Physics and Applied Physics
Program Self-Review (Draft)

January 6, 2024

1 Overview of the major

Questions: What are the Program Learning Outcomes identified for this major? What is the role of this major in undergraduate education on the campus, i.e., how does the major contribute to the undergraduate educational mission of the campus? Is the major clearly distinguished from other similar majors on campus?

The Department of Physics and Astronomy, and our majors, play a vital role in the undergraduate education mission of the campus. Ours is an ancient discipline, and much of the undergraduate program is spent learning theoretical and experimental physics from a hundred years ago or more. Yet these ideas and concepts remain highly potent in the modern world, and equally challenging and rewarding to master. While studying fundamental physics concepts, our students are exposed to the latest cutting-edge research and concepts concerning the physics of the small (nuclear processes, atomic structure, particle searches, and cellular processes) and the large (dark matter, dark energy, cosmology). Our majors are trained in the techniques of experimental physics, and we have recently dramatically expanded our training in computational physics.

We are in the process of updating our undergraduate curriculum, as described below. The catalog description of the major provides an accurate overview of the program, and the proposed undergraduate curriculum update includes changes to the catalog to maintain its accuracy under the new program.

Our department is distinguished from other departments in the cluster by the requirement of the most vigorous introductory physics courses, a diverse upper-level curriculum that develops physics concepts which appear nowhere else on campus, and a vigorous and sustained emphasis on fundamental concepts and analytic thinking. The program learning objectives specific to our major are described in detail below.

Undergraduate Curriculum Update (UCU): The physics department, led by the undergraduate curriculum committee, has been developing over the past five years an update to the undergraduate physics curriculum. The proposal was subjected to an extensive vetting process that involved assigned department readers who were not involved in formulating the initial plan. The proposal was unanimously supported by the department in a December 2021 vote. All new and modified courses have been approved in the UC Davis Integrated Curriculum Management System (ICMS). We are working toward final approval, by campus, of the proposal during AY 2023-2024.

The proposed changes to our program reflect three main observations about our current program:

- Workload over four years of study was imbalanced, with too few physics courses in the sophomore year, and too many in the junior year.
- Integration between transfer students and four-year students, who have somewhat different backgrounds, needed to be improved. Our recent departmental Climate Survey confirmed this by showing a huge satisfaction gap between the groups.
- The curriculum did not reflect the explosive growth in computational methods and their applications.

There are many other aims of the update, but these are the primary motivations.

The proposed undergraduate curriculum update will be widely referenced throughout this document by the acronym UCU. The proposal itself is far too ponderous of a document to include as an appendix here. It will be provided as a stand-alone file. The latest version of the proposal is also available for download online[1].

Program Learning Objectives (PLOs): Although we did not use the specific term PLO[2] in that document, these objectives were carefully considered as part of the development of the UCU (see Sections 4-6 in particular).

There are a number of objectives that are both widely applicable and central to the discipline of physics, most of which are reinforced in nearly every physics course that our majors take:

- Using logic and analytic reasoning to make predictions.
- Applying general principles (e.g. conservation of energy, symmetry) in specific situations.
- Testing results using dimensional analysis and limiting cases.
- Dividing complex problems into manageable steps.
- Establishing feedback to determine if something is working or not.

The next set of objectives is related to mathematical preparation:

- Understand the theory and practical application of differential, integral, and vector calculus, linear algebra, ordinary and partial differential equations. (MAT 21ABCD, 22AB, and PHY 104A.)

While these concepts are first introduced in those courses, they are continuously reinforced throughout the major. The second set of objectives are related to theoretical physics, students are expected to acquire a working knowledge of the theory and practical application of the following core topics:

- Classical Mechanics (9A/9HA,105AB): the fundamental principles of physical laws (e.g. least action and symmetries) are taught in a familiar and intuitive context.
- Electromagnetism (9C/9HD,110AB): a remarkable special case of classical phenomena that anticipate non-Newtonian physics (e.g. special relativity, gauge theories). No other force in nature can be understood so completely in such a straightforward fashion.
- Quantum Mechanics (9HC/9D,115AB): the rules governing the microscopic world are different from those governing our familiar macroscopic world. The rules are not intuitive but they can be codified and used to make quantitative predictions which can be experimentally verified.
- Statistical Mechanics (9HB/9B,9D,112): the crucial statistical explanation for how microscopic laws ultimately produce the macroscopic world which we inhabit.

A major focus of the curriculum update has been to devote more course work to computational physics.

- Develop programming skills sufficient for tackling problems from computational physics (PHY 40,45)
- Apply the techniques of computational physics to problems from theoretical physics (PHY 110L, 112L, 115L).

[1]See https://github.com/mulhearn/classwork/blob/main/curriculum/curriculum.pdf (click for link) and use the download option from the pull down menu to view the entire document.

[2]We prefer to use the word objectives over outcomes, as outcomes could be accidental, whereas objectives are intentional. Fortunately, they both have have the same acronym.

Our current programming tool set includes Python (first encountered in PHY 40) and C/C++ (first encountered in PHY 45) but these may tools may evolve over time. The next set of objectives are related to experimental physics:

- Learn how to conduct and report scientific experiments (PHY 80, 117, 118, 122A/B, 157).
- Gain practical hands-on knowledge of lab equipment, electronics, and technical trouble- shooting (PHY 80, 117, 118, 122A/B, 157).

The objective is for students to apply what they have learned previously to advanced specialized topics such as nuclear physics, particle physics, condensed matter, and astronomy. We refer to these courses as capstone courses:

- Demonstrate mastery of physics by applying it to advanced topics (PHY 129AB, 130AB, 140AB, 151-158).

2 Outcome of Previous Program Review

Please list the recommendations made at the conclusion of the previous review (these may have been made by the review committee, Executive Committee and/or Dean) and comment briefly on the current status of the matters noted in the recommendations. Discuss any other significant changes in the major since the last review.

The committee report of the Undergraduate Instruction Program Review (UIPR) and the Review Team Report from the previous review are included in the appendix. These reports were a source of motivation for the UCU described above, particularly in the specific cases noted below. The reports identified strengths in our program, which we appreciate, but in this overview, we will address only the identified weaknesses:

- **Space, Lab Conditions and Maintenance:** the review team was concerned that the undergraduate lab space was "shabby and in need of renovation". Within the UC, the cost of building renovations is shockingly expensive[3], and the university funding available for renovations is limited. Fortunately, we have received vigorous support from campus with several sizable grants for both equipment and renovations, for which we are deeply appreciative. This issue is discussed in more detail below (Section 4).

