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Nano goes to school: a teaching model of the atomic force microscope

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Abstract
The paper describes a teaching model of the atomic force microscope (AFM), which proved to be successful in the role of an introduction to nanoscience in high school. The model can demonstrate the two modes of operation of the AFM (contact mode and oscillating mode) as well as some basic principles that limit the resolution of the method. It can be used either as a demonstration experiment, simple laboratory experiment or home experiment that students can make by themselves.

S This article has associated online supplementary files.

Introduction

Nanotechnology is going to significantly change our future. Some prognoses say that its impact on our lives will rival that brought about by the steam engine, electricity, the transistor, and the internet [1]. At the nanoscale (i.e. dimensions of atoms and molecules), macroscopic distinctions between materials, and even between scientific disciplines, cease to exist. As a result, nanoscience offers the possibility of having diverse technologies and different science disciplines which converge with a common goal. Nanomaterials, with their amazing and unusual properties, are becoming ever more common in our everyday lives. For instance, several anti-ageing cosmetic products, antibacterial coatings in refrigerators, and different coatings for making stain-resistant textiles and furniture are products of nanotechnology, to name just few. On the other hand, it is becoming clear that nanomaterials represent a great potential hazard to our health and that our knowledge about how nanoscale particles affect living organisms is very limited. This is all the more reason for including nanoscience in education at different levels. As reported recently by Tibor Gyalog, president of the Swiss Physical Society [2], nanoscience education has become part of the curricula in several universities and high schools in Europe, where the major challenge for the latter is re-education of high-school science teachers. Similar changes and activities are taking place in the USA. For instance, at the Cornell University Centre for Nanoscale Systems, the Institute for Physics Teachers has been formed to upgrade high-school teachers' knowledge and understanding of recent developments in nanophysics [3].

Introducing nanoscience into schools requires new paradigms in education. Since science subjects have a so-called pyramidal structure, we cannot simply remove some 'older' topics from the curricula and substitute them with the basics

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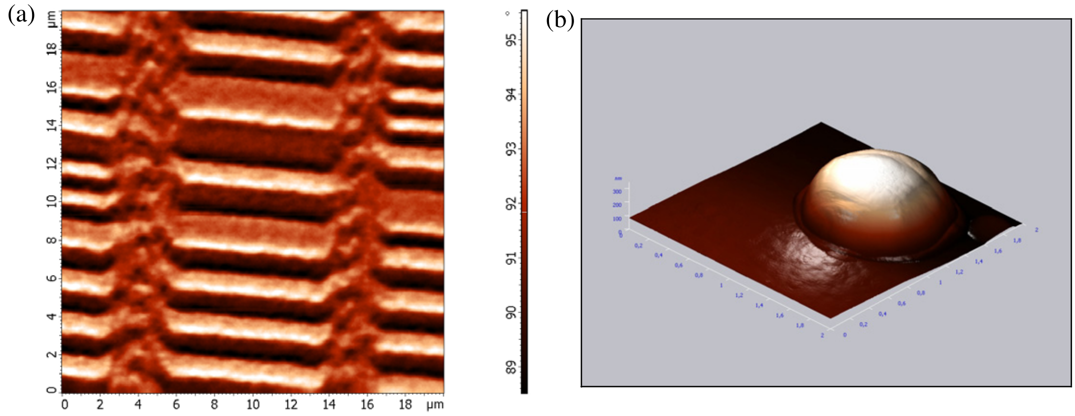


Figure 1. AFM images: (a) AFM image of a surface topography of magnetic disk surface sensing the magnetic interaction. The image was acquired over an area of 20 μm × 20 μm with a tip coated with a magnetic thin film. (b) AFM image of the bacteria *Staphylococcus aureus* sensing van der Waals interaction. The image is shown in a three-dimensional view over an area of 2 μm × 2 μm. Both images were acquired in oscillating mode with the NT-MDT AFM microscope, model Solver PRO.

