Perceiving Nanoscale Phenomena: Interpreting and Disseminating Nanoscale Images

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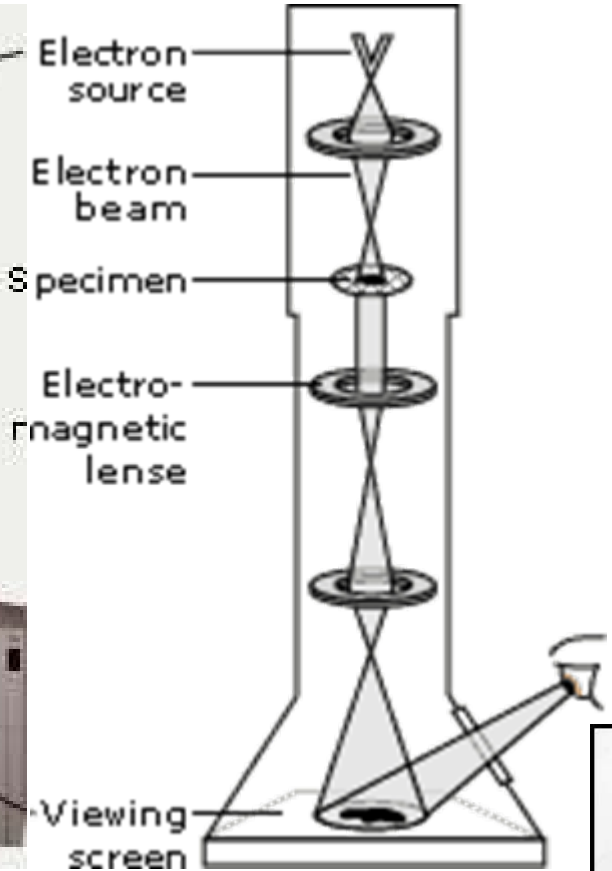
The problem

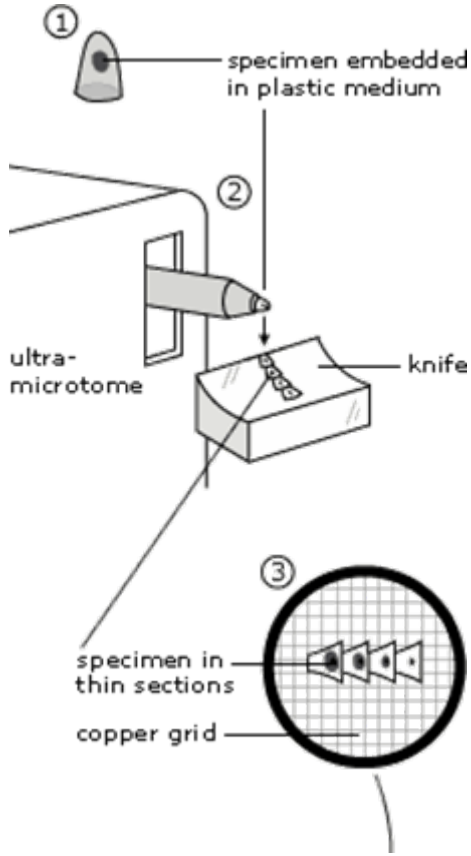
- Physicists, chemists, and biologists often describe the results of experiments that use various kinds of microscopes in terms of “observation”.
- Given the unobservable nature of some the objects that are studied (nanoparticles, viruses, bacteria), one wonders how we should make sense of this way of speaking.
- Underlying this way of speaking is a particular cluster of views regarding the reliability and adequacy of microscopes.
- In this talk, I try to uncover key assumptions that may be in place, and discuss whether we have good reason to maintain them.
- I’ll also suggest a framework to help interpreting and disseminating nanoscale images.

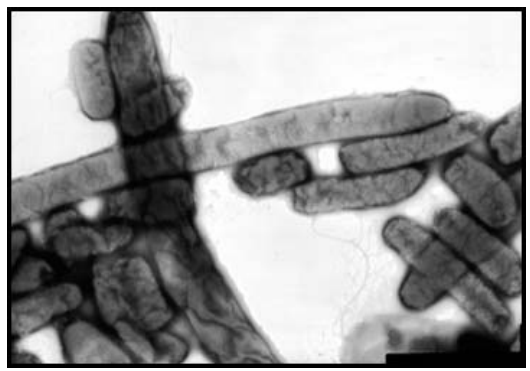
The microscopes

- The microscopes I'll discuss follow under two categories:
- (A) Electron microscopy:
  - Transmission electron microscope (TEM);
  - Scanning electron microscope (SEM).
- (B) Probe microscopy:
  - Scanning tunneling microscope (STM);
  - Atomic force microscope (AFM).

