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“The Berkeley Summer Research Program for Undergraduates”: One model for an undergraduate summer research program at a doctorate-granting university

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Historically, mathematics REUs have mainly been offered by institutions that specialize in undergraduate education. The purpose of this article is to offer one model for an undergraduate summer research program at a large research university by communicating and discussing the details of the “UC Berkeley Topology, Geometry, and Operator Algebras Summer Research Program for Undergraduates.” The author helped organize and design this program, and twice served as the research group mentor for the “symplectic geometry” group.

1 Preliminaries

1.1 The program and its funding

The “UC Berkeley Topology, Geometry, and Operator Algebras Summer Research Program for Undergraduates” was an eight week program that ran at Berkeley in the summers of 2012 and 2013. In 2012, twelve undergraduates participated, and in 2013 the program was expanded to eighteen undergraduates. The program was geared towards rising juniors and seniors, and students were recruited nationally. Participating students were placed in research groups consisting of six undergraduates and a graduate student mentor; thus, in 2012 there were two graduate student mentors and in 2013 there were three. Graduate students were then advised by a faculty supervisor.

The program was funded by an NSF Research Training Group (RTG) grant. NSF RTG grants are meant to fund undergraduates, graduate students, and postdoctoral associates in research groups that are centered on a common interest [6]. These grants can be quite large (many are multi-million dollar grants), and they are not meant to be spent just on summer undergraduate research; a chart with the financial figures from Berkeley’s grant is provided in §7. In 2009, an RTG in “Geometry, Topology, and Operator Algebras” was established at Berkeley with two faculty members as PIs and several more faculty as associated

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senior personnel. The grant funded many activities in addition to the 2012 and 2013 summer undergraduate research program. For example, it funded summer workshops for graduate students, a for-credit term-time undergraduate research seminar, and it provided summer research support for graduate students. The grant was renewed in 2014, and the summer research program for undergraduates was a key component of the proposal for renewal. We anticipate that the program will run again in the summer of 2015, and continue subject to funding.

1.2 Program designers and a disclaimer

The 2012 version of the program was designed by Michael Hutchings, Dan Pomerleano and the author. The designers of the 2013 program were Adam Boocher, Michael Hutchings, Dan Pomerleano, Pablo Solis, and the author. While we have aimed to coordinate with the other organizers, this article ultimately presents the author's point of view on the program.

1.3 Guide to the document

This article is organized as follows. In the next section, we highlight the unusual aspects of the Berkeley program. Then in §3, we discuss the details of the program in considerable depth. To illustrate these concepts, we present a specific research project in §4 that was successful. The remaining sections are devoted to reflecting on the program and analyzing it. In §5, we discuss the main challenges that came up while running the program and propose some potential solutions. Student feedback on the program is analyzed in §6, and issues involving the sustainability of the program are discussed in §7. We end in §8 by comparing the program to research programs at other doctorate-granting universities.

2 Unusual aspects of the program

We begin by highlighting some aspects of the program that to our knowledge are nonstandard, and we explain the philosophy behind these choices.

2.1 Program primarily run by graduate students

Graduate students occupied a central role in Berkeley's program. These students met with program participants every day and handled almost all organizational and advising duties.

Involving graduate students is a natural choice for a large research university that is interested in offering an undergraduate research program. Graduate students improve their own research skills by teaching others how to do research, and they gain useful experience in being research group leaders. Many graduate students are also interested in undergraduate education, so having the opportunity to participate in an undergraduate research program represents a valuable professional opportunity. Additionally, faculty at large research universities often use summers to travel to conferences and to focus on research, so an 8 or

10 week research program at a large university meeting almost every day would probably not be a good fit without substantial graduate student contributions.

2.2 "Underrepresented" topics

We offered research groups on "homological algebra" and "contact and symplectic geometry" in 2012, and "homogeneous spaces", "symplectic embeddings", and "computational commutative algebra" in 2013. Many of these topics belong to the "underrepresented" subfields of mathematics that were discussed at the "New Directions for Mathematics REUs" conference at Mount Holyoke in 2013 [7]. To briefly elaborate on what was discussed, there are important branches of mathematics that seem to be underrepresented among REU programs [7]. It was observed at the conference, e.g. in [2, 7, 8, 12], that REUs promote a spirit of collaboration and can shift the cultures of fields by seeding these fields with enthusiastic researchers who are excited about the free exchange of ideas. It is therefore highly desirable to offer REUs on a wide range of topics. It is our hope that our program will inspire more REUs in these underrepresented fields.

3 Program specifics: a "user's guide"

We now provide more specifics about how the program was run, and we also provide our reflections on these details. We go into considerable detail; ideally, this section can serve as a primer for readers interested in running a similar program.

