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Intuitive Tools for Innovative Thinking

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Abstract: In this chapter we examine the fundamental role of intuitive thinking skills in creative endeavor across the arts and sciences. The imagination manifests itself in a set of 13 non-verbal, non-mathematical, non-logical thinking tools that innovative individuals in all disciplines say they use: observing, imaging, abstracting, recognizing and forming patterns, analogizing, body thinking, empathizing, dimensional thinking, modeling, playing, transforming and synthesizing. Private, unarticulated insights generated by means of these tools are then translated in an explicitly secondary step into verbal, mathematical and other modes of public communication. Any educational effort to promote creative thinking must therefore recognize and exercise intuitional thinking skills and directly address the process of translating idiosyncratic subjetive thought into objectified public forms of discourse.

Keywords: Innovation; Intuition; Imagination; Insight; Synesthesia; Observation; Visualization; Pattern; Thinking tool.

Creative Process and 'Tools for Thinking'

Creative thinking is inseparable from intuition and aesthetic experience. While asserting such a basis for artistic activity may not seem odd, it may be surprising to find that even in the sciences and technology, ideas emerge as insights that cannot at first be communicated to other people because they exist as emotional and imaginative formulations that have no formal language. Indeed, practitioners of disciplines across the arts and sciences, including physics and mathematics, have commented that all creative thinking begins in private, sensual feelings that reveal unexpected problems (see Root-Bernstein, 'Problem Generation and Innovation', this volume) and unforeseen opportunities. Once a person feels the existence of a problem or a possibility, he or she must then work with attendant emotions and sensations to translate them, in an explicitly secondary step, into forms that can be communicated. Thus it is necessary, in any description of the creative process, to distinguish between intuitive 'tools for thinking' (Root-Bernstein & Root-Bernstein, 1999) that yield those personal insights and the translation skills necessary to turn insights into verbal, logical-mathematical, visual, kinesthetic and other public modes of communication (what Howard Gardner has called 'intelligences'). It is also necessary to reassert the fundamental role of the private and sensual in creative thinking, so often overlooked. Indeed, understanding the non-verbal, non-logical basis for imaginative thought is essential for stimulating creativity and innovation. Exercising the 'tools for thinking' that comprise this pre-linguistic form of intuitional cognition is as necessary to education as formal training in the languages and logic of public communication.

Thinking With Feeling

It is very difficult to find any major figure in any art or science who has said that creative work is done using words, mathematics, logic, or any of the other higher order forms of thinking that are supposed to characterize intelligence. Even the most verbal poets and mathematical scientists maintain that their creative work emerges from feelings, emotions, and sensual images. Consider the case of T. S. Eliot, who has been characterized by Howard Gardner in his book *Creating Minds* (1993) as a prototypical 'verbal thinker'. Eliot himself wrote that 'the germ of a poem' emerges from a musical "feeling for syllable and rhythm . . . (that) bring to birth the idea and the image" (Eliot, 1975, pp. 113–114). The object of poetry is to "find words for the inarticulate . . . to capture those feelings which people hardly even feel, because they have no words for them" (Lu, 1966, p. 134). All this occurs, Eliot wrote in *The Music of Poetry*, "before it (the poem) reaches expression in words" (Eliot, 1975, p. 114). The words of a poem, Eliot wrote, are only a translation: "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' " (Eliot, 1963, p. 97). What makes poets and novelists writers is not that they think in words, but that they express themselves preferentially in words.

Eliot's description of his creative thinking and the difficulty of translating pre-verbal thoughts into words is typical of other writers, as we have demonstrated in our book *Sparks of Genius* (1999). Most find that they can write only after they feel, see, and hear their material in their imagination. For Robert Frost, "a poem . . . begins as a lump in the throat, a sense of wrong, a homesickness, a love sickness. It is never a thought to begin with" (Plimpton, 1989, p. 68). Similarly, E. E. Cummings said that, 'The artist is not a man who describes but a man who FEELS' (*). Thus we find that for poet Gary Synder, writing comes from a process of visualizing situations that give rise to feelings:

> 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, revisiualization, I'll live through the whole thing again and try to see it more clearly.

As the emotional images become clearer to Snyder, they give rise to the same sort of musical rhythms experienced by Eliot:

> 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.

The notion that writing is a translation process occurs in autobiographical accounts of many other writers, too. Stephen Spender insisted that the challenge of writing is to find words for emotional images that have no words:

> 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.

Novelist Dorothy Canfield Fisher also found that words would come only after "intense visualizations of scenes . . .". Novelist Isabel Allende, however, relies upon gut feelings to bring forth words:

> 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 something that I've been feeling but which has no shape, no name, no tone, no voice.

Novelist and composer William Goyen characterizes the process of writing as "the business of taking it from the flesh state into the spiritual, the letter, the Word".

The same distinction between creative thinking and modes of expression can be used to characterize scientists. Consider Albert Einstein, the man Howard Gardner characterizes in *Creating Minds* (1993) as his prototypical "logical-mathematical thinker". Just as Eliot said he did not think in words, Einstein said that "No scientist thinks in formulae". The "essential feature in productive thought", he wrote, is an associative play of images and feelings:

> 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.

Einstein went on to describe thinking as the ability to associate images and muscular feelings in a repeatable way with problems upon which he was working, adding that ". . . Conventional words or other signs 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".

