Knowledge Integration in Undergraduate Research Projects

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ABSTRACT

Experience at the author's research group is reviewed, with undergraduate research participation over the past quarter century. Over 200 undergraduates have gained their initial experience of research and professional laboratory program participation in our group. The objectives of undergraduate research involvement are considered, followed by the issues identified, several approaches that have been tried out, and lessons learned. Some examples of current work are given.

Keywords: undergraduate research, orientation, project document, tacit knowledge, apprenticeship, brown bag, research meeting

1. INTRODUCTION

This paper is a case study revisited from a decade ago [1,2], in the context of new resources for vertical and horizontal knowledge integration. It is based on experience from guiding some 200-plus undergraduate engineering students in the School of Aerospace Engineering at Georgia Institute of Technology, and on related discussions with other faculty across the USA and other countries through various interactions. The issue is how to enable undergraduate students to come into a research team, quickly learn what they need to become competent contributors to an ongoing effort, and then how to integrate their contributions and knowledge into the continued development of long-term research projects. The paper is organized into the "what, why, how and lessons " of undergraduate research in an experimental research group. This organization was done to present this case study to an audience of new engineering faculty in a predominantly teaching-oriented institution.

The famous definition from Nobel Prize winner Albert Szent-Györgyi de Nagyrápolt [3] is that *"Research is to see what everyone has seen, and to think what no one has thought"*. In our context, a working definition of undergraduate engineering research is that we include "*any project taking a semester or longer of student participation, involving use of knowledge relevant to the discipline, and leading towards solution of an unsolved problem. Key features must include specific objectives and independent thinking*.

The constraint of requiring a semester or longer distinguishes a research project from a homework assignment or term paper. Using knowledge relevant to a particular discipline may exclude organizing purely social events, or doing only "busy work" requiring no discipline-related thinking. The definition of "discipline" varies from one school to another. That the project must lead towards a solution implies focused effort with progress, but not necessarily success. The problem need not be small enough to be solved in one semester. The "unsolved problem" requirement distinguishes research from what may still be good engineering where the solution is found in past work. Diligent literature search is an essential component.
Requiring specific objectives means that one must be able to explain the "why" and "what" of the project, and this must guide progress. Independent thinking is the most important component that differentiates "research" from class work. Running laboratory tests for a professor may not be a good use of undergraduate talent, though it may teach some skills. Innovation is highly desirable, and distinguishes engineering research from pure science in many cases. "Design" and "building & testing" are perfectly fine under this definition.

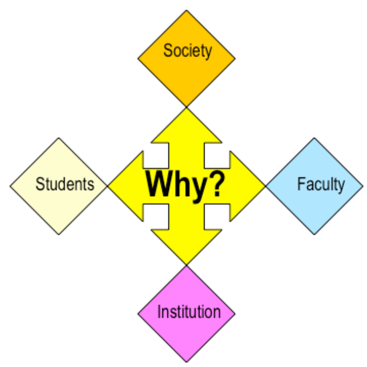

Figure 1: The "Why" of research participation by undergraduates, from different perspectives.

The "why" of undergraduate research requires more thought, and the answer varies with the role of the participant, as indicated in Figure 1. For "society", including the student's parents, neighbors and friends, a student's participation in a research project often brings pride. Society appreciates the need for well-educated innovators. Since most research projects, if properly explained, will be seen to contribute to the larger needs of society, the fact of a student's participation allows people outside the institution as well to contribute to problem-solving. Participation must be with some rational goals other than for appearances.

For students, there are many benefits, listed below.
- First experience of "real-life" in chosen career field
- Explore interests
- Gain new skills
- Build confidence
- Build experience with a systematic, disciplined process for solving problems
- Experience in working with others
- Interaction with people outside the course environment
- Launch pad to jobs
- Credentials for graduate school

What this list should not include (and sometimes does) are the expectation of an easy grade and the hope of inflating their resumes with a "research" item without serious intention of putting in the effort that it implies.

