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PARTIAL TRUTH AND VISUAL EVIDENCE

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Abstract. Newton da Costa and Steven French have argued that the concept of partial truth plays an important role in our understanding of significant aspects of scientific practice: from the status of scientific theories through the understanding of inconsistency in science to the nature of induction (see da Costa and French 2003). In this paper, I use the concept of partial truth and the associated framework of partial structures to offer a formulation of the concept of visual evidence, and I examine some of the roles that this notion plays in scientific activity.

Keywords: Partial truth; evidence; visual evidence; visualization; transparency.

1. Introduction

In contemporary science, from physics through chemistry to molecular biology, a significant role is played by various kinds of images, produced by a multiplicity of scientific instruments, which are taken as sources of visual evidence. For example, micrographs from many kinds of microscopes (such as optical, electron, or probe microscopes) are regularly used to support the existence of a variety of phenomena. These micrographs, however, often provide only partial information about the sample under study, and although in many cases they do yield visual evidence, the evidence in question is at best partial.

In this paper, I offer an account of visual evidence in science—focusing, in particular, on images from microscopy—and making room for the relevant partiality. In order to do that, it is crucial, first, to have a proper framework to represent the partiality in question. Such a framework is offered by the partial structures approach developed by Newton da Costa[1] and Steven French (2003), and I will use it in order to sketch an account of visual evidence.

Moreover, as will become clear, in order to properly assess microscopes' images, three issues need to be considered: (1) We need to be clear about how exactly the relevant microscopes' images have been produced. (2) We then need to consider whether the images (or some aspect of them) are the result of some artifact; that is, we need to eliminate relevant possibilities of misrepresentation. (3) Finally, we need to examine whether we have grounds to take some microscopes' images as giving us information about the way in which the objects in the sample *look*—a condition that can be called *transparency*. As will become clear, the latter condition not always

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relevant. But in those cases in which it is, and which depend on the particular problem under consideration, it is important to understand whether the condition is in fact satisfied.

After sketching an account of visual evidence, I will then examine the above issues by considering two case studies. The first focuses on the use of biological structures, such as DNA, to build nanostructures from the bottom up. I will discuss, in particular, the so-called DNA nanotechnology, which uses DNA as a biomimetic component for self-assembly of various nanostructures (see, e.g., Seeman and Belcher 2002). This offers an interesting scenario in which biological phenomena are guiding the construction of nanostructures, and in which micrographs from atomic force microscopes (AFM) play a crucial role.

The second case study focuses on the attempt to build a single molecular wire, and then determine whether such a wire is indeed conducting (see, e.g., Bumm *et al.* 1996). This research was based on extending the capabilities of the scanning tunneling microscope (STM) in such a way that the instrument can measure photons emitted from the tunneling junction. This provides a significant gain in spatial resolution in comparison with standard STMs, given that the photons only come from the atoms or molecules through which electrons are tunneling (Stranick and Weiss 1994, and Stranick *at al.* 1994). I will discuss to what extent in this case the micrographs that were produced offer visual evidence for the relevant phenomena. Taken together, the two case studies provide an opportunity to illustrate how the proposed account of visual evidence works.

2. Visual evidence and partial truth

Similarly to most sorts of evidence in science, visual evidence is often partial. There is much in the evidence that is inconclusive, and much that is not fully established, despite how successful the evidence is. This partiality, as will become clear shortly, can be accommodated formally in terms of the partial structures approach.[2]

2.1. Partial structures and partial truth

The partial structures approach relies on three main concepts: partial relation, partial structure and partial truth. One of the main motivations for introducing this proposal derives from the need for supplying a formal framework in which the openness and incompleteness of the information that is dealt with in scientific practice can be accommodated. This is accomplished, first, by extending the usual notion of structure, in order to accommodate the partialness of information we have about a certain domain (introducing then the notion of a partial structure). Second, the

Tarskian characterization of the concept of truth is generalized for partial contexts, which then leads to the introduction of the corresponding concept of partial truth.

The first step, then, to characterize partial structures is to formulate a suitable concept of a partial relation. In order to investigate a certain domain of knowledge Δ (say, the physics of particles), researchers formulate a conceptual framework that helps them systematize and interpret the information they obtain about Δ. This domain can be represented by a set D of objects (which includes *real* objects, such as configurations in a Wilson chamber and spectral lines, and *ideal* objects, such as quarks). D is studied by the examination of the relations that hold among its elements. However, it often happens that, given a relation R defined over D, we do not know whether all objects of D (or n-tuples thereof) are related by R, or we need to ignore some of the relations that are known to hold among objects of D, in order to study other relations about that domain in a tractable way. This is part of the incompleteness and partiality of our information about Δ, and is formally accommodated by the concept of a partial relation. The latter can be characterized as follows. Let D be a non-empty set. An n-place *partial relation* R over D is a triple $\langle R_1, R_2, R_3\rangle$, where R_1, R_2, and R_3 are mutually disjoint sets, with $R_1 \cup R_2 \cup R_3 = D^n$, and such that: R_1 is the set of n-tuples that (we know that) belong to R; R_2 is the set of n-tuples that (we know that) do not belong to R, and R_3 is the set of n-tuples for which it is not known (or, for reasons of simplification, it is ignored that it is known) whether they belong or not to R. (Notice that if R_3 is empty, R is a usual n-place relation that can be identified with R_1.)

