some of the techniques we use today to measure air pollution and water purity.

Biochemist Albert Szent-Györgyi discovered vitamin C by means of some equally mundane observations: "I suppose I was led by my fascination by colors. I still like colors; they give me a childish pleasure. I started with the question, 'Why does a banana turn brown when I hurt it?'" It turned out that plants have compounds called polyphenols that interact with oxygen to create the brown or black color — their equivalent of a scab. This observation led Szent-Györgyi to his next: "There are two categories of plants, you see — those that turn black on being damaged and those in which there is no color change. . . . Why no color in some damaged plants?" The answer was that those plants contained vitamin C, a sugarlike compound that prevents oxygen from oxidizing the polyphenols into brown or black protective compounds. You can actually gauge the vitamin C content of different fruits fairly accurately simply by noting which ones turn brown when damaged (for example, bananas) and which do not (oranges, say).

Discovering the sublimity of the mundane is not limited to scientific observers. Much of modern art has focused on rethinking the value of everyday phenomena. "The true creator," Stravinsky wrote, "may be recognized by his ability always to find about him, in the commonest and humblest thing, items worthy of note." In his pioneering choreographic work, dancer Merce Cunningham explored small-scale movements "found by watching people out the window of the studio in the street. . . . They were, mostly, movements anyone does when getting set to do a larger movement." Even awkward gestures have a beauty of expression begging to be discovered and exploited. Dancer Anna Halprin voiced the logical extreme of this view when she said, "Anybody's a dancer to me at any time when I am involved in communicating with that person through his movement." Mark Morris has made dances using everyday movements such as the gum-chewing, swagger-walking, ball-handling moves of a teenager on a basketball court. Morris makes us realize that all movement has a beauty and that everything has a meaning that is not necessarily obvious.

This is certainly the point of René Magritte's now classic painting "The Treason of Images" (1928–29), which depicts a pipe, with the written message "Ce n'est pas une pipe" (This is not a pipe). The apparent contradiction draws attention to the fact that the painting is not the thing itself any more than the word "pipe" is itself a pipe. For centuries Western art has had as its

Fig. 3-4. *Tea Bag* by Claes Oldenburg, 1966. "I often drop the bags I use when drinking tea, and the effect is that of a 'print.' . . . I always try to establish a corresponding effect outside of art for what I do in art."

goal a trompe l'oeil realism in which the retinal image created by the two-dimensional representation is identical to that cast by the three-dimensional reality. Nevertheless, the visual image is only a sign, not nature itself. Marcel Duchamp's "ready mades" — unaltered objects such as a snow shovel and a urinal — were an even more shocking reobservation of art. Think about what you see, his found objects say. Think most about what you tend to think about least. Many people claimed that Duchamp's objects simply poked fun at hundreds of years of artistic technique and development. Duchamp himself said, "I wanted to put painting once again at the service of the mind." If you bring your mind to it, you can see his point. In his wake, many artists, such as Jasper Johns and Claes Oldenburg, have asked us to look at flags, forks, plates, hamburgers, baseball bats, and tea-bag stains, not as everyday items but as things to be observed.

Observing, and rendering what we observe in some way, is indeed a function of the mind. We cannot focus our attention unless we know what to look at and how to look at it. As Harvard psychologist Rudolf Arnheim said in his 1969 book *Visual Thinking,* "The cognitive operations called thinking are not the privilege of mental processes above and beyond perception but the essential ingredients of perception itself." Consider an example. One day, preparing to go jogging, one of us (Bob) went to our closet for his typical name-brand white running shoes. On the closet floor he saw black dress shoes, brown shoes, sandals, pumps, slippers — everything except the running shoes. Clearly he must have put them somewhere else without thinking. But where? Then, just as he was about to ransack other closets, search under the beds, and crawl under the couch, the answer struck him. He was searching for something white, but the soles of his shoes were black! Instantly the shoes appeared, right where he had left them, invisible to a mind looking for something white. What he thought his shoes "looked like" influenced his ability to observe.

The mind's preconceptions can alter our other perceptual sensations, too. A simple example can be found in *Zap Science,* produced by the Exploratorium science museum of San Francisco. On page three of this stimulating book is a picture of a pizza covered with a removable piece of plastic labeled: "Mystery smell. Peel off and replace." The picture conjures in most people's minds the taste and smell of pizza. But, as the text says, "It doesn't smell like a pizza does it? It smells like . . . like . . . like . . . How come you can't think of the answer? Because we crossed up your mental wires. We put a picture of a pizza with the smell of a chocolate chip cookie. Messes up your brain." In fact, many who encounter the pizza picture find the cookie smell nauseating even though they like both pizza and chocolate chip cookies separately. Our mental expectations mediate perception just as certainly for touch, taste, smell, and hearing as for vision.

Because the "mind's senses" that control the "senses of the body" skew and filter what we experience, objective observation is not possible. As the novelist John Steinbeck and biologist Edward Ricketts wrote in their book on the marine life of Mexico's Sea of Cortez, "We knew that what we would see and record and construct would be warped, as all knowledge patterns are warped, first, by the collective pressure and stream of our time and race, second by the thrust of our individual personalities." Even in writing a nonfiction book, they understood that their version of the "truth" was just as subject to their preconceptions as was any novel. The same is undoubtedly true of this book. Our observations about what is significant about thinking are certainly filtered through our own mental biases and experiences.

So observing is a form of thinking, and thinking is a form of observing. In consequence, the purpose in practicing observation is to link sensory experience and mental awareness as closely as possible. As sculptor Beverly Pepper said, "I could draw anything, but drawing doesn't make you an artist. . . . Art is in your head. It's how you think, and what you think." Similarly, biochemist Szent-Györgyi argued, "Discovery consists of seeing what everybody has seen and thinking what nobody has thought." Observing is making sense of sensation.

Thus the mind must be trained to observe just as much as we train the eyes, the ears, the nose, or the hands. Clues as to how to do this come from one of the greatest fictional observers of all time: Sherlock Holmes, the violin-playing detective who, like a perfect artist, could size up a situation or an individual with a moment's glance. Holmes, the brainchild of physician Sir Arthur Conan Doyle, was based on the author's extraordinary pathology professor, Dr. Joseph Bell of the Edinburgh Infirmary. Bell was reputedly a man with the same wide learning, visual acuity, and deductive prowess of his fictional alter ego. It is therefore worth listening to Doyle when he has Watson say to Holmes in "The Greek Interpreter," "In your case, . . . from all that you have told me, it seems obvious that your faculty of observation and your peculiar facility for deduction are due to your own systematic training." The reader knows that this is true in part, because Watson explains in many of the novels and stories that Holmes relentlessly studied everything from types of tobacco and ink to poisons and soils, not to mention as many examples of the criminal mind as he could find. His mind was actively prepared to observe what his eyes saw, just as Bell's intense pathology studies prepared him to diagnose unusual causes of disease and death. But Holmes demurs. "To some extent," he answers Watson. "But, none the less, my turn that way is in my veins, and may have come with my grandmother who was the sister of Vernet, the French artist. Art in the blood is liable to take the strangest forms."

Indeed, there may be something to Doyle's tacit hypothesis that the arts train observational skills. As Herbert Read documented in his 1943 classic, *Education Through Art,* and as Maurice Brown and Diana Korzenik demonstrated in *Art Making and Education* (1993), teaching the visual arts has always been justified to some extent by its utility for increasing visual awareness. Some contemporary artists, such as Jasper Johns, continue to grant the arts such a role today: "Part of the activity of art is one of exercise, and an activity that keeps faculties lively, whatever the discipline touches on: the mind, the ear, whatever. And one hopes that by sharpening of such things and by an attempt to see the possibilities that are offered . . . that the senses we use in dealing with our lives will be in a state of readiness to deal with whatever may happen."

Personal accounts confirm this view. Louise Morgan once commented to artist and novelist Wyndham Lewis, "Your painting must help your writing." "It must of course do that," answered Lewis: "The habit of thinking of things in plastic and pictorial terms must have its influence upon the writer's art, when you practise both as I do. First of all, I *see!* The first — and last — thing that I do is to use my eyes. . . . The art of draughtsmanship is in the fullest sense a scientific study — it should help the writer of fiction. Anything that trains the mind to close observation should do that." Vladimir Nabokov similarly commented on the dramatic influence that learning to draw had upon his zoological and literary endeavors. The most rigorous of his drawing teachers, he recalled,

> made me depict from memory, in the greatest possible detail, objects I had certainly seen thousands of times without visualizing them properly: a street lamp, a postbox, the tulip design on the stained glass of our own front door. He tried to teach me to find the geometrical coordinations between the slender twigs of a leafless boulevard tree, a system of visual give-and-takes, requiring a precision of linear expression, which I failed to achieve in my youth, but applied gratefully, in my adult instar, not only to the drawing of butterfly genitalia during my seven years at the Harvard Museum of Comparative Zoology . . . but also, perhaps, to certain camera-lucida needs of literary composition.

It is not by accident, we conclude, that so many poets and novelists have had training in the visual arts, including William Blake, J. W. von Goethe, William Makepeace Thackeray, G. K. Chesterton, Thomas Hardy, the Brontë sisters, Mikhail Lermontov, Alfred, Lord Tennyson, George Du Maurier, Theodore H. White, J. R. R. Tolkein, Bruno Schulz, Ludwig Bemelmans, Henry Miller, and e. e. cummings. Even when a writer's interest in the arts is limited to the observation of forms and styles rather than active practice, as in the poet Robert Lowell's case, "that study seemed rather close to poetry. And from there I began."

Numerous scientists have also advocated art as a way to train observation, reiterating the theme that "that which has not been drawn has not been seen." As Santiago Ramón y Cajal, the great turn-of-the-century neuroanatomist, explained, "If our study is concerned with an object related to natural history, etc., observation will be accompanied by sketching; for aside from other advantages, the act of depicting something disciplines and strengthens attention, obliging us to cover the whole of the phenomenon. . . . It is not without reason [therefore] that all great observers are skillful in sketching." Sir Francis Seymour Haden agreed completely. Not only was he one of the leading anatomists of his day, he was also the founder of the British Royal Society of Painter-Etchers and Engravers. Haden made all of his anatomy students study art (just as the artists of the time had to learn anatomy) to develop both observational and manipulative skills: "How much sooner would the eye learn to gauge the aberrations as the signs that make up the *facies* [the general appearances characteristic] of the disease," he wrote. "How much better would the hand trained to portray them accurately be able to direct with precision and safety the course of the knife."

