ATOMIC FORCE MICROSCOPY EDUCATION

An Interactive Qualifying Project Report
submitted to the Faculty of the
Worcester Polytechnic Institute
in partial fulfilment of the requirements for the
Degree of Bachelor of Science

Submitted on: November 7th, 2015

Submitted By:
Andrew Pic
Valerie Moore

Project Advisor:
Professor Nancy A. Burnham

Abstract

Atomic force microscopy is a crucial part of nanoscience. Despite the simplicity of its design, a simple cantilever with a sharp tip, learning and teaching AFM can be difficult. Five levels of AFM education were identified from existing education infrastructure: demonstrations, single or several laboratories within another course, term or semester based courses devoted to AFM, personalized hands-on instruction, and short courses. Information was gathered from a survey as well as interviews given to figures in AFM education. Advice, general practices, and a list of resources were compiled into a website, presentation, and this report. These are intended to become a resource to help educators approach and design their own AFM educational experience.

Table of Contents

1.0 Introduction

A future physicist, a mechanical engineer, a biologist, a chemist, and an electrical engineer take their places in the same classroom on the first day of class. They each take notes on various aspects of the natural world as the professor discusses the outline of the day's lecture topics. With a different background, each sees the world through their major as a product of an educational system tailored to their future career. [i] None of these students recognize that they are sitting in a classroom with a professor who is about to change their life. This class wields the power to change perception and understanding and foster deep respect for life at its core level of existence, at the nanoscale. What is life at the nanoscale? It is chemistry, physics, materials science, biology, and electrical engineering – life at the nanoscale is overwhelmingly beautiful. Humans are privy to life at the nanoscale, but only through complex imaging systems and analysis. A common tool to witness the world at the nanoscale used in industry, research, and in classrooms is the Atomic Force Microscope. The operation of the atomic force microscope is sensitive and does require substantial patience at times, but the information gleaned from its tiny tip and focused laser is renowned for its capacity to image and collect data. The atomic force microscope has nearly boundless applications, making it an important multidisciplinary tool.

Atomic force microscopy (AFM) plays a central role in nanoscience and nanotechnology. Its design principle is simple – a cantilever with a sharp tip is moved over a sample surface and the resulting force interactions are plotted as a function of lateral position over the surface. This approach provides an image of the topography of the sample. The images can be beautiful and can draw students into learning more about science and technology. AFM is not only used for producing aesthetically pleasing images but, from chemistry to biology and physics to materials science, Atomic Force Microscopy is an integral tool providing researchers with qualitative and quantitative data from a sample, including its surface and mechanical properties. The AFM, while intriguing and useful, is a daunting instrument to learn and teach.

Despite the simplicity of its design and usefulness of the data it collects, learning to use an AFM can be challenging. In addition, the cost, time, and proper educational materials for teaching AFM have long been an afterthought in the multidisciplinary nanoscience boom of recent decades. AFM educators recognize this problem and have adapted various approaches to introduce people to the technique and quickly climb the AFM learning curve. Such approaches vary with educational level but are, just as the multitude of uses for the Atomic Force Microscope, spread throughout several disciplines. Thus the extensive list of technical uses for Atomic Force Microscopy greatly outnumbers the quantity of educational resources. AFM is widely used but rarely taught to its full extent; taught mainly as part of a larger course on microscopy or one simple method for one specific research task. This situation further cements full spectrum AFM usage as an extraordinarily specialized field reserved for those pursuing masters or doctoral degrees or those using the Atomic Force Microscopy daily for jobs in industry where AFM has clearly defined benefits and easy access.

Some benefits to graduate and undergraduate level students include raising the student into an upper echelon of the workforce. Those in the workforce generally only receive on the job training or attend week-long AFM workshops, leading to partial knowledge and excellence only in repetitive tasks. Proper training, which eases students into the challenges of AFM operation, immediately increases the marketability of students in industry and other types of post collegiate opportunities. Hands on lab courses also allow the student creative leeway and simulate a situation where they must use intuition to solve complex problems under time constraint. Multifaceted teaching strategies can be employed during the undergraduate or graduate course in order to prepare students for the daunting task of researching, displaying results in concise figures, and writing to present scientific findings in the modern scientific community. This also has applications to industry where these students will have to write convincing reports using data generated from their own well-planned and well executed experiments. While the usefulness of surface imaging and nanoscale mechanical property techniques exists throughout many disciplines, collecting, singularizing, and improving existing educational resources has become important in order to advance and familiarize more students, educators, and researchers with the instrument and its capabilities. A unit of educational materials and advice will provide educators with the ability to improve existing courses, labs, and workshops.

Atomic Force Microscopy also has impact earlier than the graduate and undergraduate curriculum. Teaching AFM at the high school and primary school grade levels also benefits students. Images generated during a classroom demonstration can pique curiosity in students. This curiosity, innate to students at any level, is tapped very easily as they begin to witness the surface of a material appearing before their eyes. This curiosity easily pushes students to pursue the growing field of nanotechnology. In addition, exposure to the nano world offers these students a rare opportunity to witness materials, their shapes, and properties, at a scale which would normally be impossible to attain without a doctoral degree or a significant amount of funding. Many students will hear, through their education, about nanotechnology, the size of a micron, and atomic lattices but in most cases they will not be in contact with any instrument or procedure that exposes these properties first hand even throughout their undergraduate career. After all seeing is believing, and through this, atomic force microscopy can be an extremely useful teaching instrument.

While it is generally common for communities such as primary or secondary school to avoid purchasing a research grade AFM, it is not unheard of for certain schools to invest in a teaching AFM used in nanotechnology courses or in physics lecture through demonstrations. Additionally certain schools that cannot afford teaching AFMs, as even these are still expensive, have utilized or created "macro" sized AFMs to achieve similar results at a much lower cost. Macro-AFMs are extremely useful to teach principles of AFM. They also allow teachers to aid students in discovering physics, lasers, forces, and springs to name a few. The AFM’s potential as a teaching tool is only limited by the instructor’s creativity and willingness. The virtually limitless sample scope of the AFM makes it a robust and useful tool while discussing the possibilities of the scientific future. A future that sees nanoparticles lining socks to make them waterproof, a future that continues to improve the quality of materials that go into the body for transplant or surgery, and a future that utilizes the Atomic Force Microscope to accomplish research tasks quickly and efficiently. The potential for this future can only be recognized if AFM is offered to students in their curriculum or as supplemental labs. Exposure is key to igniting curiosity.

This project followed the work flow diagram in Figure 1 and was conducted in accordance with Worcester Polytechnic Institute's graduation requirements for an Interactive Qualifying Project, a science in society project. As a team, background research was completed over the summer of 2015 (May-August). This included research on AFM education and as a mid-summer deliverable, a website was created for the purpose of organizing educational material as a resource for future educators. The website is linked to Professor Nancy Burnham's AFM laboratory web page. In late August, as an end of the summer deliverable, a talk was given to professionals in the AFM field. This talk included the state of our research, future directions, and proposed outcomes. It can be viewed in Appendix B: Power Point Presentation. Upon conclusion of this project the resulting text will be submitted for publication in a new book: Global Perspectives of Nanoscience and Engineering Education.

Atomic Force Microscopy has benefits to educators, workers and students of all levels. The motivation for an increase in awareness, access, and knowledge of this powerful tool stems from the rising prevalence of nanotechnology in primary and secondary schools as well as the usefulness of AFM as a trade skill for undergraduate and graduate students. The expanding prevalence and usefulness has led educators to offer atomic force microscopy as a college course or as a portion of another course. However, successfully implementing AFM as a course in of itself can be an intimidating task. The time, cost, access to equipment and availability of materials are large hurdles to overcome in the implementation of AFM in the classroom setting. For this reason in the following text, a summary of the current status of Atomic Force Microscopy education, a collection of advice from current educators and solutions to hurdles are presented.

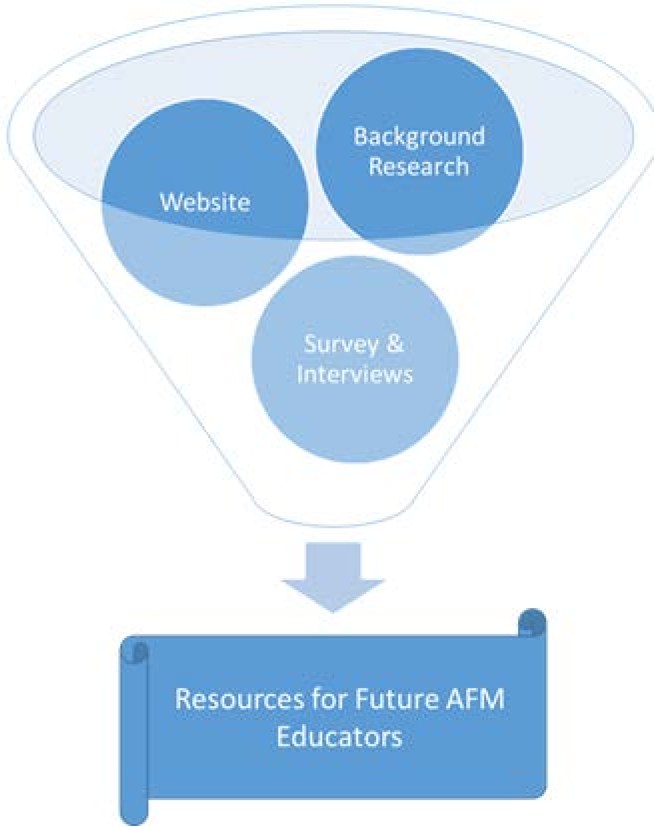


Figure 1. A general work flow diagram to visualize the informational gathering steps - background research, website creation, and survey and interviews - that leads to a unit of resources made up of materials and advice for future AFM educators, i.e. this report.

2.0 Five Levels of Atomic Force Microscopy Education

Atomic Force Microscopy in education can be broken down into five distinct levels with increasing specificity. This classification is based on existing AFM courses found through research. When reviewing existing courses, it was identified that courses fell into different levels of intensity. These levels can be organized by targeted audience as displayed in Figure 2. AFM education begins as at a basic level with demonstrations. Demonstrations are generally geared to an audience of grade school to high school students. Advancing further along the educational system undergraduate and graduate audiences receive more individualized attention with single or several laboratories within another course, term or semester based courses devoted to AFM, and personalized hands-on instruction. This is then followed by post collegiate instruction where professionals and workers attend short courses to learn or brush up on specialized skills. In the following chapter the five levels of AFM education will be described and references given for further information.

Figure 2. The five levels of AFM education - demonstrations, single or several laboratories within another course, term or semester based courses devoted to AFM, personalized hands-on instruction, and short courses - are outlined with a brief description and organized in increasing level of education from primary school to post-graduate programs.

2.1.0 High School and Grade School Integration of Atomic Force Microscopy

2.1.1 Background, Benefits, and Motivation

The integration of nanotechnology into the high school and grade school setting has many benefits to students, educators, and ultimately the work force. Educating students in nanotechnology has the potential to increase their interest in science and engineering careers [ii]; these jobs are the backbone in modern times both in the advancement of technology and the proliferation of a strong and productive workforce. Jobs in nanotechnology continue to grow as technology becomes smaller – the need for a larger workforce is paramount to the success of the field. Thus, teaching nanotechnology, from an early educational level, is beneficial to students in a major way due to its inherent multidisciplinary nature and wide ranging applications. [iii]

Currently nanotechnology is not extensively taught throughout all grade levels. AFM also remains exceedingly specific to the collegiate curriculum, graduate students, and work force training. Nanotechnology has begun to enter high school level classes but has hit several roadblocks. These roadblocks include cost of implementation, difficulty finding teachers who specialize in nanotechnology, and student challenges with visualization at the nano level. Some of these challenges can be overcome through aid of Atomic Force Microscopy, used as a nanotechnology teaching tool. It can help students visualize the nano scale and teachers from several disciplines can be educated on AFM operation. The AFM offers a wide range of functions, and can be adapted to integrate within nearly every STEM course in high school or grade school. Additional information for K-12 AFM education and nanoscience can be found at the websites [1-3] and references [iv-v] at the end of this report.

