Sensual Chemistry

Aesthetics as a Motivation for Research

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Abstract: Sensual, aesthetic, and even artistic considerations are an important motivation for general interest in chemistry and the development of specific research problems. Examples are given showing how these considerations have been put into play by many eminent physical, theoretical, and synthetic chemists. It is argued that more attention needs to be given to sensual and aesthetic issues in understanding how chemical discoveries are made and in order to better teach the subject.

Keywords: *aesthetics, art, discovery, intuition, thinking.*

1. Introduction: a personal view of chemical aesthetics

> *In the truths of the natural sciences there is […] analogy to the productions of the refined arts. The contemplation of the laws of the universe is connected with an immediate tranquil exaltation of mind, and pure mental enjoyment. The perception of truth is almost as simple a feeling as the perception of beauty; and the genius of Newton, of Shakespeare, of Michael Angelo, and of Händel, are not very remote in character from each other […]. Discrimination and delicacy of sensation, so important in physical research, are other words for taste; and the love of nature is the same passion as the love of the magnificent, the sublime, and the beautiful.*
>
> Sir Humphrey Davy (1840, pp. 307-308)

The connection between sensual experience, aesthetics, and chemistry has existed for me since the beginning of my formal education in the subject. I had the fortune to take introductory chemistry at Princeton University the last semester (1971) that Hubert N. Alyea taught that or any other course. Alyea, as befitted the real-life model for Walt Disney's 'absent-minded professor', was a one-man circus, telling stories, making jokes, and carrying out magical chemical transformations. He was so popular that hundreds of alumni

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packed the chemistry auditorium far beyond its rated capacity every year at Reunions to watch Alyea convert Yale colors (blue and white) into Princeton's colors (orange and black) to the banter of Princeton anecdotes. (One of his favorites was the Yale professor who had used phenolphthalein to monitor his titration to neutral pH of NaOH with HCl and then drank the resulting solution to prove to his class his faith in chemical equivalents. Half an hour later, this professor had to make a hasty exit, having forgotten that phenolphthalein is a strong laxative.)

I had a designated first row seat from which to observe Alyea's antics because he put everyone who wore glasses up front. As a result, I was the unwitting participant in a number of demonstrations. The most memorable was the time Alyea handed out some unidentified crystals as part of his first lecture on organic chemistry. I and several other 'guinea pigs' were asked to place these crystals on our tongues only to discover the unforgettable fact that urea was not only the first organic molecule to be synthesized, but also one of the bitterest! My tongue felt as if it were shriveling and I had a very distinct sensation of cold, as if the crystals were sucking the heat out of my tongue as they dissolved. That experience, and nearly passing out from the smell of glacial ammonia in one of the lab exercises (a smell to which I am still abnormally sensitive) gave me an unexpected appreciation of chemical sensibility.

The real marvel of Alyea's lectures, however, was not his antics, but that he gave the entire introductory course using color reactions. As an amateur artist for whom color was a primary concern, I was enchanted. I eventually learned that over many years, Alyea had developed a set of about twenty chemicals with which he could carry out all of the basic types of chemical reactions discussed during a year-long introductory chemistry course. The reactions were carried out in large test tubes placed on a modified overhead projector that made the reactions visible to hundreds of students simultaneously. His Tested Overhead Projection Series (TOPS) was famous not only to chemistry teachers throughout the United States, but also in Africa and Asia where Alyea had spent innumerable hours proving that a Princeton level course could be provided even out in the bush using, if necessary, a lantern rather than an electric light. For Alyea, there was no point thinking about chemistry until one had *experienced* it. Formulas and reactions had to refer to actual substances and processes, and he believed that the more sensual he could make the chemical experience, the more real the puzzles of chemistry would become to people. Color reactions were perfect for his purpose. Not incidentally, they were beautiful, too. I was attracted to chemistry, as no doubt Alyea intended.

In contrast, I had a distinctly unaesthetic experience a few years later (1973) in a biochemistry class. The professor went through the standard textbook explanation of how DNA replicates by unwinding to reveal each individual strand of the double helix. Each strand then acts as a template upon which a new strand is synthesized and so two new helices, each identical to the original, are produced. Almost all biology, biochemistry, and chemistry textbooks have illustrations of this process. Unfortunately, I was raised to be a skeptic. I do not believe things until I have tested them out for myself. I am also a very physical person. I had actually unwound string and ropes – or rather, tried to do so. It takes a lot of energy and one quickly gets a mess of tangles and knots unless one is extremely careful. My body knowledge said that DNA replication could not occur this way. I trusted my intuition of how things work over pretty pictures. So, foolishly, I raised my hand and pointed out to the professor that it was energetically and topologically impossible for DNA to unwind as he had just suggested. If DNA's most stable configuration (and thus energetically preferred state) was the wound-up form, then it would take a huge input of energy to unwind the helix, not to mention some sort of mechanical unwinding mechanism. Why was this problem not mentioned in his lecture or in the textbook? Surely the illustrations in the textbook and the diagram he had just put on the board were oversimplifications or simply wrong.

I (naively) did not expect the explosion that followed. Unbeknownst to me, the professor was himself working on the DNA-unwinding problem and had no intention of enlightening an introductory class about the details of his latest research (a huge mistake, in my opinion, because I suspect that most of us would have been fascinated). Instead he yelled at me that I could take it on faith that it happened, one way or another. The result of this confrontation was that I became hyper-aware of the role that different kinds of intuitive and artistic information play in the conveying of information in science. I eventually discovered that I was not the only one bothered by the topological and energetic problems posed by the double helix (Watson & Crick 1953, Pohl & Roberts 1978) and that alternative models of DNA (so-called side-by-side or 'warped zipper' models) had been proposed that did not need to unwind (Rodley *et al*. 1976, Sasisekharan & Pattabiraman 1978, Stokes 1984). I also found that I was not the only one to consider many scientific cartoons inaccurate and sometimes purposefully misleading (Gilbert & Mulkay 1984, Root-Bernstein 1996a). Thus, I learned to bring a critical mix of aesthetic criteria to my evaluation of models and illustrations that combined sense and sensibility, reason and intuition, feelings and knowledge. This mix could, I found, reveal interesting and important problems.

