A Model for Undergraduate Research

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WHY AN UNDERGRADUATE RESEARCH MODEL?

Undergraduate research (UGR) is an effective tool for preparing undergraduate students for future careers. Research has shown there are numerous benefits of UGR to the student (1). The goals of this undergraduate research model are to i) create a UGR model that can be easily replicated with success at two year institutions, ii) disseminate the model through the Nano-Link website (www.nano-link.org), and iii) provide supporting materials to help educators implement the model available on the Nano-Link website.

OBJECTIVES OF AN UGR PROJECT

The major objectives of many UGR projects are twofold. First, the project seeks to create, develop, and improve 21st century soft skills into the student. Surveys indicate that what employers value most in their employees are soft skills, these are skills that are not strictly related to the specific discipline they went to school for, such as effectiveness in problem-solving and communication (2).

One very important soft skill is critical thinking. Critical thinking is the art of objectively analyzing and evaluating information and issues while examining one's own thought process for errors and assumptions with a view to improve it (13). Employees with good critical thinking skills benefit employers by bringing in new, vetted ideas, fostering teamwork, promoting options, and uncovering new practical methods of solving problems (3).

An intrinsic desire for lifelong learning is an important 21st Century skill closely related to critical thinking that employers also value. Lifelong learning is the "ongoing, voluntary, self-motivated pursuit of knowledge" (4). This benefits the student in fostering tenacity, resiliency and relevance. When a problem arises requiring outside research the student will be self-prompted to search a solution rather than having to be guided to it.

Other valued 21st century soft skills include the ability to work in a team, effectively transfer knowledge, and deal with ambiguity. Team work can in part be fostered by critical thinking. For example, when problems with the project arise how and when should it be addressed (immediately or later on)? Does it hold priority or is it a trivial matter? Should you take up your team members' time with a problem that you could solve yourself? Transferring knowledge means applying what has been learned from various disciplines (ex: chemistry, biology, physics) to a specific problem at hand. For example, in making reasonable hypotheses about how nanoparticles may affect silkworms students need knowledge from chemistry about how to create the nanoparticles and their properties, as well as knowledge of cellular function from biology in order to consider possible interactions. Finally, learning to deal with the vagueness or uncertainty that often is a reality of research is a desirable skill. For example, how should one approach a problem where an effect might have multiple causes?

The second major goal for an undergraduate research project is in the experience of undertaking the research itself. Research methodology is best learned while doing research. This includes developing techniques required to carry out protocols in a laboratory; improving skills in creating testable hypotheses from a research question; identifying important parameters in the design of a research project; practicing skills in data analysis, including statistical and graphical analysis; demonstrating accuracy and completeness in record keeping and analysis of the data; finally the effective communication of accurate results and reasonable conclusions from the research.

PILOT PROJECT

The undergraduate research model presented in this document was developed in part with a pilot project carried out by students at Dakota County Technical College (DCTC) in Rosemount, MN. The objective of the project was to study the effects of silver nanoparticles on silkworms (*Bombyx mori*). Silkworms were fed a paste-like mixture of mulberry leaves containing various concentrations of silver nanoparticles (synthesized in our laboratory). Weight, length, and mortality rate of the silkworms was monitored and their silk production was analyzed. The initial study did conclude that silver nanoparticles negatively impact silkworm growth, but it was not clear if the silk changed or incorporated any silver.

CONSIDERATIONS WHEN SETTING UP AN UGR PROJECT

When developing an UGR project there are a number of elements to determine from clearly stating expectations of the students, to determining what project to pick, how to stock and begin the project, how to maintain laboratory notebooks and back up data, how to ensure safety and that protocols are developed/followed, how to clearly delineate what each students' responsibilities are, what to do when things go wrong, how to incorporate grading and evaluations within the project, and what is going to be delivered as the final work.

EXPECTATIONS

Clearly stating expectations, both from the instructor and the student, will help the project run more smoothly. Very early on in the process, expectations need to be stated.