But in order to accommodate the information about the domain under study, a concept of structure is needed. The following characterization, spelled out in terms of partial relations and based on the standard concept of structure, offers a concept that is broad enough to accommodate the partiality usually found in scientific practice. A *partial structure* A is an ordered pair $\langle D, R_i\rangle_{i\in I}$, where D is a non-empty set, and $(R_i)_{i\in I}$ is a family of partial relations defined over D.[3]

We have now defined two of the three basic concepts of the partial structures approach. In order to spell out the last one (partial truth), we will need an auxiliary notion. The idea here is to use the resources supplied by Tarski's definition of truth. But since the latter is only defined for full structures, we have to introduce an intermediary notion of structure to link partial to full structures. This is the first role of those structures that extend a partial structure A into a full, total structure (which are called A-normal structures). Their second role is model-theoretic, namely to put forward an interpretation of a given language and to characterize semantic notions. Let $A = \langle D, R_i\rangle_{i\in I}$ be a partial structure. We say that the structure $B = \langle D', R'_i\rangle_{i\in I}$ is an *A-normal structure* if (i) $D = D'$, (ii) every constant of the language in question is interpreted by the same object both in A and in B, and (iii) R'_i extends the corresponding relation R_i (in the sense that, each R'_i, supposed of arity n, is defined for all n-tuples of elements of D'). Note that, although each R'_i is *defined* for all n-tuples over D', it holds for some of them (the R'_{i_1}-component of R'_i), and it doesn't hold for others (the R'_{i_2}-component).

As a result, given a partial structure A, there are several A-normal structures. Suppose that, for a given n-place partial relation R_i, we don't know whether $R_i a_1 \ldots a_n$ holds or not. One of the ways of extending R_i into a full R'_i relation is to look for information to establish that it *does* hold; another way is to look for contrary information. Both are *prima facie* possible ways of extending the partiality of R_i. But the same indeterminacy may be found with other objects of the domain, distinct from $a_1, \ldots, a_n$ (for instance, does $R_i b_1 \ldots b_n$ hold?), and with other relations distinct from R_i (for example, is $R_j b_1 \ldots b_n$ the case, with $j \neq i$?). In this sense, there are *too many* possible extensions of the partial relations that constitute A. Therefore, we need to provide constraints to restrict the acceptable extensions of A.

In order to do that, we need first to formulate a further auxiliary notion (see Mikenberg *et al.* 1986). A *pragmatic structure* is a partial structure to which a third component has been added: a set of accepted sentences P, which represents the accepted information about the structure's domain. (Depending on the interpretation of science that is adopted, different kinds of sentences are to be introduced in P: realists will typically include laws and theories, whereas empiricists will add mainly certain regularities and observational statements about the domain in question.) A *pragmatic structure* is then a triple $A = \langle D, R_i, P\rangle_{i \in I}$, where D is a non-empty set, $(R_i)_{i \in I}$ is a family of partial relations defined over D, and P is a set of accepted sentences. The idea is that P introduces constraints on the ways that a partial structure can be extended (the sentences of P hold in the A-normal extensions of the partial structure A).

Our problem is: given a *pragmatic* structure A, what are the necessary and sufficient conditions for the existence of A-normal structures? Here is one of these conditions (Mikenberg *et al.* 1986). Let $A = \langle D, R_i, P\rangle_{i \in I}$ be a pragmatic structure. For each partial relation R_i, we construct a set M_i of atomic sentences and negations of atomic sentences, such that the former correspond to the n-tuples that satisfy R_i, and the latter to those n-tuples that do not satisfy R_i. Let M be $\cup_{i \in I} M_i$. Therefore, a pragmatic structure A admits an A-normal structure if and only if the set $M \cup P$ is *consistent*.

Assuming that such conditions are met, we can now formulate the concept of partial truth. A sentence α is *partially true* in a pragmatic structure $A = \langle D, R_i, P\rangle_{i \in I}$ if there is an A-normal structure $B = \langle D', R'_i\rangle_{i \in I}$ such that α is true in B (in the Tarskian sense). If α is not partially true in A, we say that α is *partially false* in A. Moreover, we say that a sentence α is *partially true* if there is a pragmatic structure A and a corresponding A-normal structure B such that α is true in B (according to Tarski's account). Otherwise, α is *partially false*.

The idea, intuitively speaking, is that a partially true sentence α does not describe, in a thorough way, the whole domain that it is concerned with, but only an aspect of it: the one that is delimited by the relevant partial structure A. After all, there are several different ways in which A can be extended to a full structure, and in some of these extensions α may not be true. Thus, the concept of partial truth is strictly weaker than truth: although every true sentence is (trivially) partially true, a partially true sentence may not be true (since it may well be false in certain extensions of A).

To illustrate the use of partial truth, let us consider an example. As is well known, Newtonian mechanics is appropriate to explain the behavior of bodies under certain conditions (say, bodies that, roughly speaking, have a low velocity with respect to the speed of light, that are not subject to strong gravitational fields etc.). But with the formulation of special relativity, we know that if these conditions are not satisfied, Newtonian mechanics is false. In this sense, these conditions specify a family of partial relations, which delimit the context in which Newtonian theory holds. Although Newtonian mechanics is not true (and we know under what conditions it is false), it is *partially true*; that is, it is true in a given context, determined by a pragmatic structure and a corresponding A-normal one (see da Costa and French 2003).

But what is the *relationship* between the various partial structures articulated in a given domain? Since we are dealing with partial structures, a second-level of partiality emerges: we can only establish *partial* relationships between the (partial) structures at our disposal. This means that the usual requirement of introducing an isomorphism between theoretical and empirical structures (see van Fraassen 1980, p. 64) can hardly be met. After all, researchers typically lack full information about the domains they study. Thus, relations weaker than full isomorphism (and full homomorphism) need to be introduced (French and Ladyman 1997, French and Ladyman 1999, and Bueno 1997).

In terms of the partial structures approach, however, appropriate characterizations of *partial isomorphism* and *partial homomorphism* can be offered (see French and Ladyman 1999, Bueno 1997, and Bueno, French, and Ladyman 2002). And given that these notions are more open-ended than the standard ones, they accommodate better the partiality of structures found in scientific practice.