Indeed, many of our greatest scientists had formal art training, including Louis Pasteur, Joseph Lister, Frederick Banting, Charles Best, Albert Michelson, Sir W. Lawrence and Sir W. Henry Bragg, Mary Leakey, Desmond Morris, Konrad Lorenz, and Bert Holldobler. Although classes in drawing for scientists and doctors are much rarer today than in the past, there is still widespread recognition that, in the words of physician Edmund Pellegrino, "The clinician's craft begins with the eye — his essential diagnostic tool. . . . Clinician and artist are united in their need for a special visual awareness. Each sees; but for each, sight must transcend appearances. As Paul Klee puts it: 'Art does not render the visible; it makes visible.' The clinician must penetrate beneath the images to comprehend what ails the patient."

The observational benefits of training in the arts do not stop with painting or drawing. Writing and reading literature can be valuable for those who deal with people, whether in the social, legal, or medical professions. Physician John Stone points to the dual medical/writing careers of such fiction masters as Arthur Conan Doyle, François Rabelais, Anton Chekhov, John Keats, Somerset Maugham, A. J. Cronin, and William Carlos Williams. Many physicians, such as Oliver Sacks and Jonathan Miller, excel as nonfiction writers. "Physicians and writers," Stone argues, "draw on the same source: the human encounter, people and their indelible stories. And the works of both depend on skillful use of the senses. As with [Sherlock] Holmes, success rests with the powers of observation. . . . Literature, indeed, can have a kind of laboratory function. . . . The medical ear must be properly trained to hear stories — a medical history, after all, is a short story." "I believe that the writing of poems makes me a better medical practitioner," says physician-poet

Jack Coulehan. "Poetry demands a style of seeing and responding that enhances my ability to form therapeutic bonds with patients."

Observational skills can also be nurtured by the study of music. Recall that Jared Diamond attributed his ability to identify bird songs to his musical training. Other bird watchers have trained their ears by listening over and over again to recordings of bird songs, comparing and contrasting until very subtle differences become apparent. Indeed, the publisher of the Peterson Field Guides has issued several volumes of *Birding by Ear* — audiocassettes designed to teach identification of birds solely by their calls. A great deal of research shows that the ear must be trained to hear just as carefully as the eye to see. Musicians tell us that although some people are born with perfect pitch, it can also be acquired through practice. And the music critic knows that only by listening to innumerable performances and by comparing, comparing, comparing can one begin to observe the subtleties of style and quality that differentiate the greatest performers from the merely competent. Studies of physicians have even found that those who are best able to draw useful information from using a stethoscope or palpating (thumping a patient's chest and abdomen) are those who have had musical training or who actively practice their listening skills. Some cardiologists play high-fidelity recordings of different heart anomalies as they drive from one place to another.

The art-improves-scientific-observation equation works in reverse as well. Writers and artists can often benefit from the careful study of natural history, medicine, or anatomy. Somerset Maugham once averred that "no education was more useful to the writer than a curriculum of medical study. Not only will he *see* human nature in the raw and all that sort of thing in the outpatients' rooms, but he will get enough science for his purpose as a writer so that he won't be entirely ignorant of a side of life that is most important in this age." Poet Marianne Moore, who majored in biology at Bryn Mawr, also felt that her scientific training influenced her work: "Did laboratory studies affect my poetry? I am sure they did. I found the biology courses — minor, major and histology — exhilarating. I thought, in fact, of studying medicine. Precision, economy of statement, logic employed to ends that are disinterested, drawing and identifying, liberate — at least have some bearing on — the imagination it seems to me."

For all these reasons we advocate explicit observational exercises in classes in every subject. All students need to develop sensory acuity. Some museums conceal natural or artificial objects in cloth-covered holes and ask the visitor to observe and identify them by touch alone, and such exercises can be adapted to home and classroom. Blindfolded, we can find out about things by feeling and smelling them, as Geerat Vermeij does, observing the bark, leaves, flowers, seeds, and nuts of trees, the feathers of birds, seashells, different types of cloth, buttons, and dozens of other common things. We can guess at the identity of objects sealed in small boxes by observing their weight, the way they roll, bounce, or slide inside the box, and the sounds they make when the box is shaken. We can learn what it means to really smell and really taste herbs and spices without seeing them. Another simple exercise is to close one's eyes and construct what is going on nearby through sound alone. Walking around in the dark also tunes a person in to the sense of space and the sense of touch. Listening to television without looking at it or, conversely, watching with the sound off is also an educational experience in observing; all too often either the visual aspect or the sound is irrelevant.

Collecting things, whether stamps, coins, insects, buttons, baseball cards, postcards, books, photographs, prints, or paintings, is another excellent way to improve visual observation. The serious collector learns to make finer and finer distinctions in variation and quality, thus training both the eyes and the mind to acquire and evaluate knowledge. You can train your other senses by collecting rocks, shells, feathers, bones, fabrics, yarns, and fountain pens that appeal to the sense of touch. You can record bird songs or other animal sounds in your backyard, in the woods, at the zoo. Or collect city sounds, folk songs, rock music, or jazz. Keep mental lists of smells at the perfume counter or the grocery store. Learning to identify cheeses or chocolates or coffees or teas or wines from taste and smell alone is no simple feat.

We also need practice in noting the sublimity of the mundane. Like an actor studying with Stanislavsky or Boleslavsky, "collect all of your attention." Select an object, notice its form, its lines, its colors, its sounds, its tactile characteristics, its smell, perhaps even its taste. Then remove the object and recall one by one as many details as possible. Write about what you perceived or draw it. Go back and observe it again. "Such an effort," Stanislavsky wrote, "causes you to observe the object more closely, more effectively, in order to appreciate it and define its qualities." Or, like Picasso and Shaler, observe and describe the same object again and again, over a period of days, weeks, even months, refining your vision through practice.

And so we return to our opening exercise, describing a television. Look at your notes and ask yourself how much you missed the first time. Are all your descriptions visual, as they are for most people, or did you think to observe more broadly? Did you observe the sounds of the TV set: the clicks of the buttons; the odd *poing* as the tube is turned on or off; the tiny crackles as the static built up on the screen? What can you tell about the materials and construction of the TV by tapping it in various places? What about smells: the ozonelike whiff of the electric charge and the odor of warm electronic components, perhaps the scent of new plastic? Did you feel the TV? How do the textures of the different components differ? Did you notice the way the hairs on your arm or head stand up from the static electricity formed when the screen is being turned on or off? How do the sound reverberations feel? Can you distinguish the different operations of the buttons by touch? And how close to the set did you get when you looked at it? Close enough to see the tiny red, green, and blue dots that form the images? (Wet your finger with water and flick a little on the screen to form miniature magnifying lenses.) Did you notice that the height of the screen divided by its diagonal is very close to the golden mean (0.616: 1.000)? Did you see how the screen distorts and alters the shape and colors of your reflected image when the power is off? Are you an acute enough observer to have drawn or noted these things down in the time it takes a TV to fall from a window on the fifth floor?

There is so much to perceive in a mundane object like a television set that only by patient cultivation of ever-new ways of observing will you discover the possibilities. As artist and choreographer Oskar Schlemmer realized in 1942, near the end of his life, observing is a skill that returns ever more, the more you invest in it. "I have recently completed a series of pictures, inspired by what I see right around me: views from my window into its neighboring window, done in the evening between nine and half-past nine shortly before the blackout. When night is falling and clashes with the scraps of interior beige-orange-brown-white-black, it produces amazing optical effects. I am experiencing with unfamiliar intensity the mystic effects of nature, and I observe that with the passing years one keeps learning to see in new and different ways." If one of the objects of education is to produce lifelong learners, what better recommendation for practicing the skill of observation could one want?

4

Imaging

THE NAME CHARLES STEINMETZ is not as well known as that of Alexander Graham Bell or Thomas Edison, yet his impact on modern life is as great. Steinmetz was the inventor of electrical generators, transformers, and other equipment that made possible the general distribution of electricity. Because of him, Bell's telephones and Edison's light bulbs became common household items. Colleagues at General Electric who knew his contributions intimately called Steinmetz "the Supreme Court" because, in their view, problems he couldn't solve were simply impossible. So in 1894 a couple of engineers approached him with a puzzler they had unsuccessfully worked on for weeks: "If you take a rod two inches in diameter and cut it [in half] by drilling a two-inch hole through it, what is the cubic content of the metal that's removed?" The problem was important; for any cost-conscious company, drilling holes in expensive metals means wasted material and monetary loss.

As the story goes, these men expected Steinmetz to sit down at his desk, pull out some paper, draw some figures, and begin a series of lengthy calculations. His first concern, they knew, would be to determine the shape of the core removed by the drill, which they had been unable to do. It isn't a ball and it isn't a rod; it's a sort of lozenge. Without knowing the shape, you can't figure out its dimensions or calculate its cubic content. Steinmetz's colleagues had every faith in him, but even they were surprised when the Supreme Court simply took a few extra puffs of his cigar and said, "The answer, gentlemen, is 5.33 cubic inches." Amazingly, he had seen the whole thing — the shape of the plug that would be produced, its dimensions, and the subsequent calculations — in his head.

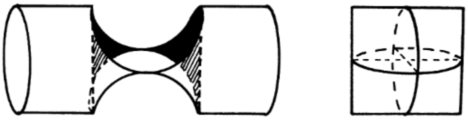


Fig. 4-1. The shape of the rod and hole imagined by Steinmetz.

Steinmetz had an extraordinary ability to visualize — to imagine the look of things not physically before his eyes. He shared this ability with other people of great accomplishment, such as his colleague and competitor Nikola Tesla, inventor of the first workable alternating-current motors and generators. Tesla related in his autobiography, "When I get an idea I start at once building it up in my imagination. I change the construction, make improvements and operate the device in my mind. It is absolutely immaterial to me whether I run my turbine in my thought or test it in my shop. *I even note if it is out of balance.*" More recently Elmer Sperry, the inventor of gyroscopic stabilizers and related mechanisms for ships and airplanes, has been described as typically "just looking into the air, when all at once he would pick up a pad and hold it at arm's length, then with a pencil in the other hand he would begin to draw. . . . 'It's there! Don't you see it! Just draw a line around what you see.'"

Inventor James Lovelock, best known for inventing the concept that the earth is a single interconnected organism, is also a skilled visual imager. Lovelock's interest in integrative systems began when he invented an ultrasensitive instrument capable of analyzing the chemistry of atmospheric changes caused by living processes. Lovelock, like Tesla, credits his success to visual imagination: "What I tend to do is to wake about five in the morning — this happens quite often — think about the invention, and then image it in my mind in 3D, as a kind of construct. Then I do experiments with the image. . . . Sort of rotate it, and say, 'well what'll happen if one does this?' And by the time I get up for breakfast I can usually go to the bench and make a string and sealing wax model that works straight off, because I've done most of the experiments already."