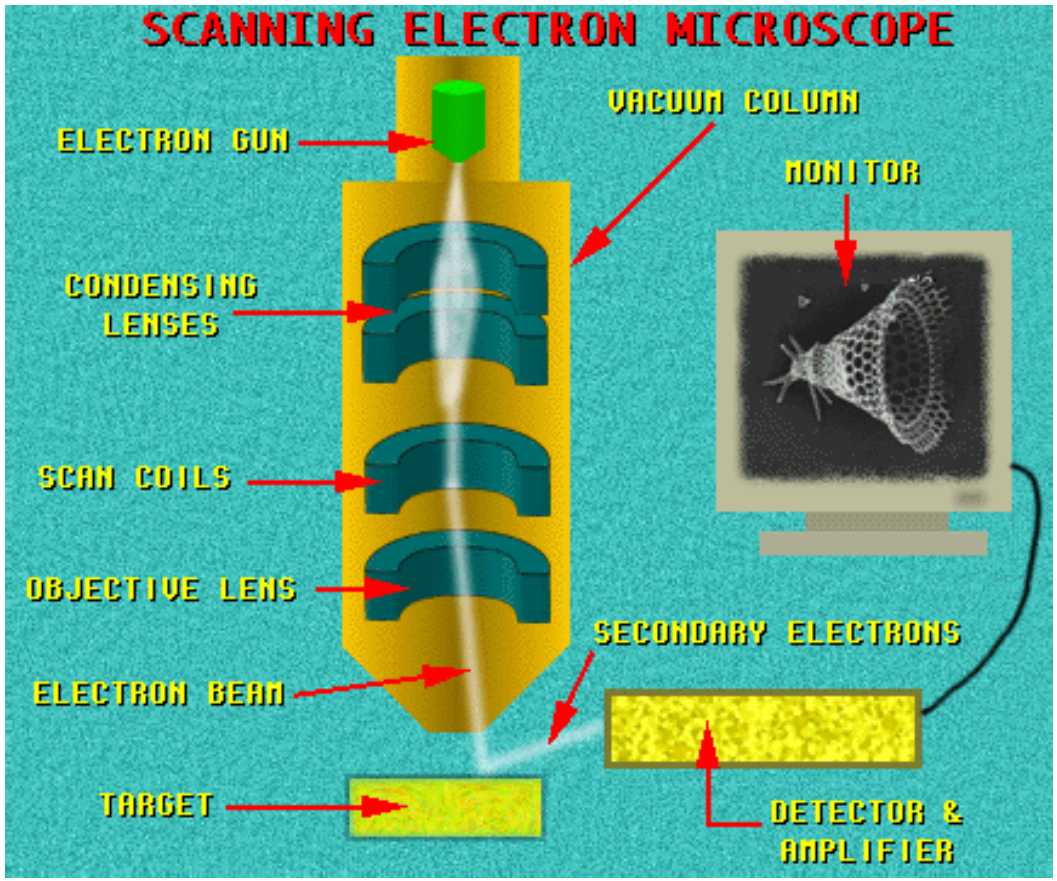
(A1) Transmission electron microscope

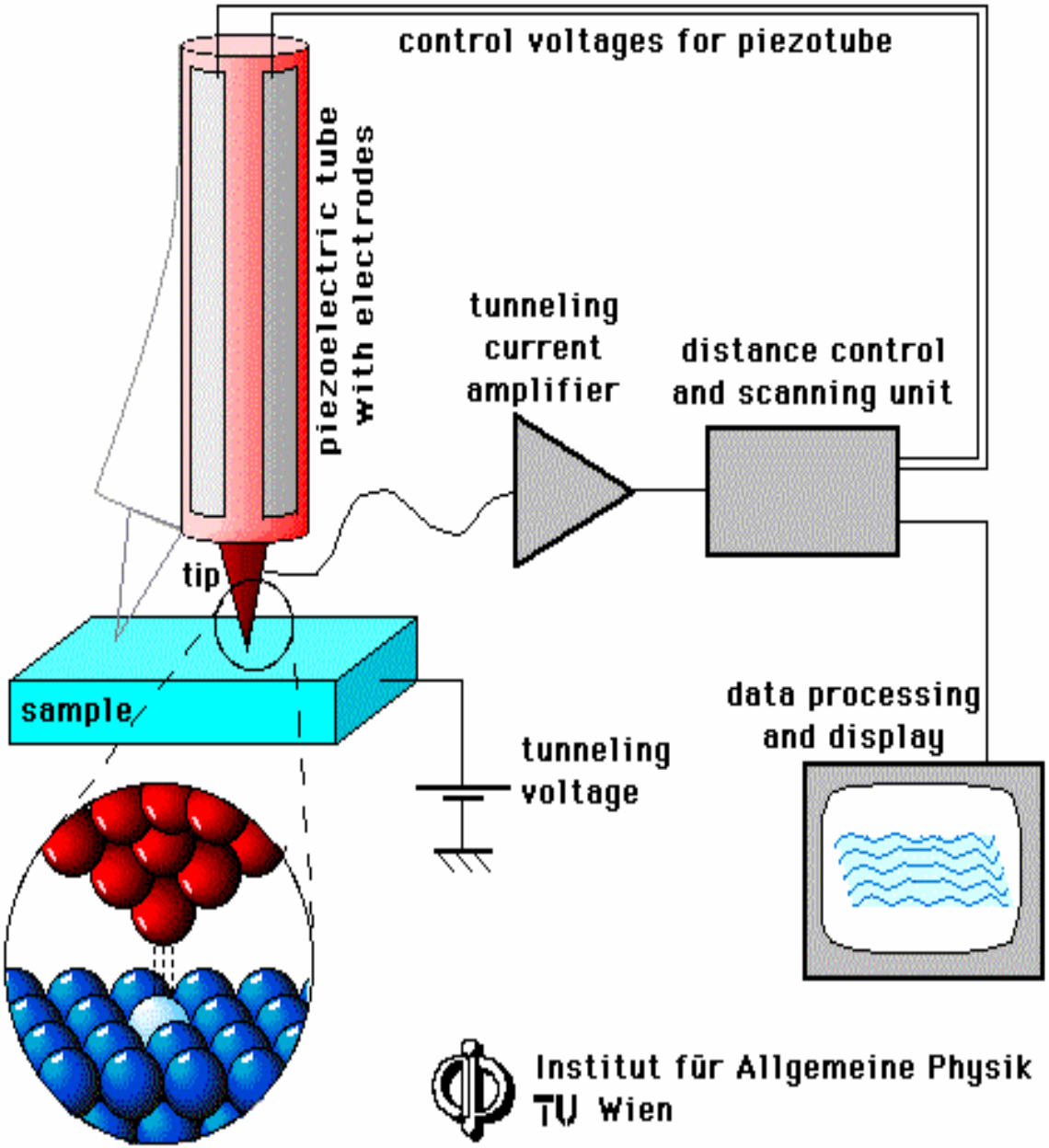






(A2) Scanning electron microscope

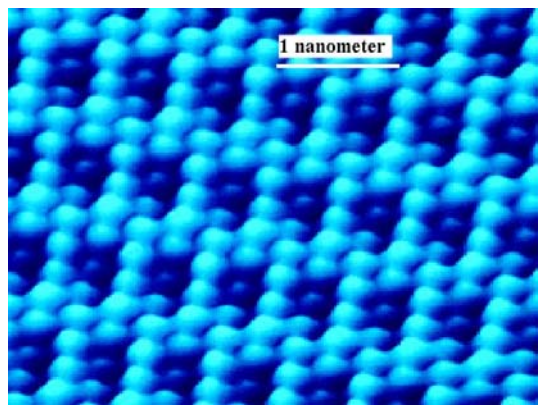




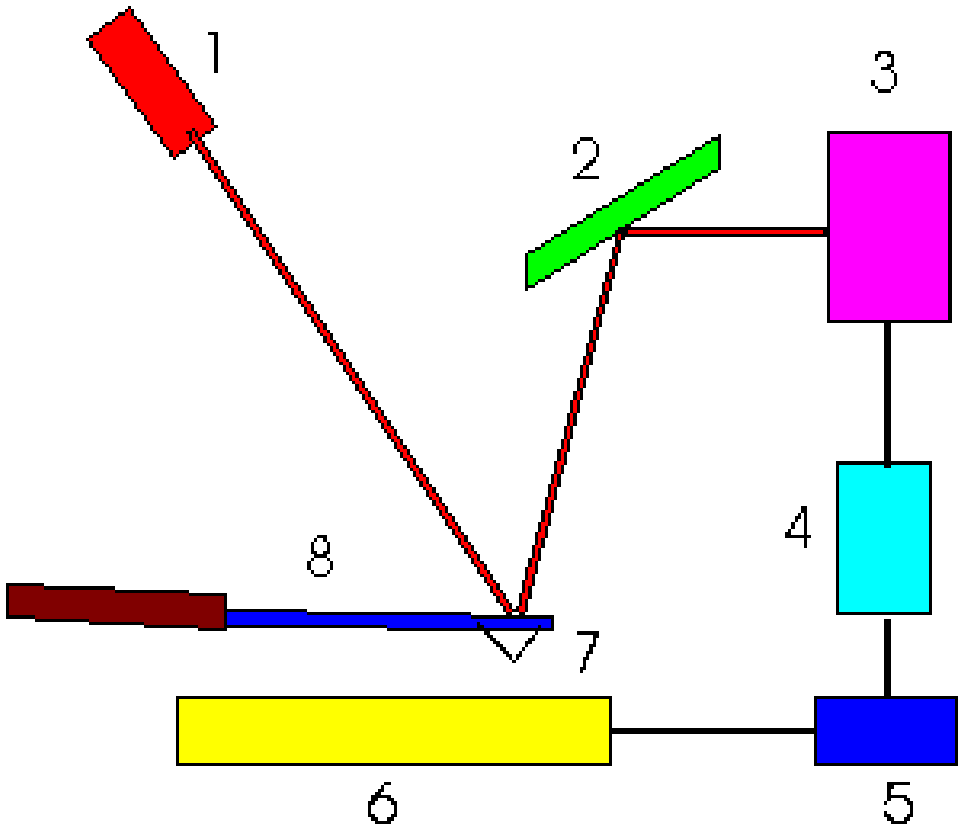
(B1) Scanning tunneling microscope

It was developed in the early 1980's by Binnig & Rohrer.

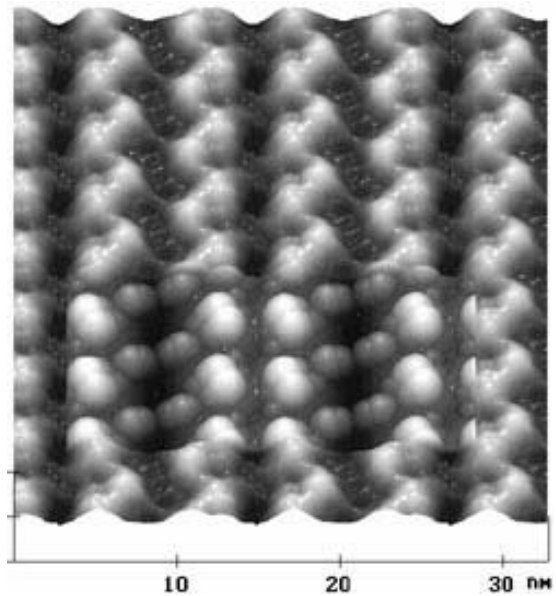
They received the 1986 Nobel Prize in physics for their work.

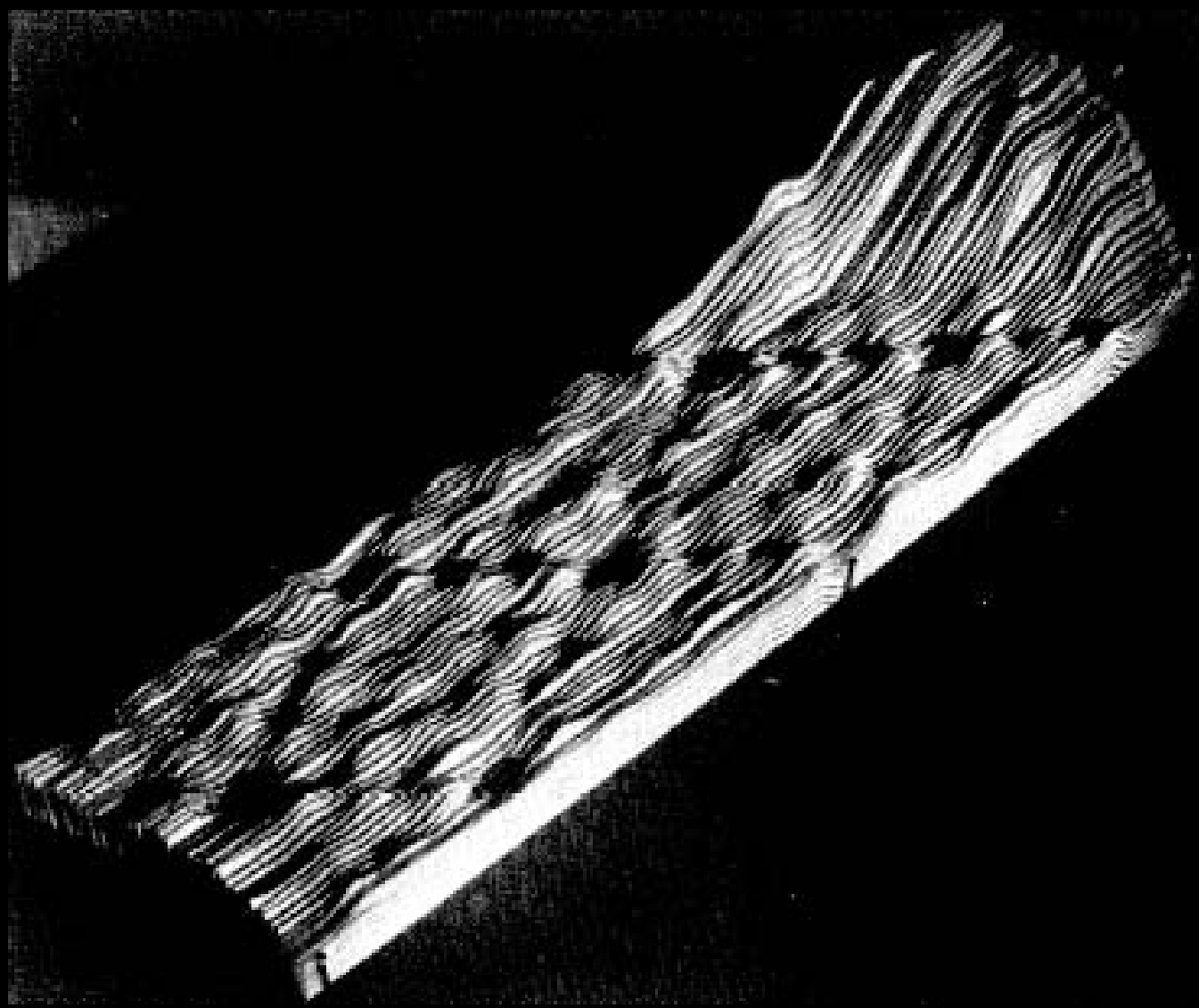


(B2) Atomic force microscope



1. Laser
2. Mirror
3. Photodetector
4. Amplifier
5. Register
6. Sample
7. Probe
8. Cantilever





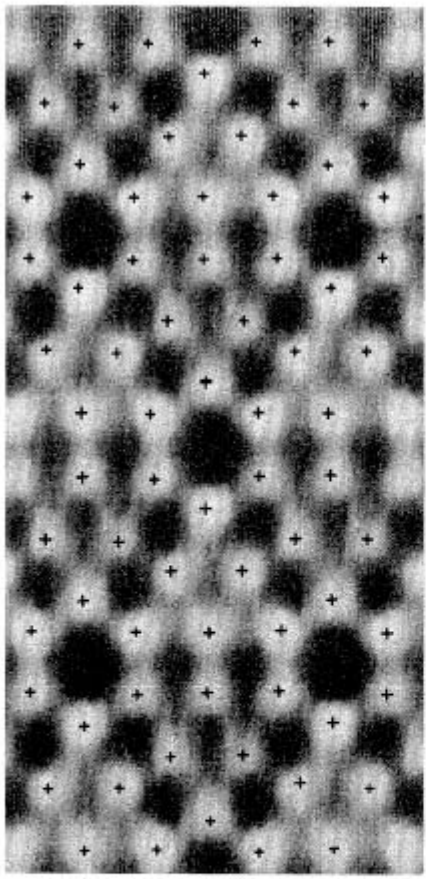


FIG. 2. Top view of the relief shown in Fig. 1 (the hill at the right is not included) clearly exhibiting the sixfold rotational symmetry of the maxima around the rhombohedron corners. Brightness is a measure of the altitude, but is not to scale. The crosses indicate adatom positions of the modified adatom model (see Fig. 3) or "milk-stool" positions (Ref. 5).

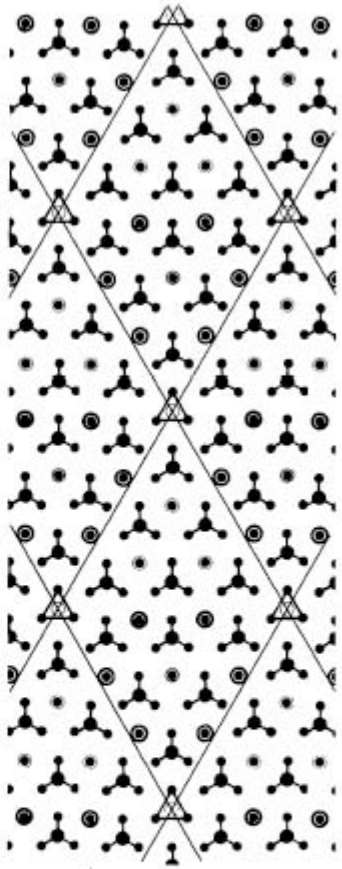
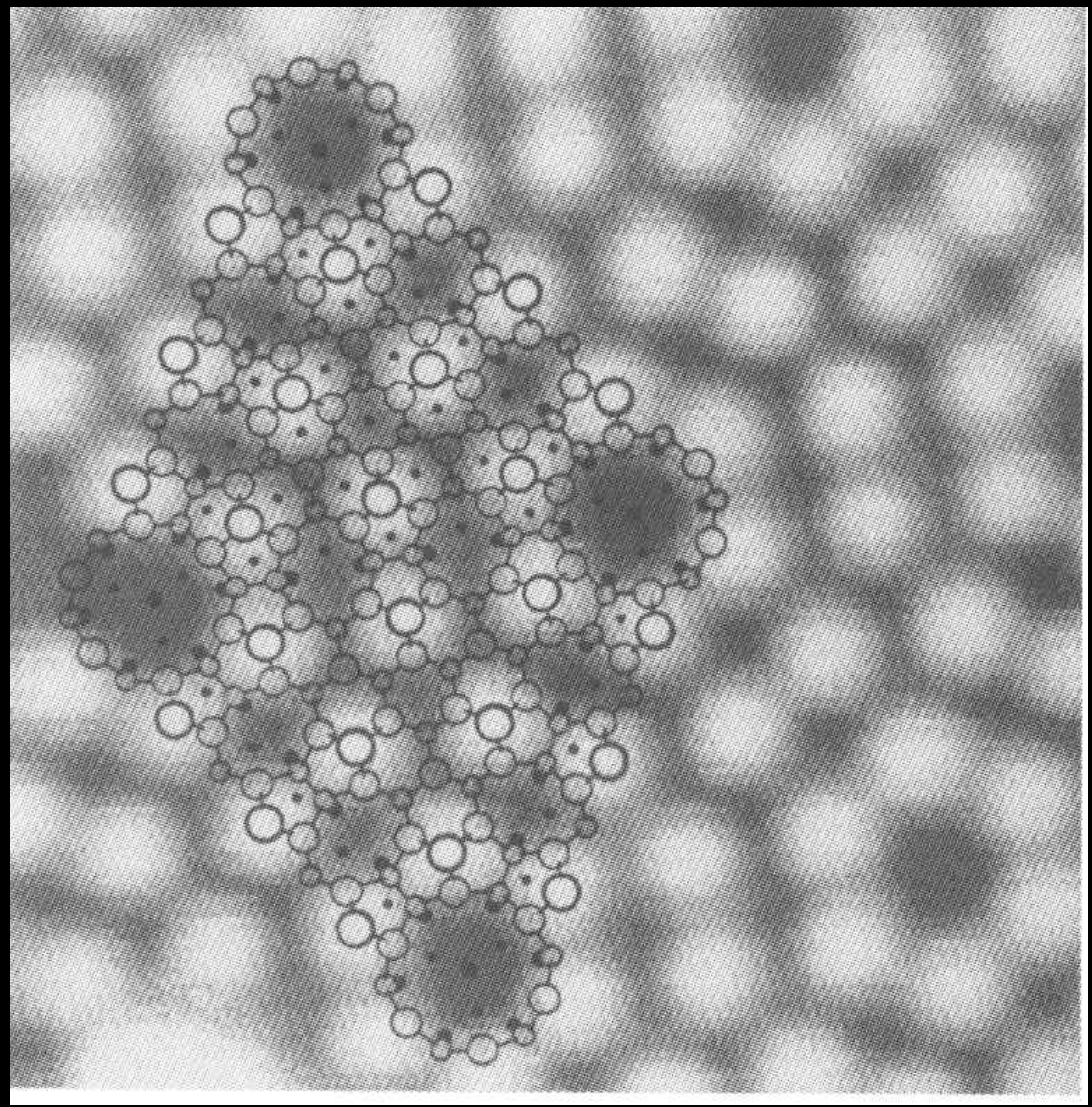


FIG. 3. Modified adatom model. The underlying top-layer atom positions are shown by dots, and the rest atoms with unsatisfied dangling bonds carry circles, whose thickness indicates the depth measured as discussed in the text. The adatoms are represented by large dots with corresponding bonding arms. The empty potential adatom position is indicated by an empty circle in the triangle of adjacent rest atoms. The grid indicates the 7×7 unit cells.