3.1 General information about the positions to be filled

Our model called for one graduate student mentor for each six undergraduates, and one faculty advisor per graduate student. All current Berkeley graduate students were eligible to apply, even students with an expected graduation date before the start of the program (in fact, one of the mentors in 2012 and one of the mentors in 2013 received their PhD during the spring of the program year). In 2012, there were 12 undergraduates, and in 2013 there were 18.

The time commitment required of graduate students was substantial. Graduate students were asked to complete almost all the organizational duties required to set up the program, design research projects in conjunction with faculty and supervise them, meet with students essentially every day for 8 weeks, and organize and attend some social activities. We will spell out these duties in more detail in subsequent sections, but in general terms graduate students were asked to spend around 30-40 hours per week on the program during the 8 weeks when it was running and probably 20 hours in total setting up the program before the students arrived.

The time commitment required of the faculty supervisors was much more modest. By far the most important role faculty filled was to help the graduate students pick appropriate problems. Faculty also consulted on important decisions, and met with the students for one or two hours during the program. In general, the time commitment required of faculty was not meant to exceed 10 hours total across the summer.

Graduate students were paid around $\$10,000$ for the summer, and faculty were asked to volunteer their time.

3.2 Organizational aspects of the program

3.2.1 Recruiting graduate student mentors and faculty advisors

Choosing the right graduate student mentors and the right faculty advisors was essential for the success of the program.

For selecting the graduate student mentors, one advantage was the large potential applicant pool. Berkeley has many graduate students, and most who were approached were interested in the program. Moreover, the author (who handled this selection process) knew many of these students personally, and conducted interviews. As such, it was not hard to select graduate students who seemed to have the potential to do an excellent job. For finding strong faculty advisors, the key was finding enthusiastic faculty who could make a significant contribution in a small amount of time. Once the graduate student supervisors were selected, it was left to them to find such faculty members. To succeed at this, being willing to ask many faculty was important. It was also important to communicate the goals of the program and explain how faculty could help very clearly. That said, finding a sufficient number of strong faculty advisors was definitely a challenge. For example, one of the graduate students asked two different faculty members for their suggestions and received only minor feedback.

3.2.2 Designing the program website and recruiting undergraduates

In both years, the first step to getting the program off the ground was to design the program website. While this was done almost entirely by the graduate student organizers, faculty input was also very valuable at this stage. To elaborate, the program website contained all the essential information about the program, including how to apply, and also contained loose descriptions of the various research projects. Faculty approved the website before it went live. It is worth emphasizing that designing the website can be somewhat subtle: indeed, in 2012 there was some confusion about the role of faculty in the program that came from unclear wording on the website.

Undergraduates were actively recruited nationally. Specifically, graduate students designed an electronic poster for the program, and emailed the mathematics departments at approximately 50 research universities and 50 primarily undergraduate institutions to advertise the program. The graduate students also arranged for the program to be listed on the AMS website. One weakness of our recruitment process was that we probably did not take enough steps to actively recruit underrepresented minorities and women. This is further discussed in §5.5.

3.2.3 Selecting undergraduate participants

Both years that the program ran there were approximately 10 undergraduate applicants for every spot. We aimed to have a diverse group of students, hailing from a wide variety of undergraduate institutions, who would interact well with each other and be able to handle the considerable demands of the program. We also wanted to be sure that at least a few students from Berkeley were included, in order to take advantage of potential synergy with other educational opportunities offered through the RTG grant.

Applicants were selected by the graduate students, with faculty occasionally giving input for difficult decisions. The application consisted of letters of recommendation, a transcript, and a personal statement. In certain close cases, a phone interview was also conducted. Each graduate student had considerable latitude in choosing his group, although efforts were made to coordinate the choices in order to ensure that the general goals for the selection process described in the previous paragraph were met.

During the selection process, no one aspect of the application was emphasized over any of the others. After the fact, it is interesting to reflect on which selection criteria seemed to have the most predictive value. Certainly the transcript is extremely important and should be read carefully. Here, the emphasis should be on ensuring that the student is adequately prepared; many students who had completed only a few upper division math courses struggled, while participants who had excellent grades in a wide variety of advanced courses rarely did. Very strong faculty recommendations also have excellent predictive value. The personal statement is probably of less use. The author also found the phone interview to be of limited help, essentially because all the interviewed applicants performed well. This was potentially because the interview questions were on the "soft" side, so a more rigorous phone interview could potentially be more useful.

3.2.4 Arranging for room and board; student stipends

The graduate student organizers also arranged for housing and meals.

For stipends, undergraduates were given the option of living in dorm-style housing, with board covered, and receiving a $1000 stipend, or receiving a $3000 stipend which could be spent towards housing they selected. This second option was primarily designed for Berkeley undergraduates participating in the program, since many upperclassmen at Berkeley already live off campus during the academic year. Most students selected the $3000 stipend.