Again, Einstein's non-verbal, non-mathematical thought is typical of scientists. Fellow Nobel laureate Richard Feynman described his problem-solving as kinesthetic, acoustic, and visual:

> It's all inspired picturing . . . . 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.

Harvard astrophysicist Margaret Geller recounts a similar approach:

> I have to have a visual model or a geometric model or else I can't do it (physics). Problems that don't lend themselves to that I don't do.

Barbara McClintock, yet another Nobelist, also described a non-verbal approach:

> 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 . . . . You work with so-called scientific methods to put it into their frame after you know.

Logic and mathematics, in other words, are the translations that scientists use to communicate their insights, just as writers use words.

Let there be no mistake: the thought processes that these scientists describe are a form of intuition. Einstein made the point explicitly:

> Only intuition, resting on sympathetic understanding, can lead to it (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 early twentieth century, agreed: "It is by logic that we prove, but by intuition that we discover". Mathematicians Edward Kasner and James Newman write similarly that, "Mathematical induction is . . . an inherent, intuitive, and almost instinctive property of mind" (Kasner & Newman, 1940, p. 35). That which is important must be deeply felt, as mathematical physicist Wolfgang Pauli made clear. During the initial phases of problem solving, "the place of clear concepts is taken by images of powerful emotional content". Indeed, according to botanist Agnes Arber, without this emotional content, creative scientific thought is stymied:

> New hypotheses come into the mind most freely when discursive reasoning (including its visual component) has been raised by intense effort to a level at which it finds itself united indissolubly with feeling and emotion. When reason and intuition attain this collaboration, the unity into which they merge appears to possess a creative power which is denied to either singly.

Thinking and feeling are, in short, just as inseparable to a scientist as to a writer or artist.

We want to emphasize the point that, despite the very real differences between the products created by artists, writers, and scientists, people in all fields use a similar set of pre-verbal, pre-logical forms of creative thinking. Pauli says that scientists must FEEL just as deeply as poet E. E. Cummings. Feynman's development of the picture as a method could just as easily be Spender's 'logic of the images'. The physical concepts emerging from Einstein's muscles could just as well be novels regurgitated from Allende's belly. The important point is that each of these creative individuals knew something sensually and somatically before they were able to describe it formally to anyone else. Until we are able to access, practice and use such pre-linguistic, somatic thinking explicitly, we are cut off from our most innovative sources of thought.

Tools for Thinking

The emotional, intuitional, pre-verbal nature of creative thinking does not place it beyond comprehension. Just as logic and language build upon skills that can be learned and practiced, so does intuition. Hundreds of autobiographical and archival sources, interviews, and formal psychological studies reveal that every creative person uses some subset of a common imaginative 'tool kit'. This tool kit consists of a baker's dozen of pre-logical, pre-verbal skills:

(1) *observing*;
(2) *imaging*;
(3) *abstracting*;
(4) *pattern recognizing*;
(5) *pattern forming*;
(6) *analogizing*;
(7) *bodily kinesthetic thinking*;
(8) *empathizing*;
(9) *dimensional thinking*;
(10) *modeling*;
(11) *playing*;
(12) *transforming*; and
(13) *synthesizing*.

We emphasize that this tool kit consists of the imaginative skills common to all creative people, and the labels are those terms they use to describe their own thinking. Artist Brent Collins, who transforms mathematical equations into stunning wood sculptures, provides an apt example. In one brief passage describing his artistic process, he refers to the relationships between logic and image, aesthetics and intuition, and to his use of physical and mental tools:

> I made (two-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 how 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 (Collins, np).

While few innovators are as succinct in their description of the tools for thinking that underlie their creative work, reference to *Sparks of Genius* will show that many are just as explicit. It is therefore worth considering what mental operations each tool for thinking represents and the many ways in which each can be used.

Observing is perhaps the first and most basic of thinking tools. As human beings we are all equipped to sense the world, but observing is a skill that requires additional patience, concentration and curiosity. The American painter Georgia O'Keeffe looked carefully at things, and forces us to do so, too, in her very large paintings of flowers. "Still—in a way—" she said, "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". Observing is paying close attention to what is seen, but also what is heard, touched, smelled, tasted and felt within the body. In dense jungles, biologists such as Jared Diamond observe and identify birds by sound; in the absence of sight, the blind biologist Geermat Vermeij observes seashells with his hands, by touch; bacteriologists and doctors observe bacteria by smell; chemists and doctors have—historically at least—observed sugar in the urine by taste. Inventors and engineers, and the mechanics they rely on, similarly observe kinesthetically by cultivating hands-on experience with tools and machines—they know how tightly the nut is screwed onto the bolt by the feel of it.

Imaging, also a primary thinking tool, depends upon our ability to recall or imagine the sensations and feelings we observe in the absence of external stimulation. We can image visually and also aurally, and with smells, tastes, tactile and muscular feelings as well. If you can close your eyes and see a thing, or imagine the taste, touch, smell, or sound of it when it is not present, then you are imaging. For example, those of us who are already good at visualizing can close our eyes and see a triangle—and if we're practiced, we can make it change color and dimension, rotate it, etc. And if we're really good at visualizing, we can imagine an object with a triangular profile from all sides—or the much more complex object Charles Steinmetz, inventor of electrical generators, was asked to envision. A group of colleagues at General Electric once approached him with a problem they could not solve: "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?" Steinmetz was able to answer the question quickly, first by visualizing the removed core, then by applying equations that calculated its volume. Such visualizing, Eugene Ferguson argues in *Engineering and the Mind's Eye*, plays a central role in engineering and invention. Without it, the engineer cannot foresee the invention he wishes to make. By the same token, the chef cannot foretaste the delicacy she wishes to create in the absence of imaging; the musician cannot forehear the symphony she wishes to write down.

