How to Understand Nano Images

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Abstract
Nanoscale objects are presented by ever more sophisticated pictures (nano images). There is a need to reflect on the status of such nano images, because the "seeing" involved is of a highly indirect kind. The aim of this paper is to complement existing philosophical critique of nano images with a scientific practitioner's perspective. First, we show some reasons to consider seeing and imaging as complex endeavours not only on the micro and nano scale, but also on the macro level. Secondly, we argue that practising scientists are not only accustomed to interpret pictures and other graphical presentations of data as being partial and simplified, but that simplification is deliberate and internal. Rather than requiring that "true" images have to be representational (Pitt 2004, Pitt 2005), the paper advocates for the fruitfulness of understanding and judging images by the amount and nature of the information they convey. Scientific literacy could be improved by creative development of visualization techniques, but also by improved public understanding of images and their correct and cautious interpretation.

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Introduction

In recent years, scientific texts as well as more general literature have come to include ever more sophisticated pictures in the presentation of research on nanoscale objects (nano images). The most common equipment for studying materials on the atomic scale, are the Scanning Tunnelling Microscope (STM), Atomic Force Microscope (AFM) and similar probing microscopes. The development of the design of pictures produced by the STM has been described by Hennig (2005). Designs have emerged that "show" individual atoms, and it is our experience that it has become common to describe such pictures by saying that one "sees" the atoms, both in regular scientific discourse and in instances of science policy discourse. A striking example was provided by the European Commission (2004).

There is a need to reflect on the status of such nano images, because the "seeing" involved is of a highly indirect kind that requires extensive data processing under a number of theoretical and experimental assumptions. Indeed, Pitt (2004, 2005) has argued that nano images should not be considered images in any ordinary sense of the word, and that they "do not allow us to see atoms in the same way that we see trees" (Pitt 2004, p. 157). Furthermore, most nano images show atoms as well-defined dots or spheres in orderly arrays, and hence, he argues, convey an idea of nanoscale phenomena as orderly and controllable. Accordingly, he concludes that claims to see or represent atoms by nano images are both epistemologically and ethically suspect, since they may mislead the public about the difficulties and complexity of nanotechnology.

We agree with Pitt that the ethical questions are important, and that the risk of misguidance in public debate and policy-making must be addressed. The issue being a difficult and complex one, we believe it to be important that different perspectives be brought into play and interdisciplinary exchange. The first author is a mathematician and atomic physicist. The aim of this paper is not to reject the analysis of nano images provided by historians and philosophers of science, but rather to complement these perspectives with that of a practising scientist in the nano field.

From this perspective, the paper argues that the epistemological status of nano images within scientific research is less problematic than what appears to be argued by Pitt (2004, 2005). First, we show some reasons to consider that seeing and imaging always implies some filtering of information, even on the macro level. Secondly, we argue that practising scientists are not only accustomed to interpret pictures and other graphical presentations of data as being partial and simplified, but that simplification is deliberate and internal, if not constitutive, to research practice. Philosophically, such claims are hardly novel, but we think they are important in the context of nano images since they have bearings on how to address the ethical challenges. We fear that it will be futile to try to police or otherwise influence scientists' and others' use of the words “image” or “seeing”or to convince them to use less powerful graphics. Rather, misguidance should be fought by offering citizens and policy-makers the intellectual resources to interpret the images correctly and cautiously. It is the objective of the paper to make a contribution to this effect by explicating how scientists think and reason about nano images.

Seeing in the Macro World

In Pitt's argument weight is given to the difference between what it is to see something (and to have an image of it) in the macro and nano world, respectively. His claim is that we do not see or have images of atoms in the same way as we do with macroscopic objects such as trees. Hence, when nanotechnologists and others claim to see atoms and produce nano images, it represents a change of meaning of these terms, a change that he finds illegitimate.

There are obvious reasons to claim that such differences exist, but we find the claimed illegitimacy of the increased extension of the terms “seeing” and “image” debatable. We see at least two routes to pursue that debate. One might address it along the lines of the debates about scientific realism, which ultimately appears to be Pitt's choice, although he does not proceed into the technicalities of that debate within the more analytic strands of philosophy of science. Typically, that route leads to an emphasis on the difference between the “indirectness” of access and empirical evidence to decide on the truth about micro and nano level phenomena, and the “directness” and readiness of our access to the truth about macro phenomena. The other alternative is a praxeological one, to reflect upon the practicalities involved in seeing and imaging both with respect to macro and nano world. In this paper, we will attempt to pursue the second route. The purpose is then not to decide or focus upon truth status, but rather to point out some similarities between the practices of nano and macro seeing and imaging. We think that these similarities constitute extenuating circumstances that are important to the consideration of the legitimacy of the claims to see and image atoms. In certain traditions of philosophy of science, pejoratively described by Hacking (1983) as “the spectator's view of knowledge”, the tendency has been to downplay the importance of the complexities of seeing and imaging in the macro world in order to arrive at general ideas of one-to-one correspondence between scientific theory and reality, and image and object. We find it important to emphasize, however, that from a *scientific* point of view, the relationships between image, seeing and object is not straightforward even on the macro scale.