The last and most difficult form of chemical aesthetics that I encountered was the beauty of theoretical insights, and I experienced it only after I became a graduate student. Having a mind that is resistant to memorization, I was handicapped in many classes by having to understand the underlying principles by which scientific processes worked in order to grasp the details. Thus, I ended up being more comfortable with physical chemistry (where the principles are very explicit) than synthetic chemistry (which I took before Woodward and Hoffmann had brought some order to the field). I also found stereochemistry much more to my taste than reaction mechanisms, perhaps because I am mainly a visual thinker. When I turned to the history of chemistry in graduate school, it was perhaps inevitable that I should therefore have been drawn to the man who best combined both physical chemistry and stereochemistry in his work, Jacobus Hendricus van't Hoff. The beauty of three-dimensional chemical forms and their interactions still intrigues me and occupies my daily research, but the most intense aesthetic experience I have ever had in science (outside of the experience of my own rare illuminations) came when I read van't Hoff's original derivations of his equations describing the thermodynamic properties of solutions. I was struck first by the brilliance of the analogy he created between the adiabatic cycle that Clausius had imagined for pistons working on a gas and the equivalent cycle that van't Hoff mentally devised using pistons working on osmotic pressure by means of semipermeable membranes. Beyond that – far beyond that – was the experience of reading the equations he then derived describing the equivalent of PV = nRT for solutions (van't Hoff 1887). It was the most brilliant, insightful poem I had ever read!

Van't Hoff's poem deriving the laws of solutions wasted not a symbol. Each one made numerous connections to existing principles so that each line became a nexus of meaning. His symbols, like a magic key, opened a door from the mansion of gas thermodynamics onto the vista of an entirely unexpected estate that nature had somehow hidden from everyone else. Order from disorder, sense from confusion, imagination, insight, surprise – van't Hoff had it all. I suddenly understood a comment that van't Hoff's contemporary, Max Planck (Nobel Prize, physics 1918), had made in his *Autobiography*, to the effect that he was drawn to science when he encountered the first law of thermodynamics in high school. It appeared to him to be "like a sacred commandment [...] sublime" (Planck 1949, p. 14). I suddenly appreciated viscerally how one could shudder before the majestic beauty of unexpected comprehension (Chandrasekhar 1987).

2. The ubiquity of chemical aesthetics

It was many more years, however, before I realized that the kinds of personal aesthetic experiences I had been accumulating were common to other scientists. Many had a visceral, sensual love affair with their experimental and even theoretical work. Concepts of simplicity, symmetry or asymmetry, elegance, and beauty were common. Reverence was expressed for fundamental laws and insights. Yet I found these things out almost slyly, by nosing around, asking embarrassing questions, or stumbling upon examples by accident. Few colleagues spoke publicly about such things. It therefore came as a revelation to discover just how completely aesthetic considerations and experiences permeate chemistry and other sciences, their teaching, learning, and meaning. The most unexpected thing I found was the degree to which aesthetic aspects of chemistry are often the primary motivation for research itself. Beauty, elegance, emotional and sensual enjoyment were not a side products of insight, but a primary ingredient. As MIT metallurgist Cyril Stanley Smith not only told me, but fortunately wrote down as well, "discovery derives from aesthetically-motivated curiosity and is rarely the result of practical purposefulness" (Smith 1978, p. 10).

The first person to enlighten me about the importance of aesthetic considerations as a motivation for research was Bob Holley. Holley, a Nobel laureate (medicine/physiology, 1968) who was one of the discoverers of transfer RNAs, had his office down the hall from me at the Salk Institute when I was a post-doctoral fellow. My discovery of his aesthetic motivations came in a roundabout way. Every Friday, I and many other researchers at Salk would surreptitiously find a way to be in a position to watch some lovely young lady wend her way to Holley's office and then disappear with him for hours on end into the special isolated quarters reserved for Fellows of the Institute. Rumors were rampant. But reality was much more interesting than the rumors. I noticed that lyrical bronze statues of ballerinas began to appear in Holley's office. When I asked after the provenance of the sculptures, I discovered that they were Holley's own work. He had converted his Fellow's quarters into an artist's atelier. Friday afternoons were his time for art. I asked him if there was any connection between his artistic avocation and his scientific research. He told me that two things motivated all of his endeavors, scientific and artistic: the search for beauty and the risk associated with taking a gamble.

Meanwhile, my undergraduate mentor, Robert Langridge, a U.C. San Francisco molecular modeler, had published an article on the structure of DNA that captured the cover of *Science*. (Langridge *et al.* 1981) The cover was divided in half diagonally. One half showed a computer model of the double helix viewed down the long axis of the helix. The other half showed a rose window from a medieval church. Both glowed with the same shimmering reds, blues, greens, and yellows. And surprisingly, both had similar rosette shapes. Having become increasingly interested in arts-sciences connections, I wrote to Langridge. He explained that for him a scientific result should be as beautiful as any work of art and that he was, in fact, intensely interested in the arts himself – a common bond we had somehow missed when I was his student. He had intended his comparison of the rose window and helix to convey the beauty he experienced in both. He also noted that he was very disappointed that many of his colleagues had missed the point, or worse, described the comparison as misleading. Art, after all, is art; science, science…

The more I paid attention, however, the less obvious became the boundaries between arts and sciences and the greater the role aesthetics played in motivating scientific exploration (Root-Bernstein 1987, 1997). A voracious reader of scientific autobiographies, I found that the themes introduced to me by Holley and Langridge kept reappearing. Was it just chance that some of the first insights into chemical structures were made by August Kekulé, who originally trained as an architect, or was there a mindset that the architect-turned-chemist brought to his work that his fellow chemists of the period lacked? Was it coincidence that the discovery of enantiomorphs was made by Louis Pasteur who, as a professionally trained portrait painter, had been explicitly taught to observe the tiny asymmetries that characterize every face, human or crystalline? Was van't Hoff's avocation of writing poetry and playing music related to his ability to compose scientific equations of such insight and impact? In these three cases, one can only conjecture (Root-Bernstein 1989, 1996b). But in many cases, chemists have made their aesthetic concerns explicit.