What kinds of students do you expect to have? What type of research questions interest them? What courses have they taken? Are they expected to work independently or in a small group? Do the students need more direction or more freedom? Should they have experience in research before this project? (5, 6)

Weekly or regular meetings are necessary to check-in on students for ensuring that they are on track, staying motivated, producing results, and have their questions answered. Hold the expectation that students come to each meeting prepared for substantive discussion – at least 1 thing to show (a plot, data table, etc.) and at least 1 question (which could also be a plot, data, etc.). In return, be ready to discuss ideas for new directions (7).

Time management is a critical skill to learn because projects often have deadlines. How much time are students expected to be working each week? A good rule of thumb may be for every one credit hour of the class there is at least 3 hours of work per week. So, for a three credit undergraduate research class, this would require at least 9 hours of work each week.

Silkworm project: formal meetings were held each week to discuss problems with how to measure the worms or care for them in make-shift incubators. Data from the scanning electron microscope (SEM), particle analyzer, and Raman Spectrometer was often discussed as to whether it was quality data or noise.

CHOOSING A PROJECT

Students from DCTC were allowed time to brainstorm and choose their project within the first two weeks of class. The final decision rested on optimizing or reducing factors that could constrain the project such as cost. Cost is an inevitable limiting factor for any project. To determine the likely total cost the importance of planning cannot be overstressed. DCTC students created a project time table displaying time frames for when major tasks needed to be done and when materials needed to be ordered in order to reach those milestones (see appendix A1).

Time is another constraining factor. How many projects can run at once? Is one class project where all the students are involved better or several projects where one or two students work together optimal? In general, more projects means more complexity. Optimizing this relies on your situation. Is there the time, facilities and funds for several smaller groups? Will one large group be too unwieldy? Will the groups have a reasonable chance to finish the project? For a small class size it might make sense for one group to break into smaller task groups rather than several independent projects and groups. For larger class sizes more time or instructors might be needed. Further, for the class at DCTC, the project had to finish by the end of spring semester which meant the students had to develop a timetable for their work that needed to be completed within 16 weeks.

Greater student engagement with the project topic was sought to further motivate their work. To achieve this, an initial guided class discussion to brainstorm project topics was held and relevant papers from peer reviewed journals were incorporated to focus and stimulate creative ideas. Students were also challenged to find research papers on topics they championed. After a short time for reflection the students decided as a group the project they would undertake; keeping in mind the constraints such as time, money and overall feasibility. For an undergraduate research project class, completely novel research, especially if starting new and not part of ongoing work, is very likely unrealistic, but attempting to mirror existing work has a greater chance of success. In our case, the effects of silver nanoparticles on silkworm health was agreed upon by the students based upon a paper found by one student. (8).

BEGINNING THE PROJECT

Once the students agree on a project or problem/question to address, then a research proposal should be written up. Research proposals are valuable for the student and the instructor. They help to answer specific questions that justify the proposal as well as indicate if the project is worthwhile. While developing a research proposal, students gain ownership because they are involved. Proposals should explain the broad significance of the project, i.e. put the project in context by providing adequate background information. Materials and funds that will be needed should be indicated as well as outline the methods, timetable and expected results for the project. A list of relevant references should also be required.

Proposed projects that work smoothly often involve instructors who clearly communicate what is expected of the students, and what the students can expect of the instructor. Details to be communicated to the students include:

1) When each portion of the project needs to be completed
2) How many hours per week the students are expected to work on the project
3) What the learning objectives for the project are
4) When the instructor is available to meet with the students or help with the project
5) How the students will be evaluated

One way to explicitly communicate details of expectations is to draw up a contract that each student will sign (9). The following information may be needed:

1) Students' and instructor's name and contact information
2) Project title and overall goal
3) Start and end date of project
4) Research and learning objectives
5) Dates to accomplish specific objectives
6) Dates for training, material acquisition, instrument time
7) Safety considerations
8) Responsibilities of student and instructor
9) Deliverables
10) Evaluation plan

STUDENT WORK, LABORATORY NOTEBOOKS, AND DATA BACKUP

Laboratory notebooks are critical for any successful project, and all too often avoided instead of embraced. They serve as the primary record of the student's work in the laboratory. In a future technological career they serve as a vital document both for legal and scientific purposes. They ensure complete notes of the procedures followed or modified, results and observations collected, names and locations of files saved on computers, as well as thoughts, plans, questions, and further actions to be taken. Laboratory notebooks are especially important to retrace steps if problems are encountered.