We would like to address some of these complexities from what we might call the practising physicist's point of view. A first noteworthy observation from this perspective is that seeing of any kind infers some filtering of information, some of this filtering is deliberate, while some filtering is inadvertent and unavoidable. The deliberate filtering is what we learn through infancy for recognizing objects; filtering out inconsequential information like background lighting, partially occluding objects, etc. The unavoidable filtering is a more fundamental limitation of human vision, and is related to what we possibly can see. Seeing something with the naked eye is inherently limited, as our eyes only convey information about a small part of the electromagnetic spectrum. . This leaves many objects more or less invisible, such as the air, glass and clean water, where if the eyes conveyed information about a different part of the electromagnetic spectrum, e.g., infra red or x-ray radiation, these objects could be all from clearly visible to opaque. Furthermore, even in the visible range of the electromagnetic spectrum we can not possibly see every detail due to the limited resolution of our eyes.

The only way to “see” features outside the visible range is to use techniques mapping the desired information back to the visible range, such as provided by a microscope, or an infrared film. This constitutes, as argued by Pitt (2004), a change in the meaning of seeing, as it extends the metaphor of seeing to include the details of handling of the instrument. However, from a physicist's point of view, it seems arbitrary to give light in the visible range a special status, given the very successful theory of electromagnetic radiation. Visible light gives some information about an object, and that information is directly accessible to the human eye. However, it certainly does not give a full account of the object, and for many applications, the important features might not be conveyed by visible light at all. It is not that seeing through an x-ray machine or a microscope is the same as seeing a tree, but one should be careful about elevating a small part of the electromagnetic spectrum to convey more *essential* information about an object.

Imaging the Macro World

Pitt (2005) argues that in order for a visual construction to be called an image, it must be representational of the original object. Requiring something to be representational implies some comparison with seeing both the object and the image.

As argued above, seeing an object always involves filtering out irrelevant and inaccessible information. Creating an image requires in the same sense some kind of filtering. However, in the process of creating an image, the filtration is more deliberate, and one always has a choice of which features to convey and which to filter out. Consider a digital photograph as an example. Taken with default camera settings in a sufficiently lit scene, a photograph must surely be said to be representational of the scene. The fact that it was taken with a digital camera which post processed the raw data to adjust white balance, remove noise and correct for visual aberrations due to the lens does not, according to Pitt's arguments, stop it from being an image. It is still a faithful representation of the original scene. However, if the photograph is modified on the computer, it becomes less obvious if it still can be called an image. How much can it be modified before it ceases to be an image and becomes a visual construction? Some adjustments of the colours are relatively safe. After all, the camera has already done this by mapping the sensor data to a white balance setting. Removing red eyes and adjusting brightness and contrast will probably also be allowed even though it changes the information in the image, as long as it does not alter any of the important features of the scene. Adjusting the brightness and contrast too much will leave the entire image completely black or white. At that point it will certainly cease to be an image, as all the important features have been filtered out.

The choice of what information to convey is even more clear when imaging objects outside the visible range, such as in x-ray photography. It is not immediately apparent what makes an x-ray photograph representational, as matter does not reflect x-rays exactly like visible light, and we cannot observe the x-rays directly. However, it is this observation that makes x-ray photography useful. It provides a different subset of information about the imaged object that cannot be observed directly. It would be pointless to try to make an x-ray photograph look as much as an ordinary photograph as possible. Rather, one should make the x-ray photograph such that it conveys information about interesting features that cannot be observed directly in order to compliment ordinary photographs.

One might extend this analysis further. Indeed, the legitimacy of the adjustments of the digital photograph (and also in classical, "analogue" photography) is not independent of the act of seeing that is supposed to be the reference. Hence, removing "red eyes" makes the photo more in accordance with what is seen by the human eye of a spectator or the photographer, while keeping the red eyes provides us with a representation of the objects (eyes) at the split-second peak of light intensity during the exposure time. Hence, there is no unique "truth" about whether eyes are red or not without specifying the details of lighting and observation. The photographer producing the image, however, has to choose: either he keeps the red eyes or he does not. In either case the choice constitutes a filtering of information, and the image will always be a representation of less complexity than the real object.