Not surprisingly, numerous studies have found significant correlations between the aptitude for visual imaging and career success in engineering. Historian Brook Hindle described the role of visual imaging in his 1981 book *Emulation and Invention,* an examination of the invention process of men such as Samuel Morse and Robert Fulton — both of whom, significantly, were excellent professional painters. In *Engineering and the Mind's Eye* (1992) engineer Eugene Ferguson argues that nonverbal imagery plays a central role in invention in general, as does Henry Petroski in his 1996 book *Invention by Design.* Indeed, imaging benefits people in all professions.

Psychologists now recognize three basic types of visual thinkers. To determine what kind of visual thinker you are, try imagining a triangle. Do whatever it takes to image that shape in your mind. How did you do it? Some people cannot "see" a triangle in their minds until they draw it on a piece of paper or trace its outline on a table with the end of their finger. Some people need to close their eyes, apparently because seeing interferes with their visual imagination. When their eyes are closed, however, they can "project" the triangle on the inside of their eyelids. Did your eyeballs move as you drew the triangle? Some rare individuals can bring up the image of the triangle with their eyes open, superimposing the triangle on whatever they are looking at. A subset of this latter group can make the triangle change size, color, and perspective; they can make it twirl, jump, and pass through other figures. Steinmetz and Tesla clearly fell into this last category.

Triangles are simple, however. For those who really want to take a shot at Steinmetz's and Tesla's "thought," consider some additional problems that require the mental construction of three-dimensional visual images:

A. What object has a round profile from the top and from the sides?
B. What object has a square profile from the top and the sides?
C. What object has a triangular profile from all sides?

If you answered sphere, cube, and tetrahedron, you're on the right track. Keep going!

D. What object has a round profile from the top and square profiles from the sides?
E. What object has a square profile from the top and triangular profiles from the sides?
F. What object has a triangular profile from the top and square profiles from the sides?
G. What object has a round profile from the top and triangular profiles from the sides?

And now, for the really skilled visual thinkers, some more complex shapes.

H. What object has a round profile from the top, a round profile from one side, and a square profile from the other?

I. What object has a triangular profile from the top and circular profiles from the sides?
J. What object has a circular profile from the top, triangular from one side, and square from the other?

In case you are wondering, all of these objects do exist (even the last one) and we offer some of the possible answers as figures at the end of the chapter. In fact, H — an object that is square from one side and round from the others — describes the shape of the plug drilled out of the rod that Steinmetz had to imagine. The rod is round; the drill is round; but a vertical section of the plug viewed lengthwise along the rod is square. We strongly suspect that Steinmetz solved his rod problem with ease because he had played the kind of visual game we have just demonstrated and already knew the answer.

By visualizing various combinations of squares, rectangles, circles, ellipses, and many-sided polygons, you can generate every basic geometric solid that exists. And if you like this sort of thing you can try more complicated imaging problems, such as those proposed by Max Wertheimer in his 1959 book *Productive Thinking.* But if you find such exercises difficult, don't despair. Although some people have a greater proclivity for visual imaging than others, everyone benefits from practice. So even if you need to draw images or model them at first, working with these problems will train your visualizing ability. The more you practice, the more you will be able to partake of and understand the visual thinking process of countless inventors, mathematicians, physicists, artists, writers, and dancers.

Imaging, in its broadest sense, is a common thinking tool in many fields. Indeed, there is a statistically significant correlation between professional success and visual thinking among scientists as well as inventors. Ann Roe, who pioneered the study of visual thinking in scientists, reported that one of her famous subjects — probably her husband, George Gaylord Simpson — saw all of evolution in his mind as if it were a motion picture. Nobel laureate and biologist François Jacob reported that he began each day by mentally recreating his room, then his house, then his neighborhood, and eventually the entire world while lying in his bed with his eyes shut. Sir James Black, a pharmacologist and Nobel Prize winner, says that the focus of his thinking "is an imaginative sense, entirely open-ended and entirely pictorial. That is a vital part of my life. I daydream like mad. . . . You can have all these [chemical] structures in your head, turning and tumbling and moving." Another Nobelist, chemist Peter Debye, has written that "I can only think in pictures." Richard Feynman also noted the elaborate visions in his mind. "It's all visual," he explained to one interviewer. "[I see] the character of the answer, absolutely. An inspired method of picturing, I guess." As Feynman made clear, he worked at refining the visual image *as the answer to a problem* well before translating his solution into mathematical equations. "Ordinarily I try to get the pictures clearer, but in the end the mathematics can take over and be more efficient in communicating the idea of the picture. In certain particular problems that I have done [however] it was necessary to continue the development of the picture as the method before the mathematics could really be done." Similarly, astrophysicist Margaret Geller of the Harvard-Smithsonian Center for Astrophysics has said, "I think that not all scientists have to have a visual image, but I do. I can't do a problem unless I have a visual image. That's how I solve problems."

For many people, including scientists, being a good visualizer ties in with being artistic. Geller, for example, says, "I'm also generally visual. I'm very aware of visual cues in my environment. I have a good visual memory, and I am very observant. So it's not so separate from the way I am in general. I have an interest in the visual arts. I think that had I not been a scientist, I probably would have done something in design." Geller is far from rare among scientists in manifesting both visual ability and an interest in the arts, as we noted in Chapter 3. In fact, in a study of forty scientists, including several Nobel laureates, we found a high correlation between artistic avocation, visual thinking ability, and scientific success. Those who visualize well in their science often visualize in artistic pursuits as well, each activity feeding the other.

Not surprisingly, artists of all sorts also depend upon visual imaging. This may seem obvious in the case of painters, who express themselves with color, line, and form, but not all painters refer as explicitly as Georgia O'Keeffe did to their mental imaging of these elements. Shortly after meeting the photographer Paul Strand, O'Keeffe wrote to him that "I believe I've been looking at things and seeing them as I thought you might photograph them — Isn't that funny — making Strand photographs in my head." Ansel Adams's entire process of photography also relied on imagining what the final print would look like before the negative was ever exposed. But visual imaging in art is not necessarily tied to pictorial expression. It may deal with visual aspects of movement, for instance, or verbal description. According to the American choreographer Anna Sokolow, the dancer's visualizing "in terms of movement" was analogous to the painter's visualizing "in terms of color, line, mass." Countless of Martha Graham's students (and Sokolow was one of them) have described her teaching and composing as "flooded with imagery" meant to "awaken our imagination" and "guide the quality of the movement." Stuart Hodes, who studied and taught with Graham for many years, recalls her urging students to see "the French film *Farrabique,* a story of birth and death on a French family farm. She particularly wanted us to notice the stop-motion sequences of plants growing. 'Watch how they spiral upward toward the sun,' she said. 'Life flows along a spiral path.' Soon I noticed that spirals were being emphasized in many of our technical moves and introduced into others."

Imaging is also an important tool for thinking among writers. Poet Stephen Spender, who described writing poems as working through the "logic of the images," found that his poems often began with "a very vivid memory, usually visual, which suggests that it could be realized in concentrated written language." As we discussed in Chapter 1, such imagistic thinking is common among poets. Dryden declared that "imaging is in itself the very height and life of poetry," while the dreamy visionary Samuel Coleridge wrote to one friend that "a whole essay might be written on the danger of thinking without images." And Siegfried Sassoon said, "Thinking in pictures is my natural method of self-expression. I have always been a submissively visual writer." More recently, Pulitzer Prize–winner Donald Murray discovered by using himself "as an experimental rat" that he was not the "linguistic" thinker he had always supposed. Rather, he found his thinking to be "imagistic, a process of seeing, then recording the language."

Many writers of fiction are visualizers. Charles Dickens declared that he simply "saw" his stories and then wrote them down. By the same token, Tennessee Williams said that *A Streetcar Named Desire* originated from a single image: "I simply had the vision of a woman in her late youth. She was sitting in a chair all alone by a window with the moonlight streaming in on her desolate face, and she'd been stood up by the man she planned to marry." Vladimir Nabokov had a photographic memory, which allowed him in student days to absorb reading assignments in a matter of minutes. Later he would imagine, step by step, every aspect of his life, from the daily errands run by his mother when he was a child to the behavior of his characters and the unfolding of plot.

Indeed, as we noted in Chapter 3, it is not uncommon for writers who are also professional or amateur artists to foresee literally the action of a book. Thackeray, for example, made notes for his books not only in writing but with pencil and brush, as did the Brontë sisters, Antoine de Saint-Exupéry, Edward Lear, George Du Maurier, Wyndham Lewis, D. H. Lawrence, and J. R. R. Tolkien. G. K. Chesterton actually cartooned the action he wished to

Fig. 4-2. *Enraged Gentleman and His Victim,* sketches for a story, by G. K. Chesterton.

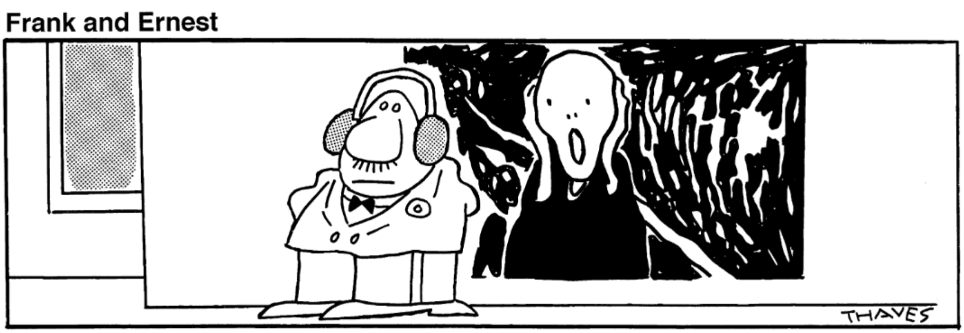
put into words, as his sketches for "Enraged Gentleman and His Victim" show. In the early stages of planning *Tropic of Capricorn,* Henry Miller, another artistic writer, visually charted the book's themes and events. And Marianne Moore, who went to college intending to become a painter, discovered she liked writing poetry and plays even better, especially since she "could visualize scenes." Imaging obviously goes beyond seeing simple geometric forms to recreating people and environments.

Clearly, inventors, scientists, and artists of all kinds find visualizing to be an important thinking tool. But conjuring visual images is only one of many types of imaging. In their 1990 book *Images and Understanding,* Horace Barlow, Colin Blakemore, and Miranda Weston-Smith make the point that images may be perceived and communicated not just as pictures, but in many other, nonvisual ways: "Artists, designers and engineers share an age-old problem, how to move facts and ideas from one mind to another: how are these mental transfusions achieved? Through the use of *images* — not just in the form of pictures and diagrams but with words, demonstrations, even music and dance." We not only see with the mind's eye, we hear with the mind's ear, imagine smells and tastes and body feelings — and any or all of these sensation pictures may be involved in the imagination and communication of images. To put it another way, if we observe with our eyes, we form a visual image. If we observe with our hands, we form a tactile as well as a hand-position, hand-movement image. If we observe with our nose, we form a smell image that may play a major role in scientific or artistic invention. What we can observe, we can imagine; what we imagine, we image.

