Student Research within Communities of Practice

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> "Learning [within a community of practice] transforms our identities: it transforms our ability to participate in the world by changing all at once who we are, our practices, and our communities" (Wenger 1998, 227). Being a scientist changes students' lives.

Synopsis We propose to explore, both qualitatively and quantitatively, the potential of undergraduate science research seminars to positively transform undergraduate science education. These seminars are specifically designed to produce student peer-reviewed journal papers and research presentations. The key, we posit, is to involve students at the outset of their college careers in scientific communities of practice where they join a research team, conduct real science, and actually become—both sociologically and technically—real scientists themselves. Being a scientist changes students' lives. Our project's exploratory goals are to train new instructors in a seminar-expanding manner, extend the seminar from astronomy to environmental science, quantitatively evaluate the associations between malleable factors and learning outcomes, and consider the potential nationwide transferability and propagation of the seminar to other sciences and venues. This project will advance science through published student research—much of it on the cutting edge—and will integrate a key social learning theory, Communities of Practice, into the teaching of science. There are no prerequisites for the seminar; each student contributes as their time, talents, knowledge, and experience dictate. This encourages women, underrepresented minorities, persons with disabilities, and non-STEM-track students to participate in a genuine research experience, completing the seminar as published scientists and, eventually, becoming professional research scientists or science-informed citizens that contribute to increasing our nation's economic competitiveness and discover innovative solutions to the many problems we face as a global community.

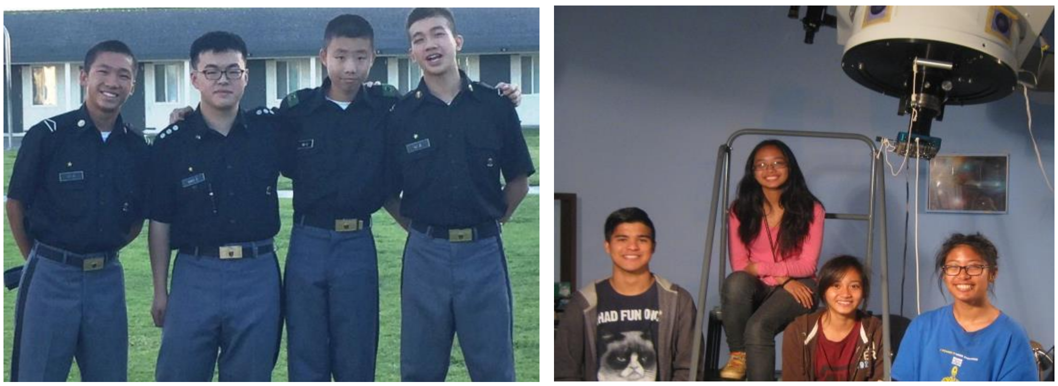
1. Introduction

For eight years, undergraduate student teams have been planning, conducting, and reporting their original research in papers published in the *Journal of Double Star Observations* and elsewhere. They have presented their results at scientific conferences. These student scientists have conducted research within a supportive, student-friendly community of practice that includes professional astronomers, advanced amateur astronomers (citizen scientists), student graduates of the seminar, and experienced educators. Some 40 papers with well over 100 student coauthors have been published within the time constraints of a one-semester community college course or a short summer science camp.

Left: a student observes a double star drifting across a calibrated eyepiece while another student times the drift. Right: students pose in front of an amateur's half-meter telescope during an observing session.

When students join a real-world scientific research community of practice, they become scientists. The transformative experience of being a published scientist leads students to careers as scientist**s**, or at least they become science-informed citizens. Being a coauthor of a research paper also enhances student careers through admissions at choice universities, often with scholarships.

There are, very purposefully, no prerequisites for our seminar. All students are welcome. We have found that a mix of science-track students with non-science, but astronomy/space "interested" students works well, and often results in the latter switching their career paths to science. As Wenger (1998) suggests, "Unlike in a classroom, where everyone is learning the same thing, participants in a community of practice contribute in a variety of interdependent ways that become material for building an identity." He continues: "What they learn is what allows them to contribute to the enterprise of the community and to engage with others around that enterprise."



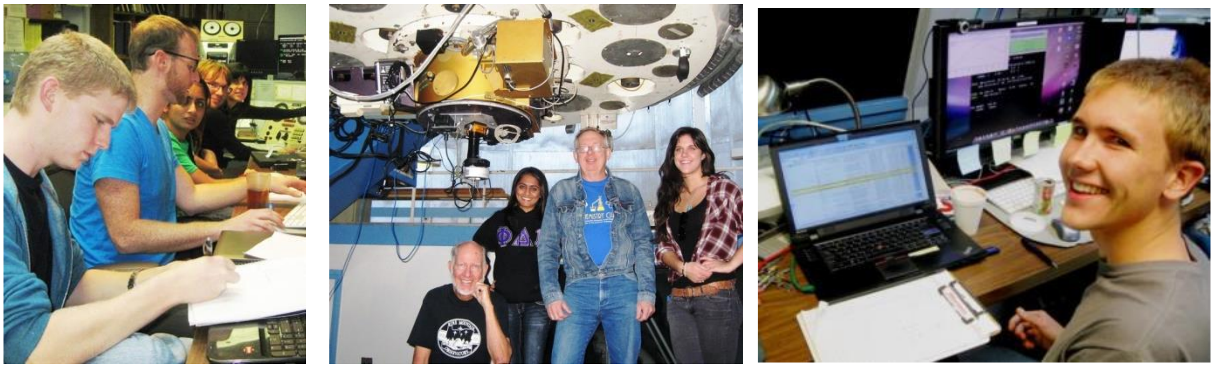
Student research teams at the Army and Navy Academy (CA) and Leeward Community College (HI).