Let $S = \langle D, R_i \rangle_{i \in I}$ and $S' = \langle D', R'_i \rangle_{i \in I}$ be partial structures. So, each R_i is a partial relation of the form $\langle R_1, R_2, R_3 \rangle$, and each R'_i a partial relation of the form $\langle R'_1, R'_2, R'_3 \rangle$.[4]

We say that a partial function[5] $f : D \to D'$ is a *partial isomorphism* between S and S' if (i) f is bijective, and (ii) for every x and $y \in D$, $R_1 xy \longleftrightarrow R'_1 f(x) f(y)$ and $R_2 xy \longleftrightarrow R'_2 f(x) f(y)$. So, when R_3 and R'_3 are empty (that is, when we are considering total structures), we have the standard notion of isomorphism.

Moreover, we say that a partial function $f : D \to D'$ is a *partial homomor-*

phism from S to S' if for every x and every y in D, $R_1xy \rightarrow R'_1f(x)f(y)$ and $R_2xy \rightarrow R'_2f(x)f(y)$. Again, if R_3 and R'_3 are empty, we obtain the standard notion of homomorphism as a particular case.

There are two crucial differences between partial isomorphism and partial homomorphism. First, a partial homomorphism does not require that the domains D and D' of the partial structures under study have the same cardinality. Second, a partial homomorphism does not map the relation R'_i into a corresponding relation R_i. Clearly a partial homomorphism establishes a much less strict relationship between partial structures.

Partial isomorphism and partial homomorphism offer mappings among partial structures that are less tight than their corresponding full counterparts—isomorphism and homomorphism. Partial mappings, as transformations that connect different partial models that may be used in scientific practice, allow for the transferring of information from one domain into another—even when the information in question is incomplete. After all, if a sentence is partially true in a given partial structure S, it will also be partially true in any partial structure that is partially isomorphic to S (see Bueno 2000).

As a result, partial mappings can be used as mechanisms of representation in scientific practice. It is in virtue of the fact that certain structures that characterize a given phenomenon bear significant relations with the latter—in the sense that there is a partial mapping between the two—that these structures can be used to represent the relevant features of the phenomenon under study. Of course, which features are relevant is a pragmatic matter, largely dependent on the context under consideration.

2.2. Partial evidence and visual evidence

The concept of partial truth can be used to formulate a suitable concept of partial evidence. Let $A = \langle D, R_i \rangle_{i \in I}$ be a partial structure, where D is a non-empty set and R_i is a family of partial relations. We say that A provides *partial evidence* for P if the (partial) information in A offers good reason to believe that P is (at least) partially true. Clearly, given that A is a partial structure, the information it offers need not be complete or final—additional information typically can be added.

This partiality allows us to introduce the concept of degrees of evidence. Suppose that something counts as evidence for a given hypothesis S if it offers good reason to believe in S (see, e.g., Achinstein 2001). What kinds of items offer good reason to believe in a hypothesis? It depends on the hypothesis in question. In some cases, a suitably constructed image will do the trick; in others, we will have the results of a certain experiments, or the presentation of certain statistical relations among relevant variables. What is important is that the various relations that are found in a given sample determine a certain partial structure, $A = \langle D, R_i \rangle_{i \in I}$. The more fully determined these partial relations are, the more good reason to believe in the result in question we have. And in each step of the way, we have partial evidence for the result. If the information provided in support of S is of a visual sort—such as the information encoded in photographs and in certain micrographs,[6] for example—we then have *visual evidence* for S.

Can an image offer *partial* visual evidence for a given result? One may claim that it can't. After all, as opposed to a verbal representation of a given situation—which can, and typically do, leave various aspects of that situation unspecified—an image (or a pictorial representation more generally) typically specifies various aspects of the object under consideration. For instance, in an image, the object is represented with a particular shape, (relative) size, color, or position (relative to other objects in the image). So, how can an image leave certain visual content unspecified?

Even though there is a significant difference between verbal and visual representation, there is still plenty of room for indeterminacy of visual representation. Here are some examples. A stick figure clearly leaves a lot unspecified (Hopkins 1998); for instance, the exactly clothing that the character wears is not settled. The micrograph from a scanning tunneling microscope represents the shape of an atom as a somewhat conic figure (Chen 1993). However, it is not specified whether this is the correct shape; more likely, that shape is an artifact of the tip of the microscope. In George Palade's original images of ribosomes (Palade 1955), the latter are represented only as small dots. Presumably, better instruments would offer further details about its shape.[7] In all of these cases, even though we are dealing with visually salient objects, there is plenty of partiality in the evidence under consideration. We can accommodate that partiality by noting that the relations invoked in the relevant structures are only partial, and by turning some of these partial relations into full relations (as additional information is obtained), less partial pieces of evidence are produced. But the description of the overall situation would typically be, at best, partially true.

Given the significance of images produced by microscopes for the discussion that follows, it is important to highlight two central epistemic conditions that reliable microscopes are expected to satisfy:

(a) *Mechanization of image formation*: The images generate by a microscope are the product of a mechanical system intended to yield images that reproduce and enhance certain features of the sample—as long as the sample is suitably related to the microscope (e.g. suitable preparation techniques have been used).

(b) *Counterfactual dependence*: The microscopes' mechanical system of image generation establish a particular dependence between samples and images,

> namely: (i) Had the sample been different (within the microscope's sensitivity range), the image produced by each microscope would have been correspondingly different. (ii) Had the sample been the same (again, within the microscope's sensitivity range), the image produced by the relevant microscopes would have been correspondingly the same.