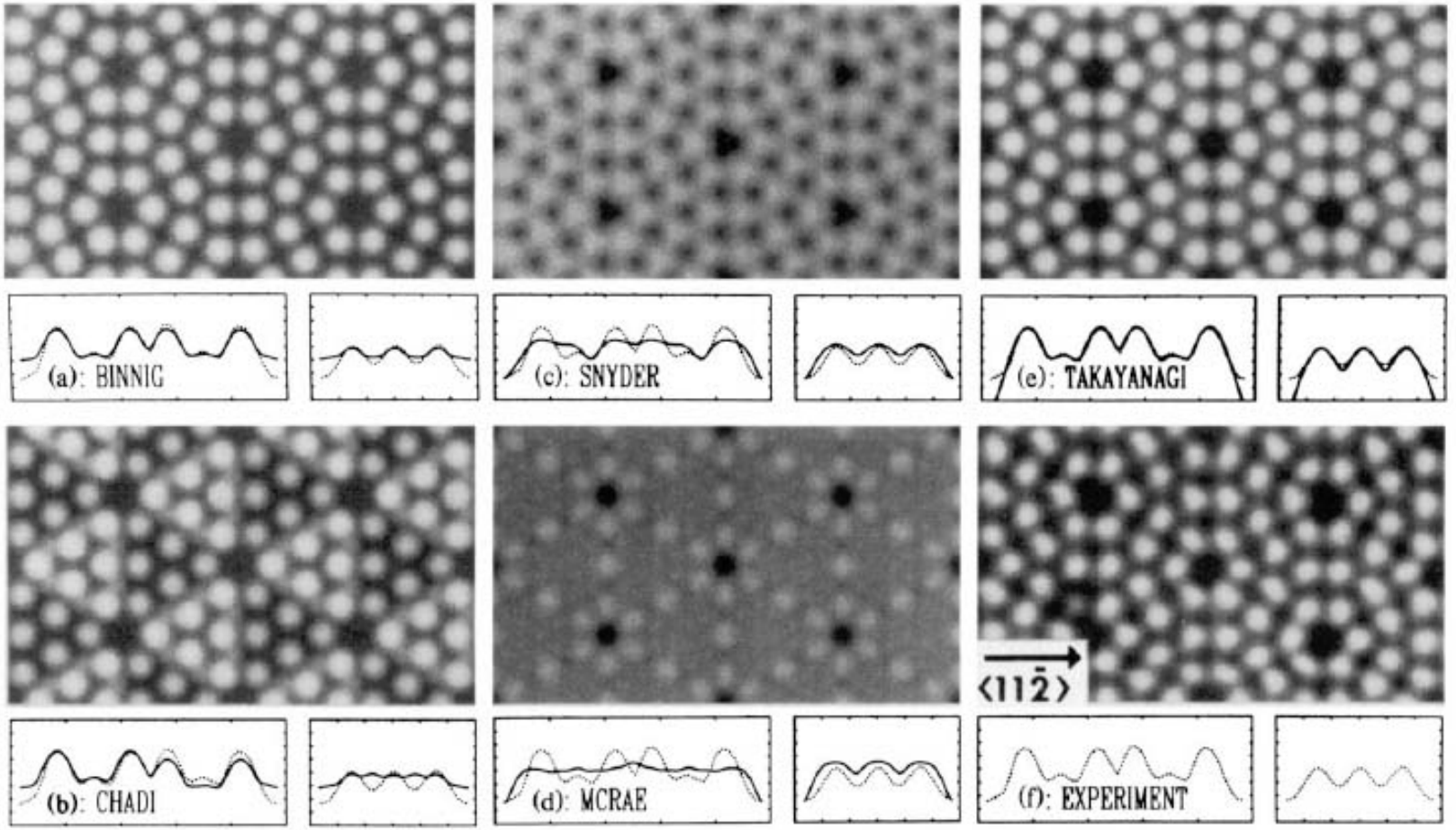
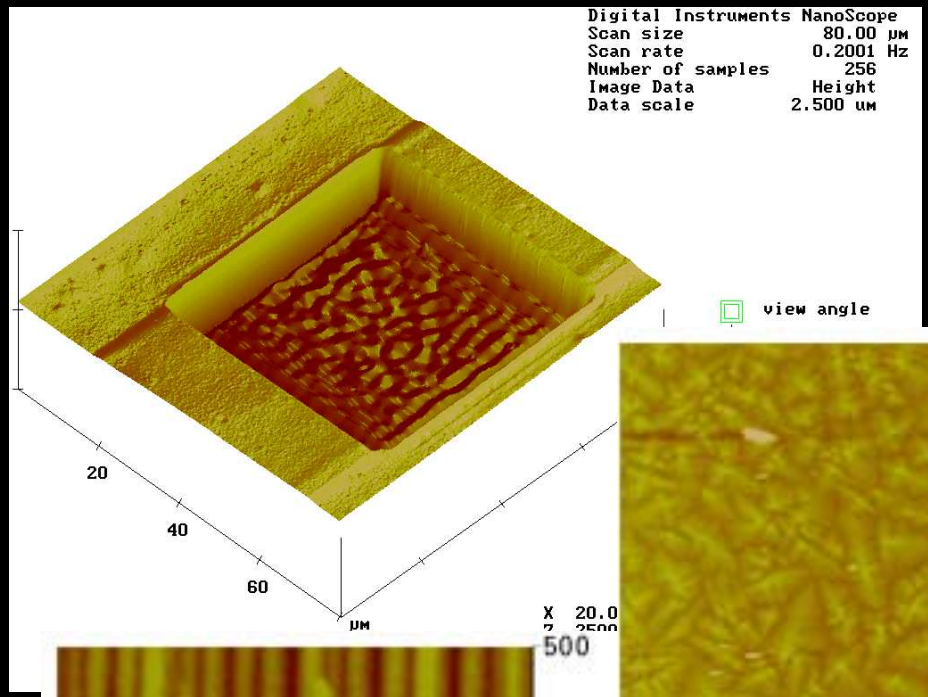
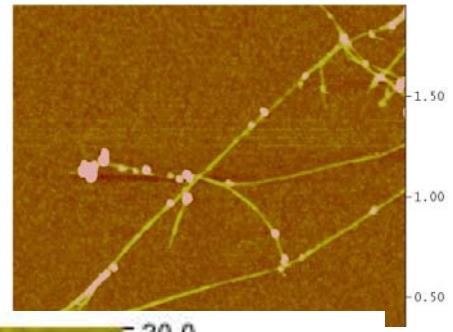
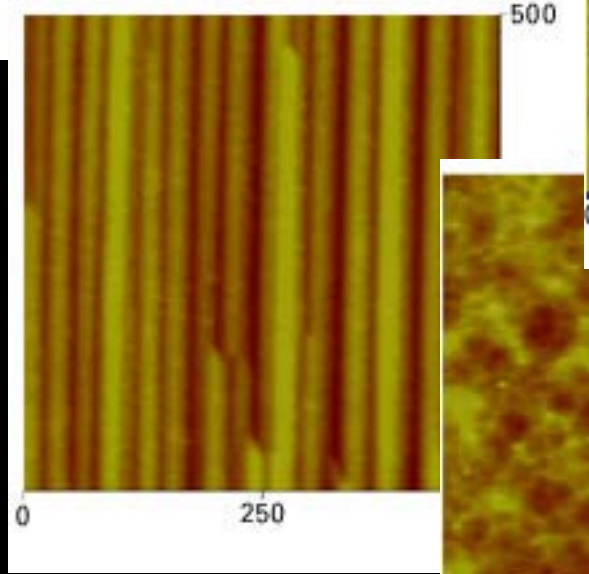
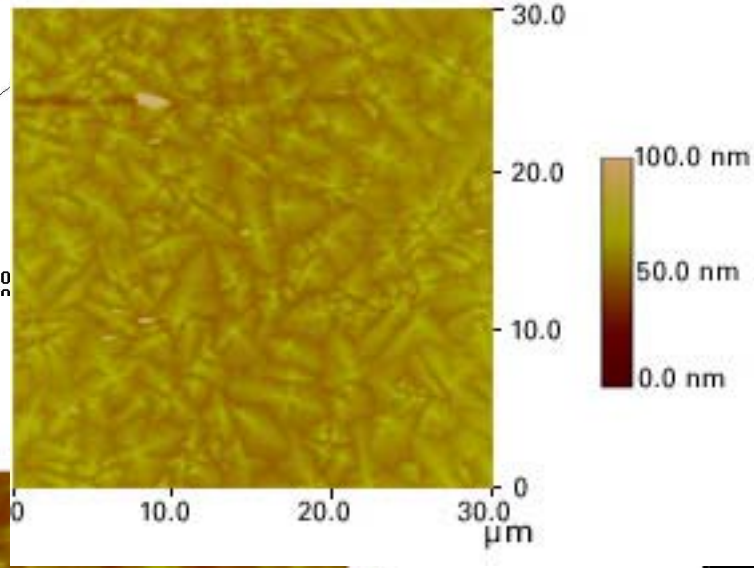


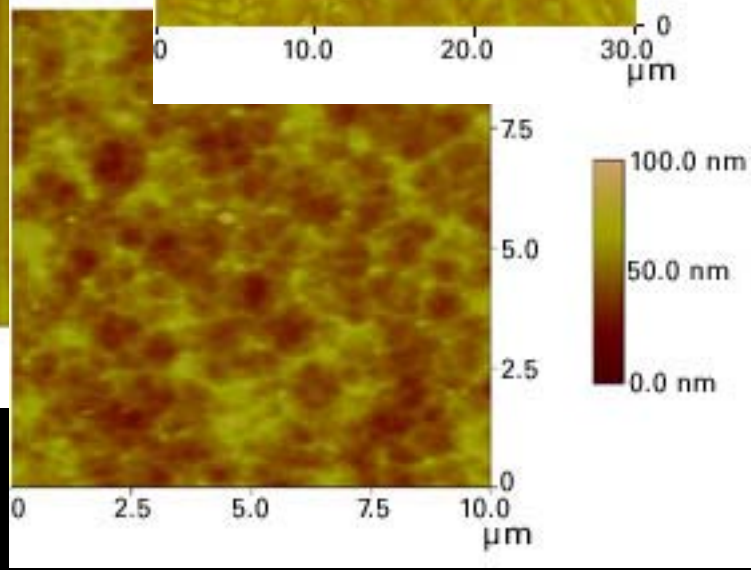
FIG. 2. (a)–(e) STM images calculated for (a) Binnig's model, (b) Chadi's model, (c) Snyder's model, (d) McRae's model, and (e) Takayanagi's model. (f) Measured STM image. The line scans run from corner hole to corner hole along the long (left) and short (right) diagonal of the (7×7) unit cell. The vertical range in these line scans is 4 Å. Solid lines are calculations, dashed lines represent the experimental results.