The research seminar was, until recently, structured as a few student teams meeting in person with the seminar's instructor at one school. This year (2015), the seminar was conducted, for the first time, as a hybrid in-person/online seminar. Each student team met with a volunteer assistant instructor at one of 10 separate, distantly located schools in California, Hawaii, Arizona, and Pennsylvania. Instruction was provided through online, self-paced learning units on double star research, planning and managing a research project, writing scientific papers, and presenting research results at conferences. The seminar's overall instructor (Genet) regularly met online with the individual teams and their volunteer assistant instructors. The entire multi-campus group met together (via Internet connection) for PowerPoint presentations by each team on their planned research and, near the end of the seminar, their research results. Many of the students went on to also present their results at scientific conferences.

The hybrid seminar's cost per student was remarkably low, thanks to the volunteer labor provided by the supportive community of practice, which included both current and retired high school and college science teachers, professional researchers from astronomy and related fields, advanced amateur astronomers (with their telescopes and cameras), and a growing number of seminar graduates who enjoyed helping new students learn how to conduct scientific research. The cost of being a published scientist within the hybrid seminar's community of practice is so low that students with no intention of becoming scientists can be accommodated. These future entrepreneurs, politicians, and educators will, for the rest of their lives, have an insider's understanding of science that they will convey to many others.

To date, the astronomy research seminar has only been taught by one highly experienced instructor and a few hand-picked volunteer assistant instructors. It took several years to formulate a smoothly-working, supportive community of practice. Training material had to be developed. A publication support community of critical yet student-friendly external reviewers had to be recruited, trained, and nurtured.

In theory, this one narrow area of astronomical research (double stars) could be propagated in seminars nationwide, since the seminar's primary educational goals of learning how to plan and conduct scientific research, write papers for publication, and present results are independent of the specific area of scientific research. As a practical matter, not only are different students strongly attracted to a variety of different sciences, but the volunteer assistant instructors and others required to make hybrid seminars work also come from various disciplines beyond astronomy such as environmental science, biology, chemistry, etc. The challenge is to find specialties within these general disciplines that (similar to double star astrometry within astronomy) are amenable to the development of student-friendly communities of practice.



Students control the 2.1-m telescope at Kitt Peak National Observatory, pose under the telescope, and log the observational results. The speckle interferometry observations they made were cutting-edge astronomical research using state-of-the-art instrumentation and techniques.

The spread, nationwide, of undergraduate student research seminars could lead to a significant increase in the number of students choosing careers as research scientists. This should lead, in turn, to both increased national economic competitiveness and innovative research-based solutions to the many problems we are now facing as a global community. It could also lead to an increased percentage of the citizenry having a meaningful first-hand experience with science as a way to investigate issues (rather than as a collection of "facts"). A more science-informed citizenry will have a more nuanced understanding of the challenges of making accurate measurements, of the significance of measurement uncertainty, and the interplay between data, models, and theory. This in turn should lead, democratically, to the adoption of improved policies into which scientific perspectives have been purposely and correctly incorporated.

If a large number of students, nationwide, became published scientists in a number of student-friendly science specialties, the benefit to the nation would be immense. While our astronomy-research seminar has clearly succeeded in transforming students into published scientists, and has provided anecdotal evidence of changes in the academic and life trajectories of many students, there has, to date, been no systematic study of the potential relationships between learning outcomes and malleable factors, or of the factors that may mediate or moderate these relationships. Furthermore, it is not at all obvious that the seminar will generalize to other sciences beyond astronomy. Thus before proceeding to an efficacy study, or attempting wider-scale implementation, it would be prudent to evaluate the seminar in at least a preliminary manner, and explore extending the seminar to at least one area of research beyond astronomy.

Environmental science was selected as the logical choice for extending the seminar to a new research area. In environmental science, like astronomy, one does not have to go to great lengths, expense, and levels of experimental sophistication to gather data. The environment (air, water, plants, and soil), just like the stars, is out there waiting to be measured and analyzed. Moreover, environmental science, like astronomy, has attracted a large and rapidly growing cadre of engaged citizen scientists that form a ready-made, professional-amateur (pro-am) community of practice (Gibb 2015). The potential transferability and propagation of the seminar into other sciences, nationwide, can be studied by analyzing in detail what happens when the astronomy seminar is extended to the test case of environmental science.

Disseminating knowledge about the seminar and the results of the proposed exploration will be critical to providing others with information on this dynamic new paradigm for undergraduate research so they can initiate other investigations and try out the seminar in other sciences and venues nationwide. The Council on Undergraduate Research—with its extensive network of educators, educational theorists, scientists, and policy makers—will spearhead the dissemination of the proposed project's results.

Evolution of the undergraduate scientific research seminar

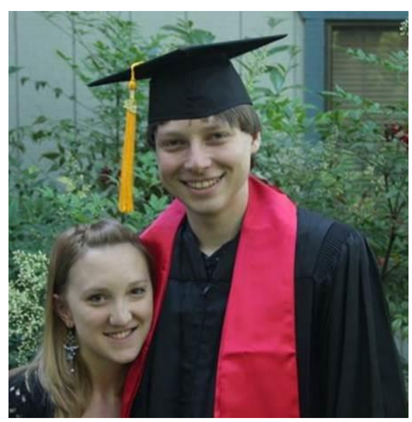
The primary goal of the astronomy research seminar from the outset was to provide undergraduate students with an authentic, real-world research experience. Traditional undergraduate research typically involves an extensive "research preparation period" (often many years) of course work to build a scientific knowledge/skill set deemed sufficiently sophisticated to engage in a research project. This would be equivalent to going to basketball practice to develop basketball skills through drills and lessons, but not playing in a real basketball game for many years after you join the team. By becoming published student-scientists within a highly specialized community of practice in their first year or two of college, we maintain that undergraduates learn through experience what it is really like to be a scientist working on the frontier of human knowledge. This is a "learn about science by doing science" approach to learning.

We have found that advanced scientific knowledge and mastery of sophisticated experimental skills and techniques are not required when the students are immersed within a supportive community of practice which, critically, includes students who are taking the seminar for a second time; they become the team leaders who know the ropes (see *Student-Assisted Teaching*, Miller et al. 2001). Curiosity, a desire to learn, and hard work suffices for new students. Prerequisites are purposefully not a requirement for this seminar, as they would bar the very students we are trying to reach: not only those students not already on a science track, but women, underrepresented minorities, and students with a disability.

