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Course Portfolio for BIOC934: Genome Dynamics and Gene Expression

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1.0 Abstract

A graduate degree in Biochemistry or any molecular life science field requires a strong foundation in molecular biology. BIOC934 Genome Dynamics and Gene Expression is a course designed to challenge graduate students whose research interests lie in the areas of biochemistry, molecular biology, synthetic biology, bioinformatics, and systems biology of prokaryote and eukaryote systems. Graduate students in these disciplines require a rigorous and thorough examination of core concepts in addition to practice applying theory to new observations while traversing unfamiliar disciplinary terrain. This portfolio describes the design of BIOC934, its implementation, and observed outcomes to identify strengths of the course and strategies for enhancement.

2.0 Introduction

The goal of this portfolio is to evaluate the delivery and assessment methods of BIOC934 to determine where improvements can be made to aid in student satisfaction, content recovery, and ability to apply theory at the frontier of molecular biology research. BIOC934 is a core course for Biochemistry graduate students and is intended to provide higher-level training in molecular biology for students who have a solid foundation in biochemistry and molecular biology at the undergraduate level. However, there are no prerequisites for the class, and BIOC934 has become popular for students from other life sciences programs who also have a strong background in molecular biology, as well as for students who desire a crash-course in molecular biology that focuses more on theory, experimental design, and difficulty than might be encountered in a 400/800-level course.

The class regularly draws students from Biochemistry, School of Biological Sciences, Chemistry, Chemical Engineering, Veterinary Medicine and Biomedical Sciences, Food Microbiology, Agronomy and Horticulture, Animal Science, and Computer Science. The interdisciplinary composition of the students in the classroom enriches the discussions, broadens the perspectives, and models the dynamic team science environments that students will encounter in academia, industry, and government where experts of diverse training lineages come together to evaluate and problem-solve. This diversity is a strength, but also represents challenges as each student finds themselves, in turn, being an expert one week and the next week feeling out of their depth. This can be exhilarating, but also uncomfortable at times. I take great care to help students understand that the high-impact papers we are reading are revolutionary precisely because the authors have been able to make discoveries using interdisciplinary logic and tools that supports their interpretations while simultaneously lowering the barrier to wide adoption by a larger community of researchers; this is a skill that we all must practice.

In my experience, students enjoy being stretched, encouraged to think creatively, and being challenged by BIOC934. As a graduate-level course, my goal is to be a guide that empowers students to ask their own questions, assists their evaluation process, and validates their judgements to ensure that their conclusions and extrapolations are consistent with established understanding in the field. The years have shown that BIOC934 ages well: several students have come back to me and expressed their appreciation because of the way that the class prepares them for real research in a way that they did not initially understand when they were first-year graduate students.

The goal of this portfolio is to reflect on which course aspects work well, and which practices could be strengthened. The mixed training background and the diverse research goals of the students can be difficult to manage simultaneously. Perennial questions I face as the instructor are: ***Am I providing enough mechanistic knowledge or resources for the novice molecular biologists, or am I boring the experienced students? How much lecturing/handholding is needed vs how much independence should be expected?*** Because of the diverse composition of the class, and because discussion plays a large role in the delivery and content mastery assessment, no two classes are ever the same. Discussion topics and tangents keep me on my toes as they are entirely unpredictable from year to year and even from week to week. Through the discussions I work to steer the concepts towards each day's plan, and I fill knowledge gaps that are uncovered so that I know the desired material has been delivered. Strategies to help students perceive they are growing their knowledgebase while engaging in semi-structured discussion would help in the course assessment and would be a useful future skill as professional scientists must rely on informal mechanisms such as publication alerts, chance encounters, conferences, and collaborations to stay current in their field. The course is designed to help students develop tools and strategies that will serve them well as they transition to becoming independent researchers who need to be able to integrate theory, concepts, and ideas across disciplinary boundaries to make cutting-edge discoveries. Ultimately, I try to inspire students to think deeply and creatively, and to have confidence in their ideas so that their unique perspectives will result in durable impact in their fields and successful future careers.

3.0 Course Description

3.1 Course Design

BIOC934 Genome Dynamics and Gene Expression is a graduate-level molecular biology course that trains students to draw from cross-disciplinary knowledge to form hypotheses, devise experimental approaches, and to test models to understand phenotypes and evolution in a wide array of organisms. As BIOC 934 is a core course in the Center for Biological Chemistry graduate degree, the topics and approaches used reflect the **American Society for Biochemistry and Molecular Biology** recommendations (1) as well as the National Academy of Science, Engineering and Math (NASEM) (2, 3), and the American Society for Microbiology (4). It is designed to focus on the ASBMB foundational concept ***3. Information Storage and Transfer*** while integrating knowledge from concepts ***1. Energy and Metabolism*** and ***2. Structure and Function***, all in the context of developing independent ***4. Scientific Skills*** through detailed discussion of problem-solving frameworks and technical approaches (**Figure 1**).

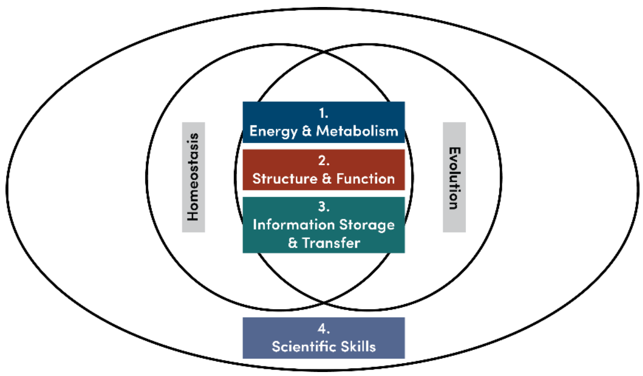

Figure 1. ASBMB foundational concepts. From https://www.asbmb.org/education/core-concept-teaching-strategies/foundational-concepts (1).

Graduate courses should be distinguishable from undergraduate or combined courses by guiding students to develop knowledge acquisition skills that increasingly mimic the processes needed in professional careers. As such, graduate courses should be heavily reliant on primary literature, discussion, and debate with peers of varying expertise, with minimal use of traditional lectures or rote memorization in favor of concept synthesis and a combination of group and individual problem-solving. In designing this course I consulted the American Society for Biochemistry and Molecular Biology (ASBMB) Education guidelines (1) and incorporated many active learning approaches to encourage engagement, satisfaction, recall, retention, positive attitudes and climate (3, 5, 6).

BIOC934 embodies the ASBMB foundational concepts and their interrelationships (https://www.asbmb.org/education/core-concept-teaching-strategies/foundational-concepts). While the course is focused on foundational concept ***3. Information Storage and Transfer***, the lectures, papers, and discussions iteratively connect concept 3 with concepts ***1. Energy and Metabolism***, concept ***2. Structure and Function*** (of proteins, enzymes, and macromolecules) in the context of maintaining homeostasis, and evolution over time, as we delve deeply into concept ***4. Scientific skills*** which include the techniques, approaches, logic, data analysis, presentation needed to understand literature and apply concepts to new questions.

Because BIOC934 is a graduate class we spend a large amount of time discussing “edge cases” or biological extrema (e.g, 22nd amino acid, split tRNAs in microbial eukaryotes, *Wolbachia*) that are compared to the canonical or model examples that are used as pedagogical foundations in undergraduate textbooks. This is designed to challenge students’ mastery of the ASBMB threshold concepts (https://www.asbmb.org/education/core-concept-teaching-strategies/threshold-concepts) of ***i) Steady State, ii) Biochemical pathways dynamics and regulation, iii) Physical basis of interactions, iv) Thermodynamics of macromolecular structure formation and v) Free Energy***. By discussing edge cases, students learn to identify research questions, to form hypotheses, to choose appropriate techniques, and to analyze data such that unexpected observations can be explained by resolving theoretical discrepancies through troubleshooting or by amending the model.

Class activities intentionally take **Universal Design** (UD) into account to maximize student potential (7, 8). I see this as especially critical considering that graduate students have demonstrated undergraduate-level mastery, are committed to their graduate training, and in the case of BIOC 934, come from diverse disciplinary backgrounds with the goal of future success in a myriad of STEM careers. UD is used to guide classroom activities and assignments by implementing the three core UD principles of 1) Engagement, 2) Representation, and 3) Action and expression (8). Engagement is exemplified through setting a supportive tone for classroom discussion, providing ample opportunity for interaction with the instructor and peers in small and large group settings, giving students agency in selecting presentation topics and continually emphasizing the utility of concepts and technical approaches to diverse research topics and STEM careers. Representation is considered through using layered communication methods to share knowledge including providing all required and optional texts on Day 1 to allow flexibility for reading, writing, and communicating at individual pace. Using multiple modes (aural/visual/kinesthetic, text/video, etc.) allows learners to find modes they are most comfortable with to ensure concepts are accessible to all (**Figure 2**). As Action and expression are supported through making lectures and presentations available through CANVAS, using assignments and assessments that indicate concept mastery and retention over short-term, medium-term, and long-term timescales through multiple modes of expression (oral, visual, and text). Assignments and activities take place synchronously in class and asynchronously, which allows students to accommodate flexibility in place and time. Flexibility in graduate courses is especially important as students engage in research at unpredictable hours and may also miss class to attend scientific conferences. Details of assignments and classroom activities are provided in subsequent sections of this portfolio.

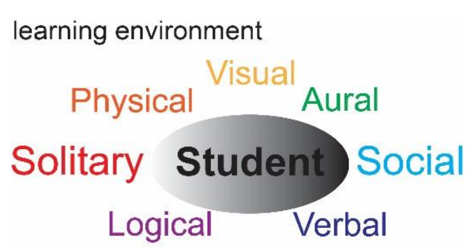

Figure 2. Seven learning styles. Each student has individual strengths and preferences in how they absorb and process information. Strengths and preferences can vary depending on the individual student and from day-to-day or topic-to-topic. A classroom learning environment should provide a rich experience that contains elements of each style so that learning by each student may be maximized during the semester.