of nanoscience. Let us focus on physics in high schools. One way to deal with the problem is to identify specific topics from nanophysics (for instance the description of an apparatus or method, or the characteristics of some special material) that can be satisfactorily explained and incorporated within the existing curriculum. Such an example may require the students to use their knowledge in a new situation or can serve as an example to show how in practice one has to apply knowledge from different topics or even from different scientific disciplines at the same time. From here one can discuss nanotechnology from other perspectives (health, social, economic, etc). An alternative is to combine the classes with some other subjects (such as biology, chemistry, philosophy, . . .) and move the discussion there (several ideas for cross-curricular themes on nanoscience can be found in [4]).

In the present paper a teaching model of an atomic force microscope is presented, which proved to be successful as an introduction to nanophysics for high-school students as well as for in-service physics teachers.

Atomic force microscope

Nanoscale particles have existed in our environment for millennia—for instance, as salt crystals in ocean air or carbon in soot. But the intentional manufacture of nanoscale particles and the exploration of their properties was only possible after special tools and methods had been developed that enabled one to 'see' and manipulate these particles. One of these local probe methods, scanning tunnelling microscopy, was developed by Gerd Binning and Heinrich Rohrer in the early 1980s, for which they were awarded the Nobel Prize in 1986. The interaction probed in the scanning tunnelling microscope (STM) is the tunnelling current between the probe and the sample, reflecting the strong distance-dependent probability of electron transport through a gap between two conducting solids. A few years later, another scanning instrument was developed by Binning's group, based on the short-range van der Waals interaction and called the atomic force microscope (AFM). Since no electron transport is involved in the AFM method, both insulators and biological samples can be investigated down to atomic resolution. The information on topography, roughness, friction, adhesion, elastic properties, interaction between tip and sample surface, distributions of electric field, magnetic field, resistivity, surface potential, etc can be obtained by the AFM with nanometre resolution (see figure 1).

In addition, a manipulation of the sample surface can be performed by the tip of the AFM via current or voltage nanolithography. The ability to perform the measurements in air, the reliable performance and the simple construction of AFM instruments make an AFM standard instrumentation in many laboratories.

The operation of the AFM is based on interaction between a sharp tip supported on a cantilever and atoms at the surface of the sample. Forces on the tip can be either attractive or repulsive. The deflection of the tip due to a change of a force is detected by the reflection of the laser beam from the back of the cantilever.

There are two basic modes of operation of the AFM. In the *contact mode*, a tip is in close proximity to the sample surface during scanning in the horizontal plane. This mode is most useful for imaging hard surfaces. In the *oscillating mode* (also known as non-contact mode), the tip is oscillating along a vertical axis during scanning over a sample surface. The advantage of the oscillating mode is less damage to the surface due to the weaker interaction between the tip and the surface, which makes the oscillating mode particularly suited for imaging soft biological specimens and carbon nanotubes. In addition, the AFM can probe the interaction between the tip and surface, giving force–distance curves, obtained by advancing and retracting the tip towards and away from the surface at a chosen position. This information yields data on the size of the interaction potential and its space dependence, that can be useful in research and applications of adhesion, wettability, colloidal interactions and more. For more information on the basics of the STM and AFM methods see the excellent textbook written by Mironov, which is also available on-line [5].

It should be mentioned that in practice the AFM often works in a slightly different way than described above. The holder of the cantilever, while scanning over the surface, is moved up and down so that the force acting on the tip (and therefore the deflection of the tip) is kept constant. This is done by correcting the vertical position of the holder so that the spot of the reflected laser beam is kept in a constant position. The shape of the sample surface is reconstructed from the movements of the holder. Though this approach (known as feedback control) is very important from the technical point of view, it is not essential for understanding the basics of the AFM operation at high-school level, and will be ignored in this paper.

