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Imaging by touching: Atomic force microscopy

Introduction

In the last few decades, atomic force microscopy (AFM) has made it possible to observe objects at the nanoscale for the first time and this has revolutionized not only scientific practice but also the debate about the representational validity of certain images to account for the nanoworld. Just as many branches of science use numbers, equations or graphs to present their results, the basic tool of nanoscience is imaging. Of course, there are supplementary ways to show the results of the nanoworld, but images definitely form the heart of obtaining, communicating and analysing nanoscale information. The importance of these images has given rise to an intense debate about their representational legitimacy and their capacity to generate knowledge (Birkeland and Strand 2009; Bontems 2011; Bueno 2006; Pitt 2004, 2005; Ruivenkamp and Rip 2011; Slaattelid and Wickson 2011). In this respect, there are numerous approaches in the literature that range from the idea that 'we can really see atoms' (Rao and Margaritondo 2011: 460301) to the suggestion that images of the nanoworld are 'a kind of collective hallucination' (Fraassen 2008: 101).

A large part of the debate focuses on the fact that on the nanoscale we obtain images of something that is, in the classical sense, invisible since its size is well below the visible wavelength (see below). We are going to make use of this paradox to focus the aims of this article, which are: (a) to analyse the construction process of images in the nanoworld; and (b) to reflect on the ontological status of nanoscale images and their epistemological validity. To do this, we are going to focus specifically on the AFM technique, through which we obtain images that are the result not so much of *seeing* a sample, but of *touching* it. This means that reflecting on observation techniques in the nanoworld is not inconsequential, as it provides us with a contemporary opportunity to reflect on the image-generating process.

In the next two sections of this article we will provide a brief outline of the leap from direct vision towards more indirect visualization methodologies to examine how, despite the increasing interaction of the subject with nature through instruments that are more and more sophisticated, a certain similarity to ordinary vision is maintained. Then we will focus on the specific technique of AFM and its technical details to argue that, in this method, the paradigm of *seeing* is replaced by the paradigm of *touching*. Finally, we will analyse certain epistemological considerations that, in our opinion, are innovative and specific to this type of observation of the nanoworld.

The visual image, paradigm of any observation

When Galileo Galilei used his telescope to observe the heavens, he introduced, without knowing it, a radical change in the validity conditions for observing nature by placing an optical instrument between the human eye and the object being observed. If Galileo's telescope brought the distant world within reach, Robert Hooke's microscope did the same for the world of the very small. This use of instruments of optical observation (as opposed to simple measuring techniques) was accompanied by two developments that are well worth emphasizing: a better understanding of the laws of optics, without which any image obtained by an instrument could be questioned, and the study of the human eye as an optical instrument.

Together with the problem of the legitimacy of the use of optical instruments for observing distant and small worlds was the problem of the transmission of the images that had been observed, because Galileo and Hooke had to draw what they saw on paper, which added a further question regarding the objectivity of their representations. Images had to be 'true to nature', as Lorraine Daston and Peter Galison put it (2007: 55–113), to be accepted as legitimate and communicable, and this did not always occur. The case of the drawings that Galileo made of the moon is famous, since they included a large crater in the middle that nobody apart from him *could see*, making clear the need for a less subjective form of representation (Shea 1990). The use of techniques such as camera obscura played an objectivizing role that culminated in the nineteenth century with the appearance of photography and the resulting *mechanization* of visual representations (Daston and Galison 2007: 115–90).

The first optical instruments (the telescope and the microscope) had to earn a legitimacy that was not, in principle, evident. Why should images provided by an instrument be trusted? Furthermore, there was also the problem of the subjectivity of the person drawing the images he or she saw through the instrument. In fact, according to Mario Biagioli (1994), in these problems of legitimacy we can find the root of many of the controversies in which Galileo and Hooke were involved. Four centuries later, optical microscopes and telescopes are rather unproblematic; in fact, they are often regarded as the source of images of the natural world that are more *real*.