The mechanization condition establishes that, once a properly calibrated and suitably prepared sample is put under a microscope, the image that is generated does not depend on the experimenter: the image is simply the result of the interaction between the sample and the microscope. The counterfactual dependence condition allows the experimenter to use the microscope to track various aspects of the sample, determining various properties of the sample over time. Ultimately, what these two conditions establish are suitable mappings between the sample under study and the corresponding image. The mappings are partial in the sense that not every aspect of the sample has a counterpart in the image, given that only some aspects of the sample are selected for representation. For example, probe microscopes (such as atomic force and scanning tunneling microscopes) produce images that represent information about the surface of the sample, disregarding details about the inner structure of the latter. In contrast, electron microscopes—in particular, transmission electron microscopes—generate images that provide information about the inner structure of the sample, while disregarding the details of the surface of the latter. Partiality is the norm here.

Even if we granted that, for a given microscope, the mechanization and counterfactual dependence conditions are satisfied, it's still possible that the images produced by such an instrument fail to give us information about the way the objects under study look. In other words, *transparency* may not be satisfied. After all, transparency would only be met if visually salient features of the sample were suitably reproduced in the microscope's images. But why should we care about transparency? Because in several cases in science what is at issue is precisely whether the microscope images give us evidence—even partial visual evidence—about the way the items in the sample look. What needs to be done in such cases is to make sure that relevant possibilities of misrepresentation of the visual properties of the objects in the sample have been eliminated.

Using this framework, I will now examine two case studies involving visual evidence in science. The first invokes visual evidence to confirm the presence of a given structure at the nanoscale: the DNA nanotechnology case. The second illustrates a situation in which visual evidence is not conclusive: the "case" for single-molecular wires in chemistry.[8] I will examine them and apply the framework to each in turn. In both cases, the framework can be used to make sense of certain puzzling features that emerge.

3. Visual evidence and DNA structures

3.1. DNA structures

As is well known, molecular structures have a crucial property: what is called 'molecular recognition'; that is, the capacity that the relevant molecules have of interacting with other molecules of suitable kinds. Due to this property, self-assembly of nanostructures becomes possible as well as the use of certain atomic and molecular structures as a template for the production of other molecular structures. As is also well known, DNA exemplifies these two features of self-assembly: (a) the molecules in question have strong affinity for each other (and thus they exhibit the 'molecular recognition' property); and (b) the molecules form a predictable structure when they associate (and thus it is possible to use them as templates for the construction of certain nanostructures). Given that DNA can be used to guide the whole process—coupled with techniques of molecular control that chemists have developed—it is possible to devise a process of molecular construction via DNA templates.

This proposal eventually led to the development of DNA nanotechnology. This is an approach to build nanostructures from the bottom up, starting with molecular systems and reaching significantly more complex nanostructures. The origin of the approach can be traced back to the 1970s, when researchers started to perform genetic manipulation by adding together molecules with "sticky ends". A sticky end is a short single-stranded overhang protruding from the end of a DNA molecule (Seeman [2003]). Current approaches to DNA nanotechnology use DNA as a biomimetic component for self-assembly; that is, the properties of DNA discussed above are used in the construction of certain macromolecules and other nanostructures (Seeman [2003], [2005], Seeman and Belcher [2002], Ding *et al.* [2004]). In particular, DNA is used as scaffolding to crystallize biological macromolecules artificially for crystallography and to organize the components of nanoelectronics.

Current DNA nanotechnology continues to explore the "sticky end" cohesion of DNA molecules. In one significant project of Seeman's group, the goal was to construct two-dimensional DNA crystals out of DNA strands (Ding *et al.* 2004). A theoretical model is first introduced in which, schematically, a progression is indicated in which one moves from the construction of stable triangles of DNA crystals to DNA hexagons built from such triangles all the way to honeycomb DNA structures built from such hexagons. The theoretical model (and, in the terminology to be introduced shortly, the corresponding theoretical image) guides the construction of these DNA crystals, and helps to assess the success or failure of the construction. I noted that the model describes the construction "schematically" since it presents the construction in stages (from DNA triangles through hexagons to honeycomb DNA structures). Whether the actual process of construction of the relevant crystals goes through in this exact way is a separate issue that does not bear on the success of the model and the corresponding construction.

Crucial for this research is the use of the atomic force microscope (AFM) in order to detect and "visualize" the proposed constructions. The AFM generates images that are sensitive to the topography of the objects in the sample, thus allowing researchers to identify relevant features in the sample's surface. The AFM outputs provide what can be called *empirical images* of the sample. The empirical images are the result of the statistical aggregation of multiple measurements, and so their construction involves a complex process of composition and combination of measurements and interactions between the sample and the tip of the instrument. In microscopy, empirical data are carefully crafted and constructed.

Similarly crucial is the interplay between empirical images (AFM outputs) and what can be called *theoretical images*. The latter are diagrams, schematic representations, theoretical models or templates created by the researchers to help them figure out what they take to be the relevant relations among the objects in the sample under study. In the case of the DNA crystals research, the theoretical images are the diagrams representing the planned progression of structures from triangular DNA crystals through hexagons all the way to honeycomb DNA structures. Of course, theoretical images only provide schematic representations rather than actual measurements of the objects and relations in the sample.

There is a close connection between empirical and theoretical images. The latter offer a guide and a strategy to build the DNA structures in question, by indicating schematically the steps that need to be taken in order to obtain the intended result. The theoretical images also provide a criterion of adequacy for the success of the final construction. In the case of the DNA crystals research, the criterion offered by the theoretical image relies crucially on visual evidence. The empirical images are supposed to resemble visually salient features of the theoretical images: honeycomb structures should be identifiable in both. In this way, the DNA crystals in the sample and the objects represented in the theoretical images are expected to have the same geometrical configuration, with the empirical images offering the link between them. After all, no direct access to these crystals is available independently of the mediation of suitable microscopes. Hence, the empirical images are taken to provide, at least in principle, visual evidence for the actual configuration of the objects in the sample.

