GENERAL ARTICLE

Truth and Beauty at the Nanoscale

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ABSTRACT

New forms of science sometimes raise issues about the relation between an object and an image of the object. What is a faithful reproduction? How do technical processes affect the image? Nanoscale images evoke these issues. To enhance our visual knowledge of nanoscale objects, the author revisits early cubist theory. This leads to suggestions in a neo-cubist spirit for making and seeing nanoscale images.

On 8 October 1993, the cover of *Science* presented a remarkable new way to see atoms. Donald Eigler and colleagues at IBM, using a scanning tunneling microscope, created the *Quantum Corral,* a ring of 48 iron atoms enclosing a standing electron wave (Fig. 1).

Indeed, when exciting developments in nanotech are communicated to the public, the news is often accompanied by a striking visual image. The media of popular science make the nanoscale comprehensible by showing what its pieces look like to the human eye—if the human eye could see things that small.

Pictures of atoms existed before this event, made by transmission electron microscopes, ion field microscopes and scanning electron microscopes [1]. Then there came a great breakthrough: the invention of the scanning tunneling microscope (STM) in 1981. Gerd Binnig and Heinrich Rohrer, the inventors of the STM, wrote that when they first captured images of a surface of silicon atoms, "we were absolutely enchanted by the beauty of the pattern" [2].

In 1987, Robert Becker and colleagues at AT&T Labs modified an atomic surface by depositing matter on a germanium crystal, with before-and-after STM images to prove it [3]. Subsequently John Foster and colleagues at IBM pinned a molecule onto a graphite surface in 1988, also illustrating their experiment with an STM picture [4]. Donald Eigler and Erhard Schweizer published a paper in *Nature* in April 1990 showing a process of moving 35 xenon atoms on a nickel surface to create the letters "IBM" [5]. Eigler later used a software program to give the top-down 2D image a 3D look and added some shading, in addition to coloring it IBM-blue. Thus was it shown to be possible to look at atoms the way we look at objects in a still-life photo. Eigler called this image *The Beginning.*

Quantum Corral, however, was genuinely different, even from *The Beginning.* Its angle of vision put the viewer's eye right at the level of the atoms, and the atoms were rendered as solid cones [6]. Together the angle and the scale gave the sense of peeking over a fence to see the electron wave within—the sense that the viewer could almost touch the fence of atoms (as if atoms were solid objects). The iron atoms were colored blue, while the electron waves were orange, thereby distinguishing atoms from the electron [7]. In scientific terms, the electron wave was more important than the atoms, for this was a variation of the particle-in-a-box experiment. The visual effect, however, was to put the eye of the viewer incredibly close to the atoms.

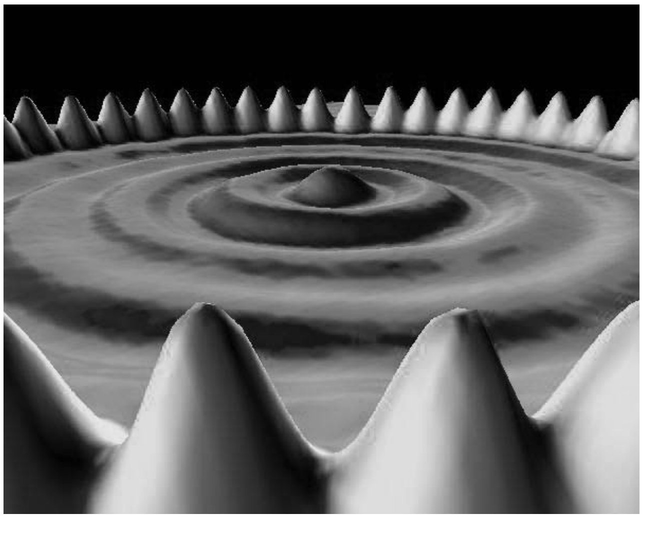
In an e-mail message of 18 July 2007, Donald Eigler wrote:

> I recently was asked how many textbooks the images [from Eigler et al.'s STM] had appeared in. With a little research (Amazon.com), I found that they appear on the cover of at least 15 textbooks, and as figures in at minimum 40 books. Of those images, the image of the *Quantum Corral* that appeared on the cover of *Science* . . . is the most widely used.

Many years earlier, another picture announced a new way of seeing. In 1907, Pablo Picasso, in his *Demoiselles d'Avignon,* used revolutionary variations on perspective and shape to initiate cubism and provoke controversy about how one views an object.