By using optical microscopes, we can increase the apparent size of objects to place them within our visual window. However, the resolution of the instrument is restricted by the wavelength of the light used. In the case of visible light, the smallest wavelength is about 400nm, which represents a magnification of about 1000 times. That is, if we want to see, in the traditional sense of the term, within the visible light range, then we must give up the possibility of resolving details that are less than 200nm. An obvious way to increase the resolution even more is to reduce the wavelength, by using, for example, ultraviolet light or X-rays. However, these forms of radiation are rather unsuitable as they are quickly absorbed by the optical system and could also damage and/or modify the object being observed, especially in the case of biological samples. Another possibility consists of taking advantage of the wave-like nature of electrons, which have a much smaller associated wavelength. Transmission electron microscopes (TEM) are based on this principle and achieve magnifications up to 100,000 but only enable us to study very thin samples (of about 100nm) under very restrictive (high vacuum) conditions, especially as far as biological materials are concerned. The treatment of the image is substantially more complex than in the case of optical microscopy and therefore the mediation between the object and the image is much greater.

The construction of new visual representations

Up to this point we have only focused on the problem of representation from an empiricist and positivist perspective, that is, by considering there is a duality between the representation and what is represented and by giving a passive role to the cognizant (to the individual observer, to the scientific community or to society as a whole) as a mere recipient or receiver of knowledge and its forms of representation. Before going into the specific nature of the nanoworld, it may be advisable to briefly reflect on scientific representation as construction and not just as simple mediation.

Here we must stress three aspects in which scientific practice shapes (rather than discovers) the object that it studies, which we will need for our later discussion about the nanoworld. The first one refers to the distinction between what Peter Galison calls mimetic, isomorphic or 'homomorphic' representations, and 'homologous' representations (1997: 19). The former would be representational images with a certain pretention to realism, such as drawings and photographs. The latter would be ones that accumulate numerical data presented in graphic form just to make them easier to handle: they have no pretention to be a specular image of reality.

The second aspect, following Ludwig Fleck, refers to the starting point for each new level of representation. To become legitimate, any new type of representation needs to follow along the lines of what has already been accepted. As Fleck says, 'many soundly established scientific facts are undeniably linked to proto-ideas or pre-scientific and more or less hazy ideas' (1986: 70), and the same thing occurs with representations and images. From his point of view, whenever a new technique produces a new type of representation, the images obtained in this way try to mimic and continue along the lines of types of images that already exist. The technique appears to be new, but the visual form of representation is constructed in analogy to those that already exist in other sciences or other disciplines until they are accepted and become common currency among scientists and between the latter and society, until they become a non-problematic part of the collective (or social) imaginary.

The third aspect that we are interested in highlighting is the construction of scientific 'objectivity'. If we follow Daston and Galison, modern scientific representation and its objectivity are the result of a framework of values and practices that have moved away from the naive 'truth to nature' to depend on what they call 'mechanical objectivity' and 'trained judgement' (Daston and Galison 2007: Chapters 3 and 6). The former consists of the automation of observations and representations in order to distance them from the subjectivity of the singular individual. Modern science, including nanoscience, is constantly striving to construct industrially standardized devices. In fact, the AFM technique, which we will discuss later, is carried out with instruments that are marketed in such a way that they have established a degree of uniformity in the practice of nanoscience and in the type of images that are produced.

As for 'trained judgement', whose roots we could find in Michael Polanyi's philosophy and his *Personal Knowledge* (1962) as well as in Michel Foucault and his *Surveiller et Punir* (1975), we must stress that in handling any experimental technique *savoir-faire* is required, practical training that shapes practice in a specific field or in applying a concrete technique. This tacit knowledge can be seen, for example, in two aspects that we will make use of later on: the capacity to judge deviations from what is expected as *background noise*, as an irrelevant disturbance, or as a phenomenon to be explored; and the acquired ability to know how to *read* a certain kind of homologous representation. For this second aspect, the harmonization or standardization of the type of images provided by a new technique is essential.

Bearing all these elements in mind, we are now going to explain the specific nature of representations in the nanoworld, especially those that the AFM technique provides us with.

Seeing or touching? AFM

Until the early 1980s, microscopy was exclusively based on the use of light (visible or not) or particles (electrons) to obtain an image from their interaction with the sample. However, the situation would drastically change from 1981 onwards. In this year, Gerd Binnig and Heinrich Rohrer at the IBM laboratories in Zurich invented the scanning tunnelling microscope (STM), the forerunner of the atomic force microscope (AFM). Binnig and Rohrer were awarded the Nobel Prize in 1986 and three years later the first commercial AFM was already available. Currently, the AFM is possibly the best tool that we have to *see*, measure and manipulate the world on a nanometric scale.

