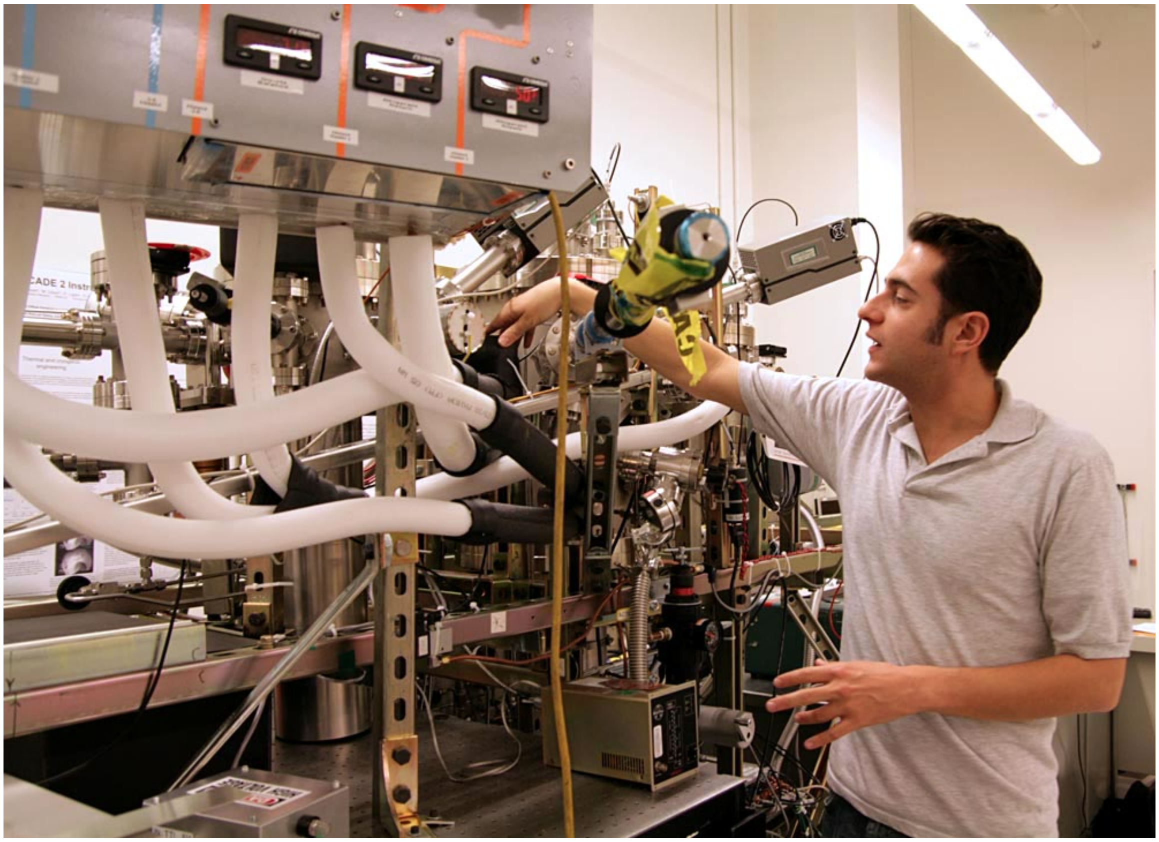
Developing Future Generations of Instrument Builders

Astro2010 White Paper



Post-doc Jack Singal works on the LSST camera test system (courtesy Tony Tyson, UC Davis)

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1. Introduction

Much of the success of modern US ground-based astronomy in recent decades has been due to the ability of researchers to equip their telescopes with innovative instruments based on state-of-the art technology. The people who have led these efforts have, for the most part, been scientists who combined an active research program with a substantial commitment to instrument development. They have acted, in effect, as a bridge between the forefront science enabled by these instruments and the technical capabilities required to build them. With the increasing cost and complexity of competitive instruments, they have also had to develop – at least informally – skills in related disciplines such as project management and systems engineering, as the size and range of skills of the teams building instruments have expanded.

In this white paper, we discuss how future generations of instrument builders can be assisted in acquiring the necessary skills and experience. We are not proposing major changes in the ways instruments are now built or are expected to be built in the future. Rather, we propose ways in which younger investigators' careers can be aided within the existing system. We expect that such supplementary programs will help bring in a broader and more diverse pool of talented and motivated people.