3.2.5 Social activities

The graduate students also organized social activities for the students during the program. These happened frequently, and included activities around Berkeley, such as group runs, ice cream outings, dinners, frisbee, and hikes, and occasionally more elaborate activities like group trips. In 2013, a joint hike was organized with Stanford's Summer Undergraduate Research (SURIM) program. Part of the purpose of this hike was to give the program participants the chance to get to know the Stanford students in advance of a joint conference, discussed further in §3.5.1.

3.3 Mathematical aspects of the program

3.3.1 Choosing research projects

Graduate students designed the research projects in conjunction with their faculty supervisors. We found that choosing the right research projects was critical for the success of the program, so we now elaborate on how this was done. First, graduate student supervisors were asked to come up with several potential projects suitable for undergraduates and then ask their faculty supervisor for their input. These projects were expected to center around original research; expository projects were not acceptable. Faculty supervisors were also encouraged to suggest any other projects that came to mind. From these discussions, a list of potential research projects was created for each group; although there were 6 undergraduates per research group, students were expected to work together to some extent, so each graduate student supervisor had between 2 and around 6 potential projects.

It should be clear from above that a significant share of the responsibility for choosing good research projects fell on the graduate students. Moreover, in general graduate student supervisors received a fairly minimal amount of structured help from faculty, e.g., there was no formal training on how to select good projects for undergraduates. Thus, in making sure that good research projects were selected, it was hugely important to select the right graduate student mentors and faculty advisors. We refer the reader to §3.2.1 for advice on how to handle this selection process. To give an example of good faculty advising, the author sent his advisor a list of 10 or so potential projects, and his advisor was quite firm in pointing out projects that were not feasible, flagging ideas that seemed good, commenting on subtleties the author had not considered, suggesting improvements, and proposing other projects. This was all done via email, and so was handled in a time efficient manner.

The author also found that it was possible to suggest projects that complemented his own work well. For example, some of the computations he assigned to a student in 2012 inspired him and his collaborators to work on a project which eventually appeared in the *Journal of Topology* [3]. This is further discussed in §6.3, and more advice on choosing appropriate research projects is given elsewhere in this article. For example, we provide details of a project that went well in §4, and we discuss specific strategies for designing good research projects in §5.1.

3.3.2 Lectures, problem sets, and problem sessions

The program had a substantial lecture component, with each graduate student giving approximately 20 hours of lecture. This was done in part because of the program's emphasis on "underrepresented" REU topics. One reason that topics like differential geometry are not usually the focus of REUs is because they are perceived to have a high barrier to entry. The idea behind the lecture component was to ease students' transitions into doing research in what are normally graduate level topics. The lecture component was also meant to enrich the students' overall experience by giving them appropriate context for their research. The organizers also hoped that the research projects and the lectures would be synergistic, in the sense that students' research projects would cause them to be excited about their field, which would in turn cause them to be more enthusiastic in understanding the details of the lectures.

In 2012, the program consisted of four weeks of lecture (meeting every day) followed by four weeks of research. After reviewing student evaluations, we found that this format was not ideal: students were dissatisfied with the amount of time it left for research, and students found it hard to stay motivated to understand the lectures for 4 weeks. Because of this, in 2013 we switched to a more integrated format, where students started their research essentially on day one and lectures were interspersed throughout. While the total amount of lecture time remained roughly the same, this format seemed to be much more effective.

In the 2012 version of the program, there were weekly problem sets and frequent problem sessions. While these seemed to be somewhat effective, we decided to significantly scale back this aspect of the program for 2013 because of feedback from the instructors and the students from 2012.

3.3.3 Supervising the research projects

Graduate students were also in charge of supervising research projects.

The undergraduates were asked to work in groups. Some care was required in arranging for appropriate groups, and this was mainly left to the graduate students' discretion. Graduate students met with students to discuss research for between 40 and 80 hours over the course of the program, and generally tried to have at least one research meeting each day. The precise nature of the graduate student supervision was left to each mentor's discretion.

It seems that choosing to meet every day, and for many hours each day, is a somewhat controversial choice (we will briefly compare the Berkeley program with similar programs in §8). For one, as discussed in §7, this format puts considerable strain on the graduate students. Moreover, it is far from clear that this is the best arrangement for the undergraduates themselves, since learning to work independently is part of learning how to become a good researcher. In the author's experience, meeting every day is probably not essential, especially in the latter weeks of the program (front loading the supervision of the undergraduates seems also to be common in similar programs, see §7). Nevertheless, a significant amount of face time between the undergraduate researchers and their graduate student supervisors is important. Eight weeks is simply not much time, especially for a program like Berkeley's that aims to have high quality writeups containing original research on graduate level topics. Thus, in running a program like Berkeley's, the author would suggest meeting around four times per week in the first few weeks of the program, and then at least three times per week the rest of the time.

Supervising the research projects effectively was one of the most difficult parts of the program, and some of the challenges that came up as well as potential solutions are discussed further in §5.1. In broad terms, it was critical to make sure that research projects were manageable and program participants stayed focused on completing them.