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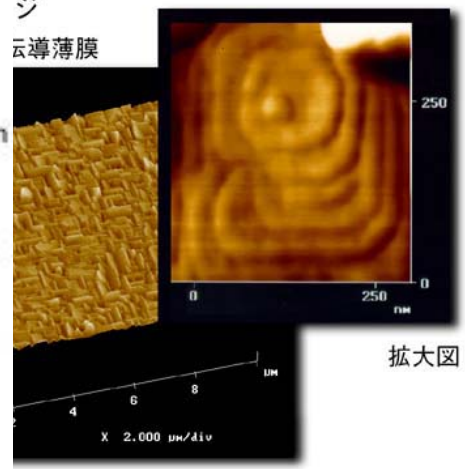
伝導薄膜



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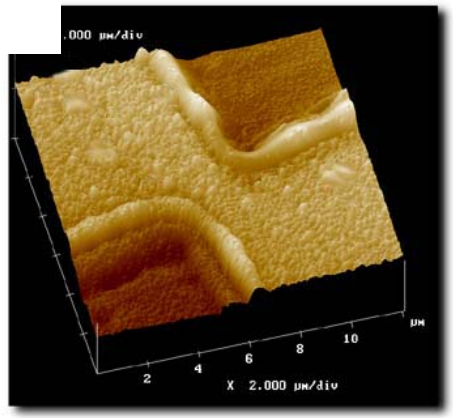
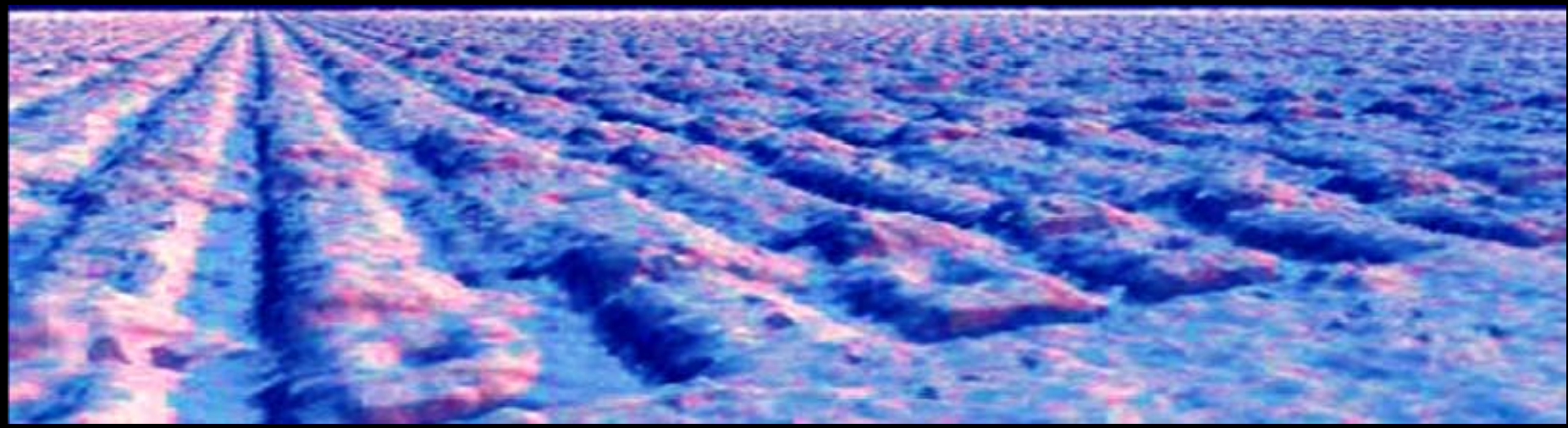
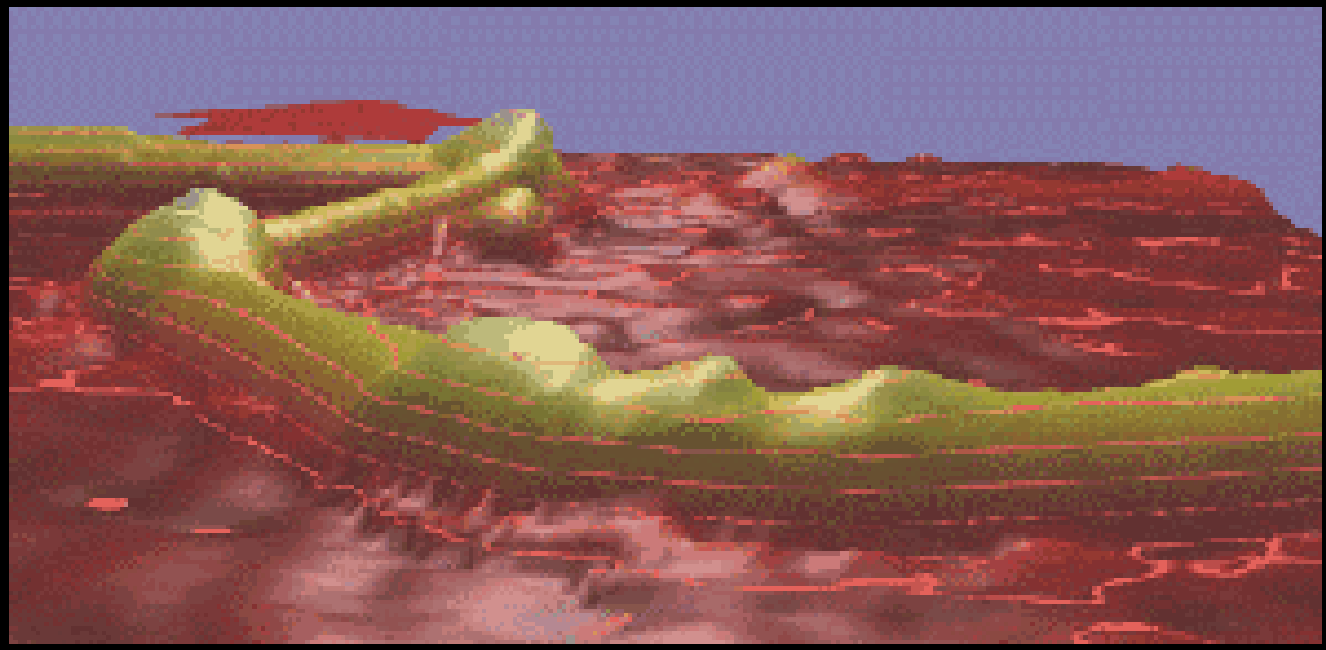
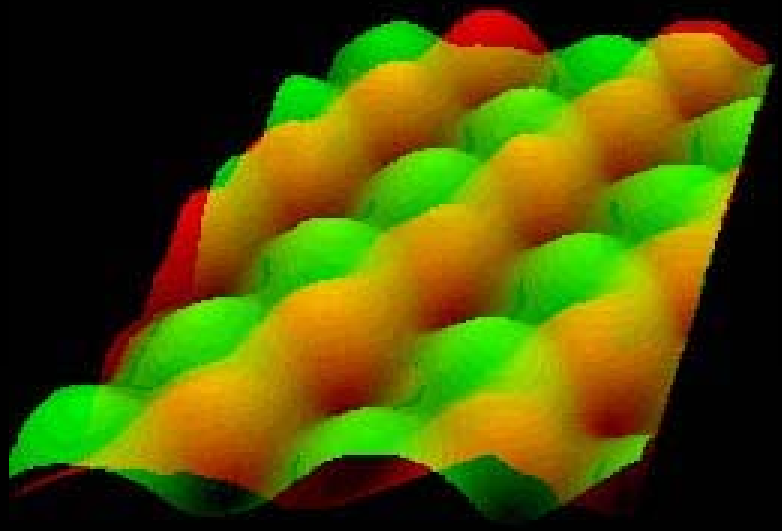


