Nano in Sight: Epistemology, Aesthetics, Comparisons and Public Perceptions of Images of Nanoscale Objects

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ABSTRACT

Images of atoms, molecules and other nanoscale objects constitute one of the principal ways of communicating scientific knowledge about nanotechnology, both within and beyond the scientific community. This paper reports on four kinds of insights from studies of nano images: (1) a critical epistemology of these images; (2) aesthetic interpretations intended to counterbalance problems identified in the epistemology; (3) comparisons with issues of visualization from other scientific areas; and (4) a consideration of how persons in the public interpret artistic pictures of nanobots. These insights demonstrate how the humanities and social sciences contribute to the understanding of nanotechnology.

From Epistemology to Public Interpretations

Over the past 10 years, scholars in the humanities have explored relations between nanoscale objects—atoms and molecules, for example—and images of those objects created by scanning probe microscopy. These scholars have also considered artistic representations of nanoscale machines that might or might not become real in the future. Proposed possibilities for the future include nanobots that navigate within blood vessels, acting as mechanical shovels to remove plaque, or nanobots that grasp blood cells.

Together, these two families of nanoscale images—pictures of atoms and molecules, and pictures of imaginary nanobots—raise a sequence of questions about our knowledge of reality at the nanoscale. When we see pictures of nanoscale objects and machines, are we looking at objects and machines as they would look if the human eye could see things that small? Are we looking at pictures that have little or nothing to do with the realities of nanoscale objects? Or are we looking at pictures that combine legitimate scientific knowledge of nanoscale objects with creative interpretations of that knowledge? Ingrained in these questions is a larger question: How do we distinguish between the knowledge we have and our interpretations of it?

Let us put it this way: How do we know what is real when we see a picture of a nanoscale object? Some philosophers have explored this epistemological question and have guided us to a conclusion that a picture of an atom or a molecule cannot visually resemble the object that the picture represents. An ancillary conclusion is that we are unlikely to realize the introduction of nanobots into our blood vessels, for example, in the ways in which illustrators picture it.

One could then conclude that the epistemology of nano images is so problematic that we might as well abandon such images. We disagree for three reasons. First, there are ways to derive legitimate visual knowledge from these images even if they are epistemologically problematic. Secondly, interpretive problems are similarly found in other areas of scientific representation, and this conjunction opens the possibility that a comparative perspective can help us learn more about nanoscale representations.

Our third reason is that these images circulate beyond a small community of microscopists and connoisseurs of epistemology. Persons in the public also see pictures of nanoscale objects and nanobots. Therefore, we must ask: In public interpretations of nanotechnology, what role do epistemological issues play?

We explore all of the questions outlined above by presenting four kinds of insight about nano images: epistemology, aesthetics, comparisons and survey research. Examining the insights gleaned allows us to demonstrate how our ideas enable us to explore issues of scientific visualization from multiple perspectives, including a connection between epistemology and public knowledge.

First Insight: A Critical Epistemology of Nano Images

What do we know about nanoscale objects when we see pictures of them? How can we bring the world of atoms and molecules to our sense of sight?

When scholars in the humanities began asking how scientific knowledge from nanotechnology is communicated in visual representations, they recognized a certain paradox of the senses. Nanoscale objects are literally invisible, in the sense that they are smaller than the wavelength of visible light. Given that they cannot be seen with optical microscopes, how can they be rendered in pictures? A landmark in this line of investigation was the section on "Imaging the Nanoscale" in the 2004 volume *Discovering the Nanoscale* [1]. There C. Mody [2] and A. Hessenburch [3] explained how instruments such as the Scanning Tunneling Microscope (STM) and the Atomic Force Microscope (AFM) convert electronic signals into visual representations of an atomic surface, while J. Pitt [4] and C. Robinson [5] explored the epistemological implications of this technology. A recent review explained that some of these instruments can now image objects smaller than 0.1 nm, which

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The papers in this special section began to take shape during the presentations and workshops at the conference "Images of the Nanoscale: From Creation to Consumption," held at the University of South Carolina, 25–27 October 2007.

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is to say that this family of instruments, known collectively as Scanning Probe Microscopy, is more advanced than ever [6].

This visual information is valuable but it entails certain problems in relations among the object, the picture of the object and the persons viewing the picture. STM images often have attractive colors, but these colors are artificial: Objects that are smaller than the wavelength of visible light have no color. The objects in these images may have shading to give them a three-dimensional look, but this too is entirely artificial. The objects look solid in those images, but atoms (and molecules made of atoms) consist of clouds of electrons in motion around nuclei. Thus we see static images of moving objects.

