Goethe and the Molecular Aesthetic

Maura C. Flannery
St. John's University

I argue here that Goethe's "delicate empiricism" is not an alternative approach to science, but an approach that scientists use consistently, though they usually do not label it as such. I further contend that Goethe's views are relevant to today's science, specifically to work on the structure of macromolecules such as proteins. Using the work of Agnes Arber, a botanist and philosopher of science, I will show how her writings help to relate Goethe's work to present-day issues of cognition and perception.

Many observers see Goethe's "delicate empiricism" as an antidote to reductionism and to the strict separation of the objective and subjective so prevalent in science today. The argument is that there is a different way to do science, Goethe's way, and it can achieve discoveries which would be impossible with more positivistic approaches. While I agree that Goethe's method of doing science can be viewed in this light, I would like to take a different approach and use the writings of the plant morphologist Agnes Arber in the process since she worked in the Goethean tradition and enlarged upon it. I argue here that Goethe's way of science is done by many, if not most scientists, that there is not a strict dichotomy between these two ways of doing science, but rather scientists move between the two approaches so frequently and the shift is so seamless that it is difficult for them to even realize that it is happening. I use as an example of such shifts the work being done in biology with molecular structures. I argue further that becoming more aware of their use of a delicate empiricism will help biologists and biochemists to be more effective in their exploration of the macromolecular terrain.

I came to the study of Goethe through an interest in the aesthetic of biology—what makes biology beautiful (Flannery, 1992). I became convinced, in the Kantian tradition, that scientific judgment involves aesthetic judgment. Exploration of this theme led me in a number of directions, including to the work of the chemist/philosopher Michael Polanyi (1962), who explores the idea of tacit knowledge, knowledge that cannot be put into words, intuitive knowledge that comes with doing, with being immersed in an activity. It is learning that involves the body as well as the mind: no matter how many books you were to read about how to drive a car, you would never be ready to take a driving test until you had spent considerable

Janus Head, 8(1), 273-289.

time behind the wheel. Polanyi, like Goethe, sees the Cartesian dichotomy between mind and body as inaccurate because it cannot account for so much of human experience, including the experience of doing science.

The Mind and the Eye

Polanyi, through a footnote, led me to Agnes Arber's (1954) *The Mind and the Eye*, an introduction to the philosophy of biology by someone who had done botanical research for decades before tackling this subject. Arber (1879-1960) was a botanist who specialized in morphological work; she studied the development of plant form as well as the relationships among different species. Though her technical work was highly regarded and she was only the third woman elected a Fellow of the Royal Society (in 1946), Arber was considered on the fringes of the plant science community because of her criticisms of evolution by natural selection. To put it briefly, she found it difficult to account for the myriad, often minor, and diverse differences among closely related species in terms of increased fitness of one slightly different form or color of leave or flower over another. By 1950 when she wrote *The Natural Philosophy of Plant Form* in which she explicitly discussed this view, the evolutionary synthesis was already firmly entrenched. So she came to be seen as a peripheral figure representative of outdated thinking in biology (Eyde, 1975). This is unfortunate because it meant that her work on the philosophy of science had less impact than it might otherwise have had.

In *The Mind and the Eye*, Arber begins by analyzing the process of scientific inquiry, which she sees as involving six steps or practices. The first is to find a research question and then to explore that question, which may mean experimentation, observation, or comparative work. In any case, after this gathering of information relative to the question comes the interpretation and evaluation of the data: does it support the original hypothesis? Then it is back to testing, to further investigating the validity of the results. If the validity is established, it is time to communicate these results, to make this science public.

For many scientists, this fifth step would seem to be the end of the process and to lead back to the beginning with exploration of another and perhaps related research question. But for Arber, there is one more step: to put the results into perspective, to examine the research in terms of larger issues in science, including historical and philosophical questions. She considers this step so important that she devotes half her book to it and delves into the basic assumptions of biology, the role of antitheses in biological inquiry and the function of art in doing biology. Arber sees this sixth step as being something that scientists would do toward the end of their careers when the pressure of producing research may have subsided. Though she had an interest in history and philosophy throughout her career, she did indeed become more involved in these fields after she gave up active research during World War II when conditions made it almost impossible to continue. At this point Arber was in her sixties, and, when bench research was no longer feasible, she saw the opportunity to step back, as she suggests in her book, and consider what she had been doing.