2.1.2 AFM in Grade School

As competitive nanoscience jobs flood the market, background knowledge is required to interest and introduce students to the powerful tools and concepts of the field. The task of educating students in nanoscience begins in grades K-8 where the subject has become integrated in some STEM preparatory schools. [iv-v] As listed above, the introduction of nanotechnology into these settings is not without challenges. Specifically, visualization of the atomic scale proves difficult as two dimensional models fall short in explaining the three dimensional world in which K-8 students experience daily. [iv] A solution to the difficulties embedded in atomic structure and

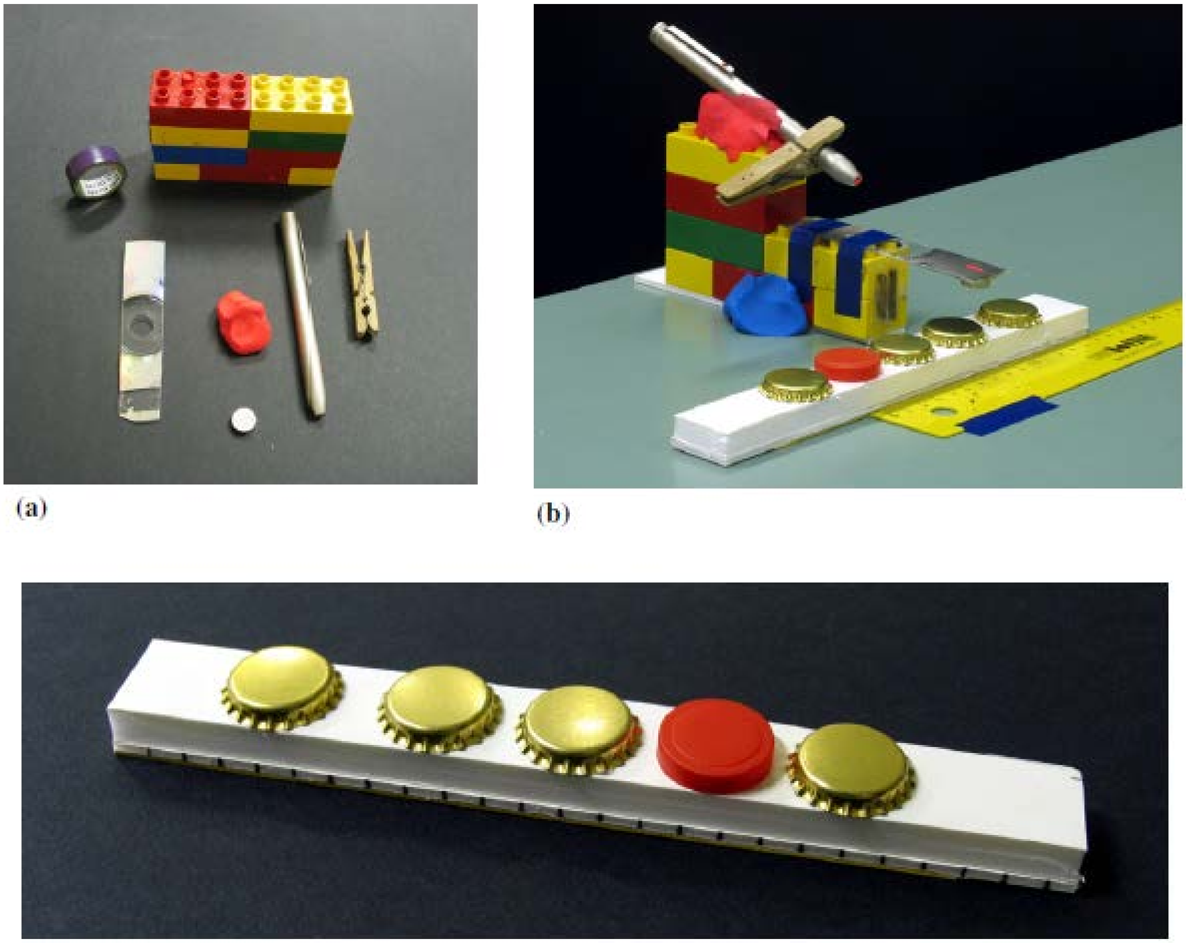
[1] http://nanohub.org/courses/afm1
[2] http://www.education.mrsec.wisc.edu/nanoquest/afm/index.html
[3] http://community.nsee.us/lessons/Macro_AFM_Simulator/Building%20and%20Using%20Tapping%20Mode%20AFM.pdf

visualization can be developed through the integration of Atomic Force Microscopy demonstrations, labs, or hands on experience.

Atomic Force Microscopy has the potential to address the challenges presented to the educational system such that students have the capability to comprehend and excel in the fields of science, technology, and math. AFM can be introduced in chemistry and biology as well as physics. Its multidisciplinary nature is advantageous to teachers, allowing for many demonstrations across several subject areas to be implemented for the purpose of introducing and reinforcing nanotechnology concepts. These benefits have proved successful in upper level education and can be adapted to cover earlier levels as well.

Atomic Force Microscopy can be used in a chemistry demonstration that explains the atomic scale through experiments with graphite. [iv] This can also be a door to explaining the organization of atoms, bonds, and the structure of life on earth. In an introductory physics course AFM can be utilized to explain the interaction of magnets, force, repulsion, electricity and other concepts. However the applications of Atomic Force Microscopy in grade school are only limited by the creativity of the educator and the detail at which they wish to introduce concepts to students.

One specific adaption of the AFM for a grade school setting was achieved by creating a macro AFM. This AFM was designed for use in teaching the principles of atomic force microscopy without purchasing a research or even teaching grade AFM. [iv] As seen in Figure 3, the model highlighted here was created out of Legos.



(a) (b) (c)

Figure 3. This figure shows a creative alternative to the Atomic Force Microscope. While it does not image at the nanoscale the AFM shown here is a representative teaching model that can help introduce nanoscience concepts in grade school through upper level education. The basic parts of this teaching model are shown (a), as well as the total assembly (b), and the bottle caps, representative of atoms (c). Reprinted with permission from Dr. Gorazad Planinsic and IOP Publishing Ltd.[iv]

This macro AFM has a cantilever, created from a CD, with a magnetic tip. This has its benefits as it is more cost effective and can also aid in teaching the students about magnetism. A laser was aimed at the cantilever which was shined onto a projector screen or piece of paper. The sample was created from a line of bottle caps and a magnet. This allows for subtle deflection over the bottle caps and greater deflection over the magnet. The laser bounces across the screen or paper and the points are recorded. This AFM can be applied in any general case while explaining introductory physics or chemistry.

Atomic Force Microscopy can connect many disciplines even in the grade school setting inspiring and intriguing students, guiding them to pursue careers in science and technology. The applications of AFM solidify it as one of the most useful tools in the field of nanotechnology and as one of the most useful tools used to teach nanoscience, being mutually beneficial for teachers, schools, and students at the primary school level.

2.1.3 AFM in the High School Classroom

As with nanotechnology in primary school, nanotechnology has been integrated in several high school curricula. The same limitations and hurdles have been documented between K-8 and high school educators. An addition challenge is finding time in a course to teach a topic, such as nanotechnology, that is not a part of the national science curriculum. [vi] Innovative teaching methods and a multidisciplinary approach to learning are required to sustain a successful program. The AFM can help teachers and students engage in productive discussion facilitating the learning process. While there is no standard curriculum integrating nanoscience-let alone atomic force microscopy-the following will highlight some of the unique applications of AFM in high school or where AFM could be used to successfully integrate nanoscience into the high school curriculum.

Utah High Schools Introduce Nanotechnology

One area where AFM may have a large impact is the implementation of nanotechnology in high schools in Utah. [vii] In Utah, high schools began a pilot program in order to prepare students for careers in technology, sciences, and math. However, these schools were met with hurdles common to nanotechnology and AFM implementation. The problems facing the high schools include where to integrate nanotechnology into their course work: should it be integrated in other courses or in a standalone course? There are benefits to integrating AFM into another course just as there are benefits to a standalone AFM course.

Here the integration of nanotechnology into other courses can be aided by introducing the AFM into the course structure. Explaining copious amounts of theory may not have as large of an impact as demonstrations or laboratory experiments, especially for visual or tactile learners. These nanotechnology implementation hurdles can be solved by hosting an atomic force microscopy demonstration or a brief hands on experiment to reinforce in-class concepts. AFM can be the bridge between the various subjects in which nanotechnology is being integrated. AFM has the capabilities and flexibility to bridge physics, chemistry, and biology. The nanoscale is important to understand for applications ranging from the undergraduate curriculum to work place.

Introducing atomic force microscopy into the high school curriculum as a short demonstration or experiment also solves the issue of who should teach nanotechnology. It would not require additional teachers. Having one or two teachers trained in the usage of the AFM will eliminate the need for additional nanotechnology teachers as long as chemistry, physics, biology, and math introduce nanotechnology concepts that can be reinforced later. A high school could possible borrow another institution’s transportable AFM, instead of acquiring an AFM of their own, greatly decreasing cost.

Rural-Suburban North Carolina High School Experiment

In a North Carolina high school an interesting and extremely successful program brought nanoscience into the classroom through the use of the atomic force microscope. This program was created to investigate alternative teaching techniques for incorporating nanoscience education into the school curriculum. This approach is unique in that it utilizes atomic force microscopy to characterize viruses in a high school setting. It connects the fields of biology and nanotechnology in a seamless application of AFM as a teaching tool. [viii]

The atomic force microscope used in this application was connected through the internet and remotely operated. This eliminated several of the common hurdles present in the use of atomic force microscopy. It helped alleviate the knowledge required to operate an AFM, which at the high-school level may not be necessary, as well as additional staff to teach specific AFM labs or courses. It helped to alleviate cost as well by limiting the amount of money required for startup as well as the amount of money required in consumables and labor.

In this course the atomic force microscope was controlled by means of joystick, offering additional ease of use features. This AFM in particular was called the nanoManipulator. The joystick was connected to the AFM which was controlled remotely over the internet and the resulting topographical image was translated into a three dimensional figure which was constructed on the computer screen as shown in Figure 4. An additional feature of this remote AFM is the haptic feedback design. The remote AFM was designed with an interactive “glove” which moved with the AFM tip. Thus through this design the user is able to feel, in first person, what the atomic force microscope is imaging. This further reinforces concepts taught earlier in the class and now students can feel features on the order of nanometers.

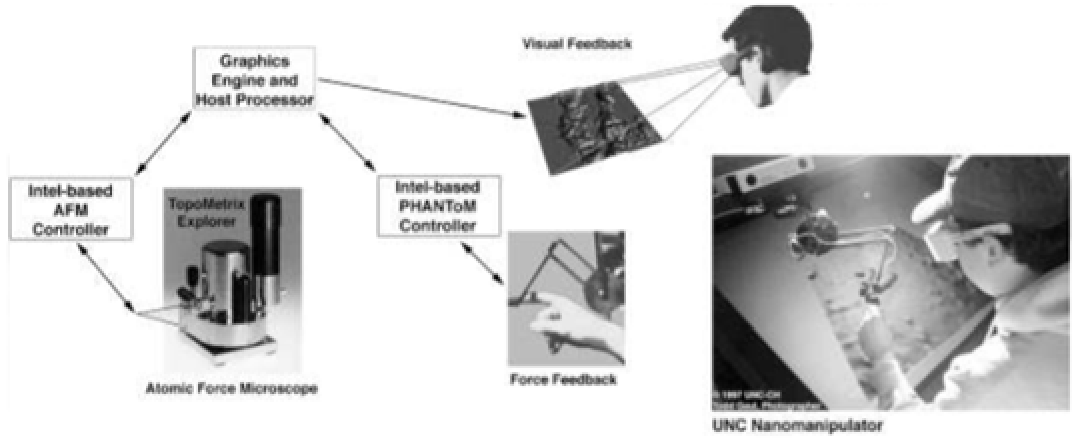


Figure 4. In this figure haptic feedback is discovered by high school students. In an effort to introduce nanoscience into the high school curriculum, the remote AFM was connected to a feedback "glove" that students wore over their finger. They could feel the nano surface as the AFM provides tactile feedback as well as visual cues to aid students in understanding the nano-landscape. Reprinted with permission from Journal of Research in Science Teaching. [viii]

This experiment was implemented in an introduction to biology class in high school due to the variety of students that will come in contact with the course. In addition to the experiments that were run, the students were required to take pre and post quizzes to assess their knowledge and determine the usefulness of the course. The target for imaging was an adenovirus, an integral topic in biology, further relating many subjects to the target audience. The students were required to organize their experiments and findings in a newspaper article, increasing the multidisciplinary aspect of AFM, biology, and nanoscience. This course was successful, with positive reviews from students and teachers alike.

One German and one Turkish High School Case Study

In a 2015 paper authored by Stephan Schwarzer[vi], a case study was conducted involving two high schools, one in Germany and one in Turkey which utilized AFM principles to effectively teach nanoscience concepts. In these high schools, the students participated in an hour long extracurricular session. Creative methods were used in two activities in both schools where students cut paper until it reached the nano scale and students probed objects inside of a concealed box with different size sticks. These concept of scale and forces between two bodies were then reinforced through the use of a teaching AFM (in Germany) and guided questions and student predictions (in Turkey). Worksheets as well as detailed accounts of the activities are included in the reference. Additional enticing conclusions determined that most students benefited from the knowledge gained in the extra-curricular activity, while using the AFM as well as teaching models, even being able to correctly formulate ideas about central nanoscience concepts.

