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# The Pipeline CURE: An Iterative Approach to Introduce All Students to Research Throughout a Biology Curriculum

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## Abstract

Participation in research provides personal and professional benefits for undergraduates. However, some students face institutional barriers that prevent their entry into research, particularly those from underrepresented groups who may stand to gain the most from research experiences. Course-based undergraduate research experiences (CUREs) effectively scale research availability, but many only last for a single semester, which is rarely enough time for a novice to develop proficiency. To address these challenges, we present the Pipeline CURE, a framework that integrates a single research question throughout a biology curriculum. Students are introduced to the research system - in this implementation, *C. elegans* epigenetics research - with their first course in the major. After revisiting the research system in several subsequent courses, students can choose to participate in an upper-level research experience. In the Pipeline, students build resilience via repeated exposure to the same research system. Its iterative, curriculum-embedded approach is flexible enough to be implemented at a range of institutions using a variety of research questions. By uniting evidence-based teaching methods with ongoing scientific research, the Pipeline CURE provides a new model for overcoming barriers to participation in undergraduate research.

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**Supporting Materials:** S1. Pipeline CURE - Table of Pipeline learning goals; S2. Pipeline CURE - Detailed implementation; S3. Pipeline CURE - Figure of Stage 1; S4. Pipeline CURE - Figure of Stage 2; S5. Pipeline CURE - Figure of Stage 3; S6. Pipeline CURE - Pre-post surveys.

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## INTRODUCTION

Across scientific disciplines, participation in undergraduate research has been linked to positive outcomes for students (1). Those who conduct research benefit academically, with increases in content knowledge, technical skills, and analytical skills, as well as personally, with higher self-efficacy and persistence in their major (2-5). These gains are observed for all students and are more pronounced for groups who continue to remain underrepresented in the sciences (6-12). However, access to research opportunities as an undergraduate is often limited and competitive, so students who could most benefit from participating in research may miss out on these positions. As long as entry to research remains opt-in, certain students will continue to be excluded, perpetuating inequity in STEM fields (13-15).

One solution is to embed research in courses, which makes participation in research a default option (13,15). Course-based undergraduate research experiences (CUREs) engage students in research during normal class time (5,16,17). CUREs effectively scale research availability to remove some barriers to participation, helping to address continued disparity among STEM majors (13,14). Those who participate in CUREs gain similar benefits as those who participate in traditional apprentice-style research, including improved self-efficacy and persistence in science (7,18,27,28,19-26). In some ways, CUREs can be more effective than traditional research experiences because they allow students to assume responsibility and develop analytical skills through peer interactions (5,27). A primary challenge for CUREs and other short-term research experiences is their duration. Lab skills can take months to master, so some research experiences end before undergraduates become confident in their abilities. Professors at institutions with little research infrastructure can implement multi-institutional CUREs that have been designed for use without prior expertise in the research system (20,25,29,30). These CUREs engage students in a national research community, but they do not draw on personal scholarship nor allow for reciprocal interactions with scientists invested in the CURE outcome.

To address these challenges at a small college, we developed the "Pipeline" CURE, which integrates a single research question across an entire biology curriculum. In a pipeline, the output of one stage is the input for a subsequent one. This metaphor suits our CURE because it uses a series of deliberately-staged lab experiences to cultivate scientific literacy. Students who have completed the Pipeline spend at least 300 hours working at the bench, which is equivalent to a full-time summer research internship. By finding ways to overcome setbacks in successive Pipeline stages, students gain resilience and confidence in their abilities. The Pipeline was developed as a collaboration between a liberal arts college and a research university. This partnership has yielded synergistic benefits, some by design and some by surprise, in a way that strengthens both partners. Here, we present our collaborative model as a widely-implementable curricular framework. The Pipeline allows us to introduce all students to scientific research, rather than just the elite few.