Though it has been neglected by biologists and philosophers alike, *The Mind and the Eye* is significant because of its clear prose and its precociousness. Written in the 1950s, when the philosophy of science was still dominated by physicists' views of what science is and by a positivistic approach, the book takes a different tack. Arber looks at biology and without explicitly saying so as later writers do (Mayr, 1982), she shows how biological inquiry involves a different approach to the world than does physics: there is more emphasis on comparison and on diversity rather than on finding unity. Arber also argues that intuition, an artistic sense, and knowledge that is nonverbalizable are involved in biological inquiry. She writes this before Polanyi and many others pointed to the fact that science entails more than a positivistic approach. I bring this up here because it relates to how Goethe's view of science still lives on in present-day research. Arber was very much imbued with the Goethean tradition. She was well-versed in his work and saw its relevance to her own, not only in terms of issues of biology but of issues of how science is done as well. In both *Natural Philosophy* and *The Mind and the Eye*, she emphasizes the importance of the visual and of observation. But like Goethe, she sees that as only the beginning. Though she doesn't use the term "delicate empiricism," she sees its value and works in that tradition. At the end of *Natural Philosophy* she writes of how perceptions are internalized and used to create ideas about the world, in this case about the plant world. She appreciates the fact, as did Goethe, that perception is a complex process.

Before going further, I want to mention two other points about Arber that are germane to this paper. First, Arber, like Goethe, was an accomplished artist. From an early age, she had received art lessons from her father, who made a living as a competent landscape painter in the latter part of the 19th century. Arber created beautiful watercolor botanical illustrations when she was in her teens, but then went to drawing exclusively in black and white. She did almost all the illustrations for her scientific papers and books, some chapters of which had more pages of illustrations than of text. Arber's experiences as an artist definitely colored her view of what it is to do science. She was much more aware of the complexities of observation and the relationship between seeing and thinking.

The second point is that from the time she was in high school, Arber was interested in Goethe's writings. In 1946 she published a translation of his *Attempt to Interpret the Metamorphosis of Plants*. In *Natural Philosophy*, *The Mind and the Eye*, and many of her other writings, the influence of Goethe is clear. In her last book, *The Manifold and the One* (1957), she admits that throughout her life she has been fascinated by the relationship between unity and diversity, a question that also occupied Goethe. In both cases, this fascination manifested itself and was nourished by an interest in plants where the many species in some genera are good examples of variations on a theme, of great multiplicity but with an underlying unity.

The influence of Goethe is seen in several discussions in *The Mind and the Eye*. Like Goethe, Arber was inspired by Spinoza's philosophy and thus there is a tendency toward idealist thinking in her work. She sees categories of form as representing mental categories more than evolutionary ones. She argues that using only the yardstick of evolution to measure and explore relationships between forms is too limiting and distorts the study of morphology. Though many do not consider Goethe a romantic, others see at least some romantic influences in his work (Richards, 2002) and the same can be said of Arber's. Both were interested in the relationships of organic parts to the whole, saw a connection between the objective and subjective, and took an idealist view of form. The fact that both had an interest in art, and in doing art, cannot be overlooked. Goethe took art lessons and immersed himself in the artistic life during his first trip to Italy (Goethe, 1962). Perhaps not coincidentally, it was also on this trip that he developed his idea of the urplant or fundamental plant form underlying the diversity of plant forms, as well as the idea of the leaf as the basic plant form, to which other plant forms such as the parts of the flower, are related.

In *The Natural Philosophy of Plant Form*, Arber traces ideas on plant form from the time of Aristotle and devotes attention to Goethe's views and how they were developed by botanists like A.P. de Candolle. She then argues that it is not the leaf, but the partial shoot which is the fundamental form in plants. While Goethe has been criticized for not having a deep enough knowledge of plant morphology and for not understanding what goes into a scientific argument, no such criticisms can be lodged against Arber. Her claims are grounded in careful observation, not only of normal plant structure, but of the abnormal, because she contends that anomalous forms often reveal a great deal about underlying structural and developmental relationships. For example, a leaf-like structure growing out of the middle of a flower hints at the relationship between leaf and petal, a relationship that is much less apparent in normal structure.