Despite the fact that people use a wide range of images in their professional work, very little research exists documenting nonvisual imaging abilities, especially those involving smell and taste. Occasionally a perfumer discusses the smell ideas that went into a perfume. Occasionally a master chef like Charlie Trotter or Pierre Hermé reveals that the "finished taste" of a dish is cooked up in the imagination before it is cooked up in the kitchen. "When I create a cake," says Hermé, "I put the flavors and texture together in my mind. . . . I already know what it will taste like before it comes out of the oven." Occasionally a writer finds "the actual idea of a novel," as Nabokov put it, springing from "such actual sensations as the melting of a biscuit on the tongue or the roughness of a pavement underfoot." That the evidence of smell and taste imaging is meager only means that we tend to privilege vision over these senses in our imagination, as we do in observing things. The case for thinking in nonvisual images is much stronger for kinesthetic body imaging, explored in Chapter 9, and for aural imaging, considered here.

The same simple "test" that determines visual imaging capabilities can be applied to aural imaging. Can you "hear" the scream of Edvard Munch's image? Do you hear anything when you read: "Twinkle, twinkle little star"? Do the words sound in your mind? Do you hear a certain melody? Now try to

Fig. 4-3. An example of aural imaging. Cartoon by Tom Thaves.



hear a scale of notes in your head. "Do, re, mi, fa, sol, la , ti, do." Did you hear silently? Did you have to hum or sing to get started? No doubt you are reading in a fairly quiet environment. Do you think you could hear the scale of notes with the radio on or at a crowded party? If you're one of those who have little "pure" aural imagery and have to hum a song or play the notes on an instrument to recreate sounds or tunes in your mind, you are in good company. As Aaron Copland pointed out, "The layman's capacity for imagining unheard sound images seems, by and large, to be rather poor." Few of us can read a musical score and hear the music in our minds. Casual musicians may be able to create a reliable internal image of music that they have played before. People without musical training may hear much less.

Some people, however, have no trouble hearing both notes and the words that go with them. And some, like those who can see triangles change color, move, and so forth, are able to hear the tune backward as well as forward, in different keys and different rhythms. Indeed, a few people who are highly skilled in aural imaging can hear entire symphonies in their mind in the same way great inventors can visualize entire machines. Wolfgang Amadeus Mozart, for example, once wrote, "The whole, though it be long, stands almost complete and finished in my mind, so that I can survey it, like a fine picture or a beautiful statue, at a glance. Nor do I hear in my imagination the parts *successively,* but I hear them, as it were, all at once."

Even Beethoven, who is often contrasted with Mozart as a slow, methodical, plodding, pen-and-paper composer, said, "I carry my thoughts about with me for a long time, often for a very long time, before writing them down. . . . I change many things, discard others, and try again and again until I am satisfied; then, in my head, I begin to elaborate the work in its breadth, its narrowness, its height, its depth. . . . I hear and see the image in front of me from every angle, as if it had been cast [like a sculpture], and only the labor of writing it down remains." Beethoven's mastery of mental imagery surely explains how he was able to compose some of his greatest music long after he had become profoundly deaf. He still heard sounds in his mind even if his ears no longer perceived them. Indeed, sonorous images seem very much the stuff of all composition, whether or not the composer ever actually hears his or her music performed. "The most perfect [musical] instrument in the world," the American composer Henry Cowell has said, "is the composer's mind. Every conceivable tone-quality and beauty of nuance, every harmony and disharmony, of any number of simultaneous melodies can be heard at will by the trained composer; he can hear not only the sound of any instrument or combination of instruments, but also an almost infinite number of sounds which cannot yet be produced on any instrument."

Thinking in sound also explains the "silent practicing" of top-notch musicians — they imagine performing their music much as athletes mentally rehearse their moves. Pianist Alicia de Larrocha says that when she is waiting in airports, "my mind is filled with music, and I'm hearing what I am going to play, and I'm practicing, every note, every phrase, every harmony, practicing my left hand." For much the same reason David Bar-Illan practices on a muted, soundless piano. "Do understand," he adds, "that during my soundless practicing I do hear the music in my mind." In similar fashion the dancer Martha Graham, after deep immersion in music, would practice her dances "in silence to the music I now felt in my body as well as heard in my mind."

As Graham makes clear, most imaging is actually polysensual. The dancer enacted the music she heard in her mind, as did de Larrocha and Bar-Illan. Moreover, kinesthetic and aural imaging is often accompanied by visual images. The American composer George Antheil, self-proclaimed "bad boy of Hollywood" during the 1930s, recounted that mental images and dreams were the primary sources of many of his musical compositions. A particularly prophetic dream accompanied by specific sounds of airplanes and giant factories found their way into his *Ballet Mecanique* (1924) in the form of airplane propellers, fans, sirens, electric bells, and other mechanical devices, all used to create "music." Stravinsky's compositions also began as detailed images of specific situations or actions. "In composing the music [for *Petroushka*]," he recalled, "I had in mind a distinct picture of a puppet, suddenly endowed with life, exasperating the patience of the orchestra with diabolical cascades of arpeggios. The orchestra in turn retaliates with menacing trumpet blasts. The outcome is a terrific noise which reaches its climax and ends in the sorrowful and querulous collapse of the poor puppet." When he wrote a polka dedicated to the ballet impresario Sergey Diaghilev, Stravinsky thought of his friend "as a circus ringmaster in evening dress and top hat, cracking his whip and urging on a rider." In both *Petroushka* and the polka, Stravinsky stated explicitly that musical themes accompanied his visions and provided the basis for his compositions.

For many musicians, visual and aural imaging involves mentally storing entire musical scores. Tenor Luciano Pavarotti recently confessed to an interviewer on National Public Radio, "I am studying with the music in my head, more than on the piano, singing the real stuff. . . . You have to see the music, you have to see the difficulty going on in a piece, so you have to put the thing in your head, photographically speaking, exactly like it is." Similarly, George Antheil had the ability — shared with Mozart, Beethoven, and many other composers — of hearing music and simultaneously seeing its written notation in his mind's eye. On one trip to northern Africa he wrote down local folk songs as they were played. "To hear was with me to see in music notes," he explained. "I needed only to hear a tune, however complicated rhythmically or melodically, to see it in my mind's eye on paper." Transcribing music "at sound" into notes usually strikes the layperson as nothing short of miraculous, as does the reverse, transcribing notation into music "at sight." Composer Arthur Honegger recalled that the question he was asked most frequently was, "You look at the notes and you really hear what is there?" For most musicians the answer is invariably yes. In fact, Copland believed that "the ability to imagine sounds in advance of their being heard in actuality" profoundly separated the professional from the amateur and especially from the nonmusician. In some cases, indeed, the talent can be almost supernormal. Henry Cowell actually preferred reading scores to listening to performances because he had complete control over the sounds in his mind in a way that he could not in real life.

Actually, there is no miracle here. Musicians and composers develop their aural-visual transcription abilities in much the same way that children and adults around the world learn to connect sounds to letters — by daily practice. Indeed, learning to read is a good model for aural imaging in general, since almost all people "hear" inside their mind their own voice speaking the words on the page. Writers often develop this skill to a high degree, as poet Amy Lowell did: "I always *hear* words even when I am reading to myself. . . . In writing, I frequently stop to read aloud what I have written, although this is really hardly necessary, so clearly do the words sound in my head." Taking internal speech several notches higher, Tennessee Williams imagined the different voices and speech patterns of his stage characters: "I have a good inner ear. I know pretty well how a thing is going to sound on the stage, and how it will play. I write to satisfy this inner ear and its perceptions." Williams took his imagery to extremes, often acting out all the parts as he developed his plays. "When I write," he said, "everything is visual, as brilliantly as if it were on a lit stage. And I talk out the lines as I write. When I was in Rome, my landlady thought I was demented. . . . 'Oh, Mr. Williams has lost his mind! He stalks about the room talking out loud!'" She didn't understand that Williams was simply expressing what he was experiencing in his mind.

Scientists also combine visual, kinesthetic, and aural images in their thinking. We noted in Chapter 1 that Einstein relied heavily on visual and kinesthetic images, but he appears to have relied on aural images as well. Many of his relatives recalled that he regularly played the violin or piano when he became frustrated with physics. "Whenever he felt that he had come to the end of the road or into a difficult situation in his work," wrote his son, "he would take refuge in music, and that would usually resolve all his difficulties." While developing the general theory of relativity, he frequently emerged from deep thought, played the piano, made a few notes, then disappeared back into his study. "There, now I've got it," his daughter Maja remembered him exclaiming as he got up from his piano. He even told his friend Shinichi Suzuki, the famous Japanese music teacher, "The theory of relativity occurred to me by intuition, and music is the driving force behind this intuition. My parents had me study the violin from the time I was six. My new discovery is the result of musical perception." In fact, Einstein called his piano "my old friend, through whom I say and I sing to myself all that which I often do not admit to myself at all."

The same multiple imaging is manifest in the work of Richard Feynman. When queried about his problem-solving techniques, Feynman listed visualizing, of course, but also kinesthetic imaging, "acoustic" — what we call aural — imaging and, like Tennessee Williams, talking to himself internally and verbalizing out loud. Family and colleagues often heard Feynman muttering, rhyming nonsense words, humming, or voicing clicks and whoops as he translated physical intuition and equation into sound. Presumably he heard but also felt the rhythmical nature of the physics in some way that was analogous to his experience as an avid bongo drummer.

We say presumably, because even though we know that imaging plays an important role in the thinking of many creative individuals, we do not necessarily know how it works in each case. Imaging is largely a private and personal shorthand of sights, sounds, and other sensations, ranging from realistic representations of phenomena to idiosyncratic abstractions and sensory associations. Moreover, different people rely more or less heavily on imaging. In some cases, a particular kind of imaging is so critical to an individual's way of thinking that he or she will purposefully choose work that draws upon that mental skill. Astrophysicist Margaret Geller says, "I have to have a visual model or a geometric model or else I can't do it. Problems that don't lend themselves to that I don't do." This sort of imaging proclivity may explain the styles and strengths of other inventive people as well.

