Creating a "Design-and-Build" Laboratory Experience

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Beginning in 2010, we began a teaching experiment in our Advanced Physics Laboratory at Caltech by adding a "Design-and-Build" (D&B) track to the course. Students in this track worked on open-ended mini-research projects where they sought to design and construct some type of apparatus. Students could provide their own ideas for what to build, but usually we had ongoing projects they could sign up for. The D&B track was optional, and it was one choice out of several tracks in the course, the others involving more traditional "preassembled" advanced physics lab experiments, such as NMR, laser spectroscopy, optical pumping, etc.

Our overarching goal for the D&B track was to provide senior physics majors with a different type of laboratory experience, one involving more independent analytical thinking than is usually required in the preassembled labs. Each D&B project was done by a group of 2-3 students during one nine-week quarter. Students worked on a variety of projects during the several years we offered the D&B track, including: 1) electrodynamic ion trapping, 2) magnetic levitation and trapping, 3) weak localization phenomena, 4) holographic interferometry, 5) thermoelectric properties, 6) quantized conductance, and 7) acoustic levitation.

Each D&B project began with a specific goal, usually a physics demonstration or gadget described in a published paper. For example, the ion trapping project focused on building different types of ion traps, as described by Winter and Ortjohann [1], the magnetic trapping and levitation project centered on the demonstration described by Sacket et. al. [2], and the quantized conduction demonstration is described Foley et. al. [3]. Occasionally, students would come to us with a topic in mind, but typically we supplied the ideas for the projects, along with the published papers.

During the term, each group of students would study the initial paper, do some online searching for additional papers and resources, calculate the underlying physics, perhaps create a mathematical model for the apparatus, examine design parameters, and finally build the hardware. The various tasks were open-ended and flexible. We found that budding theory students were more apt to calculate and model, as one might expect, whereas students more interested in hardware were always keen to start building. Students turned in progress reports every two weeks, and wrote a joint final report on the project at the end of the term.

One of the first things we learned from our D&B teaching experiment is that student interest varied widely. About a third of our students were quite enthusiastic about building something on their own, and they eagerly signed up for the D&B track. Roughly another third recognized (correctly) that the D&B track required more work than the other tracks, and these students were inclined to stick with the traditional lab experiments. And the remaining third could go either way. We had initially toyed with the idea of requiring all physics majors do some kind of D&B project, but our observations of student interest quickly suggested that the track should remain optional.

Another early conclusion was that students did not have to achieve their initial goals to enjoy a D&B project and learn from it. In many cases the students would set out to reproduce a specific physics demonstration, only to find that things did not work as smoothly as anticipated. In many cases the project remained unfinished at the end of the term. Nevertheless, even in these cases, our students reported that they enjoyed the D&B track, and they learned a lot along the way. Students found that the process of researching a project, performing necessary calculations, and working with hardware were all educational and enjoyable, regardless of the final outcome. This is not unlike undergraduate summer research, where projects do not always accomplish their initial goals.

A particularly important conclusion we reached from this teaching experiment was that D&B projects could extend through multiple terms and involve multiple groups of students. Over time we began passing projects along from one group to the next each term. Students would read the initial published paper describing the project, and they would also read the final report from the preceding term. The juxtaposition of these two documents was itself educational – the published paper was clearly written, succinctly describing a project that worked, while the final reports were typically not as well written, describing aspects of the project that were difficult and were not successful. Seeing both sides was useful from the educational perspective, and the quality of the final reports improved. We began to see that students are mostly exposed to (reasonably) clear writing in their classes, so they tend to think that all writing is of a similar quality. Trying to understand where the previous group left off on a project, using only their final report, was often an enlightening experience.