Notebooks need to be written legibly so that methodology and data can be accurately followed and analyzed by others. Students should ask themselves these questions in regard to their notes: Can data be analyzed accurately from my hand-written records? Can the procedures or alterations from procedures be understood and repeated by someone else? Can someone else 'spot' where a problem may have begun? As part of this, students can hand their laboratory notebook to their bench mate to check that they are as transparent as they should be. The instructor may want to make this a regular activity. Further, a well maintained laboratory notebook can be an impressive part of a student's future interview portfolio.

When working on the project, notebooks must always be with the student. Loose leaf paper and other alternative recording of information should be discouraged. Calculations should be done in the laboratory notebook. With the near ubiquity of camera-equipped smartphones, everyone is becoming accustomed to taking pictures to remember information rather than write it down. While great for additional documentation, especially if the pictures can be "pasted" into the laboratory notebook itself, they are not an acceptable primary location of a student's work. Although the compulsion to record the laboratory notebook with a personal camera phone may seem even beneficial as a backup of the work, most companies would at least frown on this use as well. Treat all laboratory notebooks with care, and keep them in the laboratory if at all possible.

SAFETY AND EQUIPMENT OPERATION

Students are always more important than the data or samples. Unnecessary risks in the lab must be avoided. Instructions should be given before using a new piece of equipment. If working in the lab, students are unsure of some procedure, they need to stop and ask. Students need to exercise care in operating equipment, and to inform instructors of any potential problems immediately (7).

STUDENT RESPONSIBILITIES

Although it should be trivial, students must show up as scheduled when they have agreed upon a timeline and their work duties. This seemingly simple way of demonstrating reliability is often mentioned by employers as frustratingly lacking in students. If the student must be absent, it's critical for them to communicate this in a timely manner to the group so any impacted work, especially which is time sensitive, can be attended. For example, during our undergraduate research project silkworms require regular feeding and care, regardless of a student falling ill. Another student had to be identified to manage the duties of caring for and measuring the silkworms. As part of this planned vacations/trips/events can be a special problem during a project. When planning the silkworm project, the students were asked about trips or vacations planned during the 16 week semester so that it could be factored into the project's timeline.

Independent or self-directed research is also an important skill for all in the group from brainstorming ideas for a project, dividing and conquering a large project into smaller, more manageable subprojects; and looking for new perspectives or over-looked factors to problem solve.

Another common occurrence during project-based courses is when students perceive 'down time'. These are pockets of time during a project where it appears there's "nothing to do right now." Having students become self-motivated when they originally think they have "nothing to do" is a challenging lesson. Muda, Muri, Mura is a motto of the Toyota Production system for identifying and describing wasteful practices to be eliminated (10). Muda are any activities that consume resources (money, time) without creating value. So, students must be aware of and avoid useless idling and fruitless activities. Muri refers to the overburdening of workers. The greater the demands of the project the higher or harder students may have to work. Mura is unevenness in operation. With careful scheduling and an even work pace, each student should be able to finish their work in time with others. During the silkworm project students were advised to keep these three terms in mind when executing the project. Find alternate, worthwhile activities during slow or low periods of the project. Is there additional research that can be done? Does a project team member need help with something? What should be done prior to the next phase in the project? Can parts of the final paper be written?

Beyond time management and clear communications with other team members, students should also review their role and goals in the project and clarify them as necessary. Although the goals should be clear from the beginning, students may get off track and go on exploratory tangents that do not necessarily align with the objectives of the project. A flowchart should be created to show the exact steps or phases of the project in the order that they should be done. An example flowchart for the silkworm project can be found in the appendix.

WHEN THINGS GO WRONG

Problems are inevitable during any project and that is part of the reason research classes are deemed more difficult and at the same time closer to real life. Dealing with the frustration, delays and other negative associations with problems are all skills that are actually part of students learning to problem solve. To help prevent, mitigate, or solve such problems the usefulness of proper and meticulous recordkeeping should become clear. With good note taking and observation, students will be able to better identify what the problem is and how it arose. From there, with a little self-reflection, they will be able to see what their role should be in solving the problem and what events lead up to the problem in the first place.

