brings me to my final expression of gratitude in this article: thank you, Angela Gibney, for editing this AMS column and providing the guidance and support to early-career mathematicians that I have been fortunate enough to receive from you personally for so many years now.

Noah Giansiracusa

Credits

Author photo is courtesy of Noah Giansiracusa.

When Life Gives You Lemons, Make Mathematicians

Kira Adaricheva, Ben Brubaker, Pat Devlin, Steven J. Miller, Vic Reiner, Alexandra Seceleanu, Adam Sheffer, and Yunus Zeytuncu

This is a happy story during difficult times. It is a story about how the pandemic led to something good. It also describes a new type of undergraduate summer program. We wish to start a discussion about this new approach, how it could be improved, and whether more people should pursue it. Please reach out to the authors to learn more about their experience and potential opportunities to be involved with such programs.

Our story begins in the Spring of 2020, when the pandemic made it clear that summer programs wouldn't run as usual. Many students found themselves stuck at home with nothing to do during the summer. Some programs switched to running remotely and tried to help by accepting more participants than usual (including several programs organized by the authors). However, this support was negligible compared to the number of students who were stuck.

After various Zoom and email discussions, we created the *Polymath REU* program (`https://geometrynyc.wixsite.com/polymathreu`). This is an undergraduate-level version of the original Polymath program (`https://en.wikipedia.org/wiki/Polymath_Project`). The goal of the original Polymath project is to solve problems by forming large-scale collaborations between mathematicians. The collaborative work is done on a dedicated wiki site. This project involves long-standing open problems and some of the world's leading mathematicians. The new program is similar but aimed at undergraduates. It includes modest open problems that do not require significant background. It also involves research mentoring by experts.

The Polymath REU consisted of 12 research projects from a wide variety of mathematical fields. There were 27 research mentors and over 300 undergraduates. The participants came from a wide variety of colleges and universities. There were many participants from top American institutions, from a variety of American institutions we were not familiar with, and from institutions in Mexico, Egypt, the UK, Romania, Israel, Denmark, India, Canada, Portugal, and more.

The program was a success. The exit surveys were quite positive (see Figure 1) and we expect at least 14 resulting manuscripts. We believe that many of these manuscripts will be published in nonundergraduate research journals. An up-to-date status of the manuscripts can be found on the program's website. Results have already been presented in multiple conferences. After the program ended, some participants started non-Polymath projects with their mentors.

We also had the wonderful pleasure of discovering exceptional students who were not accepted to any standard

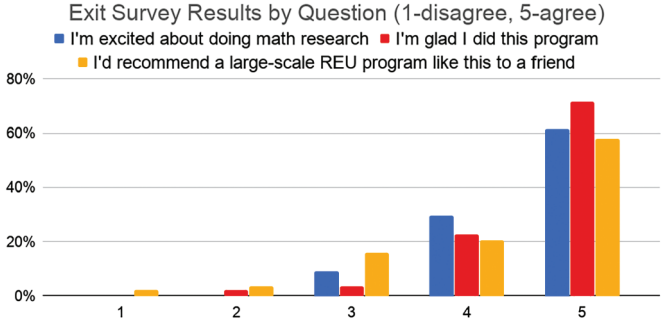

Figure 1. Some results from the exit survey. The *y*-axis is the percentage of people who marked that answer.

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REU. Some because they were not US citizens and others because they did not have much mathematical background. We found several candidates worth considering for admission to any reputable PhD program who might have been overlooked without the support gained from an experience of this sort. We also recruited students from adjacent fields such as computer science, physics, and mathematics education and utilized their skills in meaningful ways. We believe that the program is likely to have a big impact on the lives of all these students. It exposed their exceptional abilities and will open doors for future opportunities.

The program also created a community. As you might expect, groups of students became close and worked together, discussed grad school applications, mathematical riddles, and so on. We were also not surprised to see participants playing online board games together. We were surprised about a variety of other participant activities: a group for sharing recipes and pictures of dishes they cooked, a group for sharing and discussing music that they like, attempts to practice languages together, and more. These discussions and activities were open to everyone in the program.

It was challenging organizing a new type of program under considerable time pressure that gave us little notice to plan it, and we have learned a lot. Next summer we will change many things, relying on the experience gained. We now share both the good and the bad from this past summer, and welcome suggestions from readers.