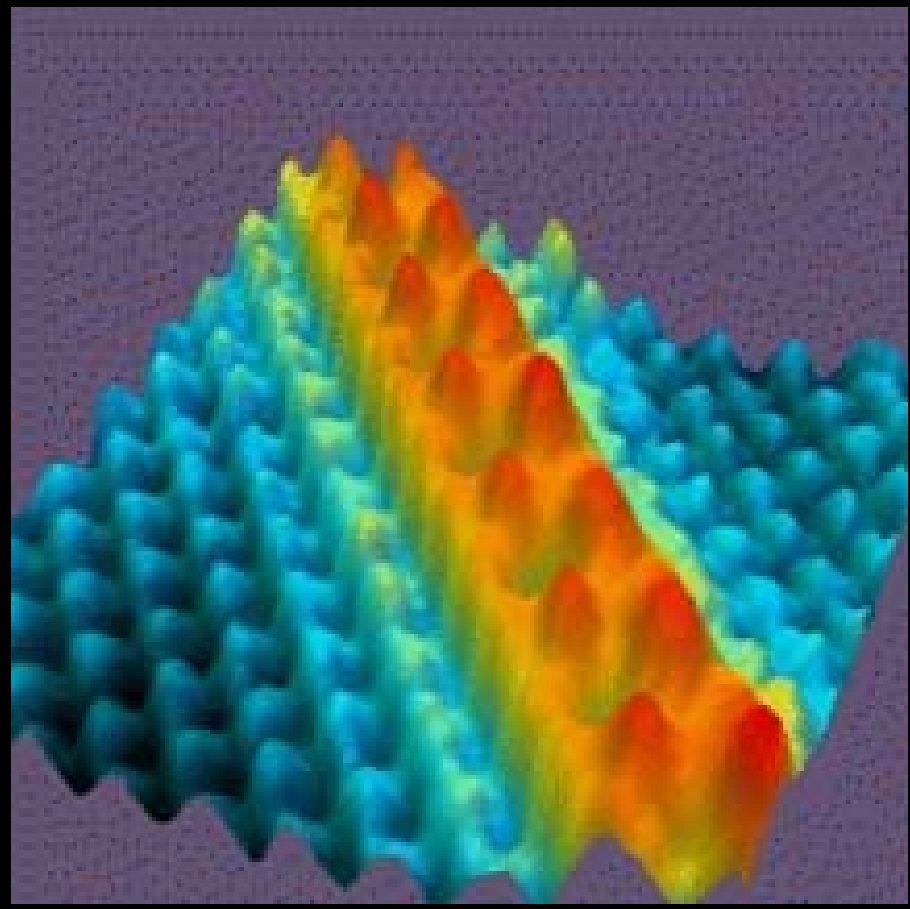
エキシマレーザ微細加工例

ビスマス系超伝導薄膜









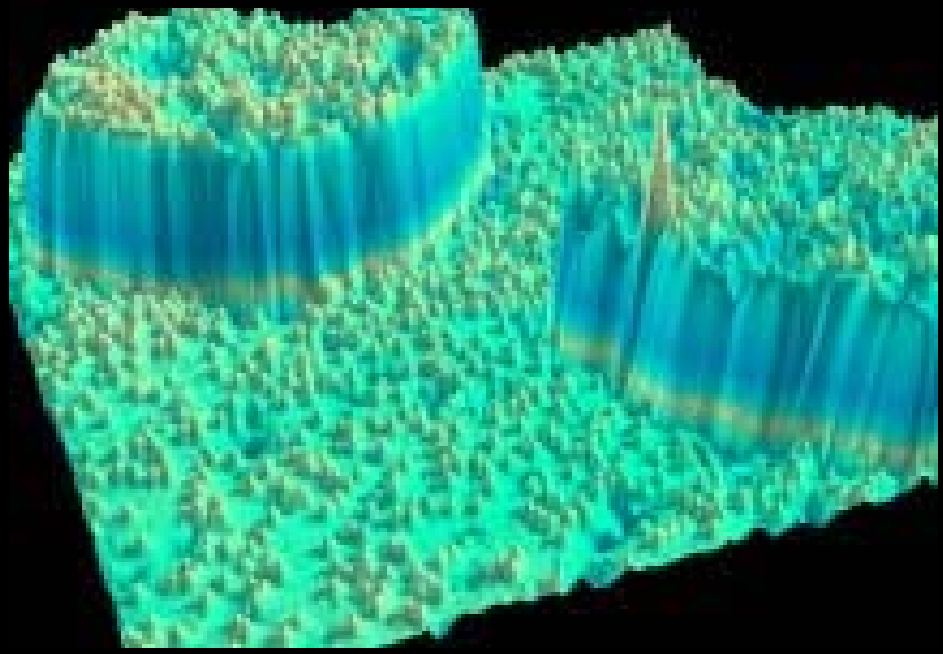
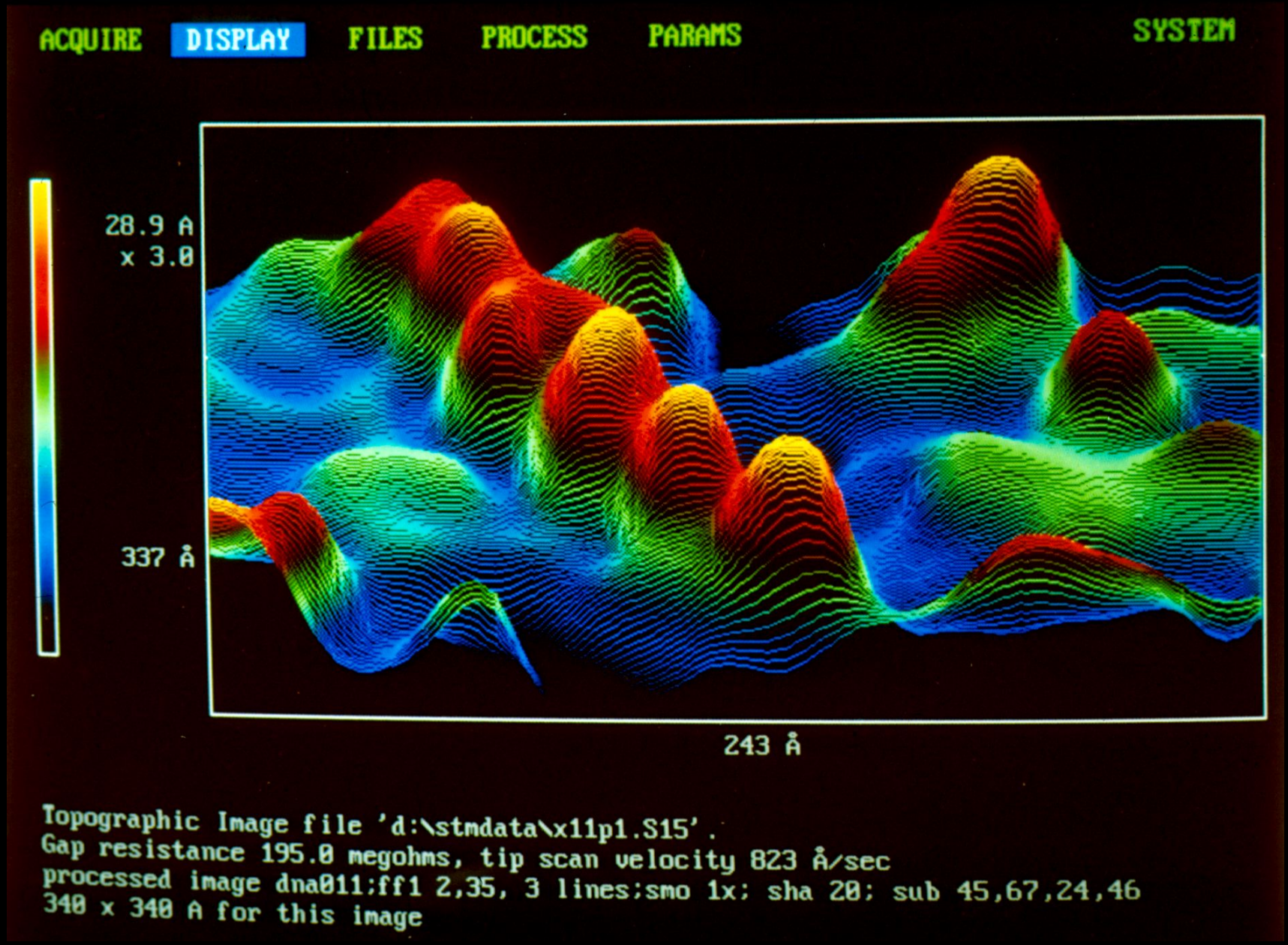
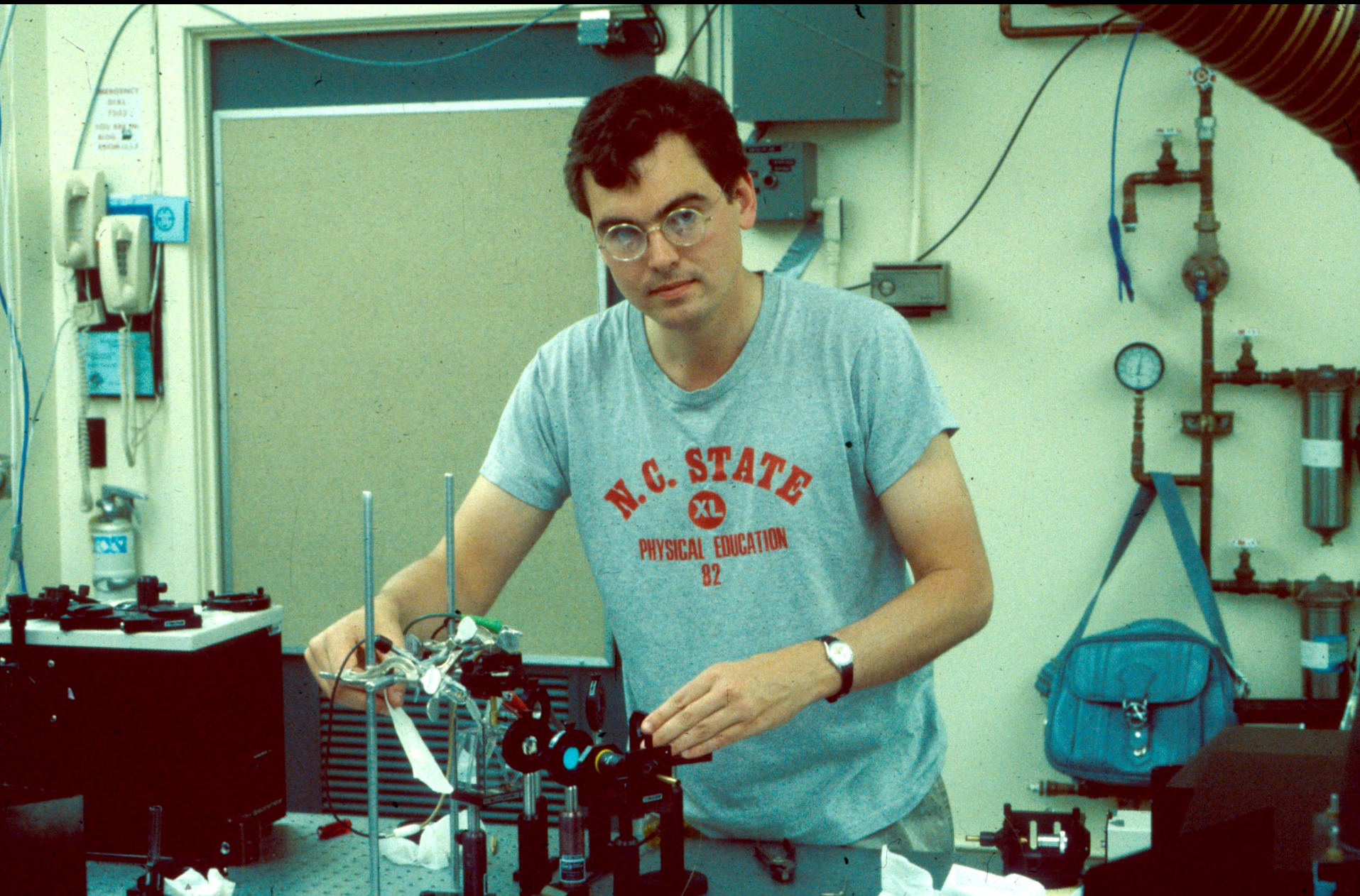


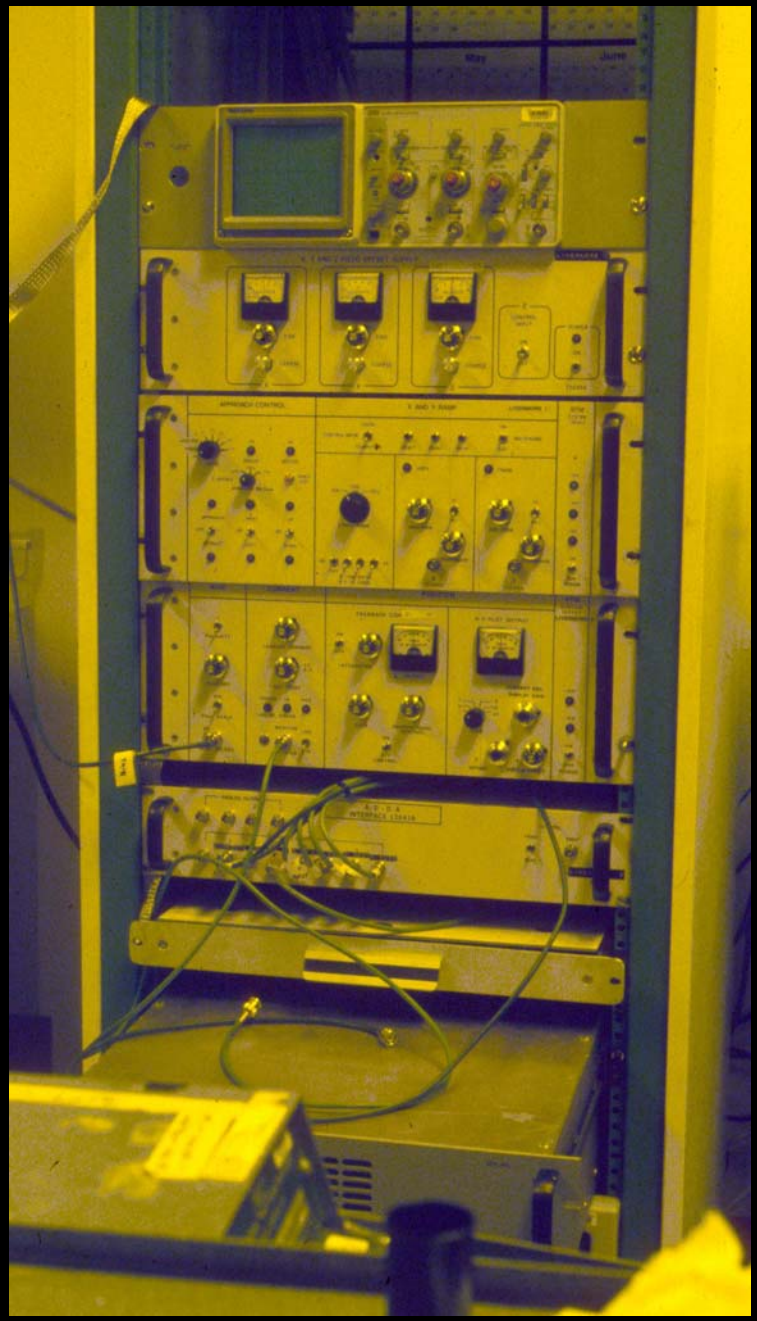
Image of a 5-turn DNA segment published in *Popular Science* (Seikhaus *et al.*, 1989).



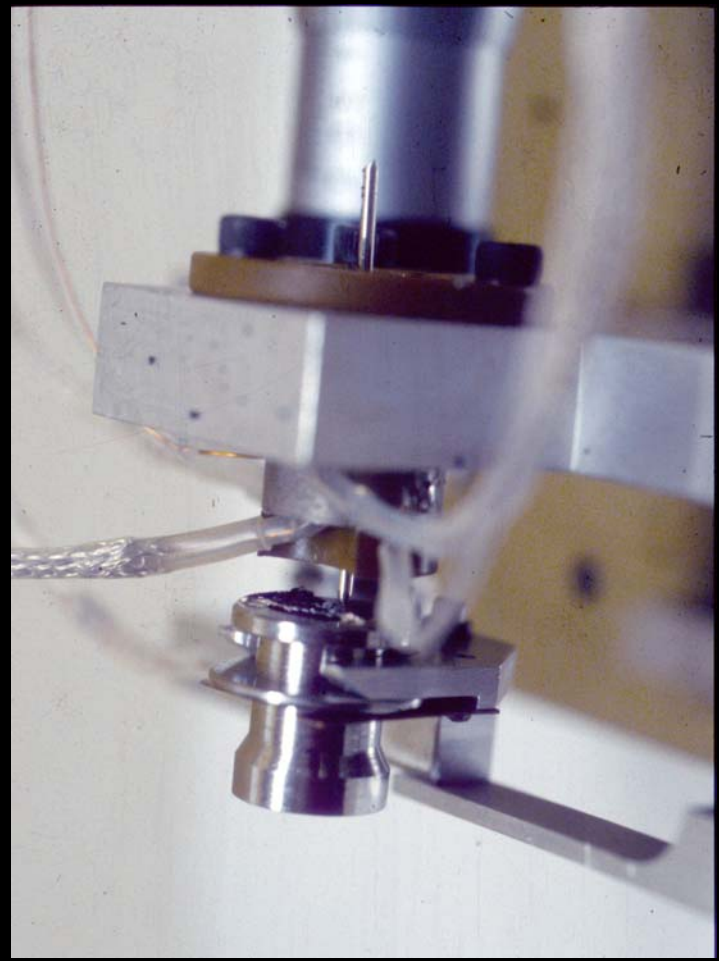
(Of course, the image
was published sideways.)

A few years earlier, a young postdoc, Michael Myrick, learned about STM.