In addition to UD, every class take principles of **diversity, equity, and inclusion** into account. Diversity of ideas and identity are celebrated through selecting discussion papers from diverse sub-fields who have authors from diverse genders, ethnicities, and institutions. These are highlighted continuously throughout the semester, and it is emphasized that the highly impactful work we are studying has directly benefitted from working on diverse teams using interdisciplinary approaches. Equity is ensured through providing all students equal access to class materials, the instructor, and equal opportunity to share ideas, ask questions, and to earn a high grade. Rubrics are especially useful in ensuring grading equity such that course grades primarily reflect concept mastery and allow room to develop language/vocabulary and communication skills over the semester. Inclusion is critical in a discussion-based class because sharing ideas and questioning are a major informal assessment leading indicator of subsequent success in the class. Discussions are moderated by me to ensure every student is given the opportunity to share thoughts and ask questions, and to act as the reporter for think-pair-share small group discussions. Every student presents a paper they select to the class, and each student has the opportunity to do their own self-paced background research that they present as the “expert” to their peers. Presentations have been key to allowing students to really “shine” in class; I have observed immediate positive change in the confidence of presenters and in the deference and consultation shown by their peers after each person presents a paper. Without fail, students develop from being a collection of strangers to a unified peer learning team over the semester. ***Watching this transformation is by far the most gratifying aspect of teaching.***

3.2 Course modules

The course modules build on an reinforce each other as we tease apart each aspect of the Central Dogma of molecular biology from a modern and interdisciplinary perspective. Each module focuses on one or more of the core concepts (see below). The course begins with a chemical biology/first life unit where students draw from knowledge of geochemistry and organic chemistry as well as biochemistry to consider the boundary between living and non-living as we discuss abiotic nucleotide synthesis, protocells, and RNAzymes. An ***overarching theme*** of the class is that *organisms are in constant communion with their environment; cells affect and are shaped by the environment they inhabit as well as the information content they contain and transmit*, and thus considering the extreme example of pre-biology/astrobiology research sets the stage for discussing how organisms use and shape the environment through evolutionary time at different levels of organization and scale. As we move through each course module, we revisit on this overarching theme to help students situate new facts in their individual mental concept inventories.

The next unit in DNA synthesis begins with familiar material for Biochemistry graduate students in that the initial classes are based on structure/function biochemistry, and then a difficult section relating to DNA damage/repair and recombination reminds students of what they learned in undergraduate molecular biology classes yet is framed in the context of previously unlearned diversity and the logic of how/why such mechanisms have evolved and how they can be used in metabolic engineering.

The next module covers RNA synthesis and again begins with the familiar RNA polymerase enzyme structure/function and traverses into transcription regulation highlighting the role of metabolic fluxes and environmental signals on transcription initiation, elongation, and termination.

The translation module is too brief and focuses on how metabolic and environmental signals cooperate to shape translation efficiency. The 21^{st} and 22^{nd} amino acids are discussed in detail to inspire conjecture about "shadow" biochemistry or astrobiology, the evolutionary selective pressures that give rise to and shape protein evolution, and the use of noncanonical amino acids in synthetic biology.

The Evolution module is, to my mind, the signature component of BIOC934. I find that students have, by and large, a limited understanding of evolution based on simplistic ideas of point mutations and environment or perhaps sex selection for favorable characteristics. In BIOC934, their eyes are opened to concepts of mutation rate variability, gene conversion, evolvability, and the myth of clonality. We hearken back to the first life/astrobiology module and consider how the environment shapes evolution from a systems perspective.

In the next section we discuss how evolution of organisms, and their phenotypes, are shaped by lateral gene transfer (including barriers to genetic transfer recalling the example of pyrollysine and restriction modification systems introduced earlier). Now that students have considered how genomes may expand and contract through homologous recombination and lateral gene transfer, we discuss "shuffling" in the context of genomic and regulatory "rewiring" and the effect on fitness.

To come full circle, we cover three groundbreaking articles on synthetic biology in the strictest sense where discuss synthesis of wholesale new organisms, hachimoji DNA, and more efficient new-to-nature biochemical pathways. In this module we draw on knowledge of DNA synthesis, metabolism, and systems biology to consider how these new pathways or organisms may evolve, what could they be used for, and discuss the biological and environmental implications of release of these organisms (risk/benefit analysis).

A key component of the presentations and discussions is tying the manuscript findings back to the big picture "Why bother?" and "Who cares?" questions that place each set of findings into a broader social context. The course wraps up with a final ethics module where recent events in human CRISPR germline engineering are discussed. In the last module, students are assigned with reading articles and federal biomedical research guidelines relating to recombinant DNA technologies and CRISPR that they use as a basis to reflect on the need for national and international oversight and limits to the use of technologies they learned about in the class.

4.0 Course goals and core concepts

At the conclusion of the course, students will have improved the following skills.

1) Identify overarching hypotheses from a body of primary literature.
2) How to design interdisciplinary experiments.
3) Identify major in gaps in logic or a lack of support for a hypothesis.
4) Be comfortable giving and receiving critical ideas to test hypotheses.
5) Draw from a broad familiarity of genome dynamics and gene expression mechanisms across all known kingdoms of life.

To achieve these goals, class activities and assignments will be designed to provide information, reinforce concepts, and build technical and professional skills. Course goals are provided on the syllabus and discussed with students in class. Goals, objectives, assignments, activities, and assessments are described in **Table 1** below.

Table 1. Course goals, objectives, and outcomes.

Goal ***Students will be able to…***	***Objectives*** ***To build these skills we will…***	***Assignments and activities***	***Assessments***
Identify hypotheses from literature and formulate new hypotheses using interdisciplinary knowledge	Read and discuss primary literature at a postgraduate level of understanding	• Textbook readings • Lectures • Class discussion • Discussion Q&A • Presentations	***Informal:*** Class discussions, Discussion questions ***Formal:*** Discussion Q&A, Presentations, Quizzes, Exams
Design interdisciplinary experiments to test hypotheses	Learn about techniques and approaches from prebiology to single-molecule experiments to systems biology and evolution	• Textbook readings • Lectures • Class readings • Class discussion • Literature searches • Discussion Q&A • Presentations • Quizzes • Exams	***Informal:*** Class discussions, Discussion questions, Literature searches, Worksheets ***Formal:*** Discussion Q&A, Quizzes, Exams
Analyze data and identify complementary tools and techniques	Apply technical knowledge to evaluate quality of data and to interpret results	• Textbook readings • Lectures • Class readings • Class discussion • Literature searches • Discussion Q&A • Presentations • Quizzes • Exams	***Informal:*** Class discussions, Discussion questions, Literature searches, Worksheets ***Formal:*** Discussion Q&A, Presentations, Quizzes, Exams
Critically evaluate data in support of a hypothesis and identify gaps in knowledge	Practice weighing experimental evidence	• Lectures • Class readings • Class discussion • Literature searches • Discussion Q&A • Presentations • Quizzes • Exams	***Informal:*** Class discussions, Discussion questions, Literature searches, Worksheets ***Formal:*** Discussion Q&A, Presentations, Quizzes, Exams
Able to give and receive critique of ideas	Practice critiquing manuscripts verbal and in written format	• Discussion papers • Discussion Q&A • Class discussions • Presentations	***Informal:*** Class discussions ***Formal:*** Discussion Q&A, Presentations, Ethics

	Practice giving peer and instructor feedback Receive peer and instructor feedback	• Ethics reflection	reflection, Participation points
Familiar with major themes in genome dynamics and gene expression in all domains of life	Read and discuss manuscripts and examples from viruses, microbes (bacteria and archaea), plants, animals	• Textbook readings • Lectures • Class readings • Presentations • Discussion Q&A • Class discussions • Presentations	***Informal:*** Class discussions, Discussion questions, Literature searches, Worksheets ***Formal:*** Discussion Q&A, Presentations, Quizzes, Exams

The core concepts of the class are:

1) RNA is capable of much of the biochemistry we associate with living systems (polymerization, enzymatic catalysis, redox catalysis).
2) The delineation between non-living and living systems is an unsolved biochemical puzzle.
3) Vertical and lateral heredity shape the properties of living systems.
4) All aspects of a living cell are subject to change through time, including but not limited to information transmission (heredity, message), information processing, genome size, metabolic networks.
5) All information in the cell is integrated (hereditary information, messenger functions, metabolism).

The core concepts are provided on the syllabus and discussed with students on the first day of class. Core concepts are then explained and explored with students through class materials, lectures, and presentations. Each class module focuses on one or more core concepts to provide iterative reinforcement of ideas. Assignments and assessments are designed to reinforce and assess each student's ability to recall and apply core concepts to a variety of real-life and hypothetical situations.

5.0 Teaching Methods and Activities

A variety of teaching methods and activities are used in accordance with Universal Design principles (8). By using multiple avenues to engage with student learning, my goal is to provide pathways to success for each student, regardless of whether they are Biochemistry majors or nonmajors. The following subsections describe teaching methods and activities used and the rationale for their use in BIOC934.

Figure 3. Photo illustration of classroom lecture by an instructor. Photo: https://jobs.theguardian.com/article/what-is-it-like-to-be-a-university-lecturer/.

5.1 Lecture

Lectures by the instructor (**Figure 3**) are only used as necessary to provide review and context for Lectures are weighted in the beginning of the semester to help first year students transition from a more familiar teaching style, eventually tapering off in favor of primarily presentation and discussion by the middle of the semester. This repetition is necessary for many students in BIOC934 (9). In my first year of teaching this class I used a flipped classroom approach almost entirely except for the first week of class. Student feedback indicated this was too drastic a format change for most students compared to what they were used to, and comments implored incorporating instructor lectures (in some cases students asked for an entirely lecture-based format!). It was clear that while students had a suitable undergraduate background as evidenced by their credentials, they were not confident in their content mastery of molecular biology or in their ability to critically read primary literature. As such, I adjusted the course format to incorporate more review lectures to cover key background knowledge and theory concepts (**Figure 4**). Over the years I have found a format that gives students the reassurance that they need from instructor-delivered review lectures, but still provides ample opportunity for engagement and developing creative thinking skills by gradually shifting to a flipped and presentation/discussion format with unstructured lectures only used to correct misconceptions that are uncovered during discussion and after assessments.