Teaching model of the AFM

The operation of the AFM relies on a few basic physics principles that make it a suitable topic to be discussed in secondary-school physics or in introductory physics courses. This also makes the AFM useful for modelling simple experiments that offer students hands-on experience and stimulate analogical transfer. One version of such a model, which demonstrates the resolution limit of scanning methods, is available commercially as a kit [6].

The model AFM described in this paper demonstrates the two basic modes used in the operation of a real AFM: contact mode and oscillation mode. The model combines the following topics that are essential for understanding the operation of a real AFM and are usually covered in school physics curricula: Hooke's law, forced oscillation, resonance and the law of reflection.

It is important to note a difference between our model of an AFM and a real AFM microscope. In our case a magnetic force is the only source of interaction between the sample and the microscope, whereas in the real AFM microscope the van der Waals force is more often employed than a magnetic force.

Our main goals in designing this model were that it can easily be built by teachers or students and that it can demonstrate the basics of AFM detection in a short enough time to be suitable for lecture demonstrations.

Contact mode

In contact mode the sample is systematically moved line by line below the cantilever, which (according to Hooke's law) deflects under the forces that act between the tip and the sample. Deflections of the cantilever reveal the corrugation of the sample surface as well as information about the interactive forces.

To make a model of an AFM that works in contact mode you will need the materials that are shown in figure 2(a). The assembled device is shown in figure 2(b).

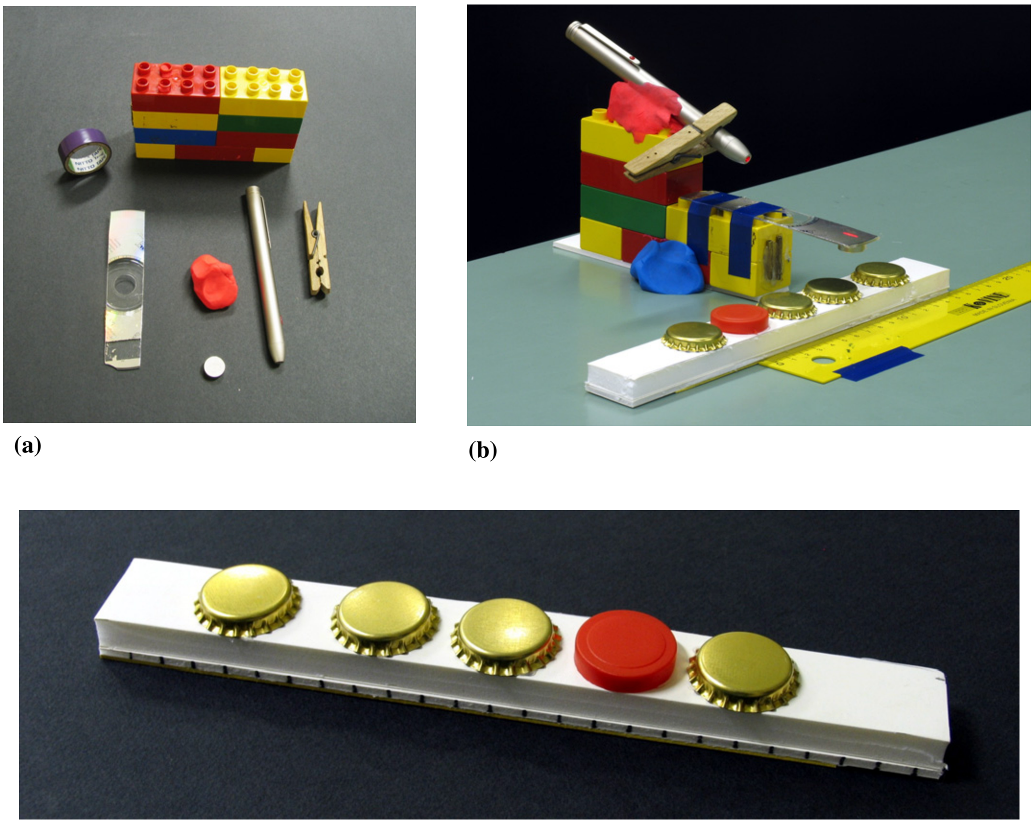
Our body of the AFM model is made from Lego blocks. The cantilever is cut from a used compact disc (CD), which combines the properties of good elasticity and optical reflectivity. Use the part of the disc that has no printing on the upper surface and fix it on the Lego block with the data surface facing downwards (the reflection from the upper surface of the CD is clearer than from the data surface, which is protected with a transparent plastic layer). Use a strong neodymium magnet (NIB) for the tip. We used a cylindrical magnet of 14 mm diameter and 5 mm height so that the size of the magnet (i.e. tip) is comparable with the size of the 'atoms' (see next paragraph). Glue the magnet to the lower surface of the cantilever, as seen in figure 2(b). Use the laser pointer as the light source. Fix the laser to the Lego blocks with plasticine. Adjust the laser to a position so that the beam strikes the free end of the cantilever at the reflective part of its surface. The softness of the plasticine allows you to make a fine adjustment of the laser.