## DESIGN

Oglethorpe University is a small liberal arts college in Atlanta, Georgia, with 1,350 undergraduates. Despite being a private institution, Oglethorpe's student body reflects the diversity of the Atlanta metro area: 33% of students belong to an underrepresented minority group, 38% are the first in their family to attend college, and 29% commute to campus. The Biology department serves more underrepresented minority students than other STEM disciplines, but these students are more likely to leave the major before graduation than their peers. Since participation in research increases student success and retention in STEM disciplines, the Pipeline was conceived, in part, to improve the outcomes for underrepresented minority students majoring in biology.

Before the Pipeline, Oglethorpe's lack of research infrastructure prevented faculty from offering sustained research experiences. To bring biological research to campus, Dr. Karen Schmeichel, a Biology professor at Oglethorpe, established a collaboration with Dr. David Katz, a researcher at nearby Emory University School of Medicine. The Pipeline is designed around a single research question in the model nematode *C. elegans*, which students commonly call worms. The research conducted in the Pipeline is both informed by and supports ongoing work in the Katz lab, placing Oglethorpe students within a wider research narrative that offers real potential for publication. Currently, this collaboration is supported by a subcontract under a grant from the National Science Foundation awarded to Dr. Katz.

We have embedded the Pipeline in four biology courses, with an option to participate in research beyond the main experience (Figure 1). In each stage of the Pipeline, prior skills are reinforced as new skills are introduced. This approach incrementally develops independence and engagement with scientific concepts over the four-course series (described in Supporting File S1: Table of Pipeline learning goals). Students first encounter worms during a short module in a required introductory course. They next spend two months working with worms in a required intermediate-level genetics course. Students can then take one or two upper-division elective courses working on a worm research project for the entire semester. Finally, those who would like to continue in research are eligible to conduct an independent study, work at Emory as an undergraduate researcher, and/or complete a senior honors thesis. As with other CUREs, the incorporation of faculty research interests creates a relationship where students and professors both benefit from the work conducted in the classroom.

## IMPLEMENTATION

An essential element of the Pipeline's success is the ease of its model system. We use the microscopic nematode *C. elegans* to investigate the regulation of epigenetic inheritance, both during development and between generations. The benefits of *C. elegans* as a model organism are manifold and have been described elsewhere (31,32), but there are several that make it especially well-suited for use at Oglethorpe. Worms are simple and economical to maintain in a lab, have a well-annotated genome, are used in a broad range of biological questions, and have a supportive community of researchers who are often willing to help budding scientists. Perhaps most important for novices in the lab, strains can be frozen and kept indefinitely in a -80°C freezer, which means that any mistakes made in animal maintenance need not be catastrophic. On the following pages, we summarize each Pipeline stage, with a more detailed implementation included in Supporting File S2: Detailed implementation of the Pipeline.

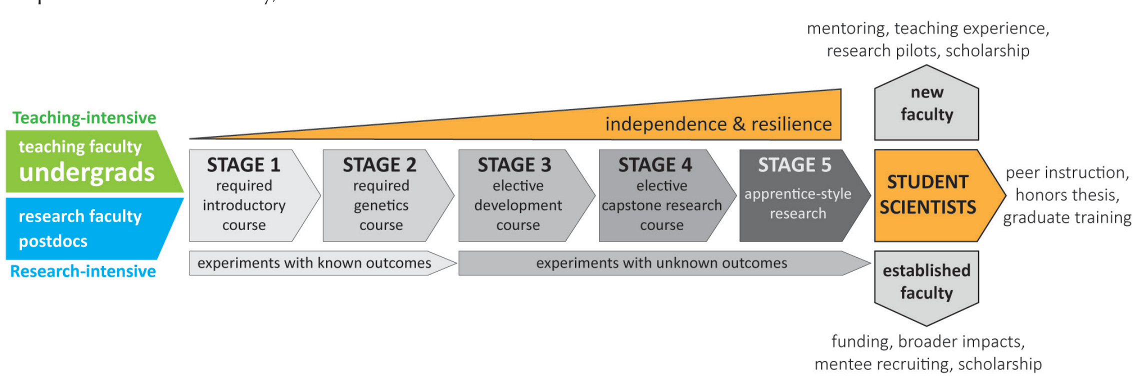


Figure 1. Summary diagram of the Pipeline CURE. On the left, faculty, research trainees, and undergraduate students from both teaching-intensive (green) and research-intensive (blue) institutions collaborate on a sequence of guided research activities that develop technical complexity and student independence (center). These activities are designed to familiarize students with an actual research environment, as well as build independence and resilience throughout the curriculum. On the right are listed the ways in which our collaboration benefits all participants.