Atomic Force Microscopy can act as a guide and an extremely useful tool for teachers to engage students from the high school level and younger in the field of nanotechnology. The AFM can be particularly useful while connecting concepts from one class to another, and is a powerful instrument to intrigue and inspire students. It benefits schools and teachers by offering many applications for lab exercises and demonstrations. The AFM may be the solution to the challenges facing teachers and schools interested in incorporating nanoscience or nanotechnology into their high school curriculum.

2.2.0 Atomic Force Microscopy Offered to Undergraduate or Graduate Students

2.2.1 An Introduction to Collegiate AFM Education

As nanotechnology remains at the forefront of advancing technology, medicine, and other areas of science, proper characterization methods are important to understanding the properties and usefulness of materials. This can be done through force curve analysis, electrical or magnetic analysis, and other sample-tip interactions with the Atomic Force Microscope. The bounds of the AFM's usefulness can be stretched as far as creativity can accomplish. As the world becomes "smaller" (as in technology), current college students require knowledge of materials as well as knowledge in material characterizing instruments. As “lab on a chip” techniques become more common, as computer processers shrink, and nanoparticles become increasingly more useful in research and industry applications, information about nano-instrumentation spreads further across many disciplines.

Introducing Atomic Force Microscopy into the undergraduate or graduate curriculum can be a costly and time consuming task. However, the enormous benefits to students has encouraged several educators to take on the challenge. The benefits to students include increased job placement, increased graduate school placement, a useful trade skill, as well as an introduction to physics phenomena at the nanoscale. The following sections will cover current course applications and laboratories in the college setting. While beginning to design an Atomic Force Microscopy class for undergraduate or graduate students one must first consider the desired outcomes. Additional references can be found here. [ix-xxi, 4-11]

2.2.2 Undergraduate and Graduate Courses

Generally courses are broken up into several pieces within the overarching unit. Most courses start with a brief introduction to the field of nanotechnology, its applications and importance. Courses then advance to include scale and size, it is sometimes difficult for students to understand the vast differences between the nano scale and the macro world in which they live. After scale and size are introduced the general physics principles can be included. The

[4] http://www.doitpoms.ac.uk/tlplib/afm/index.php
[5] https://www.youtube.com/playlist?list=PL3592A61EEF52B29A
[6] http://www.openwetware.org/images/6/6e/GEM4_teachAFM.pdf
[7] http://proed.acs.org/course-catalog/courses/understanding-and-utilizing-atomic-force-microscopy-from-basic-modes-to-advanced-applications/
[8] https://www.bruker.com/service/education-training/training-courses/afm-optical-training-courses.html
[9] http://www.aif.ncsu.edu/hands-on-instrument-operation-and-sample-preparation/
[10] http://www.ccmx.ch/news-amp-events/news-single/article/144/60/
[11] https://www.youtube.com/user/AtomicForceMicro/playlists

general physics principles on which the AFM are founded can be discussed at length – this is a good way to reinforce the theory of atomic force microscopy. After students begin to grasp the concepts behind AFM, the instrument is introduced in a simplistic form, constant force contact mode. Constant force contact mode, while simplistic, may be the most inspirational for students. It can produce beautiful images at scales students can barely conceptualize. This can provide the motivation for students to comprehend abstract physics concepts that the AFM employs.

After the basic introduction to the AFM, its theory, and practice, most courses have accomplished their end goal: to familiarize students with the type and capability of instruments available to them in industry and research. At this point many courses and laboratories diverge. [ix-xxi] Some courses and labs may conclude on that note, only to race past AFM and introduce many other materials characterization instruments. Some courses may have additional lab time teaching different techniques while deepening students' understanding of the physics principles and image processing through additional lecture time. A few courses and labs include intensive projects where the students create and implement their own experimental design and present their findings at the conclusion of the segment or class. Most of the labor-intensive courses, hands-on experiments, and presentations are geared toward graduate students looking to utilize the atomic force microscope in their research or future career. The major difference between graduate and undergraduate courses lies in the context. The content for the courses are similar; however, the detail for projects, talks, quality of work, and more difficult homework are added to the graduate courses. The following paragraphs will include information taken from both undergraduate as well as graduate courses.

University of Southern Colorado

A unique approach integrated AFM into the college curriculum at the University of Southern Colorado. [ix] In this approach atomic force microscopy was utilized well throughout the entire college career for chemistry majors. The intent of the course was to provide instruction on an important characterization instrument, the AFM, as well as visualize the nano world in an understandable hands-on approach. AFM was successfully used as a professor-led demonstration to small groups of 8-10 in the general chemistry course. However, when chemistry majors returned to take an "Instrumental Analysis" course after general chemistry there were accompanying AFM labs, which included two three-hour labs after which the students findings were documented in a well-written scientific report. From there, hands-on experience and additional opportunities are reserved for upper class and graduate students.

Purdue University

At Purdue University, a course on nanotechnology is partially dedicated to AFM. [xv] It is a general undergraduate course based on nanotechnology with units regarding the AFM. This course is an example of an instrumentation overview course where AFM is only a unit in a greater course. This course begins with background about nanotechnology and the recent boom and excitement regarding the topic. The multidisciplinary nature of nanoscience is also discussed at length where there are units on nanoscience applications of biology, physics and chemistry. As students advance through this course they are introduced to nano electronics and online simulations as well as lectures to prepare them for the atomic force microscopy labs. The technique of AFM operation is taught through interactive simulations and the theory is taught in lecture. The students are finally trained in lab in constant force contact mode. This offers the students just enough information to have a concise understanding of the potential of the AFM but places a limit on their proficiency with the instrument. For graduate students, the same intro topics are covered at a quicker pace, allowing time in the course for students to apply AFM to their own fields. Graduate students tests and reports are also held to higher standard.

University of Nevada Reno

A shorter course was created at the University of Nevada, Reno with help from Stanford University. [xviii] In this course the target audience was a small subset of the University of Nevada Reno's population, four undergraduate and six graduate students. Here the course was taught with both lecture and lab portions. Lectures covered the theoretical aspect of atomic force microscopy as well as the physics behind the instrument. The lecture was populated by daily quizzes, a midterm, and a final. Handouts for the class placed an emphasis on doctoral work and scholarly publication with AFM as an integral part of. This is one way to introduce upper level students to the multiple uses of atomic force microscopy in a practical way. Lectures, labs, handouts, and additional videos used for supplementary content emphasized both theory and practice in this course.

Worcester Polytechnic Institute

A course was created at Worcester Polytechnic Institute in order to satisfy the growing field of nanoscience and expose students to a practical and multidisciplinary tool in research.[xvii] This course has six portions. In the first portion, students participate in hands-on laboratory experiments specifically designed to teach AFM as well as introduce them to academic writing in reports that follow each lab. Mandatory pre-lab quizzes offered an easy way to prepare students for the labs, saving time which is used to gain better proficiency on the AFM. Another portion of the class that students participate in is the lecture. The lecture is designed to introduce concepts that are reinforced in several ways. The concepts taught in lecture are brought up again in videos which are available on YouTube. [12] These concepts are tested in macro-labs which teach the physics theory behind atomic force microscopy. Computer labs add additional reinforcement to concepts learned in class as well as an introduction to image processing. This course is a comprehensive, succinct, and detailed collection of information and knowledge and it is offered every other year. Data collected on the students and course demographics can be seen in Figure 5.

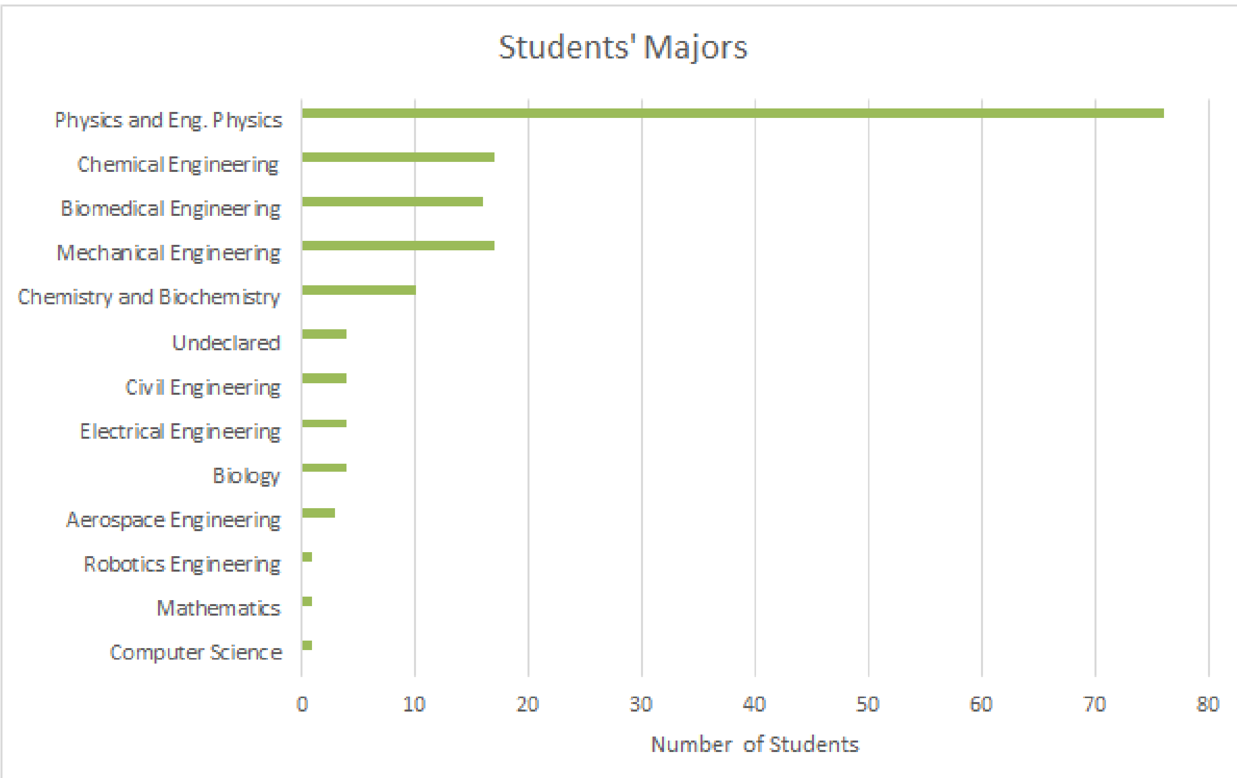


Figure 5. In this figure, data taken from the Worcester Polytechnic Institute describes the current make-up of the Institute's AFM course which is offered every other year. This course is comprised of mostly physics majors but the multidisciplinary nature is highlighted by the wide range of additional majors included. [xvii]

[12] https://www.youtube.com/user/AtomicForceMicro

While there are many approaches to achieving similar results, many courses are taught in a similar fashion that reserves the classroom for theory and physics while lab time is devoted to learning the "black art" that is operating an AFM. [13] This offers students an introduction to a powerful research tool that will help them in senior projects, future academic work, or in industry.

[13] Survey Respondent 9, Question 1; See Appendix A

2.2.3 Labs

Courses are not the only means of teaching atomic force microscopy to undergraduate and graduate students. Labs or lab courses as they are sometimes referred to, are a successful way to help students receive the personalized hands-on experience with the atomic force microscope. Lab courses, as they generally meet less than normal full credit hour courses, do have certain limitations. They may offer more time using an atomic force microscope but the theoretical and physics aspects of the full course may be lost to the students. However this may be an alternative method for educators in lieu of creating a full course. Overall lab courses are much more varied in structure and implementation than full courses. They are widely dependent on the targeted major and range from one lab session in a greater course to a full lab course in its own.

University of San Diego

An atomic force microscopy lab class was created at the University of San Diego. [xviii] This lab course was implemented in 1998 and consists of a single one-hour lab that has three stages. The lab manager essentially set up the AFM such that it could be used as a one button imaging tool. The lab at the University of San Diego consisted of parts that include an optical observation with the naked eye as well as an optical microscope. The remaining time was spent looking at the AFM, learning its technique, and taking one image. While this is a brief introduction, it is the bare minimum when it comes to introducing and making the AFM a useful tool for the students. This course was intended to be a junior level material science course, required for all engineering majors.

Another lab course is specifically targeted at chemistry majors, the use of AFM is to aid in understanding the complexities of working at and visualizing the nano scale. This lab is centered on two main projects which offer students the ability to characterize crystalline materials. Atomic force microscopy is used to determine the structure and properties of these crystalline materials. This is extremely useful to the target audience because it allows them to experience the nano properties of a material then compare and relate those properties to the macro characteristics of the material. [ix]

Arizona State University

An example of a full lab class is presented by Arizona State University.[xix] This laboratory course is offered to upperclassmen as an elective. This limits the number of participants but allows for small classes, which is beneficial during lab times. The lab course is presented with a fifty-minute short lecture on atomic force microscopy with a four-hour lab per week. This class is broken down into three major components from which students gather the necessary background, hands-on experience, and experimental process and report generation. The three categories are: "Fundamental Principles, Core Experiments, and Special Projects." Here the students have access to the lab equipment in order to design their own experiment to be presented at the end of the course.