Now you need to make a sample with a suitable 'atomic landscape'. In our model only a single line of 'atoms' is used and scanned in order to make the experiment suitable for lecture demonstrations. We also believe that at school level all important features of scanning methods can be shown by observing and studying line scans and that once students understand this the extension to a surface scan can be explained relatively quickly, for instance by using computer simulations. The metallic bottle caps proved to be perfect 'atoms' that respond to magnetic interaction, and plastic bottle caps are used for the 'atoms' that do not respond (we also tried other types of samples as described briefly in[3]). The completed sample with an 'atomic structure' used in our experiments is shown in figure 2(c). Before designing your sample, think what characteristics of the method you would like to demonstrate and do not forget to take into account the dimensions of the magnet (see Appendix A. 'Resolution'). The model of an AFM is ready to be tested. Place the device in front of a wall or white board, about 2 m from the wall, and switch on the laser. Put the sample on the table with one side of the sample under the magnet. Use a clothes peg to keep the switch on the laser in the ON position for a longer time. WARNING: make sure that the laser beam or reflected beam is kept away from students, before you switch on the laser! Fix a piece of paper with printed parallel lines (about 20 lines with 5 mm separation is adequate) on the wall so that the reflected laser beam will make a spot at the upper end of the scale. Make a zero mark at the upper line with values increasing downwards. Now, as you slowly move the sample perpendicularly to the cantilever the light spot on the screen should move up and down (in our design the maximum shift of the spot on the wall was about 22 cm). Once you are sure that the AFM model works, you can design a laboratory for students in which they make systematic measurements of the samples. This is best done in groups of three to four. The first student moves the sample in steps of 5 mm, the second student reads off the positions of the light spot on the wall and the third student records the data. When all the data are collected, the measured shape of the surface has to be compared with the shape of the sample. This can be done simply by preparing in advance laboratory sheets with a photograph of the side view of the sample and with a coordinate system plotted over it (leaving an arbitrary vertical scale). Students are asked to plot the measured points in the coordinate system and discuss the similarities and differences between the original and the measured shapes (see figure 3).

Even this very simple representation contains enough to show some basic limitations of the method (see also Appendix A. 'Resolution'). For instance, it is clearly seen that the gap between the second cap and the third cap appears to be shallower than the gap between the first cap and the second cap. Note also that the heights of the second cap and the third cap appear higher compared to the height of the other metal caps. This is probably because of a small misalignment of the caps with respect to the line of scanning.