- **Transfer Student Readiness:** the review team was concerned that many incoming transfer students were not prepared for a physics major, and were dropping out or changing major at a high rate. Following the recommendations of the review team and committee, we began selective major review in time for academic year (AY) 2021-2022. The department has since seen a substantial drop in transfer enrollment at a level that we find potentially troubling, if it persists. This is discussed in more detail below (Section 5: Students in the major). **Improving the experience for incoming transfer students was a major focus of the UCU.** By ensuring transfer students are retained, we hope to mitigate the loss of initial enrollment.

- **Computational Instruction:** The review team noted that programming course work students were taking outside of the department was not adequately training our students in computational physics. **Expanding the role of computational physics in our major was a central focus of the UCU** and we have added to our curriculum several new required courses focused on computation physics. This is described in more detail below (Section 9: Major strengths and weaknesses).

- **Academic Advising:** The review team noted low satisfaction with campus and department advising. In this report, we note that student satisfaction with advising has improved. The likely contributions to this improvement, as well as some lingering concerns, are described below (Section 6: Student perceptions of the major). The size of our undergraduate program has increased by 50%, but we still have only one undergraduate advisor.

- **PHY 122: Advanced Physics Laboratory** the review team was concerned that students were generally poorly prepared for this upper division lab course. Following the recommendations of the committee, we have introduced a new course (PHY 80: Experimental Techniques) as a prerequisite for PHY 122. **As part of the UCU, PHY 80 is now a required course**

[3]Even by the standards of cost-of-living-numbed California residents

for all physics majors (not just those taking PHY 122). This is discussed in more detail below (Section 9: Major strengths and weaknesses)

- **PHY 157:** The review team noted that demand for PHY 157 is greater than it's capacity. Regrettably, and despite diligent effort by Prof. Tucker Jones in particular, we have struggled to maintain the same level of throughput in this course, due to the retirement of the previous instructor. The practical challenges here and future plans are discussed below (Section 9: Major strengths and weaknesses)

- **Communication Skills:** The review team reported anecdotal evidence of student dissatisfaction with the level of development of skills in writing and oral presentation. As currently taught, upper division physics lab courses (PHY 157 and 122A/B) satisfy the upper division English composition requirement (WR104E) for which we have recently sought approval English Language and Literacy Committee. We discuss this issue, along with related concerns about creativity and qualitative reasoning, in more detail below (Section 6: Student perceptions about the major.)

We have taken the concerns raised during the previous review quite seriously, and have made as much progress as we could manage, to the clear benefit of our department, especially our students. We therefore look forward to a fruitful collaboration during this review as well.

3 Faculty in the major

Questions: Who does the bulk of teaching in the major? What are the demographics of instructors in the major? Will the program be affected by substantial changes in the faculty (e.g. anticipated retirements) in the next review period?

This section refers to tables which are available in the Appendix. We use a compact notation, where, for example, [B3] refers to Table 3 in Appendix B. The program was provided with an explicit list of items to discuss. To increase readability, we discuss the salient issues in the most natural order first. At the end of this section, we include a "Discussion Checklist" which indicates where each discussion point was covered, using the original enumeration (a-e) of topics provided in the original prompt. We have omitted the original prompt to increase readability. TODO: copy to other sections as needed.

Our teaching responsibilities are evenly shared by the faculty, and the demographics of our course instructors largely reflects the demographics of our faculty. A long period of limited hiring has put the department in an uncomfortable position: new hiring is not keeping up with retirements and the size of the faculty is shrinking. This contraction is occurring when the number of physics majors, and demand for introductory physics courses by non-majors, are both increasing.

Rank and Age of Faculty: There are clear trends revealed in [B1-2]. The Physics department faculty is significantly older than the the average for the College of Letters and Science (L&S), and the size of the faculty is shrinking. These trends are correlated: retirements are out-pacing new hires. While these numbers do not reflect our most recent hires (Profs. Matthew Citron and Nancy Arggawal) this has not been fast enough to avoid a shrinking department. Retirements have also left us with no LSOE (i.e. Teaching Professors with ladder-rank) faculty at present.

A significant obstacle to hiring at an even faster rate is the availability of startup funding. Under the current budget model, the physics department will struggle to maintain a pace of one hire per year, a pace which would lead to size of the physics faculty shrinking further.

Diversity, Inclusion, and Equity: The data provided in [B3-5] is incomplete, so we will address the topic of diversity of the faculty in purely qualitative terms. Most importantly, our faculty is overwhelming supportive of taking strong measures to improve the diversity of our faculty within the limits of what we are legally allowed to do. We are not looking for quick and easy fixes. Instead, we have been studying and adopting best-practices in hiring. For example, our two most recent faculty searches were intentionally broadened in scope, as this has been shown to increase the diversity of the applicant pool. As another example, we have started providing zoom interview questions in advance, as well as more details about the interview process in general, because evidence shows that members of URGs are systematically disadvantaged when such details are assumed to be already known. As is often the case when adopting best practices, we found that these steps have also made the interview process better overall. For example, when provided with the questions in advance, applicants gave better, more thoughtful, and more useful responses. This remains an urgent issue, and there remains much to be done here.

Discussion Checklist: (a-e) Discussed above [B1-5].

4 Instruction, advising, and resources in the major

Questions: How effective is the delivery of instruction in the major? Are faculty engaged in the major? Is advising adequate? Is there adequate staff support? Are adequate space and facilities available? Is the program keeping pace with developments in the field? Are grading standards appropriate? What is the role of virtual and hybrid courses in this major? Please attach or include here a sample 4 year graduation plan for your program.

Our highly-engaged faculty is dedicated to delivering effective instruction to our students, and we adhere to rigorous academic standards with respect to grading. While we do face challenges from limited resources, overall we find that advising, staff support, space and facilities are all adequate for our purposes. In the sections that follow, we attempt to provide evidence to support this bold assessment, as well as call out areas where we hope to do better than "adequate". Undergraduate physics is largely focused on the cutting-edge theoretical physics of a hundred years ago or more. Yet we do stay relevant in the modern world: those old ideas remain challenging to master and highly potent to cutting-edge applications. Our multi-year continuing commitment to the UCU is strong evidence that we continue to innovate. One exception: outside of emergencies, we have no plans to include virtual or hybrid courses in our program, as we have found, for our discipline, that no reasonable amount of effort can produce such a course which is as effective as learning in person (See Section 12). Sample four-year graduation plans (as well as two year plans for transfer students) are provided for every major and specialization, in the UCU. See Table 6 in that document, for one example[4].