> *How do we know what is real when we see a picture of a nanoscale object?*

These problematic relationships constitute unavoidable consequences of the technology needed to create pictures of nanoscale objects. Nano images are intrinsically imperfect. We can express this insight in several ways:

- An image created by scanning probe microscopy is "an interpretation . . . a mathematical reconstruction of reality" [7].
- "An STM image is a map of the variation of electron density in space . . . An STM image does not show atoms as such. . . . Instead, one images orbitals, or more correctly, the electron density of the orbitals" [8].
- "A picture of an atom or a molecule cannot possibly look like an atom or a molecule" [9].

The well-known *Quantum Corral* image (see Color Plate B) [10] is a good illustration of these conclusions. On one hand, it is an exceptional scientific accomplishment. At the same time, it contains all the problematic relationships between the object and the picture that we list above.

This insight about the imperfection of nano images is well enough established that it could serve as an entrée into a more general discussion about what an object really is. What other insights about nano images arise in the wake of the critical epistemology? How can one pursue further questions about nano images that use the critical epistemology as a point of departure?

Second Insight: Aesthetic Tools for Interpreting Nano Images

In 2009, a network of scholars interested in nano images began to coalesce around a leadership centered at the University of Bergen in Norway. A series of workshops and conference sessions convened by this network (Paris, 2009; Nottingham, U.K., 2010; Darmstadt, Germany, 2010; and Bergen, 2011) enabled scholars to generate insights that went beyond the epistemology. This latter kind of insight has a tone different from the former: If we know only that nano images are chronically problematic in the relationship between an object and a picture of the object, then we know only what is wrong with those images. Were solutions possible? Can we interpret these imperfect images so as to identify the value of the visual information in them?

Below we give three examples of how we can identify valuable visual information. In one of the earliest commentaries on nano images, C. Robinson offered a typology of images based on their intended purposes. One category was scientific documentation. Another was illustration for science fiction. Between those two was the category of schematics [11].

Schematics are not meant to be equivalent to photographs, microscope slides or other forms of mimetic representation. Instead, they isolate a relationship or principle and show its most important parts. Schematics are selective illustrations of scientific phenomena. They have a value that is close to that of scientific documentation, but their employment in isolating and depicting a particular feature also requires some creative imagination.

Robinson showed that if schematics are appreciated as such, and not criticized as incomplete scientific documentation, then it is not particularly problematic that nano images are something other than the mimetic representation that one expects of a photograph.

Our second case comes from an episode in art history. The early Cubists felt that representational art was unnecessarily limited in the ways that it presented visual information about an object [12]. Cubists then concluded that one solution was to depict the object in multiple simultaneous perspectives, known as *simultanéité* [13].

Toumey [14] suggested the case of the "Nano Flower Bouquet" for an exercise in *simultanéité*. This picture, created at Cambridge University, shows a carbon silicate structure. In the scanning electron microscope image of this object, one can see that it closely resembles a flower bouquet. The Cambridge lab depicted it in blue [15], and others have followed that color convention. Toumey showed how the color used could instead be yellow or green or violet or others. The color choice was not relevant to the information conveyed through the image: There was no loss or gain of scientific information when the color was altered. In other words, blue is not the "natural" or necessary color for a carbon silicate structure. Blue is legitimate but not exclusively so. The depiction of this object in multiple simultaneous colors makes the point that the important visual information is the structure, not the color, of the Nano Flower Bouquet.

The third example illustrates the principle of inter-instrumentality. Catherine Allamel-Raffin [16] has explained that, when one images a sample with two or more different instruments, we can sometimes improve our knowledge of that sample because the different microscopes gather different data.

An exercise in 2011 developed that idea. Two kinds of matter (human hair and red blood cells) were subjected to examination using four different instruments: an optical microscope, an atomic force microscope, a scanning electron microscope and a transmission electron microscope. This exercise demonstrated that the four instruments embody different ways of seeing hairs and blood cells. They share one common characteristic: All produce images that lack true colors, such as the red tint of a red blood cell. However, the instruments deliver four different styles of seeing these samples [17]; thus, we can appreciate inter-instrumentality in the constructive interpretation of images. We are not limited only to the conclusions of the critical epistemology.