Abstracting is yet another important thinking tool. Because sense experience and sense imagery are so rich and complex, creative people in all disciplines use abstracting to concentrate their attention. Abstracting means focusing on a single property of a thing or process in order to simplify it and grasp its essence. Scientists and engineers work with abstractions all the time, for instance stripping a physical situation of all extraneous characteristics such as shape, size, color, texture, etc. and zeroing in on point mass, spring and distance. "I'll tell you what you need to be a great scientist . . ." says physicist Mitchell Wilson. "You have to be able to see what looks like the most complicated thing in the world and . . . find the underlying simplicity". Similarly, in the arts, abstracting means choosing which simplicity captures the essence of some concrete reality. Pablo Picasso tells us how:

> 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 . . . .

And he does just that in a series of etchings called 'The Bull'. Searching for the essence of bull, its minimal suggestion, he finally finds it in the simple linear description of its tellingly distorted shape, the tiny head surmounted by enormous horns, the massive body balanced by a short, hanging tail.

Abstracting often works in tandem with *patterning*, a tool with two parts. We organize what we see, hear, or feel by grouping things all the time. Sometimes we do so visually, as in a quilt or a graph, but of course, we can group things with all our senses. *Recognizing patterns* means perceiving a (repetitive) form or plan in apparently random sets of things and processes, whether in the natural world or in our man-made world. While the ability to recognize faces, and patterns that look like faces, seems to be ingrained in every normal human being, recognizing patterns is often influenced by culture. Westerners are inclined to hunt for a linear, back and forth, or up and down arrangement of information and our tables, graphs, books, and even architecture mirrors this predilection. Thus, although spirals are a common natural form (snails, sea shells, tornadoes, pinecones, whorls of hair on head), Westerners seldom use this pattern to design buildings, graphs or tables. Culture therefore plays a major role in what patterns we recognize and expect to perceive.

Recognizing patterns is also the first step toward creating new ones. Novel *pattern forming* always begins by combining two or more elements or operations in some consistent way that produces a (repetitive) form. For instance, the pattern found in 'watered' silk is created by folding the fabric at a slight bias and then pressing it under high heat and steam with great force. This process imprints the rectilinear pattern of the warp and woof of each fold of the fabric onto the opposing material at a slight offset. The result is what is known as a Moire pattern. Such Moire patterns can be produced by overlapping almost any regular grid over another, as when we look through two window screens or two sections of link fencing. The creation of novel Moire patterns is limited only by the imagination of the individual choosing what regular patterns to overlay.

Pattern forming is also at work when engineers design complex machines. There are only a very small number of basic machines—levers, wheels, screws, cogs and so forth—from which every mechanical device is constructed. Technological invention is the process of forming new patterns with simpler components by combining elements and operations in novel patterns. The same can be said of pattern forming in language and the language arts, since a finite number of words, grammars and narrative structures can be potentially combined and recombined to myriad, innovative effect (J. Gardner, 1983, pp. 52–53).

Recognizing and forming patterns leads directly to *analogizing*, that is, recognizing a functional likeness between two or more otherwise unlike things. We use analogies all the time to broaden our understanding of things. For instance, biologists often describe different bird beaks as if they work like human tools. A nutcracker and a particular bird beak may not look the same, but they function similarly and therefore are analogous. Analogy also has an important place in engineering and invention. Velcro, as no doubt everyone knows, was developed by analogy to the grasping properties of the common bur. Biomimicry, the use of nature as source of ideas, has in fact, become a well-recognized method of innovation. One of the more striking, recent examples of bio-analogy in architecture and engineering is the Gateshead Millennium Bridge. Chris Wilkinson Architects in Great Britain took the human eyelid for its analogical model and designed a drawbridge that works like the eyelid. When the 'lid' is closed, the bridge is down and people can move across. When a ship approaches, the lid is raised and ships can pass under the resulting arch.

While reading the above description of the Gateshead Bridge, you may have paid unusual attention to the way your eyelid functions and feels. This is an example of *body* or *kinesthetic thinking*. Body thinking means just that: thinking with the body. It is based upon sensations of muscle, sinew and skin—sensations of body movement, body tensions, body balance, or, to use the scientific term, proprioception. For instance, if you can imagine how it feels in your hand to set various gears in motion, if you can imagine in your muscles how they feel in motion, you are thinking with your body. Charles 'Boss' Kettering, director of research at General Motors for many decades, is said to have chided his engineers when they became overly analytical and mathematical. Always remember, he told them, "what it feels like to be a piston in an engine". Cyril Stanley Smith, the chief metallurgist for the Manhattan Project, clearly understood his creative debt to body thinking:

> In the long gone days when I was developing alloys, I certainly came to have a very strong feeling of natural understanding, a feeling of how I would behave if I were a certain alloy, a sense of hardness and softness and conductivity and fusibility and deformability and brittleness—all in a curiously internal and quite literally sensual way.