Grading Policy: The grade distribution in [B12] shows that physics (and chemistry) are grading significantly more strictly than L&S overall, which is a conscious decision on our part. Our adherence to rigorous academic standards adds significant value to the physics degree, and to physics course work in general. For example, our top students are regularly accepted into top graduate programs, likely in part because the A's they receive in our courses represent a meaningful accomplishment. We are concerned about the ability of UCD to continue as a forefront research institution and engine of social mobility if the grade inflation that we see in L&S overall is allowed to continue or accelerate. Our students are at a disadvantage for receiving graduation honors because the thresholds are set unachievable high due to grade inflation elsewhere. In the College of L&S seniors are permitted to do an Honors thesis if their GPA falls in the top 16% (Currently 3.846). Less than 8% of our seniors typically fall above this overall GPA, or less than half the overall number.

Instructors: Our department prioritizes providing physics majors with ladder faculty instructors, particularly for upper-division course work. The student FTE per faculty FTE is increasing [B6]. This is the result of both an increase in the number of physics majors and a decrease in the number of faculty. Despite the challenges from a shrinking faculty, physics majors are being taught by ladder faculty [B9-10] for 90% of their upper division course work, a larger fraction than any other L&S department considered this cycle. They are being taught by ladder faculty for 58.5% of their lower-division physics course work, also above average for L&S.

For introductory physics course work, we also utilize the highly-effective pedagogy of Continuing Lecturers. Dr. Dina Zhabinskaya manages the PHY 7 series (introductory physics aimed at

[4]We can update this report with one example included here if requested.

bioscience) and Dr. Weideman manages the PHY 9 series (introductory physics aimed at natural science and engineering). They are both deeply committed to innovative pedagogy, are great assets to our department, and regularly share their wisdom with the rest of the faculty. We regularly hire Unit-18 pre-Six Instructors (temporary lecturers) as well. Some of our graduate students are interested in more extensive teaching experience than typical TA assignments afford, and, when we believe they are up to the challenge, we also hire Associate Instructors to teach in PHY 7 and 9.

Staff Support: Physics is a unique discipline with its own unique culture, and we are profoundly grateful to the staff members that work alongside us to maintain it. (TODO: Discuss with Tracy how we would like to describe the adequacy of staff support overall, Mike can meanwhile describe the key players in instructional support Richards comment about same number of advisors.)

Instructional Space, Equipment, and Facilities: While total assignable space has increased [B11], it has not been faster than the number of student FTEs has increase. The overall amount of assignable space is above average for L&S, but this reflects our need for dedicated laboratory space, and large lecture halls adjacent to demonstration support. As discussed in Section 2, the previous review noted a deficiency in the condition of the lab space used for undergraduate instruction. Fortunately, we have received vigorous support for acquiring new instructional equipment and renovation of lab space. (TODO: get detailed list from Tracy, e.g. 122 renovations, new computing room, equipment grants, computing lab, etc.)

Collaboration with other programs: Physics (like Mathematics) is a foundational discipline for most Science, Technology, Engineering, and Math (STEM) disciplines. Nearly every STEM discipline trains its students in our introductory physics courses. Physics itself is a rather unique discipline, and we have little competition from other fields to consider. Instead, we focus on collaboration, which is much more useful. We have a wide range of applied physics majors which afford students the opportunities to study complementary specialized topics (e.g. computer science, atmospheric science) outside of the department. The UCU strengthens those majors by affording more flexibility with a more expansive list of specialized courses to choose from. Our new course work in computational physics (particularly PHY 40: Introduction to Computational Physics, a course with no college-level prerequisites) focuses on the bare minimum of programming techniques necessary to tackle challenging physics problems (See Section 9). It moves quickly from "introductory programming" to "computational physics". This makes the course highly complementary to course work in the Computer Science and Engineering department, and the markedly different emphasis may be of interest to other disciplines as well.

Discussion Checklist: (a) Discussed above [B6]. (b) According to table [B7] only about 70% of students enrolled in upper division physics courses are physics majors. We suspect this is inaccurate, most likely double majors are not being handled correctly. But we would certainly be delighted if 30% of our upper-division students were from other majors! (c) There is an expected increase [B8] in the number of TAs that resulted from new courses, particularly PHY 80, PHY 40 and PHY 45, which require significant TA support for lab sections, as well as the addition of discussion sections to some core upper division courses. (d-e) Discussed above [B9-10]. (f) Discussed above (Instructional Space, Equipment, and Facilities) (g) Discussed above [B12] (h) Discussed above (introductory remarks) (i) Discussed above (Staff Support) (j) Staff advising is discussed in Section 6 (Academic Advising). (k) Discussed above (Instructional Space, Equipment, and Facilities) (l) Discussed above (introductory remarks) (m) Discussed above (Collaboration with other programs) (n) Discussed above (introductory remarks).

5 Students in the major

Questions: This section is intended to characterize the students in this major. How have enrollments in the major varied over the period of the review, in terms of both the numbers and quality of the students? Are students succeeding in the major both in terms of qualitative and quantitative academic standards? Are students graduating on time? Are there impacted classes (e.g., with limited offerings or long wait-lists) or other bottlenecks that unnecessarily impede student success? How do students find out about the major? Is the major reaching a wide and diverse spectrum of students? Are students who enter the major retained in the major, and if not, why not?

As described in detail below, during this review period, the undergraduate program has grown in both size and diversity. We believe there is strong demand by students for excellent physics programs, and by employers for those we train. With sufficient resources, our department could grow further to meet that demand. We hope that we continue to grow in Diversity as well. By most of the measures of student academic achievement which we consider below, physics students are performing just slightly below the average for L&S, which is a notable accomplishment given that physics courses are graded significantly more stringently than L&S on average. The most concerning metrics are a dramatic drop in transfer student admissions to eight total in AY 202-2023, and a four-year time-to-graduation for 73% of physics majors, which is significantly lower than for L&S overall (85%). The UCU includes a number of changes to our program, including the removal of bottlenecks, that we expect to impact these and other metrics. However, it is too soon to judge their efficacy. Looking at the available metrics all together, we see that our program is successful at attracting, retaining, and graduating students.