When we use aesthetic tools such as schematics, *simultanéité* of color, or portfolios of inter-instrumentality, we acknowledge the problems set out by the epistemology of representation. However, we also gain the insight that there is legitimate visual knowledge in those images. Their problematic qualities are not their only qualities. Furthermore, one can expect that different kinds of people—scientists versus nonexperts, for example—will have different experiences in assessing the visual knowledge in those pictures. We return to that point with the fourth insight.

Third Insight: Comparisons with Other Practices of Scientific Visualization

How do insights about nano images compare with comparable insights in other areas of scientific visualization? Consider the images generated by the Hubble Telescope. The Hubble does not produce photographs. It creates two-dimensional spectrographs of elements in space. Colors are arbitrarily assigned to various elements that are then combined to look like color photos. A given image that looks like a color photo is really a visual interpretation of data from a spectrometer [18]. Note how similar this is to the case of nano images produced by scanning probe microscopy [19].

Another form of scientific visualization is brain imagery—for example, CAT, fMRI and PET scans. In living persons, the brain is not ordinarily accessible for direct observation, so noninvasive imaging techniques were developed to visualize what we could not otherwise see. Do these imaging innovations, like the Hubble images, point us toward a general theory of the epistemology of scientific visualization?

Studies of scientific visualization were well developed before the conception of nano images, and perhaps such studies can help to illuminate problems with nano images and their solutions. Even so, the value of comparative insights has been recognized only recently in the study of nano images. This subject was discussed at length at the 2010 Nottingham workshop and will likely have received much consideration at a conference in Sweden in September 2012. Currently this third insight is underdeveloped.

Fourth Insight: Public Interpretations of Nano Images

Here we return to the lesson that a picture of an atom or a molecule cannot possibly "look like" an atom or a molecule. Let us stipulate that scientists know intuitively that colors, shading and other aesthetic features of nano images are artificial. For many scientists, the addition of these features is only a series of steps necessary in rendering visual interpretations of electronic data [20].

But what about nonscientists? How do they think about the nanoscale objects that they see depicted in these vivid pictures? Regarding factual accuracy, do members of the public believe that artistic renditions of how nanotechnology might work are equivalent to scientific documentation? And if a nano image is revealed to be epistemologically problematic—if a visual depiction is misleading—will nanotechnology then be discredited? Since most of the public is poorly informed about nanotechnology, what are the consequences of learning about nanotechnology by means of epistemologically problematic depictions?

B. Nerlich [21] explains that artistic depictions of nanobots are meant to make the unfamiliar features of nanotechnology seem familiar to broad audiences and to make things that do not exist seem as if they might soon exist. Nanotech will seem normal if people accept pictures of nanobots.

Artistic depictions of nanobots reflect different intentions on the part of their creators than do scanning probe microscopy (SPM) pictures. An SPM image is meant to be a documentation of empirical knowledge, but the pictures of nanobots are futuristic expressions of machines that may or may not be realized.

The public reception of nanobots may not reflect artists' and scientists' intentions. Could some of these images affect public acceptance of nanotechnology, positively or negatively? In-depth interviews with members of the public indicate that they think these kinds of images have both positive and negative valences [22].

A. Lösch [23] presented a thoughtful perspective on pictures of nanobots. Lösch traced two pictures—a classic "surgical nanobot" and a mini-submarine, both operating inside blood vessels—along with texts that explained the pictures as they appeared in German publications, including scientific, economic and mass-media articles. In the earliest phase (1999–2001), the scientists were comfortable with fantastic artistic representations such as the nanobot and the mini-submarine and with the pro-nanotech hyperbole that accompanied those pictures. This period was also the peak in the use of pictures of nanobots [24]. Subsequently scientists came to distance their scientific work from the nanobots because of the "weak reference to current developments in nanomedicine," to put it kindly [25]. While the construction of meaning was different for these pictures in scientific, economic and mass media discourses, the pictures nevertheless served as a common vocabulary for exchanging expectations for nanomedicine among all three discourses. It was not possible to insulate the science from the fantasy.

Let us consider what might happen when nonscientists read an article about targeted drug therapies to cure cancer, and the story includes an image of a nanolouse [26]. A nanolouse is an artistic creation in which a tiny machine, approximately 10 microns long, grabs a red blood cell with its mechanical claws and inserts the tube of a syringe into the cell (Color Plate A). Nanolouses (or nanolice) are one of the most common forms of imagined nanobots: They represent how nanotechnology could improve our lives by precisely controlling conditions within our bodies.