The magnetic levitation project described in [2] is an example of a project extending over many terms. The "sweet spot" of this demonstration experiment is small, so the magnetic field geometry must be carefully engineered. One of us built a working system before giving the project to students, so we know it can be done. But the design requires a careful and methodical approach in the design phase. Inexperienced students find this methodical approach difficult, especially because many parameters must be juggled simultaneously. This project was passed from one group to the next over two years, but in the end no one succeeded in building a functioning trap. Although the end result was disappointing, nearly all the students enjoyed the process and the challenge. Among other things, they learned that just because someone else did something once, that doesn't make it easy, which in many ways is a valuable lesson.

The ion trapping project generally went more smoothly. Building a working ion trap is quite easy and straightforward, and every group of students taking up the project built functioning traps. They explored different trap geometries, looked at various aspects of trap design and performance, and researched ion trapping and mass spectroscopy in general. Building on our experiences in the D&B track, we later created an ion trapping experiment for our Introductory Physics Lab course, which has been a big hit with the students, and a refreshing change from the somewhat uninspiring mechanics experiments we had been using.

The quantized conductance project was also successful each term, in that every group of students observed "steps" in the measured conductance. There is little in the way of simple theory describing these steps, however, and continued research showed that the experiment should not (and did not) produce evenly spaced steps. So while doing the experiment was relatively straightforward, producing reproducible and understandable data was not. In the final analysis, both we and the students learned quite a bit about this phenomenon along the way.

Beyond learning about the specifics of running the D&B track and the different projects, our student interactions also provided some insights into why this kind of laboratory experience is useful. While working on D&B projects with our students (mostly physics seniors), we found that the majority had little understanding of how to approach a research topic. Students focus on problem sets in their other courses, and they soon become adept at this kind of problem-solving. And summer research students tend to focus on specific predefined tasks, originated and laid out by others. As a result, our graduating seniors often leave Caltech having gained little or no experience in defining problems, searching the literature, and estimating parameters. They are not learning enough about how to work independently on real-world problems – problems that are possibly ill-defined and likely involving complex solutions. This is a deficiency in our current educational process, and we believe that the D&B projects are a positive step toward addressing it.

We also came to realize that there is often a substantial gap between conventional teaching labs and undergraduate participation in modern scientific research. The pre-assembled teaching-lab experiments are interesting, but they do not give students any experience researching and fabricating something on their own, as they will likely begin doing after graduation. At the same time, modern scientific research often involves large groups over many decades, and it also does not always provide a satisfying learning experience. The D&B projects bring the challenges of actual research, but on a small enough scale that students can take ownership of their projects.

We found that the most educational projects were those that forced students to calculate some important aspect, to connect the math to the physics. Making this connection is central to what physicists do, and mastering it is difficult. Connecting the math to the hardware is especially challenging. Thus we found that the design phase of each project was the most important for developing analytical thinking. The build phase is more about teaching specific fabrication skills.

Finally, in researching a bit of the history of laboratory teaching at Caltech, we found that D&B projects have been tried before, and likely at many times and at many universities. They do not seem to become entrenched in the physics curriculum, however, and we suspect the reason is that D&B projects are quite resource intensive. Not only is some funding needed to let students try things and break things, but the projects also require quite a bit of one-on-one interaction, and therefore quite a bit of instructor time. Projects worked best when we, the instructors, had a personal interest in researching and understanding the physics behind the project.

Our interest in D&B remains high, and we are actively searching for funding that would allow us to continue this track into the indefinite future. Our students enjoy the projects and seem to get a lot out of them, and we enjoy advising them on whatever mini research topics we stumble across. There seems to be no shortage of fascinating demonstrations and physics tidbits in the literature that are intriguing enough to investigate further. As with undergraduate research in general, we find that these smaller D&B projects serve an important function in teaching students how to think more broadly about physics and problem solving.

[1] "Simple demonstration of storing macroscopic particles in a Paul trap," H. Winter and H. W. Ortjohann, Am. J. Phys. 59, 807 (1991).

[2] "A magnetic suspension system for atoms and bar magnets," C. Sackett, E. Cornell, C. Monroe, and C. Wieman, Am. J. Phys. 61, 304 (1993).