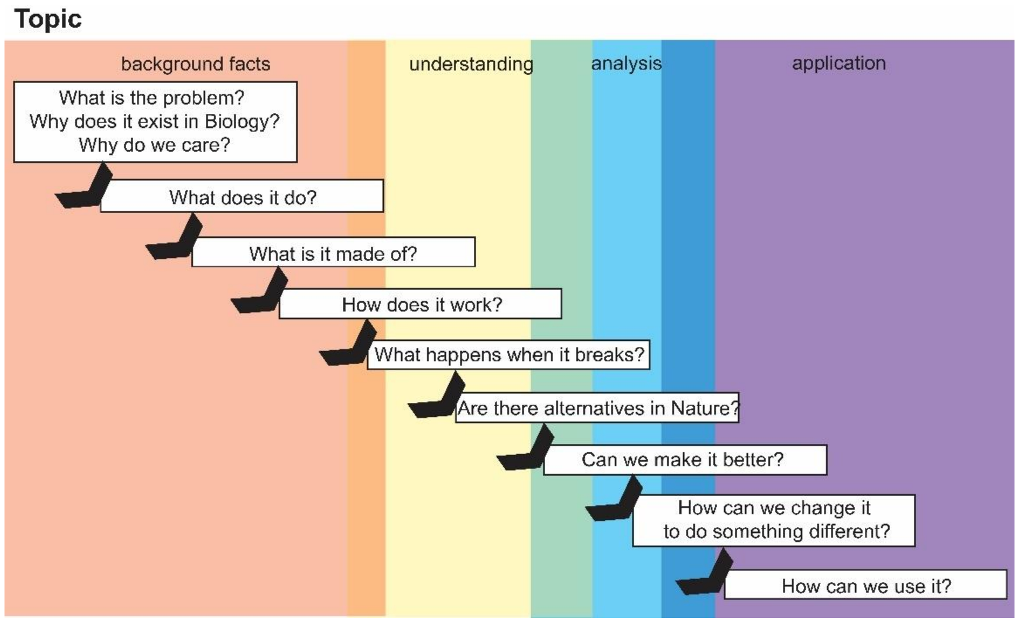

Figure 4. General lecture outline.

5.2 Flipped Classroom

Graduate students are, by and large, highly motivated to master course material and satisfy instructor expectations at a high level. I find that an excellent way to serve this need in graduate students is to provide as many opportunities to reward initiative as possible. Structuring the class overall in a flipped format (**Figure 5**) is ideal for giving curious learners free-range to explore at their own pace while simultaneously gives students who are not as confident a ready-made knowledge database that has been curated by the instructor (5, 6).

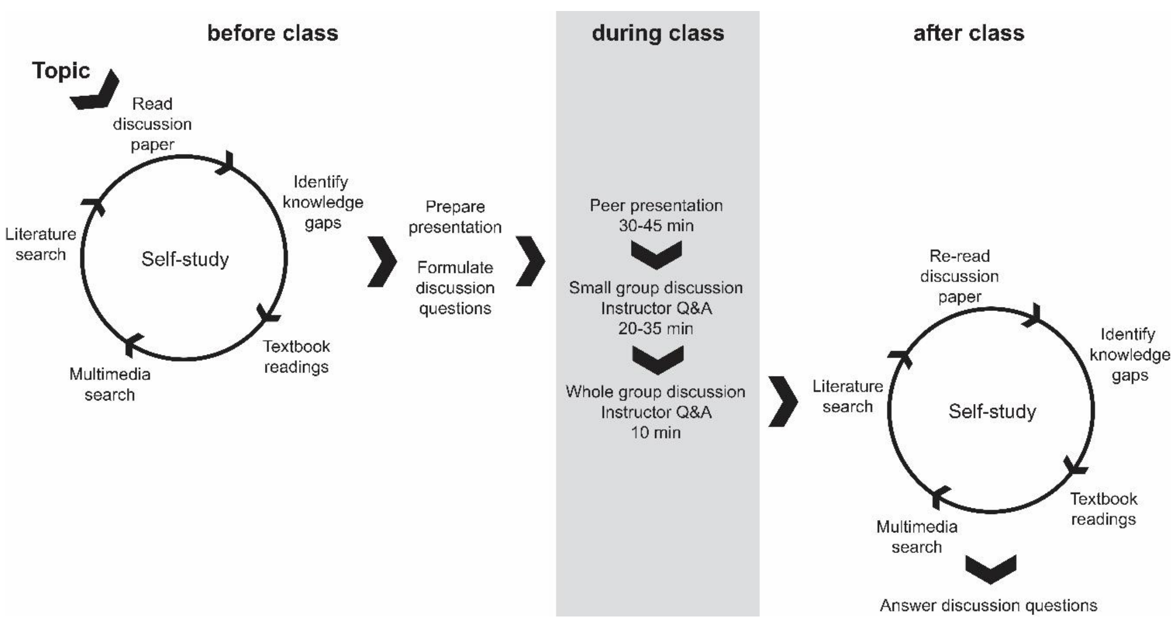

Figure 5. Diagram classroom structure and activities.

To accomplish this, students are given full access to virtually all course materials on day 1: all take-home assignments, worksheets, literature, recommended textbooks, etc. Reading assignments and discussion topics are clearly indicated on the syllabus. Students are expected to complete assigned readings ahead of class; compliance is ensured by having small groups submit discussion questions before class that serve as the basis for that day's discussion (described more in detail below). By having small randomly assigned groups responsible for forming the discussion questions, I guarantee that the presenter and >20-25% of the students have read each paper in depth before class.

Class time (>75%) is then spent on discussion in class where students work together to find multiple answers to the discussion questions and arrive at consensus about best answers. The presenter necessarily must do additional background research (both from papers I suggest in the course paper archive and from their own literature searches) to meet the rubric expectations for their presentation grade. Presenters also take questions from the audience about the paper and the techniques described, which encourages them to delve much more deeply into the interdisciplinary literature that they would if they were not responsible for presenting the paper. This represents a large amount of self-directed research outside of class time. The remaining class time is used for rigorous critique and debate of the paper(s) being discussed as we collaboratively seek new understanding and identify unexplored research questions. In many cases an understandable gap in knowledge is immediately addressed by an in-class literature search. It is typical that students will do quick literature searches, read abstracts or materials and methods sections, and collaboratively share their findings in small groups and as a whole class to answer the questions satisfactorily.

Another way the flipped classroom approach is used is that practice worksheets are completed before class on their own or as small groups. Then, before each quiz or exam, class time is spent collaboratively sharing and debating answers to the take-home worksheets that then serve as the basis for the quiz and exam questions. As students work together to share ideas about technical approaches or to multiple ways to solve the problems on the worksheet, I am informally assessing each individual's concept mastery, theory application, and technical troubleshooting skills. By dedicating a whole class to this activity, I can correct misunderstandings and encourage deeper learning immediately before the exam.

Figure 6. Photo illustration of small-group class discussion. Photo: ©iStock/Steve Debenportv.

5.3 Group Discussion

Most of the class period is spent in group discussions (**Figure 6**). Discussions are a very important way to strengthen theoretical knowledge, develop hypothesis generation and testing skills, hone data analysis and evaluation skills, and to develop the “soft” but critically important sills of debate, teamwork, self-confidence, and professional poise that will serve them well in their future careers (10, 11). ~80% of the group discussions are in small groups that range from 2-4 members. Small groups are essential for students who are less confident or who are not native English speakers. Group membership is randomly rotated to give everyone the opportunity to work with each other equally. The number of discussion sessions means that every student has multiple opportunities to collaborate and debate with every other student. By keeping most of the group work small and randomizing membership I ensure that every student has the chance to contribute, that discussions are not overly rushed, and we allow time for deeper thinking and to find the right words. Randomizing groups ensures that all students help each other and do not gravitate into cliques that may lead to feelings of exclusion, alienation, or apathy. Approximately 20% of discussions include the entire class; these occur towards the end of the semester as students gain confidence in their own ideas. During discussions I travel between each small group, and I informally assess each member and group dynamics. This is accomplished by alternating between asking:

1) What one individual thinks is the correct answer to a given question;
2) Who else in the group agrees or disagrees and why;
3) What the group decided was the best or most likely answer;
4) What the group decided was the least likely answer and why, followed up with a discussion of when an unlikely scenario could become the most likely mechanism;
5) Posing hypothetical scenarios related to the topic to an individual and asking how or whether their previous answer would change and why or why not;
6) Posing hypothetical scenarios related to the topic to the group and then moderating a small group discussion evaluating any responses;
7) Posing a hypothetical scenario to the group- if no satisfactory answers are provided, I direct them to relevant class resources or literature and then circle back to moderate a discussion and help them make connections between concepts discussed in class.

Every group can ask for clarification or to contribute new ideas. Through this process we iteratively refine our understanding of the concepts discussed in class by including successively more interdisciplinary knowledge, ideas and concepts (**Figure 7**) (12). We also continually evaluate not only the conclusions drawn from the paper by the authors, but we consider increasingly broader scopes for the work from a single mechanistic pathway to whole organisms to evolution over time and the social implications of such work. The result is that students think very small-scale in the beginning of the class and emerge able to evaluate the technical merits of a manuscript as well as identify compelling new hypotheses for future discovery.

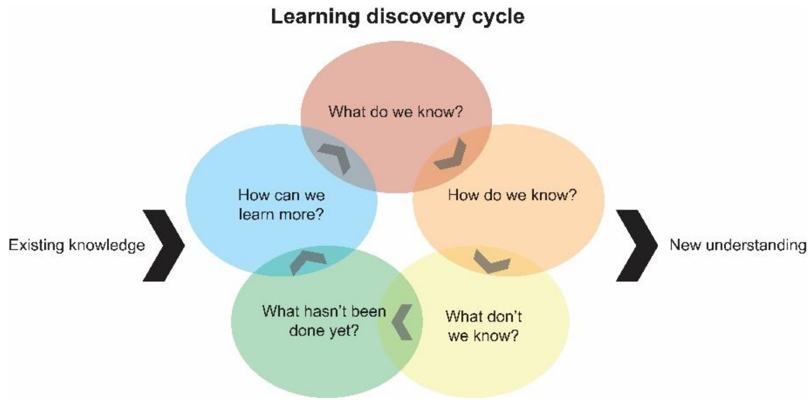

Figure 7. Diagram of how discussion questions are used to iteratively refine understanding using a learning discovery cycle.

