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STUDENT COURSE-BASED RESEARCH

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ABSTRACT

On behalf of the National Science Foundation, we assessed the effectiveness of a new pedagogy: Course-based Undergraduate Research Experiences (CUREs). A meta-analysis of 41 published articles, additional archival research, and semi-structured interviews identified multiple benefits of CUREs, including their ability to introduce more students to research. We assessed outcomes of CUREs and identified obstacles to their successful implementation. We recommended a set of features that the best CURE programs should incorporate.

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AUTHORSHIP

Chapter & Section Number	Chapter & Section Name	Names of Primary Authors	Names of Primary Editors
i	Abstract	Anne, Mohammed, Tianchang	Anne, Mohammed, Tianchang
1	Introduction	Anne, Mohammed, Tianchang	Anne, Mohammed, Tianchang
2	Literature Review	Anne	Anne, Tianchang, Mohammed
2.1	Sponsor Profile	Mohammed	Anne, Tianchang, Mohammed
2.2	Stakeholder	Tianchang	Anne, Tianchang, Mohammed
2.3	Nature of Science as a Foundation for Education	Mohammed	Anne, Tianchang, Mohammed
2.4	Literature Review of CURE and REU	Anne	Anne, Tianchang, Mohammed
2.5	How the Success of Other Programs Has Been Measured	Mohammed	Anne, Tianchang, Mohammed
2.6	Discussion of Claims	Anne	Anne, Tianchang, Mohammed
2.7	Related Case Studies	Tianchang	Anne, Tianchang, Mohammed
2.8	Summary	Anne, Tianchang, Mohammed	Anne, Tianchang, Mohammed
3	Methods	Anne	Anne, Tianchang, Mohammed
3.1	Pilot Interviews	Anne, Tianchang, Mohammed	Anne, Tianchang, Mohammed
3.2	Objective 1	Tianchang, Mohammed	Anne, Tianchang, Mohammed

3.3	Objective 2	Anne	Anne, Tianchang, Mohammed
3.4	Objective 3	Tianchang, Mohammed, Anne	Anne, Tianchang, Mohammed
4.1	Findings: CUREs Complement REUs	Anne, Mohammed, Tianchang	Anne, Mohammed, Tianchang
4.2	Findings: CUREs Emphasize Teamwork	Anne, Mohammed, Tianchang	Anne, Mohammed, Tianchang
4.3	Findings: Mentorship is Significant	Anne, Mohammed, Tianchang	Anne, Mohammed, Tianchang
4.4	Findings: Lack of Time is an Obstacle	Anne, Mohammed, Tianchang	Anne, Mohammed, Tianchang
5.1	Conclusion	Anne	Anne, Mohammed, Tianchang
5.2	Recommendations	Anne, Tianchang	Anne, Mohammed, Tianchang
5.3	Future Research	Anne	Anne, Mohammed, Tianchang

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

PROBLEM DEFINITION

Traditional classroom-based STEM education systems have received criticism for not adequately preparing students for real-word problems. This criticism of traditional teaching methods has shed light on the need for flexible undergraduate programs that prepare undergraduates for the professional life of a scientist, engineer, or high-level technician. Integrating real-life experiences into undergraduate education is a necessary and practical way for students to learn field-specific skills since they are not always taught in traditional classes.

The National Science Foundation (NSF) has begun funding a novel approach known as course-based undergraduate research experiences (CUREs) to facilitate the development of this new integrated pedagogy. CUREs provide a classroom of students with real-life problems to solve. This pedagogy has been shown to help students improve their self-esteem, develop intellectually, and clarify their career paths.

The value of CURE programs has not been widely researched. The NSF would like to evaluate the effectiveness of CUREs and similar programs and to compare the outcomes of CUREs to Research Experiences for Undergraduates (REUs). REUs are apprenticeship-style undergraduate research experiences in which one student typically works with one mentor to research a solution to a novel problem. The outcomes of this assessment can help to guide the success of future programs. Therefore, the goal of this project was to evaluate the effectiveness

of CURE programs by identifying the qualities that make such an undergraduate research program successful.

GOALS, OBJECTIVES, AND METHODOLOGIES

We formulated three objectives to fulfill our goal of evaluating what makes course-based undergraduate research programs successful. As shown in *Figure 1,* the first objective was to identify what the NSF values in an undergraduate STEM education program through semi-structured interviews with NSF officials.

The second objective was to identify the primary outcomes of undergraduate research experience programs; it which was the core topic of this project. These outcomes were found through a meta-analysis of published work, that is, through an archival review of studies related to programs similar to CUREs that have succeeded or failed in achieving the goals of CUREs. In this analysis, we examined the factors that have made these programs successful or less than fully successful. In addition, we explored how CURE has impacted learning in STEM fields and how it has affected students' performance in other scholarly areas.