In fact, Geller's choice of problems according to her imaging ability is known to apply to her peers as well. Physicist Peter Carruthers, also a visualizer, makes a broad distinction between those who are "pictorial" and those who are "mathematical." Physicists who are more mathematical don't share what Carruthers calls his "physical intuition" or his visualizing tendencies. In fact, about half of the eminent astrophysicists interviewed by Alan Lightman and Roberta Brawer in *Origins* (1990) said that they were not aware of using visual images. In various areas of the physical sciences, such as quantum mechanics, visualizing is actually discouraged by leading practitioners. Freeman Dyson has compared the strictly symbolic approach in this field to attaining fluency in a new, formal language; one understands quantum mechanics when one doesn't try to translate it into some other perceptual form or "tongue," but comprehends it directly, mathematically, the way musicians "hear" the meaning of written notes without the aid of an orchestra.

The dichotomy in science between those who think visually and those who do not was first noticed at least a century ago by Henri Poincaré. Poincaré, who wrote extensively on scientific creativity, used the example of four colleagues, Karl Weierstrass, Georg Riemann, Sophus Lie, and Sofya Kovalevskaya — a who's who of nineteenth-century mathematicians — to make his point: "Weierstrass leads everything back to the consideration of series and their analytic transformations; . . . you may turn through all his books without finding a figure. Riemann, on the contrary, at once calls geometry to his aid; each of his conceptions is an image that no one can forget, once he has caught its meaning." Lie "thought in pictures. Madame Kovalevskaya was a logician." The distinction in mathematics between imagers and nonimagers continues today. Feynman purposefully converted algebraic problems into geometric ones, asking himself, "Is there a way to *see* it?" In contrast, astronomer Fred Hoyle, who confesses to being a poor visualizer, has said, "I had to do all my geometry algebraically." (For a further discussion of algebraic versus geometric thinking, see the Appendix to this chapter.)

Poincaré realized that individual imaging preferences have important implications for the way we teach mathematics and other scientific subjects. "Among our students," he wrote, "we notice the same differences; some prefer to treat their problems 'by analysis,' others 'by geometry.' The first are incapable of 'seeing in space,' the others are quickly tired of long calculations and become perplexed. The two sorts of minds are equally necessary to the progress of science." Indeed, the two types of minds are necessary to every discipline. Moreover, if some people do algebra geometrically and others do geometry algebraically; if some people use equations to conceive reality and others use pictures; and if these pictures can combine visual with aural, as well as with olfactory and gustatory senses and bodily feelings, then we would do well to complement our usually abstract pedagogy with multi-imaging approaches to knowledge.

Everyone should be introduced to a wide range of imaging skills and be given the opportunity to master as many of these as possible. Fortunately, imaging skills can be learned and improved by exercise. At the Kanton Schule attended by Einstein, students practiced the ABC's of visual thinking as rigorously as the ABC's of language. The school's founder, Johann Pestalozzi, believed that visual understanding must in fact precede all other forms of education, and he argued in his classic didactic novel of 1801, *How Gertrude Taught Her Children,* that words and numbers must subsequently be firmly connected to this preestablished visual foundation. The young Einstein was thoroughly schooled in what modern scientists would call "thought experiments": seeing and feeling a physical situation almost tangibly, manipulating its elements, observing their changes — all of this imagined in the mind.

Other creative people have been encouraged to exercise their imaging skills by perceptive parents and supportive home environments. Margaret Geller's mother nurtured her artistic inclinations, and her father her ability to visualize three-dimensional objects. The imaging skills of Nobel Prize–winning chemist Peter Mitchell grew out of his interest in building things in his brother's workshop. "When I was a small boy . . . ," he has said, "I was always making little engines and things. I suppose that helped my development as a thinking person, because of the relationships between shapes. That's something I've kept in chemistry, of course. . . . You're concerned with the relationships in space of atoms." Such childhood experiences are common among many eminent scientists and inventors. Not everyone may have the extraordinary potential of a Steinmetz or a Tesla, but everyone benefits from the development of imaging technique that comes with hands-on experience in arts or crafts, or with simple mental practice.

Such lessons can be effective even after childhood. Engineering students at Auburn University in Opelika, Alabama, were tested for their visual thinking ability at the beginning of one semester. The tests revealed that the group was clearly divided between geometric or visual thinkers and analytical-algebraic types. All the students were then given an intensive course in two- and three-dimensional drawing as well as projection techniques. By the end of the course, those whose natural aptitude was analytical or algebraic tested nearly as high on the visual-thinking test as the "natural" visualizers. These results and similar ones from universities such as MIT, where Woodie Flowers teaches imaging skills, or Stanford, where Robert McKim teaches visual thinking, suggest that any kind of formal training in design, draftsmanship, drawing, painting, or photography can improve adult visualizing skills.

Sometimes the simple challenge to think concretely about abstract concepts can be effective. Caltech biologist James Bonner commented that he first learned how to visualize scientific situations from his chemistry professor, Roscoe Dickerson: "He told us this and he told us every day: 'You've got to really understand what you are doing.' . . . If we were plotting something, we had to see what this physically represents. All of a sudden, I learned to be able to physically visualize problems that would otherwise be abstract, or physically visualize the meanings of equations and things like that." Many teachers in the arts similarly exercise their students' visual imaginations. Nabokov counseled that good readers, who are as necessary to art as good writers, must actively "see" as they read; they must "visualize the rooms, the clothes, the manners of an author's people." One can learn to do this by paying close attention to visual, aural, proprioceptive, and other sensations daily. Imagination, after all, draws on experience.

Aural imaging skills, too, can clearly be learned by practicing. Roger Sessions notes that the degree to which one can mentally conceive a composition improves as one acquires musical skill: "The experience, I believe, is quite different for the mature and experienced composer from what it is for the young beginner. As he grows in practice and imagination it assumes an ever more preponderant role, and appears more and more to be the essential act of creation." To develop this aural skill, Harold Shapero advises would-be composers to begin by imagining accompaniments to well-known pieces and then comparing the results with the originals. Such training exercises the mind's ear and the mind's eye.

Listening to poetry and literature read out loud can also improve imaging skills, according to poet Amy Lowell. Perhaps this is one reason that reading to young children has been found to stimulate their intelligence. Listening to poetry and stories builds up their internal voices and frees their eyes from the page so they can concentrate on creating sensual images. Indeed, listening to literature read out loud is a good idea at any age, whether the reading is in person or on tape. As wonderful as television, movies, videos, and computer animation are in providing us with aural and visual "pictures," there is a corresponding danger that those who rely too completely on such prefabricated images will lose or never develop the ability to imagine their own.

Interestingly, aural practice with mathematical and scientific language can also result in a heightened imaging ability, as Norbert Wiener, inventor of cybernetics — the science of information theory — learned firsthand. As a child, he developed severe eye problems and was not able to read for six months. "Father went ahead teaching me mathematics, both algebra and geometry, by ear, and chemistry lessons went on. This period of ear training rather than eye training was probably one of the most valuable disciplines through which I have ever gone, for it forced me to be able to do my mathematics in my head and to think of languages as they are spoken rather than as mere exercises in writing." No one, of course, would recommend severe illness to improve imagistic thinking, but consider the advantages of learning a visual subject without seeing its symbols. Having once drawn a geometric figure on paper, draw it in your mind. When the images and feelings attendant in such imagining are connected with the sounds of the terms used to describe them, a deeper and broader understanding is awakened. If necessary, written and oral instructions and physical and mental drawing can be alternated, improving the connections among them.

Everything we have suggested here for the encouragement of imaging in education, from the earliest grades to the last stages of professional schooling, holds for individual self-training. Young or old, we can work on our imaging abilities just as we work on our observing skills. The steps are simple. First, recognize your own use of visual, aural, and other images. Do you see with your mind's eye just where you left your keys? Do you imagine the story you are reading as if it were a movie, as if you were acting in it, as if you were hearing it on the radio? When you imagine a banana or snow or a cat, can you see, hear, smell, and (even!) taste them all?

Second, indulge yourself. Image on purpose and to your heart's content. If you like to visualize, reimagine scenes from your favorite movie; better yet, rewrite and "resee" the movie so that it is perfect and perfectly your own. Try your hand at visual puzzles, such as those in the puzzle book *Pentagames.* If you like to think in images of sound, try to remember and hear in your mind not just the melody but the harmonies of your favorite song or concerto.

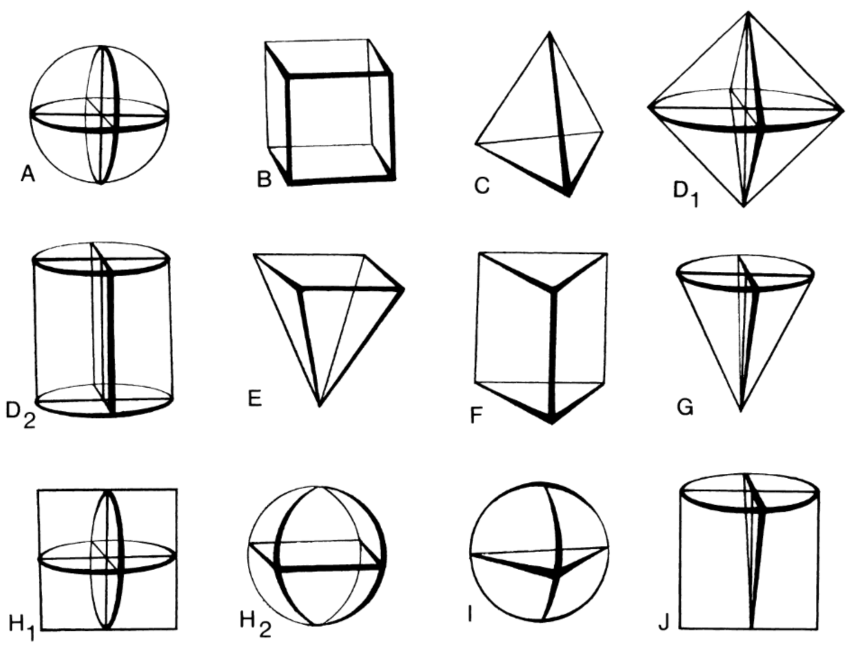
Third, take up an art. But don't just learn *about* music or dance or painting or cooking. Learn to make drawings, songs, poems, or gourmet dishes. In many of these activities imaging is part of the process of doing. Chances are you won't choose a color for your painting without thinking in color; you won't pick out a melody on the piano without thinking about and in sounds; you won't create a chicken dish without thinking about and in what tastes fair with fowl. Work at imagining these processes before you do them and at remembering them afterward. Finally, make up excuses to use your inner eye, your inner ear, your inner nose, your inner sense of touch and of body. Have someone pose math and science problems verbally for you; practice hearing different voices and seeing different physiognomies when you read a play; pay attention to what you feel and imagine as you listen to music. Like any skill, imaging becomes stronger and quicker with consistent and persistent practice.