5.4 Think-pair-share and ensuring inclusive discussion

Interpersonal dynamics can change drastically as groups go from pairs, to three, to four or more. The more people in the group, the more competitive personalities try to dominate independent of whether they have mastered the material. I find that the best way to engage all students while helping them to develop into confident debaters is to maintain a significant proportion of two-member pair discussion and think-pair-share activity (~20% of discussions). For each small group discussion activity, I progress from designating a group "reporter" who will then report on group responses (and whether there was consensus or a diversity of opinion) to the rest of the class. By designating a reporter, every student can practice note taking, moderating discussion in a small group, and synthesizing a group consensus. The shier students are encouraged to take the lead through positive reinforcement during discussion. For instance, in one strategy I will excitedly reaffirm a correct answer and share their good idea on their behalf with the rest of the class. Often, this results in the shy student loudly expanding on their idea in front of the class; something they would not have had the courage to do minutes beforehand. I want to stress here that native language or professional vocabulary have nothing to do with my enthusiasm. Instructor enthusiasm is earned for accurate factual recall, correct logic, interdisciplinary thinking and creative problem-solving. Every 1-2 weeks I relax from designating a reporter and I assess whether the self-selected reporters are equitably distributed or whether certain, more confident speakers are dominating the conversation. If the reporters are not representative of a random sampling of the whole, I revert to selecting reporters. This process is repeated if and until extrovert speakers begin to show deference to others and the more introverted students show initiative to take the lead on sharing their ideas.

5.5 Group and individual problem-solving

Problem-solving skills, as an individual and as a member of a team, are essential aspect to working as a professional scientist. Both individual and group problem-solving skills are trained in BIOC934 so that students learn by doing (5). Students build their concept mastery and confidence through individual assignments and assessments. For example, by presenting one of the papers to the class, and by taking quizzes and exams without outside assistance. By having ample opportunity to earn an individual grade, students can get individual guidance from the instructor and will know how well they can recall and apply the new knowledge they are gaining. The confidence they develop with the subject material translates into willingness to question and debate with peers and the instructor. As the course progresses, I observe students develop a willingness to also engage in increasingly creative problem-solving as they integrate more and more interdisciplinary concepts into the discussion topics.

At the same time, students learn to problem-solve as a team in class discussions and through solving worksheets. Through class discussions students brainstorm, critically evaluate, and make predictions together. One component of class discussions is to ask “What if..?” and then talk through the expected outcomes, possible interpretations, or additional approaches that should be taken on a particular research topic (10). By having such discussions in small and whole-class formats, each student strengthens their own problem-solving skills and learns to work as a team to find a best-case solution (13). Initially the problem-solving discussions are instructor led. As the class progresses the students themselves begin to lead these hypothesis-testing exercises. Worksheets are used in a similar way. The worksheets pose problems that can be solved through calculations, literature searches, and thought experiments. By working first individually, then in small peer groups, and finally as a whole class, students practice applying their knowledge and then iteratively refine their understanding by comparing to peers and ultimately getting feedback from the instructor. The benefit to having worksheets is that having a tangible/visual product reinforces the verbal learning that happens in discussions.

5.6 Individual reflection

While the class has a distinctly group collaborative feel, it is critical that space is provided for ample personal reflection (14). Some students are more comfortable learning on their own, and all students gain confidence when they can successfully solve problems without external help (**Figure 8**). To satisfy the needs of the individual, all assignments and class readings are provided ahead of time. This gives each student the opportunity to consume course material at their own pace. I encourage reading and solving worksheets individually first before engaging with the group. Students quickly learn that they have more to offer in class discussions if they take this advice, and by comparing informal assessment with test scores it is clear that group discussions inspire individual reflection and learning after the fact as students seek to fill knowledge gaps.

Important concepts are reinforced through submission of individual responses to the discussion questions that were discussed in class in groups. By requiring individual responses, students practice forming and communicating their own ideas in a written format. Points for the discussion Q&A assignment are awarded based on the depth of their answers and the use of findings from literature as supporting evidence. I regularly provide constructive feedback to these responses to encourage additional learning and to reinforce creative interdisciplinary ideas as appropriate.

The ethics reflection assignment at the end of the course is especially compelling for the students. In this assignment, they have more range to answer a set of questions about requirements for responsible conduct of research and regulatory compliance. Students are not graded on their ethical framework, instead they are graded on their ability to draw from literature and to use established guidelines to craft their responses. The ethics reflection assignment helps students see themselves as science professionals who must safeguard the use of genomic and synthetic biology technologies to improve society in a responsible way.

Figure 8. Photo illustration of individual problem-solving and reflection to enhance retention. Students must integrate facts, tools, and approaches from multiple sources to build their own knowledge framework. The new, more complex framework, is applied to propose hypotheses, evaluate, and analyze data, and develop new understanding. Knowledge mastery and retention are checked through regular informal and formal assessments. Photo: https://ctl.byu.edu/sites/default/files/Critical%20Thinking%20WEB.jpg.

5.7 Presentation

Communicating science, both one's own research and the research being done by others, is an important skill for everyone in a STEM career (5). Students in BIOC934 practice giving a PowerPoint presentation to the class on a primary research article of their choosing (**Figure 9**). The papers have been pre-selected by the instructor to serve as fertile material in terms of use of interdisciplinary concepts, tools and approaches and they all have ample figures, tables, and other supplementary material to give a well-rounded presentation. After a random draw, each student has an opportunity to choose which paper they will present. Students are graded according to a rubric that assesses the quality of the slides, the amount of material, and the confidence of the speaker. Full points are awarded to those students who: produce well-organized presentations with clear slides, show a stated hypothesis, use a variety of data types, images, videos, give sufficient detail about techniques used, correctly critique and assess the data shown, and who integrate additional papers from the related field to give a broad context for the work. Points are awarded based on what is delivered and the quality of the presentation with no requirement for mastery of the English language. I have observed that non-native English speakers have developed effective strategies for delivering excellent presentations by preparing early and by writing out key ideas as speaker notes. There is no correlation between native language and presentation grades awarded.

Figure 9. Photo illustration of peer presentations. Students learn and retain more information when they are expected to teach the material to peers. Peer presentations also provide opportunity to practice public speaking skills essential for careers in STEM. Instructor feedback is provided on slide design, presentation skills, and technical content. Photo: Getty Images/iStockphoto.

5.8 Assessments

Informal and formal assessments are used to gauge student learning, tailor instructor-student interactions, and adjust course delivery in real-time (**Figure 10**). A variety of assessment formats are used to provide opportunities for success regardless of a student's preferred learning style (15). Activities and assessments reinforce student learning by iteratively cycling through conceptual theory and practical performance assessments.

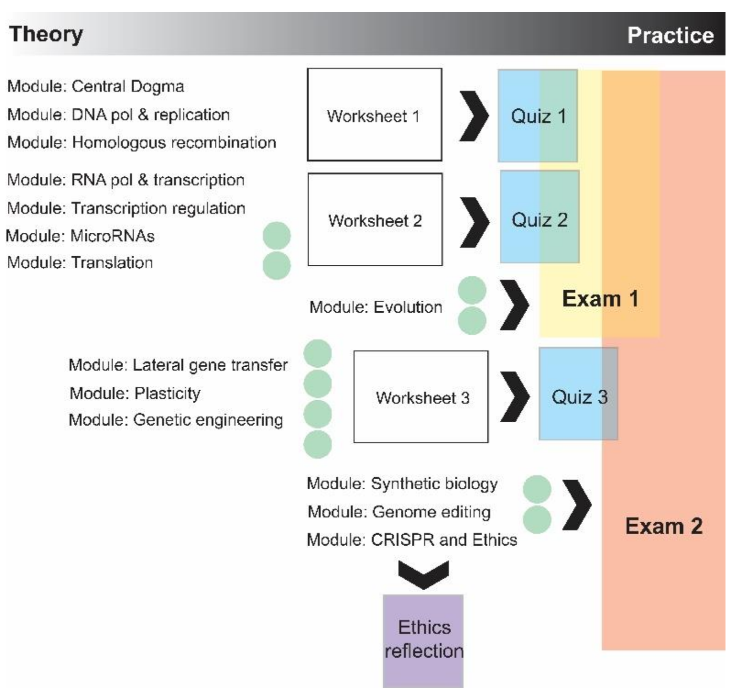

Figure 10. Diagram of how class activities, informal and formal assessments reinforce theoretical and practical knowledge. Informal assessments are shown in white boxes. Formal assessments are shown in color. Green circles indicate student presentations.

Informal assessments are continuous through classroom discussions in pairs, small group, and whole group formats (10). During class discussion sessions students are randomly assigned into groups of 2-4. Small groups collaborate to answer the discussion questions that were provided by their peers.

The quality and depth of the questions posed by peers serves as an informal assessment metric of prior knowledge. Points for the assignment are awarded based on whether the assignment was completed and whether they reflect the fact that the reading was done beforehand. This is done to encourage questioning regardless of question type. For example, I want students to ask questions about technique as well as about the conclusions drawn by the authors. If grades prioritize the type of questions, students will avoid asking lower-point questions even if they would benefit from exploring a topic in greater depth. Therefore, to validate the student's search to fill their own knowledge gaps I do not prioritize the points awarded. However, I do look at the questions as barometers that indicate whether class discussion needs to be guided in such a way as to re-teach or reinforce certain concepts. For example, if questions are mostly about a specialized technique, I may guide the class to look for additional literature that describes development of the technical approach in question and focus on the strengths and limitations of the technique. Alternatively, the questions can indicate that students need to be guided to think more interdisciplinarily about the paper being discussed. In this case I will ask small groups a certain "What if" question and then give each small group an opportunity to share their responses with the larger group to arrive at a class-wide consensus.

Group discussions are also in important avenue for informal assessment. As the small groups debate responses to the discussion questions posed by their peers, I visit each group in turn to check in with them. During this more personal interaction, I observe who is more confident and who is less so; who has prior experience about a topic; which students are encouraging of their peers; and I observe individual work ethic and engagement. I find that students are more willing to ask basic background questions in these small groups and are more comfortable admitting when they don't know something. I use this as an opportunity to re-teach missed concepts and to guide students to where they can find supplementary information. These small group interactions are valuable to encourage correct thinking or problem-solving approaches and have the effect of increasing student engagement with the material being learned. Each small group is then asked to report their findings and ideas to the larger group. Reporting out gives each student an opportunity to act as the speaker representative and thus helps them to become familiar with an informal leadership role. As they report to the larger group, I am assessing their ability to listen to their peers, identify key components, summarize discussion, and integrate ideas into the overarching topics being discussed.