University of Waterloo

A final lab course is taught at the University of Waterloo, is perhaps the most intensive of the lab courses available yet. [xx] The course requires roughly eighteen to thirty-six hours of combined course and outside work. This lab course is taught as part of a nanotechnology engineering degree at the University of Waterloo. It is a lecture of seventy to one hundred and thirty students; a significantly larger number of students than other labs had. However the course is meant for this high capacity and is designed such that the professor explains and demonstrates atomic force microscopy techniques with an AFM hooked up to a projector as shown in Figure 6. After watching the instructor on the projector, the students break into groups to use the AFM stations, of which the AFM lab at the University of Waterloo has five. This allows for multiple groups to access an AFM at one time. Additionally this lab is extensively used for senior projects.

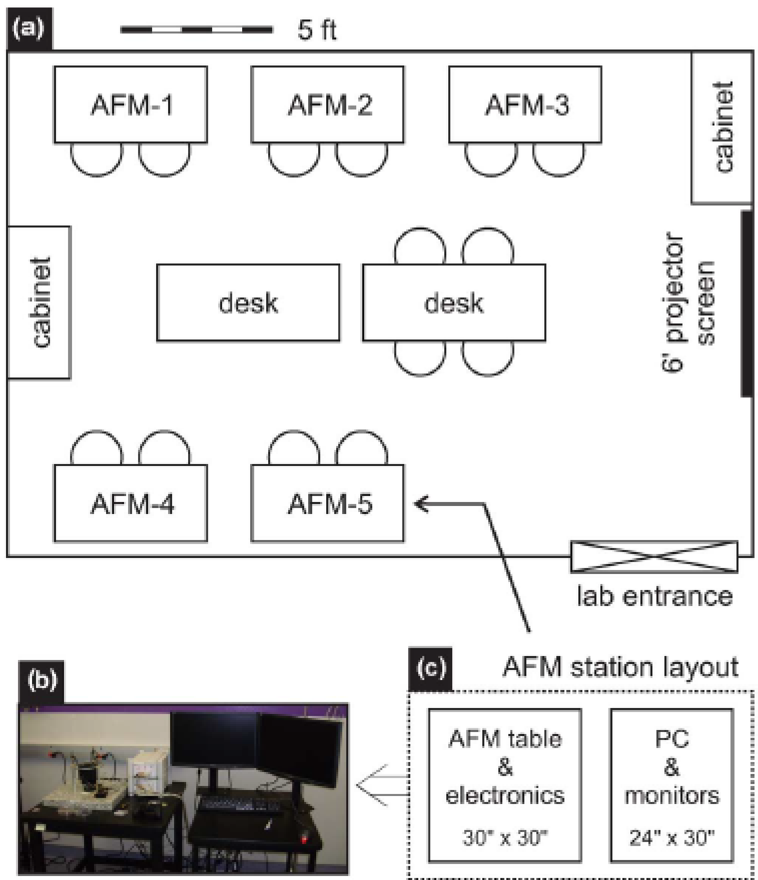


Figure 6. This figure highlights the lab setup as well as the desktop AFM used in the intensive University of Waterloo AFM lab course. The lab is widely used by researchers and graduate students, as well as for the undergraduate lab course. The lab consists of five AFM desks, cabinets for materials and sample prep, and a projector screen. Reprinted with permission from IEEE Transactions on Education. [xx]

Lab courses are an effective means to integrate the usefulness of an AFM course into the curriculum. Yet Labs offer more hands on time but less time for theory. Based on the target audience, and the amount of background knowledge needed, lab courses may be more efficient than full term or semester based courses.

2.3 Post-Graduate AFM Education

Atomic Force Microscopy is widely used in industry as well as research for many companies and institutions. This creates a need for post collegiate AFM education. Educating workers and professionals requires different strategies to accomplish the educational outcomes. Generally educators will host a workshop or brief course geared toward the specific use of the AFM needed by the student. These short courses are used as a brush-up on standard uses of the AFM as well as to learn, in depth, very specific techniques. These courses or workshops can be aimed at professionals who have previous experience operating the AFM or those who are utilizing it for a specific purpose and need to learn a specific skill.

A pilot short course was taught at ETH Zurich in the summer of 2015 by Professor Nancy Burnham using the course materials developed at Worcester Polytechnic Institute.[xxii] This short course was taught to graduate students, as an experiment in feasibility for adapting the current, term-long undergraduate and semester-long graduate courses, into a short week-long workshop. The format is ideally suited for post-collegiate AFM education. The short course ran over a period of seven days in which students became proficient in the usage of the AFM in several different modes. The differences between the short course and the undergraduate or graduate courses is the exclusion of the time consuming lab reports, writing assignments, in class work, and exams. The parts of this course are described in Figure 7. The course was successful and will be expanded from seven to ten days to allow for a more thorough educational and learning experience.

Figure 7. In this figure students from ETH Zurich take part in a summer short course on AFM operation. It was a seven day intensive course on operation and theory with components including force curves as well as contact mode AFM. Students were allowed to create and run their own project with the AFM as well. Highlighted here are the Naio AFM (a), computer labs (b), and macro-labs (c). Figure compiled by N. A. Burnham [xx] and reprinted with permission from the creative commons publication.

Many of these courses are available to take and are publically offered by atomic force microscope manufacturers. [14 -22] Additional resources for AFM educational materials can be found in Appendix C: Bibliography. The following section will review a survey given to figures in AFM Education.

---

14 http://www.afmworkshop.com/atomic-force-microscope-for-educators.html
15 http://www.london-nano.com/cleanroom-and-facilities/training/afm-training
16 http://www.schaefer-tec.com/en/germany/products/scanning-probe-microscopy/afm-workshop.html
17 http://lnf.umich.edu/nnin-at-michigan/afm/
18 http://www.afmworkshop.com/afm-webinars.html
19 http://gwyddion.net/
20 http://www.microscopedia.com/
21 http://www.teachnano.com/education/newsletter/index.html
22 http://microscopyeducation.com/home.html

3.0 Survey and Interviews

A survey and interviews were utilized to collect multiple points of view from figures within the field of AFM education.

3.1 Survey

A survey was created and sent out to prominent figures in atomic force microscopy education. [23] The survey had three sections. The first section was made up of three questions regarding the respondents' personal information. This allowed the respondents' other responses to be put into the context of their background. The second section was made up of five long-form response questions regarding the survey participant’s personal views on AFM education. Most of the information gathered was collected from the responses to questions in the second section of the survey. The third section assessed the survey takers willingness and availability to participate in an interview. Our survey questions can be found in Table 1.

Table 1: An index of the questions asked on the survey sent out to figures in AFM education.

Question 1*	Name
Question 2	Organization/Affiliation
Question 3	Years Experience in AFM Education
Question 4	What hurdles did you have to overcome in teaching Atomic Force Microscopy (e.g. cost of AFMs or consumables)? Do any remain?
Question 5	Did you have any hesitations about creating an AFM lab or course? If so, what were they? Are they now assuaged?
Question 6	What is your advice to prospective AFM educators?
Question 7	Do you believe exposure to AFM benefits students? Why?
Question 8	Do you see a future where AFM becomes more prevalent throughout all levels of education? Why or why not?
Question 9	Would you be willing talk to a student researcher for a half an hour (e.g. Skype or Google Hangouts or FaceTime) to discuss your AFM lab or course? If so, please indicate some dates before the August 22 that you would be available. Thank you for your time.

[23] The survey can be found at: http://wpi.qualtrics.com/SE/?SID=SV_29Tar5LCuDqUyu9

As part of research for the earlier section of this report, 260 figures in AFM education were identified. Each contact was sent the survey by email. Two weeks later, a reminder email was sent out to those who had not yet responded. We received 23 survey responses, a response rate of about 9%.

There was consensus for some questions. However, a few questions returned responses that varied in opinion. Instead of merely listing all of the responses to our survey questions, which can be found in Appendix A, we are instead highlighting recurring themes, as well as mentioning a few specific responses.

Question one, was *"Name"* In respect of our survey responder's privacy, their names have been removed and have been replaced with a number corresponding to the order the surveys were submitted, with one being the first survey submitted.

Question two was simply: Organization/Affiliation. Of the 23 survey respondents, 22 responded to this question. Those 22 responses included 19 unique institutions. A list of those institutions can be found in Appendix A: Survey Questions and Responses. Affiliation has been removed from the responses to protect each respondent's identity. The 19 different organizations are a good representation of different types of establishments, but only in the United States. The survey was sent to organizations across the globe, however only people established in the United States responded. This may be due to a language barrier, as the survey was written in English. It is important to keep in mind that while this was written with global AFM education in mind, there is a heavy leaning towards what occurs in the United States due to the survey responses we received.

Question three was: *"Years Experience"* in AFM Education. This optional question was answered by 22 of the 23 participants. The maximum was 27 years, while the minimum was 0 years. The arithmetic mean of the number of years involved in AFM education was 15.05. The median was 15.5. Surprisingly, the mode was 20 years. Overall, our survey respondents have had a significant amount of experience in AFM education, with more than 75 percent of the respondents having a decade, or more, of experience. There was a rough correlation between the number of years' experience and the length of responses, with the more veteran survey respondents submitting longer responses than those with less experience.

Question four, the first long-form response question, was: *"What hurdles did you have to overcome in teaching Atomic Force Microscopy (e.g. cost of AFMs or consumables)? Do any remain?"* The responses were varied, but tended to follow common themes, as shown in Figure 8. The primary themes were cost, proper educational tools and materials, time professors spend teaching, and time for students to learn theory. Most of the respondents were concerned with multiple hurdles. Respondent 17 was concerned with both cost and proper educational tools, in this case access to an AFM. Respondent 17 said: "Cost of consumables is an issue. It creates some difficulties for us that our research instrument is also used for teaching." Respondent 23 was also concerned with multiple hurdles: the time commitment for both students and professors, saying: "the difficulty in exposing teams of students to AFM when only one person at a time can really use it (with others watching) - time involved in training and writing documentation to prep students." It is the combination of these four hurdles that hinder educators teaching Atomic Force Microscopy.

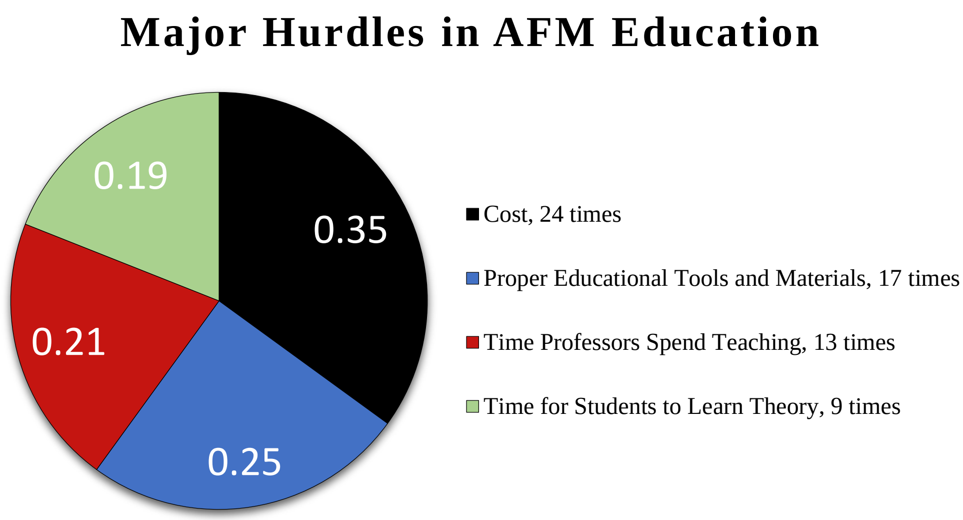


*Figure 8. Four of the most prevalent hurdles in AFM education as determined by our survey are: cost, proper educational tools and materials, time for teaching, labs and TA's, and time for students to learn the theory of AFM. Percentages on the pie chart are calculated by dividing the individual hurdle number by the total number of hurdles mentioned (e.g. Cost/total hurdles mentioned * 100 = 35.5%).*

Question five, the second long form response question was: *"Did you have any hesitations about creating an AFM lab or course? If so, what were they? Are they now assuaged?"* The most common response was along the lines of no, none, or N/A. One of a few respondents who explained their lack of hesitations was Respondent Five, who said: "No. In the mid-90s I saw the increasing applications of AFM in diverse fields as well as the preparation of students for future careers or graduate studies, the training of the use of AFM will be helpful. Besides the concept of nanoscale is easier to believe by seeing an AFM image. Now the AFM are used in many fields and it may be easier to sell the need of AFM education." Respondent 5 identifies what most of others left unsaid: that they recognized the pros of AFM education far outweighing the cons. Despite the advantages of AFM, other responders had concerns, mainly students damaging expensive equipment and the time commitment required. And yet, even those with concerns acknowledged that despite the difficulties, it was worth it. As Respondent Six said: “The difficulty of getting students trained and the risk of them breaking equipment. It's still a struggle to train students, but I think it's worth it…” It is clear that creating an AFM lab or course takes a significant amount of effort, as Respondent Nineteen said: “Creating innovative labs for AFM requires that one tries things out first and creates good documentation - that takes time." However, despite the hesitations educators might have, and the hurdles that they face, in general they acknowledge the rewards of teaching AFM make it worth wile.