### *Stage 1: An introduction to* C. elegans *husbandry*

In their first course for the Biology major, students spend two weeks learning basic worm husbandry, sterile technique, and the maintenance of genetic crosses. An example cross is shown in Supporting File S3: Figure of Stage 1. This stage uses a traditional known-outcome lab to instruct novices in the practice of conducting genetic experiments. Students work in pairs to plan their experiments, prepare reagents, and collect data. If a cross fails, students are expected to repeat it, and importantly, they have the time to do so. The nature of these crosses requires after-hours work, during which students practice personal accountability and troubleshooting in the absence of an authority figure.

### *Stage 2: Students develop strategies for independent experimental work*

Students next revisit worms in a required course typically taken by sophomores. Lab teams spend eight weeks mapping an unknown mutation using visible markers. This stage is modeled after Hartman and Caudle (33), and example crosses are shown in Supporting File S4: Figure of Stage 2. After Stage 1, students are acquainted with the research system and are ready to assume more responsibility. Stage 2 offers them a chance to become fully comfortable with the system and working independently. As they work through different linkage crosses over the two-month period, students develop an awareness of others in the lab and hone their attention to detail. The loose structure of this stage is a fundamental component of its design. The timeframe is long enough that students can attempt a single cross multiple times, which gives them the chance to remedy earlier mistakes and collect multiple replicates for statistical analysis.

### *Stage 3: Research using reverse genetic screening*

After taking the required early Stages, students can choose between two upper-division elective courses, or take both. Those who choose not to take the Stage 3 course can still take the Stage 4 course. In Stage 3, students spend nearly an entire semester conducting a candidate genetic screen using RNA-interference (RNAi) a powerful reverse genetic technique. Students use RNAi to identify enhancers or suppressors of an easily scorable phenotype, as detailed in Supporting File S5: Figure of Stage 3. This stage was developed as an extension of Katz lab research (34) and is the first time in the Pipeline that students work on a project that could yield new insights to the field. After Stage 2, students are fully aware of the commitment required for working at the bench and quickly take ownership over their experiments. During the semester, they are afforded the same amount of independence as most apprentice-style undergraduate researchers, including after-hours access to the lab. We have found that students are energized by the fact that their work may result in a novel discovery, as with other CUREs (35). They sincerely want to produce a conclusive result, a desire that is further bolstered by a visit from Dr. Katz to discuss the relationship of their data to ongoing research. The semester culminates with a poster session in which teams present their work to their peers and Katz lab members.

### *Stage 4: Research that supports postdoctoral projects*

We developed Stage 4 as an elective capstone-style course that emulates the experience of a summer research internship. This course is designed and taught by a postdoctoral fellow from the Katz lab, which gives Oglethorpe students a unique opportunity to work with a practicing biologist. In turn, the postdoc can pilot new research directions and generate preliminary data. In Stage 4, the majority of class time is spent on experiments and practical aspects of working in a research lab, with a focus on experimental design and scientific communication. Students participate in lab meetings and generate a number of research products: an electronic lab notebook, scientific poster, final manuscript, and mini-grant proposals which are reviewed in a peer-led study section. A significant portion of their coursework is spent on editing their peers' writing and revising their own work, which helps to reinforce a culture of scientific discussion. By Stage 4, students are fully prepared for independent work. They are also exposed to many research lab norms, including citizenship when using shared equipment and reagents. Student teams are encouraged to develop their own strategies for organization and communication and have the freedom to manage multiple experiments at the same time.