Starting in 2006, Cuesta College offered a one-semester Astronomy Research Seminar. Students conducted original, published, team research (Genet et al. 2010). These students realized that a published paper to their credit was a distinguishing accomplishment that could significantly improve their chances of admission to choice bachelor's degree granting colleges and universities, often with a scholarship.

In the seminar's first two years, students chose their own research questions as long as they were "astronomical." It was quickly determined, however, that unless student freedom in problem selection was limited, teams were often unable to see poorly selected projects through to completion.

Of the various research topics in our seminar's first few years, it was discovered that observations of visual double stars resulted in the highest assurance of successful research project completion. This narrow concentration, as described by former student Jolyon Johnson (2008), allowed the seminar to provide a basic introduction to double stars, and fostered the formulation of a highly specialized community of practice support team of local amateur astronomers (with telescopes), seminar graduates, and educators.



Left: one of a number of summer science camps held at the University of Oregon's Pine Mountain Observatory. Right: Jolyon (Jo) Johnson (and his high school sweetheart and later wife, Alex Johnson) at his graduation from California State University, Chico. While a Cuesta College student, Jo's research resulted in a dozen published papers. He continued on with another dozen papers, co-chaired two international conferences, coedited two books, and is the sole editor of an about to be released book, Double Star Research: A Student-Centered Community of Practice. *He is now a graduate student at the University of Washington, majoring in science education.*

Collaboration with others led to replication of the astronomy research seminar in additional venues. In conjunction with the University of Oregon's Pine Mountain Observatory, a series of highly concentrated summer seminars was initiated that resulted in a number of published papers by both high school and undergraduate students (e.g., Schrader 2010, Baxter 2011, & Brashear 2012). Soon the seminar's most seasoned and active graduates co-edited books (Genet et al. 2010, Weise et al. 2014) and co-chaired conferences, culminating in the Maui International Double Star Conference (Genet 2013).

Recently the astronomy research seminar was expanded as a hybrid in-person/online research seminar to six schools in California, two in Hawaii, and one each in Arizona and Pennsylvania. Student teams worked locally with volunteer high school science teachers serving as seminar facilitators. The Cuesta College instructor provided overall instruction and guidance, met with all the students in online sessions, and also met in person with teams in California, Hawaii, and Arizona.

Successes so far

These seminars have, over the past eight years, yielded some three-dozen published papers (with over a dozen more in the pipeline) coauthored by more than 100 students (e.g., Marble et al. 2008, Dowdy et al. 2009, & Estrada et al. 2010); and added a large number of published double-star measurements to the permanent archive of the Washington Double Star Catalog maintained by the U.S. Naval Observatory.

Seminar students have co-edited four books: *Small Telescopes and Astronomical Research* (Genet et al. 2010), *The Double Star Reader* (Weise et al. 2014), *Speckle Interferometry of Close Visual Binaries* (Genet et al. 2015a), and *Double Star Astrometry: Collaborations, Implementations, and Advanced Techniques* (Weise et al. 2015). The seminar's graduates have co-chaired many workshops as well as three major international conferences: Galileo's Legacy (2009), Small Telescopes and Astronomical Research (2010), and the Maui International Double Star Conference (2013). Two additional books on double star research, edited by seminar students, are in final editing. Considerable training material has been developed for the seminar, including numerous self-paced learning units, videos, and, nearing completion, the *Small Telescope Astronomical Research Handbook* (Genet et al. 2015b in preparation).

Many of the seminar's graduates have received scholarships to pursue science or education majors in college. For instance, Bobby Johnson, the only student to take the seminar three times, with six published papers to his credit, received an all-expenses-paid scholarship to Brown University. Many of the seminar's graduates have, after graduation, continued their research, and have helped new student researchers with their projects.

Lessons learned

The success of the student projects results, primarily, from simply following the "rules" of scientific research. These practical rules are often only learned as a graduate student, post-doctoral researcher, or even later. Frustrated that so many doctoral students were graduating without learning the basic "ropes" of being a scientist, Peter Feibelman (2011) developed a course he turned into the classic book, *A PhD is not enough! A Guide to Survival in Science*. Although we tried "softening" science's rules for seminar students, this undermined the core strength of the research seminars. Science, a highly successful form of cultural evolution, has developed its many rules for good reasons. Students like to know that they are doing the real thing, not some watered-down version that they are likely to interpret as condescending.

Follow the regular "rules" of scientific research

- Research is conducted within a community of practice, typically within a narrow frontier specialty.
- Research must be original and be published as papers in appropriate (specialty) journals reviewed and read by the members of the relevant community of practice.
- Publication is mandatory and places everyone's reputation on the line, including that of the students, instructors, schools, journal, and the seminar itself. Thus papers need to be of high quality.
- Publication is not enough. Results must be presented at conferences attended by researchers from the relevant community of practice.

- Team members are not expected to contribute equally. Author order provides justice to variations and allows each member to contribute as their time, talents, knowledge, and experience dictate.
- Team members should be included or added, as needed or desired, from outside the class.

Practical lessons learned over the years

- Students require most of the last half of the semester to write and rewrite their papers. Thus each team needs to plan on completing their observations, data reduction, and analysis in the first half.
- Student teams must not be allowed to fail, as this would impede their careers instead of advancing them, and would give the seminar a very negative reputation among students. The most frequent cause of failure is taking on too much. Instructors must help the students limit the scope of their projects such that they are achievable within the time constraints of a one-semester course.
- Instructors must help teams avoid "mission creep," or encourage them to switch to "Plan B" if their original project cannot be accomplished as planned.
- It is sometimes appropriate for the instructor to bring in outside helping experts, add team members with special skills, or call in an experienced "paper rescue team" to mentor (or tutor) the students through the final stages of their project.

Limitations based on experience to date

Training of new instructors

Although suggesting great economic promise, the hybrid version of the research seminar has only been taught by a very experienced instructor assisted by hand-selected, already knowledgeable, and often highly experienced double star researchers. It is not clear that new and somewhat naive instructors could be efficiently trained in, for instance, summer workshops. An ability to economically train instructors and provide them with appropriate material for their classes is a prerequisite for national propagation.