Any faithful description of the practices of imaging needs a concept of filtering and of necessary and relevant information. Difficult choices must be made between the more or less relevant and the more or less important details. With concepts of importance and relevance, however, come questions such as "Important or relevant for whom?" and "Important for what?" Which features are considered important cannot be expected to be universally accepted, but will in general depend on the purpose the images are created for. As an image cannot possibly be expected to hold all information about an object, one must accept some loss of information. This loss of information can be attributed to some filtering performed in the course of the entire process of creating the image. Some loss of information may be accidental and unimportant. For example, if one is to take a photograph of a tree, it might not be of importance that the sky is overexposed, and no details of the clouds can be observed. If one is to photograph the same scene for the purpose of studying the clouds, however, the overexposed sky would not convey the important features of the scene, rendering the image useless. And, as hinted at in the example of the red eyes, certain methodological choices make it possible to faithfully reproduce certain features at the expense of others.

These crude examples are certainly simplifications, but the problem of keeping a sharp distinction between what is an image and what is not is present and increasing with the complexity of the instruments used. With more complex instruments, more knowledge is required to interpret pictures, and thus also the validation of their status as representational images. A requirement of images to be representative typically either becomes unattainable (or irrelevant, since one most often does not *want* images with an undiscriminated, maximum amount of information), or some arbitrary standard must be set in the form of certain viewing conditions. Accordingly, it appears more fruitful to put the emphasis on the requirement to convey some important features of specific objects. The quality of the image would then be a matter of the value (relevance) and the quality of the information, to be judged in terms of its reliability and validity. Visual inspection will often be important in assessing reliability and validity, but not always; and it is not always the best method.

Imaging on the Nano Scale

Above, we have presented an argument against an understanding of seeing objects that grants seeing an unproblematic epistemic status, seeing things “as they are”, “directly”. We have then argued in favour of an understanding of images and visual constructions that places more emphasis on the notion of information rather than seeing. We believe this to be fruitful when trying to explicate the scientific practitioner's point of view. This is even more so when we discuss objects on the nanoscale, which cannot be seen in the ordinary sense of the word. We will pursue this by discussing how visualizations on the nanoscale are designed to carry information and hence can be considered images in our sense.

From its the discovery, scientists have used numerous models for visualizing the atom. From the scientific practitioner's point of view, a visualization technique is not developed with the intention to provide a representation of what atoms really look like. The visualizations are viewed as illustrations to show certain aspects of the system. This can be linked to how the atoms were discovered. Atoms were not discovered because they were observed directly in a large microscope. Rather, some phenomena in chemistry (i.e., the Law of multiple proportions) could not be explained by assuming that matter is continuous and can in principle be subdivided an infinite number of times. Atoms did not need an appearance, because they were postulated to be too small to be observed directly. They were therefore associated with circles, spheres or later: clouds; not because this was what they really look like, but because this choice conveyed information about some of their properties. They served as simple illustrative tools that allowed the scientist to refer to some of the atomic properties more efficiently.

This changed with the introduction of the STM in the 1980s, as researchers claimed to be able to see individual atoms as they really were, with theoretical electron density cloud as an intermediate step on this path. There is, however, still a problem with the meaning of what atoms look like.

Asking what something looks like, is asking to compare it so something else of which the visual appearance is already known. This works trivially for macro scale objects, where recognizing objects as similar to others is an important part of learning to see. It even works well for recognizing objects in a microscope, because micro scale objects reflect and transmit light in the same fashion as micro scale objects. However, trying to directly compare nano scale objects to macro world objects is a problematic endeavour, as atoms, while being the building blocks forming the matter that we see, do not react in a similar way to electromagnetic radiation when studied individually. In fact, an atom changes state by emitting a photon, and thus it cannot be expected to have the same appearance if it emitted another photon before first absorbing another. As atoms do not behave in the same way when they are isolated as they do collectively, one can argue that they do not relate to anything directly accessible to our senses at all.
If electromagnetic radiation cannot be used to see atoms in the same way as a tree or a cell through a microscope is seen, can atoms be said to have any appearance at all? Certainly not in the same sense that a tree have an appearance, but they may have some properties that can most efficiently be conveyed visually. Like an x-ray photograph, images of atoms should not be expected to be like images of trees; but rather convey some important properties of the specific atoms that are studied.