If time permits, one can go further and show, or give as a homework problem, how to calculate

[3] In our first attempts to design a suitable atomic landscape we tested differently oriented permanent magnets glued along the line on a plastic ruler. The advantage of this version is that you can show both the attractive and repulsive interaction between the sample and the tip. However, we soon realized that at an introductory level one character of the force is enough to show the basic features of the method, and so we decided to use samples made from iron (ferromagnetic material). One possibility is to use an iron strip (we used a 1 mm thick, 2 cm wide strip from soft iron) shaped to mimic the corrugation of the 'atomic landscape'. Since the magnetic force between the magnet and the iron changes very rapidly with distance, the variations of the sample height and positioning of the sample below the magnet are critical. A metal strip of the measurements given above can be bent with pliers, but it is not very easy to shape the strip into a predefined form. In addition, the real atomic surface is rather a discrete structure than a continuous surface, so the iron strip sample is questionable also from the teaching point of view.



(a) (b) (c)

Figure 2. (a) Basic material needed to build an AFM model (from top left to bottom right): adhesive tape, Lego blocks, a strip cut from a used CD, plasticine, a strong magnet, a laser pointer and a clothes peg. (b) An AFM model during operation in contact mode. (c) Sample of an 'atomic landscape' made from bottle caps. Four caps are made from ferromagnetic metal and one from plastic. Note that the separations between the caps are not equal.

tip movements from the measured positions of the light spot on the wall, knowing the length of the cantilever and the distance from the tip to the wall.

Oscillating mode

In the oscillating mode the cantilever is driven with a sinusoidal excitation force at constant frequency. The frequency is adjusted to be close to resonant frequency when no sample is in the vicinity of the tip (in our case the resonant frequency was 14.6 Hz, and the time in which the amplitude dropped to about one third of the initial value was about 1 s). If the sample is now brought near to the tip the interactive forces between the tip and the sample will have the same effect as if the stiffness of the cantilever had changed. This in turn will change the resonant frequency of the cantilever, resulting in a decrease of the oscillating amplitude (note that the excitation frequency is the same all the time). In this case the changes in amplitude of the cantilever (and also its phase with respect to the driving force) reveal the variation of the interactive force gradient ($\mathrm{d}F/\mathrm{d}z$) along the sample surface. See Appendix B. 'Change of the resonance' for an additional explanation.

To make your AFM model described in the previous paragraph work in the oscillating mode, you will need to add a small coil and obtain a sine generator (a conventional school sine generator with 50 Ω output impedance and the ability to adjust voltage frequency to within 0.1 Hz or better will do). The idea is to place the coil close above the magnet and drive the cantilever in resonance by adjusting the frequency of the current in the