The primary source of information about our major is the department website, the UC Davis course catalog, and the undergraduate academic advisor. We do considerable outreach with our students to keep them on track. This is all discussed in more detail in Section 6 under "Academic advising".

Size of the undergraduate program: The number of physics and applied majors has been growing, as the result of a mutual agreement between the university and department to begin admitting about 50% more students into the program starting in AY 2019-2020. This amount was targeted as the maximum number of additional students that physics could handle without the need for additional lecture sections in core physics courses. This increase is the main trend evident in [B13] and [B17]. Taking applied physics and physics together, the number of international students in physics [B25] has increased by roughly 25%, consistent with the increase in L&S. To accommodate the increase in the number of students, we added TA-led discussion sections to some of the upper-division physics course courses, which is something physics majors had been requesting even before the class size increase. These tables also put the ratio of applied physics to physics majors historically at 1:2, but of late the share of applied physics majors appears to be growing.

Diversity of physics majors: Combining physics and applied physics majors, the fraction [B15] who are women has increased just slightly during the review period, while the fraction of women in L&S overall has decreased by about 3%. Again combining physics and applied physics majors, the fraction [B16] who are from underrepresented groups (URGs) has increased from 14% to 19%. When the number of majors is accounted for, the increase in the number of women is not statistically significant, but the increase in the number of students from URGs is statistically significant.

Double majors and minors: There has been a noticeable increase in the number of physics majors who are double majors [B14] but the rate is still lower than the average for L&S. This lower rate is the combination of unit caps on the amount of total course work a student can take (imposed by L&S) coupled to the hierarchical structure of most science disciplines. In our experience, double majors in physics have little flexibility left in their schedule to pursue other interests and electives, so we generally do not advise them. We do heartily encourage minors, but yet few physics majors complete one [B24].

Transfer students and their experience: As discussed in Section 2, the previous review was concerned that a large number of incoming transfer students were not prepared for a physics major. Following the advice of the review committee, the department started selective review of transfer students in time for AY 2021-2022. Our hope is that by selecting students that are more likely to succeed as physics majors, we will continue to graduate transfer students as physics majors at approximately the same rate, while dramatically reducing the number of students who drop out of the program. A major focus of the UCU was improving the experience of transfer students, by leveling out their course work in the first year to avoid a "brick wall" of intense course work that previous students faced in their first quarter. It is too early the judge the effectiveness of any of these changes.

Omitting AY 2020-2021 from consideration due to the pandemic, we see that since AY 2021-2022 there has been a significant drop [B18] in the number of new transfer students, the result of a drop in applications and the tighter admission requirements of selective major review. Prior to selective major review, in a typical year we would have 120-130 applicants. Of those accepted, typically 30-35 students would start as physics majors, but typically only 10-12 would remain as physics majors past the first year. In recent years, applications have fallen to as low as 90 students, and typically about 75% of student pass selective major review. In AY 2022-2023, we had about eight new transfer students [B18] but in AY 2023-2024 (not in the appendix data set), we had 13 new transfer students. Assuming that selective major review allows us to retain those students, we should not reduce the number of transfer students that graduate as physics majors.

A significant number of transfer students in applied physics and physics require an additional year to graduate: only 22% of applied physics majors and 41% of physics majors graduate in two years as intended [B22]. This is significantly lower than 64% for L&S overall. Improving this experience for transfer students was a major focus of the UCU.

It is too soon to draw any conclusions about the changes to our program that we have made which impact transfer students. However, we have made a request for reports of additional metrics pertaining to transfer students. We plan to scrutinize these statistics to judge the impact and efficacy of these changes to our program. We are also considering outreach to community colleges to boost the application rate. These considerations fall within the scope of our departments DEI efforts as well, as many students from URGs access the university through their community colleges. It is vital that we maintain a viable path for transfer students through our program.

Student Academic Performance: The average GPA [B19] of physics and applied physics majors is around 3.2 but varies as lows as 2.8 and as high as 3.3 depending on the class and major. This is slightly lower than the average for L&S (3.3). This likely reflects the fact that physics majors take more physics courses, which we have already established are generally graded more stringently than courses from other departments in L&S. In [B20] we see qualitatively similar results with respect to the fraction of students in good standing, which ranges from 79% to 94% depending on the class and major, and is slightly lower than L&S overall. We see a slight increase in degrees conferred [B21], for both physics and applied physics majors. When the data for AY 2023-2024 are available, we should start to see an increase due to the larger number of physics majors.

Looking at time to graduation [B23] for students that remain physics majors the entire time, we see that 83.3% of applied physics majors and 72.7% of physics majors graduate within four years as planned. That rate for physics majors is significantly smaller than the average for L&S (84.5%). This is integrated from 2016 to 2022, which makes it somewhat difficult to interpret. We should monitor this metric over the next few years to see if there is a persistent problem here to address. We do expect that time-to-graduation for nominal four-year students should decrease as a result of the changes in the UCU, which includes changes that remove stalling out of four-year students in their sophomore year. But it is too soon to judge the efficacy of these changes.

Discussion Checklist: (a-m) Discussed above [B13-25] (n-o) Discussed above (introductory remarks).

6 Student perceptions of the major

Question: What are current students' and recent graduates' opinions of the major?

Our students' opinions of the physics and applied physics majors are for the most part consistent with college averages, within the limited statistics available from survey responses. In the discussion that follows, we note some areas of encouragement and concern, and include anecdotal data where pertinent.

Interpretation of student feedback: Soliciting feedback from students is a useful and important diagnostic tool, but the results must be carefully interpreted. We know that student evaluations reflect significant implicit biases[5] and are strongly correlated with student perceptions of their course grades. For example (referring [B12] and [C29]) we are not surprised to see that a department which is an outlier with respect to grading (85% of letter grades are A's) is also an outlier with respect to student satisfaction with faculty instruction (88%). In the physics department, 33% of letter grades are A's and student satisfaction (amongst junior and senior physics majors) with faculty instruction is a more modest 67%. We should not conclude that the other department is performing any better (or worse, for that matter) than the physics department, only that our approaches are different, likely reflecting the different needs of our students.