The same kinesthetic and tactile imagination is at work, too, in what is often considered the abstract reasoning of mathematics. The mathematician Stanislaw Ulam said he calculated "not by numbers and symbols, but by almost tactile feelings . . .". While at work on the atomic bomb at Los Alamos he imagined the movements of atomic particles visually and proprioceptively, feeling their relationships with his whole body well before he was able to express the quantum equations in numbers. This same muscular sense for the body in motion may also provide insight into engineering and architecture. At Princeton University one architecture student recently combined a dance production called 'The Body and the Machine' with a senior thesis, explaining that "exploring conceptual issues (in architecture) kinetically helps me understand them" (Moseley, 18).

Empathizing, our next tool, is related to body thinking, for this imaginative skill involves putting yourself in another's place, getting under their skin, standing in their shoes, integrating 'I' and 'it', feeling the objective world subjectively. Empathizing with other people, with animals, with characters on stage or in a book is standard fare for novelists, actors, and even physicians. But artists and scientists also empathize with nonhuman, even non-animal things and processes. Isamu Noguchi reified this sort of empathy in his sculpture, 'Core', a piece in basalt with carved holes. "Go ahead", he told visitors to his studio. "Put your head into it. Then you will know what the inside of a stone feels like". By putting her head 'in there', focusing her attention at the level of the corn chromosomes she studied, Nobel laureate Barbara McClintock was able to develop a 'feeling for the organism' so complete that she described herself as being down inside her preparations, and their genes became her 'friends'. And astrophysicist Jacob Shaham talked of 'reading' his equations like scripts for a play in which the 'actors'—energy, mass, light and so on—have intents and motives that he could physically act out.

Yet another tool that we most often learn unconsciously is *dimensional thinking*, rooted in our experience of space and time. Creative individuals think dimensionally when they alter the scale of things, as artists Claes Oldenburg and Coosje van Bruggen did in their *Batcolumn* in Chicago. Their ten-story-high rendition of a baseball bat strikes us very differently than the three-foot version. As any architect knows, size and mass can be altered to convey anything from flowery delicacy to dominating power. Moreover, the engineering of scale changes can be complex: different structural designs and different materials are almost certainly required as artist-engineers work dimensionally with properties such as strength and durability. Inventive individuals also think dimensionally when they map things that exist in three dimensions onto two dimensions, for instance in maps or blueprints. Indeed, this kind of dimensional thinking is at the heart of drawing in perspective. Artists, scientists and engineers also think dimensionally when they try to reconstruct three-dimensional phenomena from information recorded in two dimensions. Construction engineers interpret and build three-dimensional structures from two-dimensional instructions. In fact, how we orient ourselves in space has implications for the patterns we form in two and three dimensions. Cartesian coordinates assume a world of right angles; polar coordinates map a spherical universe. Buckminster Fuller rejected both in favor of a tetrahedral coordinate system and, based upon that system, invented his geodesic dome. Each coordinate system permits us to recognize and solve a different set of problems.

The tools for thinking briefly sketched up to this point are what might be called primary tools. They can be learned and practiced somewhat independently, though they are always interacting. Body thinking is a kind of imaging; observing feeds into abstracting and patterning; patterning in turn merges with analogizing and so forth. The last four tools for thinking, however, are clearly tools that rely upon the acquisition of primary tools and integrate them into composite tools.

The first of these composite tools is *modeling*, that is, plastically representing a thing or a process in abstract, analogical and/or dimensionally altered terms. The point of modeling is to depict something real or imagined in actual or hypothetical terms in order to study its structure or function. Artists make and use models all the time by preparing maquettes, smaller conceptualizations of pieces in planning. Scientists and engineers also create simplified models of objects and processes. In the case of flight simulators, engineers model the hands-on experience of flying planes for educational purposes by imitating the reality of that experience in space and time. Molecules that can never actually be seen or touched are built millions of times their actual size out of plastic or wood. Stars, which are beyond our ability to comprehend in any realistic sense, become a series of equations describing their actions over time frames beyond the entire experience of humanity. Modeling, as many practitioners have said, is like playing god, toying with reality in order to discover its unexpected properties.

Playing, of course, is itself another integrative tool that builds upon the other primary skills. We play when we do something for the fun of it, when we break or bend the rules of serious activity and elaborate new ones. Play is the exercise of our minds, bodies, knowledge, and skills for the pure emotional joy of using them. Unlike work, play has no set, serious goal; yet by encouraging fun, play is useful, for when creative individuals play with techniques and ideas they very often open up new areas of understanding through serendipitous discovery.

Among the greatest of players was the sculptor Alexander Calder, whose early training was in engineering. One manifestation of his play was a lifelong habit of designing toys for children (and for himself, too) out of wire and wood. In fact, Calder's first true success in the art world was as a result of having built himself a working model of a circus, complete with animals, props, entertainers with movable parts, a trapeze with a net and a tent. He actually played circus, too, inviting friends and acquaintances in the Parisian intelligentsia to watch him enact sights, sounds and stories under the big top. He was just having fun, yet his toys have been called a 'laboratory' for his subsequent, ground-breaking work. From movable toy figures he graduated to kinetic sculptures— hand-driven, then motor-driven—and finally to free-floating mobiles. In keeping with his playful spirit, however, he always refused to call his sculpture 'art', deeming the word too serious for his intentions.