For the institution, again, there are several benefits:
•Provide students with opportunities for "practical experience", and very cheaply at that.
• Individual mentoring without reducing class sizes.
• Free advertising: word-of-mouth recruiting tool.
• Free placement tool for industry.
• More students going to graduate school.
• Positive publicity with parents and community.
• Students win prizes/ scholarships/ competitions.
• Faculty generate results/ papers; reduce time to sit in staff room and complain.
• Research universities may generate proposals for much larger sponsored projects.

Finally, for faculty, the decision to participate and host undergraduate researchers must balance several positives and negatives. The positives include:
• Satisfaction: provide students with opportunities.
• Individual mentoring: work with interested students!
• Free advertising: word-of-mouth recruiting tool.
• Means of interacting with other faculty and industry
• More students going to graduate school
• Positive publicity with parents and community
• Students win prizes/ scholarships/ competitions
• Generate results, papers and proposals.
• Recruiting tool for own research program.
• "Free", enthusiastic, and motivated work force.

The negatives are important, and must be carefully recognized and understood.

• Frustrating: The "failure rate" may be greater than 50% if one measures success by the achievement of professional-level technical objectives. Many students are simply not mature or knowledgeable enough to be motivated to seize the opportunities afforded by such a project. The metrics for success must be carefully defined to reduce this frustration.
• Individual mentoring takes enormous commitments of time and thought.
• This time may be better spent in working by oneself, or with graduate students.
• Undergraduate research rarely produces publishable papers.
• One receives essentially zero help from the administration.
• More traumatic is the realization that one also gets zero recognition in promotion, tenure or salary reviews.
• "Senior faculty" often ascribe no value to undergraduate guidance.
• It will occur to every teacher eventually that the time devoted to guiding undergraduates may be better spent in organizational politics or serving top administrators, from the perspective of career advancement.

Before going on to the "how" of undergraduate research program leadership, it is useful to consider past work on the nature of engineering knowledge. Engineering knowledge is defined [4,5] as "processed information, including engineering models, experience, knowhow, etc." Central principles of knowledge management [4] are listed as:

- "The capture, storage and accessing of knowledge.
- Effective utilization of knowledge
- Identification and Filling of Knowledge Gaps"

A distinction is made [6] between "*explicit knowledge*" and "*tacit knowledge*". Tacit knowledge is described [4,5] as "*personal knowledge embedded in individual experience and involves intangible factors such as personal belief, perspective, and the value systems*". This includes, to some extent, the rationale behind design decisions which are often taken before formal documentation of the project commences. Milton [7] describes explicit knowledge as that which is expressed in language and encoded in procedures and manuals. Tacit knowledge is a more personal form of knowledge, related to individual experience and involving personal factors such as belief systems, values and culture. The terms have evolved in recent times [6] so that explicit knowledge indicates encoded or recorded knowledge, while tacit knowledge is equated to unrecorded knowledge. According to Borghoff and Pareschi [8] in their definitions: "*Explicit knowledge is formal knowledge, found in the documents of an organization: reports, manuals, patents, pictures, images, video, sound, software etc. Tacit knowledge is personal knowledge embedded in individual experience; shared and exchanged through direct eye-to-eye contact. Clearly, tacit knowledge can be communicated in a most direct and effective way*."

The capture of tacit knowledge is made difficult by the fact that tacit knowledge can include both conscious and unconscious knowledge, and often teams rather than individuals in isolation, possess the knowledge. Techniques for extracting conscious tacit knowledge include [5]:

- Put people in touch with people and allow them to talk.
- Company-wide "yellow pages".
- Communities of practice built around core competencies.
- Email discussion forums;
- Databases of lessons learnt.

To capture unconscious tacit knowledge, Brain Mining techniques have been developed. These are applied, for example, in situations where experience occurs in repeated discrete projects, such as in the case of oil exploration teams and military operations. Procedures for collecting team knowledge include strategies for making knowledge conscious. Examples of tools are:

- Army After Action Reviews.
- Compare a team's expectation of event with actuality, to find reasons for differences.
- Hard questioning, proceeding in depth to the "Five Whys" to determine true causes.
- Learning-History studies

The above body of knowledge shows that conducting projects that advance knowledge, is difficult and fraught with pitfalls, to require such in-depth consideration and so many formal techniques. A great deal of tacit knowledge is involved, and means for capturing and transferring such knowledge must be learned and conveyed to students.

