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Perspectives on Undergradua Research & Mentoring

Using the One-Room Schoolhouse Method: The Design and Teaching of a Summer Undergraduate Research Course in Phage Biology

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Introduction

George Mason University (GMU) implemented a new undergraduate research course in July of 2015 and 2016. The course encompassed an intensive ecological study of soil bacteriophage, specifically how their genomes change in response to climate factors. The curriculum is interdisciplinary and includes these themes: environmental microbiology; field-based environmental research; introductory bioinformatics; and introductory Geographic Information Systems (GIS). The long-term (multi-summer) year-over-year research goal of the course is to better understand how bacteriophage populations change (coevolve) with bacteria populations. This course builds from the HHMI SEA-PHAGES undergraduate course design but is different because the long-term research goal is about microbial coevolution. In 2016, the curriculum included a bioinformatics theme and did not include the GIS component.

The one-room schoolhouse method was used as a foundation to build the three-week research course design (Henderson, Buising, & Wall, 2008). This method engages students at different levels of experience and abilities, contrasting more traditional approaches that stratify students by age, experience level, or ability (Baxter, 2000). The course design in the first summer included nine GMU undergraduates and five advanced high school students working alongside one another, with the more experienced students helping to teach the less experienced students.

The course will run recurrently in future summers and is planned for a maximum capacity of 25 students. This course has also: (1) given the GMU biology department a foothold to create and implement a bioinformatics concentration for their biology majors; (2) helped develop stronger partnerships with neighboring high schools (e.g., one school now engages in phage biology research); and (3) expanded the number of research experiences for undergraduates and high school students.

The Benefits of Integrating Peer-Mentorship into Research Course Designs

Research-based courses involving peer-mentorship are widely hailed as important courses for educators to consider (Hagstrom, Baker, & Agan, 2009; Harmon, 2006; Miller, Groccia, & Miller, 2001; Varma-Nelson, 2004). Further, programs involving cross-age peer mentoring are desirable because of their positive research climates, promoting student interest in STEM and building scientific identity (Karcher, 2008; MacRae & Garringer, 2008). These programs, with more advanced students teaching and mentoring younger students, provide a stimulating and cohesive team environment (Henderson, Buising, & Wall, 2008). Such courses ensure a highly advantageous style of learning through sustainable peer-mentorships, important for both high school and undergraduate research experiences (Hanauer et al., 2006). The high school students' exposure to scientific experimentation through inquiry-based learning offers them a defined path to enroll in additional STEM-based courses, seek rewarding research experiences, and gain meaningful undergraduate mentorship later on in the students' academic careers (Kolb, 1983; Kremer & Bringle, 1990; Zhe et al., 2010). Extending the undergraduate research experience to include high school students increases the chance these students will major in STEM related fields (Russell, Hancock, & McCullough, 2007; Seymour, Hunter, Laursen, & DeAntoni, 2004). Early research experiences also assist in the retention of STEM majors (Nagda et al., 1998). These programs, in which "hierarchical mentoring" pervades in a structured environment, are beneficial to students, because they: 1) bridge the gap between applying learned scientific knowledge and having an active hands-on experience; 2) ensure engagement in skills necessary for a STEM career (Sadler et al., 2009); and 3) offer opportunities for significant learning gains (Sales et al., 2006).

Planning a Course Design with the One-Room Schoolhouse Model in Mind

The one-room school house method differs from traditional course designs in that it allows students to be mentors to less advanced students or students with different kinds of expertise. It "allows for one to take advantage of a wide disparity of abilities in a classroom and nearly everyone can learn more, faster, and more enjoyably than in a traditional classroom of students with similar abilities" (Abacus Education Journal, 2002, p. 1). In this setting peer-mentoring exists between a peer mentor and a peer mentee: someone who has an experience to share and someone who is new to that experience, respectively (Bhuiyan, Avinash, & Nirmala, 2015). This method helps to allow challenging course material and research approaches to be more accessible when some students have greater expertise and/or skill with a research approach (Bhuiyan, Avinash, & Nirmala, 2015). Teaching methods like this one integrate peer-mentorship directly into the course design and offer a more engaged learning environment versus traditional approaches.

"Teaching methods like [the one-room schoolhouse] integrate peer-mentorship directly into the course design and offer a more engaged learning environment versus traditional approaches."