Evaluation

Although the seminar has been taught for many years, the only basis for its evaluation, so far, has been its track record of published papers, conferences, and books—a public record accessible to all for evaluation. Although the instructor and the volunteer assistant instructors have their opinions on what factors have influenced student outcomes in favorable (or unfavorable) ways, no formal assessments—even simple ones—have ever been made. Understanding key relationships is vital to future development.

Areas of science

Only one specialty area of research within astronomy (double star astrometry) has been pursued. This area was chosen because it can be done with low cost of instrumentation, the measurements are fairly straightforward, it is conceptually simple, and (perhaps of greatest import) a research project can be completed, including a paper submitted for publication, within the demanding confines of a single semester or summer science camp.

2. Proposed Exploration

While the astronomy hybrid seminar shows promising low-cost potential, it is by no means clear that it could be taught nationwide across several other (albeit carefully selected) areas of science in an economical manner. However, we are greatly encouraged both by the level of student enthusiasm generated and by the significant student discoveries made in a "pre-pilot" summer environmental science seminar held at Concordia University in the summer of 2015 that was patterned after our astronomy seminar.

The objectives of the proposed project are to:

- Train new instructors and volunteer assistant instructors in an expandable manner.
- Explore extending the seminar to environmental science.
- Explore associations between learning outcomes and malleable factors, and the conditions that may mediate or moderate these relationships.
- Study the potential nationwide transferability and propagation of the seminar into a number of other sciences and venues, and disseminate the results of this proposed exploration nationwide.

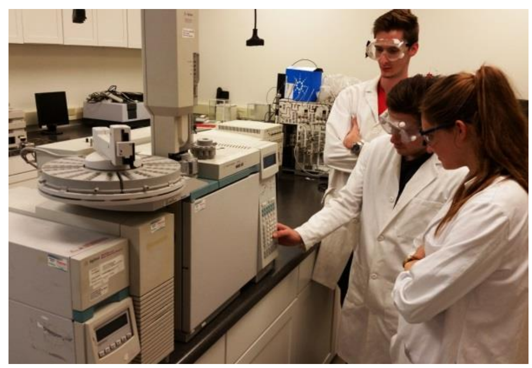
Task 1 Develop a workshop for training instructors in the student-research educational paradigm

A summer workshop will be developed and held each summer to train new instructors and assistant instructors for the hybrid version of the astronomy research seminar. The workshop and its supporting material must be readily transferable so that a large number of new instructors could be trained in the future as the seminar propagates nationally.

Task 2 Initiate a pilot, in-person, summer environmental research seminar

This entirely new area of science for the seminar will feature two types of atmospheric measurements. The pre-pilot environmental science seminar offered in the Summer of 2015 at Concordia University focused on the quantitative measurement and characterization—via CCD images obtained by optical microscopy—of the size distribution and morphology of small atmospheric particulates collected in various accessible locations in Orange County, California: (e.g., the Concordia campus and the back yards of the students in the seminar). These studies will be continued in our regular pilot environmental science seminar but will be augmented by two areas of advanced spectroscopic and chromatographic studies:

- Spectroscopic analysis (primarily infrared and Raman spectroscopy) of particulate matter that settles from the atmosphere will be used to interrogate particulates gathered on clean microscope slides laid out at various sites throughout Orange County. Spectroscopic analysis of the particulates will be conducted in Concordia University's well-equipped Advanced Scientific Instrumentation Laboratory (ASIL). Results will be correlated with local weather conditions, road traffic data, sample location, time interval, and phase of the sample collection window (e.g., day or night, during rush hour or before rush hour), and special climate events (e.g., forest fires and Santa Ana winds).
- Atmospheric gas samples will be collected systematically and analyzed in the Advanced Scientific Instrumentation Laboratory using infrared spectroscopy, gas chromatography, and by mass spectrometry.

Left: students setting up the Agilent gas chromatography/mass spectrometer in the Advanced Scientific Instrumentation Laboratory at Concordia University. Right: An undergraduate research team configures a custom spectroscopy experiment in the Chemical Physics Spectroscopy Laboratory at Concordia.

The development of a student-friendly community of practice takes time. It is best initiated by way of a small, in-person seminar with a knowledgeable instructor. Once this community of practice is well established, and student papers are being routinely published, the material and training required for a more widespread, hybrid in-person/online seminar can be developed and a hybrid seminar attempted, a task that, if the in-person environmental seminar has progressed far enough, we may attempt in the third year.

Task 3 Evaluation of the student-research teaching method within communities of practice

Methodological Approach

Multi-Dimensional Education, an experienced evaluation company, will provide an independent assessment of the seminar's various intervention strategies and outcomes. Their methodological approach for evaluation of the various versions of this seminar will focus on primary data collection and analysis. The evaluation of the interventions will include process, formative, and summative (outcome) measures.

Process and formative measures will assess the integrity and progress of the intervention implementation, while summative measures will assess outcome changes in individual student's attitudes, beliefs, and behaviors related to views on science and STEM careers.

The mixed methods evaluation will provide a rich source of quantitative and qualitative data that will provide a foundation for replication of the seminar, evaluating its efficacy, and aiding others as they plan to design/implement similar research-based STEM interventions within their communities of practice.

Malleable factors purposely varied (quasi-experimental design)

- Hybrid online/in-person seminar versus fully in-person seminar.
- Areas of team scientific research: astronomy versus environmental science.
- Experience of seminar instructors (and for hybrid seminars, the volunteer assistant instructors).

Moderators and mediators (uncontrolled covariates)

- Students taking seminar once versus taking it a second time as a team leader.
- Student age, socio-economic status, grade point average, and past science and mathematics courses.
- Type of school (community college, small private university, large public university).
- Team size, which may vary from as few as two students to as many as eight students.

Anticipated science-related student outcomes

- The seminar as an inspirational or even life-changing (transformational) event.
- Increased confidence. Being a college student with a published scientific research paper can be a confidence booster. It can also garner the respect of other students.
- Motivation. Students that successfully complete this seminar are more motivated to become scientists.
- A greater respect for and appreciation of science.
- Feeling of likely admission to a four-year college or graduate school with a scholarship.