If empirical images yield visual evidence for the success or failure of a given construction, it is by determining the content of these images that the relevant result is assessed. For instance, in the case of DNA crystals, Seeman and his team noted that if no "sticky ends" were left hanging, no stable structures are shown in the empirical images, which they take to be evidence for the conclusion that the DNA crystals were not properly formed. As a result, in order to obtain DNA crystals in the shape predicted by the theoretical images, "sticky ends" are required to be left hanging. If this is done, the empirical images display honeycomb structures, which, in turn, is taken to be evidence that the resulting crystals do become stable and acquire the shape that is represented in the theoretical images.[9] In this way, empirical images offer evidential support for the configuration provided in the theoretical images. Hence, we have a back-and-forth process between the schematic representation offered by the theoretical images and the empirical information encoded in the AFM images, in which the latter are used to assess the success of the former, and also to guide the construction of the crystals in question. This process is crucial to build the relevant nanostructures. And in the end the success of the project fundamentally relies on the production of credible visual evidence.

3.2. Transparency and visual evidence

Transparency plays a decisive role here. As used in this context, *transparency* is the claim that by looking at an empirical image researchers can see how the objects in the sample look like.[10] Perhaps photographs and portraits satisfy the relevant requirement, given that by looking at a photograph (or a portrait) of Einstein we could see how he looked. Transparency does not seem to be an unreasonable requirement in the case of photographs and portraits, since in such cases we are typically interested in capturing the way a certain object (or an event) looks. But should transparency be taken as a requirement for AFM empirical images?

Given that such AFM images can be computationally manipulated and transformed in a variety of ways, it is not clear that the images uniquely determine the way the objects under study look like. The same data produced empirically by the AFM to study DNA crystals can be displayed as an array of wavy lines or as clearly identified honeycomb structures. The preference for one mode of presentation of the empirical image over another seems to be a reflection of the expectations of the researchers, given the theoretical images they have been working with, of how the objects in the sample should look like. Moreover, changes in exposure, contrast, saturation, and sharpness of an image, to mention just a few basic factors, transform significantly the surface of an image, and the corresponding appearance of the objects as they are displayed on the latter. But clearly we do not take these changes in the image to correspond to changes in the objects. Finally, the way objects look is itself a very transient affair, which depends on constant changes in the objects themselves as well as in the environment in which they are embedded (among other factors). So, why should the way objects look acquire the epistemological significance that transparency seems to assign to it?

The answer is that transparency is not required—in general—for the acceptability of images produced in research at this scale. Transparency becomes relevant when the problem raised by a particular research question depends on establishing how certain objects, or configuration of them, look—such as whether certain DNA crystals form honeycomb structures. When questions about how objects look become prominent, transparency does seem to be a relevant constraint on image production and assessment. After all, if transparency is met, it seems that the relevant instruments are producing empirical images that give us information of the relevant sort (namely, about the way the objects in the sample look).

In the case of DNA nanotechnology, when reports of the AFM empirical images are given, a delicate ambiguity is in place. As Seeman and his team note: "The honeycomb structure of arrangements is evident from the [AFM] images" (Ding *et al.* 2004, p. 10230). When we look at the empirical AFM images, the honeycomb structure of arrangements is indeed evident. In fact, we can see honeycomb structures in the AFM images. As a description of the images, this is literally correct. The ambiguity arises when we interpret "honeycomb structure" to stand not for a description of the images, but for a description of the sample. With the assumption of transparency in place, it is as though simply by looking at the AFM images we could see exactly what the objects in the sample look like.

However, AFM images, created as the outcome of the interaction of the tip of the microscope and the surface of the sample, do not seem to be transparent. After all, an AFM image offers something analogous to what a blind person would "see" in the surface of an object by systematically touching it. The degree of perturbation to the system in the case of AFM, as in the case of a person feeling an object with his or her hand, is greater in both cases than what would happen if the person is perceiving low-energy light being reflected from that surface. Moreover, consider the information that is obtained from the AFM as the result of the interaction between the tip of the microscope and the sample. As noted, this information is heavily processed and computationally manipulated so that the resulting image displays visually salient structures (such as honeycombs) rather than a not very informative array of wavy lines. There is no doubt that a significant choice in the mode of presentation of the image was made. However, it is unclear on what grounds one can claim that this choice tracks the corresponding visual features of the objects in the sample. After all, what exactly are these visual features when we are dealing with objects that cannot otherwise be seen (that is, objects that cannot be seen without the mediation of the relevant instruments)? Hence, it is very difficult to make sense of transparency in this case. It is likewise difficult to make sense of the idea that the honeycomb structure evident in the AFM images corresponds exactly to the way things are in the sample. Clearly, some inferential link from the empirical images to the configuration of objects in the sample is still needed.

Despite that, the search for visual evidence plays a crucial role in this case study. In order to determine whether a certain result has been established (or not) researchers try to obtain visually informative images—images that show, beyond reasonable doubt, that the intended phenomenon has been produced. These images allow researchers to study properties of objects that cannot be observed independently of the instruments in question. In this case, part of the goal of the research is to produce images that highlight certain visually salient aspects of the objects in the sample, such as the possibility of visually detecting two-dimensional DNA honeycomb structures.

However, in what sense can we say that DNA molecules have visually salient properties? Strictly speaking, as is well known, there are no colors at the nanoscale. And the technologies that allow researchers to study and detect various aspects of nanoscale objects do not seem to be able to rule out relevant alternative interpretations of the empirical images, given that the same empirical data can be presented in significantly different ways from a visual point of view. So, in what sense can we say that the objects at that scale can be *seen* or can be said to have certain *visual* properties?