Beyond accurate record taking, communications within the team are again important. Is the problem solvable by one student? Does the whole team need to get involved? What does this do to the project timeline? Within our own silkworm undergraduate research project several problems or challenges were faced. One involved the use of highly specialized equipment, a Raman spectrometer, for analyzing the silk to detect the presence of silver. The problem was that most of the students had little or no experience operating the instrument. The students realized they had to do research in order to figure out how to correctly operate the machine before blindly putting in a sample. The solution was to self-teach themselves how to use the instrument by studying the tutorial videos provided by the manufacturer covering everything from how to insert a sample into the machine, how to prepare the machine for data collection, how to gather data, and how to interpret the results.

Another problem involved preventing the escape of adult silk moths. After 6 weeks or so the silkworms would pupate and transform into adult moths. They cannot fly, but they can crawl. Their holding containers were cracked to allow for air circulation, but some would escape and it would be difficult to determine from which test group they came from. One solution was to paint their wings with varying colors of nail polish matched to their level of silver nanoparticle treatment. Nail polish did not appear to alter their behavior or morphology.

INCORPORATING EVALUATIONS

Evaluations are important in a research project. As a general rule of thumb, *evaluate the way research is conducted, not on the results* (11). With any system feedback is important for regulation and improvement. More peculiarly, effective evaluations are a primary way to evaluate a program's outcomes and often can help secure future funding. Periodic evaluation in the beginning, middle, and end of a project allows students and the instructor to assess and adapt the project to ensure efficiency and effectiveness (12). Evaluations, including group and self-evaluations, should be carried out throughout the entire life-span of the project. An evaluation at the start of a project is critical and should serve as a baseline for evaluating what was learned over the course of class. Knowing what you will ask or evaluate during and at the end of the project should be mirrored in the initial evaluation. This can be information such as each student's ability to do research and familiarity on the subject matter. Evaluation methods and instruments can take many forms according to need. Students can provide individual feedback, self-evaluation, or group evaluation, informally or formally. In the beginning stages evaluations could also show how much agreement there really is with each student as to the choice of topic. Mid-project evaluation can also allow the instructor to check in with the students and see how they are coping with the demands of the project. Even having the instructor included on project emails or discussion threads there is at least an informal sense of to what extent have students communicated with each other and how the students are progressing. Final evaluations of the students' work may include more traditional devices such as a final paper or presentation. Again, any materials such as presentations created by the student can likely serve as part of their portfolio of work accomplished.

Group projects are often negatively associated with uneven individual student accountability. Although learning to work in a team is part of the purpose of a research project, individual achievement and responsibility can be determined with careful evaluation. One way to help accomplish this is by peer evaluations which can provide a measure of the amount of contribution from each individual and how much collaboration took place.

BEYOND THE FINAL WORK (DELIVERABLES)

The primary goal of an UGR project is to gain research experience. The secondary goal is to improve the students' 21st C. soft skills. Part of the experience for our undergraduate research involves submission of final work typically as a paper, poster, oral presentation, or combination thereof. The final project demands that the students effectively summarize their research efforts and verify their data and conclusions. Thinking ahead for this as the project progresses can also better focus and prioritize student efforts. However, there are further opportunities for this work if done well and with forethought.

Sometimes your home institution may have their own journal or publication where work can be published. Perhaps you may have a class, department or school webpage where approved student works can be showcased. There may be relevant conferences where students can present posters or original work. For example with our silkworm – silver nanoparticle based project, the National Science

Foundation regional nanotechnology center, Nano-Link, has an annual conference with scientists who judged poster-sessions for students.

While a single class project is likely too short to accomplish novel research leading to a peer-reviewed publication, it could be the basis for further work in other classes or summer research opportunities that do result in a paper. The process of meeting the deadlines and requirements for a conference or journal will be more demanding, but also can drive greater understanding of the complete cycle of research. It may be that most of your students are considering career paths other than research. Alternative final activities could be to submit a technical report on the findings made by the project or review what would be required to file for a patent.

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