Anticipated more general student outcomes

- Critical thinking enhanced by having research papers reviewed by other students, the assistant instructor, the course instructor, and an external expert referee.
- Improved project planning and proposal preparation skills.
- Understanding how to be a good team player by using one's own skills to the team's advantage.
- Learning and practicing project leadership skills (especially for students who repeat the seminar).
- Developing writing skills, especially concise technical writing of proposals and research results.
- Experience in preparing and giving research project presentations.

The 14-inch Celestron Schmidt-Cassegrain telescope at Concordia University will use a high speed camera to overcome seeing limitations and make speckle interferometry observations of close binary stars.

Sample

Our evaluation plan includes the evaluation of both small, in-person, single-school and instructor seminars, and large, hybrid in-person/online seminars involving multiple schools and volunteer assistant instructors. The seminars will be held at a community college (Cuesta College), a relatively small private school (Concordia University), and a large state university (California Polytechnic State University). We will evaluate the outcome of seminars in a discipline we have taught for several years for which the teaching method and material is well-developed (double-star astronomy), and a new discipline (environmental science) with less-well-developed projects and materials.

Keeping these distinctions in mind, the study's sample will consist of: (1) Cuesta College fall and spring astronomy hybrid research seminars which will provide the most experienced and largest group of instructors and students for the evaluation, thus providing a baseline; (2) the California Polytechnic State University summer astronomy in-person seminar which, in Year 1, will be meeting for the second time, and will bring four-year state university students into the study; (3) the Concordia University summer astronomy in-person seminar will be meeting for the first time in Year 1, and will bring four-year private university students into the study; and (4) the Concordia University summer environmental science seminar which will extend the education method to an entirely new area of science.

Treatment schedule and number of students

School	Format	Subject	2017/2018 Fall	Spr	Sum	2018/2019 Fall	Spr	Sum
1. Cuesta College	hybrid	astronomy	60	60		60	60	
2. Cal Poly	in person	astronomy			10			10
3. Concordia	in person	astronomy			10			10
4. Concordia	in person	environmental			10			10

Measures and analysis

The measures and analysis described below will be provided independently by Multi-Dimensional Education. The first year of the project will be used to develop the evaluation and trial applications. These will then be formally applied to students in the second two years of the study. The basic unit of analysis will be each student participating in each seminar. Analysis will also be conducted with the team and the class as units of analysis.

The students will represent the population of students in the nation who might wish to take the seminar. There are no prerequisites for the seminar, so not only will the sample include students already engaged in science, but also students wanting to explore science for the first time. Note that some students who repeat the seminar as team leaders will create a dosage or grouping variable to track and explore with respect to seminar exposure.

Multi-Dimensional Education will utilize existing validated scales through the work they have done with their colleagues and the National Science Foundation. These scales will focus on assessing perceptions related to science and learning science. All scales selected for measuring the outcome variables will have existing reliability and validity evidence. Knowledge-based tests covering the curriculum utilized in the seminar will also be developed. Data as they relate to each ethnic and gender group will be studied to better understand the needs of diverse communities. Furthermore, a great amount of qualitative data will be collected throughout the project which will be used to create, test, and improve process and formative evaluation measures.

The demographic questions measuring ethnicity and socio economic status (SES) will be used as covariates. The theory behind statistically controlling for ethnicity, SES, and pretest scores allows balancing out the effects of highly predictive variables when it comes to academics and risk factors.

All assessments adopted for the study will be piloted in Year 1. All students will be pretested prior to each seminar class in Years 2 and 3, and post-tested upon completion of the seminars. Additionally, a final posttest of all students will be given toward the end of Year 3. This will allow the implementation of a Pretest, Posttest, Posttest design in a quasi-experimental approach. Multi-Dimensional Education's online data collection and survey collection system will be used to administer, collect, and connect all measurements to students, instructors, and class assignments. All data will be cleaned, coded, and then aggregated together with survey data and utilized within Multivariate Analysis of Covariance (MANCOVA).

This outcome evaluation design provides data from an adequate sample, essential to providing the number of cases and power needed to perform Multivariate Analysis of Covariance (MANCOVA), measuring multiple outcome variables, and statistically controlling for numerous covariates. As the first step to account for missing data, a list-wise deletion approach will be conducted (Barladi & Enders 2010). Prior to performing the list-wise deletion process to configure mean scores for the scales utilized in the study, a 75% threshold will be set within the analysis syntax used to clean and recode survey data. Thus if participants did not answer at least 75% of the questions for each scale assessed by each dimension of the survey, the syntax will not compute the mean score for the answers provided. This helps to provide the detail needed to identify which cases are to be eliminated via the listwise deletion process, allowing for further treatment of missing data.

MANCOVA will be performed with the intention of connecting as many variables as possible. Such analysis facilitates exploring: (1) how the scales adopted for the outcome variables performed, (2) statistically significant differences between groups, and (3) significant differences between pretests and posttests. When more than one dependent variable exists, multiple univariate tests are not appropriate because multiple (separate) analyses of variance cannot take into account the pattern of covariation among dependent measures (Stevens 2002). MANCOVA, however, allows the multiple covariates to be entered into the analysis and statistically controlled. Therefore, to meet the expectations of the grading criteria provided, this analysis seeks to assess the dependent variables together and to control for confounding variables. Post hoc analysis will further explore how such data can inform the efforts related to gender specific minority and at-risk youth populations.

Task 4 Transferability, propagation, and dissemination of the results

This task will evaluate which other sciences, beyond astronomy and environmental science, are most amenable to the actual student research within a community-of-practice approach to early undergraduate science education. Robert Stebbins, a Canadian social learning theory sociologist, has made the study of professional-amateur (pro-am) communities his life work (Stebbins 1979, 2007/2015, and Elkington & Stebbins 2014). Stebbins has studied the astronomical pro-am community at some length (Stebbins 1981a, 1981b, 1982, 1987). Besides astronomy, sciences such as archeology (e.g., Stebbins 1980) and ornithology (Davidson & Stebbins 2011, pp. 148-149) are already known to feature cooperative professional/amateur (pro-am) communities of practice that should also be student friendly.