There is, however, one downside to becoming a dexterous imager: the better one's skill, the more frustrated one may become in trying to present images directly to other people. The need to translate through another medium can be painful. This is why Henry Cowell preferred his mental renderings of scores to live musical performance and why Einstein found the formal communication of his ideas through mathematics to be, in his own word, "difficult." The immediacy and completeness of the original conception, with its attendant images, feelings, and emotions, is lost, attenuated, or distorted. Many creative people have consequently voiced a desire for ever more direct forms of communication. For artist Max Bill, the answer is a new form of art: "Mental concepts are not as yet directly communicable to our apprehension without the medium of language, though they might ultimately become so by the medium of art. Hence I assume that art could be made a unique vehicle for the direct transmission of ideas, because if these were expressed by pictures or plastically there would be no danger of their original meaning being perverted."

Composer Charles Ives was less sanguine about the ability of art, even musical art, to fill this role: "My God!" he wrote in his *Essays,* "why can't music go out in the same way it comes in to a man, without having to crawl over a fence of sounds, thoraxes, catguts, wire, wood and bass?" Novelist Margaret Drabble also questions the necessary translation of subjective images into objective forms of communication. "Writers, like painters, tend to think in pictures," she has written, and though visual art, literature, and film can "suggest . . . private, interior mental images," this communication, however skillful, is still indirect. Drabble imagines a kind of dream machine "that can record my dream pictures as they occur, so that, on waking, I can retrace the narrative." Nikola Tesla had the same thought with reference to real, waking time: "It should be possible," he conjectured, "to project on a screen the image of any object one conceives and make it visible. Such an advance would revolutionize all human relations. I am convinced that this wonder can and will be accomplished in time to come; I may add that I have devoted much thought to the solution of the problem."

Not to be outdone, numerous science-fiction enthusiasts have also envisioned a future of image-melding minds. Witness the numerous *Star Trek* episodes featuring "empaths," whose interpersonal communications are integral and instantaneous, or the disturbing film *Strange Days,* which explores the abuses of vicarious, virtual experience. But for better or for worse, no one has yet made such science fiction science fact. We remain in that "primitive" state in which all mental images must still be translated through other mediums, be they words, music, movements, models, paintings, diagrams, films, sculptures, or mathematical treatises. And perhaps we ought not to complain. To our lack of direct-imaging abilities we owe the human world of expressive artifacts.

Fig. 4-4. Solutions to geometric imaging problems. Note that some of the problems have more than one solution. You may discover yet more!



APPENDIX

On Algebraic versus Geometric Thinking

What are we to understand by Feynman's statement that he treated algebra problems geometrically and Hoyle's that he treated geometric problems algebraically? A concrete example may help.

A classic word problem concerns a man rowing a boat when his hat falls into the river, which is flowing at 3 kilometers per hour downstream. He is rowing upstream 2 km per hour faster than the stream is taking him down. He discovers his hat is missing one half-hour after it has fallen in the river. If he turns around and rows back at the same speed relative to the river to fetch his hat, how long will it take to catch up to it?

The algebraic approach to this problem is to abstract out the key parameters in order to set up an equation and solve for the unknown. The hat is dropped and moves at 3km/hr for 0.5 hrs, so it travels 1.5 km downriver. The man rows at 2km/hr upriver for 0.5 hrs, so he travels 1 km upriver. The man is therefore 2.5 km from his hat when he discovers its loss. He reverses course. In order to travel at 2km/hr upriver, he had to be moving at 5km/hr relative to the river, so if he rows at the same rate downriver, his total velocity will be 5km/hr plus the 3km/hr that the river moves, or 8km/hr. The hat, meantime, is still moving at 3km/hr downriver. Let t be the time necessary for the man to catch his hat. Then the time it takes the man to catch his hat is $(8\text{km/hr})t = 2.5\text{km} + (3\text{km/hr})t$, the distance between the man and the hat plus the distance the hat moves while the man is catching up to it. Solving the equation yields $(8\text{km/hr})t - (3\text{km/hr})t = 2.5$ km, or $t = 0.5$ hr.

The geometric approach to this problem is to visualize it. A good visualizer will realize that this class of problems can be solved using a simple relativistic trick. Instead of imagining a man riding on a boat moving upriver, imagine you are riding the river as if it were a swiftly moving train. Suppose you drop your hat as you are walking through one of the cars in the same direction the train is traveling. You walk for thirty seconds before you discover your hat is missing. You turn around and walk back through the cars till you find your hat. How long will it take if you walk that distance at the same constant speed? Thirty seconds, obviously. The fact that the train or the river is moving with respect to the ground outside turns out to be irrelevant to the physical problem. Treating the river as if it were a train and the man in the boat as if he were walking on the river/train quickly yields thirty minutes as the solution to our problem, as before.

Although the algebraic and geometric approaches clearly yield equivalent results, the methods are equally clearly different. Algebraicists might accuse geometricians of not having proven their answer, since no calculations or theorems are evident. Conversely, geometricians might accuse algebraicists of resorting to calculations when the answer is intuitively obvious. Most people prefer one method almost to the exclusion of the other.

Einstein's and Feynman's conundrum was that they thought as geometricians but needed to communicate their results in analytical, algebraic forms to satisfy the rigorous demands of physical proofs. Hoyle's problem was that his algebraic formulations had no obvious meaning for visual geometricians like Geller, whose astrophysical studies were meant to test his theories. Very few people can switch with ease or alacrity between the two approaches, although such transformations are often at the heart of new breakthroughs, a point we expand upon in Chapter 14, Transforming.

5

Abstracting

Abstractions are so common in our society that we rarely pay attention to them. We have all seen abstract art. We read abstracts of books and articles. We often label ideas or theories as abstractions because they lack the full body of real things. Nevertheless, the process of abstracting remains largely mysterious, and many of its products go unrecognized. A challenge will help you realize the truth of this statement. We would like you to put aside this book for a few minutes to abstract an orange in as many ways as you can imagine. Then abstract a human being. Again, create as many abstractions as you can. Once you've given our challenge some serious consideration, read on.

Don't feel bad if you had problems figuring out where to begin or how to proceed with this exercise. Experience has taught us that even professional artists, writers, and teachers often have difficulty with it. They can identify abstracting when they see it, but very few can actually tell you what makes abstract art abstract. Even fewer can create imaginative abstractions themselves. Most people who do this exercise come up with trite visual abstractions: oranges that are circles colored orange; stick figures or bodiless heads that look like happy faces. Few people try to abstract the motion or the sound or the smell or the tactile feel of an orange or a human being, let alone their chemical composition or their biological role in the web of life. Nor do they think to express these kinds of abstractions in music, dance, words, or numbers instead of drawings, though any and all of these mediums can be used to express abstractions. Clearly, the process of abstracting is neither perceived to be general nor generally understood.

Perhaps some masterly examples will help. The first emerged in 1927 as

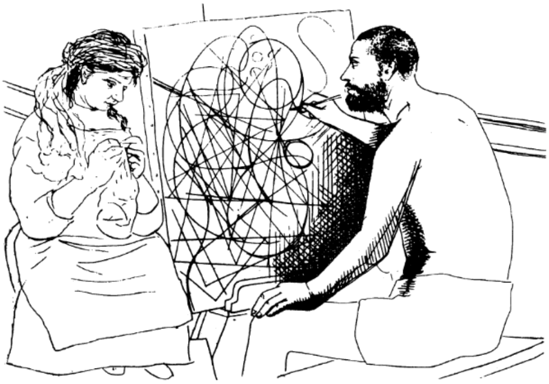
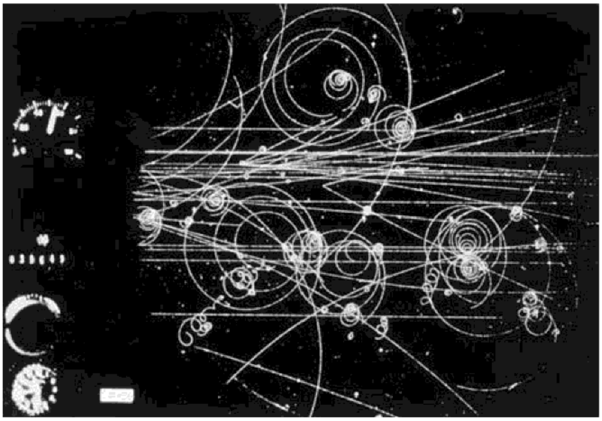


Fig. 5-1. *Artist and Model, Cahiers d'Art* by Pablo Picasso, 1932.

Picasso sketched his companion, Marie-Thérèse Walter, while she was knitting. He drew himself drawing her, and included in the picture the canvas upon which he sketched as well. The picture is thus a drawing of the process of drawing, one of Picasso's favorite themes. It is illuminating, particularly as the portrait of Marie-Thérèse looks like little more than a series of apparently random lines and curves. What was Picasso after?

At about the same time, the physicist C. T. R. Wilson was taking photographs of subatomic particles. Most of us would expect these particles to look like little bits of some larger mass. In fact, the pictures Wilson devel-

Fig. 5-2. Particle tracks in a bubble chamber, 1970.



oped bear an uncanny resemblance to Picasso's portrait of Marie-Thérèse: a bunch of spirals and curlicues that in three dimensions might look like bizarre springs. Such photographs would eventually earn Wilson a Nobel Prize. But what had these images to do with atoms?

Several decades later, one of Picasso's fans and artistic followers, e. e. cummings, produced a similarly puzzling work. In his case, the work was made of words rather than lines, and it looked like this:

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A casual glance at Picasso's etching, Wilson's photograph, or cummings's poem is likely to yield little more than confusion. The problem is that each is so incredibly simple that it is difficult to perceive its structure. But once you understand what the artist, the scientist, and the poet were about, the meanings become crystal clear. Equally surprisingly, one realizes that cummings's poem is surely the verbal equivalent of Picasso's "Artist and Model," just as thunder is the aural equivalent of lightning. Moreover, Wilson's photograph is like an afterimage of each. All three men eliminated everything except one key element from their observation and thinking. They reduced complex visual, physical, or emotional ideas to bare, stripped images, revealing, through simplicity, the power of purity. In other words, they abstracted.

Physicist Werner Heisenberg defined abstracting as "the possibility of considering an object or group of objects under one viewpoint while disregarding all other properties of the object. The essence of abstraction consists in singling out one feature, which, in contrast to other properties, is considered to be particularly important." His definition applies to any discipline, as Picasso made clear in describing the purpose of one of his abstract paintings: "I want to say the nude. I don't want to do a nude as a nude. I want only to say breast, say foot, say hand or belly. To find the way to say it — that's enough." His goal, in other words, was to find the minimum visual stimulus that can be put on paper or canvas and still evoke recognition without spelling everything out. He searched for the essence of visual language, just as Heisenberg searched for the principles of nature.