The Molecular Form

In the last chapter of *Natural Philosophy*, Arber steps back from the specifics of plant morphology and takes a more philosophical view. She is trying to justify her approach, which is holistic and looks at the relationships among parts, how they develop, and how they relate to the whole, and to the forms of other species. This is a central idea in Arber's work as it is in Goethe's. It is also central to a great deal of the structural molecular biology done today on the large, complex macromolecules such as proteins and nucleic acids that are found in living organisms. In beginning a discussion of the molecular world, I should note that while Arber and Goethe were dealing with plants that can be viewed directly with the naked eye or with a light microscope, molecular biologists are "looking" at their molecular specimens much more indirectly. Delicate empiricism here means dealing with the output of complex technology that only secondarily converts electrical signals and mathematical data into images. But still, researchers work with these images and this data in ways that are similar to the approaches Goethe and Arber used. By this I mean that the data—abstract as well as visual—is processed holistically by the cognitive and affective functions of the mind. Yes, there is analysis, but ultimately researchers have to go beyond such analysis and use aesthetic as well as rational judgments in devising forms that reflect the data they've analyzed.

It must be kept in mind that while there is a great deal known about the components of macromolecules and how they are put together, molecular structures are still created artifacts. In an article on what molecular structures do and do not really signify, Luisi and Thomas (1990) warn that when we look at representations of molecules we have to remember that they are just that. There is a great deal of idealist thinking involved in these representations, more than most chemists will admit. While biochemists may be quick to argue that Goethe's archetypes are mental constructs, they are loathe to admit the same for the structures they create. Both are the result of the processing of data by the mind, both are therefore examples of delicate empiricism.

For my analysis, I am going to focus on protein structure, because it is in general more complex and less ordered than that of the nucleic acids, DNA and RNA. Though it should be noted that as more becomes known about DNA structure, it is becoming apparent that there is not only the basic helical structure, but variations on the helix, including local variations due to specific nucleotide sequences and secondary and tertiary structures that result from the twisting of DNA into more complex shapes, often in conjunction with proteins and/or RNA (Goodsell, 2004). But proteins are made up of one or more chains of 20 different building blocks (i.e., amino acids) as opposed to only 4 different nucleotides in DNA, so by their chemical nature proteins tend to be more complex and also more diverse structurally.

Without going into protein structure in any detail, there are a few ideas that will be useful to my discussion. First, while the overall structures of individual proteins show little pattern—for example, there is little symmetry—pattern is found within parts of the molecule. Biochemists have characterized two particular forms, resulting from the folding of parts of the amino acid chain of a protein, are found repeatedly: the alpha helix and the beta sheet. A protein may contain one or more such regions. Also, a functional protein may be composed of more than one amino acid chain, and the member chains may be identical or different from each other. For example, hemoglobin, the protein that carries oxygen in the blood, is made up of four chains, two called alpha and two called beta. While the forms of each of these folded chains show no symmetry, the molecule as a whole does.

In addition, proteins are not static structures, though it is often difficult to keep this in mind since the reifications of these molecules are usually in the form of static representations. Here the tendency to move away from a delicate empiricism which would take such movement into account has created a situation where the dynamism of macromolecules is neither represented nor given sufficient attention. This viewpoint, coupled with the emphasis on alpha helices and beta sheets, has meant that proteins which do not have these structural elements and thus have more dynamic and fluid structures have been neglected (Dyson & Wright, 2005).

Movement is particularly important in enzymes, proteins which control almost all the chemical reactions in cells. An enzyme is a catalyst, which means it speeds up a reaction without itself being permanently changed in the course of the reaction. Fundamentally, an enzyme forms a site where a reaction can take place. The reactant, called a substrate, is attracted to a particular area of the enzyme. When the substrate (or substrates) makes contact, this causes a change in the shape of the enzyme, changing the conformation of the reactant(s) and chemically making it more likely that a reaction will occur. Proteins can also change shape when other molecules besides the substrates, bind to them. These other molecules can cause shape changes that make the enzyme more or less active, thus exercising control of function. Finally, it is important to keep in mind that because enzymes are very specific, that is, only attracting particular substrates and only allowing them to react in a particular way, there are many different enzymes in every cell and in every living thing.

