A guide to mentoring undergraduates in the lab

Philip S. Lukeman

Mentoring undergraduates in a research laboratory requires a different set of skills and approaches than for other lab members. However, if a mentor — be it a faculty member, postdoc or graduate student — can adopt these methods, it can lead to a significantly improved lab experience for everyone involved.

In a typical research group at a research-intensive university, a faculty member will lead a team of researchers that consists of postdoctoral scholars, graduate students and undergraduate students. Postdocs and graduate students are — by virtue of their self-selection, training and maturity — on average, more autonomous, productive and prepared than undergraduate students. With graduate students, for example, the primary role of the mentor is often to set large-scale goals, offer brief technical training and then provide occasional course-correction. With undergraduates, research training is far more detailed and didactic — and thus more time consuming. A significant undergraduate research project can, however, be the formative scientific experience of a student's career. Even if, like most undergraduate researchers, they are not destined to be scientists, providing students with a realistic conception of the joys and pains of research is likely to be of considerable value to society. The experience can also act as a filter; it is better for a student to discover as an undergraduate that scientific research — be it in general or the particular kind practiced in your lab — is not for them, rather than making this discovery after committing to a graduate degree.

I am a faculty member of a chemistry department in a US university who runs a research group consisting solely of undergraduates. We do 'wet' biomolecular nanotechnology, building and studying static and dynamic objects made from polynucleotides[1] that have applications in biosensing. My advice here is aimed at anyone who is mentoring, or thinking of mentoring, undergraduates in a research laboratory. The utility of my observations and suggestions will, of course, depend on your own circumstances and institution, but there are, I believe, a number of universal considerations for anyone who has the opportunity to mentor an undergraduate.

Be explicit about the implicit

If I can offer one general principle for the mentoring of undergraduates, it would be to make explicit how your implicit beliefs affect your practice of science. It is not enough just to train undergraduates in the technical aspects of the work, nor is it enough just to be a role model in word and deed. As a practicing scientist, you have been imbued with a set of values, norms and expectations: in short, the culture of science. Undergraduates often have little or no idea of this culture. Their experience is likely to consist of a few structured lectures and laboratory courses in which the 'answer' was known. Unless they know active researchers, they probably have a false impression of the efforts required for meaningful progress in a project, and due to coursework demands, they will spend a limited amount of time in your laboratory. You therefore need to spell out, early and repeatedly in your interactions, explicit cultural expectations[2].

Be explicit about the fact that 'radical honesty' in the performance of experiments, and recording and reporting of data, is a core, non-negotiable value. In the wider world, we are encouraged to dissemble and flatter, to be politically sensitive to what we report depending on the status of the person we are talking to. In some cultures, deference and pleasing seniors takes precedence over truth telling. Some students may be too afraid, proud or uncertain to report imperfect data, describe experimental failure or damaged equipment. Years of tightly structured schooling and the pursuit of the 'grade' may have set in their minds that looking for the one predetermined 'right answer' is the best way to progress in a field of study. You must disabuse them of these instincts, and convince them that because it is fundamental to meaningful science, honesty is the only acceptable mode of discourse in the laboratory.

Be explicit about your motivation to do science. My motivation stems from the thrill of discovery, the exercise of creativity, and the opportunity to share our work with the scientific community; from the belief that scientific discovery can do good in the world; and from the fact that the training of future scientists and science-savvy citizens is a worthwhile and enjoyable job. Undergraduates who want to work in your laboratory may have different motivations: 'mere' undirected curiosity, a need for course credit, desire for a recommendation letter/CV boost, or to earn some extra money. You can respect and enable these student motives, but you must make it clear that their motives cannot subvert the lab's purpose.

Be explicit about time commitment and expected progress rates. This will depend on the institution and the structure of the degree course, but to do meaningful work and return the significant time investment that training requires, I have found that after an initial training period, students should ideally commit a minimum of two calendar years to a lab: that is, two full-time summers and a minimum average of 10 hours per week during the academic year. Even so, progress when compared with graduate students or postdocs will be slow, and it is important that your — and their — expectations are tempered accordingly.