The key to understanding Picasso's abstraction of Marie-Thérèse is to realize that abstractions may not represent whole things but one or another of their less obvious properties. Picasso decided to focus his attention not on his model but on the space she inhabited. It is essential to the interpretation of this picture that we recognize that, unlike most models, Marie-Thérèse was in motion. Her knitting needles swung back and forth, in and out. She had to adjust her skein of wool, perhaps reach down to pick it up if it dropped, look at her pattern. Picasso has therefore drawn the curves that her head, hands, elbows, shoulders, and body swept out as they moved through space. It is as if he had attached luminescent markers that left a trace in the air as she moved — an idea, by the way, that had already occurred to various other people interested in motion, as we shall soon see. The result is a complex picture. On the one hand, Picasso tells us from his realistic portrayals of himself and his model that he could have drawn her realistically if he had wanted to. He did not. There is, his portrait says, another reality that is also Marie-Thérèse, one that is just as interesting and significantly more unexpected. You are looking, Picasso admonishes us, but you are not seeing. Don't just look — think! Find the surprising properties hidden behind the obvious ones. See with your mind, not your eyes!

Seeing with the mind is also the key to understanding Wilson's photograph. In this instance, one must understand the technique he used to capture the odd images in his photograph. He had invented an instrument called a cloud chamber to study the formation of clouds. In essence, Wilson created a saturated atmosphere of water vapor in a special box to which was attached a large piston. When the piston was drawn out, the pressure and temperature dropped, causing the water vapor to condense. As a physicist, Wilson was interested in the conditions that best favored the formation of his clouds, and he soon realized that the presence of ions — charged particles — helped the process immensely. It then occurred to him that subatomic particles, such as electrons and protons, are charged and that they could cause the water vapor to condense in the cloud chamber, creating tracks of water droplets as they passed. If the entire cloud chamber was placed within a strong magnetic field, one could tell, by the direction in which the subatomic particles twisted in the field, whether they were positively or negatively charged. Thus his photograph shows not the particles themselves, but the tracks left by charged fragments of atoms moving through a magnetic field, much as Picasso's picture shows the tracks of his model through space. From both one can make certain inferences about the subject's physical and dynamic properties — but only if one recognizes that the experiment has yielded not a portrait, but an abstraction.

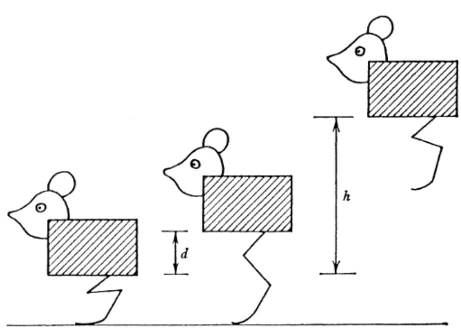
The poem by cummings is as powerful an abstraction as Picasso's and Wilson's. In fact, it is related to them. Picasso, who was enamored of Chinese ideograms, once said, "If I were born Chinese, I would not be a painter but a writer. I'd write my pictures." Just as Wilson's reputation came from forcing subatomic particles to leave their handwriting on the wall, as it were, cummings's reputation as a poet rests largely on the fact that he figured out how to force words to write pictures — in English and without resorting to ideograms.

Consider cummings's poem not just as letters and words but also as an image. The poem begins with the letter l, which can also be read as the number 1. This letter/number is the essence of cummings's abstraction. He plays on both meanings. He also plays with the structure of the poem on the page, calling his creations "poempictures." The words must be seen as well as heard, and their pattern on the page studied as carefully as the syntax. Thus, when cummings says in parentheses, "a leaf falls," you are expected to notice that the fragments of words on the page mimic this falling, forcing the reader's eyes back and forth across the page as if one were following the pendular fall of the leaf itself. (This is a technique cummings had used in other poems, such as "Grasshopper," in which the reader's eye must jump back and forth across the page.) Then the word "one" appears, reiterating the opening letter, followed by l again, and then "iness," which may be read, particularly in cummings's lowercase alphabet, as "I-ness" — the I being one, alone, single, like a leaf falling from the communal home of the tree. Moreover, combining the initial letter l with the one, l, and iness at the end of the poem (in other words, deleting the parenthetical phrase) yields "loneliness" — the state of the leaf that has left its fellows in the tree; the state of the individual, alone. Or, knowing that cummings often invented words, one can read just the letters after the parenthesis, which form the word "oneliness" — the state of being one. Perhaps equally profoundly, the whole poem appears on the page as a 1, with all of its connotations of oneness, loneliness, and I-ness synthesized in its form. So much meaning in so few letters!

Oddly, although all abstractions are simplifications, the best abstractions are like Picasso's, Wilson's, and cummings's in that they yield new and often multiple insights and meanings, using simplicity to reveal inobvious properties and hidden connections. Moreover, experience suggests that the simplest abstractions are often the hardest to perceive or devise and at the same time yield the most important insights. Take mathematics, for example, a field that is nothing but abstractions. The very concept of number is as abstract as one can get, for it can be applied to anything, anywhere, anytime. It can be manipulated without reference to reality — hence the universal power of computing. "Nothing" itself is an abstraction, zero representing that which does not exist and yet holding the place of everything that could. Mathematical physicist Paul Dirac has argued, "Mathematics is the tool specially suited for dealing with abstract concepts of any kind. There is no limit to its power in this field." And mathematicians Philip Davis and Reuben Hersh go so far as to suggest that abstracting "is almost characteristic [of] or synonymous with intelligence itself."

Every scientific theory or principle is a surprisingly powerful and insightful abstraction. Just think about the implications of the fact that any object in a gravitational field can be represented by a point mass — an infinitely small point having all of the mass of the real object — regardless of the object's shape, size, density, color, texture, consistency, or constitution. Physicists can even treat a mouse as a point mass perched atop a spring, to represent its legs, and come up with an equation that very accurately describes how high that mouse can jump. Similarly, the concepts of velocity, acceleration, temperature, density, and so forth are abstractions so universal that

Fig. 5-3. Abstraction of a jumping mammal.



they can be applied to any object anywhere. And, like Picasso's portrait of Marie-Thérèse and Wilson's portrait of subatomic particles, these properties are not at all apparent. One must learn to see past the obvious reality that we observe through our senses to perceive them with the "eye of the mind."

Language, too, is shot through with abstractions. Many words, such as love, truth, honor, and duty, represent very complex concepts. The writer abstracts these and other words from a plethora of possible texts to make a singular statement. But the abstractions of literature run deeper than this. As Samuel Johnson said, "The business of a poet . . . is to examine, not the individual, but the species; to remark general properties and large appearances. . . . [To do so he] must neglect the minuter discriminations" that do not characterize the group. A great deal of literary abstracting leaves important things unsaid as well, novelist Willa Cather pointed out. "Whatever is felt upon the page without being specifically named there — " she wrote, "that, one might say, is created. It is the inexplicable presence of the thing not named, of the overtone divined by the ear, but not heard by it, the verbal mood, the emotional aura of the fact or the thing of the deed, that gives high quality to the novel or the drama, as well as to poetry itself." Elsewhere she concluded, "The higher processes of art are all processes of simplification. . . . That, indeed, is very nearly the whole of the higher artistic process; finding what conventions of form and what detail one can do without and yet preserve the spirit of the whole."

The language of the body is also abstract. Indeed, it is so basic that body talk, like arithmetic, can bridge the most disparate cultures. People all over the world resort to pantomiming whenever verbal language fails. We make faces, use gestures, act out our desires. We invent games such as charades to test our miming abilities — and often find our skills none too good. We therefore applaud the amazing abilities of a Marcel Marceau. We pay top dollar to see the purified languages embodied in a Japanese *no* drama or a Western ballet or modern dance, in which meaning has been reduced to a gesture or a movement. Martha Graham characterized her dance "Appalachian Spring" as wholly abstract, and Oskar Schlemmer wrote to his friend Otto Meyer, almost paradoxically, "I have observed that involvement with abstraction increases one's sensitivity to reality." In dance, as in all other disciplines, abstraction gets at essences and purifies concepts, yielding, in the words of sculptor Henry Moore, "the greatest directness and intensity."

That essential directness pervades every aspect of our lives. We abstract great orchestral and pop music when we whistle a tune — a bit of the main theme dissected from its rich tapestry of notes. We abstract when we give a quick summary of a good book we've just read. We use abstractions when we choose the television program we intend to watch from the one-line plot descriptions given in *TV Guide* or the newspaper. We rely on abstractions in the form of newspaper and magazine headlines to determine whether to read a particular article. Students often resort to the work of professional abstracters who provide brief summaries of classics such as Shakespeare's plays in the form of Cliff Notes and its competitors. Caricatures are abstractions; so are a person's initials. Even epigrams are a type of abstraction, embodying in a few words the experience and wisdom of ages: "A stitch in time saves nine."

All of these — numbers, words, gestures — are so basic, so simple that they seem unremarkable. Indeed, the essence of abstractions is that we say to ourselves, "My kid could do that." It is easy to forget that although we learn to use these abstractions, few of us could invent a new mathematics, discover a new law of nature, devise a new way of portraying perception, develop a new gestural language, or describe a fundamental truth about human feelings. Such triumphs are rare and difficult to achieve. Picasso commented repeatedly on how difficult it was for him to learn to draw simply and directly. He had to learn the process step by step. The notebooks of e. e. cummings similarly show how hard he worked to achieve his simple effects. It is so much easier to see and convey the complexity and confusion of reality.

Indeed, abstracting is difficult for people in every discipline. Many famous novelists — Mark Twain and Ernest Hemingway come to mind — have written to their editors that they regretted the extreme length of their manuscripts; if they had had more time, the work would have been half as long. Winston Churchill is supposed to have said that he could talk for a day with five minutes' notice but needed a day to prepare if he had only five minutes in which to speak. The poet Edwin Arlington Robinson shifted from writing short verse to lengthy works as he got older, remarking, "I am over sixty now, and short poems require too much effort." The essence of writing, these individuals say, is not putting words on the page but learning to recognize and erase the unnecessary ones. Teachers know that preparing lessons for introductory students is much more challenging than teaching advanced students because the basics are so much more difficult to master and simplify. Similarly, when one reads a brilliantly simple paper in science, it is all too easy to pass it off as inconsequential. But as Harvard biologist George Wald once said to Nobel laureate Albert Szent-Györgyi after reading one of his typically lucid and simple papers, "This paper of yours is so lightly written that you must have sweated terribly."

There is much truth to Wald's words, not only for the writing of science but for its principles as well. Indeed, we point out at the start of every science class a very interesting fact: even the simplest textbooks written for secondary-school students are based on the achievements of the greatest names in science, such as Galileo, Newton, Darwin, Pasteur, Mendel, Curie, Watson, and Crick. If you think about it for a moment, this is truly surprising. One would expect the most important developments in science to be the most complex, but in fact, they are always the simplest. As physicist and inventor Mitchell Wilson wrote half a century ago, "I'll tell you what you need to be a great scientist. You don't have to be able to understand very complicated things. It's just the opposite. You have to be able to see what looks like the most complicated thing in the world and, in a flash, find the underlying simplicity. That's what you need: a talent for simplicity."

