Atomic Force Microscopy: Opening the Teaching Laboratory to the Nanoworld

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Instrumentation Topics for the Teaching Laboratory

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Atomic Force Microscopy: Opening the Teaching Laboratory to the Nanoworld

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Since the days of Democritus' atom and Avogadro's molecule, scientists have longed to observe these fundamental building blocks of nature. This dream came true in 1981 with the invention of the scanning tunneling microscope (STM) *(1, 2)* by IBM researchers Binnig, Rohrer, and Gerber, which allowed them to visualize individual atoms on a surface for the first time. This achievement had such profound implications in fundamental science that it earned them the Nobel Prize in physics in 1986 *(3)*. However, the use of STM is limited to electrically conductive samples. A major advancement occurred in 1986 when Binnig, Quate, and Gerber demonstrated the atomic force microscope (AFM) *(4)*, which could achieve extremely high resolutions also on insulating samples. Moreover, the AFM allows one to manipulate matter and measure forces, constituting an "all-in-one" workbench for studying matter at the nanoscale. Using simple operation principles, the AFM is an interactive tool like no other for visualizing molecules. This makes the AFM an exciting tool to introduce students to the nanoworld.

The educational value of the AFM has already been recognized by several articles in the chemical education literature: Teaching models for explaining the operation modes of the AFM for high school students have been developed *(5, 6)*, and lab experiments using the AFM have been suggested *(7–10)*. However, one may ask, "What is the connection of this advanced instrument to the chemistry curriculum?" In this paper we try to provide the answer to this question. We describe how the AFM enables students to interactively visualize molecules, and thus feel the excitement of exploring matter at the nanoscale. We suggest possible connections to both basic concepts in the chemistry curriculum and advanced topics in nanotechnology and chemical biology. We also provide useful information for making decisions about purchasing an AFM.

How Does the AFM Operate?

The AFM functions by scanning a sharp tip over a surface much the same way as a gramophone's needle scans a music record. The tip is held at the end of a cantilever beam shaped like a diving board. As the tip is repelled by or attracted to the surface by the intermolecular interactions between the atoms of the tip and the surface, the cantilever beam is relatively deflected. The deflection magnitude is captured by a detection system, commonly a laser that reflects onto a photodetector at an oblique angle from the very end of the cantilever. As the tip scans the surface, a feedback system raises and lowers the sample to keep a constant force between the tip and the surface. A plot of this upward and downward motion as function of the tip position on the sample surface provides a high-resolution image of the surface topography. This mode of operation is called "contact mode". Alternatively, the tip can vibrate rapidly up and down and tap the surface while scanning it. This mode, referred to as "tapping", "semicontact", or "dynamic" mode, is actually the most common mode of operation. In the AFM, the picture on the screen represents the surface topography, and not light transmission and reflection as in an optical microscope. A schematic of the AFM operation is presented in Figure 1. For a deeper explanation of the AFM operation, see Heinz and Hoh's paper in this *Journal (11)*. The AFM can also be equipped with a video camera that allows users to watch how the cantilever approaches and scans surface. In the teaching lab, this camera has the additional educational function of giving a notion of the scale of the experiment, and thus bridging between the macro and nanoworlds in the students' minds.

Bridging the Gap between the AFM and the Chemistry Curriculum

The existence of atoms and molecules is one of the basic concepts in the chemistry curriculum. Chemistry educators use physical models and computerized tools for molecular visualization to increase students' comprehension and performance *(12 13,)*. The AFM enables chemistry students to visualize atoms and molecules, leading them to a better understanding at the general chemistry level of molecular structures *(14)*. This was vividly expressed by a junior high school student saying: "We actually saw atoms with our own eyes!" *(15)*. The subject of intermolecular interactions is also a basic concept taught at the general chemistry level. Teaching this topic provides a natural context in which to use the AFM *(8)*. Another basic concept in the chemistry curriculum is that of order of magnitude. Teaching chemistry is an attempt to bridge the macro (the phenomena) and the micro (the atomic and molecular levels) *(16)*. The need to understand chemistry at the macro and micro levels is one reason why chemistry is difficult to learn *(17)*. The AFM can bridge the gap between the micro and the macro world by using