Worksheets are a set of take-home problem sets that cover each course module and serve as the basis for the quizzes. Worksheets are not graded but are used as a performance-based informal assessment. Students can work through the worksheet problems individually and with their self-selected peer group outside of class over a two to three-week period. As such, students can use the worksheets to focus their attention to key concepts or techniques that are being covered alongside the discussion papers. Before the quiz, we dedicate a class period to discussing the worksheets in randomized small groups where I informally assess the preparation of each student for the test. When I identify gaps in concept or practical application of theory, I use worksheet assistance as a vehicle to re-teach material and to reinforce the need for additional study effort in preparation for the quiz.

Figure 11. Photo illustration of student assessments. Formal and informal assessments are used to evaluate student learning. Quizzes and exams were previously delivered in-person on paper. Since 2020, they have shifted to using Canvas. Photo: https://www.cem.org/blog/7-questions-you-need-to-ask-about-assessment.

The formal assessments emphasize the ability to apply concepts and techniques to form/revise hypotheses, analyze data, and arrive at reasonable interpretations. Formal assessments are structured such that they require little to no rote memorization (indeed, as quizzes and exams are open book) but emphasize concept application, data analysis, problem-solving, hypothesis generation, and technical troubleshooting that are similar to situations that occur in a life sciences research laboratory. Designing formal assessments in this way ensures that students perceive them as a high-value performance assessment rather than a low-value assessment of recall ability (16). While the quizzes and exams have similar question formats as on the worksheets, the exact questions are not identical. For instance, a worksheet might ask students to design a plasmid that will integrate onto an *E. coli* chromosome. A related but not identical question on an exam may be to ask the student to describe how they may transfer a hypothetical enzyme function to a heterologous host microbe and to show all the required cis and trans genetic elements necessary using a case study “story”. Question formats also include multiple-multiple choice, data prediction, data interpretation, drawing, troubleshooting, and short answer formats. Using different question formats gives students with different learning styles and communication strengths and opportunity to demonstrate mastery of the subject material (8, 14).

6.0 Course materials

Course materials chosen to benefit students at every level of development. Whenever possible, materials are multimedia to engage a variety of learning preferences (**Table 2**).

Table 2. Student learning preferences mapped to course materials and activities.

Learning preferences	Course material	Class activity
Aural	Videos	Lecture, discussions
Logical	Textbooks, primary literature, lecture slides, technical bulletins	Discussions, discussion Q&A, worksheets, quizzes, exams, ethics reflection
Physical	Textbooks	Presentations (delivery), Discussions, worksheets, quizzes, exams
Social	Opinion articles	Presentation (delivery), discussions, discussion Q&A, worksheets, ethics reflection (thinking)
Solitary	Textbooks, primary literature, lecture slides, videos	Lecture, presentations (preparation), discussion Q&A, ethics reflection (writing)
Verbal	Videos	Presentations (delivery), discussions
Visual	Textbooks, primary literature, lecture slides, videos	Lecture, presentations, discussions, quizzes, exams

6.1 Suggested textbooks

There are two recommended textbooks for BIOC934 (**Figure 12**). Entry-level students who may not have taken or retained undergraduate molecular biology find that the popular textbook "***Molecular Biology***" by Craig et al. (17) provides and in-depth comprehensive foundation, while experienced students are familiar with the text (as they are likely to have used it previously) and find it to be a useful reference. Advanced students who are ready to consider molecular phylogeny and statistical analysis of biological data more deeply are served by Eugene Koonin's book "***The Logic of Chance: the nature and origin of biological evolution*** " (18), which is an excellent inspiration for undertaking big-picture research projects that push the frontier of what is knowable and what is possible to achieve with Biology. This text traces theory, development, and application of bioinformatics to understand patterns in evolution at the molecular genetic scale. Suggested textbook readings are indicated on the syllabus to supplement lectures and presentations. Examples and figures from both books are used in lectures to provide background information. Throughout classroom discussions these texts are referenced as a resource to find foundational primary literature and review articles.

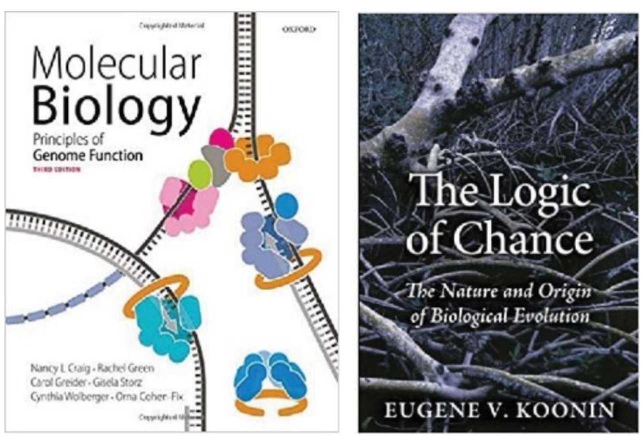

Figure 12. Recommended textbooks for BIOC934.

6.2 Videos

Lectures and presentations often include videos that illustrate key concepts in molecular biology such as DNA replication, CRISPR, homologous recombination, transcription, translation, etc. Videos are provided as part of the recommended textbook (17), and I encourage students to use curated videos from STEM educational institutions (universities, philanthropic foundations), that can be accessed on YouTube or on publisher or research laboratory websites. Using videos whenever available helps more visual learners to build mental models to reinforce concepts and aids in content retention (11). Although many of the students have seen some of these videos before as part of previous courses in molecular biology, it is helpful to revisit familiar material from an interdisciplinary lens. For instance, videos of DNA replication may have been previously learned from the perspective as molecular machines. In BIOC934 we go into greater depth to critically evaluate this analogy by considering where and how metabolism or environmental factors affect function of the replisome, or how researchers would engineer the replisome to achieve greater fidelity and how that may affect evolutionary trajectory of the organism lineage. This iterative refinement of previously introduced models improves concept learning and retention (9).

6.3 Lecture slides

Lectures, slides, and transcripts are recorded and made available as study guides. Slides contain figures, tables, and videos with reference citations to integrate required and recommended materials with each topic module. Providing these materials through Canvas allows students who have missed class due to illness, inclement weather, or conference attendance an opportunity to access content asynchronously and stay abreast of coursework upon their return to in-person class. They are also useful study guides for completing course worksheets and preparing for quizzes and exams.

6.4 Primary literature and review articles

A set of high-impact primary publications form the bulk of the course material. These are chosen for their conceptual impact, the broad-reaching scope of the research questions being addressed, the interdisciplinary nature of the techniques applied to the research question, the quality of the writing and logic, the abundance of figures and supplementary data (often including multimedia) available. A second cohort of primary articles are provided as reference material to support and supplement discussion papers and course modules. Required primary literature reading is indicated in the syllabus and serves as the basis for presentations and other assignments. Articles to be discussed in class are continually updated, with older manuscripts being “retired” to the reference folder, while current publications are added to the syllabus rotation. Recommended reading is provided in a separate Canvas file folder and are meant to supplement the required readings. As such, quizzes and exams are not directly related to any material in the recommended readings.

6.5 Opinion articles

An aspect of graduate training that can be challenging is the questioning of whether one’s research is important to society or will have impact in society. In my experience, every graduate student will struggle with existential questioning at some level while in graduate school. They may also wonder why their graduate program or thesis committee insisted they take BIOC934 instead of giving them more time in the lab. To reinforce the social need for acquisition of genetics and molecular biology knowledge, I use popular science articles from verified journalistic sources as supplementary reading. These readings are occasionally included in lectures and in discussions but are not formally assessed. Topics which students find valuable perspectives include prebiology, origins of life, astrobiology, and the risks and benefits to genetically modifying plants, animals, and humans. The popular debate is used as a springboard to understand federal funding trends, federal compliance regulation, and to form hypotheses and design experiments to address concerns of the public in class discussions.

6.6 Technical bulletins and US Federal Reports and Statutes

In addition to primary research articles and opinion articles, I provide the students with publications and reports from professional societies and U.S. federal agencies. These readings are incorporated into lectures and discussions. They also serve as curated reference material for the Ethics module and the ethics reflection assignment. One question at the end of Exam 2 awards bonus points for correctly identifying when a researcher should notify the institution when designing an experiment involving genetically modified organisms. Graduate students are aware that they must follow university biosafety and responsible conduct for research guidelines, but they are often unaware that these policies are derived from U.S. federal law. By providing relevant technical bulletins from professional societies, they make the connection that professional scientists participate in drafting guidelines that eventually become policy. In this way they learn the role of each person in maintaining responsible and ethical use of the research they are learning about in class and which they are doing in their research labs. While discussing the literature I briefly introduce the concept of using their graduate degrees in non-traditional STEM careers or for future public service roles.

6.7 Assignments

Assignments are designed to involve individual and group work, in-class as well as take-home, and involve multisensory components as much as possible. Lectures and textbook readings serve to remind and orient students to framework concepts, while classic and recent primary literature serves to provide material to identify gaps in knowledge, learn how and why interdisciplinary tools and techniques are used to address the research questions, and to serve as the inspiration for subsequent experiments. Small groups or pairs of students cooperate to form discussion questions relating to each paper that are then used as the basis to explore gaps in knowledge and to practice synthesizing concepts from new and prior knowledge. As the course progresses the class format is increasingly “flipped” where each student is tasked with presenting the primary research articles to give them an opportunity to practice oral/visual presentation skills and inspires them to delve more deeply into the topic through literature searches. For the past two years I have assigned students to also answer the discussion questions as an individual take-home assignment in which their answers must be supported by primary literature beyond the assigned manuscript. This reinforces the concepts discussed as they practice advocating for an experiment or interpretation. For each module I have developed take-home worksheets that reinforces key skills and give students an opportunity to practice experimental design and troubleshooting. The worksheets are not graded and can be done individually or in groups. They are discussed in class right before the quiz so that students can co-teach, and concept mastery is informally assessed and corrected as necessary by the instructor. Rubrics and credit points are provided upon assignment for each graded activity.