It may be said that, in the case of DNA nanotechnology, the AFM micrographs (empirical images) do look like as the theoretical images suggested they should, with honeycomb structures being displayed on the surface of these images. However, as noted, the visually salient features of AFM micrographs are, in part, the result of particular coding conventions regarding the presentation of such images—conventions that favor the honeycomb format over the one based on the array of wavy lines.[11] Thus, whether honeycomb structures are evident in the AFM image or not depends on the adoption of such coding conventions. As a result, significant amount of work gets packed under (the choice of) these conventions. If the latter change, the resulting images change accordingly. In fact, the same data from an AFM can be used to produce different AFM empirical images based on different coding conventions. The difference in the images emerges from the fact that they have significantly distinct visual features. Hence, it is unclear what exactly we can conclude about the actual visual properties (if any) of the objects and relations in the sample based on these images. The fact that certain AFM micrographs are visually more informative to us than others gives us no reason to believe that those images are more likely to capture the way the objects and relations in the sample look like. After all, this is in part a pragmatic feature of the images rather than an epistemic one.

Despite the partial mappings that are established between the surface of empirical images and the samples under study, it is unclear whether the resulting images ultimately provide full visual evidence in support of the way the objects in the sample look like. After all, for the reasons just discussed, it is unclear that AFM empirical images in this case give good reason to believe that the objects in the sample look like the way they are represented in the relevant images. However, AFM images do provide at least *partial* visual evidence for the intended conclusion, given that they offer *some* reason to believe in the latter. Perhaps that's all we can get at this point.

An empiricist, as usual, will invite us to be cautious. He or she will raise concerns as to whether we know that the counterfactual dependence condition discussed above is in fact met in the case of an AFM. Recall that according to such condition, had the sample been the same (within the microscope's sensitivity range), the image produced by the microscope would have been the same. However, as just noted, the same sample can generate different images, e.g. via the adoption of different coding conventions for image production. Given the importance of properly identifying the visual properties of the sample in this case, and the variance in the images that are produced without a corresponding variance in the sample, some cautious is indeed justified. In the end, the empiricist will resist the conclusion that the experiments in question ultimately establish the intended result, despite the partial evidence provided.

4. Visual evidence and molecular wires

4.1. Molecular wires

In a paper published in *Science* in 1996, Bumm, Weiss and their collaborators claim to have constructed one of the thinnest conducting wires possible: a single molecular wire that is fully functional. Clearly, the possibility of building such a wire has significant relevance for computer engineering with direct implications to potential reductions in the size of computer chips—a relevant goal also in nanotechnology.

What is striking about this research is the way in which it exploits a particular development in physics—more specifically, improvements in scanning tunneling microscopy—and employs it to attempt to achieve a significant goal in nanotechnology: the construction of single molecular wires. Here, in outline, is the central feature of the work:

> Molecular wire candidates inserted into 'nonconducting' *n*-dodecanethiol self-assembled monolayers on Au{111} were probed by scanning tunneling microscopy (STM) and microwave frequency alternating current STM at high tunnel junction impedance (100 gigohms) to assess their electrical properties. The inserted conjugated molecules, which were 4,4′-di(phenylene-ethynylene)benzenethiolate derivatives, formed single molecular wires that extended from the Au{111} substrate to about 7 angstroms above and had very high conductivity as compared with that of the alkanethiolate. (Bumm *et al.* 1996, p. 1705)

The crucial idea is to establish a conducting link from the gold substrate through the 'non-conducting' material to the top of the sample under study. The conducting link is formed by molecular wire candidates, which are conjugated molecules that have been inserted through the 'non-conducting' material. The researchers' hope is that a *single* molecule is formed when the molecular wire candidates are so inserted. And a central part of the experiment is to determine that this is exactly what happened, and to rule out those possibilities that would prevent the experiment from establishing the intended phenomenon.

By using a scanning tunneling microscope (STM)—in particular, a microwave frequency alternating current STM—Bumm and collaborators are in a position to assess the electrical and topographic properties of the sample. After all, the STM provides information about both the topography of the sample and the electric features at the sample's surface (given the use of the special kind of STM just mentioned). The surface of the STM image the researchers obtained has some clearly noticeable bright spots that indicate the presence of molecules protruding through the 'non-conducting' material. These molecules are highly conducting (which can be determined by the STM), and some of them, on the researchers' view, amount to single molecular wires (which are suggestively denoted in the paper by '**1**′').

As Bumm and collaborators point out:

> STM images of the ['nonconducting'] DT and [the nanowire candidate] **1**′ SAM [self-assembled monolayer] are shown [. . .]. We believe that the (bright) topographic features protruding through the DT film are due to **1**′ [the single molecular wire candidate] because these features were not obtained in the DT films before exposure to the solution of **1**′. (Bumm *et al.* 1996, p. 1706)

In other words, given that no bright spots were present on STM empirical images before the solution of **1**′ was applied to the sample, but such spots were detected after the solution was used, it is reasonable to suppose that the spots emerged from **1**′.

However, simply looking at the STM empirical images is not enough to establish that *single* molecular wires have in fact been formed. After all, why would a series of different bright spots on a STM image establish such a conclusion? In order to address this issue, Bumm and collaborators need to reason about the STM images, and offer a suitable interpretation of them that rules out relevant factors that otherwise conflict with the hypothesis that there are single molecular wires in the sample.

In an attempt to establish the intended hypothesis, Bumm and collaborators seem to rely on an inference to the best explanation: the best explanation as to why the bright topographic features are salient on the STM images is because these spots are produced by the single molecular wires. This inference is then supported by three kinds of considerations: (i) Some of the bright spots (are taken to) have the same shape, size, and orientation, which indicates that the molecules that produce the spots are much sharper than the STM tip. This, in turn, is taken to support the conclusion that such spots stand for single molecules. (ii) Some of the bright spots on the surface of the STM images are significant larger than others. The researchers take them to be clusters of single molecules. These clusters are only observed at the gold substratum's step edges, a region in which the researchers expect that the single molecules would be more easily accommodated, and so it would be easier to form such clusters. (iii) The smaller bright spots (which are taken to be single molecular wires) are significantly separated on the terraces, and they occur for the most part at the structural domain boundaries. I will discuss each of these considerations in turn.