3.3.4 Writeups

Student participants were asked to write up their work. In 2012, this requirement was not pursued very aggressively, and some students' writeups ended up being weak. As a result, in 2013 this was made an emphasis of the program. This is discussed further in §5.2.

The writeups were expected to present original research and be of publishable quality. To give more specifics, the 2013 symplectic group produced three writeups. These were between 7 and 30 pages, and were written in the format of research articles; two were submitted for publication, and we expect that the third will be as well. One [9] has been accepted for publication in the *Ramanujan Journal*, and another [5] was recommended for *Involve*. For reference, *Involve* is a journal which publishes high quality articles by undergraduates (more senior coauthors are welcome too), while the *Ramanujan Journal* publishes original articles in fields that were influenced by the mathematician Srinivasa Ramanujan. The computational commutative algebra group also produced a paper [1] with their graduate student supervisor that has been recommended for publication in the *Annals of Combinatorics*, a top combinatorics journal.

We did not provide the students with any formal training on how to write a research article, but the graduate student mentors worked closely with their undergraduate advisees in helping them polish the writeups and make them suitable for public dissemination. It was important to supervise much of this writeup process and start it early. For example, in 2013, we asked the students to begin writing up their work in the seventh week of the program. It proved infeasible to complete the writeups within the 8-week time frame of the program, so graduate students stayed in touch with their undergraduates after the program to put the finishing touches on this work. In some cases, these ongoing conversations lasted up to a year after the program (in fact, some are still in progress).

3.4 Program blog

In the 2013 program, we also ran an online blog [10] for several weeks. Pablo Solis (the graduate student mentor for the "homogenous spaces" group) made the most heavy use of the blog; for example, Pablo posted expository notes, and had several other students contribute to the blog in the early stages of the program. He found that it was a good way to evaluate to what degree students were digesting the material. Pablo also felt like if the program were run again, the blog should have been used more. For example, having students blog on what they are learning would be a great way to ease them into the writing process.

3.5 Presentations

3.5.1 Student presentations and a joint conference

The program participants were asked to give presentations. This was particularly emphasized for the 2013 program. At the end of the 2013 program, there was a joint conference with the SURIM program at Stanford where each research group gave a 20 minute presentation. To train for this, the Berkeley students gave a practice presentation on their research to the other program participants. The program participants were also asked to give expository talks about their research field.

Students received feedback from their peers and from their research group mentors about how to improve their presentations.

3.5.2 Colloquium series

In 2013, the program also had a weekly colloquium series. This mainly featured mathematical talks by faculty members, but also occasionally addressed more practical issues: for example, the graduate student mentors ran a panel discussion on how to apply for graduate school and the NSF graduate fellowship.

3.6 Links with other programs

As mentioned in §3.2.5 and §3.5.1, in 2013 a hike and a conference were scheduled in conjunction with Stanford's "SURIM" program. These activities were highly successful, and it would be great to forge similar joint ventures in future versions of the program. For example, the program was in no way affiliated with MSRI's "UP" program, but in future years it would be desirable to forge some connections with this program, and to strengthen connections with SURIM.

3.7 Survey data

At the end of each summer, we asked students 10 specific questions about their experience. This was done anonymously via an online program, with a 100% response rate each time. We asked a combination of multiple choice and free response questions. The questions covered many different aspects of the program. For example, there were questions about the social activities, the timing of the research projects, and the quality of the graduate student supervision. We found this data quite useful, especially in making improvements between 2012 and 2013.

4 A case study

We now present a research project from 2013 that was supervised by the author in order to further illustrate the above program concepts.

In 2013, three students in the symplectic geometry group worked on a research problem involving the symplectic geometry of four-dimensional "toric domains". These are open subsets of $\mathbb{R}^4$ with a high degree of symmetry, and they have a natural symplectic form given by restricting the "standard" symplectic form on $\mathbb{R}^4$. It is interesting to ask when one four-dimensional toric domain symplectically embeds into another, and there is a new family of symplectic embedding obstructions, called embedded contact homology (ECH) capacities, that can be used to help answer this question. ECH capacities can be computed purely combinatorially for some toric domains in terms of lattice point counts in certain planar regions, making them particularly well-suited for exploration by undergraduates.

The three undergraduates first extended this combinatorial formula to more general toric domains by explicitly constructing certain symplectic embeddings. They then studied symplectic embeddings out of a family of toric domains from this class, and showed that ECH gives a sharp obstruction to embedding elements of this family into balls in some interesting cases, thus obtaining new results about symplectic embeddings. The students wrote up their work [5], and it was recommended for publication in *Involve*.