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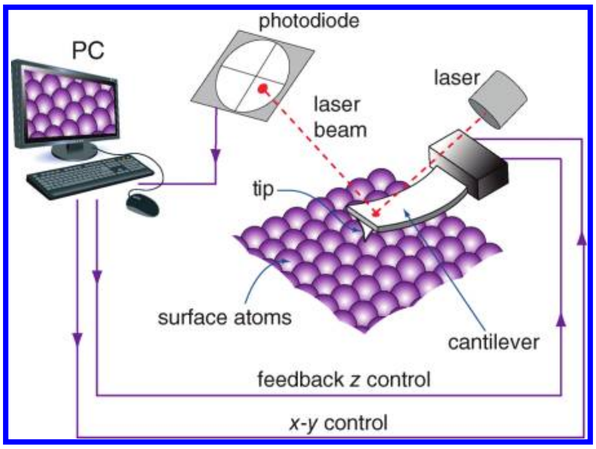

Figure 1. A schematic illustration of an atomic force microscope connected to a computer.

the video camera (macro level) and the AFM scanning mode (micro level). Students can simultaneously observe both the AFM cantilever scanning the surface (as recorded by the video optic zoom) and the surface image being recorded at nano resolution (by the AFM tip).

In addition to amplifying basic chemistry concepts, the AFM can also be used in modern and advanced chemistry education. Most students know that DNA is the central molecule of life. But, can a student tell his or her friends that he or she has actually seen it? Hands-on experience in observing single molecules of DNA can enhance students' understanding of DNA's properties *(18, 19)* like no other method can. An extremely exciting experiment is to observe the structure of supercoiled DNA, which resembles a twisted telephone cord, and how it varies with salt concentration owing to the screening of its electrostatic self-repulsion *(19)*. In the context of a course covering topics of nanotechnology *(20)*, the AFM is obviously the best-suited tool to visualize and characterize nanostructures, such as carbon nanotubes and gold nanoparticles, which are probably the most popular nanomaterials. Here, the AFM can be demonstrated as a measuring tool to determine the nanostructures' shape, length, diameter, and so forth.

Setting Up an AFM Teaching Lab

Measuring accurately at the atomic level places stringent requirements on both the AFM's instrumental design and the working environment. Whereas typical building vibrations can be on the order of units of micrometers (μm) in amplitude, the measurement noise must be at the angstrom (Å) level or lower. Major sources of noise are vibrational (building vibrations, motors and mechanical equipment, even walking in the room), acoustic (including talking), and electromagnetic (mobile phones, power lines, etc.). In practice, vibrations can be effectively reduced by placing the AFM on a commercial vibration isolation platform stage, or more simply on a heavy table (e.g., made of a thick marble plate on a robust iron frame with rubber spacers between the two). In any case, the major part of noise reduction is already taken care of by the design of the instrument itself. The AFM is usually built in a compact and rigid design so that crude measurements on the tens of micrometers (μm) lateral scale can be carried with no special precautions. Sometimes there will be a trade-off between letting a maximal number of students participate in a laboratory session and controlling noise levels. In our teaching lab, we

Table 1. Comparison of Some Technical Specifications of Educational Models of AFM

		Instrument Attributes[a]						
Company, Model	Scan Range, *xy*:*z* Values, μm	Optical Microscope	Liquid Cell	Vibration Isolation	Auto-Alignment	*XY* Stage	Educational Packet Available	Price, US Dollars[b]
Agilent, 5420	10:2; 100:8	No	Yes	Yes	No	Yes	Yes	—
Nanonics, Academia	100:100	Yes	Yes	Yes	Semi	Yes	Yes	55,000
Nanosurf, Easy Scan2	10:2; 79:14; 110:22	Optional	No	Optional	Yes	Optional	Yes	31,000[c]
Nanosurf/easyScan 2 FlexAFM	10:3; 100:10	Optional	Optional	Optional	Yes	Optional	Yes	48,000[c]
NT-MDT Nanoeducator	100:10	Yes	No[e]	No	No	Yes	Yes	31,800[d]
Park Systems, XE-70	5:12; 50:12; 100:25	Yes	Yes	Yes	No	Yes	No	65,700