A number of sciences have found that engaging citizen scientists in data collection over long timelines or diverse geographical locations provides useful data that the scientists themselves would be hard pressed to gather. See, for example, Davidson & Stebbins 2011, pp. 142-143 (botany), pp. 149-150 (entomology), pp. 133-137 (mycology), and pp. 53-55 (meteorology).

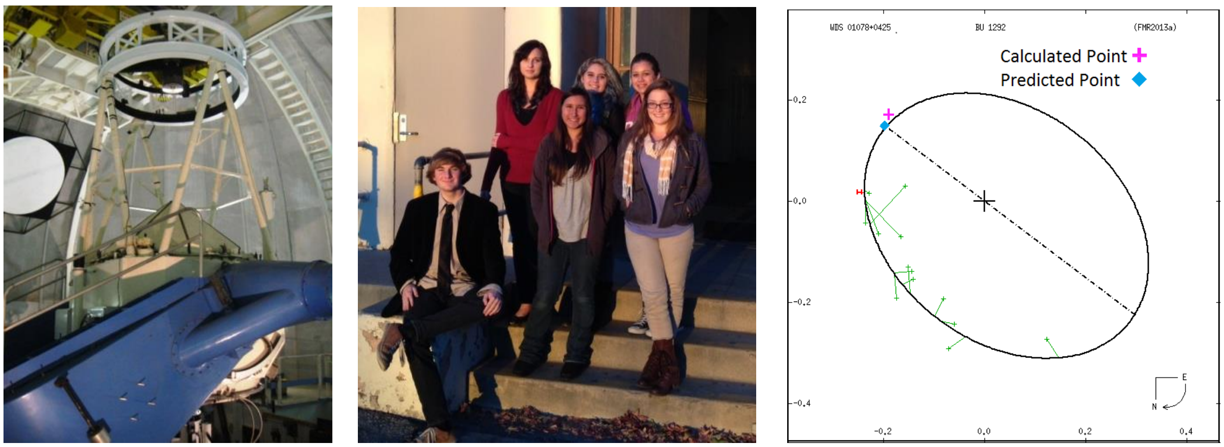
The results of this project's exploratory research will be disseminated in papers in both education and scientific journals. The data base from the student evaluation and the accompanying details of the analysis will be placed online for convenient access. The Council on Undergraduate Research (CUR) will monitor the program via the engagement of members of their Education Division, and will organize and conduct a focus group of 20 to 30 national education and policy experts in Year 2 of the project. Based on this focus group's findings, CUR will write a summary white paper, in conjunction with the other grant partners, on how to understand, expand nationally, and scaffold the research seminar's paradigm of students as scientists within a community of practice paradigm. CUR will distribute this white paper internationally as a publication at the end of Year 3 of the grant.

3. Intellectual Merit

This project will make two major intellectual contributions: (1) advancement of science through published student research, much of it on the cutting edge; and (2) the application and refinement of a social learning theory, Communities of Practice, as it applies to undergraduate research.

Intellectual advancement of science itself through published student research

As mentioned previously, there are areas of research where professional scientists have purposely enlisted the help of advanced (serious) amateurs (i.e., citizen scientists) to provide the observations that are either too numerous or to spread out in space or time for the professionals themselves to make much of a dent in the needed observations. Bringing a large number of undergraduate student researchers to bear in these areas will help provide the observations needed to advance these sciences.



Left to right: the 2.1-m telescope at Kitt Peak National Observatory, a student seminar team, and their orbital plot of a binary star. Team leader Bobby Johnson landed a four-year scholarship at Brown University, while Merle Adams (far right), was first author of their paper (2015) and received a four-year scholarship to Yale University.

Close visual binary star astrometry is an excellent example of how undergraduate students and serious amateurs are providing the observations required to advance binary star analysis. If the position angles and separations of close binary stars are observed over time, their orbits can be deduced, and Kepler's three laws can be applied to determine their dynamical mass—a key to understanding stellar evolution. The problem is that there are thousands of known binaries, tens of thousands of potential binaries, and their orbital periods are decades or centuries long. Professionals have enlisted undergraduate students and advanced amateurs to make most of the observations to establish and refine binary star orbits.

An example is the state-of-the art, cutting-edge measurements of the position angles and separations of over a thousand very close binary stars by student teams at the large (2.1 m) telescope at Kitt Peak National Observatory. Other student teams have been analyzing these observations. The team first to do so, only weeks after the observations were made, was a six-student Cuesta College Astronomy Research Seminar team (Adams et al. 2015). Their paper was published in a special issue of the *Journal of Double Star Observations* (and a hardcover book) that contained many other student papers (Genet et al. 2015a).

Intellectual contributions to educational theory

We are developing a unique educational theory based primarily on the integration and extension of the social learning theory of "communities of practice" developed by Etienne Wenger (1998) and others. This theory, and its integration into the student research seminar, is discussed in some detail below.

The seminar also draws from selected elements of both authentic learning (Reeves 2006, Rule 2006, & Lombardi 2007) and experiential learning (Kolb 1984, Cell 1984, Bee and Bee 1998, & Colin & Wilson 2013), as well as a number of inductive approaches to learning. The seminar is particularly indebted to the theories and practices of project-based learning (Laur 2013) and team-based learning (Michaelsen, Knit, & Fink 2002, and Sibley & Ostafichuk 2014).

Last, but certainly not least, the seminar draws from genre-specific writing theory which supports writing papers for a critical, expert, specialty audience (such as scientific research). Cary Moskovitz and David Kellogg (2011) maintain that scientific writing is best learned in the context of doing science. Science papers have a distinctive format and style that students, with practice and considerable feedback, can master. Students can be taught a writing strategy that provides, explicitly, the steps needed to plan, revise, and edit their papers (Writing Next 2007). Once taught, the students can implement this strategy and write and revise their paper as a team (MacArthur, Schwartz, & Graham 1991). During each iteration, the instructor makes comments on the paper with the intention of increasing the "specificity, focus, and impact of the writing" (Hillocks 1982). Collaborative (team) writing has been shown to be an especially effective approach to improving the quality of student papers (Yarrow & Topping 2001).