[3] "An undergraduate laboratory experiment on quantized conductance in nanocontacts," E. L. Foley et al., Am. J. Phys. 67, 389 (1999).

Figure 1. The *Physics Design&Build Lab* at Caltech. Students worked in groups of 2-3 on their projects, and each group was assigned lab space that remained undisturbed in their absence.

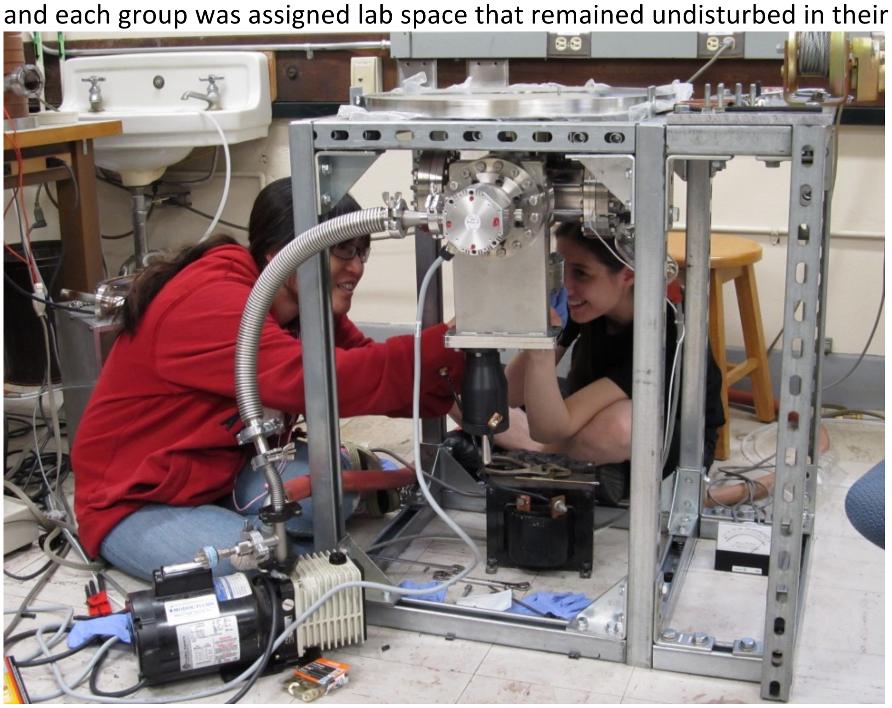

Figure 2. Our bell jar vacuum system under construction. Once assembled, students evaporated thin films of silver on glass slides to study weak localization phenomena.