7.0 Assessments

Informal and formal assessments of various formats are used to gauge concept mastery throughout the year. **Figure 13** shows the assessments, points, and grade point distributions according to the course syllabus. As the course is discussion-based, informal assessment occurs continuously. This is where the soft skills which are essential for success in the workplace are modeled and trained. The environment should be encouraging, non-judgmental, and collaborative while at the same time must result in a rigorous critical evaluation of data, interpretations, and ideas. It is essential that students feel comfortable proffering ideas and conjectures. Small groups are rotated continuously and randomly to give each person an opportunity to work with each other as pairs and in groups of varying sizes (up to whole-group discussions). By tracking student participation, I ensure that each student is contributing to pair/group assignments and to the whole-class discussions that I moderate. Participation in small groups is ensured when visit with each group to answer or pose questions. Students are also called on to answer questions in small group settings or report back to the whole class after pair or small-group discussion. Through the discussion sessions I model the formation and honing of hypotheses by offering extreme or fantastical-seeming ideas that we then winnow down as a group to identify missing information and ultimately reach a viable testable hypothesis with several experimental objectives to pursue. As I write this passage it occurs to me that one aspect of the class that could be improved is to visually diagram this process for the students to show them explicitly what is pedagogically happening during these discussions. I will discuss this more in ***Future Plans***.

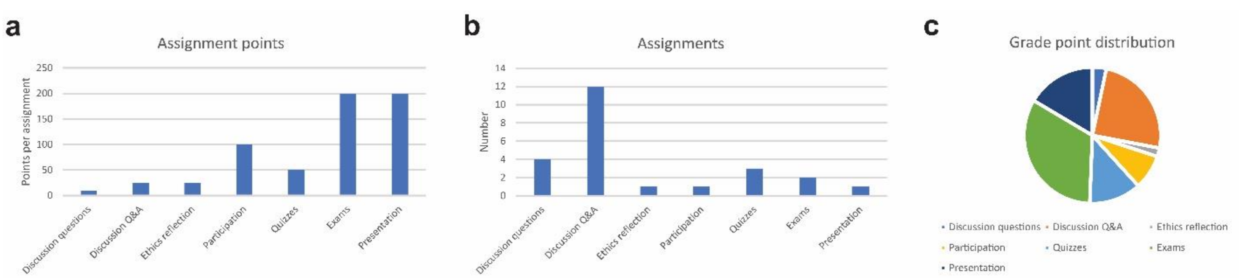

Figure 13. Assessment tools and point distributions. Panel a, point values for each submitted assignment. Panel b, number of each assignment type. Panel c, distribution of total points by assignment type.

Formal assessments include presentations, discussion questions and responses to those questions, an ethics reflection, quizzes, and cumulative exams. Grades are assigned according to the published rubric and when points are deducted, detailed feedback and suggestions for improvement (including reference to primary literature and course materials) is provided. I also use a strategy of randomly shuffling submitted work and grading anonymously whenever possible to limit any bias that may occur due to grading or submission order, time of day, outside distraction, etc. Rubrics are used for all formal assessments to ensure grading equity; these can be found in the **Appendices** of this portfolio. Details of each of the formal and informal assessment tools are provided below.

7.1 Class participation

Class participation is worth 100 points in the class. Points are awarded based on quality of engagement in class discussions as gauged by taking the initiative to ask and answer questions both in smaller groups and in whole group discussions. Points are subtracted if students exceed the attendance requirements of the course (more than two absences per semester). Typically, all students are awarded 100% possible attendance points. This high level of attendance and engagement indicates that the students find the course to be valuable for achieving their own educational and career goals. Student feedback indicates the class environment is supportive, stimulating, and rigorous.

7.2 Presentations

Presentations are delivered as 45-minute PowerPoint presentations worth 200 points. Students select the paper they will present after a random order drawing on the second day of class. Students have access to all papers through Canvas and have full knowledge of where each paper is in the syllabus, how it is related to each instructional module, and hence when the presentation will occur. This allows students to plan their schedules to take experiments and course load burdens into account. Allowing them to select the paper they present gives them the opportunity to choose a subject area that they have previous familiarity with or that they wish to delve more deeply into. The minimum time to prepare a presentation is three weeks and there is no correlation between grades awarded and placement in the syllabus. Points are awarded according to a defined rubric that assesses depth of background and content delivered as well as oral and visual presentation skills.

7.3 Discussion questions

Discussion questions are formulated by pairs of students who are randomly assigned to each group and each paper. The five questions are compiled and distributed before class using Canvas. Thus, each pair must carefully read the papers ahead of time and arrive at a consensus set of questions that are clear, thought-provoking, or challenging, and which they think distill the main takeaway messages from the paper being discussed. Points are awarded for timely submission of the five questions (10 points per set of five for a total of 40 points). At this stage I do not evaluate the questions themselves, as my intent is to encourage students to ask questions that they find to be useful and compelling. For example, if points were subtracted for asking basic technical questions, I would run the risk of sending the message that students are punished for asking these types of questions when it could very well be a point of confusion for them. This scenario would be opposite of the interdisciplinary and creative problem-solving discussions graduate students should be having.

After class, students are given 48 hours to submit their individual written responses to each of the five discussion questions up to two pages in length. The Discussion Q&A assignment (25 points) gives students practice in communicating their ideas using supporting evidence from literature. Points are awarded based on the depth of answers provided, demonstration of concept mastery, and use of supporting evidence. Points do not depend on language proficiency. In addition to point grades, I provide feedback as additional questions or corrections as needed. By holding students accountable to what was retained from the class discussions, Discussion Q&A assignments have increased engagement across all papers and has elevated the quality of student interaction with the class materials. Students appreciate the opportunity to assess their own learning progress in preparation for quizzes and exams.

7.4 Worksheet discussion

Worksheets are practical exercises that serve as the basis for quiz and exam questions that reinforce the learning objectives of each instructional module. In 2021 semester (shortened due to COVID), three worksheets were provided. Each worksheet is comprised of 10-12 questions arranged by concept module and discussion paper. Worksheets assess quantitative and visual skills as they include drawing figures, calculating probabilities and the like. Worksheet questions include a variety of question and answer (Q&A) types, from multiple choice to pictorial to short answer. Questions are designed to reinforce techniques and concepts that were directly discussed in class or presented as part of a discussion paper and to inspire development of more in-depth knowledge through literature searching. Hypothetical research case studies are used in each module to develop hypothesis-testing and troubleshooting skills.

Students find the worksheet assignments to be a very useful informal self-assessment tool. Worksheets are not submitted for a grade, but they are discussed in small groups and as a class. Students who may struggle to communicate their questions and ideas verbally nevertheless may show mastery at communicating visually, for instance. Using a variety of Q&A modes allows me to assess their skills, gives them feedback on where to study more intensely, and gives them confidence that they understand concepts and can apply them to research situations even as they develop a professional vocabulary.

7.5 Quizzes

Quizzes are approximately 10 questions and is designed to be completed in one class period (75 minutes). Quizzes are worth 50 points each. In 2021 semester (shortened due to COVID) there were three quizzes for a total of 150 points. Each quiz covers one class module, and while they are not cumulative, key concepts are iteratively reinforced. When delivered through Canvas, students have 75 minutes to complete the quiz but have opportunity for multiple attempts to account for internet connection issues. Using Canvas to deliver quizzes has not resulted in significant changes to test scores as compared to previous years when the quizzes were delivered in-person on paper. Grading for quizzes is done by rubric with partial credit breakdown. Instructor comments are provided for missed questions so that students can use these as study guides for exams.

7.6 Exams

Exams are cumulative ~15 question assessments that focus more on story problems that assess each student's ability to form and test hypotheses, design experiments with proper controls, troubleshoot unexpected results, make predictions, analyze, and interpret data. Each Exam is worth 200 points, for a total of 400 points in the class. Students are given one day to complete the exam. Exam questions use hypothetical examples based on actual situations which allows for an open-book format while providing a better assessment of the ability of students to apply their knowledge to new and unfamiliar scenarios. Grading for exams is done by rubric with partial credit breakdown. Instructor comments are provided for missed questions on Exam 1 so that students can use these as study guides for the final Exam 2.

7.7 Ethics reflection

The ethics reflection is an individual writing assignment due during the last week of class that gives students an opportunity to reflect and summarize ethical considerations that arise with synthetic biology research. Students write a two-page essay for 25 points that answers the following questions:

> ***Topic: What should scientists do to regulate synthetic biology research to protect public safety?***
>
> ***a. When is regulation necessary?***
>
> ***b. How do we decide what to regulate? What should be regulated?***
>
> ***c. Who should regulate?***
>
> ***d. What are the appropriate punishments for infractions?***

e. Who enforces the regulations?

Grades are awarded according to a rubric that rewards use of literature references to support answers. References may include the curated compendium of class materials, but students may also include other primary or technical literature based on their independent research. The instructor provided feedback when necessary. Feedback is solely constrained to discussion of pro and con arguments, the use and interpretation of references, and to the quality of the writing. Grades and instructor feedback are not influenced by any personal ethical judgements expressed by the student.

8.0 Integration between assessments and course goals

The formal assessments are designed to map directly to the course goals. **Table 1** above shows which assessments measure progress for each goal. The following provides additional details about how formal assessments are integrated with course goals.

8.1 Goal 1: Identify overarching hypotheses from a body of primary literature

Lectures, presentations, and class discussions all begin with identifying one or more hypotheses being tested in a field of study and by the authors of papers we are contemplating. If hypotheses are not explicitly stated in their presentations, they will lose grade points on the assignment. Discussion Q&A assignments regularly have questions that relate hypotheses tested across papers, and full points are awarded for answers that include reference citations from the work performed by different research groups. Quizzes and Exams include questions that likewise ask students to explain, compare and contrast the evidence for support of hypotheses from multiple papers that were read by the class.

8.2 Goal 2: How to design interdisciplinary experiments

Discussion Q&A, Quizzes, and Exams include questions that require students recall methods and technologies from a variety of disciplines. For instance, discussion questions often ask for detailed description on the strengths, weaknesses, and uses of a wide variety of techniques such as total internal resonance fluorescence microscopy, single molecule force measurements, computational fitness modeling, bioinformatics algorithms, genetic crosses, and transduction, among many others. Quizzes and exams assess the ability of students to correctly propose, predict, and troubleshoot using the techniques discussed in class to answer case study questions.