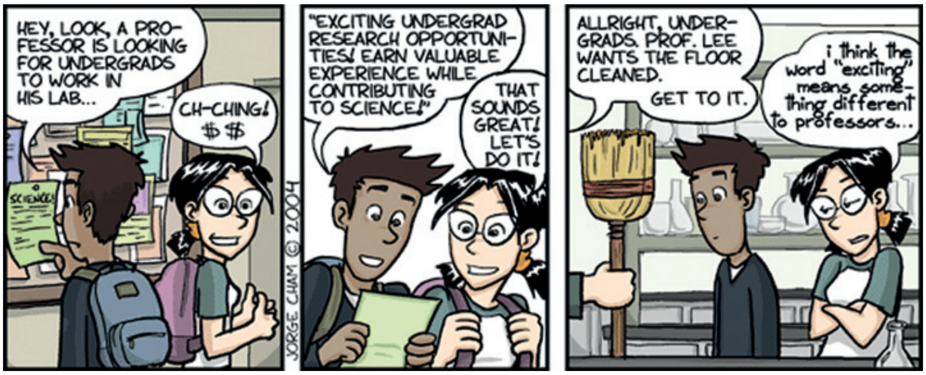
Be explicit about the nature of 'time spent' in the laboratory. The temptation will be to set hours that the students must keep. However, if they are to become scientists then they should start to develop time management skills and, if necessary, the flexible schedules that more senior researchers adopt. Explain that there are no rewards for merely being present in lab; correctly executed experiments drive science, not clockwatching.

Be explicit about the roles of a professor and student. Explain why, after the training period, you are likely to be seen behind a desk writing/reviewing papers, grants or syllabi while they are running their *n*th gel, microscope session or surface analysis of the week.

Be explicit about safety. As well as the more general training that departments offer, have lab-specific training, preferably with a laboratory manual documenting the procedures and protocols of the lab. Good documentation reduces your liability, acts as a reference and minimizes misunderstandings based on misremembered or misheard conversations.

Be explicit about the serious nature of the scientific enterprise. Many scientists do not display trappings of authority: clothing, demeanour and language are often quite informal. Some students who are used to authority coming in a more 'conventional' package mistake this for a lack of seriousness.

After an initial training project, my students sign a clearly written contract describing the rights and responsibilities of laboratory members. This contract signing formalizes the relationship and also acts as a lesson about the importance of contractual obligations.



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Undergraduate researchers have a lot to offer a laboratory.

Recruiting students

Assuming you have a choice in who you recruit for the position, active recruitment at a fixed time each year (putting posters up in buildings where science students meet, advertising on social media, sending e-mails to student lists) will increase your applicant pool, save time and improve the likelihood of finding a match for your laboratory. As an initial screen, advertisements can describe time commitment, course prerequisites and any other 'deal breakers' that the intellectual and practical demands of your research will set.

Applicants to my laboratory must attend a mandatory presentation (with pizza!) where I give a research and training talk, which outlines some of the explicit science-cultural points described above, and finishes with a general-interest question and answer session. This meeting allows my individual student interviews to focus on them and their strengths and interests.

In terms of what to look for in a mentee, formulae used for graduate students and postdocs may not apply; students are unlikely to come with existing experimental/theoretical strengths or research experience. More holistic questions usually pertain. Do you want worker bees or free spirits? Raw promise or polished and prepared? Science-career focused or finding their way? Are there particular disciplines you want represented? Are there socioeconomic, gender, minority or disability participation philosophies that you want your lab's membership to reflect?

I have found that grades (above a certain minimum) and recommendations from faculty who have had a student in large classes are weakly correlated with laboratory performance. Self-reporting of student ability and drive often indicates little more than a personality type. From my perspective, meaningful enthusiasm (evinced by having done some background reading about the field and maybe even having questions to ask) is more important than a perfect transcript — 'interested' is more important than 'interesting'.

Training students

My postdoctoral mentor, Ned Seeman, developed a training programme[3] that aims to expose the trainee to all of the core experimental techniques that his laboratory uses. A trainee completes the programme when they successfully reproduce key results from published DNA nanosystems[4–7].

My undergraduate-appropriate adaptation of this approach uses the DNA '3-pointed-star' and two-dimensional array developed by Chengde Mao[8]. By demonstrating the formation of these structures, students are trained in the main techniques we use in our laboratory. Using four commercially available DNA oligonucleotides, we run both preparative and analytical denaturing and non-denaturing acrylamide gels, conduct UV spectroscopic DNA quantitation and image samples using atomic force microscopy[9]. In principle, this system could also be used for training in fluorescence microscopy, transmission electron microscopy and dynamic light scattering. Whatever training programme you adopt, it should be feasible and relatively brief, offer useful feedback on conceptual and practical errors a student makes, and exemplify most (if not all) of the techniques they will use in their project.