Since the invention of the STM an entire new family of microscopes has emerged, generally called Scanning Probe Microscopy – SPM (Eaton and West 2011). The operating principle of SPM represents a radical break with what was understood that microscopy ought to be: we no longer see objects, but we *touch* them. A scanning microscope constructs the image of an object, dot by dot, by scanning a specific area of its surface. The sensitive element, called the tip (or probe) of the microscope, scans the surface line by line, until it covers the area of interest. For each dot on each line, the microscope measures the interaction between the tip and the surface of the sample and allocates it a numerical value. For monochrome images, for example, this number will correspond to a specific brightness value (or intensity). The scanning of the sample corresponds, line by line, to the scanning of a cursor on the computer screen, which assigns the corresponding value of the interaction between the tip and the sample to each dot in the image (see Figure 1). The image obtained in this way represents a mapping (dot by dot) of the interaction between the tip of the microscope and the surface of the sample. Neither light nor particles intervene in this process; the image that we obtain is, in an initial approach, a kind of 'tactile' seeing (Rip 2009: 407).

But even this touching is not really touching. In our day-to-day world, touching means putting two things in contact, where there is no distance between them. But extending this concept to the nanoworld is at the very least problematic (if not impossible). The tip–sample interaction in an AFM involves a small number of atoms in some cases. An atom is not a compact element; there is no way of determining exactly where it begins and where it ends. In a rather classical image, we can imagine it like a vague cloud with indefinable boundaries. The problem becomes even more complicated

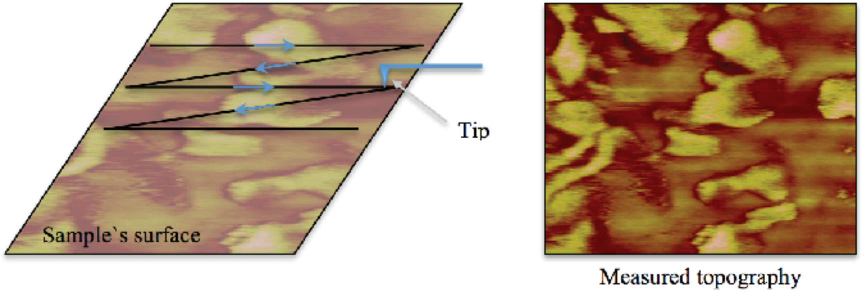

Figure 1: The tip of the AFM scans the surface of the sample measuring at each point the interaction between the probe and the surface. The intensity of this interaction is represented on the computer`s screen according to a given bright (or colour) scale.

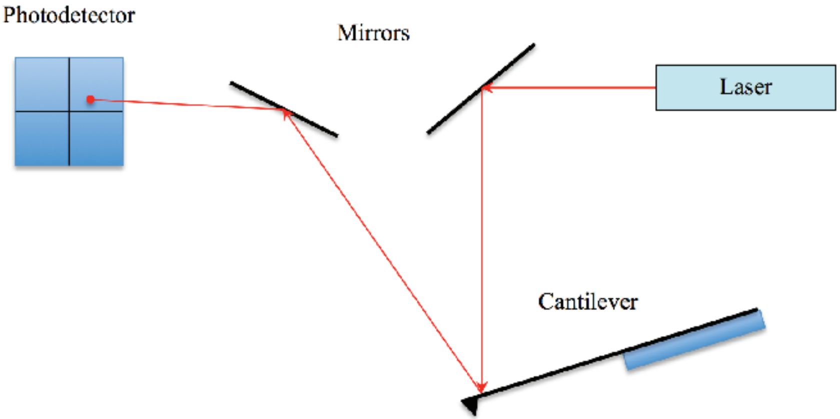

Figure 2: The laser beam is reflected by a first mirror and guided towards the extreme of the cantilever. The reflected beam is then sent to the photo sensor by means of a second mirror. The photo sensor measures the changes in the oscillation of the cantilever due to the interaction between the tip and the surface of the sample.