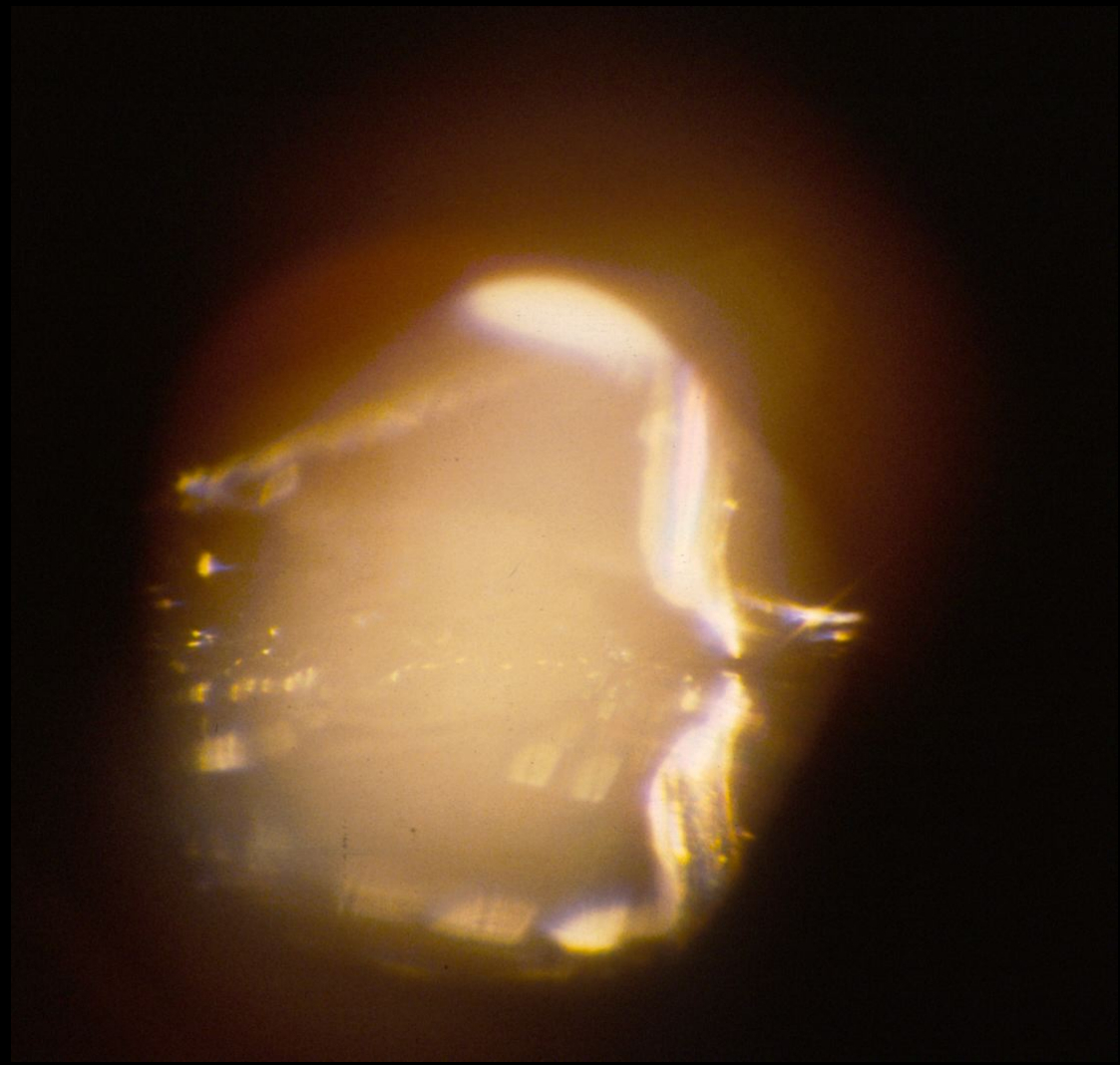


Myrick’s homebuilt STM.

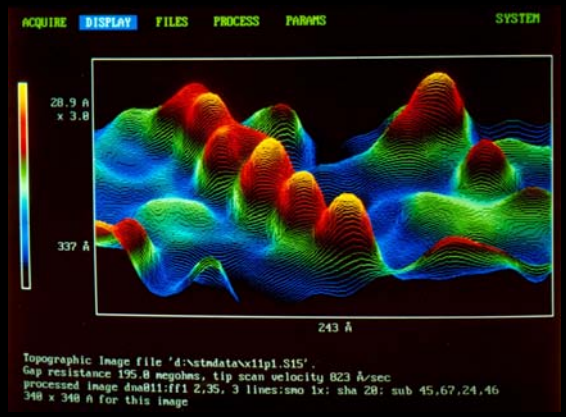


Beware: sharp tips!

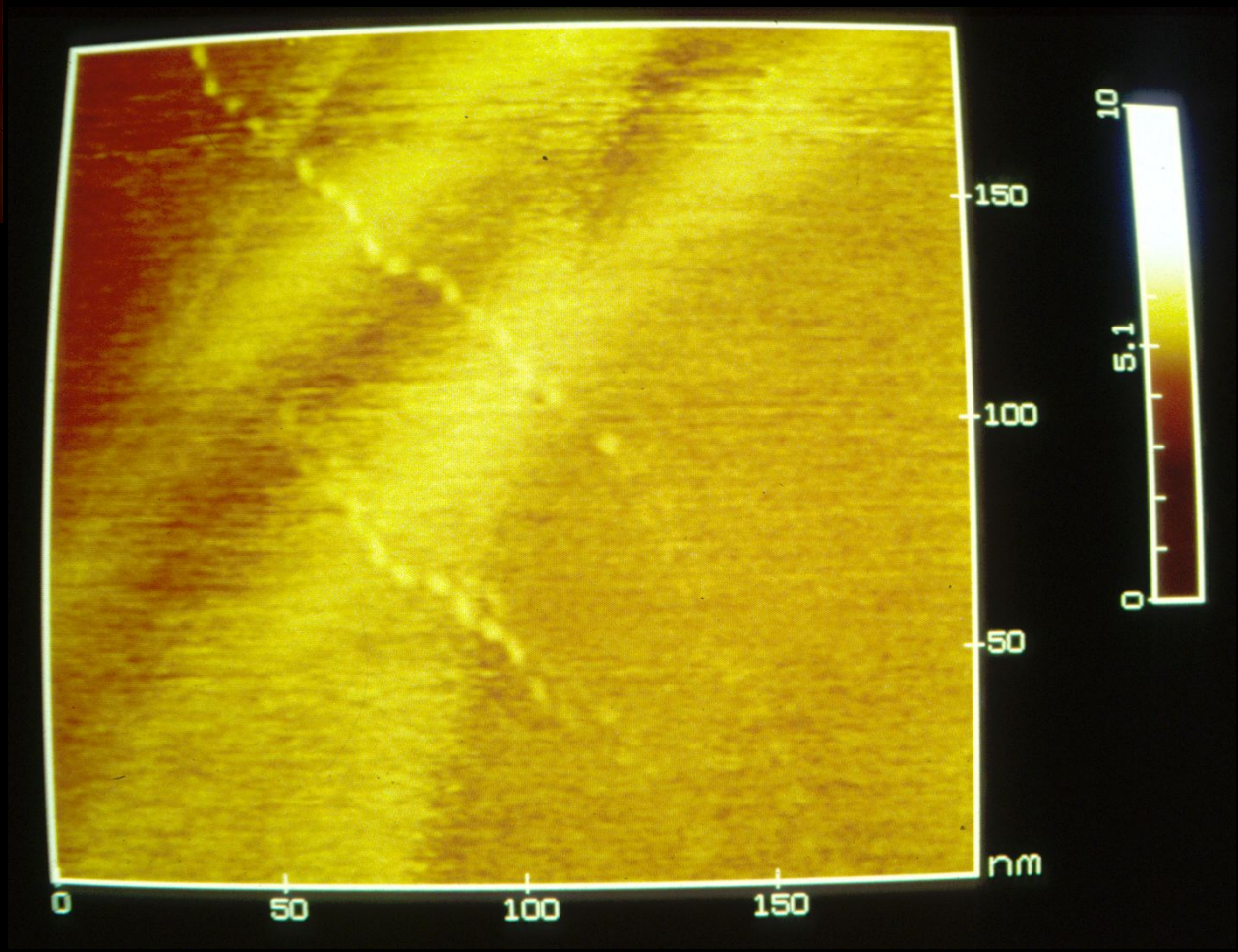
View of an STM tip approaching a surface.

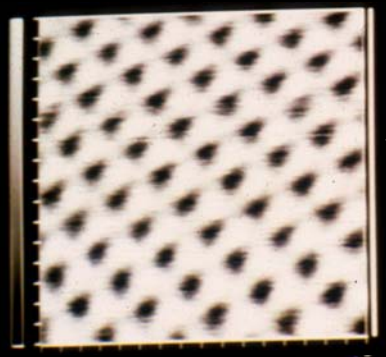


Myrick’s picture of DNA

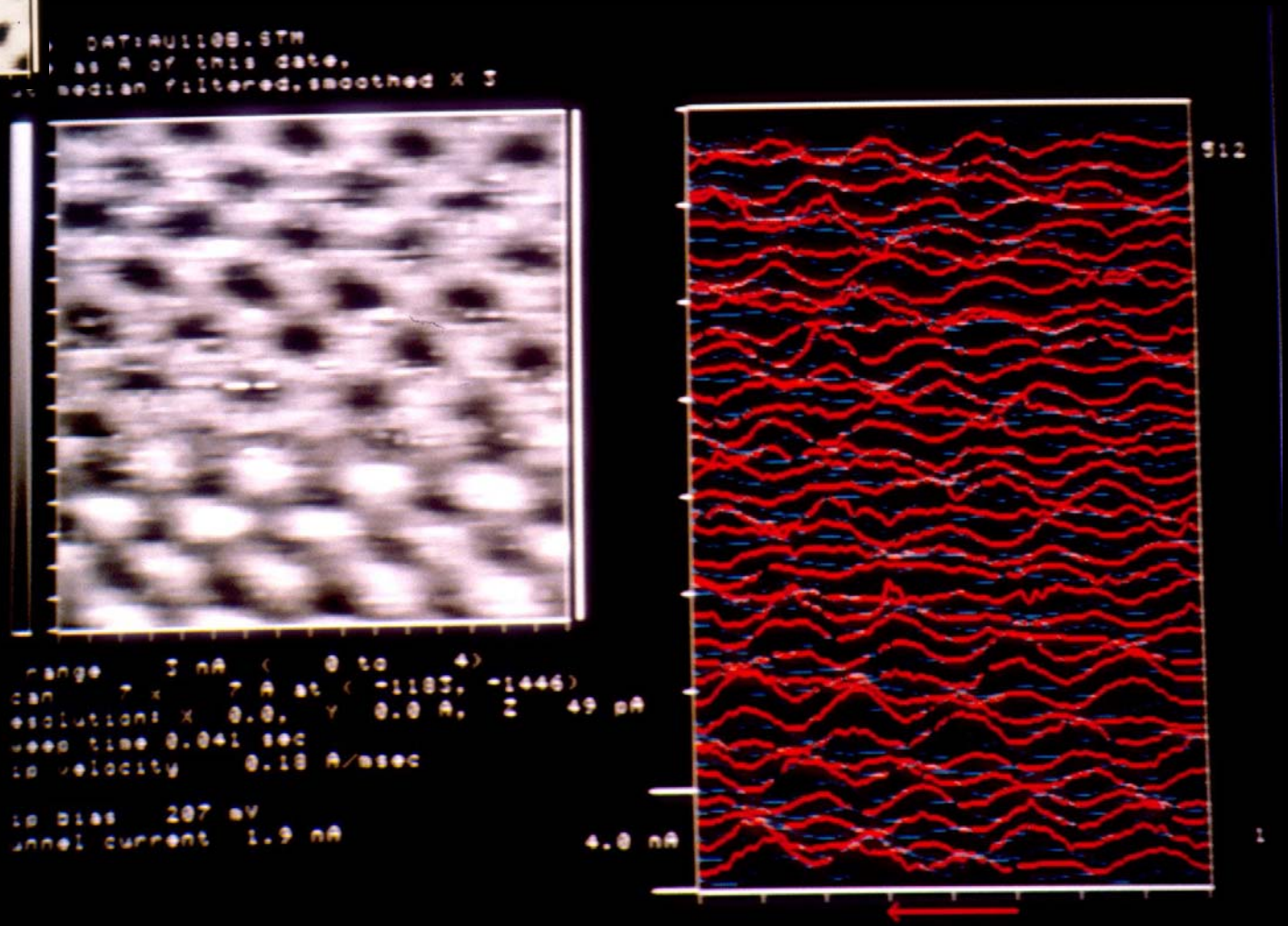


It’s better than the *Popular Science* image, isn’t it?





Symmetry is sometimes in the eye of the beholder.



So, beware what you search for.

You may find it!

Interpreting nanoscale images

- The interpretation of nanoscale images demands attention to some details:

(a) Kinds of nanoscale images:

- How was the image obtained (e.g., via probe microscopy, electron microscopy)?
- Which sort of information is the image intended to convey (e.g., information about the surface, or the inner structure of the sample)?

(b) Possible sources of bias:

- What kind of artifacts may be included in the image?
- For example, are there artifacts regarding the image's content (that is, does the image correctly capture its target)?

Interpreting nanoscale images

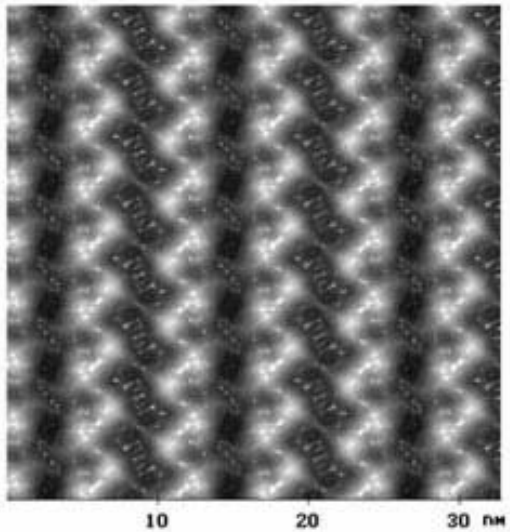
(c) Inferential devices:

- Nanoscale images are often used as exemplars in the domain from which they emerged.
- How can such images be used as inferential devices that allow researchers to generalize the information provided in a particular image to other samples (whether in the same domain or in related ones)?