Question six, the third long form response question was: *“What is your advice to prospective AFM educators?”* Once again, all of the responses shared similar themes. By far the most common theme was to be patient. Respondent 3 simply put it: “Be very patient.” There are many things that can go wrong, whether it be with the equipment, or with the students, and many respondents stressed the necessity to be patient and work through these problems. One major problem the respondents said to watch for was things breaking. Respondent 13 summed it up saying: “students will break a lot of probes and even the AFM.” The reality is that students will break things, and that extreme patience is necessary to move forward.

Respondents also advised future educators to keep in mind the importance of creating a balance between theory and practice. Many of the existing courses in AFM emphasize the necessity of both teaching the theory, as well as creating a hands-on portion. As Respondent 12 said: “Include both a significant theoretical and practical component. I think it is important for students to have a good grasp of the scientific background related to any microstructural tool that a student will use in his/her work.” Part of the beauty of AFM is its ability to open a door into the nano world, and there are significant advantages for the students to be the ones operating the door, as Respondent 1 emphasized: “You have to allow the students hands on experience.”

Letting the students do the work increases their investment in their own learning, as Respondent 7 said, “Let students find out themselves how it works. Most motivating experience.”

An additional category of advice the respondents gave was about decreasing cost, which was the biggest hurdle identified by educators in the survey. Some respondents suggested alternatives to costly research grade AFMs, such as Respondent 15 who suggested a teaching grade AFM saying: “Find a way to purchase a dedicated teaching AFM that is generally cheaper.” Other respondents gave advice on establishing funding sources. Respondent 5 said: “Find time and write proposal applications to funding agencies or talk to school administrators and justify the need of AFM for education.”

Question seven, the fourth long form response question was: *“Do you believe exposure to AFM benefits students? Why?”* The consensus of the responses was a resounding yes. Respondents valued AFM’s educational value because of its widespread presence in industry and research, as well its application of physics, and its overall versatility. Respondent 2 thought that AFM was especially important for students majoring in physics, saying: “Sure, especially physics majors. A lot of our majors are interested in doing research, so it helps them to learn advanced tools.” Meanwhile, Respondent 15 thought it was particularly useful for material science majors saying: “Yes. Especially in a Materials Science department. This technique is becoming very widespread in industry.” Multiple respondents thought that exposure to AFM benefits students in terms of research, including Respondent 18 who said: “Yes. It's a tool to interest them in conducting research. A very powerful tool.", as well as Respondent 14 who said, “Yes - SPM techniques are now an essential tool in a wide range of research fields. It is a skill set that is often in demand. I have had more than a few students tell me that the AFM course helped them in interviews for Post-doc experiences and research positions.”

Several respondents thought AFM was powerfully useful for creating a more comprehensible hands-on example of concepts which students were learning in class. Respondent 8 said, “Yes - it provides training in a truly modern experiment, which is rare in Physics.” Respondent 6 said: “Yes, it's one of the few accessible tools that give students direct access to the nanotechnology revolution. AFM also contains many aspects of fundamentals from their courses, e.g. physics, optics, controls.” It is clear that the respondents believed AFM to be extremely useful to students in terms of academic knowledge and research applications. However, AFM is more than just a way of learning concepts, it is a tool that motivates curiosity. As Respondent 7 said: ““Yes. They see that a simple instrument can reach atomic resolution. This is inspiring.”

Question 8, the last long-form response question was: *"Do you see a future where AFM becomes more prevalent throughout all levels of education? Why or why not?"* Unlike the other questions, the responses to this question did not generally agree, but instead fell along a spectrum. Some respondents felt very strongly that AFM education will grow: “Yes. There will be increasing numbers of used AFMs available, making it possible for all levels of schools to have access, and with the increase in students understanding of nano in the world, an AFM makes more sense.” While others felt more indifferent to AFM compared to other options like scanning electron microscopy, or transmission electron microscopy saying: "Probably not. Why should AFM be more important than some of the light microscopy imaging technologies, or TEM, or SEM, etc.?" Others were more negative, saying: “Not really." The most common thing cited as a barrier to AFM becoming more prominent was cost: “Not really. It is very nice technique, but is only one of many. It is not cheap and the bar to entry is somewhat high.”

Question nine, the last question was: *"Would you be willing talk to a student researcher for a half an hour (e.g. Skype or Google Hangouts or FaceTime) to discuss your AFM lab or course? If so, please indicate some dates before the August 22 that you would be available. Thank you for your time."* Several respondents indicated a willingness to be interviewed, and two interviews were conducted. More information on interviews can be found in Section 3.2.

The general consensus was that the main hesitations and hurdles were cost, access to equipment and materials, and time. A breakdown of challenges and hesitations can be found in Figure 4. Despite these challenges, the survey respondents agreed that the advantages of an AFM education made it worthwhile. Survey respondents encouraged other educators to greet the challenges of teaching AFM with great patience. For many difficulties involved with teaching AFM, there are ways to overcome them. Some such solutions are explained in greater detail in Section 4.0 Major Hurdles and Solutions. Additional first-hand information is discussed in the following section where two interviews were conducted to get an educators perspective on the current stages of AFM education.

3.2 Interviews

As mentioned in Section 3.1 Surveys, we inquired as to whether or not the survey respondents would be interested in participating in an interview. Out of the 23 survey participants we received two responses in the positive on a time scale that we could accommodate. The goal of our interviews had three parts: first, to obtain free responses from our contacts, which may cover topics we had not included in our survey, second, to obtain more information on what students go on to do in academia or industry, and third, to identify what works well when teaching AFM.

The first interview confirmed for the most part what we had found in the surveys. The one interesting addition was the usage of a lab fee to help cover costs. Our interviewee had instructed a course that was made up of a 1-2 hour lecture and a 3-hour lab per week. The labs started with the practical basics, mainly using calibration samples. Then the lab moved onto a topic that the student was interested in, for which the student would bring in their own lab samples. Having students examine samples that they were individually interested in has two main advantages: first, because students prepare the samples themselves, the samples are relatively low cost. More importantly, it allows the students to be inspired by the AFM's usefulness in their own field of interest. The professor stated that there wasn't enough time to do everything, so they heavily relied on a grad student. If there was no grad student with the necessary background, they simply did not hold the course. In addition to the lab fee, probes were recycled to lower the cost further. In this course, the students do not handle the scanner to limit damage.

The second interviewee offered a different position in AFM education and experience. As a part of a national research lab in California this professor has contact with post graduate and graduate AFM education. He stated no difficulty with access to material or knowledge but did state some challenges with teaching students not to pour liquid over the scanner. The biggest hurdle this professor brought to our attention is summarized in his statement to us, "it is very difficult to find the right level of information, it is hard to explain to a biomedical engineer about a mechanical oscillator, while it is hard to explain to a mechanical engineer about sample prep." In a succinct way this professor touched on the lack of information available for each level of education. As with the multidisciplinary nature of the AFM, there are an overwhelming number of sources, and sifting through that information can be tedious and fruitless. The interviewee also spoke on sample prep and the difficulties that also ensues, "Sample prep is often underestimated, it may take years to prepare or perfect getting a clean or liquid free surface." He specified how during high level research applications sample prep plays an integral role and cannot be overlooked as far as a course or lab goes. For graduate level or post-graduate level AFM courses or labs a sample prep section may be integrated to fully develop students as competent researchers.

After discussing common challenges and the current status of atomic force microscopy education, a section on major hurdles and solutions, to immediately follow this section, was rounded out with their advice and opinions.

4.0 Major Hurdles and Solutions

A course on AFM education requires arguable more effort than the average college-level intro course. For an AFM course that has a lab portion, in addition to the normal set of tasks associated with a lecture course, there are also the requirements for running a lab with expensive equipment. As shown in Figure 9, there are four main hurdles, but there are also solutions for each one of them. Cost is one of the biggest hurdles. Another big obstacle is the amount of time a course requires, both for the instructor and the students. A third major impediment is access to AFMs for a lab portion. A fourth challenge is access to resources, including good preexisting documentation. The following sections will address each topic of Figure 9 in the order Cost, Time, Equipment, and Resources.

Solutions and Advice for Common AFM Hurdles

Cost

- Grant money can alleviate cost
- The AFM will always be in use (loans and research)
- A lab fee may be used instead of a book cost

Time

- Lab supervisors and teaching assistants can save time
- Existing courses can offer a basis for implementing a new class

Equipment

- Table 2 shows where to access AFMs and equipment in a cost effective way
- Creative alternatives can be used like macro-AFMs and computer labs
- Prelab quizzes help students to use equipment efficiently

Resources

- Additional resources for teaching aids, YouTube videos, and material can be found in the References and Bibliography sections along with established courses and text books

Figure 9. In this figure solutions for common AFM hurdles are presented. The solutions are based on background research as well as survey responses.

4.1 Cost

Cost is a big factor when dealing with AFM. A research grade AFM can be extremely expensive, not to mention the cost of consumables. However, a research grade AFM is not required for every AFM course. There are several more economic alternatives. One possibility is to use an AFM remotely over the internet. This removes the possibility of students damaging the AFM, however, it also removes some of the hands-on nature of an AFM lab. An application of this is explained in greater detail in Section 2.1.3, AFM in the High School Classroom. Another solution is using a macro AFM. This is not an AFM in the traditional sense, but instead has the same components as an AFM, at the significantly cheaper macro scale. These types of AFMs are explained in greater detail in Section 2.1.2, AFM in Grade School.

A third solution is to use a teaching grade AFM. These are still AFMs capable of measuring on the nano scale. However, they are not necessarily as accurate as their research counterparts. This means that they are cheaper, but are still useful for teaching. An example of the offerings for teaching AFMs can be found in Table 2. It is important to keep in mind that the prices listed here, were as of 2015, and may have since then changed.

Table 2. A selection of different teaching AFMs, their prices, type, and where to find them. All prices are given in USD as of 2015.

Name	**Price**	**Type**	**Distributer**
TT-AFM	$26-32,000	Tabletop	AFM Workshop[24]
Eddy	$21,000	Tabletop	Anfatec[25]
NaioAFM/ TraxAFM	$20-27,000	Transportable	Nanosurf/nanoScience Instruments[26-27]
ezAFM	$15-33,000+	Transportable	NanoMagnetics [28]

The TT-AFM, provided by AFM Workshop, has the option to either be purchased assembled, or purchased as a kit. [29] Accompanying the AFM is the option to purchase a seat in a TT-AFM assembly workshop. This workshop lasts five days, and is advertised to run several times a year. The workshop teaches participants not only how to assemble and perform maintenance on their AFM, but also how to run test samples and make images. [30] The Eddy AFM, like the TT-AFM is a tabletop model and is provided by Anfatec for a slightly cheaper price. Interestingly, both the NaioAFM and the ezAFM are transportable. This opens up a lot of

24 http://www.afmworkshop.com/tt-afm.html
25 http://www.anfatec.com/anfatec/eddy/eddy.html
26 https://www.nanosurf.com/en/products/naioafm
27 http://www.nanoscience.com/products/afm/traxafm/
28 http://www.nanomagnetics-inst.com/enhttp://www.nanomagnetics-inst.com/en/products/ambient-microscopes/ezafm-1
29 http://www.afmworkshop.com/tt-afm.html
30 http://www.afmworkshop.com/tt-afm-kit.html

opportunities for using the AFM. A single AFM could be moved between schools and used for outreach. A university doing outreach at a high school could bring along the AFM with them, instead of just bringing images and other media. A transportable AFM could have a very high return on investment because it could very easily nearly always be in use.

The cost of consumables is also a factor. There are many different manufacturers of probes. Different probes can have widely varying qualities. Students using an AFM don't necessary need high quality probes. Probes with less accuracy could be acceptable. Teaching probes, in 2015, can cost about $20 each, or $10 if purchased in bulk. Both MikroMasch [31] and Budget Sensors [32] sell probes applicable to education situations. Existing old research probes, perhaps too dull for research, but still functional, could be used by students.