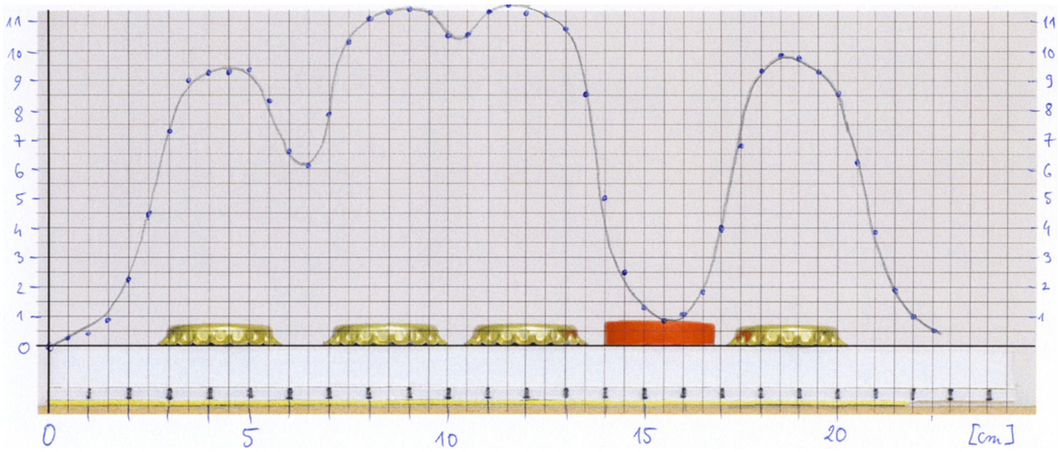
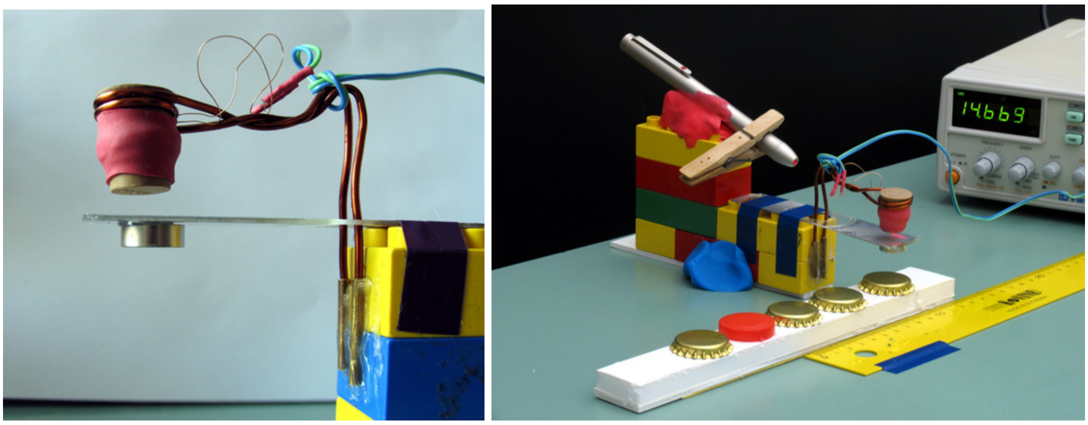


Figure 3. Laboratory sheet: graphical presentation of the measurements obtained in the contact mode and original sample. The positions of the light spot on the wall (vertical axes) are measured in arbitrary units. The presented data were obtained in less than 5 min.



(a) (b)

Figure 4. AFM model for operation in the oscillating mode: (a) coil for driving the cantilever (windings are protected with thermo-shrink tube); (b) AFM model during operation in the oscillating mode.

coil. We made our coil by winding 100 turns of 0.2 mm thick lacquered copper wire on a rubber stopper (with a diameter of about 15 mm). The holder for the coil is made from 3 mm copper wire, with its ends inserted into two brass tubes that are glued onto one of the Lego blocks. This design allows one to switch easily between the contact and oscillating mode design. The coil with a holder is shown in figure 4(a), and the assembled model during the operation in oscillating mode in figure 4(b).

When working in the oscillating mode you have to first adjust the frequency and the amplitude of the current in the coil so that the cantilever (without a sample underneath) is in resonance, but also so that the trace of the reflected laser light on the wall is of suitable length (about 40 cm in our case). When this is done, place the sample under the cantilever. The amplitude of the oscillating spot should decrease (the decrease is also partly due to higher damping caused by eddy currents in the caps, but the dominant effect comes from the shift of the resonance). Then move the sample step by step, as in the previous experiment, and each time measure with a large ruler the length of the trace (i.e. peak-to-peak amplitude) of the