### *Stage 5: Independent research and honors theses*

The primary goal of the Pipeline is to provide Oglethorpe students with research experiences that are not otherwise available. All biology majors (and many other pre-health students) are served by Stages 1 and 2, with a large subset choosing to participate in the research experiences of Stages 3 and 4 (some students have even chosen to participate in Stage 4 twice). For those interested in a research career, the Pipeline includes a limited number of traditional summer research experiences, which are often a prerequisite for entering a doctoral program. Since we started the Pipeline, more students have expressed an interest in summer internships, indicating our success in removing some barriers that previously prevented them from participating in research. For the last four summers, a rising senior has worked on an independent project under the supervision of a postdoc mentor in the Katz lab. Three summer students have extended their projects into successful honors theses. To our knowledge, all previous biology theses at Oglethorpe were literature reviews, making the Pipeline projects the first research-based theses in the biology department.

Stage 5 greatly enriches the experience for both institutional partners. When Pipeline students start their summer projects at Emory, they progress quickly to intensive data-collection. In fact, students who continue in research after they have completed the Pipeline will have more experience working with their research system than most other students who participate in traditional research experiences. The most recent Pipeline honors thesis generated data for a publication and informed the direction of a mouse neural development project. The success of this project supports the efficacy of using the Pipeline as a pilot study for new research directions. Another benefit of having an Oglethorpe student deepen their research expertise is that they can subsequently serve as a teaching assistant for earlier Pipeline stages. Since all stages require significant after-hours work, having a student hold evening and weekend office hours turns out to be essential for smooth operation of the Pipeline. For students, having a peer instructor made benchwork seem more approachable. These peer instructors are also valuable insider contacts into a larger research network for other Oglethorpe students, especially after they graduate and pursue STEM careers.

## DISCUSSION

### *Developing independence and resilience*

We present a new model for CUREs by embedding a single research system in multiple stages of a biology curriculum. The Pipeline CURE takes a deliberate and developmental approach to making research more accessible to all biology majors at a small liberal arts institution. Following the recommendations of Corwin and colleagues (26), we will assess the outcomes of the Pipeline CURE in three phases, which we hope to present in future manuscripts. We have started by measuring short-term outcomes of each Pipeline stage with a pre-/post-test, which is modeled after the CURE survey and included in Supporting File S6: Pre-post surveys (30). A significant advantage of the Pipeline over other CUREs is that it incorporates opportunities to revisit prior challenges or mistakes in successive courses. We will present the full data in a future manuscript, but one interesting preliminary result is that students who have completed Stages 3 or 4 focus less on technical frustrations and more on their own ability to generate high-quality data.

One of the most valuable elements of apprentice-style research is the chance to overcome the challenges of working in research. It is difficult to replicate this full effect in a single semester or even during an intensive summer, because mastery is founded upon repeated exposure (36-39). Resilience is cultivated in a feed-forward loop: mastering challenges increases self-efficacy, which boosts motivation, which in turn improves the likelihood of overcoming new challenges (37,40-42). Our preliminary surveys raise the possibility that students may experience the same benefits as those who work in a traditional apprentice-style setting for multiple semesters. If these results are supported by our future assessment, then the Pipeline would present a model for undergraduate training that does not require further extracurricular work and may improve retention for those most at risk of leaving the major (14,18,42,43).

### *Professional development for teaching faculty and research trainees*

In addition to helping students, the Pipeline has also generated unanticipated benefits for Oglethorpe faculty. Through conferences, seminars, and lab meetings, it provides an opportunity for a teaching-focused faculty member to interact with a research community that would not otherwise be available. By collaborating with the Katz lab, the impact of the work performed at Oglethorpe is amplified and situated in a wider scientific context (44). Additionally, Oglethorpe faculty can leverage their collaborations with research-intensive partners for salary increases, merit-based promotions, and institutional grants. Because excitement and support for the Pipeline has percolated through campus, the benefits may extend beyond the Biology department. For example, the Pipeline has been used to garner funding and support from alumni, trustees, and donors, and this collaboration was an important stakeholder in designing a new science building.