We address only in passing another topic which is at least as important for the overall health of the discipline, which is how students can acquire scientific skills and interests, starting at the pre-college level and progressing through their undergraduate careers. At these levels, development efforts should not be narrowly specialized, and the authors of this paper are probably not the group best suited to make recommendations. It is our hope that white papers on precisely these issues will be presented to the Astro2010 panels, and we urge that this topic be taken seriously. Most of the authors of this paper developed these interests in instrumentation while quite young – but it was often positive experiences in high school or college that provided critical reinforcement.

A third important topic we address only peripherally is use of instrumentation development projects to promote diversity, both among the astronomers involved with such projects and among the technical staff associated with them.

Although the emphasis of this white paper is very much on "hardware", we note that large software projects have similar issues[1]. The solutions are surely somewhat similar as well. The emphasis in this paper is on ground-based OIR instrumentation, based on the collective experience of the authors. The situation in related fields (radio, airborne astronomy) is surely very similar.

The authors of the paper are primarily people with experience in building major instruments for ground-based telescopes, as well as experience in other systems of similar complexity (e.g., large survey programs). We represent a range of starting points in our

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[1] Though some may think of instruments as *purely* hardware, this is incorrect – there are substantial software elements related to instrument function and, increasingly, data processing. In the sections that follow, software engineering is presumed to be included among the technical disciplines discussed.

careers of more than two decades and therefore bring both a historical perspective as well as recent experiences similar to those we wish to promote.

Most of the senior people now engaged in instrument development started their careers in an era when state-of-the-art instruments consumed far fewer resources and took much less time to build – when it was reasonable to assume that a post-doc, if not a graduate student, had acquired all the necessary skills and was ready to move on as an independent instrument builder. This situation changed with the advent of digital detector arrays, of ever-increasing size, and more recently with the implementation of complex adaptive optics systems on larger telescopes. The real cost of cutting-edge instruments has increased (in real terms) by roughly an order of magnitude over the last 25 years – and the duration of such construction projects has increased from perhaps a year to several years (now typically 5 years or longer if the time to obtain funding is included). The consequences of failure, both to the funding institution and to the lead scientist, have obviously increased radically.

The solution to this need for experience is one that has been already arrived at informally, which is to extend the training period for younger scientists who are potential instrument builders through participation in projects led or mentored by a senior, experienced scientist. In this white paper, we discuss ways in which opportunities to gain this experience might be strengthened with a modest amount of additional funding support for a formal development program. We also discuss, in this context, models for construction of instruments that are beyond the capabilities (or risk tolerance) of individual institutions.

2. Historical Background

Large digital array detectors became available to astronomers in the early 1980s for visible wavelengths, and in the mid 1980s for infrared wavelengths. Instruments previously had been either relatively simple single-channel devices[2], or based on photographic plates. With the advent of detector arrays, complexity was added in the form of readout electronics, vacuum and cryogenic requirements. Furthermore, the ability to perform accurate sky subtraction often led to more stringent requirements in terms of instrumental background and stability.

Over the years, the initial generation of detector arrays was replaced by arrays of increasing size, and eventually by mosaics of arrays. The overall increase in pixel count has been well over a factor of 10^3 (close to 10^4 if one includes instruments now under development) with a corresponding increase in the size of optical elements and instrument weight and volume.

In addition, technical requirements – factors ranging from wavefront error to throughput to mechanical and thermal stability, plus many others – have become increasingly demanding. To meet these requirements, technical innovation is required, though

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[2] Or modest arrays of such devices.

astronomy is not a major market for such innovation. Hence astronomers must often rely on technological diffusion from other fields.

While many of the early array-based instruments were built for a cost under $2M (current dollars[3]) and in about a year, the duration of present-day instrument projects is several years – 5 years is perhaps typical – and costs of some of these exceed $10M, with more ambitious projects costing far more. This should not be read as implying that an innovative instrument *must* cost many millions of dollars, but it should be recognized that projects costing less than $3M or so are the product of a very focused effort (and good cost control) by the instrument builder.