Since there is such diversity among proteins, since most do not have regularly symmetrical shapes and have more than one configuration as they function, the field of protein structure is a complex and difficult one. It took Max Perutz (1998) 30 years to work out the structure of hemoglobin, one of the first proteins for which a structure, down to the level of individual amino acids and atoms, was found. While this was seen as a scientific triumph, what was not noted was the tentative nature of Perutz's model, as Luisi and Thomas (1990) discussed in the paper I cited earlier.

Though proteins structures can now at least sometimes be worked out within a matter of weeks or months, it is more difficult to develop a good understanding of the relationship between a protein's shape changes and its activity. In most cases, the molecular biologist works out the structure of a protein in a particular state, for example in the case of hemoglobin, it would be with or without oxygen bound to the molecule. The conformation of hemoglobin is different in the oxygenated and deoxygenated states, but the transition between the two forms is not directly observed and can only be extrapolated from the two more stable states. Biochemists are coming to realize the limitations of their models, which are representations rather than reality itself, and as such, do not give the whole picture of what is happening at the molecular level.

To find the structure of a protein, in most cases the protein has to be processed into a crystalline form. In a crystal, the protein molecules are arranged into a regular lattice or array, and when this array to bombarded with

X-rays, the rays bounce off the molecules to form a regular, repeating pattern on film. The positions of the spots on the film correspond to the positions of the atoms in the molecule. It would seem a relatively straightforward process to correlate the spots with the positions in the molecule and figure out the structure. The catch is that the spots form a two-dimensional array and the molecule is three-dimensional; needed positional information in three-dimensional space is therefore missing.

There are ways around this problem but they are not straightforward. Even with these tricks, there are still complex mathematics involved in working out the atomic positions. It took Perutz 30 years because he had to develop the necessary techniques, and for much of that time he was working without benefit of computers. Today computers not only do the calculations, but also convert the results into visual images of the molecules, another process that used to take months because the positions of atoms at each of hundreds of planes or levels of the molecule had to be transferred to clear vinyl sheets. Stacks of these sheets gave some idea of molecular form which could then, in turn, be translated into a three-dimensional model, as well as two-dimensional drawings. Before computers took over the work of converting data into images, these tasks were done more directly by the human mind, and thus the tentative nature of the results was more apparent to the researchers. In other words, there was a more direct form of delicate empiricism going on.

Goethe, Arber, and Form

I am going into the process of developing a concept of a protein's form in some detail because I want to compare the perceptual processes that Arber and Goethe used in their work on plant form to what is done with molecular form. Goethe worked almost exclusively at the level of form visible to the naked eye. He looked at plants, observed the structures of their parts, in some cases dissected them. This was a portion of his delicate empiricism. Then there had to be some unity, some common denominator found underlying the diversity of the observations, and then this would lead to a new view of the phenomenon under observation. In other words, this delicate empiricism involved complex mental processes of making sense of the observations and moving beyond them to a new view of the phenomenon.

Arber too saw observation as only the first step, but with her, things became more complex because some of her work was done not with whole plants, but with cross sections through plant structures that she would then study under the microscope. The technique she used involved dissecting the plant and taking, for example, the ovary, the structure within which seeds are produced, and putting it into melted wax. When the wax hardened, the specimen was sliced, producing thin sections of plant tissue which could be stained and viewed under the microscope. By looking at a succession of such sections from the same piece of tissue, it was possible to create a representation of the three-dimensional structure.