Even the most serious innovations often have their origins in play. Alexander Fleming's discovery of penicillin has been traced to his hobby of collecting colored microbes for the 'palette' with which he created microbial 'paintings' on nutrient agar. Charles 'Fay' Taylor, the MIT engineer who made major strides in automotive engine design, explored mechanical objects by playing with kinetic sculptures. And Nobel laureate Richard Feynman said that his Nobel-winning work in quantum mechanics began when he started playing with the rotation of plates thrown in the air.

Play teaches us that how one learns something has no bearing on the importance of the lesson learned. What counts is the practice gained in extending the abilities and experience of one's mind and body. What counts is the practice gained in the use of more than one thinking tool at a time. Playing thus feeds into yet another imaginative tool, *transforming*, the serial or simultaneous use of multiple imaginative tools in such a way that one tool or set of tools acts upon another. To play is to transform, for one takes an object, observes it, abstracts essential characteristics from it, dimensionally alters the scale, and then, using body skills, creates a physical or mental representation of the object with which one can play. Take a look at any creative endeavor and you'll find such combinations of thinking tools being used to transform ideas and insights into one or more expressive languages.

In order to invent strobe photography, for example, engineer Harold Edgerton of MIT first transformed his mental image for a strobe light for ultrafast flash photography into a visual diagram, and then transformed the diagram into a working model. He played around with different versions of the strobe until he achieved one that matched his mental picture. Then, using his prototype, he played with setup conditions, different kinds of subjects and motions until, finally, he transformed all these components—film, camera, strobe, subject—into the results he wanted: a photograph that was both a scientific experiment and a work of art. In retrospect we can see that Edgerton made use of several imaginative tools: visualizing, modeling, playing, and something more, too, for without the ability to translate his ideas into words, diagrams, strobe and photograph his imaginative invention of ultrafast flash photography would have come to naught. Indeed, such transformations are typical even of data, as Edward Tufte has beautifully demonstrated in his books on visual information. Every table or graph or illustrated set of instructions for assembling something is a transformation of one kind of knowledge into another.

The necessary consequence of transformational thinking is our final mental tool: *synthesizing*, the combining of many ways of thinking into a synthetic knowing. When one truly understands something, emotions, feelings, sensations, knowledge and experience all combine in a multimodal, unified sense of comprehension. One feels that one knows and knows what one feels. Einstein, for example, claimed that when he sailed he felt the equations of physics playing out through the interactions of the boat, the wind, and the water. He became a little piece of nature. Similarly, artists and writers describe the creative process as a melding of sight, sound, taste, touch, smell, and emotion in which all become interwoven in an experience so powerful that they lose their sense of self. Feeling and thinking become one in a process that is often described as 'synesthetic'.

Synesthesia is a neurological term that refers to the experience that some people have of seeing colors when they hear certain sounds, or perceiving tactile feelings when tasting various foods. Artists and musicians, many of whom have some form of neurological synesthesia, often describe the ultimate aesthetic experience as being one in which a performer or observer of an art experiences all possible sensations simultaneously. A picture or a symphony may, for example, generate visual, acoustic, and tactile sensations along with definite emotions and even tastes, smells, and movements in the observer. One way to judge art is the degree to which it provokes such a multi-modal experience.

If we refer back to the descriptions of scientific thinking given by Einstein, Feynman, McClintock, Arber and other scientists in the opening of this chapter, then it is clear that scientists, too, experience a form of synesthesia. Ideas are inseparable from the emotions, the visual and tactile images and other sensations that accompany their genesis. Since the result of such sensory and somatic integration is not just an aesthetic experience, but also an intellectual one, we have suggested that it be called 'synosia', from a combination of 'syn', meaning together, and 'osia' from 'gnosis', the Greek word for knowledge. Synosia, in short, is the combination of knowledge and emotion, objective and subjective understanding into a synthetic whole.

The fact is that true understanding (by which we mean the ability to act upon the world), as opposed to knowledge (which is the merely passive acquisition of facts, often without the skills to use them), is always synthetic. Immanuel Kant wrote many years ago that "The intellect can intuit nothing, the senses can think nothing. Only through their union can knowledge arise". He understood that we recognize that which is important by its emotional impact on us and use our senses to explore how to respond. Thus, we can now understand why Einstein, Poincaré, and so many other innovators have claimed that intuition rather than reason is the basis of creative thought. To feel is to think, just as to think is to feel. Only when the two are integrated is innovation possible.

Training Intuition

Since intuition develops from the kinds of non-verbal, non-mathematical tools for thinking that we have just outlined, it can be exercised. The use of mental tools is no different than the use of physical tools: both require training and practice. Fortunately, many of the innovative people who have discussed how they have used observing, imaging, patterning, analogizing, and all the rest of the tools, have also described how they acquired skill in using these tools. The one thing they all say is that intuition results from doing things, not passively learning about them. One builds up a sense of how things should work by having experienced how they actually do (or do not) work. Thus, more than one innovator has stated that an expert is an individual who has made all the mistakes in the field.