During the training period, I explicitly reinforce cultural expectations. Initially, I give students a non-technical review introducing the field[10] as well as the study that we will be reproducing[8]. We meet and discuss what will be expected in terms of safety, laboratory documentation and their development of expertise (that is, they do not need to comprehend everything initially); during this process I try to convey excitement about the field, why we train the way we do, and how the technical aspects of the training project links into the bigger picture.

While training, developing technique mastery in the laboratory is a key confidence builder in the trainee. The mentor's confidence is also improved; if the mentee has shown they can execute a particular technique to the lab's standards, this improves trust in the data they will generate in the future using that technique and reduces the likelihood of misunderstanding becoming the source of experimental error.

As the training projects progress, I demonstrate each of the techniques in the laboratory including common conceptual and practical mistakes to avoid. Initially, we write out in almost excruciating detail the mechanics of each experiment; as we progress, instructions and notes become more abbreviated. I show them previous trainee results (encouragement that a novice can do this work), and describe errors students have made in doing experiments and recording data (showing that honesty is a good policy as admitting errors is not penalized). During training and beyond, I insist on students acting safely using practices that are described in the laboratory manual[11]; I also insist on anyone who enters the laboratory following the same rules.

Further resources on laboratory management, mentoring skills and the funding of undergraduate research can be found on the websites of the Howard Hughes Medical Institute[12], the Council for Undergraduate Research[13] and the American Chemical Society[14]. It is also worth noting that there are opportunities available for undergraduate researchers to be involved in wider community events. For example, competitions exist in synthetic biology[15] and biomolecular design[16] that allow undergraduates to present their projects, and for both students and their mentors to get together and discuss best practices.

One last thing...be kind

If novice students are afraid of your emotional response to mistakes they unwittingly make or misunderstandings they display, they will not be open with you about their work or come to you for guidance. They will also develop negative associations with what should, hopefully, be a joyful experience. As a side effect, the atmosphere among others in the laboratory will also suffer. For every 'macho' student that flourishes in an intimidating, high-pressure environment, many more students will be soured on research and lost to the practice of science. Research leaders are under pressure to produce results for publication, promotion and funding; passing on this pressure to undergraduates does them a disservice, and it is your job to shield them from most of it. I make it clear to students that wanton safety violations, serious breach of promises or dishonest behaviour are the only time they will be sanctioned.

Uri Alon describes a good laboratory as "a nurturing environment that aims to maximize the potential of students as scientists and as human beings", where students are not viewed merely as means to ends of a project[17]. He describes motivated research groups[18] as places where competence, confidence, autonomy and social connectedness coalesce into a gestalt. I endorse this view wholeheartedly. ❐

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Learning and research in the cloud

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Research and teaching in nanoscience can, and should, be thought as one joint endeavour. nanoHUB, a cyberinfrastructure that aims to use interactive cloud-based software to meet the needs of both code developers and end-users, is redefining research and education in nanoscience and engineering.

Physics Nobel Laureate Carl Wieman has repeatedly called for physics teachers to use "tools of physics"[1] to teach students scientific concepts. Inherent in this call is the need to tie pedagogical approaches to cutting-edge scientific endeavours and best practices in research. The approach to education therefore needs to evolve as a given field evolves. Fundamental, sometimes revolutionary, changes in a research domain field should be promptly reflected in teaching curricula.

The advent of informatics tools and the Internet has had a profound effect on science and its culture of research and learning. Bainbridge and Roco[2] use the expression "progressive convergence" to describe the disruptive merging of information technology, nanotechnology, biotechnology and cognitive science. In particular, the nanotechnology and information technology components are foundational to this transformation. Nanotechnology provides learners with the opportunity to explore science at the most fundamental scale of nature. Information technology provides the ability to make complex scientific phenomena that are difficult to grasp or visualize more approachable. Because advances in nanotechnology are fuelled by our ability to model and simulate ever-increasing complexity, when coupled together, these two technologies can have a transformative impact on teaching practices and learning strategies in engineering and science.

As the acquisition of new knowledge and the development of characterization and modelling tools progresses at an ever faster pace, the scientific community faces the complex task of disseminating