Our third objective was to formulate recommendations for the best implementation of CUREs. After we met these objectives, we were be able to identify clearly the actual outcomes of research-based learning programs such as CUREs, to make a comprehensive comparison between CUREs and REUs, and to provide recommendations to the NSF on how to make such programs more effective.
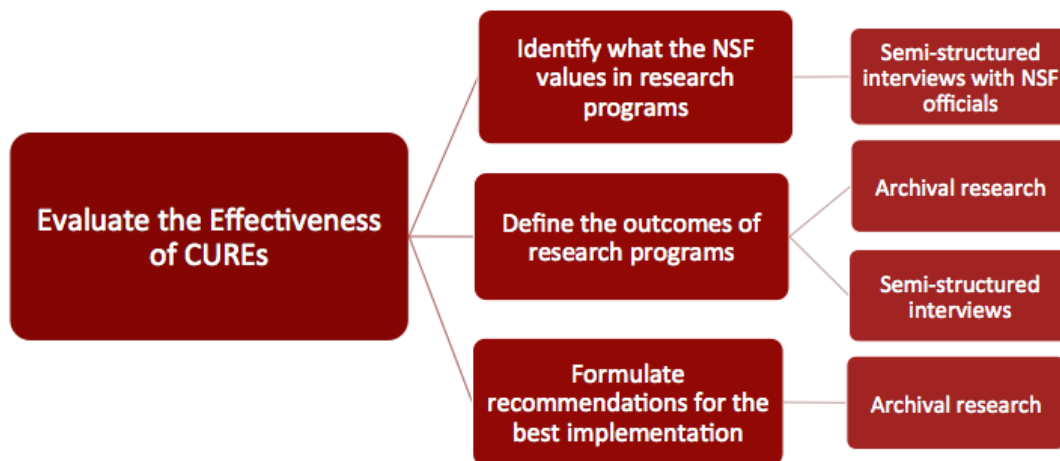
Figure 1: Outline of Goal, Objectives, Methods. In order to evaluate how effective CUREs are, we identified what parts of research programs the NSF values, defined research program outcomes, and then recommended how to best implement CUREs. Our methods include semi-structured interviews and archival research.

DEFINITION OF CURES

In order for a program to be distinguished as a CURE, it should engage the students in five critical activities: the use of scientific practices, discovery, meaningful work, collaboration, and iteration, as illustrated in *Figure 2*. Scientific practices include asking questions, analyzing data, constructing hypotheses, and communicating results and findings. This deals with the nature of science, which describes how science is created. CURE exposes the students to the benefits of teamwork, and thus allows them to understand the importance of such synergy. The work the students do in CURE should also be of a benefit for society. Finally, CURE should engage the practice of iteration in order increase the retention of students. The unique structure of CUREs avoids the difficulty of incorporating these five practices simultaneously into a traditional classroom and provides students in STEM fields with a real-life research experience.
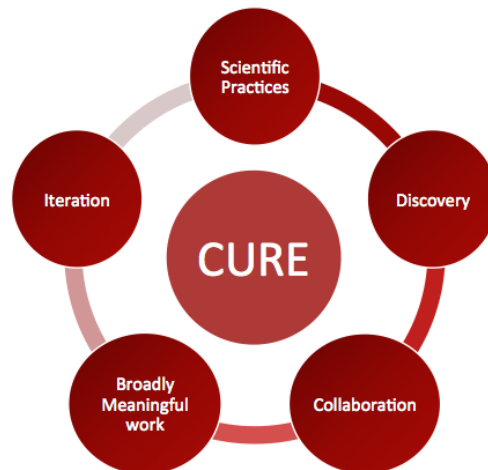
Figure 2: CURE Definition. CUREs must engage students in scientific practices, incorporate discovery of new knowledge, require collaboration among students, engage the students in meaningful work, and involve iteration of procedures.

PILOT INTERVIEWS

We conducted sixteen interviews to students who presented their NSF-sponsored REU projects at an NSF symposium on October 27th, 2014. The goal of these interviews was to give directions to what outcomes should be looked for during the archival search as well as to allow a comparison between CURE and REU to be performed. The audio from all the responses was recorded for analysis at a later time. Students were asked about the length of the programs and the mentorship style they had. Also, students were asked about the top three benefits they obtained from their research experience. In addition, students were asked about their expectations about their REU experiences before they entered it. Finally, students were asked to provide recommendations on how to improve REUs in the future. *Table 1* and the pie diagrams in *Figure 3* below summarize the results of these interviews.

Figure 3: Pilot Interview Results. The most common program length was 10 weeks, but it varied from 7 weeks to over a year. Mentorship styles consistently had at least one undergraduate student and one professor, the most common occurrence, but varied in the number of undergraduate students or graduate students. Students most commonly mentioned that they thought the top benefits of participating in a CURE were that they gained an understanding of what research required, as well as had opportunities to network. Among the other top benefits most often mentioned are learning more material, understanding what graduate school requires, becoming more confident, learning about topics related to their major, becoming better critical thinkers, and that the project had a positive impact on them.

Expectations	Recommendations
Be introduced to the culture of research	Allot time to learn about the background
Gain experience	Increase students awareness of the existence of the REUs
The REU would be very different experience than any other experiences in undergraduate	Make REUs accessible to a large number of students
The REU would be just like other experiences in which students forget about the material over time	Change mentorship (more or less monitoring)
Networking	Period of research is not enough
No expectations	Everything was perfect

Table 1: Pilot Interview Results. Students were asked what their expectations were prior to entering the REUs, as well as what ideas they had to improve their program.