While the article in question only touts benefits, and the author believes that the image buttresses this interpretation, the nanolouse is ambiguous. Is it attacking the blood cell? Is it inserting something into the cell? Extracting cytoplasm from it? Is it merely grasping the cell so as to move it elsewhere? Is there some other purpose? Furthermore, the image is colored mostly red, which in many cultures implies danger. Despite the author's intent, nonexperts might respond negatively to the image.

To investigate how nonexperts react to these images, M. Cobb conducted a nationally representative survey in the United States measuring public reactions to a picture of a nanolouse. A survey was fielded by Knowledge Networks (KN) in April 2010 and included 849 members of the KN panel. Individuals from households selected to join the KN panel completed the survey online, with a completion rate of 69.0%, while the recruitment rate (AAPOR response rate #3) was 19%.

The survey's focus was to measure public opinion about the potential of "converging technologies" to cure the sick and enhance human performance. Within the survey, an experiment was conducted by randomly assigning respondents to either a control group or a treatment group exposed to an image of a nanolouse [27]. Respondents were asked to respond to the following statements and questions to estimate the impact of viewing the nanolouse.

(1) "Overall, I support the use of nanotechnology for human enhancement."
(2) "Using nanotechnology for human enhancement will be risky."
(3) "Using nanotechnology for human enhancement will be beneficial."
(4) "How worried are you that you and your family will not be able to af-

ford drugs and other treatments for human enhancements once they become available?"

(5) "Once they become available, should medical insurance be required to cover most kinds of human enhancement, or should people that want enhancements have to pay entirely out of their own pocket?"

Answers to the first three statements were each recorded on a 10-point scale, while "worrying" was measured on a 4-point scale ("very worried" to "not at all worried"), and the preference about coverage (Question 5) was a dichotomous choice.

Exposure to the nanolouse had no apparent effect on the first three survey items. Respondents were slightly less supportive of nano if they saw the image (a mean 3.9 versus 4.1, *ns*) and they were also a little less likely to report that it would be beneficial (4.5 vs. 4.7, *ns*), but these same respondents compared to the control group also thought nano would be less risky (6.8 vs. 7.1, *ns*). Yet respondents who viewed the image were significantly more likely to report being worried about the affordability of drugs and treatments ($p < .01$), and a majority of those viewing the image said insurance should be required to cover enhancements. Conversely, only a minority of those in the control group said the same thing (55% vs. 44%, $p = .06$).

A key distinction in past surveys has been between those who have some prior awareness of nanotechnology and those who have virtually none. While the former group is usually a smaller percentage of the population, they are significantly more supportive of nanotechnology [28] and its applications for human enhancements [29]. These two groups could have importantly varying reactions to images of nanoscale objects, much as we would predict scientists and nonscientists to interpret scientific images differently. This possibility was examined by repeating the analysis above while comparing the treatment effects based on respondents' prior awareness of nanotechnology. At the beginning of the survey, respondents were asked how much they had "read, seen or heard about nano to enhance human mental, emotional, or physical abilities." Over half (52%) reported knowing absolutely nothing about nano. Subsequently, the sample was divided between those who knew nothing and those who thought they knew at least a little about it.

Repeating the analysis of the first three survey questions by taking into account respondents' prior awareness of nano revealed a few mediating effects. First, if respondents had prior knowledge about nano, the attitudes of those in the treatment condition (those who saw the nanolouse) were virtually indistinguishable from their counterparts in the control group. On the other hand, respondents without any prior knowledge of nano were modestly affected by seeing the image. Within this group, exposure to the image led to reduced overall support (3.8 vs. 3.4, $p = .32$), but both perceived fewer benefits (4.5 vs. 4.0, $p = .17$) and fewer risks (7.1 vs. 6.7, $p = .39$). In other words, the image appears to increase uncertainty among the uninformed.

> *A depiction of an object that is not real now and may never become real nevertheless affects public attitudes about the health and medical implications of nanotechnology.*

Turning to the last two survey questions, prior awareness had statistically significant mediating effects. Viewing the image increased concern about the affordability of nano but it did so by affecting uninformed respondents. While 38% of uninformed respondents in the control group reported being somewhat or very worried, 52% felt that way if the image was viewed ($p < .05$). Seeing the image had a similar effect on more informed respondents (worrying increased from 39% in the control group to 46% in the treatment group) but this smaller difference was not significant ($p = .20$). Conversely, viewing the image failed to alter uninformed respondents' belief that individuals should have to pay out of pocket for enhancements (51% vs. 52%, *ns*) but it dramatically changed the minds of more informed respondents. In contrast to the control group, where a solid majority (60%) supported out-of-pocket payments, an even larger majority (63%), after viewing the image, favored requiring insurance to cover enhancements ($p < .01$).