Limited Statistics from Alumni Responses: We also need to be careful not to draw sharp conclusions from samples with limited statistics. There were few responses collected from physics alumni: three from applied physics majors and 17 from physics majors. We have carefully checked all of the alumni responses [C12-22], [C31-36], [C41-43], and [C49-54]. Amongst the questions, the only ones which yielded a statistically significant deviation from the college average were:

- Questions [C18], [C21] and [C22] none of which we found to be illuminating.
- Questions [C31] and [C32] where we do see (borderline) statistically significant dissatisfaction with the grading system and use of information technology.
- Question [C43] which references peer advisors, which we do not have in physics.

Maximizing Statistical Uncertainty from Student Responses: To maximize the sample size from current students, we have included all years in the survey result (the default results include only juniors and seniors). We have also computed a weighted average of the responses from both applied physics and physics majors. This combined sample has a size of N=61 (with a slight variation from question to question that has been neglected from our analysis) from which we estimated a naive binomial statistical uncertainty. The results are reported in Table 1.

Understanding of the major: Using the combined survey results in Table 1 we see that understanding of the major [C1], program requirements [C2], program policy [C3], and accuracy of the catalog [C4] were all comparable to the L&S average, with the last two being low by about one standard deviation. Even though there is therefore no statistically significant evidence to support the claim, we do suspect there may be some student confusion in the context of the UCU. For

[5] See, for example: Kreitzer, Rebecca J. & Sweet-Cushman, Jennie. Evaluating Student Evaluations of Teaching: a Review of Measurement and Equity Bias in SETs and Recommendations for Ethical Reform. Journal of Academic Ethics 20 (1):73-84 (2021).

Table 1: Survey results from Appendix C, using results from freshman through seniors, combining results from physics and applied physics majors. The sample size is N=61 from which a binomial statistical uncertainty has been calculated. Results as a percent are organized by question (Q) and the results for physics and applied physics majors (Physics) are compared to the College (L&S).

Q	Physics	L&S	Q	Physics	L&S	Q	Physics	L&S	Q	Physics	L&S
C1	90 ± 4	91	C5	55 ± 6	64	C23	53 ± 6	76	C38	55 ± 6	52
C2	91 ± 4	90	C6	71 ± 6	74	C24	84 ± 5	68	C39	56 ± 6	47
C3	79 ± 5	85	C7	57 ± 6	60	C25	84 ± 5	73			
C4	89 ± 4	93	C8	78 ± 5	79	C26	82 ± 5	76	C44	46 ± 6	37
			C9	30 ± 6	46	C27	48 ± 6	61	C45	52 ± 6	56
			C10	68 ± 6	69	C28	39 ± 6	49	C46	41 ± 6	54
			C11	69 ± 6	69	C29	52 ± 6	66	C47	55 ± 6	59
						C30	75 ± 5	61			

example, we have begun teaching newly approved courses, even though they are not yet required by the major, as the UCU has not yet reached final approval. We have done our best to communicate the situation to our students, and we are encouraging them to take the new courses even though they are not required yet. We would not be surprised if some confusion exists in this context. We plan to complete the approval process and make the necessary catalog updates as soon as possible, at which point we are confident that any confusion will begin to dissipate.

Satisfaction with major: Using the combined survey results in Table 1, we see that the responses from our majors regarding fair treatment [C6], faculty access [C7], ability to get into major [C8], library resources [C10], and overall satisfaction [C11] were all consistent with college averages within statistical uncertainty of the survey sample. As discussed above, there are no statistically significant results from the alumni survey that warrant further discussion.

Our majors were less satisfied ($30\% \pm 6\%$) than the college average (46%) with respect to [C9] "Education enrichment programs". In the current program, it is nearly impossible for our majors to study abroad, which likely contributes to the observed student dissatisfaction. In the UCU, four-year students have sufficient flexibility that more students may find it feasible to study abroad. The department does provide other sources of education enrichment, such as student research, and it would be illuminating to probe student satisfaction with specific avenues of enrichment.

Our majors were less satisfied ($55\% \pm 6\%$) than the college average (64%) with respect to [C5] the "faculty being open to discuss students' needs, concerns, and suggestions". Even though this is just barely more than one standard deviation from the college average, it is disappointing to learn that so many students feel this way. This is something we should consider as a faculty.

Satisfaction with Instruction: Using the combined survey results in Table 1 we see that our majors believe plagiarism is not being adequately explained [C23]. We encounter plagiarism most frequently in physics courses through the use of online websites, such as Chegg, to provide answers to homework questions. There is growing evidence that using sites such as Chegg for cheating expanded during the pandemic and hasn't receded. We wonder if the low score here is reflecting student and faculty disagreement as to what constitutes plagiarism, or, conversely, if it indicates students' concerns that we are not doing enough to discourage and condemn this relatively new form of cheating. Clearly more discussion between students and faculty is needed about cheating.

The results of [C24-26] show that students believe they are well practiced in recalling, explaining, and analyzing concepts, methods, and ideas. However, when it comes to qualitative judgment [C27] and creativity [C28] physics majors reported lower than average practice, which we discuss further below.

Our majors are quite well satisfied with their TAs ($75\% \pm 5\%$) compared to the college average (61%). This is heartening, if not surprising. TA's are most often cast in roles which directly support students, helping them work through their homework problems in discussion sessions, for example.

Satisfaction with faculty is lower ($52\% \pm 6\%$) than the college average (66%). This is concerning and warrants a closer look at the data. If we consider physics majors only, and restrict ourselves to junior and seniors. we we see 67% are satisfied with faculty instruction, just a bit higher than the college average. Further investigation confirms that the heightened dissatisfaction comes from two contributions: current freshman and sophomores, and all applied physics majors.

One major difference between applied physics and physics majors is the amount of course work that is taken outside of the department. We are well aware of the frustration that applied physics majors are facing in completing their course work outside of physics. Perhaps part of the dissatisfaction stems from this. The UCU aims to give applied physics majors more flexibility which we hope will improve this situation. In any event, it is clear that additional outreach with applied physics majors and physics majors in lower division courses is needed to determine the root causes of this elevated dissatisfaction.

Academic Advising: The satisfaction of alumni with advising was all consistent with the college average, within the statistical uncertainty of the sample. The only exception was a question regarding peer advising, which the physics department has just recently begun providing. Amongst our majors, using the combined sample of Table 1, we see that students are satisfied with the quality of academic advising ($55\% \pm 6\%$) slightly higher than the college average (52%) and with access to academic advising ($56\% \pm 6\%$) higher than the college average (47%). Only the latter is (borderline) statistically significant.