FINDINGS

CUREs are beneficial since they bring research to more students. They provide networking opportunities and ways to improve scientific skills while learning new material. Students leave CUREs with a better understanding of what graduate school entails. CUREs lead to the development of teamwork and critical thinking. Students also improve their research and communication skills. These outcomes all contribute to boosting students' confidence. Our research identified obstacles to successful CURE implementation including:

- Lack of time for mentors to design programs and provide an authentic research experience
- Lack of resources that limit the number of participants (funding, space, mentoring staff)
- Balancing mentorship styles

CURE AND REU COMPARISON

We used the results from the interviews and the archival search to perform a comprehensive comparison between REUs and CUREs, which was a minor goal in our project. We compared the properties of both programs such as the goal, length and collaboration style shown in *Table 2*. *Figure 4* describes the comparison of outcomes of CUREs and REUs. CUREs and REUs share several outcomes, however, CUREs integrate a level of teamwork that is not seen in REUs. REUs provide a more concentrated time period of research, where the student only has to focus on the research, not any other classes.

Description	CUREs	REUs
Purpose	Introduce students to scientific research	Introduce students to scientific research
Expected Research Background	Not required	Basic techniques
Length	Depends on the program	7-10 weeks
Collaboration Style	Always team-structured	Independent / team-structured
Mentorship	Usually a professor & multiple graduate students	Usually a professor & a graduate student
Availability	All students	High-performing students

Table 2: Comparing and Contrasting CUREs & REUs. The purpose, expected research background, program length, collaboration style, mentorship, and availability of CUREs and REUs is compared.
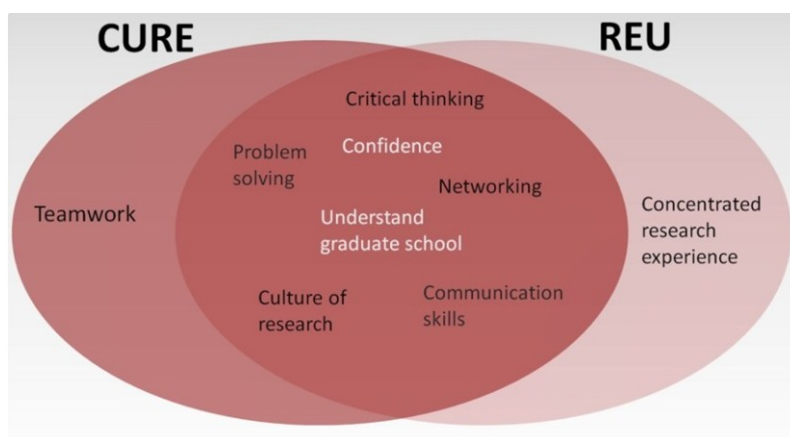
Figure 4: Outcome Comparison. CUREs and REUs share many outcomes; Teamwork is emphasized more in CUREs, while REUs provide a more concentrated research experience.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, our research shows that CUREs are good supplements to REUs. CUREs, if implemented effectively, supply students with bona-fide research experiences. Our research identified obstacles, outcomes, and benefits associated with CUREs, shown in *Figure 4*. We found that CUREs result in numerous benefits and positive outcomes, including the development of teamwork and critical thinking, as well as improving scientific, communication, and research skills. CUREs provide an opportunity for students to work in teams to investigate a problem or implement a design, giving the students a chance to develop teamwork skills in a research environment. CUREs can accommodate more students than REUs usually do; therefore, more students will become exposed and possibly interested in research. Moreover, our analysis showed that both the quality of mentorship and the time devoted to integrating real-life research into undergraduate STEM courses have a tremendous impact on the success of CUREs.

We also recommend continued study of ways in which the course structure can be improved to provide better outcomes and overcome obstacles such as lack of time and resources, as well as keeping the research authentic and balancing mentorship styles. As education changes, so may the need for CUREs. However, right now, they are a useful tool for educating students about research and STEM fields. We want to make it possible for students to be motivated by research, and we believe that following our recommendations will inspire generations of students to CURE our world.
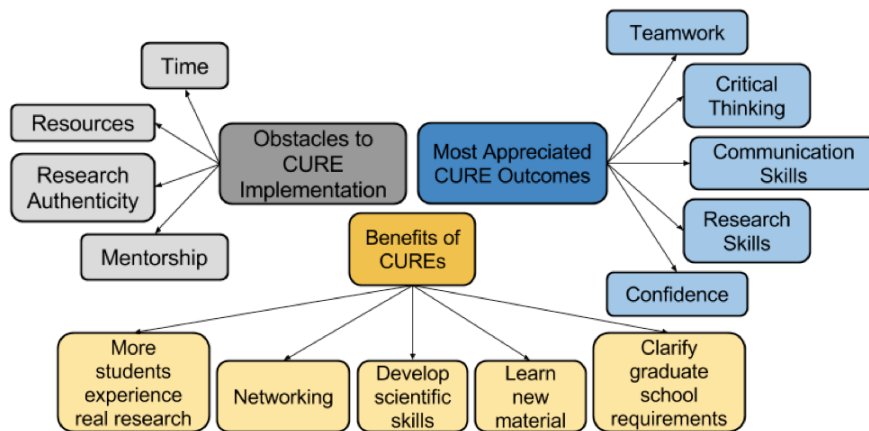
Figure 5: Obstacles, Outcomes, and Benefits. Overcoming obstacles referenced here will result in better outcomes & benefits.