The project was specifically designed so that the students could work with many explicit examples without having to understand many of the intricacies behind the ECH capacities, which involve complicated ideas like Floer homology and pseudoholomorphic curves. But after completing the project, one of the undergraduates was motivated to learn more. He gave an expository talk on a related idea called "cylindrical contact homology" to his peers, and this student was so interested in learning about ECH that he asked the author to serve as a co-advisor for a senior thesis project on ECH, even though he was not a Berkeley undergraduate. The author agreed to do this. The undergraduate then decided he was interested in learning more about differential geometry and low-dimensional topology, and so applied for external fellowships to complete Part III at Cambridge. He won a Marshall scholarship, and will try to learn more about these topics during the $2014-15$ academic year.

One of the other students in this group was motivated by the project to explore a classical tool for lattice point enumeration called the Ehrhart polynomial, which is also connected to ECH capacities of certain toric domains. The student proved several interesting results about this tool which were accepted for publication [9].

5 Challenges and potential solutions

We now discuss in more depth some challenges that came up while running the program and we mention how we attempted to address them.

5.1 Difficult research projects

Many of the program's research topics involved fields that are generally not studied until graduate school. As such, finding projects at a suitable level for students could sometimes be difficult. For example, some of the students in the 2012 program mentioned on evaluations that they had a hard time understanding the context for their research problems and sometimes found it demoralizing to work with tools that they had not yet fully absorbed.

We worked hard in 2013 to try to make it so that these issues would not come up. One way we attempted to do this was by making sure to choose "hands-on" research problems, as in §4. In general, problems were chosen for which one could compute many examples and make use of computer exploration, and efforts were made to simplify the technical demands of problems as much as possible. For example, the symplectic geometry group worked exclusively with open submanifolds of $\mathbb{R}^{2n}$, and many of their projects involved exploring certain symplectic embedding obstructions that were very combinatorial in nature.

We also tried to make the research problems more "dynamic". Specifically, we tried to have students start the research projects by completing some simple computations and solving relatively easy problems. Then, if they finished this quickly, we would give them something more challenging to think about. Similarly, if students seemed to be excessively struggling with their research problem, we would redesign the goals of the project to make them more attainable. In other words, we asked the graduate student mentors to play an active role in making sure that students were appropriately challenged throughout the program. Exactly how this was carried out was left to the discretion of the graduate student supervisor.

In the author's 2013 symplectic group, there was no one standardized way in which this process was handled. One of the groups, which consisted of three advanced students, was given as an ultimate goal a quite general conjecture; they were quickly able to prove it in many special cases, but the general case eluded them. Another group was given a specific problem at the beginning of the program, and they were able to complete it. This took the group essentially the full eight weeks, and so the timing for the project worked out quite well.

In general, we found that it could be frustrating for students if they did not achieve their original goal; this came up for example with the first group from the previous paragraph. In the author's experience, if it is made clear to the students that this is a natural part of research, then students do not get too demoralized. The key is for the graduate student supervisor to make sure that at least some progress is made, and provide positive feedback when this happens.

5.2 Lagging enthusiasm for the writeup

As mentioned in §3.3.4, it was sometimes challenging to get students to produce high quality writeups. Writing a good research article takes time, and when many students imagine an ideal summer doing math, they do not think of spending considerable time writing up their work clearly and correctly. Moreover, some students can become disappointed if their projects do not pan out in full generality, and this can drain enthusiasm for a long writeup process.

We found that the students were in general highly motivated to see their work appear in print, but that it was also necessary to make it very clear to them that their writeups were mandatory, and would be read by the graduate student supervisors and ideally by Berkeley faculty as well. In the author's opinion, some direct supervision and lots of persistence were also important. The writeup phase for two of the three projects from the author's 2013 symplectic group lasted well past the end of the program, and it seemed likely that at least one of the groups would not have finished their writeup if they were not occasionally reminded by the author. Positive encouragement, especially for groups that were somewhat disappointed in their work, was also quite valuable.

Getting good writeups from the students also required choosing good projects, as in §5.1. We tried to ensure that every group completed some piece of original research, and this was done by making sure that projects were well chosen and well supervised.

5.3 Graduate student inexperience

We found that graduate student inexperience could sometimes be a problem. The graduate students who participated in the program had little to no experience mentoring undergraduates, and were generally close to the beginning of their own research careers. This sometimes made it difficult to choose good problems for their students to work on. For example, in retrospect one of the groups in the 2012 program worked on a problem that was simply too difficult. It was also sometimes challenging for graduate students to exude confidence that their advisees' research projects would progress well, since they themselves were new to research; we found that this was sometimes demoralizing for the undergraduates. Similarly, some of the undergraduates reported that it was frustrating to not have much faculty supervision.

We tried to address these problems in advance of the 2013 program. In general, we tried to make sure that faculty were involved in helping to select appropriate research problems, and we also tried to choose graduate students who were almost at the end of their PhD and who had successfully produced math research before.

5.4 Difficult students

In 2012, there was one student who did not always do what was asked of him throughout the program, and this came to a head at the end of the program when he refused to promptly submit a writeup and a faculty member had to get involved. In retrospect, the graduate student supervising the student should have contacted his faculty advisor for help much sooner.