These results are encouraging. As discussed in Section 2, low satisfaction with advising was noted by the previous review. We believe we understand the source of the improvement, based on our own anecdotal data from individual student interactions. Most importantly, Prof. Boeshaar runs a physics career seminar and Prof. Knox runs an alumni speaker seminar. These are not required courses, but the scope of discussion typically extends to academic advising, particularly for subjects that students are concerned about. Secondly, the staff undergraduate advisor, Amy Folz and the vice-chair for the undergraduate program, Prof. Mulhearn, have devised a highly effective triage system, whereby typical issues are handled by Folz, and more complicated problems are immediately kicked up to Prof. Mulhearn. We have found this arrangement to be quite effective. Folz also arranges multiple annual outreach events (pizza nights) which provide a forum for academic advising. Prof. Mulhearn is an annual speaker in the physics career seminar. Lastly, a significant number of students participate in undergraduate research, and research advisors are a natural source of academic advice as well. Our attempts to impose a more top-down assigned faculty advisor had lackluster results, with a clear lack of student and faculty interest, which was compounded by the pandemic. Fortunately, it seems that our more organic, fully optional avenues for academic advising are proving to be effective. Prof. Boeshaar is continuing to play her pivotal role past her recent retirement, but we cannot expect this to continue indefinitely.

Course Offerings: Using the combined data sample from Table 1, we note that our students rated access to small class sizes [C44] higher (46% ± 6%) than the college average (37%). Our students rated the availability of courses needed to graduate [C46] at lower (41% ± 6%) than the college average (54%), and this lower level of satisfaction is present for both physics and applied physics majors. Anecdotally, we are aware that applied physics majors struggle to schedule outside course work. We are addressing this problem in the UCU by increasing the number of choices available to applied physics majors for their course work outside of the department. We are also discussing with the computer science department the possibility to give higher priority to our applied physics (computational physics) majors in their impacted courses. We are also aware that physics majors struggle to schedule advanced physics labs, and we are attempting to improve throughput in these courses as well. We offered a fall section of advanced physics lab for the first time in AY 2023-2024. We have also begun renovations to provide more space, and are adding additional lab modules, toward increasing the number of students in each section. Our students rated the availability of general education courses [C45] and the variety or courses [C47] at levels consistent with the college average within the statistical uncertainty of the sample. The alumni responses were all consistent with the college average within the statistical uncertainty of the sample.

Communication, Creativity, and Qualitative Judgment: Oral and written communication was mentioned as a concern in the previous program review. Our students gain experience in scientific writing by writing lab reports in their experimental physics courses. One area where we could probably add more practice with writing is in student homework. We generally grade homework looking for just enough steps to show the student understood the problem. We could easily assign students longer write-ups for specific problems, in which they would need to explain what they are doing in a clear and concise manner. If done correctly, this might actually make homework easier to grade!

When it comes to oral communication, this immediately runs into several practical challenges. With a throughput of order 60 students per year, even having each student provide a 15 minute presentation would be a commitment of 15 hours: 50% of a standard lecture course. That's a big tine commitment, and one we cannot afford in our core required course work. However, many instructors of upper division specialty courses include oral presentations as part of their curriculum. We also note that students are free to choose about 50% of their undergraduate course work, so they could take "CMN 001: Introduction to Public Speaking" as just one of many possible avenues for gaining additional practice in oral communication.

We saw above that when it comes to qualitative judgment [C27] and creativity [C28] physics majors reported lower than average practice. This is disappointing, if not entirely surprising. A large fraction of the undergraduate physics degree is invested toward understanding well-established theories which more mostly developed a century ago or more. Problems for these theories which have exact analytic solutions are limited and so students invest a lot of time solving problems that have been being solved by students for a century or more as well. This paints perhaps too bleak a picture, as instructors do labor to breathe life into their subjects every quarter, but they are facing strong headwinds, and these results most likely reflect those headwinds. One area of the undergraduate physics degree where creativity and qualitative judgment are more naturally exercised is in computational physics and experimental physics. Here students devise and debug their own code or experimental apparatus, face new problems not constrained to those with exact analytic solutions. It will be interesting to see if the improvements and increased focus on these subjects in the curriculum update will lead to students getting more practice in these topics.

Discussion Checklist: (a-e) Discussed above [C1-52].

7 Post-graduate Preparation

Questions: How well does the major prepare students for postgraduate education and careers? Do the students have opportunities to meet and work with faculty outside the classroom setting? Is there sufficient support for internships or experiential learning opportunities? Are there ample opportunities for students to learn about career options?

Table 2: Survey results from Appendix C, using results from only junior and seniors, combining results from physics and applied physics majors. The sample size is N=37 from which a binomial statistical uncertainty has been calculated. Results as a percent are organized by question (Q) and the results for physics and applied physics majors (Physics) are compared to the College (L&S).

Q	Physics	L&S
C54	60 ± 8	46
C60	90 ± 5	74
C75	49 ± 8	42
C76	58 ± 8	65
C77	62 ± 8	62

Our students' rate their opportunities for undergraduate research [C54] and their plans further academic study [C60] significantly higher than the college average. The difference is large enough as to be statistically significant even considering the limiting sample size of the survey. They rated faculty access (in various ways) [C75-77] as comparable to college averages, within the statistical uncertainty of the survey sample.

Limited Statistics of Survey Data: The limited statistics in the survey data from physics alumni renders [C55-59],[C61-74],[C78-80] of limited use and they are not considered here. Following the procedure of the previous section, we have computer the weighted average of responses from applied physics and physics majors in Table 2. Because these questions pertain to issues that arise later in a typical students career (such as undergraduate research) we have included only juniors and seniors, which limits the sample size to $N = 37$.

Preparation for Workforce: Absent statistically significant results from the alumni surveys, we can consider our own anecdotal data. Many faculty maintain contact with their former students long after they graduate. This keeps us well informed about issues related to workforce preparation. The networks of former students that faculty develop are an extremely valuable tool for helping newly graduated students enter the workforce[6]. A recurring theme is that the advanced labs (122, 117, 118, and 157) were the most valuable learning experience the student encountered. We are optimistic that our investment in computational physics will yield similar feedback in the future.
Discussion Checklist: (a) Discussed above [C54], (b) Discussed above [C60], (c) Discussed above (Preparation for Workforce), (d) Discussed above [C75-77].

[6] In some cases, we have former students interviewing former students!

8 Educational Objectives and Assessment

Question: How does the program monitor and evaluate its success in achieving its Program Learning Outcomes (Section 1)?