Charles Thomson Rees Wilson, for example, revealed in his physics Nobel Prize lecture (1927) that his invention of the cloud chamber for observing ions was not motivated by any scientific rationale, but his love for beautiful phenomena. "In September 1894 I spent a few weeks in the observatory which then existed on the summit of Ben Nevis, the highest of the Scottish hills. The wonderful optical phenomena shown when the sun shone on the clouds surrounding the hill top, and especially the colored rings surrounding the sun (coronas) or surrounding the shadow cast by the hill top or observer on mist or clouds (glories) greatly excited my interest, and made me wish to imitate them in the laboratory" (Rayleigh 1942, p. 99). Only afterwards did Wilson realize that ions were a critical part of cloud formation, and thus of use for visualizing scientific experiments. Many years later, recreating these effects was one of the things that drew William Lipscomb (Nobel Prize, 1976) into science: "I have seen the glory effect, and have made a Wilson cloud chamber when I was a youth. Both effects are beautiful indeed." (Lipscomb, in Curtin 1982, p. 20)

Hans von Euler-Chelpin (Nobel Prize, 1929) provides another surprise. His career actually began as an art student at the Munich Academy of Art. He became so enamored of the theories of color that had recently been proposed by the chemist Michel Eugène Chevreul and physicist Ogden Rood that he decided to pursue the scientific aspects of the subject (Ihde 1971). These led him to enroll at the University of Berlin, where the exciting work of Max Planck, Emil Warburg, and Emil Fischer quickly captured his imagination. His artistic education was not wasted, however; it had trained both his visual imagination and his manipulative skill so that he had no difficulties mastering the technical aspects of his new craft.

Similarly, Dorothy Crowfoot Hodgkin (Nobel Prize, 1964) was taught to draw and paint by her mother, a professional painter. Hodgkin thus made her first academic contributions as an artist, drawing the mosaics of ancient churches for her father, a classical scholar and archeologist. Her experiences investigating ancient sites were so enthralling that she was torn, for a time, between archeology and crystallography, which she had recently discovered through Sir William Henry Bragg's book, *Concerning the Nature of Things* (1925) – Bragg himself (Nobel Prize, physics, 1915) being an amateur painter. Hodgkin found a way to avoid the conflict initially by performing chemical analyses on fragments of colored glass that her mother found at the archeological sites. She became quite expert in inorganic analysis. She said that eventually, the geometric beauty and elegance of crystals won her over to crystallography full time (Ferry 1998, Hunter 1993, Farago 1977).

Lipscomb has provided one of the most explicit descriptions of how aesthetic considerations and artistic modes of thinking influenced his research. "From my experience," he said at a Nobel Conference on The Aesthetic Dimension of Science in 1980, "I would certainly not separate aesthetics from science. When, after years of research I realized that a whole area of chemistry (of boron) was really quite different from anything that had previously been thought, I felt a focusing of intellect and emotions which was surely an aesthetic response. It was followed by a flood of new 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 of these unusual molecules. Both the structures and wave functions describing the bonding were based on simple polyhedra of high symmetry and their fragments. Was it science? Our later tests showed that it was. But the processes that I used and the responses that I felt were more like those of an artist." (Curtin 1982, p. 3-4)

This artistic sense was something that Cyril Smith, the MIT metallurgist, developed into an explicit research strategy. He spent innumerable hours studying the ancient arts of metal smiths as well as modern Oriental printmakers and even op artists in search of structural insights. "I have slowly come to realize," he wrote of these experiences, "that the analytic, quantitative approach I had been taught to regard as the only respectable one for a scientist is insufficient. Analytical atomism is beyond doubt an essential requisite for the understanding of things [...]. Yet granting this, one must still acknowledge that the richest aspects of any large and complicated system arise from factors that cannot be measured easily, if at all. For these, the artist's approach, uncertain though it inevitably is, seems to find and convey more meaning." (Smith 1978, p. 9)

I began to think that the distinction that is usually made between the subjective, emotional, sensual thinking that artists employ and the objective, rational, disembodied thinking that is supposed to characterize scientists is misleading. The two were, at least for a significant number of very successful scientists, synergistic (Root-Bernstein 1989, Root-Bernstein & Root-Bernstein 1999). Personal aesthetic and artistic intuitions often seem to lead people not only into science, but to scientific insights, too.

3. Sensual Chemistry as a basis for aesthetic intuition

As I learned more about chemical aesthetic experiences, it slowly became clear to me that many scientists were drawn to their subjects directly through the sensual beauties they experienced (Root-Bernstein 1987, 1990). For organic chemist Robert Woodward (Nobel Prize, 1965), the attraction of chemistry was in part the challenge of performing syntheses that no one else could carry out, but it was certainly the sensual aspects of the subject, too. "It is the *sensuous* elements which play so large a role in my attraction to chemistry. I love crystals, the beauty of their form – and their formation; liquids, dormant, distilling, sloshing (!); swirling, the fumes; the odors – good and bad; the rainbow of colors; the gleaming vessels of very size, shape, and purpose. Much as I might *think* about chemistry, it would not exist for me without these physical, visual, tangible, sensuous things" (Woodward 1989, p. 137). Robert Mulliken (Nobel Prize, 1966) also confessed that, "I have sometimes experienced very strong feelings of intimacy with nature […]. I loved molecules in general, and some molecules in particular" (Mulliken 1968, pp. 9, 19).