Observing and imaging, for example, are often learned together through the practice of fine and applied arts and hobbies of all sorts. Collecting anything from stamps or coins to butterflies or buttons teaches an individual visual discrimination and memory. These talents are raised to a higher level by the practice of applied and fine arts. The artist-writer Leo Lionni's first drawing teacher was his architect uncle who gave him lessons as a small boy. Similarly, the writer Vladimir Nabokov also learned as a child to make detailed drawings both from life and from memory of objects that he examined over and over again. By his own admission, he used his observing and imaging skills equally in his research on butterflies at the Harvard Museum of Comparative Zoology and in his literary undertakings. Many Nobel laureates in the sciences have echoed Santiago Ramon y Cajal's statement that "that which has not been drawn has not been seen". And the same lessons have applied to observing well in sound, smell, taste, and touch and recalling the images derived from these senses. Pioneering composer Charles Ives was taught by his musician-father to hear the 'music' in a thunderstorm or the tone of a pane of glass when it is tapped—things that most of us overlook, or more accurately overhear. Chemical ecologist Thomas Eisner was taught by his father, a perfumer, how to use his nose to identify the composition of substances. Eisner now uses that faculty to study the ways in which insects use odors to communicate with one another.

Abstracting can also be learned and practiced by observing how other people have performed the process and by copying them. Even the expert artists have to learn the abstracting process of eliminating all the unnecessary clutter to reveal some basic property of an object. This process is beautifully illustrated in Randy Rosen's extraordinary book, *Prints* (1978). He shows how Pablo Picasso and Roy Lichtenstein both eliminated various features of a bull, step by step over many months, to yield very different and yet very evocative abstractions of 'bullness'. Guides to good writing, such as *The Elements of Style* by Strunk and White, recommend that writers revise by cutting out words, sentences, paragraphs that are unnecessary—in other words, they advise writers to abstract, to jettison all but what is essential to the work. No better example of written abstracting exists than the one-line plot descriptions given in the TV Guide. Trying to duplicate such one-line descriptions is excellent training in discovering the essence of things.

Patterning can be learned by similar experience. Richard Feynman recounted that his first formal introduction to patterns was as a very young child. His father gave him a set of small ceramic tiles, some blue and some white, and then had him create simple patterns: all blue; all white; alternating blue and white; two blue and one white; one blue and two white; etc. Simply learning that patterns have permutations was the beginning of one of Feynman's greatest ideas, which is that nature always employs every possible path to achieve any given end. There is a lesson here for creative thinking, too. The greater the number of patterns one knows, the greater one's understanding of possibilities. Many forms of pattern recognition require formal training in music, poetry, and symmetry, and books about these subjects abound. Far better, however, is active participation in composing music, poetry, and artwork, since doing always teaches more than reading. For the same reasons, much can be learned about patterns by playing word games, building puzzles, learning to dance, becoming a chess master, or doing recreational mathematics. When one can recombine what one knows to invent new chess puzzles, choreograph a new dance, or invent new mathematical problems or poetic forms, then one has graduated to pattern forming, which brings creative joys unmatched by any passive hobby.

Artist-inventor-psychologist Todd Siler has written extensively on how to generate patterns connecting like and unlike using a process he calls 'metaphorming'. To metaphorm, one uses any and all forms of connection-making—including visual analogy, metaphoric figures of speech, narrative cause and effect and rational hypothesis—to explore the meaning inherent in the comparison of two or more things. Take any given object, he advises, and ask yourself what else is this like, what does it remind me of? And why? Articulate the connection as metaphor, as hypothesis, a symbol, as pun. To metaphorm the mind with garden means to assert that the mind is a garden, that there are gardens of the mind. Thoughts germinate like flowers. The imagination is the soil in which they grow. The mind, layered like an onion, requires cultivation and nourishment. Ideas root themselves and become difficult to dislodge. Dangerous ideas create 'mind fields'. Taken literally, of course, there are 'mind fields', which can be studied by means of functional magnetic resonance imaging and other neurological techniques. Are we on the verge, as mind-gardeners, of intervening physically to enhance or otherwise influence the growth of a mind-plant? Metaphorming ideas in as many ways as possible is good practice in making the structural connections and functional analogies that animate art, science and technology. Similar pattern forming techniques have been adapted for elementary and secondary classroom use, for instance in *The Private Eye, Looking/Thinking by Analogy* guide for learning in art, writing, science, math and social studies (Ruef, 1992). Analogizing, that particular search for similarity of function, especially involves looking at things and processes in order to discover not simply how they work, but how they might work outside their given context. Young people exposed to such training acquire the active habits of mind necessary to the intuitive generation of novel ideas.

Body thinking is another tool best developed through active participation with the world. This may seem self-evident, but in an age when people spend increasing amounts of time in front of computers, simple body skills among students are declining dramatically. Children—and adults, too—spend less and less time handwriting, drawing, running, jumping and playing physical games and sports of all kinds. But the truth is, they cannot learn to ride a bike simply by reading about it. Nor can they really understand structural forms such as buildings or bridges without experience of thinking about the muscular supports of their own body; they cannot really understand physical processes such as the molecular behavior of solids, liquids and gases, without incorporating notions of speed and vector within themselves. All kinds of physical activity, including organized arts and athletics, work to develop body-thinking skills. Sports and dancing build gross body-thinking; finer body thinking skills result from making music, art, and building things. For added bonus, body thinking can be reviewed and practiced mentally. For instance, the pianist can see and feel herself playing a piece of music, remembering every detail without so much as moving a finger. The downhill skier can imagine each moment on a race course without leaving his room. Studies of people in every discipline from sports to music, engineering to design, show that imaging how it will feel to perform a particular set of actions can actually improve subsequent performance.