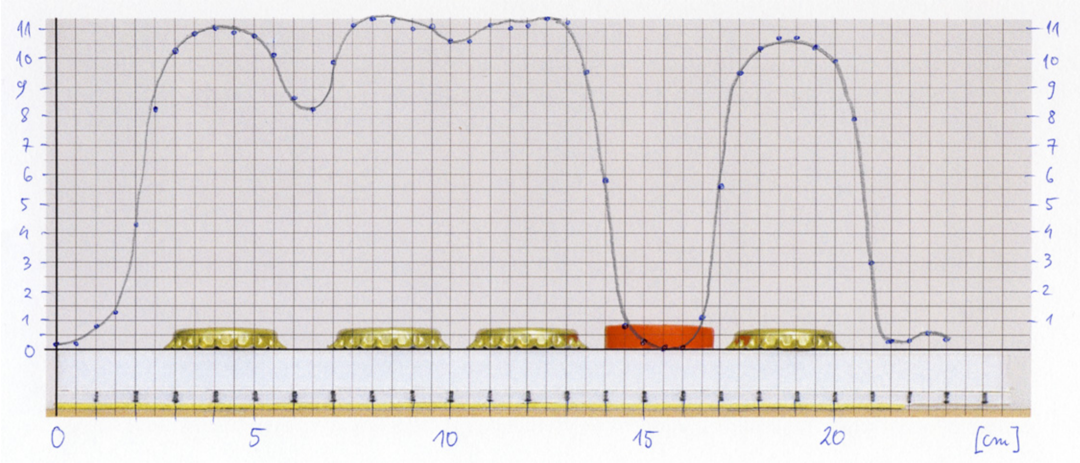


Figure 5. Laboratory sheet: graphical presentation of the measurements obtained in the oscillating mode compared with the original sample. The vertical coordinates of the points (given in arbitrary units) correspond to the amplitudes of the oscillating light spot on the wall and were all subtracted from the largest measured value.

oscillating light spot on the wall. As in the previous case, the measuring procedure is quicker if performed as a group activity.

When all the data are collected, the measured amplitude variation can be compared with the variation of the shape of the sample. Again, this can be done by plotting the measured values in the prepared laboratory sheets. Since the largest protrusions in the sample will produce the smallest amplitudes, the measured shape in this case will appear upside-down. The upright shape can be obtained by subtracting the measured values from the largest measured value (figure 5).

Since in this experiment the interactive force is of the same character all the time (i.e. attractive force between the magnet and induced magnetic dipole in the ferromagnetic caps), the oscillating mode measurements give a similar shape to the contact mode.

The measurements described above and presented in figures 3 and 5 can also be performed by a single student using a digital camera. For each measured point a photograph of the spot on the wall is taken from a fixed position with a digital camera. From the sequence of photographs the coordinates of the spots (or lengths of the traces) can easily be measured using one of the programs for analysing digital images (we used freeware ImageJ [7]).

An interesting additional experiment can be shown with the model that works in oscillating mode. Place a permanent magnet below the cantilever, so that you can switch between attractive and repulsive forces simply by turning the magnet around. If you now search for the resonant frequency of the cantilever in three different situations (without the magnet below the tip, with a magnet in repulsion, and with the magnet in attraction) you will find that the measured values agree qualitatively with the prediction given in the Appendix B. 'Change of the resonance'. In our case the cantilever resonant frequency was 15.1 Hz; when the magnet in attraction was added the resonant frequency decreased to 14.3 Hz, and when the magnet in repulsion was added it increased to 15.7 Hz. The cantilever when in rest was about 45 mm above the plane of the lower magnets.

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Appendix A. Resolution

One of the most important factors influencing the resolution of an AFM is the sharpness of the scanning tip. In the simplest approximation we can imagine the tip as a wheel of radius R rolling over the surface (figure A.1) (in practice the effective radius is somewhat larger than the tip

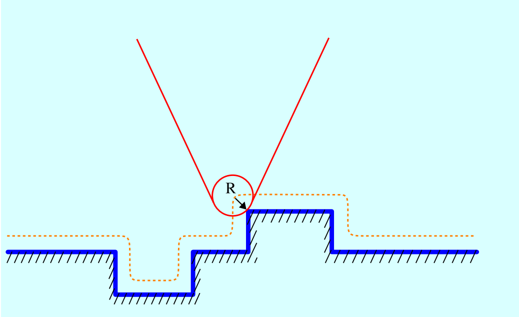

Figure A.1. In the shape described by the movement of the tip the protrusions appear wider and the depressions appear narrower than they are in reality.

radius). When the tip moves over the protrusion the tip centre circumscribes the shape, which is wider than the protrusion, but when the tip moves over the depression the shape is narrower than the depression. Note also that depressions with a width smaller than the tip diameter will appear shallower than they are. These effects are sometimes described as tip convolution. In practice the resolution is also determined by the sensitivity of the height detector. The best tips today may have a radius of curvature of only around 5 nm.