An unusual aspect of chemicals that particularly attracted Mulliken and some of his colleagues was their smells: "I […] found it interesting to smell the various compounds and to look for resemblances or differences in the odors of similar or related compounds. I have always been fond of color and odors, and, for the latter, I feel I am somewhat of a dog" (Mulliken 1968, p. 20). Chemical ecologist Tom Eisner has also made a career with his nose. He often sniffs out the chemicals left by insects or used by them to fight off predators, identifying them by odor. Trained by his perfumer father to recognize the chemical components of complex mixtures, Eisner jokes, "I'm essentially a nose with a human being attached" (Eisner 1988, p. 451; Horgan 1991, p. 60). Primo Levi, the famous chemist-novelist, has also described the joys of olfactory sleuthing. "I'm very glad that I educated my nose," he wrote (Levi & Regge 1989, p. 62). Odd, then, that although we were taught the proper way to smell a chemical ("carefully wave your hand over the test tube to waft a bit of the vapor toward your nose") no one ever enthused over the odor of a chemical product or developed lab exercises using olfactory analysis. It could be done.

Save for Alyea, no one made much of color, either, though it has a much more explicit role in motivating chemical work and always has. Wilhelm Ostwald (Nobel prize, 1909) was first attracted to chemistry through the fabrication of his own oil paints, pastels, and fireworks and later contributed fundamental insights into the ways in which ions contribute color to solutions and formulated the first scientific description of color and the first gray scale (Ostwald 1926-7, Birren 1969). For other investigators, color raised questions. Albert Szent-Gyorgyi (Nobel Prize, medicine/physiology, 1937), for example, revealed that color motivated his discovery of vitamin C: "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' […] 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?" (Szent-Gyorgyi 1966, pp. 116-117). Alan MacDiarmid (Nobel Prize, 2000), who was one of the discoverers of conductive polymers, was also motivated by his love of color. One day he was shown a polymer to which too much catalyst had been added resulting in an amazingly silvery plastic material. He was enchanted and asked for a sample to investigate. It turned out to be polyacetylene and it conducted electricity. "There were no scientific reasons whatsoever," he said for his studies of polyacetylene: "My motivations have been driven by curiosity and color […]" (Russo 2000).

4. Chemistry as art

Since sensual and aesthetic concerns are primary to so many successful chemists, some explicitly compare their work to that of an artist. Max Planck, for example, argued that, "the scientist needs […] an *artistically* creative imagination" (Planck 1949, p. 28). Donald Cram (Nobel Prize, 1987) agreed: "In my opinion, organic chemists are part artist and part scientists, and thus apply both lobes of their brains to their work. To the extent that they are artists, they develop a research style expressed in their choice of research problems, how they address these problems, the degree of craftsmanship they bring to their research results, the extent to which they document their results, the readership they address in their papers, and their style of writing papers" (Cram 1990, p. 122). "I submit that the synthesis of complex molecules is a form of art like painting or architecture," writes William S. Johnson. "Both areas require an immense amount of experience way beyond what can be learned from books or listening to lectures by experts" (Johnson 1998, p. 182). Similarly, Derek Barton (Nobel Prize, 1969) wrote that, "Like an artist, I seek elegance and personal satisfaction" (Barton 1991, p. 109). Richard Willstätter's (Nobel laureate, chemistry, 1915), who linked his hobby of collecting fine art to his scientific aesthetic drive made a similar analogy: "I look for the lover of nature in the artist," he wrote, "and for the artist in the scientist. We belong together" (Willstätter 1965, p. 395). These men confirm that scientific imagination is more than just an accumulation of facts. It requires the acquisition of technique, acute observational skills, the ability to invent patterns and to abstract out essences and meanings from complexity, and the development of style (Root-Bernstein 1989, Root-Bernstein & Root-Bernstein 1999).

Chemical research is like artistic exploration in one other unexpected way, as well. It is often said that art differs from science in that if you give ten artists a scene to paint you will get ten different pictures, but if you give ten scientists a problem to solve, you will get one answer (Root-Bernstein 1984). This view of the differences is a gross oversimplification as I have pointed out elsewhere, but one element of it is particularly relevant to the issues I am addressing here. It turns out that one of the most common statements made by highly productive scientists is that they never look for *the* answer to a problem, but rather investigate the widest possible *range* of answers. Robert Mulliken, for example, wrote that, "I have a compulsion to look at all possibilities, both probable and improbable [...]. This habit [...] has helped me find original ideas in the course of my research" (Mulliken 1989, p. 19). Linus Pauling (Nobel prize, 1954) tied this strategy into aesthetic considerations, saying that his success came from asking, "What ideas" – note the plural – "about this question, as general and as aesthetically satisfying as possible, can we have that are not eliminated by these results of experiment and observation?" (Pauling 1963, p. 47). Thus, the goal of science may be to obtain an objectively verifiable solution to a problem, but the process by which such answers are obtained more often involves the exploration of many aesthetically pleasing possibilities (Root-Bernstein 1984, Root-Bernstein 1989, pp. 196-203, 212-215, 291-95).