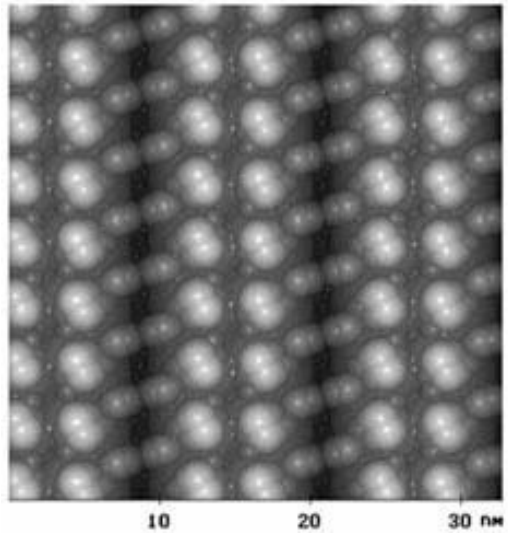
(d) Convention codes:

- To interpret a nanoscale image, it's crucial to be able to identify the convention codes that are in place (e.g., what do colors, shapes, and brightness in the image stand for?).
- Unless convention codes are specified, misunderstandings can emerge.

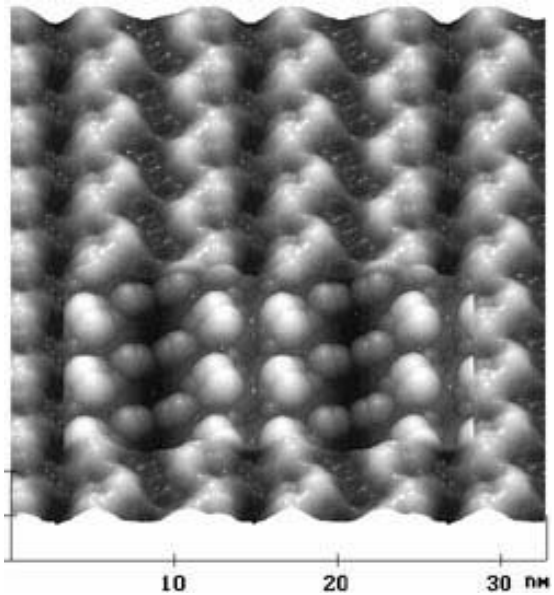
The framework in action



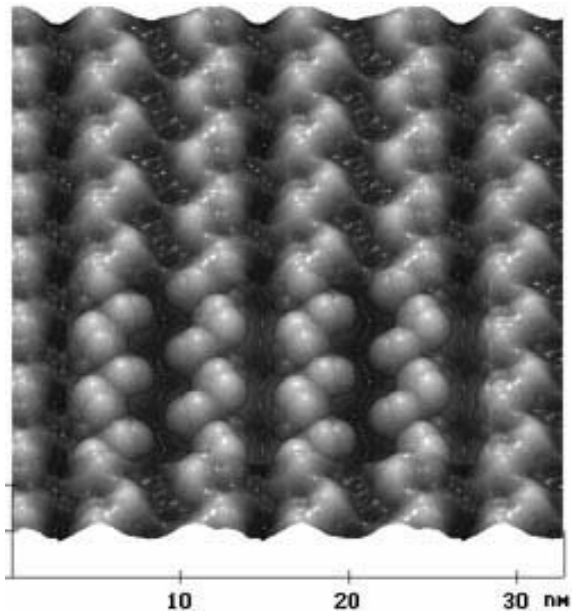
Experimental AFM image



Theoretical image



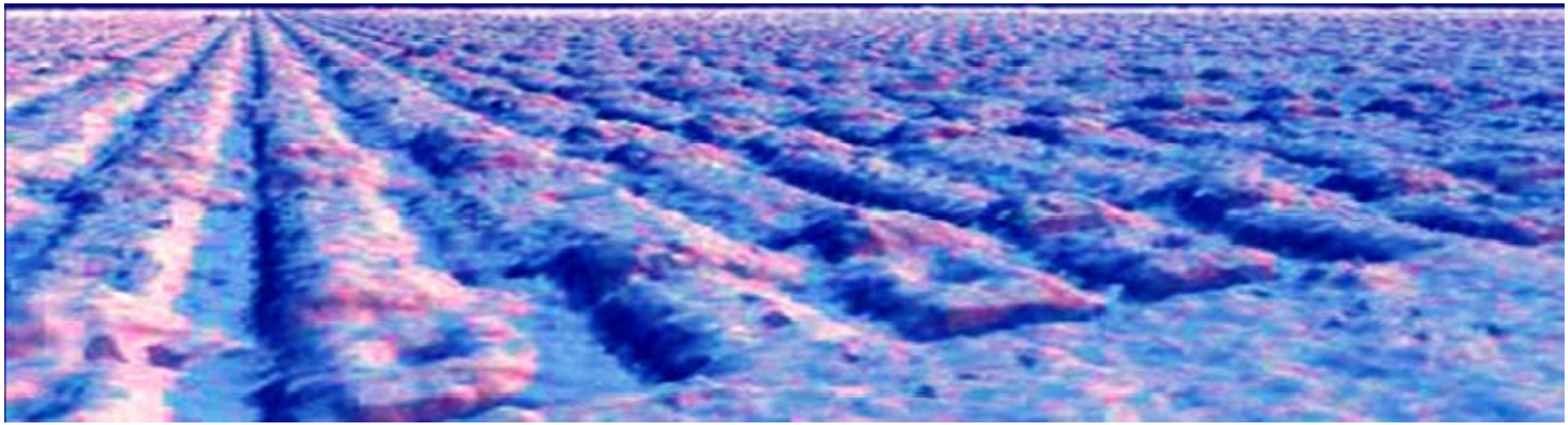
First hybrid image

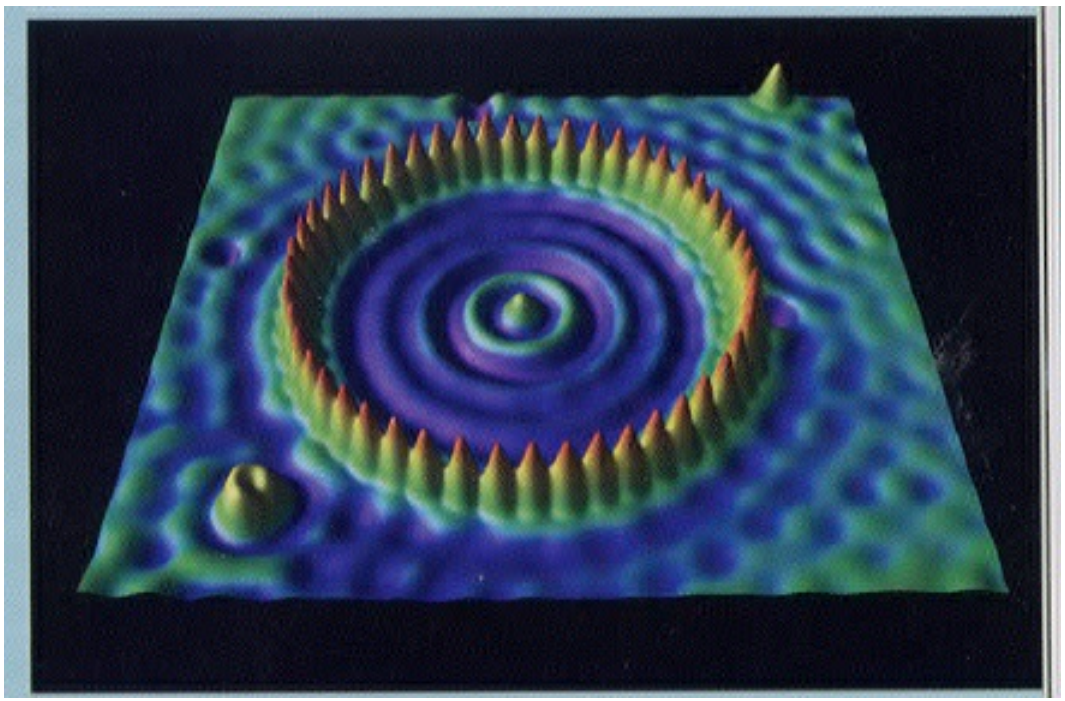


Revised hybrid image

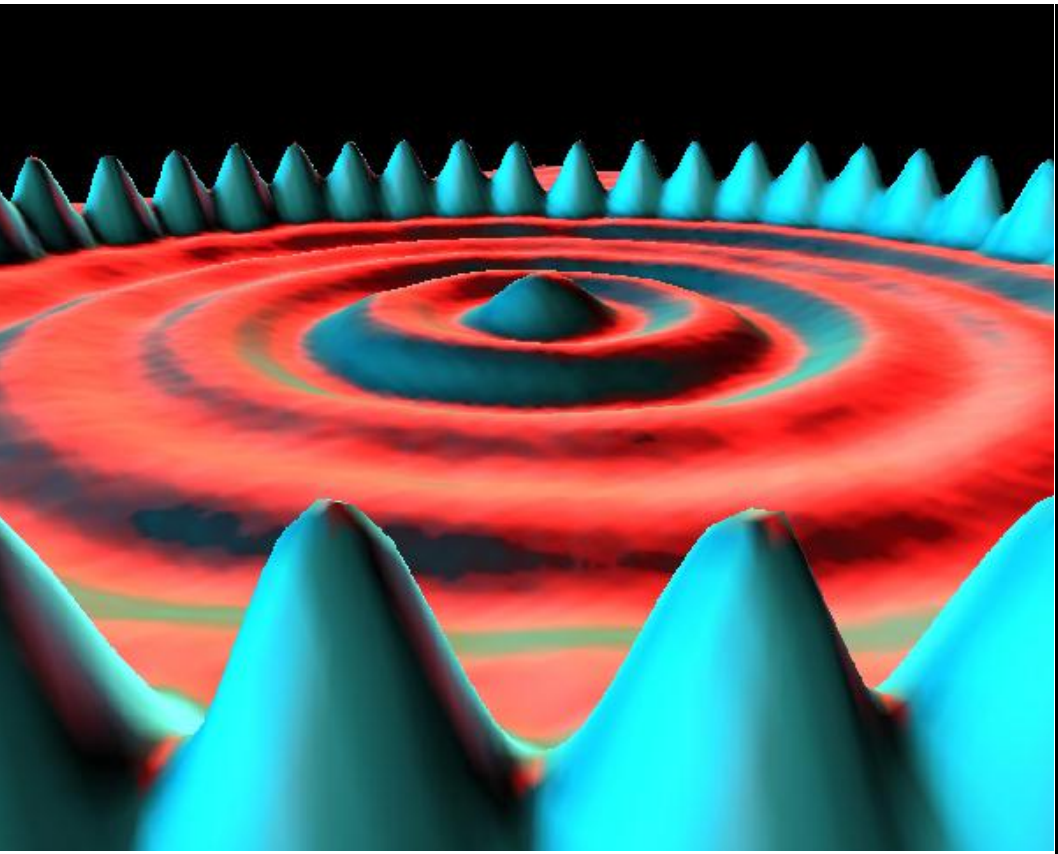
Convention codes

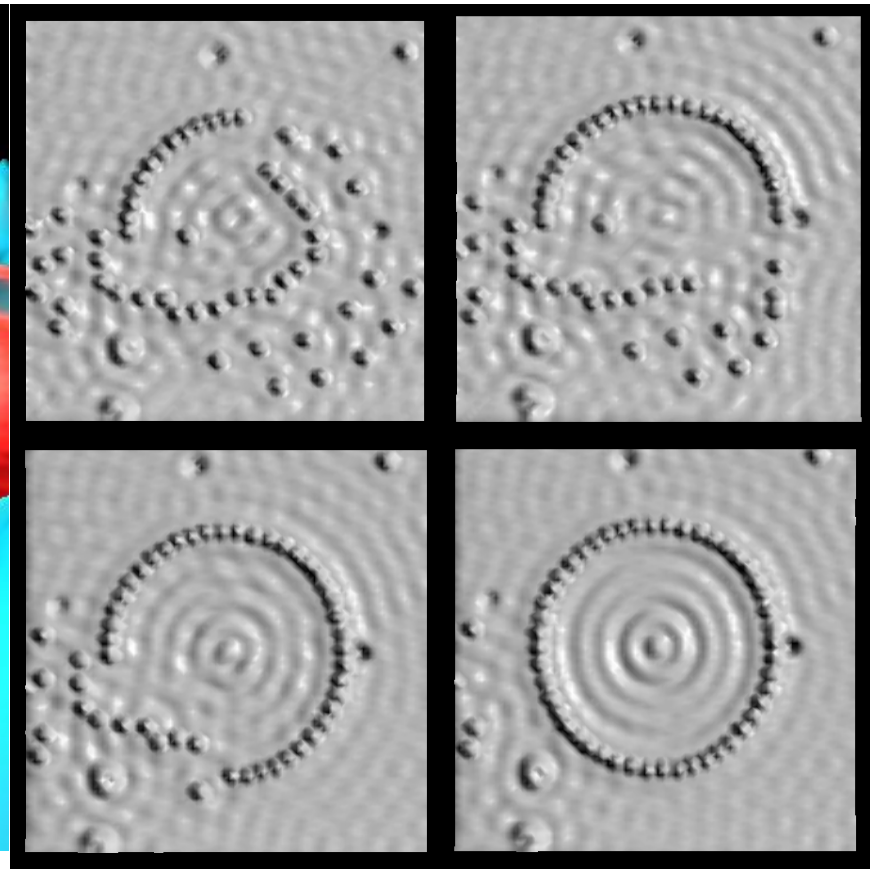
Convention codes





Convention codes





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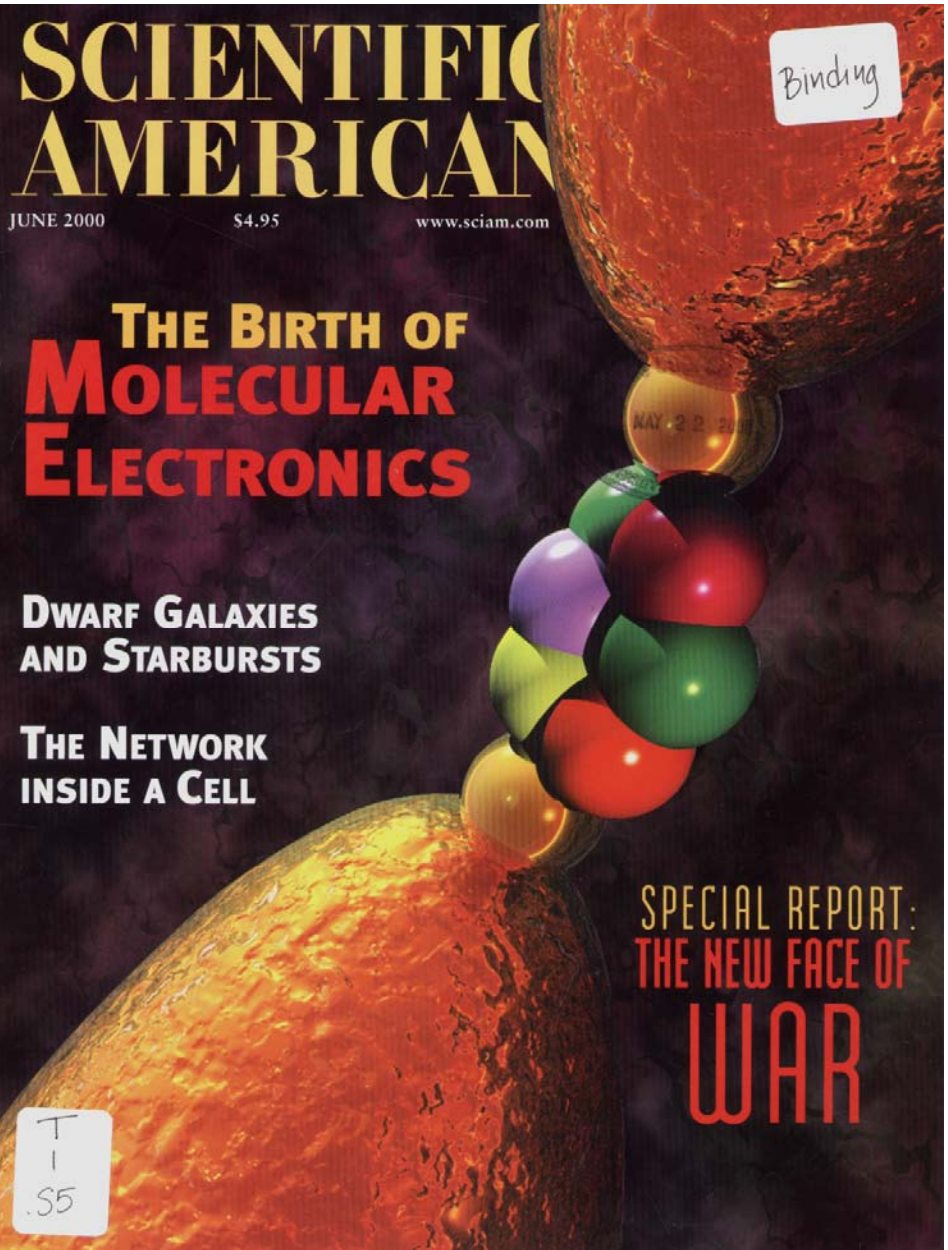

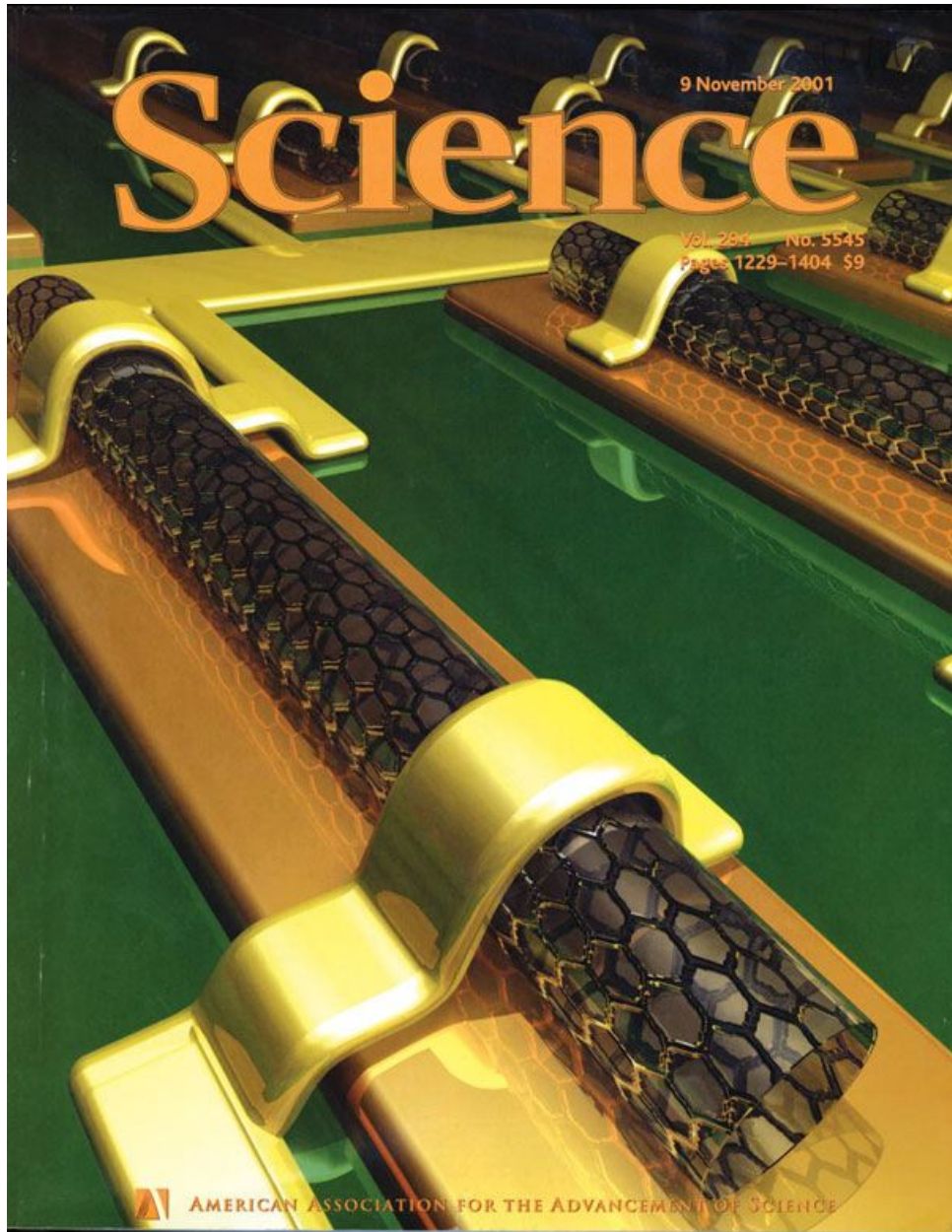

An epistemic account

- Despite the differences between the microscopes discussed so far, they still seem to share four epistemic conditions:
- **1. *Mechanization of image formation***: The images generate by each 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.
- **2. *Counterfactual dependence***: The microscopes' mechanical systems of image generation establish a particular dependence between samples and images, namely: *had the sample been different* (*within the microscope's sensitivity range*), *the image produced by each microscope would have been correspondingly different*.

Common epistemic conditions

- **3. *Tracking***: The counterfactual dependence between the sample and the image that is generated by the microscope allows for each microscope to *track certain features of the sample in space and time.*
- This is accomplished in two ways:
- (i) If the relevant features were present in the sample, the microscope would detect them.
- (ii) If the relevant features were not present in the sample, the microscope wouldn't detect them.
- **4. *Resolution***: Within certain boundaries (determined by the physical principles underlying a microscope), it's possible to *improve the resolution of the images* by constructing a series of better microscopes.
- If these 4 conditions are met, we have good reason to believe in the results provided by the microscope.
- But (i) are these conditions met? And (ii) can we *know* that they are met?

Some difficulties

1. How can we know that the mechanization of image formation works in the *intended* way?

- Typically, there is no independent form of access to the sample: the access is *mediated by some other instrument*.

2. How can we know that the counterfactual dependence between sample and image is *fine grained* enough?

- Even if the image were to change depending on changes in the sample, how can we know that the changes in the image reflect the *corresponding* changes in the sample?

Some difficulties

3. How can we know that the features of the sample that are being tracked by each microscope are those that *we take it to be tracking*?

- To assume that the relevant features of the sample are being tracked *presupposes that the microscope is already working properly*.

A possible response

- The difficulties just raised assume that for the microscopes to provide us with reliable information about the sample, not only the four epistemic conditions above have to be met, but we also *need to know* that they are met.