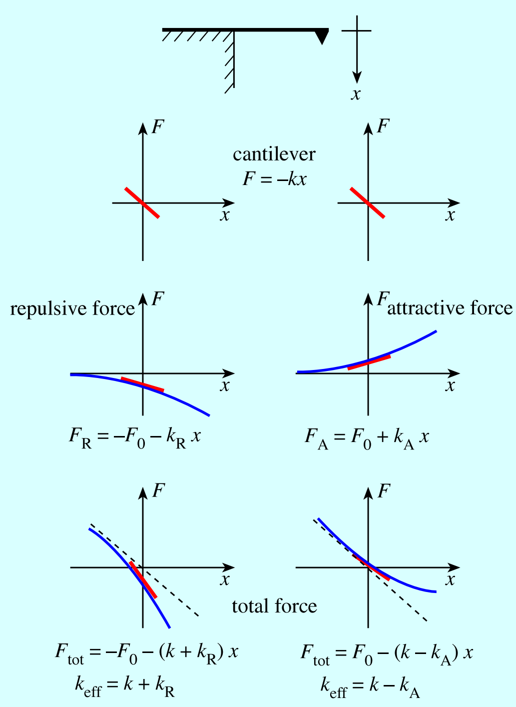

Figure B.1. The change of the cantilever effective spring constant (k_{eff}) in the presence of the repulsive/attractive force. Only the linear term for the attractive/repulsive force near $x = 0$ has been taken into account. The choice of the coordinate system is shown at the top of the figure.

Appendix B. Change of the resonance

The cantilever and the tip make an oscillator (similar to a mass hanging on a spring), which has a characteristic resonance frequency ν_0. For small deflections of the cantilever the force–deflection dependence is linear (Hooke's law) and can be qualitatively presented with the graph in figure B.1. The slope of the line in the force–deflection graph is equal to the spring constant of the system k, which also determines the resonant frequency if the mass is kept fixed ($\nu_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$). The stiffer the cantilever, the higher the resonant frequency.

If in addition to the spring force an attractive/repulsive force acts on the tip, this will result in an apparent change in the cantilever stiffness (i.e. a change in the slope of the force–deflection graph) and consequently in the decrease/increase of the resonant frequency. The effect of additional forces is shown and explained in figure B.1, where effective spring constants have been expressed using a linear approximation for attractive/repulsive forces near $x = 0$. Note that no particular forms for the attractive/repulsive force have been assumed, only the sign and the fact that both forces have to vanish if we move away from the sample. Note also that the additional force changes the equilibrium position of the cantilever (i.e. the position where $F_{tot} = 0$).

Using a linear force–distance dependence as described in figure B.1, the change in resonant frequency can be expressed in the following way:

$$\nu = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m}} = \frac{1}{2\pi}\sqrt{\frac{k+k'}{m}} \approx \nu_0\left(1 + \frac{k'}{2k}\right),$$

where ν_0 is the resonant frequency when no sample is present. In the case of a repulsive force $k' = k_R$ and $\nu > \nu_0$, while in the case of an attractive force $k' = -k_A$ and $\nu < \nu_0$.

The teaching model of AFM has been tested by the group of 30 physics teachers as one of the activities during the workshop

'Nano goes to school' held at the GIREP-EPEC conference in Opatija, Croatia in August this year. The response from teachers was very positive. The worksheet for student experimental activity based on the AFM model is available at stacks.iop.org/physed/43/37.

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[7] Program ImageJ for analysing digital images can be downloaded from http://rsb.info.nih.gov/ij/

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