FUTURE USE

To use these results, we suggest that our recommendations be incorporated into the materials distributed to program designers in the NSF's call for proposals. This will give applicants access to recommendations that are based on what the NSF values, giving them a better chance at delivering effective CURE programs the NSF will approve for funding.

FURTHER RESEARCH

Relation of discipline to course design:
Our limited research into this topic revealed that research projects (using existing procedures to develop new scientific theories) are more likely to be implemented in science, and mathematics disciplines while technology is suited to design projects (using existing knowledge to combine and tailor existing methods to a new problem). Design and research projects can both be successfully implemented in engineering, depending on the specific topic. Are there specific relationships between the discipline and the organization of a CURE?

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CHAPTER ONE: INTRODUCTION

Traditional classroom-based education systems have received criticism for not adequately preparing students for real-word problems (Zilberberg *et al.,* 2010). This criticism has emerged in the context of recent global technological development, accompanied by lagging adaptation of innovative educational strategies. Undergraduate students in science, technology, engineering and mathematics (STEM) need to learn field-specific skills in order to compete with others in their career field after graduation. This criticism of traditional teaching methods has shed light on the need for flexible undergraduate programs that prepare undergraduates for the professional life of a scientist, engineer, or high-level technician (Zilberberg *et al.,* 2010). Integrating real-life experiences in undergraduate education is a necessary and practical way for students to learn these field-specific skills since they are not always taught in traditional classes.

The National Science Foundation (NSF) has begun funding a novel approach known as course-based undergraduate research experiences (CUREs) to facilitate the development of a new integrated pedagogy. CUREs provide a classroom of students with real-life problems to solve. This pedagogy has been shown to help students to improve their self-esteem, develop intellectually, and clarify their career paths (Russell *et al.,* 2011; Szteinberg & Weaver, 2013). However, until recently, a fixed definition of CUREs had not been reached; experts and professionals in a community network, named CUREnet, provided a complete and comprehensive definition of CUREs.

CUREnet was launched in 2011 with funding from the National Science Foundation. According to a report published by CUREnet*,* in order for a program to be distinguished as a CURE, it should engage the students in the use of scientific practices, discovery, meaningful work, collaboration, and iteration. The unique structure of CUREs facilitates incorporating these five practices simultaneously in a class and provides students in STEM fields with a real-life experience (Auchincloss *et al.,* 2014).
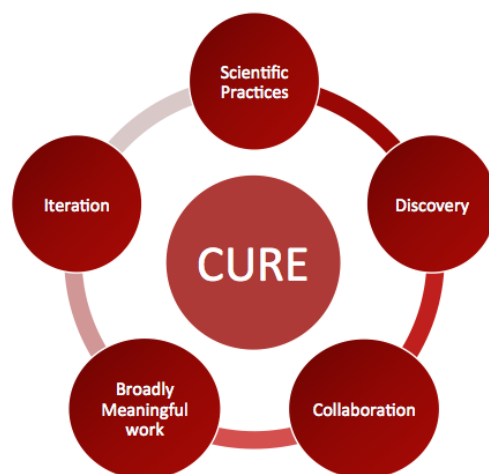
Figure 1*: CURE Definition.* A CURE must engage students in scientific practices, incorporate discovery of new knowledge, require collaboration among students, engage the students in meaningful work, and involve iteration of procedures.

The value of CURE programs in general has not been widely researched. The students, parents, and mentors involved in CUREs are investing in these programs without necessarily having a complete picture of their benefits and challenges. At the same time, it is important to be able to judge the success of the programs to insure that the NSF is investing public funds well when it supports CUREs. The NSF would like to evaluate the effectiveness of CUREs and similar programs, since the agency intends to use CUREs to encourage education and research in all STEM fields. Hence, the NSF requested an evaluation of CUREs and similar programs, as well as a comparison of the outcomes of CUREs and REUs, or Research Experiences for Undergraduates. REUs are apprenticeship-style undergraduate research experiences that involve one undergraduate student and one mentor solving a novel problem.

We formulated three objectives to fulfill our goal of evaluating what makes course-based undergraduate research programs successful. The first objective was to identify what the NSF values in an undergraduate STEM education program.

The second objective was to identify the primary outcomes of undergraduate research experience programs; it was the core topic of this project. These outcomes were found through a meta-analysis of published work, that is, through an archival review of studies related to programs similar to CUREs that have succeeded or failed in achieving the goals of CUREs. In this analysis, we examined the factors that have made these programs successful or less than fully successful. In addition, we explored how CURE has impacted learning in STEM fields and how it has affected students' performance in other scholarly areas. We also assessed changes in

the students' academic research skills, oral and written communication skills, and their abilities in the lab environment.