The Polymath REU is an Inclusive Program

We accepted all applicants who took a proofs class and had a supportive letter from a math professor. Out of 352 applicants, 303 were accepted. We expected some participants not to be active in the program, but wanted to give everyone a chance. Some participants found it difficult to make progress with the research but contributed in other ways (writing, running the website, or even organizing social events). Rather than setting an expectation for all participants to contribute new findings, we encouraged students to join the program to learn more math and get an idea about what research looks like.

The above raises an issue: who gets to have their name on any published papers? We decided that anyone who spends a reasonable amount of time on a project gets to have their name included. Imitating the original Polymath Project, some of our papers use a pen name such as "Polly Matthews Jr." (with a list of the authors below). This is not a perfect solution, since some participants contributed considerably more than others. As expected, some projects were pushed forward by a small group of exceptional participants.

We made the above issue clear when first advertising the program, so as not to mislead anyone. Participants who made significant contributions can ask for a letter of recommendation from a mentor. Thus, when applying to grad school or a job, students who contributed more will have stronger support.

The following is our rough and possibly inaccurate estimate:

- About a third of the participants were inactive.
- About a third of the participants were actively participating in the research work.
- The last third were following along but not actively contributing to the research.

Comments in the exit surveys complained about many participants not contributing. This happened for a variety of reasons; for example, some students had to work significantly more hours than they expected to help their family (some students sadly withdrew from the program due to such considerations). Still, we feel our approach remains the best solution, or at least a good start: *everyone has the opportunity to participate, it is up to them to choose to do so*. While this problem is not unique to our Polymath program, it is something we will consider for future iterations. What can we do, especially at the start of the summer, to increase those who actively participate?

The following remarks from the exit surveys give a flavor for what different participants enjoyed:

- "My favorite part was reading the literature and collecting data that would support or contradict our conjectures."
- "My favorite part were the people in the program."
- "This was my first research experience so it was also very nice to see how research is done and to contribute some results to it."
- "While not being a big contributor to the group, I had fun learning what I could and challenging myself with the exercises."
- "I really enjoyed the freedom I had to research what interested me the most within my project."
- "My favorite part was the presentation."

The Structure of the Program

The program was split into projects, and each participant belonged to just one (though some mentors ran two unrelated projects). We had groups in number theory, combinatorics, complex analysis, convex geometries, commutative algebra, and representation theory. Each project had a main mentor, who not only was an active researcher in the relevant field but also had previous mentoring experience. Most main mentors were also organizers of standard REU programs (we thus wanted a program that mentors could run while still doing previous commitments). Each project included additional mentors, who were mostly postdocs and graduate students. In addition to helping manage the time commitments for the senior mentors, this allowed us to help train some of our junior colleagues in mentoring research.

The program ran for eight weeks during June–August of 2020. The first week of the program was dedicated to introducing the various projects, via Zoom talks, introductory documents, and more. Each participant then ranked their

preferences. This worked better than expected. With a single exception, all participants joined one of their two top choices, and each group had between 19 and 30 students.

Imitating the original Polymath Project, we created a wiki site for the program, but ultimately this did not work well. While the wiki served as a central repository for posting resources such as papers and videos, most of the technical work was done through Overleaf and Zoom.

The more interesting development was suggested by the students—Discord. A Discord server consists of chat rooms, voice channels, and more. Each project had forums for work purposes (usually multiple rooms for different parts of the project). There were also chat rooms for social activities, for the various groups (games, music, food, and so on), chat rooms open only to mentors, and so on. The students used voice channels, mostly to chat with others who happen to be online and schedule working meetings. In the exit survey, the participants marked that they found Discord to be the most helpful resource, and then their peers and the mentors. The wiki page was marked as significantly less helpful than anything else.

We were worried about toxic situations in the Discord chat rooms, such as students disrespecting or discouraging others. We appointed a group of student volunteers to be chat room moderators. It was also rare to have a time when none of the 27 mentors were connected. This worked! We only had a single falling out among students, due to an impatient student. No moderator ever stumbled upon a serious incident and our anonymous complaints form never contained such a complaint.

The program ended with a two-day Zoom conference, where each group presented their results. We let participants invite family, friends, and teachers. We encouraged each group to have multiple speakers, to allow many students to practice their presentation skills. We also encouraged the participants to present their results in other conferences. These include local conferences about undergraduate research and conferences such as the Joint Mathematics Meetings.