Dimensional thinking must also be learned by doing. One must learn how to translate a three-dimensional object into two dimensions by drawing or photographing it. One must learn how to transform the information given on a two-dimensional blueprint or assembly diagram into the three-dimensional object. Such skills can be acquired through formal classes in drafting and modeling, or through informal experience building furniture, knitting, sewing, or doing any other craft. Perhaps most challenging is learning how to transform a linear set of mathematical symbols into a graph or physical model of the equation—an exercise that was once common in geometry and algebra classes and which should be re-instituted universally.

Playing, and the modeling that it so often entails, is especially important to the exercise and training of intuition. Most innovators build models of sorts, play with a wide variety of games and tools, and generally have extensive experience with making things of all sorts. Carl G. Jung, the famous psychologist, recalled untold hours building models of castles as a teenager. He then took up painting, through which he discovered the function of mandalas (world images) as models for the psychological lives of his patients. Einstein, of course, spent his most creative years in a patent office, daily analyzing and playing with models of inventions. Many artists and writers, including Claes Oldenberg and H. G. Wells, created entire imaginary civilizations with which they played as children and teenagers and from which they subsequently drew novel ideas for their arts as adults. Alexander Calder, as mentioned above, modeled a circus and derived from his experience not only contacts with the art world, but specific ideas about how to design moving sculptures. Such experiences are common among imaginative people. Indeed, one of the few good correlations that exists to predict which individuals will be creative reveals that they have, often from childhood, *made* things with hands and mind.

Just as all roads lead to Rome, all the experiences gained from the exercise of imaginative thinking tools lead towards synthesizing, that ability to pull together all one imagines with all one knows, that drive to meld sensual knowledge with received wisdom into a unified knowing that we have called synosia. We are often most aware of the ‘rational’ or sense-making character of synthetic breakthroughs in human thought—for instance, the explanatory power of Alberti’s drawings in perspective or Einstein’s theory of relativity, but non-rational feelings and perceptions play an equally important role in the generation of synthesis. There is that deeply troubling sick feeling in the pit of one’s stomach when one looks at a situation and knows that something is wrong; or the unmatchable ‘high’ that accompanies the ‘Aha!’ of an unexpected insight. For mathematician-philosophers Bertrand Russell and Norbert Wiener, creative work almost always began with feelings of physical discomfort evoked by certain unsolved problems in mathematics (Hutchinson, 1959, p. 19; Wiener, 1956, pp. 85–86; Wiener, 1953, pp. 213–214). Equally physical, orgasmic feelings of relief and achievement attended the solution of those problems. Nobel laureate Sabrumanyam Chandrasekhar has called this “shuddering before beauty” (Curtin, 1982, p. 7).

Ultimately, all thinking tools, but especially modeling, playing, transforming, and synthesizing, give birth to the inarticulate sense-making called intuition. Intuition involves non-explicit expectations of what should happen when something is tweaked, of how a system will behave when it is twisted, of what kind of response a person will give in a particular situation. We build vague models of how things work and people behave based on our experiences. These models often owe a great deal to playing with tools, games, people, and systems to find out how they respond to various stimuli. We develop a ‘feel’ for what should happen, But because we have not analyzed our experience in any formal way, we cannot explain the resulting ‘intuitions’. They remain what philosopher and physicist Michael Polanyi has described as ‘personal knowledge’—pre-verbal understanding that yields insight before it yields the means to explain insight. Though personal knowledge is just that, personal and unspeakable, it is nonetheless valid and useful. In fact, Neils Bohr used to chide his students with the comment, “You’re not thinking; you’re just being logical!” (Frisch, 1979, p. 95). His colleague Enrico Fermi was known to dismiss mathematical ‘proofs’ of concepts with the comment that his ‘intuition’ told him they were wrong. Because Fermi had so much experience actually doing physics, building, making and inventing things, most of his colleagues trusted his intuitions, which were often right (Wilson, 1972). Learning to pay attention to that which moves us—to an accumulation of unarticulated but felt experience that forms our intuition—is key to creative work (Root-Bernstein, 2002).

Intuition and the Future of Innovative Education

Having placed intuition on a comprehensible footing, and outlined its role in the comprehensive, creative knowing that is synosia, we can now think about the educational implications such recognition must imply. Education in every discipline rightly emphasizes analytical, logical, technical, objective, descriptive aspects of each field. These inform the nature of public discourse between practitioners and their formal communication of disciplinary knowledge. But, as must by now be evident, the subjective, emotional, intuitive, synthetic, sensual aspects that make up the private human face of all creative inquiry deserve equal educational recognition. It is this human face, after all, that fuels desire to discover, to invent, to know. Without it, creative work has no motivation, no driving force. This is not to argue that practice of imaginative thinking and the exercise of intuition is of greater import than mastery of the logical, analytical, technical aspects of any discipline. Far from it. Innovation is possible only when individuals emotionally engage in a subject and intuit novel ideas *and also* evaluate ideas and results logically and translate them into forms appropriate for communication and analysis by other people. Synosia cannot do one without the other, nor can an education that truly seeks to prepare students for innovation and invention.