Institutional budgets have not increased by anything like these amounts, so the consequences of cost or schedule overruns are potentially far more severe. This risk has been addressed by insisting on far more rigorous project management than was used 20 or 30 years ago and by spreading risk through multi-institution collaborations; there is also an obvious (and logical) reluctance to rely on inexperienced people in key positions. This risk aversion also makes it difficult for qualified, younger investigators to obtain funding through a program like MRI - given a choice, review panels would rather see a lengthy track record than a short one, no matter how successful the latter may be. How, then, does a young, motivated and inexperienced graduate student evolve into an older, wiser, experienced (but still motivated) PI?

We do not propose to go quite as far as NASA, which has implemented specific experience requirements for mission PIs in certain cases. (This is difficult to implement in any case, given the range of funding sources for ground-based instruments.)

3. Evolutionary Path for Individuals

The best way to gain needed experience is by working alongside other more experienced people. In general, the individual’s role in a project or projects will expand as he or she gains experience.

More formal exposure to instrumentation or related disciplines can be of immense value, provided these courses and labs are well taught (and up to date). Such programs exist at some universities, and should be a model for others. It may be difficult for smaller institutions to provide this kind of instruction, so other avenues (e.g., summer schools or inter-disciplinary courses) may need to be implemented to reach a broader pool of students.

Thus, a student may play an initial role performing a non-critical task (typically one that is necessary but that someone else could take on if the student does poorly without serious impact on schedule or cost). He or she would then take on more responsibility, perhaps in connection with thesis research. It is important at this point not to tie the student so closely to the project that his or her graduation is dictated more by the project

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[3] CPI 1983-2008 = 2.16

schedule than by individual progress. Undergraduates can fill somewhat similar roles, although they typically have fewer skills and a tighter schedule for graduation.

After graduation, the next step is typically a post-doc, which represents a critical part of acquiring enough experience to assume greater responsibility. We focus on this part of the career path because we believe that this is both the area that is weakest and one that can most readily be strengthened. In particular, in order for the person to acquire the necessary range of experience, the duration of the post-doc should cover a period starting as early as practical in the instrument design phase, through fabrication, integration, and commissioning, and into early science use – in which the post-doc should participate as an active member of any “science team” associated with the instrument.

Although it would be desirable in principle to start such a post-doc during the very early design stages of the instrument, in practice funding will be limited and the instrument may not be built in the end. Unless the post-doc’s funding can be guaranteed separately from the instrument’s funding, the position should be filled after a commitment to construction is made (typically post-PDR). Also, few institutions build many instruments at a time, so an instrument that does not receive funding could leave an instrumental post-doc stranded at a very vulnerable time in their career. Given the schedule for typical instruments, the duration of the post-doc should be more than 3 years – 5 years may often be needed. It is essential for the post-doc to gain experience using the instrument at the telescope for real research, not just commissioning activities, so the post-doc must extend long enough for this to happen. (This is important for the individual’s career, but it is also a very good way to ensure that knowledge of how best to use the instrument and its data is developed early on.) Since it is crucial to ensure that the post-doc period extends into early science use, for instruments with lengthy schedules it may be necessary to further delay the start of the post-doc in order to ensure its duration is reasonable (no more than 5 years).

In practice, arrangements like this occur already, but in some cases they may be constrained by funding or by institutional constraints on post-doctoral positions. One way to address this issue would be for the NSF to provide a supplemental fellowship program for developing instrumentation scientists. This would fund a position for up to 5 years to work on a suitable instrumentation project. Projects could apply for such funding, either in conjunction with the application for NSF funds for the instrument itself, or separately if the instrument is funded by other means. Programs aimed at developing facility astronomical instruments like TSIP or ReSTAR (if funded) could include such fellowships as a requirement or as an option. (Funding the post-doc as an increment and not as a "tax" is likely to work better. This way the added resources for the post-doc offset the mentoring effort required from the PI or Co-I) This is not a large program, but is likely to significantly enhance the development of scientists with needed skills. People funded under this program would be expected to devote most of their time (perhaps 80%) during the first years of the fellowship to work in support of the instrumentation project[4].

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[4] This is thus very different from a “science” fellowship, which (often explicitly) is intended to minimize service functions performed by the post-doc.