Our third objective was to formulate recommendations for the best implementation of CUREs. After we met these objectives, we were be able to identify clearly the actual outcomes of research-based learning programs such as CUREs, to make a comprehensive comparison between CUREs and REUs, and to provide recommendations to the NSF on how to make such programs more effective.

Our research demonstrated that CUREs are a good supplement to REUs. CUREs, if implemented effectively, supply students with bona-fide research experiences. CUREs provide an opportunity for students to work in teams to investigate a problem or implement a design, giving students a chance to develop teamwork skills in a research environment. Since CUREs can accommodate more students than REUs usually do, more students can be exposed to and possibly become interested in research. Moreover, our analysis showed that both the quality of mentorship and the time devoted to integrating real-life research into undergraduate STEM courses have a tremendous impact on the success of CUREs.

CHAPTER TWO: LITERATURE REVIEW

This chapter provides in-depth background on the National Science Foundation and a synopsis of published reports pertaining to research-based learning. We present two case studies related to research-based undergraduate education programs. To preface these case studies, we discuss the profile of the NSF and other stakeholders first.

2.1 SPONSOR PROFILE

The National Science Foundation (NSF) has a strong commitment to funding programs that support STEM learning. Typically, the NSF sends out a call soliciting proposals for a certain subject area. Then, once it receives proposals, third-party experts in the subject area review the proposal and give their recommendation on how to proceed. If the third party approves the proposal, then NSF reviewers receive a set of guidelines to pick which proposals are awarded funding. Once the program has been completed, a report is sent to the NSF Annual Reports database to keep a record of program results.

Starting about seven years ago, the agency began to support and fund programs called Classroom-Based Undergraduate Research Experiences (CUREs) in order to create a new, advanced teaching method in education that could potentially bring global benefits. In 2010, the NSF funded twenty-nine CURE-style programs (Woodin, 2010). One organization, CUREnet, was founded in 2011 with a grant from the NSF to research the effectiveness of and how to improve CUREs by encouraging communication between those involved in CUREs (About CUREnet, 2013). CUREnet brings together scientists and researchers involved in CUREs to bring about programmatic improvements. The NSF strives to maximize the uses of its funding from the U.S. government by funding valuable programs in a variety of areas. For example, the NSF plans to fund the NSF Research Traineeship (NRT) program for five years with a total budget of up to thirty million dollars (National Science Foundation, 2014). With strong financial support from the NSF, American universities can afford to provide educational research that could improve the overall quality of science education while simultaneously training future top scientists.

The NSF additionally funds programs called Research Experiences for Undergraduates (REUs). REUs are one-on-one student training and research programs for undergraduates,

typically in the life sciences. The agency needs to define the main attributes of CUREs, evaluate how participating in different programs, including CUREs and REUs, generates various outcomes, and uncover gaps in understanding of CUREs and REUs.

2.2 STAKEHOLDERS

Several key institutions and agencies are committed to the ideas behind this research-based approach to undergraduate learning. In addition to the NSF, the American Association for the Advancement of Science (AAAS) has participated in REU-related projects. Furthermore, one the AAAS's goals is specifically to "foster education in science and technology for everyone" (American Association for the Advancement of Science, 2014). Universities and colleges are also important stakeholders since the results from our research may be used to improve their current research programs. The Association of American Colleges and Universities (AACU) is another important stakeholder. The AACU, for example, aims to empower students in higher education by providing them with opportunities to enhance their involvement in science, which matches our project's goal. Those interested in funding or furthering research in any way, including undergraduate research, are providing important resources for advancing the health of our world.

2.3 NATURE OF SCIENCE AS A FOUNDATION FOR EDUCATION

Education in STEM fields is based on a concept known as nature of science. Nature of science is defined as "the epistemology and sociology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development" (Lederman, 1992). Nature of science explains how science is performed, ranging from the development of the hypothesis, testing through experimentation, confirming the hypothesis, and, finally, forming a theory. These are the elements that give depth to the science; a solid understanding of them is important for both students and professionals. Educators need to understand nature of science in order to convey the ideas of this concept to their students accurately. Students need to comprehend the concepts of nature of science both explicitly and implicitly. Accordingly, modern undergraduate learning experiences such as CUREs and REUs have been shown to expand the understanding of nature of science (Rowland, 2011).

One way to increase the students' understanding of nature of science is by providing developmental courses that increase the conceptual understanding of nature of science for teachers. An example of this is the development of an inquiry experience aimed at elementary school teachers. The goal was to raise their understanding in nature of science. The teachers were interviewed before and after the program in order to assess their knowledge of nature of science. Not only did the teachers benefit from their development inquiry experience, but these benefits were also reflected in their students' achievements (Russell & Weaver, 2011). Traditional classroom-based courses can emphasize the importance of the conceptual ideas of nature of science, while laboratory-based courses enhance the students' understanding of these ideas (Russell & Weaver, 2011).