Unfortunately, not only does our education system generally ignore the emotional and subjective aspects of creativity, so do the cognitive sciences. This is too bad, for theories in cognitive psychology do not mirror so much as they inform educational practice. And as mathematician Seymour Papert of MIT makes clear, the enormous impact cognitive theories often have on educational practice can be to the detriment of innovation. He writes:

> Popular views of mathematics, including the one that informs mathematical education in our schools, exaggerate its logical face and devalue all connections with everything else in human experience. By doing so, they fail to recognize the resonances between mathematics and the total human being which are responsible for mathematical pleasure and beauty . . . (Papert, 1978, p. 104).

Papert finds grounds in this oversight to question the validity of cognitive theories as they inform education:

> Implicit in the confrontation of these views of mathematics is a broader question about the legitimacy of theories of psychology, often called cognitive, which seek to understand thinking in isolation from considerations of affect and aesthetics (Papert, 1978, p. 104).

Papert has a point. The separation of cognition from somatic sensation and aesthetic feeling is both inaccurate and inappropriate: inaccurate, for if, as Einstein and McClintock both said, one must become a piece of nature in order to discover the hidden mysteries of nature, then the oversight of imaginative and intuitive thinking undermines our understanding of creative endeavor; inappropriate, because the same dualistic divorce of mind and body, emotion and reason, has had a deleterious effect on education. Psychologist Jeanne Bamberger has documented just how harmful. She studied a group of Boston teachers and some of their students who were considered bright but who performed poorly in school. Teachers and students were brought to Bamberger's Laboratory for Making Things in Cambridge, Massachusetts where they were asked to build mobiles. Most of the children had no difficulty building mobiles, but when asked how they did it and what physical principle they used, they were unable to answer. As one young man said, he "just knew . . . . I had a feeling of it, like on a teeter totter' (Bamberger, 1991, p. 38). The teachers, however, had learned the principle underlying mobile construction, which is the same as balancing two weights on a lever: 'weight times distance must be equal on both sides of the fulcrum'. They, however, were mostly unable to implement this principle in practice, and few built a functional mobile (Bamberger, 1991, p. 44). There is something obviously wrong with an educational system that can produce students unable to explain how they do what they do and teachers unable to do what they can explain.

The crux of the matter with education lies in the dissociation of mind from body and thus sciences from arts. For most of the twentieth century, psychology was dominated by an over-simplified use of Lewis Terman's theory of intelligence, which relied solely upon verbal and mathematical measures of problem-solving ability (Seagoe, 1975). Practitioners overlooked the fact that Terman himself had actually found that for very creative people, but not for average people, verbal and mathematical scores were sufficient to predict high achievement on visual, analogical, mechanical, physical and other tests. Initially, at least, communication skills with words and numbers were understood as predictors/indicators for some of our most important imaginative thinking skills: visualizing or imaging, analogizing, modeling and body thinking. As Terman's work affected the field, however, the communication skills that predicted creative intelligence took precedence over the imaginative substance of that intelligence—as evidenced by the heavy testing of verbal and mathematical skills at all levels of schooling.

Unfortunately recent multiple intelligences theories such as Howard Gardner's (1983) threaten to exacerbate the problem by focusing much-needed attention on a broader set of communications skills such as kinesthetic, musical, verbal, visual, and inter-personal abilities without simultaneously distinguishing them from creative thinking skills. The fact that people can be highly verbal, extraordinarily artistic, or wonderfully musical and at the same time have little or no creative ability seems generally to have been overlooked or ignored. Most creative people are, in fact, polymathic and utilize their skills in multiple domains (see Root-Bernstein, 'The Art of Innovation . . .', this volume).

Bamberger, Papert and others point the way towards a more balanced view of innovative thinking by forcing us to look at mind as part of the body. Neurologists such as Antonio Damasio (1994) remind us that people who, for reasons of disease or accident, lose emotional affect also lose their ability to act reasonably. Rational decision-making, he argues, cannot be divorced from emotional affect. The anecdotal reports of so many of the world's most creative people are finally finding an analytical basis.

The implications of these findings for cognitive sciences and education cannot be underestimated. What they tell us is that any theory of mind that claims to account for creative thinking must describe the sensual, emotional, and somatic manifestations of thought as well as their analytical, objective, and communicable formulations. Moreover, the transformational process by which ideas are translated from their personal, bodily forms into formal languages for communication must be made explicit. Educationally, each of these points has equivalent importance. Words and numbers are not sufficient to produce innovative people, nor are the tools for thinking that we have outlined here. Tools for thinking are necessary to develop the sensual, emotional, bodily forms of thinking from which new ideas emerge, but tools for thinking are not sufficient for communicating these ideas to other people. In order to provide a complete education, tools for thinking need to be taught in an integrated fashion with a variety of expressive skills—verbal and mathematical, to be sure, but also bodily-kinesthetic, visual-spatial and others that pertain to Gardner's multiple domains. Translating and transforming skills that link imaginative tools to expressive modes and expressive modes one to another are equally necessary. Only when mind and body, synthesis and analysis, personal thought and public communication skills are all part and parcel of cognitive studies and educational practice will an enhanced capacity for innovation become available to everyone.

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* All quoted material with the exception of individual items that are followed by a reference may be found in Root-Bernstein, R. S., and Root-Bernstein, M. M. (1999). *Sparks of genius*. Boston, MA: Houghton Mifflin.

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