Social Learning within Communities of Practice

"Communities of practice" is both a cornerstone concept in social learning theory and the title of the seminal book in which Etienne Wenger (now Etienne Wenger-Trayner) lays out the theory (1998). A more recent introduction to the concept proposes this definition:

> Communities of practice are formed by people who engage in a process of collective learning in a shared domain of human endeavor: a tribe learning to survive, a band of artists seeking new forms of expression, a group of engineers working on similar problems, a clique of pupils defining their identity in the school, a network of surgeons exploring novel techniques, a gathering of first-time managers helping each other cope. In a nutshell: Communities of practice are groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly (Wenger-Trayner, Wenger-Trayner, & de Laat 2015).

The social learning theory of communities of practice provides a foundation for our project at three levels:

- In the development of a new pedagogy, it allows us to theorize what students learn with our approach and why it is important.
- To support this pedagogy, applying the theory also suggests ways we can expand scientific communities of practice to offer new opportunities for young students to participate in scientific practice.
- Finally, in the conduct of our project, we are seeding a community of practice that could prepare the field of education to adopt this approach at scale.

A pedagogy rooted in social learning theory

Science instruction has traditionally taken a cognitive approach. It has consisted of classroom lectures and laboratory exercises that allow students to move through many subjects within a single discipline, exploring all of the essential knowledge of the field. The students listen and apply concepts in laboratory exercises, often under the supervision of teaching assistants. Laboratory activities develop student skills in measurement, analysis, and report writing. In contrast with this approach—where learning takes place when knowledge is successfully transmitted from a source of knowing to someone who doesn't know—social learning takes place in the process of becoming a member of a community that defines what competence means in a specific domain of expertise. As Wenger (1998) points out:

> Learning is a matter of engagement: it depends on opportunities to contribute actively to the practices of communities that we value and that value us, to integrate their enterprises into our understanding of the world, and to make creative use of their respective repertoires … Practice is a process of interactive learning [that] enables newcomers to insert themselves into existing communities. It is the learning of mature members and of their communities that invites the learning of newcomers (277).

A key pedagogical implication of communities of practice is that they naturally have a spectrum of participants, from core members to more or less peripheral participants. In any specific scientific research community of practice, such as astronomy, there is a gradation of participation and learning that takes place as people move toward full participation. Full participation generally reflects the degree to which the conduct of scientific research is one's primary vocation. Research scientists at research institutes and universities are normally in charge of most research projects. Under their leadership, much of the work on these projects is accomplished by graduate students working on their doctoral degrees (as well as a variety of support staff). Graduate students often also assist research scientists in their teaching duties. More peripheral are serious amateurs, and sometimes undergraduate or even high-school students. Unlike science graduate students working toward their doctoral degree, undergraduate and high-school students are not normally granted professional standing and are therefore not given access to the full range of research instrumentation, professional societies, and meetings.

We are endeavoring to change that, and to grant these students a role as peripheral participants in selected scientific research communities of practice. The students in our seminars are learning by developing actual proficiency in the practices of a community of scientists, and publishing their work in places where it can be accepted or rejected by experienced members of that community. The process of introducing students to a specific practice of that community (writing a scientific paper) is not simply a matter of teaching them a set of writing conventions that they then apply: it involves expert members of that community acting as gatekeepers to the dynamic practices of the community.

For these students, learning scientific practice is not just learning a skill but developing a new identity, which Wenger (1998) describes as a core dimension of learning in a community of practice:

> … Learners must be able to invest themselves in communities of practice in the process of approaching a subject matter. Unlike in a classroom, where everyone is learning the same thing, participants in a community of practice contribute in a variety of interdependent ways that become material for building an identity. What they learn is what allows them to contribute to the enterprise of the community and to engage with others around that enterprise (271) … Learning [within a community of practice] transforms our identities: it transforms our ability to participate in the world by changing all at once who we are, our practices, and our communities (227).

More recent work in social learning theory has provided two additional resources for our work. On a practical level, it has produced a formal framework to evaluate this type of learning with a mix of qualitative and quantitative data (Wenger, Trayner, and de Laat, 2011). On the theoretical level it has situated learning in communities of practice in a broader landscape of practice (Wenger-Trayner and Wenger-Trayner, 2014). In a complex, dynamic world, the boundaries between scientific disciplines also become potential places of learning, as in multi-disciplinary approaches to problem solving and exploration, or in new scientific areas where traditional disciplines converge. In this case, focusing on a community of practice *and its boundaries* is a significant part of the learning process. This is all the more important because some students may never become scientists in their core discipline, but rather, they may develop an identity that traverses several communities in that landscape. They become sufficiently competent in one or more communities to develop enough legitimacy and knowledgeability to navigate the landscape successfully, and perhaps transform it.

Expanding opportunities for legitimate peripheral participation

The first goal of our approach is to open new avenues for students to engage with scientific practices through personal experience. But in doing so, we are also changing the relationship of scientific communities to the broader landscape of practice in which they are located (Wenger-Trayner and Wenger-Trayner, 2014). In particular, emerging social-media technologies have the potential to open new forms of periphery around scientific communities where students can have legitimate forms of participation in scientific work. While the exploratory nature of our project will not allow us to pursue this avenue to its full significance, we believe that this is an important side effect of our work with implications for both education and science. As Wenger (1998), suggests, the benefit of involving peripheral participants also serves the community:

> There are all sorts of reasons to shelter newcomers from the intensity of actual practice, from the power struggles of full participation … Similarly, there are all sorts of reasons to shelter old-

> timers from the naiveté of newcomers and spare them the time and trouble of going over the basics. … When old-timers and newcomers are engaged in separate practices, they lose the benefit of their interaction. … Communities are thus deprived of the contributions of potentially the most dynamic, albeit inexperienced, segment of their membership – the segment that has the greatest stake in their future.