Such a process is not easy to do. It demands great mental agility; it definitely requires a delicate empiricism. Looking at a single cross section or even a series of them is not enough. These two-dimensional images have to be used to construct a three-dimensional representation. For his work on chicken embryos, in which he used a technique comparable to Arber's for studying cross sections, the German embryologist Wilhelm His found it necessary to create three-dimensional wax models of the embryos (Hopwood, 1999). Arber didn't seem to need such assistance; she was able to mentally manipulate the two–dimensional images to create an image of what the three-dimensional structure would look like. Only when such an image had been created could she go on, as Goethe did, to see this image in the larger context of its relationships to some basic form or to forms in other species.

Today in macromolecular research this process of reconstruction is done not by the mind, but by computers. There are a number of different programs that will image a protein on a computer screen and that image can be manipulated in space, turned around to reveal the "top," "bottom," or "back" of the molecule. The same thing can be done for embryological structures. Wilhelm His would marvel at computer visualization programs that allow the user to manipulate three-dimensional images of embryos and other anatomical structures. It's possible to look at particular cross sections and then to see where that cross-section lies relative to the structure as a whole. With such tools, it might appear that part of Goethe's approach has been taken over by the computer and no longer has to be done by the mind. This is a seductive idea and a dangerous one. While the computer can produce visualizations, it cannot produce understanding. The human mind is still needed. As Arber notes, the mind still must internalize and mentally manipulate such images if it is to make sense of them. There are still many difficult mental processes required for understanding. This is particularly true for understanding macromolecular structures and how they function.

As mentioned earlier, one of the problems with models of these structures is that they are usually static. Dynamism is more difficult to visualize than structure; form is easier to visualize than function.

While mentally recreating a plant or animal structure from thin sections is grounded in direct observation of these structures, the same is not true of macromolecular forms. You can touch an embryo or a plant ovary, but you can't touch a single hemoglobin molecule. And touch is very much a part of perception. Visual and tactile impressions are integrated and can augment each other. Without the tactile, visual perception is less rich. Many molecular biologists try to overcome this problem by having models constructed of the molecules they are studying. The noted nucleic acid chemist Jacqueline Barton keeps a model of DNA on her desk so she can not only look at it, but touch it and experience the form of its groves and twists (Amatniek, 1986). The Nobel Prize-winning chemist, Donald Cram, used to walk around with large models of molecules when he was trying to figure out how they would fit together (Chang, 2001). Such practices are not described in research journals. They are not considered under the "Methods" section, but they might well be among the most important methods that distinguished researchers use in their work.

Linking the Objective and Affective with the Aesthetic

As Goethe knew well, intuition is important to the process of science, and working with the hands is a way to provide more input to the brain. It is becoming increasingly apparent that there are complex connections between parts of the brain, so that there is an integration not only of various kinds of sensory data like touch and sight, but also of sensory data with higher order thinking processes and of both of these with those parts of the brain involved in emotions. These last connections are significant to my argument. Goethe, through delicate empirical exploration of his own thought processes, was well aware of the link between feeling and thinking. That link has been grossly neglected in studies in the philosophy of science. In an effort to emphasize the objectivity of science, the intuitive aspects of inquiry were ignored. More than ignored, they were denied. Science was seen as the antithesis of feeling. Yet, scientists knew better. It was just that there was no forum for this aspect of their work. The process of discovery was in fact very different from the process of justification, but it was only the latter that need be communicated in order to advance science. At least that was the argument used. But by hiding the affective aspects of discovery, scientists were communicating a false view of their enterprise and in essence shutting off from the field all who could not so radically divorce affective from objective.

The case of Barbara McClintock is well known (Keller, 1983). Here was a scientist whose work won her the Nobel Prize and yet who described her research style in terms foreign to most scientists. She spoke of being one with her study material, of being down in the cell and moving around in it, of identifying with subcellular structures. While observers find it difficult to criticize McClintock's research, they do question Keller's descriptions of it, despite the fact these are based on McClintock's own words. Even those who accept McClintock's words, see her as an anomaly, someone outside the mainstream of science, with an implication that being a woman in a man's world is at least partly responsible for her atypical behavior. But Nathaniel Comfort (2001) argues that Keller's view is not accurate, that McClintock was much closer to mainstream science, that she was in fact a hard-headed scientist whose approach differed little from that of others in the field.