Bumm and collaborators note:

> We *infer* that these [bright topographic] features are due to *single* $\mathbf{1}'$ molecules because of the following observations: (i) Images of these features where the DT molecular lattice is resolved show that the *single* $\mathbf{1}'$ molecular features are imaged with exactly the same shape, size, and orientation, which are *indicative* of features that are much sharper than the STM tip. (Bumm *et al.* 1996, p. 1706; italics added.)

But there are problems with this argument. First, it is not clear that claim (i) is true. After all, an inspection of the STM empirical images reveals that the $\mathbf{1}'$ molecules are *not* imaged as having *exactly* the same shape or size in the relevant images. The molecules in question, as represented in the images, have at best and very roughly a *similar* shape and size. However, the argument to the effect that the molecules are much sharper than the STM tip relies crucially on the assumption that the bright spots on the empirical images have indeed *exactly* the same shape and size. After all, the idea is that these bright spots are ultimately artifacts of the STM, given that the latter is unable to resolve them. Second, even if $\mathbf{1}'$ molecules did have exactly the same shape and size in the relevant STM images, this fails to establish that the bright features in these images are the result of a *single* molecule rather than, e.g., a pair or a small group of such molecules. The presence in the STM images of spots with the same size and shape does not require the uniqueness of the underlying molecule. These spots can be accounted for by the presence of more than one molecule. What is needed here—but which is not provided in the paper—is the measurement of the size of the alleged single molecules in order to determine whether there is indeed a single molecule rather than a couple, or a small cluster, of such molecules in the relevant portions of the sample.

Two additional reasons to the effect that single molecular wires have been formed in the sample are then provided:

> (ii) Larger features (which we assign to clusters of $\mathbf{1}'$) are only observed at Au{111} step edges where the DT SAM is expected to be conformationally relaxed and the $\mathbf{1}'$ molecules would be more easily accommodated [...]. (iii) The $\mathbf{1}'$ molecules are observed to be widely separated on the terraces [...] and tend to occur at DT structural domain boundaries. (Bumm *et al.* [1996], p. 1706)

But there are also difficulties here. We can certainly grant that $\mathbf{1}'$ molecules are widely separated on the terraces and that clusters of such molecules are found at the step edges. An inspection of the STM empirical image supports that reading. However, the empirical image is still compatible with *small* clusters of $\mathbf{1}'$ molecules on the terraces and *larger* clusters of such molecules at the step edges. Given that these possibilities have not been ruled out, the intended conclusion regarding the presence of a single molecular wire—the *uniqueness* claim—has not been established yet.

Later in the paper, two additional arguments are offered in support of (i), and hence as reasons to believe in the uniqueness claim. The first argument expands on the discussion of (i) offered earlier in the paper:

> STM topographic images are a convolution of the tip and surface geometry. When features of the surface are much sharper than the tip, such as the $\mathbf{1}'$ single molecular protrusion about 7 Å higher than the DT film, *each molecule is rendered as an image of the tip*. This is shown schematically [in a diagram] and can be seen in the images of $\mathbf{1}'$ molecules [STM empirical images], where each appears *nearly* identical in shape, size and orientation. (Bumm *et al.* 1996, p. 1707; italics added)

However, there are problems with this argument too. First, the authors now acknowledge that the bright spots on the STM image are *artifacts*: the molecules are rendered as an *image of the tip* rather than of the molecules in question. And curiously Blum and collaborators invoke this artifact as a reason to conclude that single molecules are indeed involved, given that the protruding features on the surface of the sample are taken to be "much sharper than the tip" of the microscope. What needs to be established, however, is precisely *how much* sharper than the tip the protruding features actually are. If this point is not settled, it is still possible that *two* small molecules—rather than a single one—produce bright spots on the STM image. The resulting spots would be indistinguishable from those that are actually found in the STM empirical images under consideration. Moreover, the reference made in the quotation above to a diagram (see Bumm *et al.* 1996, p. 1707) that depicts schematically the situation involving the alleged single molecular wires clearly does not show (i.e. it does not establish) that single molecules have been formed. The diagram simply assumes the point in question.

The second additional argument for (i) addresses directly the possibility that a couple of molecules are involved. The argument runs as follows:

> If more than a single $\mathbf{1}'$ molecule were adjacent at the structural domains boundaries, each would contribute to the tunneling current. Thus the 'tip image' from such a feature would be repeated and overlapped in a characteristic way. This is rarely found at the structural domain boundaries on

> terraces but is commonly found for the **1**′ molecules at substrate step edges. (Bumm *et al.* 1996, p. 1707)

This is an important attempt to rule out the multiple molecules possibility—at least for the molecules located at the structural domain boundaries on terraces. However, the argument is far from conclusive. It presupposes that two adjacent **1**′ molecules, when combined in a cluster, can be precisely individuated by the STM tip, so that the resulting "tip image" is "repeated and overlapped in a characteristic way". But two adjacent **1**′ molecules can still be small enough to produce the artifact of a "tip image" rather than an image of the individual molecules under consideration. This possibility has not been effectively eliminated.

Given that none of the arguments that have been offered in support of the single molecule hypothesis seem to go through, I conclude that the experiment fails to establish the claim that just a *single* molecule is involved in the molecular wire. I am not challenging that the experiment has established the presence of a wire—even a significantly small one. After all, the STM does detect the currents in certain regions of the sample. The concern is whether a *single* molecular wire was in fact constructed, that is, that enough evidence has been provided to establish successfully this phenomenon. To show that such a phenomenon obtained was the major goal of the experiment. It is then safe to conclude that the latter failed to achieve what the researchers set out to do.