5.5 Recruiting women and underrepresented minorities

As mentioned in §3.2.3, we aimed to enroll a diverse group of students. While we were successful in finding students from a range of educational institutions, we had less success finding applications from underrepresented minorities, at least anecdotally (unfortunately we did not collect data about this). One obvious way to address this is by stepping up attempts to actively recruit these students, see the end of §3.2.2. A potentially related problem was the low stipend in comparison with similar programs. We have no data to confirm this (and indeed, no students even contacted us about this), but it is certainly conceivable that low-income minority students were deterred from applying to our program because of a need for greater financial support during the summer. Perhaps the stipend should be increased, or a need based supplement made available.

We also would have liked to receive more applications from women: for example, in 2013 only about 1 in 5 applicants were female. While we were happier with the gender balance in the pool of students who ended up participating in the 2013 program (6 out of 18), this could be improved as well. For this, better recruitment as in §3.2.2 should help.

5.6 Excessive demands on graduate students

Another concern is that the program places excessive demands on the graduate students. Probably only advanced graduate students are generally capable of handling all the responsibilities of the program, and for such students time is often at a premium. The amount of time asked of the graduate student supervisors is definitely an issue and is discussed elsewhere in this article, see §7. We note, though, that all four of the graduate students who participated in the program successfully applied for postdocs after participating in the program, and accepted multi-year positions; these were at the University of Utah, Harvard University, Imperial College London, and the California Institute of Technology. See also §6.3 for more graduate student feedback.

6 Feedback

We surveyed the students after each program, and we now present some of the results.

In general, feedback was very positive. In 2013, all 18 undergraduate participants and all four graduate student mentors described the program as good or great on anonymous surveys (14 out of the 18 undergraduates and 3 out of the 4 mentors described it as great). We now discuss the feedback in greater depth.

6.1 Student feedback

The first set of results we discuss involve changes made to the program between 2012 and 2013. Specifically, after 2012, we reduced the amount of lecture and increased the amount of time devoted to research. As the charts at the end of this section show, these changes were effective. It is also interesting to note that the balance we struck between lecture and research was good, with 56% of students describing both the amount of lecture and the amount of research as "just right".

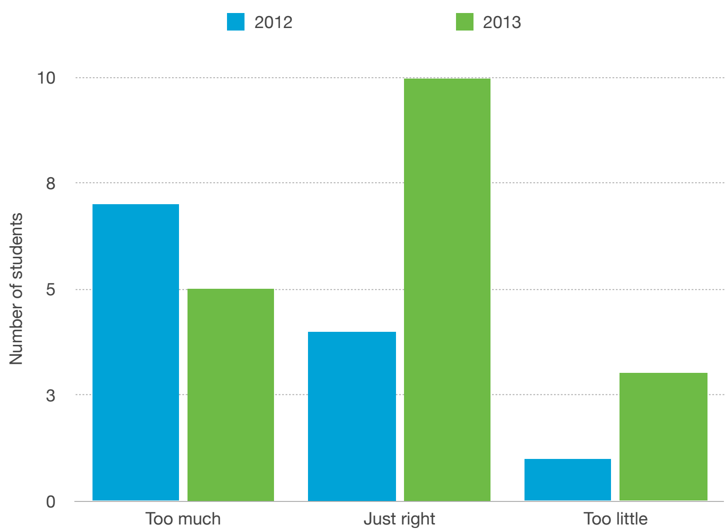
Most of the written feedback was positive. One student in the 2012 program wrote: "I really enjoyed my research project. At first it seemed too difficult, but after the lecture portion of the program, my project turned out to be at a good level for me." Another from 2012 said "I thought it was a great experience, and I learned more math than I thought would be possible in a single summer." A student from the 2013 program wrote "I will never forget this summer: the people I've met and the insight I've gained into math research in general. I had a wonderful time both socially and academically." A different student wrote that the program "was a great experience and has encouraged me to push myself more in math during the school year."

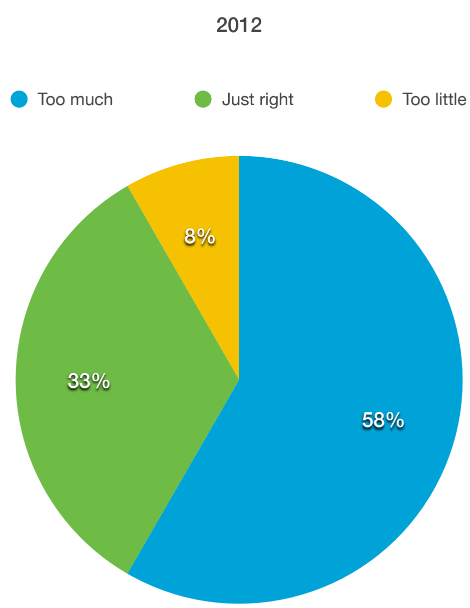
The suggestions for improvement were varied. One student in the 2013 program commented on our efforts to achieve a gender balance: "the fact that the split [between males and females] was so exact in each group seemed a bit artificial...and made me feel a bit uncomfortable." Another suggestion involved how the students' collaborations were managed: "I wish that the project could have been broken apart more such that there weren't three people working on the exact same problem at a time." There also seemed to be some concern that lectures were too advanced and moved too quickly. In a different direction, a student from 2012 suggested that their project "could have been more open ended".