Is *Quantum Corral* a latter-day *Demoiselles?* Yes, *Quantum Corral* is analogous to *Les Demoiselles* in the sense that it gives us a new way to see objects and think about them. At the same time, however, *Quantum Corral* represents a package of problems that come with scanning probe microscopy. We can address those problems by examining early cubist principles.

Fig. 1. Donald Eigler and colleagues, *Quantum Corral*, 1993. (© American Association for the Advancement of Science <www.sciencemag.org>. From [6]. Reprinted by permission. Image originally created by IBM Corporation.) An electron from a copper surface is a series of waves within a corral of atoms.



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Scanning Probe Microscopy

A paradox of the senses lies at the heart of scanning probe microscopy. This technology earns credibility for itself by generating attractive pictures of atoms and molecules with precise details of shape, size and color. None of this detail, however, is truly visible in the same way that an object in a photograph is visible. Some aspects of the images made by scanning probe microscopy are truly representational, while others are artifacts of the process.

The process for making pictures with the STM is as follows: An ultrafine metal probe, ideally one atom wide at the end, is brought to within less than a nanometer from an atomic surface. An electric current runs from surface to tip, causing electrons to move from surface to tip in a process called "tunneling." The tunneling of the electrons can be quantified. The tip moves in two dimensions across the surface of the sample in a pattern known as rastering, while the current is held constant. When there is a depression on the surface, that is, a gap between atoms, the tip moves into the depression to maintain the steady electrical current. When there is a topographical elevation, for example a molecule or a raised surface, the tip rises up to ride over the elevation. There are some tricky exceptions in which the tunneling signal is affected by phenomena other than topography, but the main value of the STM is that it collects continuous data about the topography of the surface in three dimensions [8].

There are other ways to use the STM, and there are other instruments, for example, the Atomic Force Microscope (AFM), but they all have one thing in common: Their ultrafine tips use nanoscale forces to "feel" an atomic surface. This means that they "know" the surface as numerical data that record topographical variation, not visual impressions. Next, software packages convert the data into a simple visual image. Typically, the higher points—large atoms or molecules—are rendered as light shades, while the lower points are seen as dark shades. These are often shades of gray, but they can be depicted in any color ranging from light to dark. In the Eigler and Schweitzer article, for example, the xenon atoms are shown as white dots. The nickel substrate is depicted as a smooth gray background, as if its atoms had been ironed flat [9]. These simple images are also top-down views of a surface.

Objects imaged by an STM are smaller than the wavelength of visible light, so they literally reflect no color and have no shadows to make them look three-dimensional. Color, shading and diagonal point of view are created after the fact.

Note that images of nanoscale phenomena made by an STM are not photographs [10]. Neither are they optical images like the scenes we see when we look into a telescope. Instead, they are the result of a process of touching the nanoscale, converting tactile sensation into data, converting data into visual sensations and enhancing visual sensations with color, shading and three-dimensionality. The difference between the beginning and the end of the process is so great that it is virtually impossible for a picture of an atom or a molecule to be faithful to the object the way we think a photograph is. If someone asks, "Is that what an atom really looks like?" the honest answer is, "No, but this is the best approximation we can create."

This condition is not unique to scanning probe microscopy. Atoms are sometimes depicted in wire-frame models, but an atom is not really an intersection of three wires. Ball-and-stick models show relationships between atoms and bonds, but one must not conclude that atoms are solid balls and bonds are little sticks. Again, representations are not entirely faithful to natural objects. Few people seriously argue that atoms and molecules are fictitious, but there is no picture or model of an atom that is equivalent to a photograph of an object at the human scale.

Realism and Constructivism

Some people have been exploring problems of representation in nanoscale images, most notably Otávio Bueno, Felice Frankel, Valerie Hanson, Jochen Hennig, Brigitte Nerlich, Alfred Nordmann, Julio Ottino and Chris Robinson. A pair of conferences in Columbia, South Carolina (March 2004), and Bielefeld, Germany (May 2005), raised concerns about relations between nanoscale objects and images.

Frankel [11], Ottino [12] and Robinson [13,14] caution that the process of making pictures with scanning probe microscopy can lead to excessive manipulation of variables such as color, and that excessive manipulation is tantamount to misrepresentation. Photos are trusted, states Robinson, because we believe we can confirm them with our eyes, but we cannot do the same with pictures of the nanoscale [15].

Furthermore, these issues have an ancestor, so to speak, in the question of realism in science. In *Representing and Intervening*, Ian Hacking delineated the philosophies of "scientific realism" and "anti-realism." "Scientific realism says that the entities, states and processes described by correct theories really do exist" [16]. One can, in this view, be confident that descriptive theories can be true, or "close to the truth" [17], and that representation devices "ultimately denote some independently existing non-cognitive structure" [18]. Anti-realism depicts descriptive theories as beliefs that one needs to ponder something, but that elevate fiction to reality. "There are no such things as electrons. . . . The electrons are fictions. Theories about them are tools for thinking." "The model [of a molecule] may help us arrange the phenomena in our minds. . . . but it is not a literal picture of how things really are" [19].