4.2. Visual evidence

Similarly to what happens in the DNA nanotechnology case, images also play a significant role in this research. However, STM empirical images are used at best as indirect evidence that a single molecular wire has been devised. These images cannot be used as independently standing pieces of evidence for the success of the relevant construction, given that a particular reasoning is required to establish how the images in question should be interpreted.

As opposed to what happened in the DNA nanotechnology case, the transparency requirement does not seem to be in place in the single molecular wire study. The researchers realized that the STM empirical images were not sufficient to establish, on their own, the presence of a single molecular wire, and they offered additional considerations as to how exactly these images should be interpreted. But, as we saw, it is unclear that these considerations successfully rule out a relevant alternative interpretation of the STM images that is incompatible with the single molecular wire hypothesis (namely, that only clusters of molecular wires are present in the sample).

Note also that it is not clear that we know that the counterfactual dependence condition (discussed above) is in fact met in the STM case. Recall that, according to that condition, had the sample been different (within the microscope's sensitivity range), the image produced by the microscope would have been correspondingly different. As just noted, if the sample contained only clusters of molecular wires—some small, some large, but without the presence of any single molecular wires—the resulting images need not be different from the STM empirical images that have in fact been obtained. Thus, it is unclear that we are in a position to know that the counterfactual dependence condition has been met. This raises a concern about the reliability of the STM in this case.

Despite this concern, the search for visual evidence is crucial in this experiment. In the end, one worries as to whether there is enough evidence to believe that the phenomenon under consideration—the presence of a single molecular wire—has indeed been created. Although the resulting STM empirical image is visually striking—and it does seem to display at least some of the visual features researchers expected—it is still unclear whether it does establish what is really going on in the sample. In this sense, one may take the evidence in question to be at least, and perhaps at best, partial. The trouble, however, is that the empirical STM images are compatible with the negation of the intended result. Given that there are legitimate interpretations of the STM image in which the intended conclusion does not hold, the STM evidence can be legitimately challenged, given that it does not seem to offer reason to believe that a single molecular wire has been created.

In the end, the visual evidence presented is far from conclusive. Despite the lack of success in this particular case, the search for significant visual evidence is a common feature that the research on molecular wires shares with the DNA nanotechnology work. Perhaps with additional information, and better instruments, less partial visual information and more positive results can be obtained in the future.

5. Conclusion

If the account sketched here is near the mark, a conception of visual evidence that makes room for partiality can also be articulated. By offering progressively less partial information, visual evidence can, in some cases, offer significant support for a given hypothesis: Palade's case for ribosomes illustrates this point (see Bueno 2008). In other cases, more information may be needed to establish the result (as in the DNA nanotechnology case), or an entirely different approach may be required (as in the molecular wire case). This is as it should be. In science, as elsewhere, partiality is the norm rather than the exception.

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Resumo. Newton da Costa e Steven French têm argumentado que o conceito de verdade parcial desempenha um papel importante na compreensão de aspectos significativos da prática científica, incluindo o estatuto das teorias científicas, a compreensão das inconsistências em ciência, e a natureza da indução (da Costa e French 2003). Nesse artigo, emprego o conceito de verdade parcial e a abordagem baseada em estruturas parciais para apresentar uma formulação do conceito de evidência visual. e examino algumas funções que essa noção desempenha na atividade científica.

Palavras-chave: Verdade parcial; evidência; evidência visual; visualização; transparência.

Notes

[1] It is truly a pleasure to offer this paper to Professor Newton da Costa to celebrate his 80th birthday. Few people can pack well over 120 years worth of novel ideas, theories, and results in about 60 years of original work. In fact, most people cannot even work so creatively and productively for that long! But when someone like him reaches 80 years with the enthusiasm and energy of a 20 year old, and the wisdom of a great master, we all realize that the world is a better place because he is part of it. And we can only appreciate our fortune for being there for (some of) the ride—and what a ride! My thanks go to him for all he has taught me, continues to teach me, and will, no doubt, teach me in the future. The inspiration and support he has given, the challenges he has raised, and specially his true friendship are such wonderful gifts that no paper can even begin to repay. As we would say in Portuguese: "Muito obrigado, Professor Newton!"

[2] Further details about the approach can be found, e.g., in da Costa and French 2003, Bueno, French, and Ladyman 2002, and Bueno 1997.

[3] The partiality of partial relations and structures is due to the incompleteness of our knowledge about the domain under investigation. With additional information, a partial relation can become a full relation. Thus, the partialness examined here is not ontological, but epistemic.

[4] For simplicity, I'll take the partial relations in the definitions that follow to be two-place relations. The definitions, of course, hold for any n-place relations.

[5] A partial function is a function that is not defined for every object in its domain.

[6] Microscopes provide visual evidence just in case we know that they satisfy two conditions introduced below (mechanization of image formation and counterfactual dependence).

[7] For a discussion of Palade's work in the context of an empiricist account of scientific representation, see Bueno 2008.

[8] I discuss these case studies in Bueno 2011, where they were put to a different use.

[9] The protruding "sticky ends" possibly attach to other molecules in the environment, and this may help the resulting crystals to become stable.

[10] I am adapting here to the case of probe microscopy some of the discussion about photographic realism in aesthetics. For a fascinating discussion of the latter, see Walton 2008, particularly Chapters 6 and 7.

[11] Bas van Fraassen has emphasized the importance of coding conventions in the production and interpretation of images (see, in particular, Sigman and van Fraassen 1993; a broad discussion of scientific representation is developed in van Fraassen 2008). Although van Fraassen hasn't discussed images produced by probe microscopes, coding conventions are clearly important in this context as well, for the reasons indicated in the main text.