An Anxiety Issue

Impostor syndrome was a main concern throughout the program. It was caused by students coming from different backgrounds, by some students having previous familiarity with the topic of their project, by the social media phenomenon in which others' lives or skills seem rosier when presented online, and more. We tried a variety of approaches and will continue to think about how to address this issue.

During the first week of the program, we ran Zoom meetings that introduced the projects. We wanted students to get to know the mentors and the problems before committing to one. On the third day we had a welcoming session, where we mentioned that it's standard not to understand many parts of a math talk. This was clearly a moment of big relief for many participants. Another such moment happened when we discussed impostor syndrome. We should have stated both at the beginning of the first day.

Every project started with learning the relevant material and thinking about exercises. Some students were having difficulties learning the material but were too embarrassed to tell their mentors. The number of active participants increased when mentors ran additional Zoom sessions to support participants who were struggling.

The Future

We suggest the name MOO-REU for a Massive Online Open REU. The Polymath REU program is a MOO-REU, but one can imagine different types of MOO-REU programs. One question is whether there exists a more effective format than the one we used, or perhaps several as one size rarely fits all perfectly.

MOO-REUs are clearly useful during a pandemic, when many students are stuck at home with nothing to do. Are MOO-REUs also useful in more standard times? We believe that the answer is yes, for several reasons:

- The number of available spots in math REUs is currently significantly smaller than the number of qualified applicants. Some people claim that it is easier to get accepted to a PhD program than to an REU program. Even if this is an exaggeration, the current situation seems unhealthy.
- We believe that the most important aspect of MOO-REUs is providing opportunities to students who usually do not get into REUs. In particular, such programs provide opportunities to international students and to students who come from a college and high school that do not have many mathematical activities. This lack of opportunity to demonstrate their abilities makes it unlikely for them to get accepted to a standard REU.
- Participating in a MOO-REU requires a smaller commitment from the participants. It is an opportunity for students who cannot commit to a full-time program. It is also an opportunity for students who are not sure if they should do math research. Such students can be partially active in the program, learn more math, and get a first impression about what research looks like.
- It is also valuable for mentors, providing them an opportunity to help create a research program.

We believe the MOO-REU model can be exported to many theoretical sciences; it would be wonderful if a version could be created for lab sciences, as many of the students who lost summer opportunities hailed from there.

Participants also believe that the program should continue, as the comments below from the exit surveys indicate:

- "I'd like to know when the next one is."
- "I would really hope this happens again in the future!"

- "I really would want REU like this to happen again next summer!"
- "This program was the highlight of my summer so thank you for this cool opportunity :)"
- "This made my summer 10 times better than it was going to be."

Our Main Conclusion: Make Lemonade

The most important conclusion from this story might not be about the Polymath REU or even about math. It is that *one can make a big impact in a difficult situation without having many resources*. Sometimes, all you need are good intentions and time.

We were surprised by how simple it was to create a new kind of large-scale program. Tools such as Zoom, MediaWiki, and Discord allowed us to quickly build something large and complicated. The important thing was to have people who want to help and are willing to spend time on the program.

The program owes much of its success to the many dedicated mentors who supported the students. It is unfair that only the main mentors have their names on this article and in some other places. We thus wish to include the names of all other mentors here. This wouldn't have happened without them: Madina Bolat (University of Illinois, Urbana-Champaign), Galen Dorpalen-Barry (University of Minnesota), Ben Drabkin (University of Nebraska-Lincoln), Nóra Frankl (London School of Economics), Claire Frechette (University of Minnesota), Gent Gjonbalaj (Tufts University), Elizabeth Kelley (University of Minnesota), Surya Mathialagan (MIT), Erin Meger (Université du Québec à Montréal), Clayton Mizgerd (Williams College), Jonathan Passant (University of Rochester), Fei Peng (Carnegie Mellon University), Tudor Popescu (Carnegie Mellon University), Abigail Raz (University of Nebraska-Lincoln), Cody Stockdale (Clemson University), Eric Nathan Stucky (University of Minnesota), Tingting Tang (San Diego State University), Nathan Wagner (Washington University in St. Louis), Nawapan Wattanawanichkul (Bowdoin College).


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