Even the Design of this Course Engaged Undergraduate Researchers

To support the research endeavor and course, the instructor selected two undergraduate students to begin the research, help design the course, and help staff the course. Two experienced undergraduate researchers (Lindsey Cundra and Caroline Benzel) were chosen to spearhead the project, beginning with the course design. With periodic feedback from the course instructor, these students incorporated what they believed would be the most advantageous curriculum for implementing the course (our 2015 course design and experiences can be found online at http://goo.gl/U3GmeZ), considering what students would benefit from engaging with as a team of researchers, in a 3-week course using the one-room school house method (Abacus Education Journal, 2002).

Dr. Schwebach suggested that the undergraduates (coauthors of this paper) design the course based on a successful Phage Finding program he created and ran at a Howard Hughes Medical Institute (HHMI) laboratory in past summers, while acknowledging the scheduling challenges and needs of GMU undergraduates. Dr. Schwebach had previously outlined a method for teaching the basics of the curriculum in a summer course for high school students (Schwebach & Jacobs, 2003), and the undergraduates and Dr. Schwebach (the curriculum team) agreed that a summer opportunity would be in high demand for GMU undergraduates seeking research experiences. The curriculum team agreed to use peer-mentorship and the one-room schoolhouse method as an engaging environment that would include an authentic research endeavor. The curriculum team outlined a timeline for what could be accomplished in a 3-week program. Their development of the course was funded by GMU's Students as Scholars program (George Mason University, 2015; see Figure 1).

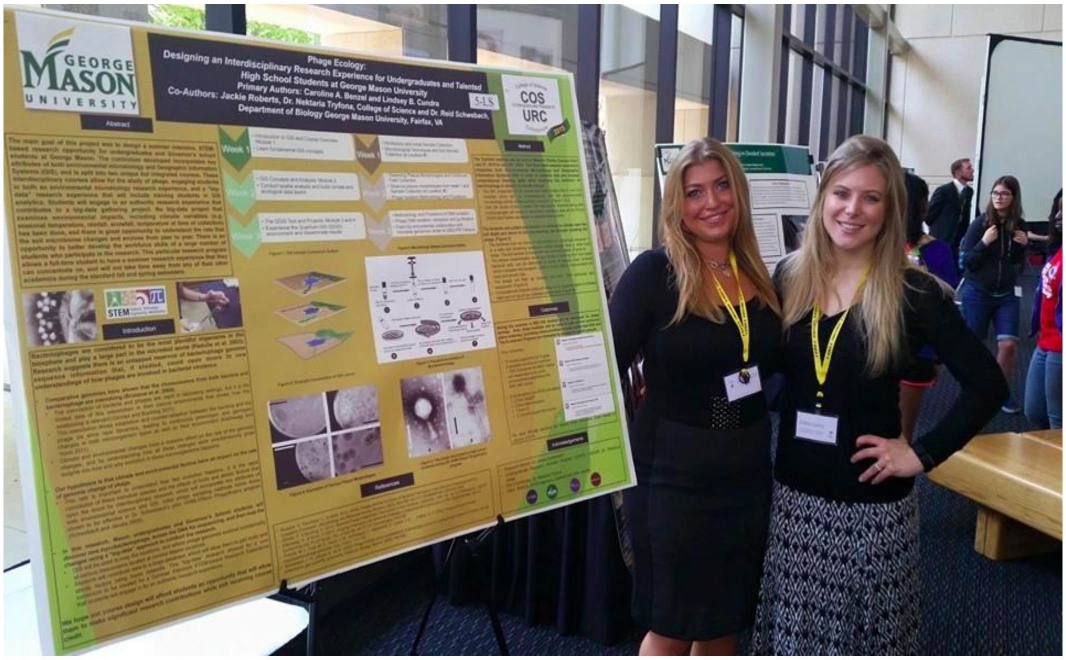

Figure 1

College of Science Undergraduate Research Colloquium, May 5, 2015. Office of Student Scholarship, Creative Activities and Research (OSCAR) students Caroline Benzel (left) and Lindsey Cundra (right) took the leading roles to design the Phage Ecology Research Course at George Mason University.