2. VEHICLES FOR UNDERGRADUATE RESEARCH PARTICIPATION

Distilled to what can be done in the context of engineering school, several approaches are evident, as discussed below.

Year-long Project

In 5-year Bachelor of Technology programs that existed some decades ago [9], the last two semesters included 20 credit-hours of "project" experience. This was often devoted to design projects rather than research, but came under our working definition of undergraduate research participation when utilized effectively. It was distinct from the "capstone design course". For many graduates from those times (such as the author's generation), it was the Project, rather than their capstone design course reports, that formed the basis for career choices.

External Internship Requirement

A different way of conveying research experience is for the university to simply require students to go to an outside institution for a summer or two of research participation. This technique is increasingly seen in universities for instance in France, Singapore and India. It does not necessarily imply lack of opportunities within the institution, and may in many cases be an excellent means of cross-pollination of ideas and experience from all over the world.

1-semester Special Problem

This is the preferred mode at our institution. Students sign up for letter-grade credit, typically for 3 semester hours. In many cases, the student goes on to two or more such experiences in the same lab or different labs, often transitioning into graduate school. In our group, several of our alumni participated in such Special Problems while they were in their academic semesters, using them as springboards to Cooperative Plan or Internship assignments in industry or government labs in alternate semesters.

Competition projects with course credit.

National team competitions provide the foci for several efforts. These also include course credit, understanding that the grade is for the effort, and comes much before the results of the competition entry are announced. Competitions certainly bring out exceptional effort and initiative from students. One danger is that the drive to win induces team leaders and advisors to forget that students are also taking full loads of other courses, and that they are there to learn. "Burnout" and dropping out of school, are egregious consequences of over-emphasis on competitions, and require the attention of senior faculty to moderate.

Collaborative external projects

Sometimes opportunities arise for students in different institutions to collaborate on some larger effort. Each is a unique opportunity. The difference from the previous item is that any competition is only in being able to see and in trying to match or exceed, the standards of effort and professionalism that other teams achieve. In these cases, the external coordinating entity for the project has a large degree of control in how the participating teams work. This can be good and bad from the point of view of the advisor in each particular institution. One outstanding example is the initial round of the "NASA Means Business" strategic planning student experiences conducted at the Lunar and Planetary Institute in Houston, by the Texas Space Grant Consortium. The first of these brought 6 winning proposal-writing teams from different universities together for a 3-day planning exercise, where the "competition" was mainly to be more useful to the overall objectives of the entire group. Certainly students learned at a great pace from each other and paced themselves against their peers, but there were no "losers" in this exercise. That unfortunately came with the "improved" versions of the program in later years. To the author the lesson is that no external judges are needed (and they can do a lot of damage) when several such teams are brought together for a collaborative exercise.

Paid research projects (scholarship)

Finally, there are occasional opportunities for students to work on research, under scholarship or fellowship awards. Where there is a clear proposal behind the work, this works somewhat better than in cases where the scholarship is awarded at the beginning based on potential, with no serious pull to complete the project.

3. TYPES OF PROJECTS

In the author's experience, several types of undergraduate research experiences are possible and have been tried. Over time, the organizational means have been rationalized so that they are independent of the type of project.

1. **Team member on a sponsored research project:** This is the most common type of project in many research groups, and it was the initial model pursued in our group starting in the 1980s. The general expectation is that undergraduates learn from the graduate students, and gradually take over more and more of the operations. The in-depth knowledge comes from the graduate students and the professor. In this model the undergraduate is basically an apprentice, learning quickly to assume responsibility.
2. **Advanced Concept Development:** When students come by asking for guidance in pursuing "far-out" projects such as interstellar propulsion, this forces some soul-searching, chafing against the "what will the Senior Faculty say?" fear of the untenured assistant professor. The easy answer is that one should not hesitate to guide undergraduates in such projects. This led in our group to increasingly bold concept design exercises, going far into the unknown and learning to reduce uncertainties in such projects.
3. **Preparation for Off-Site Projects:** Opportunities to conduct experiments or planning/presentation exercises at industry or government sites posed unique opportunities requiring several team members. This triggered studies of how to capture and transfer knowledge in the short and long terms. Several projects detailed in [1] challenged our capabilities, but our solutions rose to the challenge.
4. **Testbed development.** These are mostly low-level, unfunded projects where testbeds for future research / field test systems are steadily developed by undergraduates. Progress rates are slow, so the knowledge capture problem here is how to transfer the project across student teams and semesters.