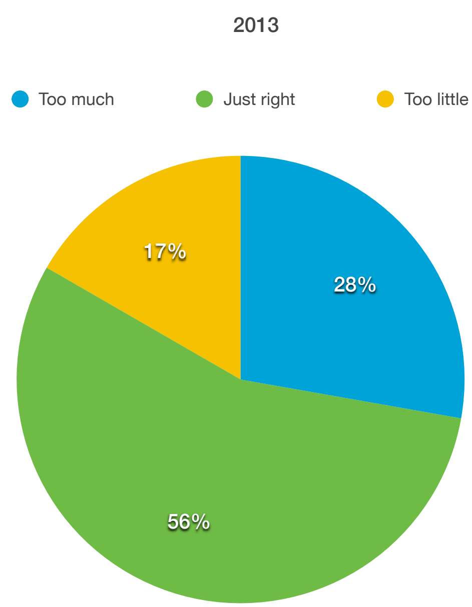
Comparing student satisfaction with the amount of lecture. Question: “How did you feel about the amount of time devoted to lecture?”

Student Satisfaction: Lecture

DESCRIPTION	2012	2013
Too much	7	5
Just right	4	10
Too little	1	3



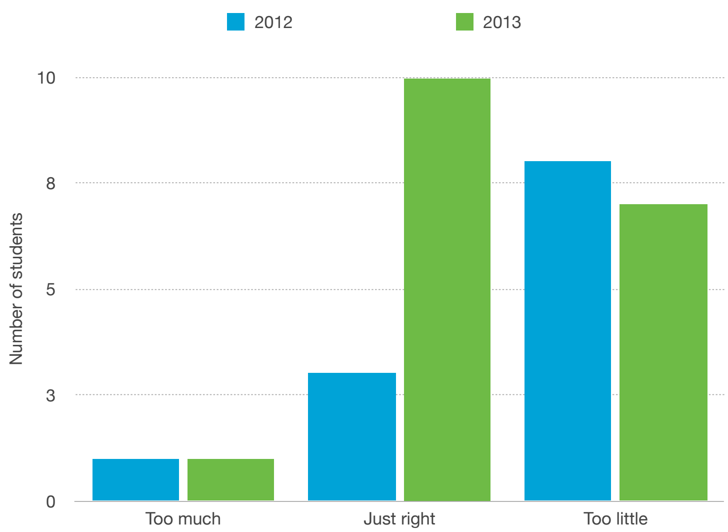


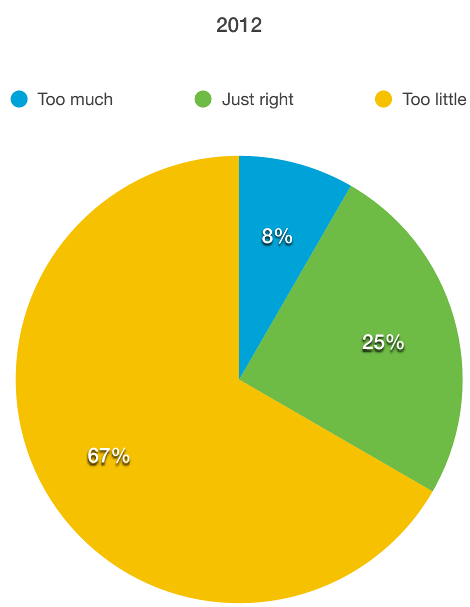


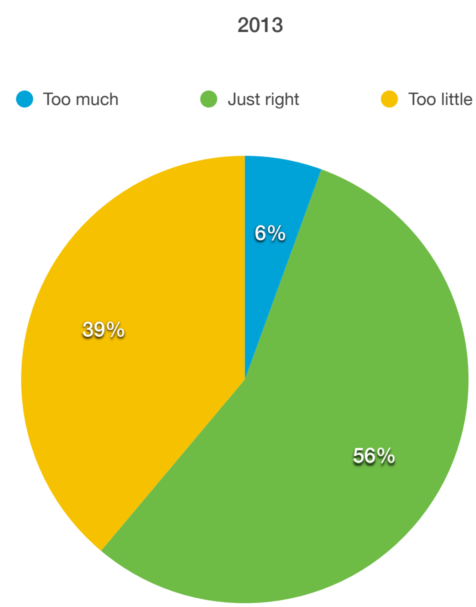
Comparing student satisfaction with the amount of time devoted to research. Question: “How did you feel about the amount of program time devoted to research?”