In the same respect, the STM visualizations can be called images, because they represent at least some of the important properties of specific atoms, namely the conductivity of vacuum near the surface of a conducting sample. Other probing microscopes use different techniques to make images of other features of the atoms. An Atomic Force Microscope (AFM) uses a laser to detect minuscule changes in force applied to a cantilever as it is moved over a surface. Other probing microscopes use other techniques to map out the surface of a sample. If one were to apply different techniques to the same sample, the images produced would in general not be identical; they would highlight different properties of the studied atoms. One could argue that this difference means that one cannot be certain what is a correct representation of the atoms, and thus that the images produced are not images at all. On the other hand, one can again make the comparison with x-ray photography. Pictures taken of the same object with a normal and an x-ray camera, will certainly not be identical. They will not convey the same properties of the objects photographed, which is probably why x-ray photography was used in the first place. In the same sense, AFM and STM images will probably not portray the same features of the sample, but they are images in the sense that they represent some of the features of the sample.

It boils down to an example provided by Pitt (2005), where one is to map out a stone wall with a very accurate device shooting tennis balls at the surface. One should then detect the angle of deflection as they bounce back and visualize the data. Pitt seems to be sceptical to call the result of such an endeavour an image. To the argument presented here, the other hand, it represents some of the important properties of that specific wall, and could thus be called an image. It would be an image of the mechanical reflective properties of the wall, in contrast to a photograph, which would be an image of the reflective properties for electromagnetic radiation in the visible part of the spectrum.

Important Features

As discussed above, the phrase “*important features*” implies some use of the images. One can therefore not discuss the status of images without also looking at how the images are used. As what is regarded an important feature cannot be expected to be universal, but rather dependent on the use of the images, and more importantly, the background knowledge of the intended recipients, one should not try to present STM images in a similar manner to a diverse audience. A material scientist working with STM images daily certainly knows a lot more about the use and limitations of the STM instrument than an average member of the public. This implies that what might be considered the important features of an STM image will most likely not be the same. The untrained public eye might see a 3D STM image, and compare it to pictures of a jagged mountain range. By making such comparisons, one can easily be led to attribute other features to the nano world than just visual similarity and thus be led to believe that on the nano scale, the world is solid and controllable, or – in physical jargon – *classical*, while, according to Pitt *“The world at the nano and quantum mechanical level is a buzzing, shifting, constantly in motion in non-linear and non-classical causal fashion” (*Pitt 2005). This kind of simplification has received criticism from several authors (Pitt 2005, Nordmann 2004 and Robinson 2004) for conveying a simplified image of the nano world where “everything is under control”. Pitt suggests that one should not try to show a simplified view of the nano world to the public, but rather try to convey its complexity and thus create more sympathy for the difficulty involved in nano science in the public. However, simplifications are an essential part of physics; trying to understand something about nature by creating a simplified model that carries some important features of the studied phenomenon. In that sense the STM images fit nicely into common practice in physics. It highlights some of the properties of a sample such as structure, at the expense of neglecting other properties deemed not interesting for the current study. Even if this practice is common in physics, it does not change the fact that it may confuse the public, or others without the necessary knowledge to understand the limitations of STM imagery. Therefore, it is very important to accompany the images with information about how they were created, what the limitations of the instrument are, which features are considered interesting by the creators, and also why it was represented in this specific way.

Colours, shadows and other lighting effects on the nano scale are clearly artificial, in that they do not exist in the same sense as in the macro world. However, as previously argued, atoms do not have any obvious visual form, so any visual representation can be called artificial in that sense. One can therefore argue that using colours, shadows and other 3D effects is not problematic in itself, as long as it highlights important features of the image. While the reason for choosing certain colours and other visualization effects may have been obvious to the creator of the image, it certainly will not be obvious to an average member of the public. Most people have not seen many STM images, and more importantly, they have never *learned* to see the nano world. However, in a world where nano technology is increasingly becoming mainstream, and blockbuster movies portraying a completely unrealistic image of nano technology, it is crucial to teach people to see nano images for what they are, and not a small step from Drexlerian machines.

Advanced visualization techniques certainly have their place in science, and it is impossible to prohibit the use of such images when conveying information about nano science/technology to the public. We believe it to be equally futile to fight against the term “image” and “imaging” and insist on calling them visual constructions; indeed, this paper argues that it is reasonable to call them images. Independent of terminology, however, scientific citizenship in the 21st century requires an understanding of not only the phenomena studied by science and the technology developed from it, but also of the practices of scientific knowledge production and dissemination, including how scientists communicate in words and graphics. This social learning process should involve scientists, citizens and scholars who study science engaging in mutual, interdisciplinary critical discourse (see e.g. Goodsell 2006 for a good example). Creativity is also needed, for instance in the development of visualizations (above all movies) that convey non-classical, probabilistic, fuzzy and/or chaotic features of nanoscale phenomena. Accompanying text that explains the making and limitations of images may also be useful. With the apparent growing know-how and understanding of digital imaging techniques among young people, we are not too pessimistic in this respect.

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