Following such a post-doc, this person should be capable of working with greater independence, as an assistant professor or equivalent research faculty position. Would they be ready to assume the role of PI on a $10M instrument? Almost certainly not. But since, as we discuss below, the trend for such large instruments is toward multi-institution collaborations (both to spread risk and pool talent), there could easily be a role as a co-investigator in such a large instrument. Would they be ready to assume the role of PI on a $2M project? Probably not, although there may be exceptions, and it is certainly the case that this might be feasible with institutional support in the form of a mentor or senior Co-I.

Once a junior individual has demonstrated the skills needed to take on a project of moderate size – perhaps reinforced by institutional support or support from a more experienced individual - there remains the problem of actually obtaining funding for such a project. While, obviously, programs that fund such projects (e.g., NSF ATI) must weigh risk when evaluating proposals, there is a danger that the assessment criteria will steer awards primarily to individuals with lengthy track records, and make it very hard for less-senior individuals to get funded. There is a level of experience where risk is reduced to an acceptable level, and a lengthy track record should be balanced against the quality of the proposal itself and the advantages of expanding the pool of highly-experienced instrument builders.

One other requirement to work in such an independent role is access to a technical group providing a stable set of key skills. This “core group” is not the full set of people needed to undertake a major project, or a share of a major project, but rather a smaller subset of people capable of leading such an effort. Maintenance of such a group is a serious problem for most institutions. The increasing size of instrumentation projects tends to confront individual groups with a “feast or famine” situation. If this technical group is shared within a department or even a larger division of a university, it will enhance funding stability. An alternative would be an increased willingness to collaborate with other institutions. This implies ceding a share of the creative role to others, and also carries with it the overhead of additional coordination. There are already some precedents for this in the community. In principle, a department that is committed to a significant role in instrument development could be prepared to provide back-up funding to maintain stability. In principle, this might also be funding that the NSF could provide – but it would make sense only if the group is providing a capability that is unique (or nearly so) at the national level[5].

One final issue is how this career path matches the path to tenure. This is a decision for individual institutions, and not one where it is appropriate to propose a national policy. In essence, if a university or other institution wishes to develop the ability to build astronomical instruments, it must support this not only financially but through promotion and tenure (retention) of its talented staff. Often, relatively simple issues need to be addressed. (Are SPIE papers considered legitimate publications, for example?)

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[5] Could the “unique capability” be telescope time? This should not be ruled out.

4. The Future of Instrument Development

The next generation of ground-based telescopes will be very large indeed, and the instruments and adaptive optics systems associated with them will mostly be very large, complex and expensive. These costs can be justified by the need to make full use of the capabilities offered by the telescopes themselves.

At the same time, there will continue to be a need for instruments on smaller telescopes (10 m and smaller), both to keep these scientifically competitive and as a proving ground for new concepts. The emphasis with these instruments will be on speed and cost control while retaining competitive performance.

Thus, even though the two categories (which admittedly overlap a lot) will cover a range of at least an order of magnitude in budget, the underlying pressures to contain costs and maintain schedule will be present for both. The main difference is at the low end of the range – which is still likely to involve total costs ranging from a million dollars to several million dollars for a facility instrument – where the scope and risk are within the capacity (and tolerance) of a single institution. This is not true as costs escalate beyond $10M, in some cases well beyond that amount. The solution lies in collaboration between institutions. This spreads risk and pools talent, but does impose an additional “overhead” for coordination, project management and compensation for different institutional cultures and procedures.

The NSF MRI rules, which count each institution in a proposal as a separate proposal (to be counted against the overall limit per institution) can discourage collaboration. These rules should be revisited.

Within this model there are two potential roles for a relatively inexperienced instrument PI. One is as the PI on an instrument of modest scale (ideally in an environment where mentoring or some other advisory role for a senior person is possible). The other is as a co-PI (i.e., institutional lead) on a larger project, where the junior person and his/her institution are responsible for only a modest part of the overall project. Both models are clearly reasonable, and provide alternatives for people with somewhat different temperaments. As noted above, funding agencies should note that there is a legitimate policy purpose served by expanding the pool of people in both areas, and should take this into account in evaluating funding proposals.