- This is an *internalist* requirement.
- But microscopists need *not* be internalist!
- They may insist that as long as the four epistemic conditions above are met, microscopes provide us with reliable information about the sample (*externalism*).

Problem with this response

- Clearly, microscopists need not assume internalism.
- But if the reliability of the microscopes is going to be based on the four epistemic conditions *alone*, one needs at least some reassurance that these conditions *are reliable*.
- However, it's unclear how one could support the reliability of these four epistemic conditions without invoking *additional* epistemic conditions that may be, in turn, questionable.

Arguments for reliability

- Two forms of arguments can be used to support the reliability of the four epistemic conditions (and hence, of microscopes):

(A) Overlap arguments

- Whenever possible, compare the images produced by a microscope with unmediated observations of the corresponding sample.
- If the images coincide, infer that the microscope provides reliable information *even about samples whose access we only have through the microscope*.

(B) Multiple independent access arguments

- Compare the images of the same sample produced by different kinds of microscope.
- If the images coincide, infer that the microscopes provide reliable information about the sample.

Underlying assumptions

- Each argument has underlying epistemic assumptions that might be questioned:

(A) Troubles for overlap arguments

- Overlap arguments assume that the samples whose access we only have through the microscope *behave in the same way* as those samples to which we have unmediated access.
- What guarantee do we have that this is the case?

(B) Troubles for multiple independent access arguments

- Multiple independent access arguments assume that there is a *common cause* for the sameness of images generated by different microscopes.
- What guarantee do we have that this is the case?

An alternative picture

- Perhaps the whole business of trying to provide epistemic conditions for microscopy is wrong headed.
- No such unproblematic conditions can be given, and none are ultimately needed.
- Microscopists will go on doing their work in the absence of any epistemological story that completely justifies what they are doing.
- This is a *Pyrrhonist attitude*.
- Alternatively, if microscopists are externalist (and can live with the fact that the four epistemic conditions discussed earlier may turn out *not* to be reliable!), they can still be fine.
- So, in the end, either by becoming Pyrrhonist or by embracing externalism, microscopists can be in good epistemological standing.

In conclusion

- Do we *see* through a microscope then?
- In general, we don't.
- But for those instruments that are such that we *know* that they satisfy the four epistemic conditions, although we don't technically see through them, the results we get from them are epistemically just as good as seeing.
- For those instruments that are such that we *don't know* whether they satisfy the four epistemic conditions, clearly we don't see through them. (Perhaps we *hear* with an AFM!)
- This differentiates clearly the epistemic attitudes we have toward these instruments and the results they offer.
- And this is as it should be.