Given the expensive of running an AFM lab course, it may be necessary to get additional funds to run the course. One option is to apply for grants, or look for a sponsor. Nanotechnology is an important and growing field, so there are companies looking for students with a background in AFM. These companies might be willing to help finance an AFM course, or donate an instrument to use. Another option is to charge a lab fee. It is not unusual for a course to require the purchase of a textbook. In an AFM course, where there may not be any written materials to be purchased, it may be reasonable to charge a lab fee. As an example, in 2015, the required textbook with online access for an introductory calculus-based physics course at Worcester Polytechnic Institute, costs $360 through the official book store. [33] Although, charging $360 would be an additional financial burden for students, it would be comparable to what they would be expected to pay in other classes.

[31] http://mikromasch.com/
[32] http://www.budgetsensors.com/
[33] http://wpi.bncollege.com/webapp/wcs/stores/servlet/BNCBTBListView last accessed (9/21/2015)

4.2 Time

Time is a precious resource, for both instructors and students. An AFM course is a big time commitment for both parties. Students often underestimate the difficulty of participating in an AFM course. To alleviate some of the stress that such a large time commitment comes with, it is important to make sure that the students understand, at the beginning of the course, what they are getting themselves into. Some students may not fully believe exactly how much time a professor says the class will require, but many will appreciate the warning.

In terms of making the time commitment manageable for instructors, it may be necessary and advisable to hire one or more lab supervisors. An AFM course with a lab component will require students, who are relatively unexperienced, to use expensive equipment. To protect the equipment and the students, it may be necessary to always have someone supervising the students when they are in the lab. Depending on the number of students, the number of instruments, and the length of the lab, the number of hours that require supervision will change. Worcester Polytechnic Institute's undergraduate AFM course, has 6 lab sessions a week in 2015, each lasting for two hours. So, each week there were twelve hours during which students had to be supersized. An additional twelve hours per week to supervise students in a lab is a huge burden to expect a professor to take on. Lab monitors or teaching assistants can also aid the professor in grading homework, exams, and lab reports. Additionally in order to make the time spent on the equipment more meaningful and efficient, pre-lab quizzes may be administered. This helps enforce proficiency in the students as well as reduce wasted lab time.

When creating an AFM course, it may be possible to save time by basing labs, homework, pre-lab quizzes, and overall class structure on previously existing courses. Examples can be found in Section 2.2.2 of this document.

4.3 Equipment

Obtaining access to AFMs for a course can be extremely difficult. In a university where there are existing AFMs, time on the instruments may be completely taken up by researchers. Additionally, researchers may not want inexperienced students using their AFMs. However, in some cases there may be an older AFM which researchers may be willing to let students use. In a university where there are no existing AFMs purchasing a research grade may not be economically feasible. Additionally, finding lab space for such an instrument may be difficult. There are several alternatives to purchasing a research grade AFM, such as purchasing a teaching grade AFM, remotely controlling an AFM, and making a macro AFM. More details on these alternatives can be found in Section 4.1 Cost.

Additionally, not all lab activities necessarily require an actual AFM. It is possible to explain the basic concepts in a macro or computer lab, as an alternative to an AFM lab. For example, Worcester Polytechnic Institute's undergraduate AFM course contains only twelve hours of actual lab time for a given student. However, there are an additional two to three hours a week spent in a combination of a computer lab and a macro AFM lab. These alternative labs allow students to spend time to understand the concepts while interacting with a model of an AFM, without having to spend additional time on an AFM. This results in the time spent on the AFM being extremely productive, and a decrease in the number of necessary supervised AFM lab hours.

4.4 Resources

There are few good sources of documentation on AFM education. That is in fact one motivation for this book chapter. There are some resources for AFM education, however they tend to be very spread out, often across resources for several disciplines. For information on online nano education resources, please refer to chapter three of the book "Global Perspectives on Nanoscience and Engineering Education." In an effort to create a singular resource reference, a website was created.[34] The website includes information on academic articles, websites, and even YouTube channels which focus on AFM education. There are also several books on Atomic Force Microscopy. Our recommended starting documents are listed in Appendix C.

Resources, information, interviews, and many other perspectives on atomic force microscopy education have been gathered and shed light on hurdles and hesitations of teaching AFM. These hurdles and hesitations have been addressed with possible solutions. From the body of research and compilation of information, several concluding thoughts will be addressed in the following section.

[34] http://www.wpi.edu/academics/physics/AFM/nanoed_resources.html

5.0 Conclusion

Atomic Force Microscopy has proven to be a powerful tool in both research and industry but it has potential for even wider applications. AFM can be used in an educational setting to provide important knowledge and be utilized as a teaching aid. The current status of AFM in educational systems can be broken down into five general levels which encompass each level of schooling from primary school/middle school, high school, college, graduate programs, and to post graduate education. Throughout these educational platforms AFM can be used to help implement nanoscience programs in grade school to high school levels. In college AFM is utilized in a variety of ways: to provide exposure to an industry tool, to accomplish research, or as a supplement in other microscopy courses to provide a few examples. The current status of atomic force microscopy in the educational system has been discussed and analyzed. AFM has many benefits to students and educators alike, but it is not without its challenges. Implementing atomic force microscopy takes significant dedication by students and teachers in the form of time, cost, access to equipment, and educational materials. These hurdles are daunting and intimidating, however the aforementioned surveys, interviews, and a website full of educational resources has been compiled in an attempt to offer help and advice to prospective AFM educators.

7.0 References

i. A. Goonewardene, et al, Am. J. Phys. **79,** 693 (2011)
ii. C. N. Jones and J. Gonçalves, IEEE Transactions on Education **53,** 328 (2010)
iii. J. L. Feather and M. F. Aznar, *Nanoscience Education, Workforce Training, and K-12 Resources* (2011)
iv. G. Planinsic and J. Kovac Physics Education **43**, 1 (2008)
v. H. Margel et al, J. Chem. Educ. **81**, 4 (2004)
vi. S. Schwarzer, S. Akaygun, et al, Journal of Nano Education **7**, 10 (2015)
vii. A. Kurtz, M. Anderson, and T. Kar, in Proceedings of Nanomodeling II, San Diego, 2006, edited by A. Lakhtakia and S. A. Maksimenko
viii. M. Jones et al, Journal of Research in Science and Teaching **40**, 3 (2003)
ix. D. Lehmpuhl, Journal of Chemical Education **80**, 5 (2003)
x. M. Maye, J. Luo and C. Zhong, Journal of Chemical Education **79**, 2 (2002)
xi. C. Zhong et al, Journal of Chemical Education **80**, 194 (2003)
xii. K. Winkelmann, Journal of Nano Education **1**, 1 (2009)
xiii. R. Blonder et al, Journal of Chemical Engineering **87**, 12 (2010)
xiv. A. Goonewardene et al, American Journal of Physics **79**, 693 (2011)
xv. H. A. McNally, IEEE Nanotechnology **7**, 19 (2013)
xvi. J.D. Adams, B. S. Rogers, and L. J. Leifer, IEEE Transactions on Education **47**, 51 (2004)
xvii. N. Burnham, Journal of Nano Education **5**, 2 (2013)
xviii. M. A. Hawkins and S. M. Lord, in American Society for Engineering Education National Conference, Charlotte, North Carolina, 20-23 June 1999, pp. 4.169.1-4.169.6.
xix. W. S. Glaunsinger, B. L. Ramakrishna, A. A. Garcia, and V Pizziconi, Journal of Chemical Education **74**, 310 (1997)
xx. D. Russo, R. D. Fagan, and T. Hesjedal, IEEE Transactions on Education **54,** 428 (2011)
xxi. W. Huachuan et al, Journal of Nano Education **5**, 79 (2013)
xxii. N. A. Burnham, A. Arcifa, M. Divandari, C. Mathis, S. N. Ramakrishna, and N. D. Spencer, Accepted for the 2015 Conference on Laboratory Instruction Beyond the First Year of College, College Park, Maryland, 22-24 July 2015.

6.0 Acknowledgements

We would like to thank our interviewees as well as the survey respondents for their contributions to our final work. The detail as well as quality of advice found in this document is attributed to them. This succinct compilation of advice and materials for current and future educators would not be possible without them. We would also like to acknowledge our advisor Professor Nancy A. Burnham, without whom none of this would have been possible.

Appendix A: Survey Questions and Responses

This appendix contains survey questions with accompanying responses from those who answered our survey. The responses to question one have been omitted, and the responses to question two reformatted in respect of the survey respondents' privacy. For every other question, respondents' answers are organized by the order in which they completed the survey.

Question 2. Organization/Affiliation?

Table 3: Organizations/Affiliations reported in the survey.

Organization/Affiliation
Appalachian State University
George Washington University
Georgia Institute of Technology
Iowa State University
Johns Hopkins University
Lawrence Berkeley National Laboratory
North Carolina State University
Oregon State University
Pennsylvania State University
Rensselaer Polytechnic Institute
College of William & Mary
Tufts University
University of Pennsylvania
University of Houston
University of Nebraska Medical Center
University of North Texas
University of Notre Dame
Virginia Tech
Wayne State University

Question 4.
What hurdles did you have to overcome in teaching Atomic Force Microscopy (e.g. cost of AFMs or consumables)? Do any remain?

Respondent 1: "Biggest problem is finding time on the equipment as it is used heavily in research."
Respondent 2: "There is no problem if there is a lab with the AFM equipment and experience."
Respondent 3: "The cost is not great, in terms of cantilevers, etc. Mostly, though, AFM is just more delicate than SEM, or optical microscopy. So students have a tendency to break things. You have to watch them like a hawk."

Respondent 4: "1. Lack of research grade AFM for teaching. Cheap alternatives are not as good. Learning by using them would be rather misleading.
2. Multidisciplinary interest to this technology brings students with different backgrounds. As a result, I typically need a special course to teach about intermolecular forces before effective teaching of scanning probe microscopy."
Respondent 5: "The initial cost of the purchase of an AFM and later the consumables such as tips, tweezers, etc. In addition, the course or lab needs good teaching assistants who are experiences in using an AFM and preparing samples."
Respondent 6: "Cost of consumables, complicated equipment to teach (computer software, electronics hardware, optics, physics of oscillating systems). Students have a big hill to climb before they are competent."
Respondent 7: "AFM to get images is easy but quantitative Images with correct interpretation can be challenging. It was difficult to get access to instruments to large classes."
Respondent 8: "The only hurdle for me was that there are no "standard" experiments in microscopy. We were lucky to have a good instrument partly through university teaching funds that was designated for use in our Senior Lab course."
Respondent 9: "The general operation and use of AFM is not too difficult to teach. Obtaining topographical images of a substrate in air is relatively easy to do. This becomes more complicated depending on the information you wish to obtain from the AFM measurement. For instance, obtaining high resolution images (e.g., lattice imaging) is very difficult. It can be challenging to use techniques such as phase imaging. Using AFM for more advanced operations, such as in situ imaging to capture dynamic events in real time, takes time to learn. One of the most difficult aspects of teaching AFM is that much of it is a "black art." Over time you learn how to obtain better images, but it becomes more of an intuitive feel rather than an exact science. In terms of AFM costs, tips are expensive and it is important that people operating the instrument know to be careful with them. At the same time, you aren't a true AFM operator unless you've broken your fair share of tips! Advancements in technology are making many of the more complicated aspects of AFM easier. For instance, positioning the laser on the cantilever, engaging the surface, and tuning are becoming more automated, which makes it easier for the user to learn the technique. I don't foresee these advancements coming to a point that completely eliminates the "art" of AFM; however, this is what makes it fun!"
Respondent 10: "I have been doing AFM for a very long time and when we first started even the people who had invented the technique knew relatively little about how it worked. So, one of the biggest hurdles was figuring out the surface and interfacial processes and determining what was artifact and what was 'real' in an image. One of the biggest 'hurdles' has always been teaching people how to identify different artifacts and I still get lots of papers to review with incorrectly interpreted data. There were no textbooks on AFM and most people in my field didn't know much surface or interfacial chemistry/physics. I wrote a textbook on Environmental Surfaces and Interfaces that I have used to teach a course and that helps. It has a section on different methods including AFM. I think it's important for students to actually see an AFM in action which can be difficult for a big class. In that case, I break the class up into several smaller groups so that some can visit the AFM lab while others visit XPS, etc. and we rotate."
Respondent 11: "While we use AFM in our research we do not teach an AFM course or lab."