[a] These specifications were obtained through responses from companies that were identified as promoting a model for educational use. A detailed description of each instrument is beyond the scope of this article; please consult company Web sites and local representatives for more specific information.[1−5] [b] The purchase prices here reflect suggested pricing as provided by company representatives; they will vary and are meant for comparison only. [c] The price for this model is provided in Swiss francs (CHF). [d] The price for this model in Euros (€) is 25,000, which was converted to USD in September 2010; a package of 5 units linked to workplace for instructor can be purchased for $ 191,000. [e] Liquid operation is performed in droplet.

deal with this problem of large groups by connecting the AFM computer to an overhead projector wired to a smart board in the lecture room.

The other consideration in the teaching lab is what is needed besides the AFM. Near the instrument there should be a workbench and basic materials for sample mounting and handling: tweezers (including specialty tweezers for handling the probe chips), adhesives (double-sided sticky tape, superglue, and conductive paint and tape), and scalpel. An air gun connected to a dry nitrogen tank can be very useful for quickly and cleanly drying samples prior to measurements, and a magnifying glass or eyepiece is helpful for mounting the AFM tips.

What AFM Systems Are Available for the Teaching Lab?

AFMs come with various options and choices. Several companies offer an educational model, as presented in Table 1.[1−5] Educational model AFMs typically use a simplified software control that enables only basic features, simpler tip placement and alignment, and a sample kit for instruction. An educational system need not have all the latest bells and whistles, but potential buyers should consider a few features:

1. Ease of probe change: Some systems require manual optical alignment of the laser, cantilever, and photodiode for optimizing the deflection signal. Other systems have an automatic alignment system requiring no user intervention. If operating costs are a consideration, check whether the AFM requires dedicated (expensive) probe types.
2. Available modes: AFM operation in contact mode gives excellent images for many samples and, under proper conditions, can allow atomic resolution on certain samples. On the other hand, shear forces can lead to smearing and blurred images on soft or brittle samples. Dynamic mode allows a wider range of samples to be investigated.
3. Size of scanner: Scanner *XY* ranges can be as small as 1 μm or larger than 100 μm; the *Z*-range usually spans about 2−20 μm. A larger scanner will typically be noisier than a smaller one, but it will also let the user observe larger features and make it easier to search for a specific object.
4. Optical microscope: In principle, the AFM can operate without an optical microscope. However, this view helps the students correlate between the macroscopic and microscopic levels, as we have emphasized. Moreover, an optical microscope is essential if you need to find a specific object on a surface.
5. *XY* stage: To precisely move the measured scan to a specific place requires several millimeters (mm) of motion in the *xy* direction. This can be done with a pair of micrometric screws operated manually or by computer.
6. Liquid cell: For biological samples, a liquid cell lets the user explore the nanoscale under real-life conditions. Forces also vary dramatically between different environments.

Table 1 lists some AFM models that are promoted as educational systems, including some basic features. It is important to clarify with the company what features are included in the system offered and which can be added (usually simple to add on later) for an additional price.

Conclusions

We have shown that the AFM is not only a powerful scientific tool but also a powerful educational tool. The AFM gives students a vivid notion of the structure of matter at all scales, all the way down to the level of atoms and molecules. The interactive and open-box mode of operation of the AFM, which allows students to zoom in and out at any region of a sample, adds a great deal of excitement, arouses students' curiosity, and eventually encourages them to learn what chemistry is about. We thus believe that the AFM should be an integral part of the chemistry teaching lab. Any chemistry high school laboratory or educational institution that does not have an AFM in their teaching lab has a very good reason to order one now.

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Notes

1. Agilent Technologies Home Page. http://www.home.agilent.com/agilent/home.jspx (accessed Sep 2010).
2. NT-MDT Home Page. http://www.ntmdt.com/ (accessed Sep 2010)
3. Nanonics Imaging, Ltd. Home Page. http://www.nanonics.co.il/ (accessed Sep 2010).
4. Nanosurf Home Page. http://www.nanosurf.com/ (accessed Sep 2010).
5. Park Systems Home Page. http://www.parkafm.com/ (accessed Sep 2010).

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