2.4 LITERATURE REVIEW OF CURE AND REU

We will now examine how CUREs and REUs develop students' understanding of, and interest in, scientific research.

2.4.1 RESEARCH EXPERIENCE FOR UNDERGRADUATE (REU)

Apprenticeship-style research experiences have been arguably defined as the best way to "teach students to think like scientists" (Lopatto, 2008). These experiences typically occur as full-time summer positions. Students work one-on-one with a mentor, who is usually a professor or graduate student, as they are introduced and immersed into scientific culture. By the end, students have developed a better mindset towards what they will hopefully choose for a career. Some students may decide to continue in the scientific field and get a higher degree, while others may choose to enter a different field. All student participants, regardless of their eventual career paths, gain experience in a professional environment and develop the ability to network with other researchers and students. These experiences also allow the students to contribute to the field in which they are performing research (Lopatto, 2008). The students who participate in REUs tend to have a more in-depth understanding of how research is conducted and how it affects society. For a REU to be successful, the students must also hone their time-management abilities (Rowland, 2011).

While most students who take part in REUs have positive experiences, there are also drawbacks to this specific environment and gaps in results. Some students do experience career objective clarification; however, instead of realizing that they enjoy research, this experience may help them to determine that they want to stay away from research (Rowland, 2011). There is also evidence that REUs are not the ideal starting positions for students who are just entering the research field. The stakes in a professional laboratory are higher than those in a classroom environment. The student may transfer from an environment where their success only affects their grade, to an environment where a mistake on their part might set back an entire research project. Even well-adjusted and confident students can sometimes perform experiments incorrectly. Participating in these programs means putting more responsibility on the student. The student must find a lab with research that interests him or her, find a professor willing to take an intern, and then learn a set of new techniques. This challenges participants to invest time and effort into finding the right lab. If less-confident, inexperienced students enter this environment, they may choose to quit. If these participants stay, they may hinder the progress of the lab. This liability, in addition to the student's probable need for training, may prompt a professor to accept only students who have previously worked in a lab (Rowland, 2011).

In addition, REUs can leave students with an incomplete understanding of scientific results. Students who experience REUs might not see the short-lived and ever-changing dynamic of scientific knowledge. They may come away with the feeling that what they discovered will forever remain as true and reliable, which is not always the case. Also, since the students are given the research question and are not required to compose it on their own, they miss out on the development and finalization of a complete research design experience (Rowland, 2011).

2.4.2 COURSE-BASED UNDERGRADUATE RESEARCH EXPERIENCE (CURE)

To rectify the shortcomings of REUs, the NSF and other institutions have created research programs that are classroom based, such as CUREs. The University of Queensland (UQ) has created a unique solution that allows for both REU and CURE-type experiences (Rowland, 2012). A class was designed that focused on biochemistry and molecular biology. UQ had previously run a typical laboratory class in which students followed a

cookbook-like protocol, using little to no innovation. The students in these classes gave positive feedback about tutors and the laboratory practice. However, they suggested that, instead of having a few major reports, a larger number of smaller reports building up to the final report should be assigned throughout the course, as long as they received frequent feedback. The students also wanted the lab protocols to have more flexibility, with an added element of design in experiments. They also wanted to learn a larger variety of experiment techniques. In order to accommodate enrollment of 450-500 students from different disciplines into one class, the University of Queensland created a bifurcated class that allowed students to choose to participate in an experience similar to a CURE, or to enter into a REU within the class (Rowland, 2012). The class for students in the CURE-like experience, entitled a "Laboratory Experience for Acquiring Practical Skills" (LEAPS), retained most of the aspects of a traditional laboratory and only changed a few elements. For some aspects, the students were no longer given directions; they were now required to research and design their own approach to the experiment. Those in the REU, called "Active Learning Laboratory Undergraduate Research Experience" (ALLURE), were tasked with researching an extension of an existing research project, with the hopes that they would provide useful results. After a tutorial session, the students were given the tools to design, run, and fix their own protocols, with assistance from an expert (Rowland, 2012).

This class's two streams considered previous students' suggestions on how to improve the traditional laboratory experience. The time allotted for experiments was extended by two extra weeks so that the students didn't feel rushed or as if they couldn't handle the complexity of the work. In order to reduce stress and confusion, students now handed in two separate lab reports instead of one final lab report. These reports were returned to students with feedback on how to improve. To keep the streams equal in terms of effort and time management, the students were required to turn in reports at the same time, although the reports were at different levels of complexity. The LEAPS practical added an inquiry portion, while the ALLURE stream added a considerable amount of experimental freedom for the students (Rowland, 2012).

The University of Queensland's bifurcated class is an example that can be used for simultaneous comparison of CUREs and REUs. It also provides an analysis of how to effectively deal with large groups of diverse students in science courses, which will help with CURE program development. Students were assessed on their confidence in both technical and analytical skills before and after the course. Even though LEAPS and ALLURE students

participated in different activities, their confidence in their skills increased similarly. The ALLURE students learned more skills pertaining to the nature of science, while LEAPS students perceived that they gained more technical skills. They also earned similar grades, which indicated that the class difficulty was appropriate for the students enrolled in each stream. Eighty-five percent of the students also reported that they were happy with their choice of laboratory stream. Those in the ALLURE program liked the REU because it challenged them and involved them in new research, even though it was also perceived as stressful by a few students. A caveat here is that the students may have reported that they were happy with their stream choice in order to combat any cognitive dissonance associated with having a bad experience with something they chose to do. Providing students with a choice seemed to improve self-direction and student satisfaction (Rowland, 2012).