Respondent 12: “AFM enters into my teaching principally through a joint undergraduate/graduate course I give on Surface Science. It is mostly a classroom course but sometimes we include an AFM lab module. This module utilizing an existing AFM in another professor's lab so we have no issues regarding cost. Since it is not the principal focus of the class we do not encounter any issues to overcome.”
Respondent 13: “consumables”
Respondent 14: “Cost was an issue but alleviated by using the AFM in my lab. The biggest hurdle was making sure I had TA support - usually one of the students in my lab. Consumables were covered by a course fee.”
Respondent 15: “Cost for sure. I typically simply describe it in class and show images. ps - John Simonsen forwarded me this survey since I teach it far more than he does.”
Respondent 16: “Equipment cost and availability is definitely an issue. Other issues are: (i) the required background in dynamics takes some time to acquire; (ii) the field is multidisciplinary, so students aren't generally prepared for it (e.g., engineers like equations but not physics, physicists like the physics, but not necessarily the dynamics and equations, etc.); (iii) until recently there wasn't a good textbook for it, and even now, the available materials are a bit advanced and geared mostly toward graduate students; and finally, (iv) there aren't too many AFM experts who are familiar with most AFM variants and are available to teach the subject in depth - funding for AFM research is very limited since it is often seen as 'only instrumentation' so most researchers may not have the time/resources to dedicate themselves to teaching AFM.”
Respondent 17: "Cost of consumables is an issue. It creates some difficulties for us that our research instrument is also used for teaching."
Respondent 18: "Cost of AFM was main hurdle. AFM is like many musical instruments. You can get moderately good pretty quickly. To get the best images requires quite a bit of practice and patience. This is something that undergrads don't always have."
Respondent 19: "Cost is always an issue. Other issues are instrument maintenance and making sure the instrument does not get damaged. But the biggest issues is to create meaningful, but doable labs for AFM, which is not always an instrument that provides immediate results."
Respondent 20: "The two primary hurdles are 1) cost of instrument/consumables and 2) long time for learning how to operate the instrument and interpret the data."
Respondent 21: "I have only taught (a) a graduate course with no lab, hence no consumables and (b) my own graduate students."
Respondent 22: "Availability of good text books is still a problem. Eaton/West has been a step forward, but I feel like there is still a huge need for more and better books (and other materials)."
Respondent 23: "- cost of a dedicated AFM- access to existing AFM's (hard to enable inexperienced students to use expensive AFM's used for research - risk of damage, use of time)- the difficulty in exposing teams of students to AFM when only one person at a time can really use it (with others watching)- time involved in training and writing documentation to prep students"

Question 5.

Did you have any hesitations about creating an AFM lab or course? If so, what were they? Are they now assuaged?

Respondent 1: “I have not taught a specific course on it, but in previous years I used it as part of a general biomaterials/surface science lab course. I had no hesitations at that time.”
Respondent 2: “No.”
Respondent 3: “I still haven't created a course specifically dedicated to AFM. Rather, I have units on AFM as parts of other courses, like our SEM course, or one of our senior physics labs. That's the paper you saw.”
Respondent 4: “None”
Respondent 5: “No. In the mid-90s I saw the increasing applications of AFM in diverse fields as well as the preparation of students for future careers or graduate studies, the training of the use of AFM will be helpful. Besides the concept of nanoscale is easier to believe by seeing an AFM image. Now the AFM are used in many fields and it may be easier to sell the need of AFM education.”
Respondent 6: “The difficulty of getting students trained and the risk of them breaking equipment. It's still a struggle to train students, but i think it's worth it. The risk to damage to the equipment is still there. This year, for example, I was forced to come up with $3500 to repair a broken part on the AFM.”
Respondent 7: “No.”
Respondent 8: “No.”
Respondent 9: “I did not have any hesitation. Our lab is open to outside users, so there is always the risk of people using your instrument who have not been properly trained. My students and I take precautions to make sure that outside users and new users in our group are properly trained. Since we almost exclusively work with liquid cells, the most stressful part of AFM is the potential for leaks, which can be costly. We are in the process of expanding our lab. We currently have three AFMs and I have no hesitation to establish a user facility where other groups have access to these instruments. In terms of an AFM course, I have not considered this and do not think there would be enough interest at my institution for a formalized course, although many groups do use AFM.”
Respondent 10: “Again, when I first started doing AFM and running the AFM lab at Stanford, we were using the very first AFM ever sold (by what was then Digital Instruments) and there wasn't even a manual for it. But, I just dove in and started teaching other people individually or in groups. The biggest problem has always been making sure that people know how to use the instrument correctly and that they identify artifacts. So, if someone is going to use AFM for an actual project s/he needs to spend a lot of time getting to know the instrument or else work with someone who knows it well. Else, data may be produced but they may be incorrectly interpreted.”
Respondent 11: “N/A”
Respondent 12: “We have a course (offered by another professor) on various microscopy tools used for materials characterization that involves AFM. Since another professor offers it I have not had any motivation to offer my own.”
Respondent 13: “students breaking the AFM, no”
Respondent 14: “None at all. I was able to bring an offering that did not exist on campus despite having several groups using SPM techniques.”

Respondent 15: “We don't have any AFM labs. It's too costly and there is too much chance for something to break and affect research.”
Respondent 16: “I haven't actually created an AFM course. I have given many introductory lectures on the topic, I have included AFM in my courses as an example, and I have taught small groups of students how to use the instrument, but I have never created nor taught a complete course on it. I have mostly carried out research on the subject with graduate students (mostly PhD students, since the required background takes so long to acquire).”
Respondent 17: "No"
Respondent 18: "Don't have an AFM lab course. Use it in undergrad research"
Respondent 19: "Creating innovative labs for AFM requires that one tries things out first and creates good documentation - that takes time."
Respondent 20: "No. "
Respondent 21: "The reason I have never taught a lab class to other students is that the instrumentation is very expensive so (a) I don't have multiple sets and (b) it has been heavily used for research."
Respondent 22: "No."
Respondent 23: "No"

Question 6.

What is your advice to prospective AFM educators?

Respondent 1: “You have to allow the students hands on experience.”
Respondent 2: “Keep tracking with the methodology progress. In addition to topographic imaging, there are other AFM modalities, force spectroscopy in the first place. Time lapse imaging is the major attractive feature for AFM making it superior to all other nanoimaging techniques. Note the high-speed AFM that is coming out. It has a lot of potentials with biomedical applications.”
Respondent 3: “Be very patient.”
Respondent 4: “I honestly don't know. Probably, to learn the AFM technique before teaching it :-)”
Respondent 5: “Find time and write proposal applications to funding agencies or talk to school administrators and justify the need of AFM for education.”
Respondent 6: “Structure your program as an apprenticeship if possible with senior students training the new students, with the instructor as the overseer and quality control on all levels.”
Respondent 7: “Let students find out themselves how it works. Most motivating experience.”
Respondent 8: “I think the educational settings involving AFM are so varied that it is hard to give useful advice to another teacher.”
Respondent 9: “Be patient! This technique, like many others, requires time to properly learn. In order to get that "intuitive" feel for the instrument, you need to gain experience. You also must be persistent. Oftentimes you are required to troubleshoot problems, which can be extremely frustrating. If you stick with it, and when necessary consult with the AFM company, you will solve the problems. It is also important to realize that even after you have become an expert, not all AFM runs work. You are always going to have a day that is lost because something went wrong (either with the tip or the sample). This again requires patience.”

Respondent 10: “It takes time. Just because you can produce an image or get a curve doesn't mean it's 'real' or easily interpreted. Realize that some students will have difficulties with all the tiny parts and with being patient enough to get good images. Modern instruments often are more automated than the older ones but they still require delicate work such as adding a new tip. If you are just going to teach about AFM, make sure you include the pros and cons. If you are going to teach ow to use AFM, take your time so that students can feel comfortable and make sure you teach about artifacts and potential difficulties. Make sure you teach about surface forces and surface reactivity. I guess I could recommend my book but that might be self-serving. ;-)”
Respondent 11: “N/A”
Respondent 12: “Include both a significant theoretical and practical component. I think it is important for students to have a good grasp of the scientific background related to any microstructural tool that a student will use in his/her work.”
Respondent 13: “students will break a lot of probes and even the AFM”
Respondent 14: “Ensure good hands on training and let students guide projects based on their interests.”
Respondent 15: “Find a way to purchase a dedicated teaching AFM that is generally cheaper.”
Respondent 16: “I would have to give this question a bit more thought, since I haven't yet considered what would be the best way to teach AFM given the constraints. However, careful evaluation of the challenges is always a good start.”
Respondent 17: "It is a good option for upper-division undergraduates."
Respondent 18: "I would think that a course in AFM is a bit narrow within the milieu of a liberal arts education? Perhaps a one-credit interest/introductory course? Or possibly embedded in a course on microscopy that includes several other technologies."
Respondent 19: "Take your time to create good documentation and testing things carefully to identify potential pitfalls."
Respondent 20: "You should not be intimidated about teaching AFM to undergraduate students because the basic instrument setup is fairly simple to teach and students in general show great interest in AFM. We implemented a virtual AFM lab module with two way communications to teach AFM to a large number of undergraduate students and it is working very well. There are also a lot of AFM training materials online."
Respondent 21: "N/A"
Respondent 22: "None in particular."
Respondent 23: "- plan ahead, secure access to an instrument, recruit an experienced TA for help with training, take advantage of existing resources e.g. nano hub website, existing books"

Question 7.

Do you believe exposure to AFM benefits students? Why?

Respondent 1: “Yes. It is a powerful tool, but very different than traditional surface science tools that are used in vacuum. I don’t believe it occurs to students that this might be available without being introduced to it.”
Respondent 2: “AFM is getting as a rather routine imaging tool and students should be exposed to this technique.”

Respondent 3: “Sure, especially physics majors. A lot of our majors are interested in doing research, so it helps them to learn advanced tools.”
Respondent 4: “Yes, if students decide or think they would work with any aspect of surface science in the future. AFM is one of the fastest-growing microscopy, which is way more than just a microscopy. It is one of the most important (if not the) techniques responsible for the emergence what is called nowadays nanotechnology. Knowing it will definitely benefit any students decided to be familiar with nano tech.”
Respondent 5: “Students who took the AFM course not only can absorb the scale of nano but can also think its applications in various fields. The skill in AFM is useful for their future graduate study or work in diversified areas.”
Respondent 6: “Yes, it's one of the few accessible tools that give students direct access to the nanotechnology revolution. AFM also contains many aspects of fundamentals from their courses, e.g. physics, optics, controls.”
Respondent 7: “Yes. They see that a simple instrument can reach atomic resolution. This is inspiring.”
Respondent 8: “Yes - it provides training in a truly modern experiment, which is rare in Physics.”
Respondent 9: “I feel that AFM is one of many analytical techniques. I personally have benefitted from knowing how to use AFM since my research heavily relies on the technique; however, I would not say it carries any more weight than other techniques in the sense that it good for scientists to have exposure to a variety of instruments. If your research can benefit from AFM, then certainly it is worth learning. If your work only requires occasional use of AFM, then the time invested to become an expert may not be necessary. I think the benefit really depends on the user and how AFM can be used in the research project.”
Respondent 10: “Absolutely. Surfaces and interfaces are extremely important in many fields of science and engineering and AFM is a very approachable instrument that provides great data as long as one has the background needed to correctly interpret the data.”
Respondent 11: “N/A”
Respondent 12: “In materials science and engineering (my department) and related fields AFM is an important characterization tool and all students should have some exposure to it.”
Respondent 13: “yes, it’s a good characterization technique”
Respondent 14: “Yes - SPM techniques are now an essential tool in a wide range of research fields. It is a skill set that is often in demand. I have had more than a few students tell me that the AFM course helped them in interviews for Post-doc experiences and research positions.”
Respondent 15: “Yes. Especially in a Materials Science department. This technique is becoming very widespread in industry.”
Respondent 16: “Most definitely. AFM is one of the most powerful and versatile tools in nanotechnology. I think that we are at a disadvantage here, especially relative to Japan and Europe.”
Respondent 17: "A variety of instrumentation experiences are always helpful."
Respondent 18: "Yes. It's a tool to interest them in conducting research. A very powerful tool."
Respondent 19: "It's a very common research tool, it's very versatile and very visual. It can applied in many different contexts (materials, biology etc)."

Respondent 20: "Yes. Students are impressed by what AFM does and the exposure motivates students to learn more about nanotechnology."
Respondent 21: "N/A"
Respondent 22: "Yes, as it is a very versatile and in many ways unique research tool."
Respondent 23: "Yes, it gives them the opportunity to use a real research tool; to visualize something not observable either to the naked eye or through a microscope; to appreciate the importances of contact and tribology; to understand the instrumental methods that have been a key component of launching nanotechnology; to understand how scientific research equipment works."

Question 8.
Do you see a future where AFM becomes more prevalent throughout all levels of education? Why or why not?