Pauling's faith in aesthetic criteria (which led him astray at least once with regard to his DNA triple helix!) is echoed by physicist and historian of science Gerald Holton and his colleagues Hasok Chang and Edward Jurkowitz. Like Pauling, they emphasize the artistic nature of creative scientific thinking, noting that, "scientists from Kepler to Kekulé, from Newton to Crick and Watson, were guided in the early stages of scientific research by a visually powerful, highly symmetric geometric design". Francis Crick (Nobel Prize, medicine/physiology, 1962), for example, wrote to Lipscomb that two aesthetic criteria, symmetry and simplicity, played key roles in the discovery of the DNA double helix (Curtin 1982, p. 11); and James Watson (Nobel Prize, medicine/physiology, 1962), himself, said in *The Double Helix* that the model was too beautiful not to be true (Watson 1968, p. 114). Crick records that on one occasion, Watson, a bit worse for alcoholic intake, "gazed slightly bleary-eyed [at the double helix model]. All he could manage to say was, 'It's so beautiful, you see, so beautiful!'" Crick himself added, "but then, of course, it was" (Crick 1988, p. 79). The fact that not everyone agrees, as I noted above, only reinforces the subjective nature of such an aesthetic evaluation.

This subjective aspect of aesthetic motivation is emphasized by Holton and his colleagues. They suggest that aesthetically motivated "personal thematic presuppositions", such as Watson's and Crick's belief in the beauty of helical structures, are essential guides for many far-reaching research programs. The example they cite at length is the peculiar role of visual symbolism in the discovery of high temperature superconductors. The first such superconductor was found in the mineral perovskite by Karl Alexander Müller (Nobel Prize, physics, 1987). Müller revealed to Holton and his colleagues in interviews that his choice of perovskite was not rational, but based upon an unusual symmetry that endowed the mineral with aesthetic qualities that had attracted him since the beginning of his scientific career. "The perovskite structure was for me, and still is, a symbol of – it's a bit high-fetched – but of holiness. It's a mandala, a self-centric symbol which determined me [...]. I dreamt about this perovskite symbol while getting my Ph. D. And more interesting about this is also that this perovskite was not just sitting on a table, but was held in the hand of Wolfgang Pauli, who was my teacher [...]. I was always dragged back to this symbol" (Holton, Chang, & Jurkowitz 1996, p. 372).

Such aesthetically motivated symbolic thinking is not an example of rational scientific thought as it is usually portrayed to the public or to students of science. Yet if Holton and his colleagues are correct in saying that such thinking is at the basis of many, if not most, major scientific breakthroughs, then we need to rethink how we present the so-called 'scientific method' and reconsider the process by which scientific discoveries are made (Root-Bernstein 1989).

5. Aesthetic cognition and synosia

Over many years, I have come to the conclusion that aesthetic considerations are in and of themselves ways of thinking about scientific ideas and that sensual experience is the basis of the intuition we bring to our work. I have recently introduced the concept of 'aesthetic cognition' as a way to talk about such sensual and aesthetic thinking (Root-Bernstein 2002). Following in the footsteps of physical chemist Michael Polanyi, I firmly believe that we each develop a kind of 'personal knowledge', or intuition, about how nature works that comes from our own, sensual and intimate interactions with it (Polanyi 1958). The result is that we each develop two types of understanding: formal knowledge of things that we learn through books, lectures, conversations, and other forms of communication; and equally important, intuitions that we develop through our sensory interactions with materials in experiments and other forms of play. In addition, we bring to everything we do a sense of aesthetics that we develop in part through our professional activities (what is an elegant experiment) and our hobbies (why is this painting or poem or song more beautiful than another?). Combine the intellect, the senses, and aesthetics and one gets what I call 'synosia', from the root words 'synaesthesia' (using all one's senses interactively) and 'gnosis' (Greek for knowledge). Synosia, in short, means 'synthetic knowing' that melds objective and subjective ways of knowing. One knows what one feels and feels that one knows (Root-Bernstein & Root-Bernstein 1999). Aesthetic cognition results from the fact that there is a 'meta-logic' to the intuitive responses that is embedded in what we call scientific aesthetics. From the examples given above, it must be clear that aesthetic cognition precedes and is distinct from formal logic, nonetheless yielding insights that are amenable to logical development and analysis. In sum, aesthetic cognition combines knowledge and feeling into synosic intuition that is the basis for creative scientific thinking.

The concepts of aesthetic cognition and synosia unexpectedly integrate two outstanding problems in the philosophy of science. One problem is the division made by Karl Popper and many other philosophers of science between the 'logic of research' and 'psychology of research'. Logic, in this formulation of the philosophy of science, is applicable only to well-formulated ideas that have already been expressed in mathematical or verbal formulations by scientists. How such well-formulated ideas come into being is relegated to the realm of 'psychology of research', which most philosophers have placed beyond the consideration of their field. The other problem that aesthetic cognition and synosia bring into the fold of the philosophy of science is the consideration of aesthetics itself. While there is a very strong tradition of philosophical discussion about aesthetics in the arts that can be traced at least to the ancient Greeks, the role of aesthetic considerations in science is a relatively new and undeveloped field. My contention is that understanding the role of aesthetics in science requires consideration of sensual and emotional responses to nature similar, if not identical, to those involved in considerations of aesthetics in the arts (McAllister 1996). Understanding how these individual and subjective sensual and emotional responses underlie the urge to do science – that is to understand nature itself – gets us directly, via philosophical considerations, into novel areas of cognition. Thus synaesthesia, as a basic concept within aesthetics, turns out to be a form of cognition – hence, aesthetic cognition.

The view that sensual and aesthetic considerations are a way of thinking about science should not, for all the reasons I have summarized above, be a surprising conclusion, but I suspect that for many people it will be. Science is often described in textbook formulations of the scientific method as being distinguished from the arts by being objective, intellectual, analytical, unemotional, and verifiable. The arts, in contrast, are supposedly subjective, sensual, synthetic, emotional, and idiosyncratic. Recognizing that all scientific insights originate in highly subjective, sensual, and aesthetic ways suggests that this science-art distinction does not hold water. The interesting philosophical issue becomes the problem of how emotional, sensual, and idiosyncratic intuitions can form the basis of objectively verifiable analytical results. The connection involves how scientists perceive problems and patterns. What is an hypothesis or theory but a pattern that we recognize within diverse sets of data; and what is a problem but the breaking of a pattern or our inability to perceive how some data fit into any known pattern?