4. TECHNIQUES

Techniques are listed in ascending order of formality:

0:Open door acceptance policy

The first requirement for successful research mentoring, in the author's view, is to have open office doors and minds. Most of our outstanding success stories in research mentoring started with a shy undergraduate coming in the office door asking if there was any opportunity to visit the professor's labs and maybe help out. This is not the time to make tough judgments on what the student can contribute immediately based on academic transcripts or CVs. Today these enquiries come mostly by email, often at the last minute during course registration. One has to be swift and precise in response.

1: Orientation Manual
The time spent in developing an Orientation Manual is well spent. Students need clear instructions on many things that the professional workplace takes for granted, such as what to do in an emergency, or indeed, where to find a roll of tape. In our school there are exemplary groups where large numbers of undergraduates are introduced to the workings of a group using very detailed orientation manuals.

2: Apprenticeship Teams & Leadership
The best way to get a new student started, beyond providing the Orientation Manual, is to assign a graduate student or an experienced undergraduate to follow. This can be formalized to assign some undergraduates as project team leaders. In our experience, the "leader" designation is inverted. Graduate students are asked to take the attitude that they are help resources, not instruction-givers, so that the undergraduate is encouraged to start thinking and taking the initiative as early as possible, consistent with safety. The undergraduate team "leader" is left in no doubt as to the relative glamour versus responsibility - the "leader" is a coordinator, and faces the questions when the team is not communicating or working together smoothly.

3: Countdown Lists
Most students come with good intentions and grand ambitions. Few are capable at the beginning of adjusting their pace to the schedule needed to meet objectives on time, and they often do not seem to have much direction as to what to do next. A "countdown list" such as those used in rocket launches is an extremely useful tool to shake up disorganized teams and set them in motion towards clear objectives. "Active walls" are used: we invested in adhesive-backed whiteboard sheets to paste on every exposed swath of wall space. They are quickly filled with lists, diagrams and calculations – none except the first countdown list being done by the professor.

4: Assignment Lists
Derived from the countdown list is an assignment list, showing clearly who is responsible for completing what part of the work. This requires careful management, usually from a senior graduate student if not the professor, to ensure that tasks are matched to capabilities and course loads of individual team members.

5: Weekly Research Team Meeting
A weekly team meeting is an essential part of running undergraduate research projects (and graduate research). Besides giving every student the opportunity and imperative to think, prepare and speak up, it also allows students to "see through the eyes of classmates" and learn much. The nonlinear benefits multiply when students start contributing ideas to each other's problems. This can also be used to exorcise high school habits and teach the idea of getting up early. We have recently gone to a simple system to schedule Monday morning meetings: those who have no 8AM class come in at 8AM. The (few) others come in at 7:45 and are promised a short, succinct meeting.

6: Weekly Progress Report
Weekly reporting on progress is absolutely essential. The format of the reporting varies, and we have tried numerous types, ranging from oral reports to the present insistence on updating a Project Document.

7: Live Project Document
The idea of the project document draws on practices used by the Defense Advanced Research Projects Agency. Although we do not need advanced document and version control features, the format is valuable. The document shell is created by each team in the first week of the project, and details are filled in and modified through the semester. Ideally, this should enable the professor to check at any time and find an up-to-date report on the project. It should also remove the end-of-semester report-writing frenzy where students scramble to organize their scattered notes.

For each project, a Live Test Document is developed. Its front pages contain "News" lists, "Task lists" and a "Current Schedule". Each team member is allowed to modify the document, but has to let everyone know through the News pages and upload the latest to the website set up for the purpose. Each team member, regardless of level or specialization, is emphatically told that s(he) is held responsible for knowing the contents of the document. Instrumentation manuals, cabling schematics, experiment diagrams, operational procedures, example calculations of parameters, and "mundane" details such as contact addresses, phone numbers, driving directions etc. are all placed in the same document. Typically, a test document approaches 50 to 100 pages in length, with more voluminous equipment manuals, etc. being added to a Test Document Folder. By this process, every team member discovers that they are not considered to be "low-level" and hence could not expect to sit around waiting for orders. As students gain experience and confidence with the TD, they become much more versatile at all aspects of the project.