5. Expanding Participation

Few, if any, facility instruments are now built just by astronomy faculty and students. Instead, astronomers provide scientific leadership and some specialized skills (project leadership, data pipelines) while key technical tasks are performed by people with appropriate training and experience. Where do the people with these skills come from? There are several possibilities, all of which have been used successfully from time to time.

The most common situation is one where the department or instrument group actually has a core technical group that handles key tasks and can manage more junior technical people or sub-contractors to whom additional tasks are delegated. This approach has had wide success and should be adequate for those cases where the range of high-level skills required is available through the core team (or teams in the case of collaborations). This approach lends itself to development of junior technical personnel who are added to the team for the duration of the project, and who become qualified to go on to more demanding positions at the end of the project. These development efforts could mesh with programs aimed at developing engineers from under-represented groups.

There can, however, be situations where the skills needed are not available within typical astronomy departments, and here there are two possible solutions: other departments, and industry.

It is usually the case that the mechanics of collaboration with another department is easier within the same institution, but it may be that the required skills are available only at another university. Some examples that have been cited are complex opto-mechanical analysis, complex control systems or control algorithms, and laser development. These inter-disciplinary collaborations can be very productive provided the collaborative project is given an appropriate priority. If the project is treated as “filler” or assigned to second-tier personnel, the results can be disastrous. If, on the other hand, the collaborators are genuinely motivated the collaboration may be a tremendous success. These arrangements will work best when they represent true collaborations rather than something viewed as a vendor/customer relation.

Industry is best used for fabrication capabilities that can benefit from economies of scale (e.g., circuit boards) or require specialized facilities (large dewars, detectors, and so on). Industrial suppliers are normally more expensive, so they should be used in circumstances like those cited where there are still overall cost savings or significant risk reduction. Of course, where a commercial solution for a required component or sub-system is available, it is almost always preferable to use that rather than trying to develop something allegedly better in-house.

Both of these options have been used in the past, but perhaps not as much as may be needed in the future (especially inter-disciplinary collaborations).

A suggestion occasionally surfaces when the difficulty of producing large instruments and training people to lead such efforts is discussed, which is that the efforts should be completely out-sourced to groups allegedly better suited to carry them out.

Collaboration with any of these groups is valuable, as described above, but the value diminishes if they are not collaborators but primary developers, especially if they are not as motivated as the astronomers they are theoretically replacing. Furthermore, their expertise will not fully replace the expertise someone familiar with ground-based astronomical instrumentation possesses. Finally, if astronomers abdicate the instrument-building role completely, the required astronomy-specific expertise will eventually disappear.

6. Funding and Policy Recommendations

Recommendation 1: Funding post-doctoral fellowships to work on major instrument projects for ground-based facilities, up to five years. The number of new fellowships should be at least 3/year for OIR instrumentation. “Instrument projects” should be broadly defined, the concept certainly includes AO, possibly includes (mid-sized?) telescope projects or software projects. A broader range of projects implies a more extensive program (more fellowships per year). If the cost of a post-doc is roughly $100K/year, then “steady-state” funding (3 new post-docs per year, duration 5 years) would be around $1.5M annually.

Recommendation 2: Programs that feed potential instrument builders into the field through programs at the pre-college and under-graduate level should be supported. These should include programs that target under-represented groups and technical specialties, not just astronomers. Such programs will most likely be broader than just astronomy or physics education, but astronomy is an attractive means of interesting students in scientific and technical careers. As noted above, there are development opportunities in other fields associated with astronomical instrument construction.

Recommendation 3: The NSF and other funding agencies should review the criteria used for programs providing instrument grants to ensure that younger investigators with adequate experience and mentoring can compete successfully. Proposals that include such mentoring by senior investigators should be strongly encouragedThe agencies should also review any other criteria (e.g., MRI rules related to institutional collaborations) that may harm joint projects involving less-senior investigators.

Recommendation 4: The survey panels looking at facility development should examine ways to promote a more stable environment for university instrumentation groups (as well as those at equivalent institutions). Some *focused* funding from the NSF or other agencies may be part of such a solution, for example by support of centers of excellence. This should be viewed as a means of making funding of such groups more robust, not a sole source of funding under normal circumstances. The services or other benefits provided to the community by such centers should be broadly available and extensively utilized.

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