The fact is that we *feel* what is right and wrong about scientific ideas. Thus, the importance of aesthetic cognition is that it makes intuitional understanding comprehensible and useful by showing us how sensual ways of knowing are connected to rational ways of knowing. Our feelings tell us whether what we are learning or observing or theorizing fits with the somatic and sensual understanding of nature that we call intuition.

Thus, I have found that the bodily feelings, emotional responses, and visual images that I had when I looked at the drawings of the DNA double helix and imagined unwinding it like a rope are not uncommon among creative chemists. Some, indeed, go much further than I did, actually imagining themselves to be the objects of their study (Root-Bernstein 1990). Thus, Peter Debye (Nobel prize, 1936) said that the key to his insights was, "to use your feelings – what does the carbon atom *want* to do? You had to [...] get a picture of what is happening. I can only think in pictures" (Debye 1966, p. 81). Cram was similarly visual: "I have always felt that I understood a phenomenon only to the extent that I could visualize it. Much of the charm organic chemical research has for me derives from structural formulas." (Cram 1990, p. 122) For Cyril Smith, chemistry involved all of his senses: "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, even before I had a sensual contact with the alloy itself." (Smith, 1981, 353) He goes on to say similarly, that his later work, "on interfaces really began with a combination of an aesthetic feeling for a balanced structure and a muscular feeling of the interfaces pulling against each other!" (*Ibid.*) The mathematical physicist Wolfgang Pauli (Nobel Prize, physics, 1945) also maintained that scientific thinking begins within the "unconscious region of the human soul," where, "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" (Heisenberg 1974, pp. 179-180; Chandrasekhar 1987, p. 146). Karl Popper has gone so far as to actually recommend such empathetic thinking as the basis of creative scientific thought. "I think the most helpful suggestion that can be made […] as to how one may get new ideas in general [is …] 'sympathetic intuition' or 'empathy' […]. You should enter into your problem situation in such a way that you almost become part of it" (Krebs & Shelley 1975, p. 18).

Intuition developed through careful attention to feelings, sensual and aesthetic, are therefore at the basis of chemical knowing, not the antithesis of rational thought. When Mulliken wrote that he "smell[ed] various compounds […] to look for resemblances or differences in the odors of similar or related compounds," (Mulliken 1989, p. 20) this was a process that differed in no way from the chemist who examines tables of data or chromatographic charts in search of patterns of properties. Each approach yields information useful for thinking about chemical properties. The fact that one is sensual and the others analytical does not alter their utility as ways of thinking about chemistry. Thus feelings are a way of thinking just as intrinsic to science as logical analysis.

A necessary corollary to my concept of aesthetic cognition is that ideas arise in individual minds in private terms that must be translated in an explicitly secondary process for communication with other people (Root-Bernstein & Root-Bernstein 1999, chap. 1). We discover in very personal ways using private 'mental languages' such as emotional feelings and sensual images that only we understand. These need to be transformed into publicly traded forms. Lipscomb, who like Debye is very visual, has addressed this translation process directly: "My language is my visualization of what molecules are doing either in their structure, their transformations, or their reactions, and I translate that either into chemical language or into mathematics, but not into English. It's surprising how little one uses English in the actual working out of science. Most people who are not scientists believe that they think in terms of language. I'm not quite sure that they do. I know that I don't. I later put it in English, but it's the third stage of the process." (Curtin 1982, pp. 134-135) Smith has written similarly that, "before publishing anything I tried to put it in respectable scientific terminology and it was fun to do so, but the stage of *discovery* was entirely sensual and the mathematics was only necessary to be able to communicate with other people" (Smith 1981, p. 353). Perhaps it is the fact that insights are always developed through such private forms of thinking that has hidden the crucial roles that sensual images and aesthetics play in discovery processes in favor of the public forms of discourse that scientists employ between one another. In any event, it seems to me that this translation process is another aspect of the 'scientific method' that is badly in need to formal study and instruction (Root-Bernstein 2002).

6. Conclusions: putting aesthetics at the center of chemical methodology and education

It has taken me thirty years to get to this point in my thinking about aesthetics in science. What strikes me in retrospect is that the intellectual and sensual journey I have made to discover the aesthetic underpinnings of science has taken so long. No one ever lectured about it in any science course I ever took, not even Alyea. None of my colleagues lecture about it now, though many are personally aware of the aesthetic feelings I have just described. Finding written descriptions of these sensual experiences and feelings is like looking for needles in haystacks. They are, for some reason, not considered part of chemistry proper. Aesthetic, sensual, and empathetic considerations are rarely discussed in formal descriptions of the 'scientific method'. The result is that, as Lipscomb has said, "so little of these matters are accessible in our schools and universities [that] 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" (Curtin 1982, p. 19).

Note that Lipscomb mentions aesthetics and originality in one breath. They *are* linked; linked in intimate yet subtle ways that I have explored throughout this essay. The fact is that we scientists rely to an inordinate degree on sensual, intuitional, and aesthetic approaches to our science, whatever we may admit to in public. We act like guilty lovers who revel in the sensual aspects of our craft and experience orgasmic and awe-inspiring insights yet tell our students about the objectively verifiable *results* but not about our subjective, personal *experiences* of them. And then we wonder why so many students take our courses but so few are attracted to our professions. A recent comment by one of Roald Hoffmann's former students is illuminating. She said that she decided to become a chemist after learning about the Hoffmann-Woodward rules, which she considered to be the most beautiful insight in all of science. We need to promote this beautiful face of science. The aesthetic dimension is what makes science both worthwhile and compelling and provides the emotional stamina to carry out a lifetime of work.