Note that issues of realism and anti-realism can be usefully explored using pictures of the nanoscale. Why do those images lend themselves to a position of anti-realism, or at least fail to affirm one's confidence in realism? Part of the answer comes from constructivism, used here to refer to a sociological approach to scientific thought developed in Edinburgh in the 1970s. The core principle of constructivism is that our understandings of scientific knowledge and belief are contingent upon social conditions. That applies to both scientists and non-scientists. Thus understandings might vary according to one nationality or another; one gender or another; one scientific discipline or another; and so on.

Certain forms of constructivism are equivalent to hard anti-realism:

- "There is no obligation upon anyone framing a view of the world to take account of what twentieth-century physics has to say" [20].
- "Nothing 'scientific' was happening inside the sacred walls of [scientific laboratories]" [21].
- Or this, from deconstructionism, which sometimes emulates constructivism: "The Einsteinian constant [i.e., the speed of light] is not a constant. . . . It is the very concept of variability" [22].

Other forms of constructivism are less anti-realist. Michael Lynch published a series of commentaries on the question of whether or how a scientific image reflects the reality of a natural object. Traditionally, stated Lynch, studies of scientific images were framed as comparisons between the natural object at the beginning and the image at the end, with insufficient attention to the process in between [23]. He then wrote a series of papers that treated image-making processes as social practices: one can find "artisan skill, craft technique" and other labor practices between the object and the image [24–27].

A good example is the case of astronomers constructing pictures of comets. Lynch and Edgerton found that, at certain times, astronomers have acquired new artistic vocabularies. With the introduction of digital photography, they adopted false colors and other arbitrary features. They are more conservative about colors in works for publication and less conservative about colors for other purposes. Thus, within certain limits, astronomers shape their scientific images to suit artistic conventions [28,29].

Yet even while social scientists observe the social practices that lead to scientific images, this need not reflect an anti-realist position [30]. Those processes are interesting and perhaps remind us that scientific images are only approximations of natural objects. Knowing this, however, does not have to lead to the conclusion that comets and molecules are fictitious, or that another group of scientists would produce images that were more visually faithful.

We can use observations of labor practices to enhance our visual knowledge of an object from the nanoscale. This way a certain style of constructivism could point toward realism [31]. I have in mind some practices that make sense in terms of early cubist theory.

Learning from the Cubists

Early interpretations of cubism, from art-history perspectives, pointed to inspirations from Paul Cézanne. More recent accounts with broader *zeitgeist*-based explanations point to inspirations from Henri Poincaré, Bernhard Riemann and Henri Bergson. These views are not mutually exclusive. Both elements contributed to early cubism [32].

Cézanne felt that painting had become mere "illusionism," limited to the three Euclidian dimensions of height, width and depth, and frozen in one point of view at one moment [33,34]: Why is it "that a picture must represent a single moment in time and be seen from a fixed position in space"? [35]. In response, they sought new ways to see and depict objects, including a subjective perception, as if "the observer is moving during the process of perception" [36,37].

At the same time, Poincaré was arguing that perceptions of space are subjective. Different people have different experiences with the same space [38–40]. Riemann explained that, in non-Euclidian geometry, figures change according to their spatial position [41,42]. It is well documented that Picasso and other early cubists learned about Poincaré, and possibly also Riemann, from Maurice Princet [43]. Finally, Bergson's lectures on the value of intuition contributed to a sense of the subjectivity of perception [44–46].

There was also a series of new ideas about time, from Bergson and William James, that criticized the moment-frozen-in-time style of painting [47–49].

It has been speculated that early cubist thought might have been influenced by Einstein [50], but recent research argues strongly that Picasso and his circle were not influenced by Einstein [51,52].

Early cubist painting was meant to be a solution to those problems of space and time: a new style of realist representation that expanded one's perception of reality. This would presumably be a more complete realism than the paintings limited to the three Euclidian dimensions, from one perspective at one moment [53–58]. Thus there were multiple views of the same object within one picture, known as *simultaneité*, intended to give the viewer more knowledge of the object [59–61]. "The painter no longer has to limit himself to depicting the object as it would appear from one given viewpoint, but wherever necessary for fuller comprehension, can show it from several sides, and from above and below" [62]. As Georges Braque put it, one needs three simultaneous perspectives to know a house: plan, elevation and section [63].