Developing and spreading a new pedagogical practice

Communities of practice constitute both a learning theory and a practical approach to enabling learning (Wenger et al., 2002). This peer-to-peer approach to learning has been adopted across sectors where the development of advanced practice requires rapid learning loops across fields of application (Wenger-Trayner at al., 2015 forthcoming). By involving educators in our research, our project will begin to create the kernel of a community of practice of educators and researchers who learn together how to take this approach to the teaching of science. This means that beyond our project, this community of educators and researchers has the potential to continue the development of this pedagogical practice and spread the approach by inviting others to join their community (Wenger, McDermott, & Snyder 2002).

4. Relation to Longer-Term Goals, Present Knowledge, and Work in Progress

The Principal Investigator's longer-term goals are to: (1) formally evaluate the seminar he has been teaching for a number of years, (2) determine if the "student-research" teaching paradigm will transfer to another area of science, and (3) consider how this highly economical hybrid "on-line + in-person" seminar could be spread nationwide. The proposed project, if approved, will contribute all three of these longer-term goals. By enlisting a leading expert in social learning theory, as detailed above in the section on Intellectual Merit, the link to present knowledge in the field has been firmly established. Finally, by enlisting the Council on Undergraduate Research, mentioned above, as a project partner, the link to similar work in progress nationwide has been made.

5. Results from Prior NSF Support

Russell Genet, none; Dwight Collins, none; and John Kenney, none.

Elizabeth Ambos: NSF-DUE-CCLI III #0920275, $1,172,290. 1/1/10-12/31/14. *"Transformational Learning Through Undergraduate Research: Comprehensive Support for Faculty, Institutions, State Systems and Consortia"* (Collaborative award; PIs: E. Ambos, M. Malachowski, J. Osborn, K. Karukstis).

Intellectual Merit: This award addressed the critical national need for continued and more comprehensive dissemination of effective practices for initiating and sustaining faculty-student collaborative undergraduate research (UGR) as a powerful form of engaged learning. The project focused on state systems and public and private consortia and their member institutions as a way to leverage the power of the systems/consortia to advance UGR. Each workshop curriculum was tailored to the needs of the individual systems/consortia. A key follow-up brought together the participants of each system/consortium for a second workshop one year after the original one. In addition, a summit meeting with representatives from all institutions was held in Washington, D.C. Significant progress was achieved in embedding UGR at the institutional level and advancing UGR as a larger collective unit.

Broader Impacts: Our research found common challenges for system/consortium-level leaders, including getting accurate information about the status of undergraduate research on different campuses, configuring system assistance to match widely varying campus needs, and promoting a reasonably consistent vision for UGR across numerous and diverse campuses. These insights are important for any complex federation of institutions pursuing transformative change.

Publications and Products: Eight (8) reviewed journal articles were produced, most within a theme issue of Jossey-Bass –New Directions for Higher Education series; and 18 presentations made at national professional society meetings.

6. Broader Impacts of the Proposed Work

Unlike many educational opportunities, this seminar has no prerequisites. This allows each student to contribute to the seminar as their time, talents, knowledge, and experience dictate—the door is opened to students without extensive science and mathematical backgrounds to fully participate. Due in large part to inequities in testing, representations of science and scientists, and teacher-centered classroom practices (such as initiation-response-evaluation and direct-instruction), females and racial minorities are particularly underrepresented in science education. Ong (2008) suggests that students of color, especially females, rarely interact with real scientists, professional or otherwise. Our hybrid in-person/online seminar allows schools with a high percentage of underrepresented minorities to be specifically targeted to form a student team and interact directly with members of the scientific community. The emphasis on the final product—quality published research—allows each team member to contribute in their own way. This further opens the door to students with special needs and advanced English language learners via differentiated instruction (Tomlinson 1995 and McNiell & Krajcik 2012).

The highly economical nature of our hybrid seminar—with its volunteer high school teacher assistant instructors, advanced amateurs, and retired professionals from a community of practice—allows the seminar to reach well beyond students on STEM career paths to non-STEM future teachers, writers, and lawyers. What our seminar really teaches is how science works, not some specific scientific discipline, even though our seminar's research projects are always set in the context of a very specific discipline. Our seminar graduates, who understand the nature of science, are science-informed citizens who will help to shape science-informed policies that will result in a better nation and planet.

Although this dynamic new paradigm for student undergraduate research is being pioneered within science, the broadest impact of the proposed work stretches well beyond science education to all of education itself in the 21st century. Our nation would benefit if many more of our students joined, early-on, the communities of practice most relevant to them. As Wenger (1998) suggests:

> … schools gain relevance not just by the content of their teaching—much of which can be acquired just as well in other circumstances—but by the experiments of identity that students can engage in while there. Consequently, deep transformative experiences that involve new dimensions of identification …even in one specific or narrowly defined domain – are likely to be more widely significant in terms of the long-term ramifications of learning than extensive coverage of a broad, but abstractly general curriculum. … This is especially true in a world where it is clearly impossible to know all there is to know, but where identity involves choosing what to know and becoming a person for whom such knowledge is meaningful.

Finally, we return to the central theme of our proposed work, and that is the application to undergraduate education of the insights of sociological learning theory—specifically communities of practice. We close our proposal with the solution to an educational paradox that is the closing paragraph of Etienne Wenger's (1998) founding book:

> If learning is a matter of identity, then identity is itself an educational resource. It can be brought to bear through relations of mutuality to address a paradox of learning: if one needs an identity of participation in order to learn, yet needs to learn in order to acquire an identity of participation, then there seems to be no way to start. Addressing this most fundamental paradox is what, in the last analysis, education is about. In the life-giving power of mutuality lies the miracle of parenthood, the essence of apprenticeship, the secret to the generational encounter, the key to the creation of connections across boundaries of practice: a frail bridge across the abyss, a light breach of the law, a small gift of underserved trust – it is almost a theorem of love that we can open our practices and communities to others (newcomers, outsiders), to invite them in our own identities of participation, let them be what they are not, and thus start what cannot be started.

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