Respondent 1: "Yes. There will be increasing numbers of used AFMs available, making it possible for all levels of schools to have access, and with the increase in students understanding of nano in the world, an AFM makes more sense."
Respondent 2: "I would not say prevalent. It should be taught along with all other imaging disciplines, such as confocal microscopy."
Respondent 3: "I see SEM becoming more prevalent before AFM does. SEM works at TV rates, and even the fastest AFMs aren't there yet (the ones with scan rates at ~100 Hz, for example, and that only for flat samples). People aren't as patient as they need to be with AFM. SEM is easier. And the tabletop SEMs are reasonably priced-sort of."
Respondent 4: "As any technology, AFM has the basic and advanced levels. The basic level would be okay to include in a course on experimental techniques for undergrads. The advanced level is definitely for graduate students. The reason for inclusion I described above."
Respondent 5: "In the one credit AFM course with lab there were both graduate students and undergraduate students. But in the experimental physics course mostly undergraduate junior students perform the AFM experiment."
Respondent 6: "There is the opportunity certainly, if the issues of cost and ease of use continue to be improved."
Respondent 7: "I hope so. Over the last decade instruments have become easier to use, however, we are still far away from a one-button take image instrument. But I see this coming in the near future."
Respondent 8: "Instrumentation costs are too high for this to become really common. I think it will increase as the cost of commercial instruments decreases though."
Respondent 9: "With the increased interest in nanotechnology and advanced materials synthesis, I do believe that AFM is becoming, and will continue to become, more prevalent. I am not certain if undergraduate students need to learn this technique, but they should at least be aware of its operation and what can be gained from it. I teach a nanotechnology section as part of a freshman introductory course, and in this section I introduce the students to AFM. I also teach a graduate elective (Colloids and Interface Science) where I spend time discussing the technique. To this end, I do expose a variety of students to AFM."

Respondent 10: “Yes. I have brought my AFM into elementary and high school labs many times over the years, and started doing this about 25 years ago. Why? Because the instrument tends to be fairly portable and inexpensive. It's also a great instrument for students working on science fair projects.”
Respondent 11: “Not really. It is very nice technique, but is only one of many. It is not cheap and the bar to entry is somewhat high.”
Respondent 12: “I think it is important right now for both undergrads and graduates students to be exposed to AFM as it is an important and standard tool as mentioned above.”
Respondent 13: “maybe, there are high costs involved”
Respondent 14: “Possibly - at undergraduate levels providing hands-on experiences for large classes will become a challenge. Without hands-on experiences, I think the impact will be less.”
Respondent 15: “Only if it becomes cheaper.”
Respondent 16: “I am not sure this will be the case in the US. AFM research is still dominated by Europe and Japan (this has been the case for a long time). We have a relatively small group of AFM researchers in the US. They are very good, but they are relatively few. We have many AFM users, but teaching AFM requires a bit more than that.”
Respondent 17: "No opinion"
Respondent 18: "Probably not. Why should AFM be more important than some of the light microscopy imaging technologies, or TEM, or SEM, etc."
Respondent 19: "I think it will remain somewhat specialized, because doing really interesting things with it requires skill and previous knowledge. Imaging some prepared sample is nice, but does not really teach very much unless you prepare the sample yourself and know what you are looking for. Force measurements require even more prior knowledge."
Respondent 20: "Yes because AFM is an essential tool for nanotechnology."
Respondent 21: "Yes, there are now cheaper AFMs that could be dedicated to teaching and that would solve a lot of the problem."
Respondent 22: "Not really. "
Respondent 23: "Yes, since lower cost mass-produced systems should eventually become available, allowing students to use, explore, and innovate. This hinges on easy-to-use mass-produced systems, perhaps through MEMS technology."

Appendix B: Power Point Presentation

This power point presentation was given as a talk to three panelists who are AFM experts. This was completed as an end-of-summer, two-thirds of the way through the project, deliverable.

WPI

Perspectives on Atomic Force Microscopy Education

Andrew Pic & Valerie Moore
Advisor: Professor Nancy A. Burnham

Atomic Force Microscopy

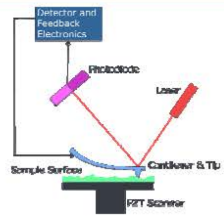


Image released into the public domain by creator "OverlordQ" and can be found at https://commons.wikimedia.org/wiki/File:Atomic_force_microscope_block_diagram.svg

2 Worcester Polytechnic Institute

Why Teach AFM?

- Powerful tool in research and science
- Helps visualize the nano-world
- Application of physics phenomena
- Exposes students to techniques used in research and industry

3 Worcester Polytechnic Institute

Project Goal

Compile a cohesive and comprehensive book chapter titled *Perspectives on AFM Education* which will be included in *Global Perspectives of Nanoscience and Engineering Education.*

4 Worcester Polytechnic Institute

Why Our Project is Important

- Our project creates a singular source of AFM education information and advice, currently spread out across many sources due to its multi-disciplinary nature
- We want to provide this project as a resource to professors who are contemplating teaching AFM in order to make the implementation of a course or lab easier.

5 Worcester Polytechnic Institute

Outline

- Research
- Website
- What we have learned
- Survey
- Survey Responses
- Gaps
- Future Plans
- Summary

6 Worcester Polytechnic Institute

What We Have Done: Research

- Collect information on courses, labs, and workshops
- Looked through academic articles, websites, YouTube channels, and the NSF database
- Found prominent figures for research and teaching AFM

7 Worcester Polytechnic Institute

What We Have Done: Website

Found at: www.wpi.edu/+afm

8 Worcester Polytechnic Institute

What We Have Learned

- Atomic Force Microscopy has been taught on middle school and grade school levels using very creative methods.
- Demonstrations
- Single or several laboratories within the context of another course
- Personalized hands-on instruction
- Term- or semester-based courses devoted to AFM
- Short courses

9 Worcester Polytechnic Institute

What We Have Learned

- AFM courses are generally reserved for physics and engineering majors with the inclusion of materials science programs.
- AFM is more often than not a selection of lectures or a lab within a wider reaching course.
- Big schools and small schools alike - as long as the funding is there - they have AFM labs.
- AFM can be a powerful tool to help introduce students to the Nano-World

10 Worcester Polytechnic Institute

What We Have Done: Survey

Contacts identified: 260
Survey responses received: 23
Response ratio: ~ 1:10

11 Worcester Polytechnic Institute

What hurdles did you have to overcome in teaching Atomic Force Microscopy (e.g. cost of AFMs or consumables)? Do any remain?

- Time
- Monetary cost
- Obtaining proper equipment
- Teaching the theory behind the practice
- Quality textbooks

Respondent 2: "There is no problem if there is a lab with the AFM equipment and experience."
Respondent 6: "Cost of consumables, complicated equipment to teach (computer software, electronics hardware, optics, physics of oscillating systems). Students have a big hill to climb before they are competent."
Respondent 17: "Cost of consumables is an issue. It creates some difficulties for us that our research instrument is also used for teaching."

12 Worcester Polytechnic Institute

Did you have any hesitations about creating an AFM lab or course? If so, what were they? Are they now assuaged?

- No, none, and N/A
- Students damaging expensive equipment
- Time
- Cost

Respondent 6: "The difficulty of getting students trained and the risk of them breaking equipment. It's still a struggle to train students, but i think it's worth it. The risk to damage to the equipment is still there. This year, for example, I was forced to come up with $3500 to repair a broken part on the AFM."
Respondent 19: "Creating innovative labs for AFM requires that one tries things out first and creates good documentation - that takes time."
Respondent 20: "No. "
Respondent 21: "The reason I have never taught a lab class to other students is that the instrumentation is very expensive so (a) I don't have multiple sets and (b) it has been heavily used for research."

13 Worcester Polytechnic Institute

What is your advice to prospective AFM educators?

- Be patient
- Things will break
- Create a balance between theory and practice
- Apply for grant money

Respondent 1: "You have to allow the students hands on experience."
Respondent 5: "Find time and write proposal applications to funding agencies or talk to school administrators and justify the need of AFM for education."
Respondent 12: "Include both a significant theoretical and practical component. I think it is important for students to have a good grasp of the scientific background related to any microstructural tool that a student will use in his/her work."
Respondent 13: "students will break a lot of probes and even the AFM"

14 Worcester Polytechnic Institute

Do you believe exposure to AFM benefits students? Why?

- The consensus was: yes
- Respondents valued AFM's
  - Widespread presence in industry and research
  - Application of physics
  - Versatility

Respondent 7: "Yes. They see that a simple instrument can reach atomic resolution. This is inspiring."
Respondent 8: "Yes - it provides training in a truly modern experiment, which is rare in Physics.
Respondent 18: "Yes. It's a tool to interest them in conducting research. A very powerful tool."
Respondent 14: "Yes - SPM techniques are now an essential tool in a wide range of research fields. It is a skill set that is often in demand. I have had more than a few students tell me that the AFM course helped them in interviews for Post-doc experiences and research positions."

15 Worcester Polytechnic Institute

Do you see a future where AFM becomes more prevalent throughout all levels of education? Why or why not?

- Varying responses from positively yes to absolutely not

Respondent 1: "Yes. There will be increasing numbers of used AFMs available, making it possible for all levels of schools to have access, and with the increase in students understanding of nano in the world, an AFM makes more sense."
Respondent 8: "Instrumentation costs are too high for this to become really common. I think it will increase as the cost of commercial instruments decreases though."
Respondent 11: "Not really. It is very nice technique, but is only one of many. It is not cheap and the bar to entry is somewhat high."
Respondent 18: "Probably not. Why should AFM be more important than some of the light microscopy imaging technologies, or TEM, or SEM, etc."
Respondent 22: "Not really. "

16 Worcester Polytechnic Institute

Gaps That Remain

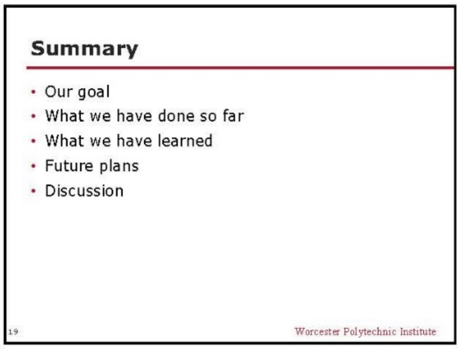
- Free responses from contacts regarding our conclusions
- What students go on to do in academia or industry
- We have stories of struggle but very little about successes or what works.

17 Worcester Polytechnic Institute

Our Future Plans

- Complete interviews with contacts
- Write a book chapter
- Book sections include:
  - Why AFM is such an essential tool for research and education
  - AFM through different education levels
  - Major hurdles and how to overcome them

18 Worcester Polytechnic Institute


Summary
• Our goal
• What we have done so far
• What we have learned
• Future plans
• Discussion
19
Worcester Polytechnic Institute

Appendix C: Bibliography

This appendix contains a list of sources deemed important for future educators. It contains resources for material as well as textbooks and previous course offerings.

Websites

- http://www.afmworkshop.com/afm-webinars.html
- http://www.afmworkshop.com/atomic-force-microscope-for-educators.html
- http://www.aif.ncsu.edu/hands-on-instrument-operation-and-sample-preparation/
- https://www.bruker.com/service/education-training/training-courses/afm-optical-training-courses.html
- http://www.education.mrsec.wisc.edu/nanoquest/afm/index.html
- http://lnf.umich.edu/nnin-at-michigan/afm/
- http://nanohub.org/courses/afm1
- http://proed.acs.org/course-catalog/courses/understanding-and-utilizing-atomic-force-microscopy-from-basic-modes-to-advanced-applications/
- http://www.teachnano.com/education/newsletter/index.html
- http://www.wpi.edu/academics/physics/AFM/nanoed_resources.html
- https://www.youtube.com/user/AtomicForceMicro/playlists
- https://www.youtube.com/playlist?list=PL3592A61EEF52B29A

Journal Articles

- D. Lehmpuhl, Journal of Chemical Education 80, 5 (2003)
- H. Margel et al, J. Chem. Educ. 81, 4 (2004)
- G. Planinsic and J. Kovac Physics Education 43, 1 (2008)
- N. Burnham, Journal of Nano Education 5, 2 (2013)
- H. A. McNally, IEEE Nanotechnology 7, 19 (2013)
- N. A. Burnham, A. Arcifa, M. Divandari, C. Mathis, S. N. Ramakrishna, and N. D. Spencer, Accepted for the 2015 Conference on Laboratory Instruction Beyond the First Year of College, College Park, Maryland, 22-24 July 2015.

Textbooks

- Pier Carlo Braga, Davide Ricci, Atomic Force Microscopy: Biomedical Methods and Applications, Methods in Molecular Biology, Humana Press 2004
- Peter Eaton, Paul West, Atomic Force Microscopy, OUP Oxford, Mar 25, 2010 - Science- 256 pages
- Greg Haugstad, Atomic Force Microscopy: Understanding Basic Modes and Advanced Applications, John Wiley & Sons, INC., Publication, 2012