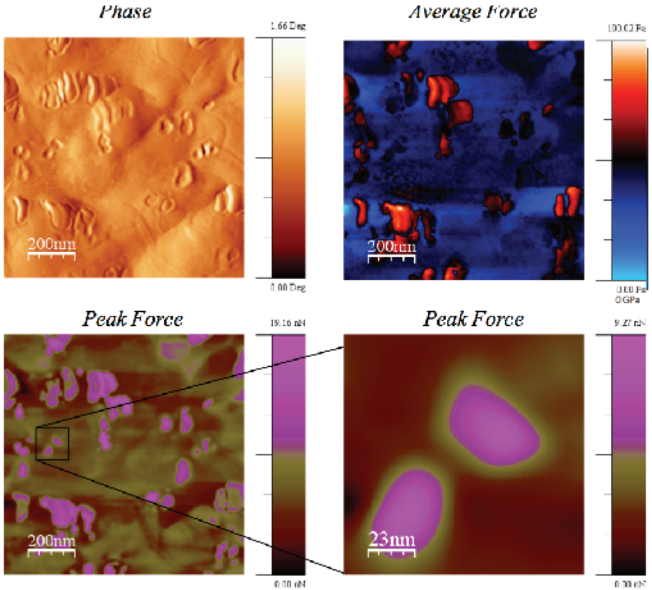

Figure 3: Different AFM channels measured simultaneously over a sample with nano-particles embedded on a polymeric matrix. Each channel gives information about different properties of the sample. Besides some morphological similarities, it is evident that the images are different on each channel. The last picture (bottom right) is a magnification of the previous image where two individual nano-particles can be clearly observed. This is not the morphology of the nano-particles but a map of the peak force between the tip and the surface of the sample.

when we consider two *close* atoms; the electronic clouds of both atoms repel each other and prevent them from approaching *too much*. The concepts of *close* and *too much* in this case are rather ambiguous and a more precise definition requires knowing what type of atoms we are talking about, their potential for interaction and other considerations that go beyond the purposes of this article. Let us just say for now that when two atoms approach each other, an electronic repulsion force appears between them.

Tip–sample interaction in an AFM involves interaction between two groups of atoms: some on the surface of the sample and others on the end of the tip. Depending on the conditions of the experiment and the relative distance between the tip and the sample, various types of forces will appear: attractive, repulsive, short- and long-range, van der Waals, etc. Many of these interactions are well-known and can be modelled with a certain degree of accuracy. However, the forces involved (even the well-known ones) depend on factors that we cannot specify exactly (such as, for example, the exact shape of the tip); we must therefore make hypotheses and/or accept some degree of uncertainty. Tip–sample interaction is therefore dominated by a series of interatomic forces that depend on the geometry of the sample, the tip, its relative distance, and that also vary according to the parameters of the experiment. The result of all these forces is what the AFM finally measures on each dot of the sample. The image that we obtain results from measuring, dot by dot, the atomic interaction between the end of the tip of the AFM and the surface of the sample. The tip and the sample do not even *touch each other* as we understand this on a macroscopic level; on the contrary, a force can be observed (an interaction), which can be attractive or repulsive depending on the distance. Our way of seeing is not even a kind of touching but is rather a feeling, an 'indirect feeling' (Baird et al. 2004), or better yet, a tip–sample *dialogue*.

However, how can this tip–sample interaction force be seen? What does an AFM do to measure this interaction and what information can it give us? To what extent does an image obtained in this way represent the sample? There are various operating modes for AFM, but we are going to focus on a mode called tapping or intermittent contact as this is one of the most commonly used (Bhushan 2007, Chapter 26). The basic operating principle consists of having a very fine tip (with a radius of a few nanometres) located on the end of a cantilever that oscillates with a certain frequency. When the tip is close enough to the sample, the interaction forces make the cantilever modify its frequency and oscillation amplitude and these changes can be detected and measured by the AFM. The most commonly used detection system consists of a laser beam that is reflected by the mobile end of the cantilever and is detected by a photo-sensor (see Figure 2). The variation in frequency or oscillation amplitude can be detected and quantified by the photodetector. In tapping mode, the cantilever is made to oscillate close to its resonance frequency, at constant oscillation amplitude, through a piezoelectric on which the fixed end of the cantilever is based. When the tip approaches the surface of the sample, the interaction forces between these will vary the oscillation amplitude of the cantilever. However, the system continuously modifies the distance between the tip and the sample to keep the oscillation amplitude constant. In this way, as the tip scans the surface of the sample, the system adjusts the distance between the tip and the sample to keep the oscillation amplitude at a certain value. The map that results from graphing the tip–sample distance at each dot of the image is what is called topography of the sample.

We might then ask ourselves: what type of representation is the image obtained in this way? We have seen before that tip–sample interaction depends on atomic forces that can vary in turn according to the conditions of the experiment. If the tip of the AFM is oscillating relatively far from the surface of the sample, only the long-range forces will affect the oscillation of the cantilever. On the other hand, if the tip oscillates close to the surface, the short-range forces will start playing an important role in the oscillation of the cantilever. In each case we will obtain different images depending on the conditions of the experiment and the characteristics of the sample. There is not, then, a *correct* image. Furthermore, the different channels of the AFM can provide us with supplementary information (see Figure 3). The phase, for example, is more sensitive to changes in the mechanical properties of the surface than the topography. Even for a completely flat sample, the phase could supply information about variations in the mechanical modulus or in the composition of the sample that would not be observable from the topographic image. Once again, both images would not be the same but would be representing different aspects of a single thing.