The problem is that science has two faces that have evolved from the split between aesthetic cognition and the translation process needed to transform personal insights into public forms of discourse. One is a private face involving the personal foibles, stylistic quirks, and emotional responses that allow each of us our personal style and creativity. This face we hide even from other practitioners, embarrassed to reveal the idiosyncratic, subjective, or even incorrect bases of our discoveries (Root-Bernstein 1989). The other face is the public face, which consists of the objectively verifiable results that we obtain stripped of the artistic, psychological, historical, and social trappings that allowed us to achieve them. The public face of science does not usually admit the existence of the private face. Yet I would like to suggest, for all of the reasons outlined above, that the creativity that we so admire in scientists cannot exist separate from its private face, and that sensual, emotional, and aesthetic sensibility is the core of creative insight. Moreover, I believe that we are handicapping our students by hiding this sensual and aesthetic face of science from them, for without it, there is no motivation or attraction to our subject.

Our students deserve to know that so many eminent and successful chemists have described their science as an art and that aesthetic considerations can motivate not only an interest in chemistry, but in particular problems and solutions. The artificial distinctions between reason and passion, sense and sensibility, intellect and intuition, serve only to harm the scientist. What makes science scientific is not the elimination of passion, sensibility, and intuition from daily work but the harnessing of these subjective modes of insight to the rigorous demands of skeptical validation or disproof. For, as Henri Poincaré pointed out, the methods of logic are sterile. They can tell us whether we are on the right path once we are on it, but they cannot direct us into the regions of the unknown (Poincaré 1946, pp. 365-368). The scientific explorer, like any pioneer, must leap beyond what logic can reveal. The artistic imagination can provide the means to make such leaps.

Thus, it is fitting to end this essay with the words of the first Nobel laureate in Chemistry (1901), van't Hoff. Frustrated by the dismal response to his first great innovation, the stereochemistry of the tetrahedral carbon atom, he lashed out at his detractors in an inaugural address delivered at the new University of Amsterdam in 1879. There can be no great science without great imagination, he said, and it is not, therefore, without reason that the greatest chemist of his day, Sir Humphrey Davy, was also a poet and visionary commended by no less than Coleridge himself. For Davy's "discoveries", said van't Hoff (1878), "were the fruits of that great gift which [English historian H. T.] Buckle describes: 'There is a spiritual, a poetic, and for aught we know a spontaneous and uncaused element in the human mind, which ever and anon, suddenly and without warning, gives us a glimpse and a forecast of the future, and urges us to seize the truth as it were by anticipation.'" Those who know not the beauty of science can never glimpse this poetic forecast.

References

Alyea, H.N.: 1968, *TOPS. Tested Overhead Projection Series, Microchemistry Projected*, Princeton University, Princeton.

Barton, D.H.R.: 1991, *Some Recollections of Gap Jumping*, American Chemical Society, Washington, DC.

Birren, Faber (ed.): 1969, *The Color Primer. A Basic Treatise on the Color System of Wilhelm Ostwald*, Van Nostrand Reinhold, New York.

Chandrasekhar, S.: 1987, *Truth and Beauty. Aesthetics and Motivations in Science*, Chicago UP, Chicago.

Cram, D.J.: 1990, *From Design to Discovery*, American Chemical Society, Washington, DC.

Crick, F.H.C.: 1988, *What Mad Pursuit. A Personal View of Scientific Discovery*, Basic Books, New York.

Curtin, D.W. (ed.): 1982, *The Aesthetic Dimension of Science*, Philosophical Library, New York.

Davy, H.: 1840, 'Parallels between art and science', in: John Davy (ed.), *The Collected Works of Sir Humphrey Davy*, Smith and Cornhill, London, vol. 8, pp. 306-308.

Debye, P.: 1966, 'Peter J. W. Debye', in: *The Way of the Scientist. Interviews from the World of Science and Technology*, Simon and Schuster, New York, pp. 77-86.

Eisner, T.: 1999, 'Seventy-five reasons to become a scientist', *American Scientist*, **76**, 451.

Farago, P.: 1977, 'Interview with Dorothy Crowfoot Hodgkin', *Journal of Chemical Education*, **54**, 214-215.

Ferry, G.: 1998, *Dorothy Hodgkin. A Life*, Granta, London.

Gilbert, G.N.; Mulkay, M.: 1984, *Opening Pandora's Box. A Sociological Analysis of Scientists' Discourse*, Cambridge UP, Cambridge.

Heisenberg, W.: 1974, *Across Frontiers*, trans. by P. Heath, Harper and Row, New York.

Hoffmann, R.: 1989, 'Molecular beauty IV: Toward an aesthetic theory of six-coordinate carbon', *American Scientist*, **77**, 330-332.

Holton, G.; Chang, H.; Jurkowitz, E.: 1996, 'How a scientific discovery is made: a case history', *American Scientist*, **84**, 364-375.

Horgan, J.: 1991, 'Profile: Thomas Eisner', *Scientific American*, Dec., 60-61.

Hunter, N.W.: 1993, 'Dorothy Hodgkin', in: L.K. Jones (ed.), *Nobel Laureates in Chemistry, 1901-1992*, American Chemical Society and Chemical Heritage Foundation, Washington DC, pp. 456-461.

Ihde, A.J.: 1971, 'Euler-Chelpin, Hans von', in: C.C. Gillispie (ed.), *Dictionary of Scientific Biography*, Scribner's, New York, vol 4, pp. 485-486.

Johnson, W.S.: 1998, *A Fifty-Year Love Affair with Organic Chemistry*, American Chemical Society, Washington DC.

Krebs, H.; Shelley, J.H. (eds.): 1975, *The Creative Process in Science and Medicine*, Excerpta Medica, Amsterdam.