8: Paper Abstract Submission; Deadlines
An effective albeit highly stressful and somewhat risky tactic is to welcome a student with the declaration: "Congratulations! The abstract for your paper has been accepted by the XYZ professional society. The paper with results and conclusions is due in 4 months". Though few students will show any reaction, co-authorship of professional papers is a major source of pride, and usually induces a strong sense of ownership and responsibility. The tactic may also backfire if the student simply does not put in the effort, and leaves the professor facing the deadline with no results.

9: Brown Bag Seminar
Our institution uses the tool of a weekly "Brown Bag Seminar", often Friday at noon, with snacks inducing strong attendance from students at all levels and several faculty. Student presenters are assured that the presentations are on "work in progress", but the reality is that these require intense preparation, and that the faculty will ask questions just as they ask at professional conferences, however kindly they may phrase them.

10: Gantt Chart
Many industry and government researchers have been heard to remark that university professors come to work with no thought given to what they plan to accomplish that day. There are good reasons for this (both the feelings of industry and the mode of operation of faculty) that are beyond the scope of this paper. However, in some cases, Gantt charts that show the status of specific steps in research are effective tools in making progress. Having said that, the author's observation is that the time spent in making them could be better spent in thinking and representing progress in some simpler albeit not as pretty way.

11: Design Reviews
In major projects, design reviews are major events requiring intense preparation, and are often traumatic experiences for presenters as experts point out what they have not thought about yet. Again, these are drastic and formal tools, to be used with great caution, but may have a place in some projects. We have used them where inventions were developed that had to be tested in facilities, and safety considerations were involved.

5. Application of KI/KM techniques to the Team Project Problem

Issues encountered in the team project problem, and their relevance to KI/KM, are listed below. Many of the issues faced by industry teams setting up "discrete projects"5 were faced by the student team as well.

Knowledge Capture
Only 1 or 2 students may actually know the methods used to solve given problems, and conduct given types of measurements. The KI issue is to retain and transfer experience before these students graduate.

Effective utilization of knowledge
Experience must be available in documented form for newer users. Best practices must be determined, from knowledge of past experiences. Tacit knowledge held by PhD candidates must be made available to newer team members when needed to solve problems.

Identification and Filling of Knowledge Gaps Documentation and "habits" must be checked against repetitive experiments to identify mis-diagnosed phenomena, missed steps, etc. The issue is capturing experience in sufficient depth to enable generalization of conclusions. Various measurement techniques and instrumentation types involved: must work together. No student is knowledgeable in all the techniques. The KI issue is integrating diverse sources of knowledge. The results of these, as seen from team project experience, are summarized in Table 1 below

Table 1: Knowledge Management in Team Projects

KI issue	Approach
Retain & transfer experience	Test Document and intranet resources
Best practice	Brainstorming using mockup tests
Communication	Test Document: task list
Integrating diverse sources of knowledge	Test Document: integrate user manuals, equipment specs, and procedures into one manual.
Cross-discipline innovation	Students discuss project with teachers and others; mockup tests.
Retaining depth in team capabilities	Each member participate and reads Test Document
Synchronizing progress	"Status Update" pages at beginning of Test Document

6. Conclusions

This paper summarizes a case study on undergraduate research participants in an experimental aerodynamics group over the past 25 years. There are strong reasons to enlist and mentor undergraduates in research projects, but careful and thoughtful mentoring is required. Despite some frustrations, faculty, as well as the institution and the general public, can all draw benefits from such student projects. Several mechanisms are available to recognize student participation participation, including paid experiences and academic course credit. Undergraduate participation opens up opportunities to devise several kinds of projects, with broad leeway for innovation and experimentation. Informal and formal techniques that have proven successful in motivating students, and facilitating organized progress, are summarized in the paper. Research results on knowledge capture and utilization can be formally implemented, in the context of internet-based resources. Such resources then enable deeper and swifter learning through student projects.

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