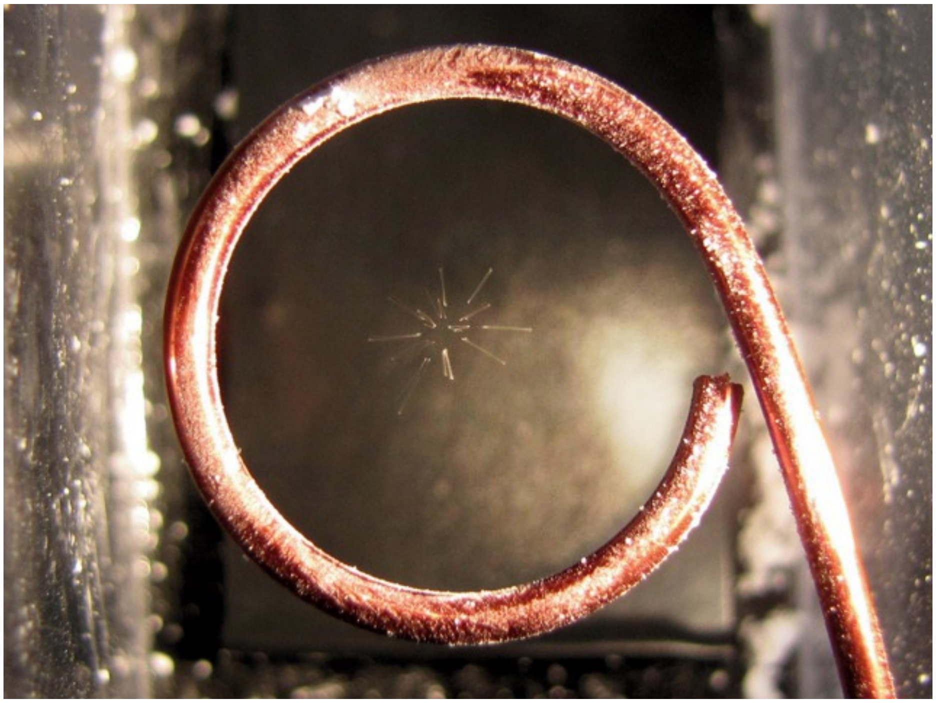

Figure 3. A student photo of one of our first ion traps (6 mm in diameter) showing about a dozen trapped particles (before we learned to illuminate the particles with laser light). The particles oscillate at 60 Hz, making them look like small bits of string. Their mutual repulsion causes them to form an ionic "crystal" inside the trap.

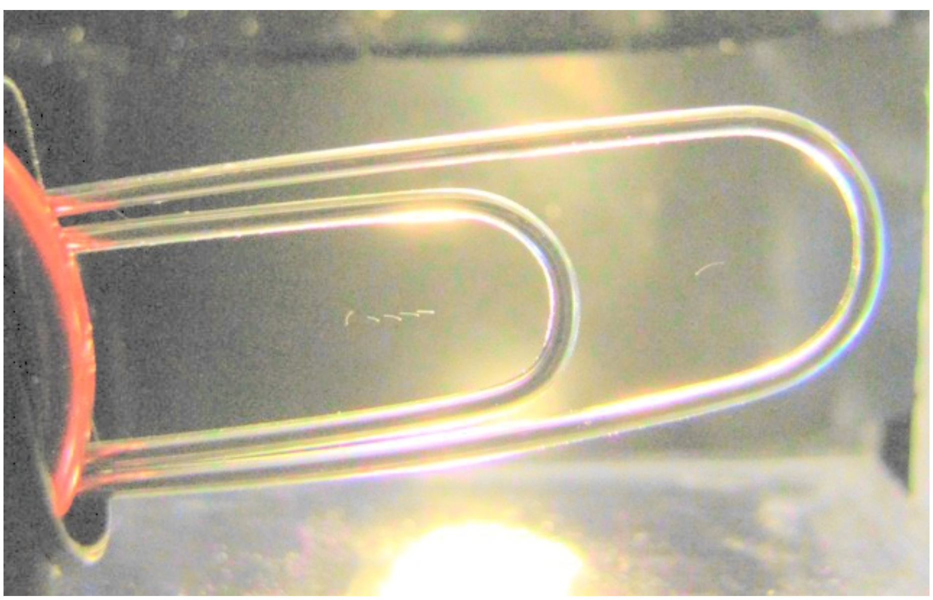

Figure 4. A student photo of a paper clip ion trap. A single particle is trapped on the right, and five are trapped on the left.