Student Satisfaction: Research

DESCRIPTION	2012	2013
Too much	1	1
Just right	3	10
Too little	8	7







6.2 Faculty feedback

We asked Michael Hutchings, who was a faculty supervisor for the program in 2012 and in 2013, to comment on his experiences with the program. In general, he was happy with the program. When asked, he said that the time commitment requested of him was small, and supervising the program did not meaningfully affect the time he had for research. One of his graduate students participated in the program, and he did not think that the program affected the graduate student's ability to graduate on time. Hutchings added that he felt the most critical component for the success of the program was selecting the right problems. When asked what could have gone better, he mentioned the problems with the writeups from 2012 that were mentioned in §3.3.4.

6.3 Graduate student feedback

As mentioned at the beginning of §6, the graduate students who participated in the program were very happy with their experience. For example, the author felt that he grew as a researcher and as a research leader.

In terms of suggestions for improvement, all of the graduate student participants felt that the time commitment required of them was perhaps excessive, especially in the final weeks of the program. Each of the graduate students found it difficult to get enough research done given the substantial demands on their time that the program involved. Two of the graduate students from the 2013 program also felt that the writeups should have been started sooner, and one of these students would have preferred more faculty involvement, particularly from faculty who have experience working with undergraduates. One of the graduate students from the 2012 program wished that more efforts had been made to ensure that students were broken up into subgroups with similar experience levels.

On the topic of losing time for research, we want to emphasize that at least in the author's case the time expended ended up being extremely fruitful for his research program. To elaborate, the author's thesis work was primarily on topics not appropriate for an 8 week undergraduate research program. Thus, the author was motivated to learn about symplectic embedding problems in order to serve as an effective mentor. This has proved very fruitful. For example, as mentioned at the end of §3.3.1, the author wrote a paper about this topic that appeared in a top journal [3]; he also has completed several other projects related to this work that he expects will be accepted for publication, and he is currently working on a collaborative project with one of the top researchers in this field. None of this would have happened were it not for his experiences in the program, and his discussions with his students in the program have proved very fruitful for him. As mentioned in §3.3.4, another graduate student has had a strong paper [1] recommended for publication that he wrote with his students from the program.

7 Sustainability

While the program was designed with sustainability in mind (for example, we tried to arrange it so that the demand on faculty's time would be minimal), we anticipate two obstructions to the future success of the program. One is finding consistent funding. The program represented a relatively minor slice of the total RTG grant in the years that it ran, as the following table illustrates:

	2012	2013
Total RTG money awarded to Berkeley	\$470,000.00	\$470,000.00
Money spent on the program	\$60,000.00	\$100,000.00

Table 1: Amount of RTG money spent on the program in the years the program ran (figures approximate). Note that the RTG grant also awarded $\$470,000.00$ annually from $2009-2011$.

In this sense, then, the program is quite sustainable as long as a university can get such a large grant. There are several ways the program could be run with a smaller grant. The most obvious way to scale back spending would be to decrease the number of undergraduate participants. The graduate student salary worked out to around \$30 per hour, and could also be slightly reduced.

Another obstruction to sustainability comes from finding graduate students who are excited about the program and willing to spend a lot of time. As mentioned in §3.1, the amount of supervision given to the undergraduates was probably excessive and should be cut back (this would also make the program slightly less expensive). Also, it would perhaps make more sense to hire more graduate student mentors and reduce the time commitment for each mentor.

8 Comparison with other programs at research universities

As mentioned in the introduction, it seems that most undergraduate research programs are run at institutes that primarily focus on undergraduate education. We now briefly mention some other undergraduate research programs at large research universities. This is by no means supposed to be a comprehensive survey (we apologize in advance for any omissions), but it hopefully places the Berkeley RTG in an appropriate context.

Since 2000, the University of Chicago has been running an REU through its *VIGRE* program. The Chicago REU has grown over the years, and is much larger than ours. For example, it had 98 participants in 2009 [4]. While graduate students are also important to the Chicago model, faculty play a much larger role than in our model. The Chicago program also has students participate in an outreach program, for example by teaching high school students. Unlike our program, the Chicago program is only for University of Chicago undergraduates. Another difference is that while students in the Chicago program are also required to write a paper, their paper can be expository if they choose. The amount of required supervision in the Chicago program is also less.

The *Stanford Undergraduate Research Institute in Mathematics* (SURIM) program has been mentioned elsewhere in this article. This is a ten week program for Stanford students that has been running since 2012. We benefited greatly from learning about this program from presentations by Yanir Rubinstein and Ravi Vakil at the "New Directions for Mathematics REUs" conference at Mount Holyoke [7, 12]. In many respects, SURIM is quite similar to the Berkeley program; one difference is that students have the option of working one-on-one with faculty.

9 Acknowledgements

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