Freshman Seminar: Building a Scanning Tunneling Microscope

Course catalog description:

The aim of this seminar is to teach students who are considering careers in science or engineering the skills necessary to build a complicated piece of scientific equipment from start to finish. Small groups of 3-4 students will be given guidance to build a scanning tunneling microscope from simple materials. The scanning tunneling microscope (STM), invented in 1982 and awarded the 1986 Nobel Prize in Physics, was the first tool which allowed scientists to "see" individual atoms. Through the construction of an STM, students in this seminar will learn mechanical skills such as metal machining and vibration isolation; electronic skills such as soldering and wiring a current amplifier, filters, and a feedback circuit; and software skills such as communication with a data acquisition board, and programming image analysis. More broadly speaking, students will be introduced to engineering and design, laboratory teamwork and resource management, and the debugging and trouble-shooting skills necessary for success in the laboratory. The class will also read one weekly paper on current research related to scanning probe microscopy, and each student will present one paper to the rest of the class.

Curricular description for Freshman Seminar Committee:

Overview:

The basic aim of this course is to empower students to build a real piece of scientific equipment from start to finish. Students will to work together in groups of 3-4 on a fun project with a concrete goal. They will learn numerous practical lab skills along the way (milling, soldering, debugging an electronic circuit with an oscilloscope, programming, etc.) More importantly they will get a taste of how lab science works. They will be introduced to the process of doing a new experiment: start with an idea, some scratch paper, and a budget; read the available literature on how similar projects have been accomplished in the past; purchase equipment, divide the labor, and set time goals; build the pieces, and debug obstacles as they arise.

Goal:

The goal is for each group of 3-4 students to build a working STM which images nanoscale features. The next goal for each group, when/if the basic STM is complete, will be to improve the resolution of the microscope as much as possible. The ultimate goal will be to achieve atomic resolution on graphite. Atomic resolution is possible, but may not be likely for freshman in a semester-long course, unless they are very enthusiastic and devote significant extra time outside of scheduled meetings. Nanometer-scale resolution is by itself a very significant achievement.

Structure:

The class size should be limited to 6-8 students, who will be split into two groups of 3-4 each. This STM project divides into three categories: mechanical, electronics, and software. Students may work relatively independently on the three parts, but they will need to maintain good communication in order to make it all fit together in the end.

The class will meet twice a week for 3-4 hours each, similar to other undergraduate lab-based courses such as physics 123 and physics 191. In the first week, I will lead informal lecture/discussion to explain the project: both the how-to and the overall scientific relevance. I will also meet with each group individually to help them set up a plan. Some students may also arrange to take the physics department machine shop course in the first few weeks. Once the students get started building, I will be available for the 6-8 hours per week to answer questions and help trouble-shoot.

In addition to lab work, the class will read relevant scientific papers, approximately one per week, on current research with scanning probe microscopes. Each student will give a half-hour presentation of one paper to the rest of the class; this will be followed by half-hour discussion.

What each group of students will start with:

<u>mechanical:</u>

- photos & rough mechanical drawings of STM parts
- access to physics student machine shop course
- reasonable budget & suggested parts list

<u>electronics:</u>

- detailed circuit diagrams
- access to simple electronics components (resistors, etc.)
- oscilloscope, function generator, etc. for debugging circuits

<u>software:</u>

- outline of functions necessary to control an STM
- computer with an installed programming language (probably Matlab)
- multi-purpose data acquisition card

What students will be expected to do (with plenty of advice):

- divide the labor and make an ordered plan
- purchase relevant components
- build, wire, and program according to plan
- debug as necessary
- discuss frequently amongst themselves to make sure the various parts are in synch; help each other out if not
- attempt to image first a rough gold grid; then if successful try for atomic resolution on graphite
- do a literature search and suggest design improvements to increase the resolution

Skills to acquire:

Some skills which are *crucial* to success in experimental science are:

- The ability to distill the central few concepts from an important paper which should have been explained in 10 pages with 8 figures but instead had to fit into the 4-page, 4-figure format of the journal in which it was published, and is therefore almost completely opaque.
- The ability to trace the references backwards and the citations forwards, to decide whether the reported result is valid, or whether the effect occurred only because some graduate student forgot to unplug a noisy lamp while the data was being acquired.
- The ability to take a difficult concept and clarify it through words and pictures, so that somebody outside of the immediate area of specialization can understand and appreciate it (and maybe fund it).
- The confidence and charisma to stand up and give a scientific presentation, to make it interesting and clear, and also to answer new technical questions on the fly.
- The ability to work closely with a small group of people: to divide the labor and to organize the goals. To avoid working at cross-purposes and to avoid wasting time on bitterness when different parts of the project move at different speeds, or when it appears that somebody is not pulling their weight.
- The ability to trouble-shoot a recalcitrant piece of lab equipment. To come at the problem from several different sides: "ok, we can't figure out what's wrong because it always screws up when we're not looking, so let's write a program to monitor the output overnight and see how many screw-ups we have recorded by the morning, and whether they happened at regular intervals or whenever somebody used the elevator outside the lab."
- The ability to hack together a simple experiment quickly, as a prototype or proof-of-principle for the experiment we will really spend money and time on. For example, instead of spending $13,000 on air springs and an optical table, can we rig up some temporary vibration isolation with bungee cords, just for a quick test to see if our noise-sensitive instrument will work? If we always wait for the time and funding to do science in the prettiest possible way, we will never get anything done.

Date	Lecture	Papers to read	Mechanical Goals	Vibration Goals	Electronics Goals	Software Goals
3-Feb	intro to STM (pictures)	none	interview students	interview students	interview students	interview students
8-Feb	STM components	none				
10-Feb	masses & springs	none	machine shop course	machine shop course	machine shop course	machine shop course
15-Feb	Fourier transforms	student STM construction	Solidworks/machine shop	Solidworks/machine shop	test spect. analyzer & breadboards	install software, DAQs
17-Feb	basic electronics	home-built STM websites			outline necessary circuits	outline necessary software
22-Feb	STM theory- density of states	STM invention			basic circuits on breadboards	basic input/output
24-Feb	STM theory- tunneling	STM review articles		design box for geophone		
1-Mar				shop- make box		
3-Mar				shop- make box		
8-Mar				shop- make box		
10-Mar			finish machine shop course & finish learning Solidworks	measure vibrations	finish electronic design	
15-Mar				measure vibrations		
17-Mar				set up speaker		
22-Mar			finish designing STM parts	sweep frequencies, measure geophone response		
24-Mar				design vibration isolation		
5-Apr				construct vibration isolation		
7-Apr				design acoustic isolation		
12-Apr	student talk		finish machining STM parts	construct acoustic isolation		
14-Apr	student talk			construct acoustic isolation		
19-Apr	student talk			test		
21-Apr	student talk		complete construction	complete construction	complete construction	complete construction
26-Apr	student talk		debug & play with STM	debug & play with STM	debug & play with STM	debug & play with STM
28-Apr	student talk		debug & play with STM	debug & play with STM	debug & play with STM	debug & play with STM
3-May	student talk		debug & play with STM	debug & play with STM	debug & play with STM	debug & play with STM
5-May	student talk		debug & play with STM	debug & play with STM	debug & play with STM	debug & play with STM