8.3 Goal 3: Identify major in gaps in logic or a lack of support for a hypothesis

Most of the class time is dedicated to poking holes in primary research papers and weighing evidence. While the discussion sessions are informally assessed, the Discussion Q&A assignments are used to formally assess how well each student has internalized the information and their ability to clearly and succinctly communicate where a lack of experimental support for a hypothesis exists and how those gaps could be addressed. Student presentations also include their own independent evaluations of the papers they present, and points are deducted if this is omitted. Quizzes and Exams include questions that use case studies where students must correctly identify where a hypothetical researcher's technique, data interpretation, and conclusions have gone awry. Full points are awarded if students identify the fallacy and propose a correct modification.

8.4 Goal 4: Be comfortable giving and receiving critical ideas to test hypotheses

As part of the classroom discussions, students receive participation points for demonstrating a willingness to engage in constructive criticism of papers and each other's ideas in a collegial atmosphere. This is formally assessed in the Discussion Q&A assignments when students write out their critiques. Class presentations must include critique of the paper being discussed for full points. Grades on quizzes and exams indirectly reflect the ability of the students to internalize the feedback of the instructor and peers from discussions and assignments as they adjust their previously held conceptions in favor of the new knowledge they are gaining. The ethics reflection assignment provides students an opportunity to critique responsible conduct in research policies and compliance regulations. Full points are awarded for ethics reflections that are thorough in their criticisms and use appropriate references to support their claims.

8.5 Goal 5: Draw from a broad familiarity of genome dynamics and gene expression mechanisms across all known kingdoms of life

The module topics and primary literature intentionally include research done on a wide variety of systems, from pre-biology, viruses, bacteria, archaea and eukarya (single- and multicellular plants and animals). As naturally follows, the presentations and discussion Q&A assignments award points based on the student's knowledge of genetics and gene expression mechanisms across all domains of life. Quizzes and Exams include compare/contrast questions that require students to understand the differences and similarities (or unknowns) between major classes of organisms and viruses. These questions can be in the form of multiple-multiple choice, illustration, or case studies.

9.0 Analysis of student learning

Student learning is continually analyzed to adjust the rigor and expectations of the course to benefit high-ability learners as well as to identify those who may be struggling. Assignments and quizzes are graded typically by the next class period, at most within the week following the due date. This allows me to assess student learning on a real-time basis, provides maximum opportunity for me to adjust lectures and classroom activities, and for students to meet with me to correct misconceptions.

Figure 14 shows the average grades awarded for each assignment during the 2021 class. While there is an undulating pattern that can be seen in the quality of responses to answers to the discussion questions for each paper, the average grades are not significantly different. In my experience, the course grades correlate loosely with Spring Break and exam schedules as students juggle several courses in addition to research. While most assignments are written and could be assumed to disadvantage non-native English speakers, use of a rubric to assess ideas, and use of literature to support ideas and conclusions results in no correlation between grades and native language. Likewise, presentation grades reflect amount, content, and delivery of material to the class that is independent of native language. All written assignments are submitted through Turnitin to assess plagiarism. Interventions that involve personally contacting the student (to remind about a late submission) or the Graduate Chair or PI is only rarely necessary. These indicators show that the course expectations are generally at the appropriate level and rigor for the students to manage.

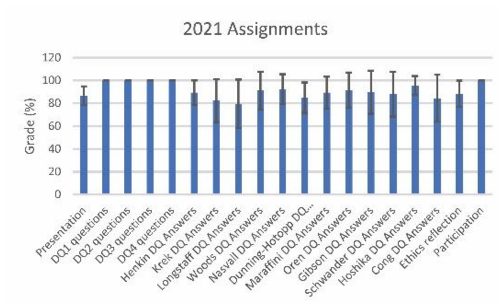

Figure 14. Analysis of grades awarded for each graded assignment in 2021. DQ: discussion questions. Each bar represents the average class grade. Error bars indicate standard deviation. Error bars are not applicable for DQ question assignments or Class participation because all students received 100% available points over the semester. Classroom size = 9 students.

Quizzes are a useful way to gauge learning, retention, and ability to synthesize concepts in a short timescale. In 2021, timed quizzes were delivered using Canvas. Students had one hour to complete the exam with unlimited tries. Each quiz covers a specific course module that includes lectures, presentations, worksheet-related problems, and readings. **Figure 15a** show the quiz results from 2021. After each quiz, I assess grade trends to determine whether students are improving (**Figure 15b**). When grade decreases are identified I adjust the class lectures and discussions to give more attention and opportunities for learning to the students. Occasionally it is necessary to have a "recap" discussion to re-teach a concept when quiz answers were confused or did not have the depth I expect from graduate students. These recap discussions occur immediately following the quiz at the next classroom opportunity. Positive trends in quiz scores indicate that quizzes are effective means of providing skill-based assessment feedback that students use to improve the depth of their learning for each module (**Figure 15c**).

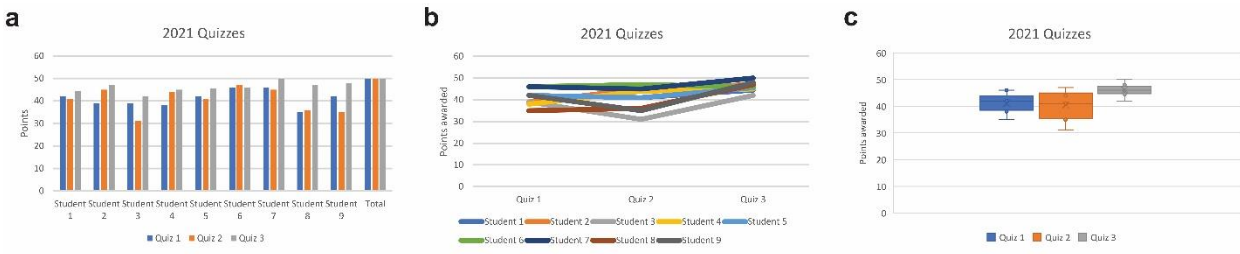

Figure 15. Analysis of student performance on quizzes in 2021. Panel a, points awarded for each quiz by student as well as the total possible points available. Panel b, trend lines plotting grades received by each student over time. Panel c, Box plot showing mean, median, quartile, and outlier point distributions of the class for each quiz.

Exams are cumulative. Students are given 24 hours to complete each exam over Canvas. The same process I use to analyze quiz grades are used to evaluate performance on exams. **Figure 16** shows the exam grades awarded to each student (**Figure 16a**), the trendline (**Figure 16b**), and the grade distribution in 2021 (**Figure 16c**). Exam score trends indicate that by Exam 2, students are acclimated to the test question types and have a good understanding of the grading rubric (**Figure 16b**). Exam 1 scores show a wider distribution that Exam 2 scores, however the average score for Exam 2 is higher (**Figure 16c**). These results are taken to indicate that overall Exam 2 is more difficult than Exam 1 (as expected), but that middle- and lower-performing students at mid-semester are able to significantly raise their grade in Exam 2 at the conclusion of the semester.

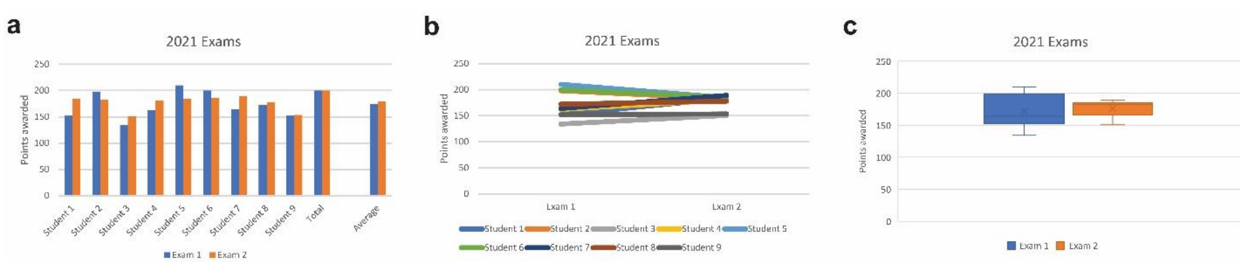

Figure 16. Analysis of student performance on exams in 2021. Panel a, points awarded for each cumulative exam by student as well as the average points awarded. Panel b, trend lines plotting grades received by each student over time. Panel c, Box plot showing mean, median, quartile, and outlier point distributions of the class for each exam.

At the end of the semester, I assess test mastery to determine if there appear to be any concerning trends in the student learning trajectories due to test format (**Figure 17a**). This analysis shows most students had a relatively neutral response to the quiz format and had scores that varied by only a point (out of 50 points per quiz, for a variance of 2%). Exam score trends varied by 7.5%. Two students had positive trends in both quizzes and exams, indicating that 2 out of 9 students developed highly successful test preparation strategies. Two students had score decreases in the Exams but had positive scores for quizzes indicating they were more comfortable with assessments that captured fewer concepts and required test focus over a shorter duration. Four students did better on longer-form exams than quizzes, with one student showing a strong preference. One student had negative trends in both quizzes and exams, however their quiz score was close to neutral suggesting that they weren't able to acclimate to the quiz format and struggled a bit with Exam 2. I was happy to see that no students showed significant decreases in both quizzes and exams during the semester which could suggest they require additional support for success in graduate school by this albeit limited metric.

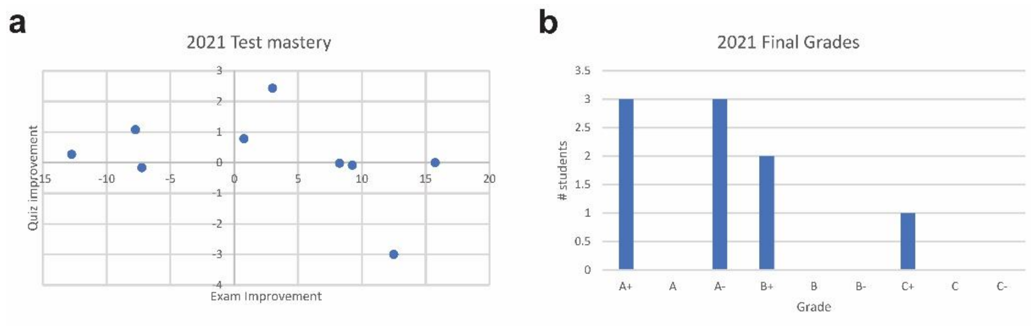

Figure 17. Correlation analysis of test mastery and final letter grades awarded in 2021. Panel a, trendline slopes of quiz grades are plotted against trendline slopes for exam grades to identify correlations between performance on quizzes and performance on exams. Panel b, Final grades awarded in 2021.