Here epistemology meets public interpretation. We see how a depiction of an object that is not real now and may never become real nevertheless affects public attitudes about the health and medical implications of nanotechnology.

Concluding Thoughts

Any visual representation of a person or an object is accompanied by common epistemological questions about what is real. Did statues of Egyptian pharaohs, Greek philosophers or Roman statesmen really look like them? How much of a photograph is faithful to the flesh-and-blood appearance of the person being photographed, and how much is distortion, selective representation or misrepresentation?

Nano images and their epistemological problems offer what some see as an extreme case: We can see no nanoscale objects with our own eyes, so can images of these objects offer visually faithful renditions of them? Even with the representation problem, there are reasons to accept that Scanning Probe Microscopy ordinarily collects good electronic signals from samples and that SPM represents that data in pictures of the topography of the sample. Nano images from SPM are imperfect visual approximations at best but they are neither deceitful fabrications nor wild fantasies.

Meanwhile, artistic renditions of imaginary nanobots confront us with another set of problems. These pictures are peculiar because the nanobots are unreal, but some people expect them to become real in the near future. Instead of arguing about whether that expectation is realistic, the instinct of the social sciences is to ask how different kinds of populations react to these pictures. The question does not concern nanobots per se but rather reasons underlying the variance in people's perceptions of them.

To summarize, the visual representation of objects in the nanoworld (whether in SPM micrographs or depictions of nanobots) constitutes another way to explore the enduring question of whether a visual representation of an object is truly faithful to the appearance of the object. The issues that we present in this paper are arguably more problematic than those of other cases—for example, whether a photograph of a person's face is faithful to the reality of that face. Nevertheless we recognize that the difficult epistemological issues associated with visual images did not originate with nano images. We address issues of nano images by trying to draw helpful insights from sources beyond nanotechnology.

At this point we identify four families of insight: (1) the epistemology of representation, which produces a critical epistemology of images from Scanning Probe Microscopy; (2) constructive aesthetic concepts for identification and appreciation of the visual knowledge in images that are epistemologically problematic; (3) insights that we may derive from comparisons with other cases of scientific visualization, for example, outer-space spectrometry; and (4) information about the ways in which members of the public perceive and evaluate depictions of nanobots. Perhaps others will present additional kinds of insights.

We appreciate that the first three kinds of nano insights are anchored in the humanities. As they address questions about relations between an object and a picture of an object, they benefit from philosophy and art. The fourth kind of insight shows us that the social sciences have a role, too. Here one asks a basic social-science question: How do different kinds of people—different elements of society—engage with a certain form of representation? It is through these studies that we have learned about some measurable differentials between people with some knowledge of nanotechnology and those with none. This finding suggests a potential problem going forward, considering that Corley and Scheufele [30] have found a growing information divide within the public.

We can also retrospectively understand the first three kinds of insight as social-science phenomena. Let us hypothesize that scientists engage with nano images by intuitively accounting for the difference between what is known about atoms and molecules versus what is seen in nano images. Presumably scientists concentrate their attention more on images made with Scanning Probe Microscopy and Electron Microscopy, while devoting little time to artistic interpretations like nanolouses. We can imagine that philosophers engage with these artistic images differently than do scientists, because the philosophers' interest is to make explicit the epistemological problem of the difference between an object and a picture of an object (but see Gimzewski and Vesna [31] for the philosophical reflections of a scientist and an artist). We can then surmise that the interpretation of nano images is sociologically variable. These images convey different meanings to different kinds of people.

Much has happened in the past 10 years in the study of nano images, but the importance of this topic endures, because here science, technology and the humanities interact. We do not suggest that the concerns of the humanities should supersede scientific knowledge about the nanoscale, but we note that epistemology, aesthetics, comparisons and the study of public perceptions can complement scientific knowledge. Scientists know well that atoms and molecules are not really colorful solid objects like yellow golf balls or blue cones, as they are sometimes depicted in images from Scanning Probe Microscopy. Their colleagues in the humanities have added additional layers of understanding to the problematic relations between an object, a picture of the object and the persons viewing the picture, which arise from the technology for making pictures of nanoscale objects. In other words, the humanities (and the social sciences) contribute to the question of how we bring the world of atoms and molecules into our sense of sight.

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