The PLOs for our majors are defined in Section 1 along with specific courses which reinforce those objectives. We have not historically hosted these objectives publicly, but as this has been requested as part of the review we are planning to do so. Let's get these hosted PLOs hosted somewhere ASAP.

Responsibility for monitoring the effectiveness of our program at enabling our student to reach these objectives lies with the vice-chair for the undergraduate program and the undergraduate curriculum, in collaboration with the physics faculty. As part of the curriculum update, we have developed a new procedure for continuously monitoring, discussing, and revising the curriculum. Each spring, the undergraduate curriculum committee organizes a faculty meeting devoted entirely to the undergraduate program. The instructors of core undergraduate courses prepare short summaries of their courses, covering how they taught the course, including notable differences from example syllabi which we now maintain, and any observed shortcomings in student preparation from prerequisite courses. If any changes to the example syllabi are needed, the UGCC prepares new versions, and the faculty votes on whether or not to adopt the new versions.

The acquisition of PLOs related to mathematics and theoretical physics are most directly assessed through in-person final exams in core courses (e.g. 104A, 105AB, 110AB, 112, 115AB). The faculty members that teach core courses are generally able to immediately spot short-comings in student progress from the final exam performance. The experimental physics PLOs are assessed mainly through student lab reports. Instructors of PHY 80 have also recently introduced a lab practical examination which we have found to be quite successful.

Professors engaged in teaching our new computational physics courses are learning new pedagogy appropriate to that discipline. We have become quite found of Parsons problems, which have students provide the correct ordering of (scrambled) lines of code, in order to meet a given prompt. Not only are these a fast and practical means for evaluating programming abilities in person, they also train students to "compile in their head" instead of relying (as many new students do) on trial and error. We also evaluate submitted programs, but we are concerned, in the long run, that students might get by on simply copying existing solutions, unless we have an effective means of in-person evaluation.

This self-review is synergistic with the years of prior effort that our department has invested in understanding the performance of our program, and proposing improvements. The strengths and weaknesses we have identified are summarized in Section 9 and our future plans in Section **??**. However, we heartily encourage the reviewers to read through the UCU proposal document. It is rather long, but it represents years of effort on our part.

Discussion Checklist: (a-g) Discussed above.

9 Major strengths and weaknesses

Summarize the major overall strengths of the program as well as any current problems that you perceive.

All happy departments are alike; each unhappy department is unhappy in its own way. Fortunately, ours is a happy department, and so our strengths are those fairly universal ones. We have a collegial faculty that works well together, allowing each faculty member to effectively add their unique talents and interests. Our staff is dedicated and effective. Our students are diligent and inquisitive, and they support one another. They are remarkably empathetic. Together we have built an impressive and productive departmental culture.

Our small class sizes and an active undergraduate research program promote strong ties between faculty and students. Ours students receive a considerable amount of personal attention both in and out of class. We have an exceptionally varied offering of advanced undergraduate specialty courses, the work of a dedicated faculty directed at its students.

Computational Physics: Our curriculum now include a substantial number of required computational physics courses. In PHY 40 (Introduction to Computational Physics) students learn the basics of Python and then move directly into solving numerical and physical problems using computational methods. In PHY 45 (Computational Physics) they are introduced to C++, without much concern for advanced language features, and tackle more advanced physics problems based on their course work in introductory physics. Later, they take 2-3 one-unit computational lab courses, designed to work alongside their upper division course work. Much of the earlier computational physics problems focused on mechanics; now they use computational physics to tackle problems from upper division quantum mechanics, electricity and magnetism, and statistical mechanics. These courses are just the core. As the faculty gains confidence in our students computational abilities, we should see computational physics spread throughout our program. We cannot make every physics major a computer scientists any more than we can make every one a mathematician, but we can make every physics major as effective at solving physics problems with computer programs as they are with calculus.

Experimental Physics: Following the advice of the previous committee, we have introduced PHY 80: Experimental Techniques to better prepare students for the PHY 122A: Advanced Lab in Condensed Matter Physics and PHY 122B: Advanced Lab in Particle Physics. We developed a course that introduces basic laboratory equipment, analog electronics (up to the diode), introductory statistics, experimental uncertainty, and analysis and presentation of experimental data. After learning these techniques, primarily through lab activities, students apply them to the measurement of fundamental constants like the speed of light and Planck's constant.

As part of the UCU, we have made PHY 80 a required course for every physics major (not just those taking 122A/B). We have adjusted the other upper division lab courses to take advantage of it:the 116ABC sequence (Electronic Instrumentation) has been replaced with PHY 80, PHY 117 (Physics Instrumentation with Analog and Digital Electronics) and PHY 118 (Physics Instrumentation for Data Acquisition).The latter two courses can be taken in any order, and are in a nearly continuous state of renewal by Prof. Prebys, in order to take advantage of new technology (such as systems that host programmable digital logic and a CPU on a single chip) well suited for students.

Unlike the the setups for the lab exercises in PHY 80, 117, and 118, which are easily duplicated, each experiment in PHY 122A, 122B, and 157 generally uses a unique custom designed apparatus.

The complicated nature of these experiments also require a lot of personal attention from the professor teaching the course. For all of these reasons, the throughput in these advanced lab courses is limited, and requires precise rationing by the undergraduate advisors to ensure students can finish the course in time to graduate. We are making several changes in an attempt to increase throughput. We taught our first fall section of 122A in 2023, which was feasible as a result of scheduling and prerequisites changes which are part of the UCU. If we add a third 122B section, these changes alone will increase throughput by 50%. However, finding professors that are qualified and willing to teach these extremely demanding courses is a challenge. We have also begun renovations of the first floor of physics, to provide space for additional experimental setups, which should allow us to increase the number of students in each section. However, we must take care not to reduce the amount of personal attention students receive in this lab, or make it even more demanding for the instructors.

The throughput in PHY 157 is even more limited, due to other practical considerations such as the time of year during which weather is favorable for observation, safety concerns which limit the number of people that can be on the roof for observation, and limited faculty qualified to teach the course. With the retirement of Prof. Tony Tyson, Prof. Tucker Jones has been teaching the course, but we have struggled to maintain throughput, let alone increase it. Will the new telescope help with throughput, other ideas?