> Dr. Schwebach said:
>
> *"To develop this course, it was best to have the undergraduates currently conducting the phage research take the lead. Much like the use of movie storyboards to direct film production, students were able to design activities and protocols, which are elements of the course they were designing. I could review these, move them around in the course sequence, ask the students to find and organize additional information that needed integration, and because of their prior scientific investigations on phage, they used their expertise to adjust and modify the design. The undergraduates also considered how they would like to be mentored during the research experience, which shaped the design and the activities we would implement as a research team."*

Learning Assistantships Support the Peer Mentorship and Student Researchers

An important aspect of the course design is the Learning Assistantships (LAs) that supported the course instruction. Learning Assistants (University of Colorado at Boulder, 2014) are undergraduate co-instructors who support the students' individual learning (in this case, the creation and completion of small-group and individual research projects) alongside the instructor. For this course, the LAs take a leading role in teaching the students the phage isolation methods. The 2015 LAs, Caroline and Lindsey, evaluated the course learning outcomes for their own independent research, and two students who took the course in 2015 were LAs for the course in 2016 (one is now a graduate student and is conducting research that, in part, uses and acknowledges the 2015 and 2016 undergraduates' discoveries). These LAs are well versed in the methods and protocols of the phage finding program. The instructor and LAs, alongside external presenters who guest-lecture, contribute not only to the instruction of the class but also help to give the students a foothold in beginning independent research projects during the course.

Other Important Course Features

1. Students have the opportunity to contribute their findings to a larger "Big Data" framework. We are creating a database for the scientific community as a whole, and for use in this perennial course.
2. The course was designed to allow for adaptation of new research protocols and the use of both new and old data (phage and soil samples).
3. Students follow standard procedures of data collection (phage isolation and extraction procedures), but design individualized hypotheses and experimentation.
4. Each student develops a research idea with mentorship from the instructor.
5. Throughout the course, students are writing their single research paper, and the instructor provides bi-daily feedback.
6. The course research continues daily, and students spend a good part of each day conducting their research (e.g., propagating microbial cultures).
7. By engaging talented high school students in innovative research alongside undergraduates, we offered an environment in which more advanced students help teach and mentor students who are less experienced and who have completed different amounts of coursework.
8. This course is a bridge to more complex, later coursework. The course introduces students to bioinformatics, and undergraduates who have completed genetics are able to work independently to learn and use bioinformatics software affiliated with http://seaphages.org/. Many of these students then take the HHMI courses that are now taught at GMU.

These course features provide students with genuine research experiences and training while also requiring them to determine individualized research paths. The independent focus served as a mechanism for six of the 2015 students to continue their research after the summer course ended and a majority of the 2016 students continued their research in the new HHMI genome annotation course, now part of the new bioinformatics concentration for the Biology Bachelor of Science degree.

More about the Biology Research and this Specific Course Design

The curriculum course design is a distinct variant of the many phage-finding programs across universities, high schools and beyond, with support from the HHMI Science Education Alliance. Bacteriophages are considered to be the most plentiful organisms in the biosphere and play a large part in the microbial world (Pedulla et al., 2003). Research on the genomes of mycobacteriophages revealed that phages are an untapped reservoir of sequence information that help us understand how phages are involved in bacterial virulence and how organisms respond to infections from bacteria (Pedulla et al., 2003). Comparative genomics has shown that chromosomes from both bacteria and bacteriophage are coevolving (Brussow et al., 2004). The coevolution of bacteria and phages is rapid, and there is limited analysis of how they coevolve in their natural environments (Gomez & Buckling, 2011). Therefore, we are conducting a long-term investigation of this coevolution in a natural setting, with students sampling exactly the same locations on a 914 acre GMU field station used for environmental science research. Our multi-year investigation will investigate environmental and climate factors that drive adaptation and counter-adaptation between bacteria and the phages, which lead to continuous phenotypic and genotypic changes in both microorganism types, as well as their environment (Kashiwagi & Yomo, 2011; Pedulla et al., 2003). Understanding the impacts of these changes on the rate and kinds of genomic change that we discover will give us insight into how and why evolution in microorganisms happens. We are looking for possible new models of coevolutionary change.