2.5 HOW THE SUCCESS OF OTHER RESEARCH-BASED LEARNING PROGRAMS HAS BEEN MEASURED

Being able to determine the outcomes of research programs is integral in determining the success of a program. Experts can then draw their conclusions on the impact of CUREs and REUs and provide recommendations on how these programs could be improved. Otherwise, the outcomes of these programs and their effectiveness on the students would be unknown, and the efforts put into implementing them would be meaningless to future program designers. Interviews and surveys are the most common methods used to evaluate the outcomes of learning experiences like CUREs and REUs. In order to use the tool of interviewing effectively, pre-interviews and post-interviews are conducted (Russell & Weaver, 2011; Ryder & Leach, 1999; Szteinberg & Weaver, 2013). These interviews allow the conductors of the study to discern if there are changes in the students' responses before and after the course. If the questions are asked appropriately, information can also be obtained on what made the responses change or stay the same. The responses of the students are transcribed and then analyzed qualitatively through the use of qualitative analysis software (Russell & Weaver, 2011; Ryder & Leach, 1999; Thiry *et al.*, 2011). CUREs and REUs are often implemented to increase students' knowledge in a variety of ways, including teaching them relevant skills. In order to assess whether these objectives have been reached, the pre-interviews create a baseline of what the

students know before they enter the learning experience. Post-interviews indicate how much the students have gained from this experience by comparing them to the pre-interviews. In addition to pre-interviews and post-interviews, some studies conduct interviews during the course to more accurately monitor the students' development over the course of the term (Ryder & Leach, 1999). The results of these interviews are then compared to the results of a different set of interviews of another group of students who have been taught the same principles that the CUREs and REUs students have been taught, but in a standard classroom environment (Ryder & Leach, 1999).

As an example, a study was conducted in five American universities to determine how the students' understanding of the nature of science changed after taking a certain course. Students were randomly placed in three different laboratory learning environments: one similar to CUREs, one similar to REUs, and one similar to a traditional laboratory experience. They were interviewed and asked questions related to the nature of science before and after the course to see if their understanding of the nature of science has improved or not. Those who took part in the CURE and the REU were able to define the nature of science more accurately than their counterparts in the traditional laboratory (Russell & Weaver, 2011). This ability could be a sign of whether CUREs and REUs succeeded. Such comparisons enable researchers to determine if experiences like CUREs and REUs enable students to learn more and are thus worth implementing.

Typically, researchers want to find out whether the students have gained the skills that CUREs and REUs were designed to promote. For example, one of the desired outcomes of experiences like CUREs is to promote critical thinking and creativity. It is expected that students will encounter some obstacles while learning. Therefore, researchers want to know if the students successfully overcame those obstacles and how they were able to do so. An indicator of the success of programs like CUREs and REUs is if students reported that they had to be innovative in order to solve the issues they had encountered, and if they could explain how scientific problems were solved. Professors can be interviewed to get their impressions about such learning experiences. In addition to interviews, surveys are also used as a tool in measuring the success of CUREs and REUs. Similar to the method of interviews, students' and professors' feedback are analyzed to determine the results.

2.6 DISCUSSION OF CLAIMS

Topic One: Do CUREs provide future benefits for students in science?

The first claim asserted throughout research papers is that inquiry-based or research-based laboratory curricula should be able to promote students' interest in science and increase their sense of accomplishment and confidence (Harrison, 2011; Drew, 2008). An inquiry-based laboratory curriculum includes a small research experience in which the students construct their own research projects after identifying their problem statements. After participating in the classroom-based research course, students retained more information, developed their research skills, and had a higher level of interest and enthusiasm for research (Drew, 2008). After comparing the outcomes from these two models, both learning models proved that they improved students' skills in communication and laboratory techniques. Both programs encouraged students to pursue a higher educational degree in science and helped students decide if they wanted their future career to include scientific research. Also, both used surveys as an assessment tool. From the comparison of both programs, the outcomes of the CURE style programs were similar. As opposed to other research programs, which usually just involve students who already have high academic performance, CUREs tend to engage a variety of students with various academic performances. This can be a result of a less competitive application since more students are allowed in these courses than in a REU.

Topic Two: What is the common weakness of assessment of CUREs programs?

A limited sample size is a common concern when analyzing CUREs (Harrison, 2011; Pantoya, 2013; Siritunga, 2011). It is rare to find a paper, such as the University of Queensland's study, in which a large cohort is assessed. The majority of CURE assessments that we studied used models with a low number of enrolled students. The low number of participants could cause inaccuracies in the conclusions drawn from collected data. For example, in the Phage Genomics course model, which will be discussed in more depth, the majority of the students was already earning biology degrees and in honors programs (Caruso, 2009). The outcomes from this model show that CUREs were effective for students who had a background in biology and a better grade point average (GPA). However, this model did not show how CUREs could improve the learning of students who did not have high GPA's nor did the model indicate how to encourage disinterested students to pursue advanced degrees (Harrison, 2011).