It seems to me that both Keller and Comfort are right, that they are looking at different aspects of one scientist's work, with Keller focusing more on the process of discovery and Comfort more on the process of justification. Taking just one approach limits our view of McClintock, and thus of how science is done. It is obviously Keller's view that more closely jibes with what we see as Goethe's approach, and Keller's view is questioned by the scientific establishment for the same reason that Goethe's view was. For both Goethe and McClintock, the affective is allowed to mix with the objective and this is anathema to the dominant view of the scientific enterprise. Just as it makes more sense to look at McClintock's work from more than one perspective, the same is true of Goethe's scientific work. Yes, it can be disparaged for not being as empirical as more positivistic research might be, but by the same token, just looking at the idealist side of Goethe's work denies the very valid results he obtained and the rich hypotheses he developed using his delicate empiricism, his combination of the empirical and the intuitive.

If McClintock were the only example of the combination of empiricism with intuition in scientific inquiry, then it might be valid to deem her an anomaly. But there are many instances of scientists using her approach. Joshua Lederberg, another Nobel Prize winner, also writes of being down with the molecules he is studying, in his case within bacterial cells (Judson, 1980). The chemist and Nobel Prize winner, Roald Hoffmann (1990), has written a series of articles on the aesthetic of chemistry: what makes chemicals beautiful. He sees the aesthetic side as essential to the work of chemists: This is what attracts them to the field, determines the choice of topics they study, and perhaps most importantly, the scientific clues they follow.

I could multiply these examples, but Robert Root-Bernstein (1989) has done a good job of collecting many of them in *Discovering*. He argues that the aesthetic is a major part of scientific inquiry, especially in the development of ideas and the shaping of them. He sees an indication of this in the link between artistic talents and scientific talents found in so many of the most noted scientists. He contends that the fact that Hoffmann writes poetry, that Alexander Fleming painted, that Einstein was a gifted violinist, are not coincidences but go to the heart of what it is to be a truly imaginative scientist.

In a more recent publication, Root-Bernstein (2002) explores the complexities of aesthetic cognition. It is a 21st century analysis of phenomena of thought and perception that Goethe dealt with. Root-Bernstein notes that "many of the unsolved problems that philosophers of science have had in making sense of scientific thinking have arisen from confusing the form and content of the final translations with the hidden means by which scientific insights are actually achieved" (p. 61). These problems would seem to me to include the place of Goethe in the history of science. By taking a broader view of the process of science, a view more in keeping with current findings in neurophysiology on linkages between the cognitive and affective (Damasio, 1994), it becomes more obvious that Goethe's working methods were indeed scientifically valid and could lead to fruitful results, as many observers think they did. Goethe's work on the intermaxillary bone opened up the issue of homology in biology. His work on the leaf as the primal form in the plant gave botanists a new way to look at plant anatomy, a view that is still used today. The latest research on homeotic genes—developmental elements involved in laying down the basic structures in a plant—indicates that all flower structures are indeed based on the leaf form (Theißen & Saedler, 2001).

To review my argument: I contend that by looking at the aesthetic of science and at inquiry as involving more than empiricism and reasoning, then the validity and significance of Goethe's method of scientific inquiry becomes much more evident. Why is this important? Because a richer view of how scientists work could very well draw more individuals, with a greater range of talents, to the scientific enterprise. And now, having made this point, I want to go on to my second point, that Goethe's delicate empiricism can play a significant role in the study of macromolecular form.

Molecular Form

This argument seems to be difficult to make, since Goethe's delicate empiricism involves direct observation with the eye, while as I have already noted, such observation of molecules is impossible. However, data from X-ray diffraction and MRI studies can yield data that serve as the basis for visible atomic models. While some researchers aim to create such images, for others these images are just the starting point because the relationship between form and function is not always obvious. Researchers have to figure out how structure relates to function: what parts of the molecule are responsible for its activities, including its interactions with other molecules. This is not a matter of structure alone. There can easily be two proteins with similar structures and very different functions. In addition, there is not a clear correlation between amino acid sequence and structure, though this is something those in the field are eagerly seeking. Some progress has been made toward this goal but prediction of structure from sequence data is still crude, as is relating structure to function.