We use the bacterial host *Mycobacterium smegmatis* because it is a safe soil-inhabiting bacterium, whose phage has a wide host-range, and we use the HHMI research protocols (http://seaphages.org/). Briefly, we analyze filtrates extracted from soil samples and plate these onto a solid media in petri dishes, where bacteria grow and phages form plaques where they are lysing (destroying) the bacteria. Students search for these visible zones of bacterial death and know there is a phage, which we then further investigate. The plaque morphologies can be described in terms of density, size, turbidity, (which indicates the lysogenic cycle of DNA incorporation into bacterial DNA) and growth rate (see Figure 2). The phage be grown further and the DNA extracted and shipped to a collaborator for sequencing. The resulting genetic information will be analyzed in other GMU undergraduate courses in the bioinformatics concentration (and sometimes by graduate students) and the research findings will come back to inform the research in the summer phage course.

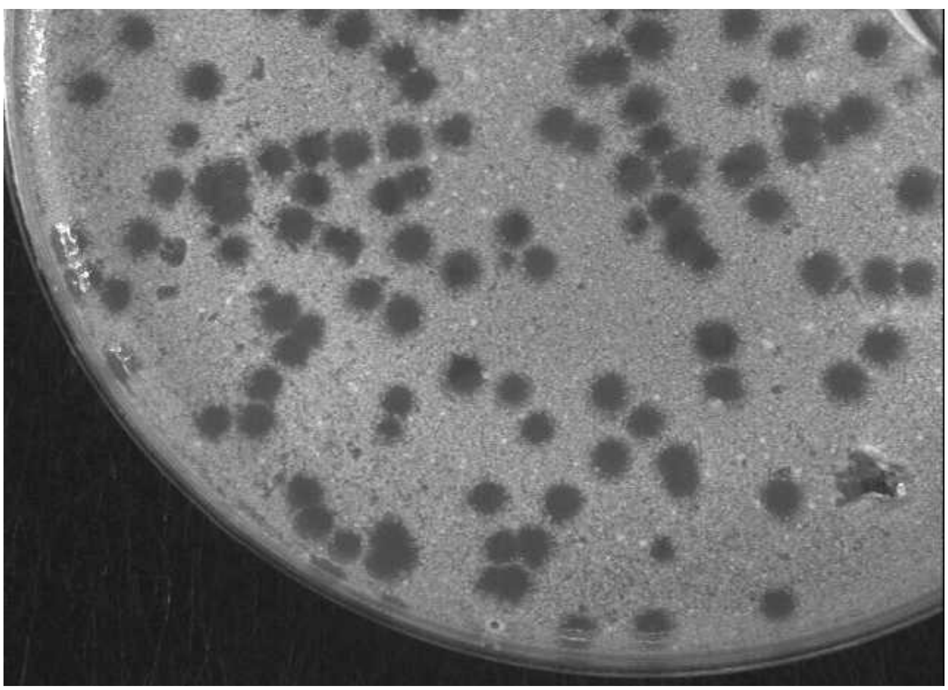

Figure 2
Isolation of phage and plaque morphologies: Petri dish containing *M. smegmatis* bacteria. The plaques are where phage have destroyed (lysed) bacteria.

Biological Context and Scope of the Research-Based Peer-Mentorship Course

The Phage Ecology research course incorporated an interdisciplinary approach: Our phage ecology research curriculum included environmental microbiology, field-based environmental research, basic lab-skills training, introductory bioinformatics, and introductory GIS. The primary interest was to investigate the evolution of bacteriophage based on climate and environmental factors. A student-created blog designed and maintained by phage student Jennifer Jones, outlines the details of the 2015 summer course. It also includes an inventory of the samples, sampling locations, experimental procedures and written discussions by classmates. The 2016 blog at the same link also shows how the course evolved and continued the next year.

> Jennifer reflected:
> *"The Phage Ecology Research Program not only provided me with valuable laboratory and research skills, but also encouraged me to further explore many of the vast fields that Biology encompasses."*

At the beginning of the 2015 course, the students collected numerous soil samples that would later be used for phage isolation and extraction. Using the United States Department of Agriculture (USDA) Web Soil Survey database, undergraduate researcher Melissa Fuerst pinpointed the GPS locations of 6 different soil types on the 914 acre field station (Environmental Studies on the Piedmont, a field station non-profit in Warrenton, VA). The students came to the field station to learn about soil sample collection and to gather their samples for bacteriophage isolation. As a team, they gathered three samples from each of the six sites, for a total of 18 samples (see Figure 3).

Figure 3

Environmental Studies on the Piedmont, Warrenton, VA. July 8th, 2015: Phage Ecology Research team on their soil-collection trip.