It is also important to note the ways in which the Pipeline benefits our partners at the research-intensive institution. As described above, the Pipeline serves as a useful pilot for exploratory projects for the associated research lab, or for an individual postdoc's future work. Additionally, postdocs who participate in the Pipeline develop a skill set that will be indispensable in their future careers, whether in academia or elsewhere. By successfully teaching a research-based course, postdocs also demonstrate their ability as an instructor and a principal investigator, making them attractive candidates for faculty positions at a variety of institutions.

### *Future implementation*

Although the Pipeline's research paradigm is tailored for the Katz lab, we believe that this approach is scalable and easily adapted for other research questions. At its heart, the Pipeline CURE scaffolds a single research system at all levels of a curriculum. Its core mission can be applied in many types of institutions and does not require two partners for its success. Institutions with strong research support can collaborate in-house on a research question, while those with less support could collaborate with government institutes, medical schools, research centers, or industry partners. The current implementation of the Pipeline is funded by an extramural grant, most of which is used for stipends to support summer undergraduate research. However, all of the course-embedded aspects of the Pipeline could be covered using student fees associated with lab courses, if extramural funding were not available. Research questions are not limited to molecular biology, as most research skills can be taught using a wide number of paradigms, like bioinformatics or public health. A single framework suited the size of Oglethorpe's Biology department, but other institutions could offer students a choice between multiple research systems. The Pipeline prioritizes a deep dive into one research system over topical breadth, but we have seen that Pipeline students who continued in research adapted quickly to new experimental systems. Thus, the experiences of the Pipeline develop research generalists rather than worm specialists.

The Pipeline CURE uses repeated exposure to a single research system to develop research ability incrementally over the course of a Biology curriculum. This approach expands research access to those who are least likely to seek out these experiences but who may benefit the most (13). By uniting evidence-based teaching methods with ongoing scientific research, the Pipeline CURE provides all students with a chance to participate in the research endeavor within the classroom.

## SCIENTIFIC TEACHING THEMES

### *Active learning*

The Pipeline CURE engages students with a unified research system (*C. elegans*) at all stages of the biology curriculum, where they work in small teams to maintain strains, prepare reagents, and execute experiments. In the later stages of the Pipeline, experiments can take several months, and planning is completely left up to student teams. Teams are also responsible for collecting, analyzing, and communicating data to their peers. In early Pipeline stages, students write lab reports and present in small team meetings. In later Pipeline stages, students present posters, give lab meeting, and write manuscripts.

### *Assessment*

Formative assessments vary throughout the Pipeline's stages, but include whole-class discussions of the primary literature, scaffolded writing assignments (lab reports, manuscripts, and grant proposals), peer editing of writing drafts, presentation of lab meetings and posters, and periodic team meetings with the instructor. Summative assessments include final written or presentation products (lab reports, lab meeting, posters, manuscripts, and grant proposals) and exams. In addition, at the end of each Pipeline stage, groups were asked to evaluate the contributions of each individual. At all stages, we evaluated student attitudes towards research and the nature of science using a survey or focus group discussions.

*Inclusive teaching*

The Pipeline CURE introduces students to the practice of working with the research system (*C. elegans*) in their first two mandatory biology courses. By the time students make a decision to participate in research in upper-division electives, their familiarity with the system helps to remove some of the institutional barriers that prevent students from seeking research opportunities. By embedding the Pipeline's research within two upper-division courses, students can participate in research without any extra-curricular commitment or extra cost, which removes some barriers to entering research.

## SUPPORTING MATERIALS

- S1. Pipeline CURE: Table of Pipeline learning goals
- S2. Pipeline CURE: Detailed implementation
- S3. Pipeline CURE: Figure of Stage 1
- S4. Pipeline CURE: Figure of Stage 2
- S5. Pipeline CURE: Figure of Stage 3
- S6. Pipeline CURE: Pre-post surveys

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