In this way, we can clearly see an aspect that, without being exclusive to nanoscience, is quite apparent in a way that is obvious and at the same time easy to understand: *the observation process explicitly modifies the same properties in the object that we hope to observe*. This is something that is not familiar in the day-to-day world. And yet in the macro-world any observation also alters what we are observing; a disturbance in the system is inherent to how measuring instruments work. We observe atoms by analysing their interaction with other atoms; and as we want to observe increasingly smaller objects, the disturbance introduced by the measuring instrument is greater and greater. When the tip of the AFM gets closer to the surface of the sample, their atoms are (to a greater or lesser extent) altered. The instrument then measures this interaction between the tip and the sample, but which in actual fact represents the interaction between the tip and the sample that has been altered by the presence of the tip. To be really strict, we must not forget that the atoms on the extreme of the tip are also altered by the presence of the atoms in the sample. So what we actually measure is the interaction between the tip, modified by the presence of the atoms of the sample, and the surface of the sample, altered by the presence of the tip: an entanglement between the object and the observer. It is as if on taking a photograph both the camera and the object being photographed were altered at the same time.

The specific nature of observation in the nanoworld

Scientists and philosophers hold a wide variety of positions regarding the epistemological value of representations. In the last few decades, ideas of performative representation have appeared in the philosophical debate. According to this move, a representation is the outcome of a process of entanglement between the observant and what is observed (Barad 2007; see also Ibarra and Mormann 2006). Although it is true that images of the nanoworld share with other scientific images their dependence on a strong theoretical basis, on the nanoscale a fundamental difference appears: the partial mapping that we obtain, this image that supposedly only represents certain aspects of the object, does not strictly match the properties of the object but rather the result of the interaction between the tip of the AFM and the surface that we hope to characterize. The result of the measuring process, the image that we obtain of the object, is not in actual fact a representation of the object (not even of any of its properties) but is rather a representation of the interaction between the object and the tip of the microscope, a representation that comes from *touching* rather than *seeing* the sample.

The construction of the collective (or social) imaginary of the nanoworld should dispense with the sensationalism of spectacular headlines, like the famous 'photograph' of the atoms forming the IBM logo (Binnig and Rohrer 1999), and make the 'entanglement between making images and imagining' more explicit (Ruivenkamp and Rip 2011). In this way, we will avoid extreme positions like Sacha Loeve's stance, who, considering representations of the nanoworld to be an almost exclusive product of artists, claims that 'the originality of nanotechnologies is not that they produce representations of what is invisible, but that *what they produce are not representations*' (2011: 207, original emphasis).

To avoid some sensationalist extremes, it is vital not to lose sight of the highly interdisciplinary nature of nanoscience. If Bernadette Bensaude-Vincent (2004) stressed that this was the result of the convergence of two cultures – the culture of engineers and that of chemists – the attention that we are paying in this article to representations means that we have to highlight the participation of more *cultures* in this process, including the world of aesthetics, popularization and many others. In this sense the analysis provided by Astrid Schwarz and Alfred Nordmann is correct when they stress the need for 'the strategies employed to familiarize ourselves with the nanoworld through the use of images of the meso- and microscopic worlds' to be totally public; strategies in which 'the practices, images and objects […] form part at the same time of the spheres of knowledge and practice, of usefulness and curiosity, of surprise and control, of technical expertise and popular culture' (Schwarz and Nordmann 2011: 234).

Conclusions

In this encyclopaedia article, we have described and analysed the process of forming representational nanoscale images in order to be able to understand their ontological and epistemological status. We have also seen that the outcome of this process can be understood as an entanglement between the observer and the object that is observed. We have emphasized that the images thus obtained represent a particular case of homologous representation and that, for this reason, their realism is extremely indirect. In turn, this analysis has led us to distance ourselves from the analogy of sight to understand images of the nanoworld and to replace this with the analogy of touch. As we have repeatedly stated throughout this article, on the nanoscale, rather than *see*, what we do is *touch* the sample, in a very specific way by using the AFM technique.

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