Les Demoiselles d'Avignon is credited as the first painting to achieve *simultaneité* and is a good example of that principle [64]. There were also artistic attempts to incorporate time as a fourth dimension. Marcel Duchamp's *Nude Descending a Staircase* [65] was the most successful of these. In a single 2D painting, he gave the viewer height, width, depth, *simultaneité* and the elapse of time.

Three Cubist Perspectives for Pictures of the Nanoscale

As we address issues of representation in pictures of the nanoscale, we can make use of the cubist principle of knowing an object better by adding more perspectives to the picture, for example, *simultaneité* or temporality. Here is a starter kit with three devices:

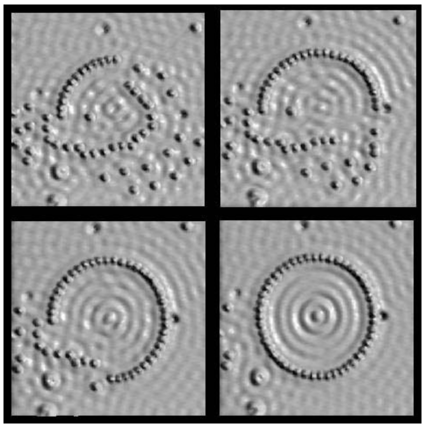

Fig. 2. The time sequence for the creation of *Quantum Corral*, 1993. (© American Association for the Advancement of Science <www.sciencemag.org>. From [6]. Reprinted by permission. Image originally created by IBM Corporation.)

First, add a temporal perspective. Some well-known images are frozen in time, literally. At the nanoscale, mild thermal vibrations are massive earthquakes, and an atom is not able to stand still to have its picture taken. In the cases of the xenon atoms spelling "IBM" in 1990, it was necessary for Eigler and his team to reduce the temperature within the STM chamber to nearly absolute zero [66].

Eigler's team added a sequence of images to show the process of creating the final picture. A panel of six images accompanied the 1990 "IBM" picture, and a panel of four accompanied the 1993 *Quantum Corral* (Fig. 2). One can see the process of creation and imagine a reverse symmetry, that is, the dissolution of the atoms from formation back to randomness when the temperature was relaxed. Sequences such as these help the viewer see the temporal relation between the object, the image-making process and the image. As such, they are analogous to *Nude Descending a Staircase:* They add temporal information to a picture.

Next, add a color perspective. Most nanoscale phenomena are smaller than the wavelength of visible light, so they literally have no color of their own. The human eye, however, needs to see some color, or at least shades of gray, to make sense of an image. Some nano-images have many colors; some have few; but all colors are added arbitrarily.

At the workshop on imaging the nanoscale, in Bielefeld, Germany, *The Nano Flower Bouquet* was discussed at length. This is a structure of silicon carbide, created by Ghim Wei Ho and colleagues at Cambridge University, with petals and other flower-like parts. The picture, made with a scanning electron microscope, truly looks like a bouquet.

The SEM picture of *The Nano Flower Bouquet* is usually rendered in blue. At the Bielefeld workshop, one person commented that the bouquet had the *shape* but not the *color* of a bouquet of flowers, as blue is cold and lifeless. Another dissented, saying its color was very reminiscent of certain blue flowers, such as the hydrangea.

What is the correct color for *The Nano Flower Bouquet?* It could be blue, violet, yellow, green or any other color. By observing the same object in multiple color perspectives simultaneously, the viewer can see that all these colors are equally artificial (Color Plate C). The scientific value of *The Nano Flower Bouquet* is in its silicon carbide structure, not its color.

Third, add a tactile perspective. We ordinarily think that atomic surfaces and the objects that lie on them are far too small for us to touch. Instead, we have ultra-sensitive instruments such as the STM and the AFM to feel the surface for us. There is a device, however, that enables one to feel nanoscale objects.

The NanoManipulator, made by 3rdTech of Durham, North Carolina, begins with an AFM, which can touch and scan an atomic surface and objects on that surface. Data from the AFM scan are converted to a 3D image of the sample's surface.

After seeing the atomic surface, the operator can switch to a haptic mode. The last scan is held static, and the operator can use a haptic device—a feedback system connecting the scan data to a hand-held stylus—to create the sensation of moving the tip of the AFM back and forth on the surface (Fig. 3). This gives the operator a virtual feel of the shapes of molecules and other objects captured on the scan.

In a third mode, one can use the haptic device to push the AFM tip against those objects, that is, to move them by hand as the NanoManipulator steers the AFM. After doing so, the operator returns to scanning mode to see how that action has changed the sample surface.