From fundamental simplicities spring basic theories. And each basic theory is exactly analogous to cummings's poem in which the concept of I/l/1 has a multitude of possible interpretations and applications. Abstracting, by simplifying, yields the common links, the nexuses, in the fabric of perception and nature. But seeing through the complexity of reality to discover these simple principles often takes the greatest genius. As Picasso said, "Whatever is most abstract may perhaps be the summit of reality," and as Werner Heisenberg wrote, "The step toward greater generality is always itself a step into abstraction — or more precisely, into the next highest level of abstraction; for the more general unites the wealth of diverse individual things." Richard Feynman put it more simply still in one of his notebooks: "Phenomena complex — laws simple. . . . Know what to leave out."

Knowing what abstracting is and why it is so important, though, is only half the problem. The other half is learning how to find the simple concepts hiding among complex expressions. How do you do it? Fortunately, many creative people have left detailed records of how they invented their abstractions. One mistake many people make is to begin by ignoring reality. Bridget Riley, an artist famous for her nonrepresentational and op-art paintings, tells us that abstractions must evolve from something real. Bryan Robertson, a writer and art lecturer, once said to Riley, "I like Gertrude Stein's funny remark quoted in *The Autobiography of Alice B. Toklas:* 'I like a good view, and I like to sit with my back to it.' I think that's probably the best approach to nature for most artists working abstractly." Riley replied succinctly, "She should be shot." Observing that natural view is a first and important step for any artist. Even for someone like Riley, whose purpose in painting is to awaken "recognition of the sensation without the actual incident that

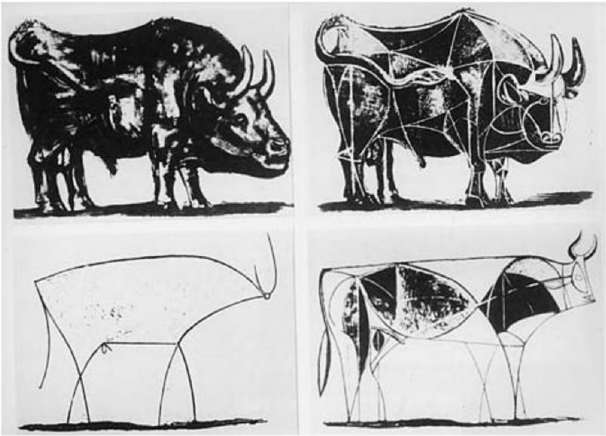


Fig. 5-4. *The Bull* by Pablo Picasso, 1946. *Clockwise from upper left:* second, fourth, eighth, and eleventh states.

prompted it," the sensation must first be experienced and understood and then purified.

Picasso also cautioned other painters, "To arrive at abstraction, it is always necessary to begin with a concrete reality. . . . You must always start with something. Afterward you can remove all traces of reality. There's no danger then, anyway, because the idea of the object will have left an indelible mark. It is what started the artist off, excited his ideas, and stirred his emotions." True to his word, Picasso began his well-known *Bull* series with a realistic image of a bull. Then he became interested in the planes defining the bull's form. But as he experimented with these planes, he realized that what defined them were their edges, which he then reduced to simple outlines. Finally, he eliminated most of these lines, leaving a pure outline that still conveys the essence of "bullness." Note that the head, which is massive in the original print, has become insignificant in the final print, yet we still have no difficulty recognizing the image as a representation of a bull. For Picasso, bullness was not in the size or shape of the head but in other very simple features, such as the horns. None of this was obvious at the outset. Other, less evident discoveries become manifest if one compares Picasso's bull series with another made many years later by Roy Lichtenstein, which can be seen in Randy Rosen's wonderful 1978 book, *Prints.* Lichtenstein used the same theme but developed his abstraction in a very different way, thereby revealing other aspects of bullness than Picasso's prints focus on.

Because abstracting is a tool, it has multiple uses. Just as two artists may find very different ways to represent bulls, so there may be many ways of abstracting any object or idea that will reveal different fundamental aspects of it. Often the result depends upon the properties that are observed and simplified. The painter Ellsworth Kelly, for example, tends to focus on color and plane, as in his 1973 painting *Yellow with Red Triangle,* which consists of a large oblique rectangle of bright yellow to which is attached a slightly smaller equilateral triangle in red. When asked how he came up with the idea for this apparently simple painting, Kelly explained that "the shape of the two panels was abstracted from something I observed in the architecture of a house near my studio. The sloping roof of a house became a yellow rectangle placed on a diagonal; the dormer window on this roof seen from the side became the red triangle. . . . Everywhere I look, I see relationships — forms and colors. And I break them down to the bare essential forms." The process of looking, drawing, and painting, often from various angles or viewpoints, always begins with "the world rather than my own invention." For Kelly, abstracting comes down to discovering the simplest relationships between form and color in things that he observes.

Henri Matisse also abstracted in his own way. Late in his life he was confined to his bed, unable to paint because of chronic illness. Nevertheless, finding that he could manipulate scissors with some agility, he produced his famous cutout collages. A set of snails particularly illuminates his methods. We know that Matisse, like Picasso, could draw realistic-looking snails if he wished. His scissors suggested novel ways of abstracting them. In one case he imagined what would happen if one cut a snail shell along the lines of its curvature, then flattened it out as if it were a piece of paper. Another inspiration led him to portray the essence of "snailness" as a spiral formed by a series of hinged blocks of paper. In both cases, his object was to focus our attention on the snail's articulation of a complex shape.

Fig. 5-5. Sketches showing basic abstractions employed in *The Snail* by Henri Matisse, 1952 and 1953.

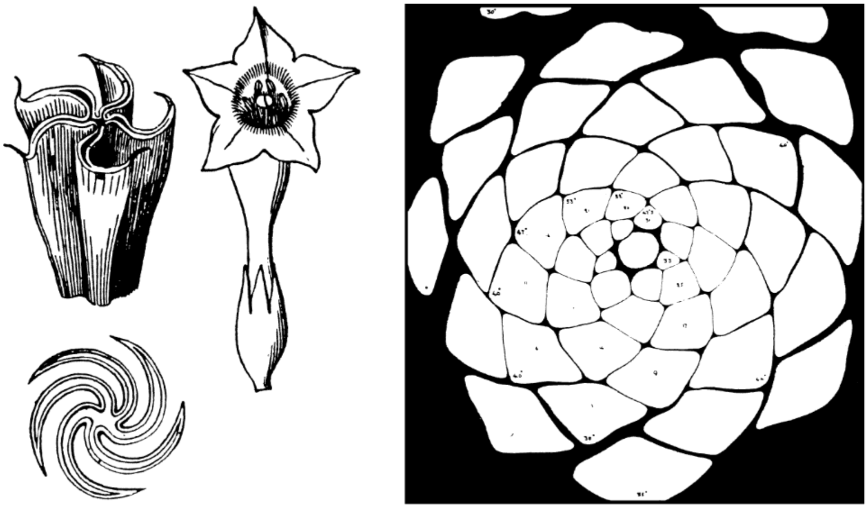


Fig. 5-6. *Left: Stramonium,* showing the flower, the corolla, and a cross-section of the corolla; *right:* Transverse section of the apex of a seedling pine.

The lesson we may draw from Matisse, Kelly, Picasso, and Lichtenstein is that many abstractions are possible for any given object, each of which illuminates some hidden truth. One might even say that reality is the sum of all possible abstractions and that in coming to know these possibilities, we understand reality better. This is a lesson scientists, too, have learned. Like Matisse, biologists have often found it useful to "cut" — sometimes literally — the objects of their study into various forms to study their fundamental structures. Thus, nineteenth-century botanists such as Asa Gray frequently characterized flowers by means of a series of abstract sections, none of which, singly, looks like the flower as we view it. To understand the development of the structure of a fruit, such as a pineapple, botanists have followed the same procedure Matisse used with one of his snails: cutting through the outer surface and flattening it out (see Fig. 5-7). In this abstraction a previously hidden pattern suddenly emerges from the apparent randomness of the fruit's surface. Indeed, a mathematician can take this pattern a step further by writing an equation for it. In this case, the equation emerges from the ratio of two numbers in the Fibonacci sequence, which is generated by beginning with the numbers 0 and 1 and adding the last two numbers of the series to generate the next: 0, 1, 1, 2, 3, 5, 8, 13, 21, and so on. The sequence gives us some of nature's most common patterns. A pineapple can be described as

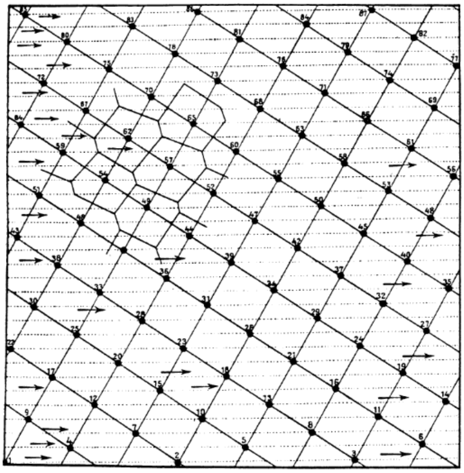


Fig. 5-7. Analysis of pattern arrangement in the pineapple.

the ratio of the number of times (eight) you must spiral around the fruit before its pattern repeats exactly (twenty-one sections): 8/21. Pinecones, flowers, and other natural objects can be described in similarly simple terms using the Fibonacci sequence.

Another example of abstracting, which involves a series of inventors, scientists, and artists, helps to demonstrate that not only is the process identical from one field to another but it transcends disciplinary boundaries. One of the most important, revolutionary, and, for many people, incomprehensible paintings of this century — Marcel Duchamp's abstract *Nude Descending a Staircase* — represents the culmination of a series of innovations that began more than a century ago with a man named Eadweard Muybridge. In 1878, Muybridge had taken up the challenge posed by a deceptively simple question: did a running horse ever have all of its feet off the ground at the same moment? The answer was not obvious. Observers could not agree, and there seemed to be no way to prove the issue until Muybridge came up with an innovative idea. He realized he needed to freeze time, which he could do with the newly invented camera. However, he needed to freeze time in a succession of instants to show a horse with all of its feet in the air simultaneously, if that in fact happened. No existing camera could do this, so Muybridge improvised. He set up a series of cameras, which he triggered with a timing mechanism so that each went off just a fraction of a second after the previous one. After many experiments, Muybridge succeeded in obtaining his an-