Unit Caps: A typical course with three hours of lecture per week at UC Davis rates as three units[7]. Four-year students typically graduate with around 180 units, and students must receive special permission to register for any more classes once they reach 225 units. **Within L&S, we are allowed to require a maximum of 110 units in our majors.** Prerequisite courses, even those outside our department, count toward this maximum. This unit cap places severe limitation on what we can do with our program.

The ostensible reason for the unit cap is to allow sufficient time for students to explore areas of interest outside of their major. We are sensitive to that consideration, but find that this mixture is too lean (on major course work) for our purposes. Our students invest a great deal of time in prerequisite course work, and by the time they are ready to take on advanced course work in physics we run into the unit cap.

The situation is even more dire for applied physics majors. We must make substantial cuts in core physics material (such as second quarter in mechanics and quantum mechanics) simply to make space for required course work outside of their major. Offering a degree that combines two scientific disciplines, such as bio-physics or chemical physics, is effectively impossible. Achieving a double major in two scientific disciplines is also nearly impossible due to the limit of 225 units on total course work.

We propose a compromise: lower-division prerequisite course work **outside the host department** should count at a pro-rated amount of 50% toward the 110 unit cap. This would ensure that our students have plenty of exposure to course work outside of physics, while giving us some breathing room for advanced course work. It would enable us to develop applied physics majors that are much more useful to our students. By limiting the concession to additional lower-division course work, it should help preserve a feasible two-year path to graduation for transfer students.

[7] Most of our physics courses are actually rated as four unit courses, due to extensive problem solving in the homework.

10 Future Plans

Describe current or proposed plans to strengthen educational objectives of the program, such as increasing enrollments, improving student performance, and increasing the contribution of the program to the campus educational objectives. Comment on the long term strategy or goals regarding hybrid and virtual instruction in this program. Describe and justify if new resources are needed to preserve or strengthen the program.

Our most immediate future plans for the undergraduate program are centered on receiving final approval and finishing the implementation of the UCU. Following that, we will want to monitor the performance of the program carefully. Of particular importance are the impact of selective major review and the curriculum changes to transfer students. Ideally we will see that we continue to graduate at least 10-12 transfer students in physics each year, with hardly any leaving the program.

We have an annual faculty meeting devoted to a review of the undergraduate program, and evaluating the impact of the UCU will be a central topic for the next few years at least. We will likely want to make small further adjustments. This process has given us expertise in the various tools for updating course descriptions and catalog copy, and so we would like to invest some time in bringing those up to date as well. The scope of the undergraduate curriculum update did not include introductory physics (PHY 7 and PHY 9) so we plan to tackle those next.

We see our substantial investment in computational physics as merely a start. Our hope is that professors will take further advantage of student expertise in computational physics as it becomes more reliable. For when you calculate an analytic solution *and* write a computer program for the same problem, and they agree, then you have understanding and *confidence*.

The biggest challenge facing our department is the decrease in the size of the faculty, because hiring is not keeping up with retirements. While the faculty is shrinking the demands on our department are increasing. We have more physics majors, but also more undergraduate students taking our introductory physics courses. We need substantial investments from campus to dramatically increase our hiring rate. Here the main hold-up is startup. And yet these retirements are saving campus enormous sums of money. If we direct some fraction of those savings toward start-up expenses of new hires, we could likely avert disaster for our department. We also need more investment in staff. We have only one undergraduate student advisor on the faculty who is severely taxed to keep up with not only our majors, but the myriad of issues that arise with the *thousands* of students that take introductory physics each year.

11 Minors

Please comment on the minors currently administered by your department.

The department offers a minor in physics which 1-3 students complete each year. The objective for the physics minor is to provide an opportunity for students to gain a meaningful understanding of physics concepts and expertise in putting them to practical use, but without committing to an entire degree.

The requirements for the minor are quite simple to state: students must complete six upper division physics courses (excluding a small set of ineligible courses, e.g. independent study). However, achieving this minor is quite challenging due to the hierarchical nature of our course work. Upper division course work generally requires completing six courses in mathematics, four courses in introductory physics, and many courses further require PHY 104A (Math Methods in Physics). This large number of prerequisites likely discourages many students. And those that have completed these prerequisites for their own major are likely already science majors, and therefore see little benefit to a physics minor.

We believe the physics minor is well designed for those relatively few students dedicated enough to their interest to pursue. We see no need to make adjustments and we accept that demand for the minor is small.

12 Emergency Remote Instruction

The review team, UIPRC, and UGC understand that the emergency remote instructional environment required by the COVID-19 pandemic presented extraordinary demands on department faculty, staff, and students. Please address the successes and challenges faced by your program during emergency remote instruction. Provide information about any new practices that were beneficial and the program plans to continue, as well as any practices and outcomes that fell short of your standards.

Our faculty made a heroic effort during the COVID-19 pandemic, but the quality of instruction suffered tremendously nonetheless. In qualitative terms, we saw that the top 1/3 of students managed reasonable well with remote instruction, but the bottom fell out for the remaining 2/3. We believe we saw a dramatic increase in cheating, and there is growing evidence that it has not receded. We also believe that we are still seeing residual effects of the pandemic on current students. Specifically, the level of mathematical preparation and study habits have not fully recovered to pre-pandemic levels. These are subjective evaluations, but they have been widely observed by our faculty.

During emergency remote instruction, student engagement dropped precipitously. Early advice to instructors urged us to provide asynchronous course work as much as possible, to accommodate students that might struggle, under the circumstances, to connect at a fixed time. We soon discovered, however, that fully asynchronous courses were a disaster for student engagement and morale. Most instructors quickly reverted back to fully live (via zoom) lectures, a mixture of **short** asynchronous pre-recorded lectures[8] punctuated with live in-person discussions.

For faculty teaching lab courses, the burden was even greater. These are crucial experiences for our students, and faculty generally went to extraordinary lengths to provide kits or other means for students to gain some hands on experience. This generally required redesigning entire courses with little notice.

During live (via zoom) lectures, instructors were generally faced with a wall of blankness: students nearly universally leave their cameras off, and deeply resent being forced to turn them on. With few exceptions, faculty despised remote instruction. But we did our best.

And despite all of these efforts, there was no meaningful equivalency between the online courses we provided and our traditional in-person courses. Any instructor has seen that students that do not attend lecture generally become demoralized, detached, and perform well below their abilities. COVID-19 forced something like that onto every single one of our students. May we never have to do that again.

[8] Video hosting sites which monitor viewer engagement over time showed that students generally drop out of pre-recorded lectures after about ten minutes