This means that such predictions remain as much "art" as they are "science." What do observers mean when they make a comment like this? I contend that what they mean comes close to Goethe's delicate empiricism. They mean using the information available, gleaning as much from it as they can, and then internalizing it. In the mind, the linkage of information processing areas with perceptual brain regions, and affective areas, means that several different processes are going on at once, and the results of these processes can be referred to as intuition. This is a word often used for something that is not well understand. If something happens in our mind beyond the steps of logical reasoning, if the mind seems to have leapt from empirical data to an idea that seems only tenuously tied to that data, intuition is of use in describing what is going on.

For many, this explanation is enough, and in the past that is about all we could say. With the new work in neurophysiology, we are now able to see intuition in a new light. Neurophysiological data linking cognitive and affective processes appear to bring intuition into the realm of science. For many scientists it is now easier to accept a richer view of scientific inquiry and one that is closer to what actually goes on. In a sense, science—that is, neurophysiology—is making research look less "scientific" if we mean by this term the positivistic view of the enterprise that is still at least subliminally accepted by scientists. While scientists accept that the process of science is more complex than positivism warrants, in their research they are still driven by the positivistic vision (Fuchs, 1993). Now neurophysiology is making it more difficult to accept this positivistic view and easier to see the validity of Goethe's delicate empiricism.

There is also another way in which Goethe's delicate empiricism throws light on structural molecular biology. Computer-generated images of molecules are not "pictures" of these structures in the same sense that photographs of people are pictures of them. A computer image is really a translation, not of reality, but of images in the mind, the graphic artist's view of what a molecule should look like, as Martin Kemp (2000) writes of Irving Geis's "portrait of the protein myoglobin: "Geis gazed [at a brass skeletal model of the protein] with remorseless concentration in painting his portrait of the molecule, using his unrivaled command of perspective, light and shade, color recession, and judicious distortion, to reveal in a two-dimensional surface the intricate sculptural web of spatial linkages" (p. 119). Yes, such an image is based on data, but the data are in the form of numbers, points in three-dimensional space and a long way from the rather substantial looking images that can be created on paper and now manipulated on a computer screen. The images can have color, dimensionality, substance. They can be composed of balls and sticks, like the old models used in chemistry class, or lines, called wires (Meinel, 2004). So the images that exist only in electronic space are metaphorically referred to as solid physical objects. The structures could be more realistically portrayed as electron density maps, and such views are used, but these lack the coherence and clarity of the more metaphorical forms.

Today as we struggle with difficult issues in molecular biology, as we try to understand molecules, how they work, and how they interact with each other at deeper and more complex levels, it becomes incumbent on us to use all available methods. These include making a more conscious effort to use the methods of delicate empiricism, to use the aesthetic, to foster the interplay of the perceptual and the affective as well as of the cognitive and the affective. There has been very little philosophical analysis of what it is to understand molecules and how they work. There has been little work done on the visual images used in this work—on the computer programs, and what assumptions underlie the images they create and how these influence the research based on these images. Yes, the models can be rotated, but these models are not nearly as dynamic as molecules actually are, and magnifying them so greatly makes it difficult for researchers to appreciate just how small they are and how this great difference in scale influences how molecules function. For example, because molecules, even macromolecules, are so small, they can interact much more rapidly with each other than objects visible to the naked eye. Also electronic forces hold sway and the effect of gravity is negligible.

Making molecules look tangible implies that they are subject to the same forces as tangible objects are, and this influences how researchers think of them. Perhaps we should rely more on the mental images and processes that Goethe used; he did not see his images as directly translatable into drawings and instead worked with them in his mind. Maybe we need to do more of this, do more of what Arber and many other morphologists have done: rely more on the visual abilities that draw people to biology. This may seem like taking a step backward and being anti-technology. On the contrary, I revel in computer-generated molecular images as much as anyone, but I also realize, because of my interest in Goethe's approach to science, that the mind can work in ways computers can't and deal with images much more complexly. The sophisticated scientific problems of today do indeed call for Goethe's delicate empiricism. This is an approach that opens up scientific inquiry to a different kind of analysis; it focuses on a different part of the process of science than is ordinarily highlighted. In essence, this is what Goethe was trying to do. He was arguing that the Newtonian view of science which held such sway in his day, and really still does, was limited, and therefore the results obtained by doing science in light of this view were also limited.