Overall class points were used to assign final grades as shown in **Figure 17b**. Three students had high marks in assignments and tests and earned A+ grades. Another three earned A-, and two students earned B+ grades. While quiz and exam grades were generally quite good, one student struggled with meeting expectations for work assignments. These issues pulled down their earned total points and as a result they were ultimately given a C+ for the class.

Upon completion of a semester, I also compile historical trends to evaluate whether course expectations and student performance has remained consistent even as individual assignments or test questions change every year. **Figure 18a** shows the grade distribution each year. While grade distributions vary depending on cohort, the total average distribution of all students over time has an average of 88.7% with a uniform distribution. **Figure 18b** shows the letter grades awarded each year. Note that the students each semester ranges from eight to thirteen, with a total of 104 students having taken the class since 2012 (average of 10.4 students per semester). The letter grade distributions are shown in **Figure 18c**. Grade distributions fluctuate as the cohort size changes from year to year, however the distributions of the cumulative awarded grades are evenly distributed. 64.4% of students have received an A- or above, 32.7% of students have received a B- to B+, and 2.9% of students have received a C+ or below.

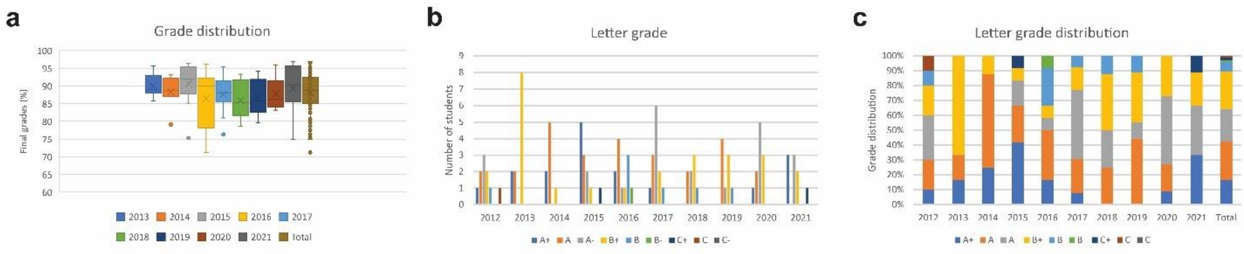

Figure 18. Historical analysis of student learning in BIOC934. Panel a, Box plot showing mean, median, quartile, and outlier final grade distributions of each class. 2012 data is not available as we transitioned from Blackboard to Canvas. Total = 94 students. Panel b, Class letter grade distributions by year. Panel c, Class letter grade distributions expressed as percentile populations to show overall performance trends. Total = 104 students.

10. Summary

Overall, BIOC934 has been a popular class with graduate students from across life sciences programs. In addition to the 4-6 graduate students form the Center for Biological Chemistry program, many students have taken the class upon recommendation by peers who had taken the class in previous years. Thesis committees have recommended it based on its emphasis on critical interdisciplinary thinking and substantial presentation and writing components.

10.1 Successful aspects of the course

10.1.a. Lectures and presentations

Instructor lectures do not make up a majority component of BIOC934, although key lectures are included at the beginning of the class to provide base level familiarity with key concepts and to provide a review for more experienced learners. By giving the first few lectures, I model my expectations for interdisciplinary thinking, creative questioning, and problem-solving approaches that students then emulate when they give presentations on discussion papers. Overall "role modeling" class expectations are an effective way to encourage student learning. Instructor lectures are increasingly supplanted by student presentations. Lecturing is then only used to fill knowledge gaps, to re-teach when necessary, or to briefly review before exams.

The student presentations maintain the class flow but shifts the mantle of "expert" to the students. Students relish this aspect of the assignment as it gives them an opportunity to practice presentation skills and it drives them to read and research topics more deeply than reading and discussion alone. The student presenters have "ownership" of the topic. Because they self-selected their paper, they are maximally engaged in the presentation topic. modeling by instructor, then practice. As a result of presenting, students show marked confidence and respect for the insights of their peers. Seeing students develop their confidence is extremely gratifying.

10.1.b. Worksheets

Worksheet assignments have been very successful in helping students practice using the knowledge they have learned in class. Worksheet questions assess how well students can apply concepts to real-life and hypothetical situations. Students gain confidence in using knowledge to solve a concrete problem by developing an experimental plan to address hypotheses and honing their troubleshooting skills. By having the worksheets be ungraded, the worksheets are not perceived as a competitive graded assignments and students are more comfortable asking questions and collaborating to solve problems together. As a result, they all learn the material better and they individually feel more prepared for quizzes and exams. I regularly receive feedback on student evaluations that they value the worksheet assignments.

10.1.c. Interdisciplinary team learning through class discussions

One signature aspect of the course is that there is no prerequisite besides graduate standing. Therefore, BIOC934 attracts a breadth of life sciences trainees from computer science, agronomy, biochemistry, and others. Students also take the course at different stages of their graduate program. The Biochemistry students take the class in their 2nd semester of their first year while students from other programs have taken the class in their 2nd or 3rd years. Rather than viewing the disciplinary variety and the variance in bench expertise of my students as a challenge, I have leaned into this diversity as a source for collaborative interdisciplinary learning. The result is a rich classroom experience that prepares students for future careers where they are expected to contribute among professionals with divergent expertise to solve shared problems. Students share their unique experience and perspectives to help the class arrive at deeper understanding about techniques, tools, and experimental systems. As a group, the class practices creative problem-solving across traditional disciplinary boundaries. BIOC934 encourages asking ambitious research questions and hypotheses, and helps students build collegiality and cooperativity in group problem-solving and idea-testing. The disciplinary diversity represented in the classroom drives students to delve more deeply into the literature and concepts so that they contribute to the conversation and so that they can communicate with peers of a different background. The result is that each BIOC934 class becomes a learning community where everyone helps (and challenges) each other to grow as researchers.

10.2 Limitations of the course

One challenge in teaching BIOC934 is the resistance of students to engage in team-based learning. For the first few years of teaching, I would receive student feedback that many preferred a full traditional lecture course. Student feedback indicated they wanted a more passive experience where "correct" answers are provided by the instructor and assessments reflected rote memorization. Some students found it difficult to transition to graduate coursework expectations where they are expected to critically analyze and evaluate research and to demonstrate ability to form open-ended hypotheses and to design experiments to test those hypotheses (without actually doing them). It can be very uncomfortable for students to adjust to courses in which knowing a concept alone is not enough; they are graded on ability to apply concepts and on their quality to communicate ideas. Through the years I adjusted the class to include more lectures, more types of performance-based assessment (worksheets, adjusted quiz and exam questions), and more individual written assignments (discussion Q&A) to provide familiar learning content cues while still maintaining the demand for rigor. In the past three years the requests for more lectures have almost been eliminated and student feedback has been increasingly positive. I have also been frequently approached by senior graduate students who admitted they didn't appreciate the class much when they took it as a first year but have since come to see BIOC934 as a transformative class in their development. While I have confidence that the methods and content of the class are appropriate and valuable, I am always trying to help the one or two students each semester who struggle adjusting to a different class format than they are used to and to higher graduate-level expectations.

10.3 Future Plans

Every year I refine BIOC934 to incorporate student feedback and to keep abreast of research advances. Discussion papers are curated each year to refresh with new primary literature while maintaining the module topics to increase engagement while continuing to conform to ASBMB recommendations. I am always looking for improved videos or other multimedia components to assist students with learning and engagement. In the past I have experimented with social media, using game theory, and building physical models; while these learning approaches are popular for undergraduate learners, graduate students soundly rejected these activities. I have found more success orienting the class goals and activities towards professional development and interdisciplinary teamwork. I will continue to find new ways to connect what we learn in class with future career responsibilities and expectations.

At the request of students through the years I have integrated more textbook material to provide students who do not have as strong of a molecular biology background a better on-ramp so we can have deeper synthesis, hypothesis-testing, and troubleshooting discussions. I have also included more lectures throughout the years. This year I included recap lecture/discussions and I integrated the recommended textbooks into the lectures more thoroughly to help students see that the concepts have a strong theoretical anchor that the primary literature is built upon. For the past two years students have not requested more (or fewer) lectures, and it is possible I have found a good balance for the course. I plan to monitor student needs and adjust the lecturing up or down as needed to ensure learning goals are achieved.

I have also increased the quantity of instructor feedback on assessments. Doing so has been appreciated in subsequent student responses and contributes to improvement in assessment scores over time. I will continue to provide encouraging feedback as often as possible to help students achieve their potential.

Based on past student feedback I began requiring written responses to discussion question with literature citations just this past year. Surprisingly, the drastically increased workload (for an already intense class) resulted in an increase in student engagement and satisfaction. I plan to monitor whether the workload continues to be appropriate and adjust as needed.

The most substantial change I plan to incorporate for 2022 is to work with students to visually diagram our learning process. Producing this portfolio has given me the epiphany that while I have created a structured iterative process to identify hypotheses, map concepts, analyze data, critique arguments, and evaluate new knowledge before adoption, I have never formally communicated my pedagogical method. I am personally a highly visual learner; one of my weaknesses as an instructor is that I forget students may struggle with creating their own multi-dimensional mental maps and models. It occurs to me that visually showing students how I do this may help them “learn how to learn” interdisciplinary concepts more effectively. I plan to test whether creating a flow chart tool and using it during class will help them get more learning out of the discussion sessions. Perhaps the interactive tool will help students collate facts and ideas to produce a tangible study guide to complement the worksheets. Having a physical product of class discussions may also increase engagement and ultimate satisfaction for the overall course. I look forward to exploring this possibility in 2022.

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12. Appendix

Appendix 12.1 – Schedule and Syllabus
Appendix 12.2 – Presentation Discussion Schedule
Appendix 12.3 – Literature critique guidelines
Appendix 12.4 – Class recording weblinks
Appendix 12.5 – Presentation tip sheet
Appendix 12.6 – Example presentation
Appendix 12.7 – Presentation grading rubric
Appendix 12.8 – Discussion question assignment
Appendix 12.9 – Example discussion question and answer
Appendix 12.10 – Worksheets
Appendix 12.11 – Worksheet re-teach discussion
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Appendix 12.13 – Exam preparation discussion
Appendix 12.14 – Exam1
Appendix 12.15 – Ethics reflection assignment
Appendix 12.16 – Example ethics reflection