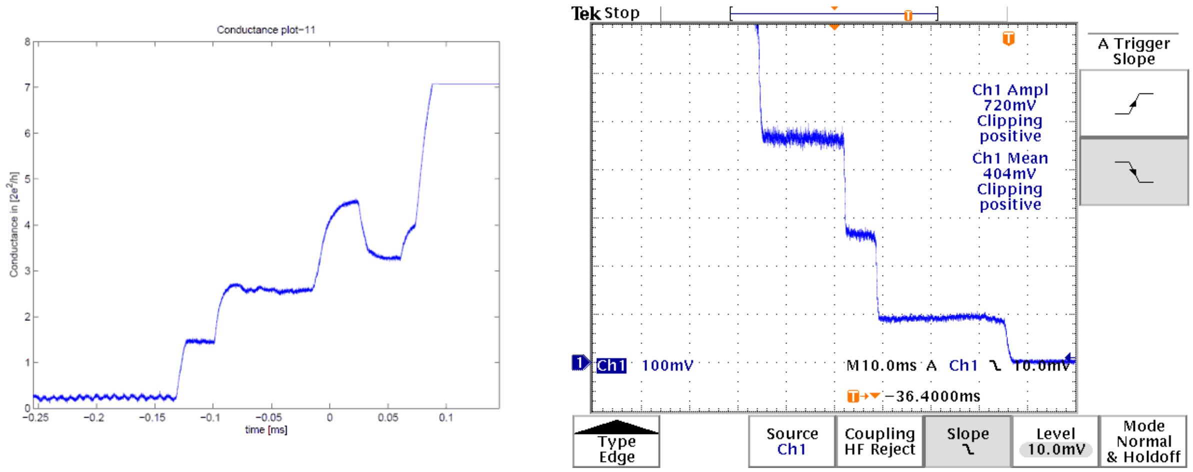

Figure 5. Left: Conductance as a function of time as a two conductors were brought into contact, showing quantized conductance steps. The signal is not especially clean and each trace is different – typical characteristics of simple nanocontact experiments on quantized conductance. Right: The light transmitted through an optical fiber as the fiber was heated and stretched until it broke. The intensity dropped in steps as the number of transmitting modes was reduced. The fiber experiment serves as an optical analog to the quantized conductance experiment. (Both plots generated by students.)

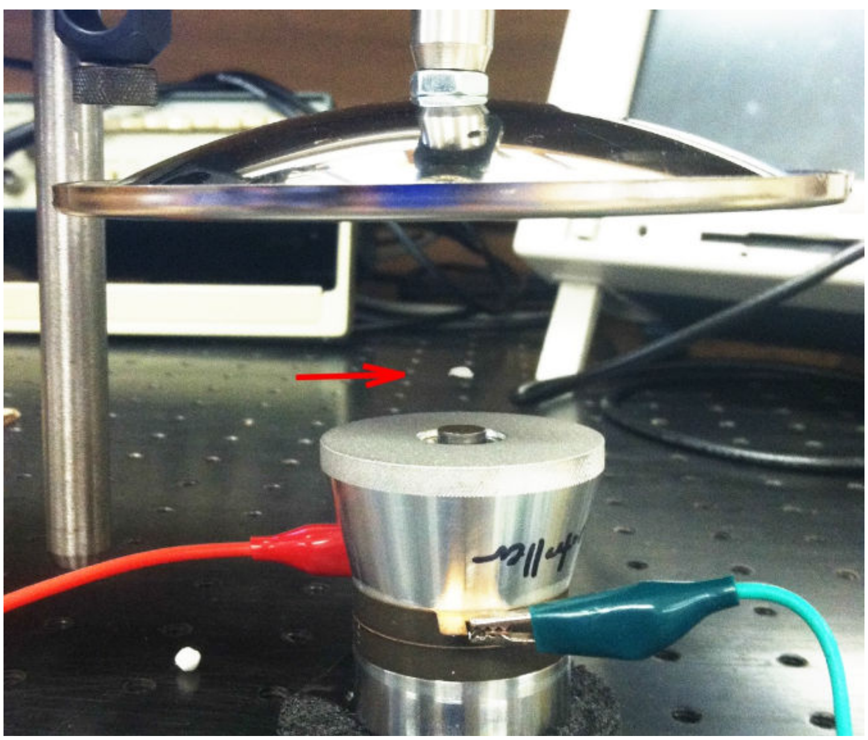

Figure 6. A student photo of a small Styrofoam fragment held in place by acoustic levitation, using an ultrasonic cleaner transducer purchased on eBay.