Langridge, R.; Ferrin T.E.; Kuntz, I.D.; Connolly, M.L.: 1981, 'Real-time color graphics in studies of molecular interactions', *Science*, **211**, 661-666.

Levi, P.; Regge, T.: 1989, *Dialogo*, trans. by R. Rosenthal, Princeton UP, Princeton.

McAllister, J.W.: 1996, *Beauty and Revolution in Science*, Cornell University Press, Ithaca.

Mulliken, R.S.: 1989, *Life of a Scientist*, Springer-Verlag, Berlin.

Ostwald, W.: 1926-7, *Lebenslinien: Eine Selbstbiographie*, Klasing, Berlin, 3 vols.

Pauling, L.: 1963, 'The genesis of ideas' *Proceedings of the Third World Congress of Psychiatry, 1961*, U of Toronto Press & McGill UP, Toronto, vol. 1, pp. 44-47.

Planck, M.: 1949, *Scientific Autobiography and Other Papers*, trans. by F. Gaynor, Philosophical Library, New York.

Pohl, W.F.; Roberts, G.W.: 1978, 'Topological considerations in the theory of replication of DNA', *Journal of Mathematical Biology*, **6**, 383-402.

Poincaré, H.: 1946, *The Foundations of Science*, trans. by G. Halsted, Science Press, Lancaster, PA.

Polanyi, M.: 1958, *Personal Knowledge: Towards a Post-Critical Philosophy*, University of Chicago Press, Chicago.

Rayleigh, Lord: 1942, *The Life of Sir J. J. Thomson., O. M.*, Cambridge UP, Cambridge.

Rodley, G.A.; Scobie, R.S.; Bates, R.H.T.; Lewitt, R.M.: 1976. 'A possible conformation for double-stranded polynucleotides', *Proceedings of the National Academy of Sciences, U.S.A.*, **73**, 2959-2963.

Root-Bernstein, R.S.: 1984, 'On paradigms and revolutions in science and art', *Art Journal*, Summer, 109-118.
Root-Bernstein, R.S.: 1987, 'Harmony and beauty in biomedical research', *Journal of Molecular and Cellular Cardiology*, **19**, 1-9.
Root-Bernstein, R.S.: 1989, *Discovering*, Harvard UP, Cambridge MA.
Root-Bernstein, R.S.: 1990, 'Sensual science', *The Sciences*, Sep.-Oct., 12-14.
Root-Bernstein, R.S.: 1996a, 'Do we have the structure of DNA right? An essay on science, aesthetic preconceptions, visual conventions, and unsolved problems' *Art Journal*, 55, 47-55.
Root-Bernstein, R.S.: 1996b, 'The science and arts share a common creative aesthetic', in: A.I. Tauber (ed.), *The Elusive Synthesis: Aesthetics and Science*, Kluwer, Dordrecht, pp. 49-82.
Root-Bernstein, R.S.: 1997, 'Art, imagination and the scientist', *American Scientist*, **85**, 6-9.
Root-Bernstein R.S.: Root-Bernstein, M.M.: 1999, *Sparks of Genius*, Houghton Mifflin, Boston.
Root-Bernstein, R.S.: 2002, 'Aesthetic cognition', *International Journal of the Philosophy of Science*, **16**, 61-77.
Russo, E.: 2000, 'Nobel impact', *The Scientist*, 11 December, p. 10.
Sasisekharan, V.; Pattabiraman, N.: 1978, 'Structure of DNA predicted from sterochemistry of nucleoside derivatives', *Nature*, **275**, 159-162.
Smith, C.S.: 1978, 'Structural hierarchy in science, art, and history', in: J. Wechsler (ed.), *On Aesthetics in Science*, MIT Press, Cambridge MA, pp. 8-53.
Smith, C.S.: 1981, *A Search For Structure*, MIT Press, Cambridge MA.
Stokes, T.D.: 1982, 'The double helix and the warped zipper – an exemplary tale' *Social Studies of Science*, **12**, 207-240.
Szent-Gyorgyi, A.: 1966, 'In search of simplicity and generalizations (50 years of poaching in science)', in: N.O. Kaplan & E.P. Kennedy (eds.), *Current Aspects of Biochemical Energetics*, Academic Press, New York, pp. 63-76.
Van't Hoff, J.H.: 1878, *De verbeeldingskracht in de wetenschap*, P.M. Bazenkijk, Rotterdam, 1878 (German trans. 'Die Phantasie in der Wissenschaft' by E. Cohen in *Jacobus Henricus van't Hoff, sein Leben und Wirken*, Akademische Verlagsgesellschaft, Leipzig, 1912, pp. 150-165; English trans. 'Imagination in Science' by G.F. Springer, *Molecular Biology, Biochemistry, and Biophysics*, 1967, **1**, 1-18).
Van't Hoff, J.H.: 1887, 'Die Rolle des osmotischen Drucks in der Analogie zwischen Lösungen und Gasen,' *Zeitschrift fur physikalische Chemie*, **1**, 481-508 (English translation by James Walker in *The Foundations of the Theory of Dilute Solutions*, Alembic Club, London, 1929, no. 19, pp. 5-42).
Watson, J.D.: 1968, *The Double Helix*, Atheneum, New York.
Watson, J.D.; Crick, F.H.C.: 1953, 'The structure of DNA', *Cold Spring Harbor Symposia on Quantitative Biology*, **18**, 123-131.
Willstaetter, R.: 1965, *From My Life. The Memoirs of Richard Willstaetter*, trans. by L.S. Hornig, W. A. Benjamin, New York (German original: Verlag Chemie, 1949).
Woodward, C.E.: 1984, 'Art and elegance in the synthesis of organic compounds: Robert Burns Woodward', in: D.B. Wallace & H.E. Gruber (eds.), *Creative People at Work*, Oxford UP, New York.

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