The core research experience of the 2015 course involved both microbiology and computational analysis. We used [ArcGIS Geographic Information System] analysis software for the team to better organize and display the sampling sites and data. GIS allows users to visualize "layers" of climate data (e.g., soil temperatures, vegetation, and topography), and compare the phage data. The 2015 undergraduates mapped the phage morphologies with soil profiles. The comparison of the two "layers" of data is helping to visualize trends congruent with both layers. The 2015 team began to analyze the dynamics of how climate differences (e.g., rainfall) affected the types of phage that were discovered, and this analysis will continue in future summers. Each year, the database of phage sequences and environmental data will be expanded. We hope to publish these results in a few years, with most of the students as authors.

Assessment of Peer-Mentorship Impact and Students Gains

> Bri commented:
> *"Using ArcGIS was very simple and easy to use, having no previous knowledge. We were able to create maps and visualize important data collected from our research."*

We evaluated the initial outcomes and student feedback to assess and improve the course. A richer assessment of student learning will happen after the course is taught for several more summers. Student interest for the summer of 2016 was very high, with 22 students applying for the 15 course seats. Outcomes included the discovery of new phage, and the 2015 and 2016 students created research outcome papers (student papers, not for publication), which are helpful to implement the next summer course. Student Assessment of their Learning Gains (SALG) questions were used to investigate how the course enabled student learning (Mathieu et. al., 1997). A mix of SALG questions and other questions comprised an online post-survey used to assess the 2015 students' course experiences. The Learning Assistants administered the questionnaire during the last two days of the course. The Learning Assistants obtained IRB approved consent for all human participants (see Appendix). Survey Monkey online software was used to gather the feedback. We evaluated all student responses to understand students' views about: the peer-mentorship aspect of the course; attitudes toward research; the impact the course experience had on their future career goals; and how the course influenced their research aspirations.

Our survey results indicated that the students had positive views about the power of peer-mentorship, the need for integrated research experiences as undergraduates, and the hands-on research skills acquired in the course:

- 100% of respondents (*n* = 6, of 9 undergraduate participants, 3 did not respond; high school students were omitted from the survey because of IRB requirements) said the course inspired them to do other independent research, and 2 years later, 8 of 9 students did conduct additional undergraduate research;
- 100% of respondents reported they were likely to pursue a career that involves research;
- Student comments' indicated that the course had a positive outcome on their attitudes toward research, e.g., students stated: "I want to be more engaged in further research, with further immersion in biological and genetic research," and "I liked the trust given to the students. It motivated me to want to work harder."

These responses indicated that the course structure was evoking individualized critical thinking skills, and was helping to build student confidence as independent researchers. Other comments included:

- "The Learning Assistants created an environment that was very supportive, and I felt like I could learn and grow."

- “I thought the fact that the LAs were students and that everything was student guided made it more interesting and beneficial for everyone.”
- “It was important for me that the research group all [got] along and [worked] cohesively as a team with one another.”

Regarding the length of the course, 100% of respondents (*n* = 6, of 9 participants, 3 did not respond) reported that they wished the course would be longer than a 3-week duration. One student said, “Making the class longer so that we could vary experimental procedure based on our results,” would be desirable. The instructor’s long-term plan was to design a second capstone course that students can analyze the phage genomes in, using the SEA-PHAGES course recommendations, and this second course is now taught in the fall. These two courses are now part of a new Bioinformatics B.S. concentration, offered by GMU’s biology department.

Qualitative results showed that the course seemed to have influenced students’ personal perceptions about their research trajectories. Upon consideration of her experience in the course, one student noted: “The Phage Ecology Research Program not only provided me with valuable laboratory and research skills, but also encouraged me to further explore many of the vast fields that biology encompasses.” This student later explained the experience helped her decide to pursue graduate studies in bioinformatics, and she is now pursuing an M.S. degree in bioinformatics. One of the high school students won a regional science fair, and one of the undergraduates obtained a prestigious internship at Johns Hopkins for summer 2016. One of the LAs was admitted to medical school. Future analysis of course outcomes will assess students’ continued learning and career progress. Anecdotally, the 2015 students (the students we followed for this study) are doing very well.