References

Amatniek, J.C. (1986). Card-carrying inorganic chemist explores a biological world. *The Chronicle of Higher Education*, 5 February, p. 7.

Arber, A. (1946). Goethe's botany. *Chronica Botanica, 10, 63-126.*

Arber, A. (1950). *The natural philosophy of plant form*. Cambridge, United Kingdom: Cambridge University Press.

Arber, A. (1954). *The mind and the eye: A study of the biologist's standpoint*. Cambridge, United Kingdom: Cambridge University Press.

Arber, A. (1957). *The manifold and the one*. London: John Murray.

Chang, K. (2001). Donald J. Cram is dead; Shared Nobel Chemistry Prize. *The New York Times*, 20 June, p. A17.

Comfort, N. (2001). *The tangled field: Barbara McClintock's search for the patterns of genetic control.* Cambridge, MA: Harvard University Press.

Damasio, A. (1994). *Descartes' error: Emotion, reason, and the human brain*. New York: Putnam.

Dyson, H.J., & Wright, P.E. (2005). Intrinsically unstructured proteins and their functions. *Nature Reviews: Molecular Cell Biology, 6*, 197-208.

Eyde, R.H. (1975). The foliar theory of the flower. *American Scientist, 63*, 430-437.

Flannery, M. (1992). Biology is beautiful. *Perspectives in Biology and Medicine, 35*(3), 422-435.

Fuchs, S. (1993). Positivism is the organizational myth of science. *Perspectives on Science: Historical, Philosophical, Social, 1*(1), 1-23.

Goethe, J.W. (1962). *Italian journey* (W.H. Auden & E. Mayer, Trans.). London: Collins. (Original work published 1827).

Goodsell, D. (2004). *Bionanotechnology: Lessons from Nature*. New York: Wiley-Liss.

Hoffmann, R. (1990). Molecular beauty. *The Journal of Aesthetics and Art Criticism, 48*, 191-204.

Hopwood, N. (1999). "Giving body" to embryos: Modeling, mechanism, and the microtome in late nineteenth-century anatomy. *Isis, 90*, 462-496.

Judson, H.F. (1980). *The search for solutions*. New York: Holt, Rinehart and Winston.

Keller, E.F. (1983). *A feeling for the organism*. San Francisco: Freeman.

Kemp, M. (2000). *Visualizations*. Berkeley, CA: University of California Press.

Luisi, P.-L., & Thomas, R. (1990). The pictographic molecular paradigm. *Naturwissen-schaften*, *77*, 67-74.

Mayr, E. (1982). *The growth of biological thought: Diversity, evolution, and inheritance*. Cambridge, MA: Harvard University Press.

Meinel, C. (2004). Molecules and croquet balls. In S. de Chadarevian & N. Hopwood (Eds.), *Models: The third dimension of science* (pp. 242-275). Stanford, CA: Stanford University Press.

Perutz, M. (1998). *I wish I'd made you angry earlier*. Cold Spring Harbor, NY: Cold Spring Harbor Laboratory Press.

Polanyi, M. (1962). *Personal knowledge: Toward a post-critical philosophy*. Chicago: University of Chicago Press.

Richards, R. (2002). *The romantic concept of life: Science and philosophy in the age of Goethe*. Chicago: University of Chicago Press.

Root-Bernstein, R. (1989). *Discovering*. Cambridge, MA: Harvard University Press.

Root-Bernstein, R. (2002). Aesthetic cognition. *International Studies in the Philosophy of Science, 16*(1), 61-77.

Theiseen, G., & Saedler, H. (2001). Floral quartets. *Nature, 409*, 469-471.

Author's Note: Correspondence concerning this essay should be addressed to Maura C. Flannery, Department of Computer Science, Mathematics and Science, Bent Hall 281, 8000 Utopia Parkway, Jamaica, NY 11439. E-mail: flannerm@stjohns.edu.