This is thus a process of first seeing the nanoscale in 3D; feeling it in 3D; changing it with a precise 3D force; and finally seeing the results immediately in 3D.

We know that the STM and the AFM can make images of nanoscale objects; we also know that they can manipulate atoms and other objects. With the NanoManipulator, however, one can feel and change an atomic surface in close to real-time conditions.

The spirit of this neo-cubist approach is not to ask the makers of nanoscale images to choose only one style of representation, let alone to produce a perfect depiction of an atom or a molecule. Rather, its spirit is to add to visual knowledge by adding information from more than one perspective. Surely there are additional ways to add information to pictures of the nanoscale.

Truth and Beauty

Around the time that Binnig and Rohrer invented the scanning tunneling microscope, the art historian Pierre Daix wrote:

> Atomic physics has demolished the belief in any simple correspondence between visual appearances and the intrinsic structures of reality, largely invalidating the notion of realism. . . . Seeing, we now know, is by no means a passive record, a mere tracing, of forms perceived by the eye [67].

Daix was right. There is no such thing as a simple and direct photograph of an atom. We see diagrams, schematics and illustrations, plus pictures made with scanning probe microscopy, but we do not see atoms the same way in which one can see an apple or a picture of an apple. Instead, we see mediated interpretations of atoms.

However, if we find these images lacking because we contrast them with photography, we should remember that photography, too, generates mediated representations [68]. In its early days, photographs captured three-dimensionality and details so well that some people thought they were perfect representations of reality. However, anyone who worked in a darkroom knew that photos could be manipulated by cropping, dodging, burning and other techniques.

One notorious 19th-century photo showed Mary Todd Lincoln with the ghost of her deceased husband, Abraham Lincoln, placing his hands on her shoulders. Photographers knew that this trick was created by printing two separate negatives on the same paper, but to a layperson it could have looked like a genuine snapshot of a spirit comforting his widow.

I do not suggest that any such deception is coming from the scientific labs that make images of atomic surfaces, but it is wise to be aware of the consequences of mediated visual interpretations. Joshua Greenburg gives the example of the "Pillars of Creation." The Hubble space telescope captured an image of enormous linear gas clouds in another galaxy, in which stars and planets could have been coalescing. The original, in gray tones, was converted to color, with colors arbitrarily representing elements or chemicals. Some of the stars in the picture were screened out to make the picture clearer. The contrast was enhanced. Finally, the image was rotated to make the gas clouds appear vertical [69].

The final interpretation was spectacular. Its richness enabled people to see various objects in the "Pillars of Creation," and some Christians saw Jesus in it. The scientists did not embrace that interpretation, but for individuals who felt that this picture affirmed their religious beliefs, the fact that enhancements were added by the scientists was ignored. Instead, the final picture was taken to be a "pure," *un*mediated picture. To acknowledge the enhancements would be to explain the image of Jesus as a mere artifact. Greenburg therefore reminds us that scientific images are "augmented with additional meaning," that is, meaning that does not answer to scientific standards [70].

This is also the case with images made by scanning probe microscopy. Layper-

Fig. 3. 3rdTech's NanoManipulator adds 3D perspective and tactile feel to an atomic surface. (© J.N. England)

sons are likely to appreciate nanotech more in terms of its lovely pictures than in light of phenomena such as electron tunneling, van der Waals forces, or covalent bonds. Will, however, additional meanings not intended by nanoscientists arise for colorful images of matter that actually has no color? Or when pictures show shading where in reality there are no shadows? Or when objects that appear solid in a picture have little mass in reality? Will that be harmful to nanotechnology? One can say no, these are not really conventional photographs, they are mediated visual interpretations of tactile data. Who, though, will make that distinction?

Keats wrote that "truth is beauty, beauty truth." Perhaps so, but a process of touching an atomic surface, instigating electron tunneling, quantifying the tunneling, converting the tunneling data into a 2D top-down gray-tone image, and tilting that image while adding color and shading is a long way from using our eyes to admire a Grecian urn. At the nanoscale, beauty is not necessarily equivalent to the sense of truth that Keats had in mind.

The cubists of a hundred years ago confronted some interesting issues of truth and beauty. As we work through these questions of the relation between a nanoscale object and images of the object, we might imagine ourselves as neo-cubist thinkers.

Acknowledgments

I have learned much about pictures of the nanoscale from the list of people I cited above (Bueno through Robinson), but I have learned the most from Chris Robinson. I would also like to thank two anonymous reviewers of the previous draft of this paper for constructive comments and helpful suggestions. This article is based on work supported by National Science Foundation awards 0304448 and 0531160.

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