> Mimi said:
> *“After developing the preliminary soil sampling protocol, I communicated my findings and methods with students in the course and guided the team in the field to the designated soil sites. From my experience as a Learning Assistant and Student Researcher, I have noticed that the dialogue between experienced and potential student researchers makes the undergraduate research realm seem less intimidating and more conceivable. This course acts as that space for dialogue that fosters students’ interests in research and opens doors for new research opportunities. The hands-on, real-world experience offered through this course fostered deeper learning and new research possibilities for the students involved.”*

Outcomes and Future Prospects

Because of the individualized student attention and course flexibility, many exciting opportunities presented themselves as continuations and expansions of “phage finding” during the 3-week intensive research duration. The team is now using a computational bioinformatics approach. One researcher, Jennifer Jones, is now an M.S. student at GMU, continuing her own independent research, and she noted: “After further discussion on how to continue our research, we determined that identifying the entire microbiome—including all bacterial organisms—in our soil samples is essential to determine how bacteriophages evolve over time.” Another undergraduate, Brianna Nielsen, was funded by GMU’s Office of Student Scholarship, Creative Activities and Research (OSCAR) program to conduct independent research in collaboration with Jennifer. Brianna and Jennifer initiated their own research endeavor and are working with Dr. Patrick Gillevet at GMU’s Science and Technology Campus, because this Professor has the sequencing and computational technology needed for the research. Dr. Gillevet made his laboratory available in 2015-2017 for student visits and collaborations. Our group also obtained funds provided by a 4-VA innovations award grant to use his laboratory resources in 2016-2017 for the students to analyze the data. He also gave several lessons to the students during the 2016 summer course to introduce them to the bioinformatics software (and also to help other faculty and graduate students learn how to use these software).

The course currently counts as an independent study (students can enroll for variable credit), and has become an upper-level 3-credit course, which is now a core component of a new bioinformatics concentration in GMU's biology department. For students wanting to complete an 18-credit bioinformatics concentration in the biology degree, they need to complete an individual research requirement and this course helps them do just that.

The course also fostered these longer term outcomes: (1) helped students progress from course-based research experiences to more sophisticated "out-of-course" independent research projects; (2) created data for a 2nd bioinformatics (computational) course that follows this course, for undergraduates enrolled in the new bioinformatics concentration in GMU's Biology B.S. degree, which began in Fall 2016; (3) spawned the creation of additional research-intensive undergraduate courses in the biology department, in the bioinformatics concentration (with assistance from GMU's Students as Scholars Office; and (4) is generating research outcomes that are congruent with the biology department's interests in ecology and evolution.

The one-room school method, with Learning Assistants assisting the course design and teaching, is an approach that can be adopted for other courses. This method supports and integrates undergraduate research experiences into the coursework (e.g., in lieu of traditional laboratory-experiences, which accompany a lecture course).

Concluding Remarks

The Learning Assistants (LAs) and faculty team designed a course using the one-room schoolhouse method (Henderson, Buising, & Wall, 2008) to teach phage ecological research, by melding students' perspectives and experiences on undergraduate research with the instructor's teaching objectives and bioscience expertise. These efforts greatly assisted the instructor in leading a laboratory-intensive research course that uses LAs to support the research and instruction.

> Lindsey, now a medical student, commented:
> *"The defining moment of my research experience was the chance to teach the course I helped create. From drafting the initial syllabus to organizing lecture notes for the next day's class, I was able to experience the continuum of research from the very birth of the idea to its final execution."*

This research approach uses the one-room schoolhouse method to foster close mentorships between students, teachers, and collaborators. Not only does this program offer powerful research themes for both high school and undergraduate researchers, it provides a learning environment with peer-mentorship as its crux. We recommend that instructors who are inspired to create a summer research experience with these features consider the interactions of the students (including the level of knowledge exchange) to promote ongoing research during, and after the course. These peer-mentorships will kick start various in-course and out-of-course research endeavors in a motivational and inspiring ecosystem of learning to engage students in research.

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Appendix

Core Research Questions from the Questionnaire

Please comment on how the way this class was taught helps you remember key ideas.
Please comment on what skills you have gained as a result of this class.
Please comment on how this class changed your attitudes towards this subject.
Please comment on how the instructional approach to this class helped your learning.
What did you like about this course?
What did you not like about this course? What would you change?
What was the most important thing to you about the mentorships/relationships in the course?
Did you like the way the course was organized (the one-room school house method)?