2.7 RELEVANT CASE STUDIES

Here, we present two case studies that demonstrate the implementation of CUREs programs.

Case one: Phage Genomics course at Cabrini College

The first program that we studied was the Phage Genomics course, conducted at Cabrini College in 2009 (Caruso, 2009). This model was a classroom-based research course in which sixteen undergraduate students were enrolled. These students came from various majors and programs. Thirteen students were freshman biology majors; nine students were in an honors program; three students were honors sophomore non-science majors, and four students were not in the honors program but were biology majors. The course had two sessions of four and a half hours of laboratory instruction each week for the fall semester. The spring semester schedule included three hours of laboratory instruction and one hour of a traditional biology lecture once per week (Harrison, 2011). The fall laboratory session began with giving students instructions on how to isolate mycobacteriophages from an on-campus soil sample. Then, students purified the phage species before isolating genomic DNA. After that, students needed to determine the phage morphology and complete presentations on their findings. Students voted on the sample they believed would be best for future sequence analysis. The next semester, students worked in pairs to identify genes in a sequenced phage genome using a gene-searching tool (Harrison, 2011).

The project team used a pre-survey and a post-survey, a student focus group, and a follow-up focus group. The pre-survey was conducted in the first week of class during the fall semester, and the post-survey was distributed in the last week of class during the spring semester. A student focus group was organized in the final week of class, and the follow-up focus group was organized in the semester after completion of the course (Harrison, 2011).

The outcome of the surveys showed that students who attended this course had increased interest in attaining a higher degree of education and pursuing research careers in science. The students gained a comprehensive understanding of research processes and better understood how to become a scientist. From the students' responses, the research experience in this course was the most valuable component. The students learned to appreciate the value of individuals who conduct research in a greater depth. Students responded that, since there were no strict expected outcomes and no step-by-step instructions to follow, the lab was more attractive to them than the

traditional cookbook-style lab. The students learned significantly from their mistakes during the lab and repeated lab procedures without hesitation (Harrison, 2011).

Case Two: Bacterial Genome Sequencing at the University of Florida

The University of Florida offered a course called Bacterial Genome Sequencing, aimed to prepare undergraduates to become biological researchers and to understand and participate in high-throughput research. One of the course objectives was to encourage students to learn about genome sequencing and common bioinformatics tools. The other two objectives were to develop communication skills and to promote interest in biological research. Students worked collaboratively to analyze the sequence of *Enterobacter cloacae*. This course ran two three-hour sessions per week, including a one-hour lecture and two hours of research practices. There were seventeen students in this class, including fourteen undergraduates and three graduate students (Drew, 2008). In this model, the project development team used examinations, writing assignments, oral presentations, pre-surveys and post-surveys and final exit surveys to assess student learning, scientific communication skills and student attitudes to biology. Students responded in the surveys that they learned new material from the course and had positive attitudes about the course. This course demonstrated that, compared to traditional lecture courses, active learning exercises enhance student learning and increase student confidence and enthusiasm. The pre-surveys and post-surveys indicated that students learned more about genomics after taking the course. Students explained that they felt a significant increase in scientific communication skills but not in scientific writing skills (Drew, 2008).

The project development team gave recommendations on improving the course, mainly suggesting greater emphasis on teaching students how to credit publications and when to cite. The group also suggested that instructors explain expectations for oral presentations and provide an initial educational overview on the main research topic (Drew, 2008).

Similarities and Differences

One of the similarities between the Phage Genomics course and the Bacterial Genome Sequencing course was that both are classroom-based research style undergraduate courses in biology. The project development teams for both models expected improved research skills and communication skills and an increased interest in a research career in science. One difference between the two models was the different structure of courses, since both class models had different design concepts.

Topics & Case Studies Relationship to Project Proposal

The two common topics discussed above highlight the weaknesses of CUREs models, while providing insight about how these programs benefit students. The case studies demonstrate examples of implementations of CURE-like programs. The sample questions in the surveys from the Phage Genomics course are valuable references on how to design survey questions. Since a large part of our project's purpose is to study the effectiveness of CUREs, the models of the Phage Genomics course and the Bacterial Genome Sequencing course could give us a better understanding of how to assess the outcomes of CUREs.

2.8 SUMMARY

This chapter reviewed several selected reference cases that were related to our project. We found CURE-related papers in science disciplines, specifically, biology and chemistry, through the Google Scholar search engine. Engineering and mathematics papers were mostly found in the education research database, ERIC, and the engineering database, COMPENDEX. The number of institutions where programs like CUREs have been implemented is growing. Therefore, data collection for CURE programs and principles underlying the analysis of collected data are more readily available.

CHAPTER THREE: METHODS

The National Science Foundation (NSF) needs to be able to analyze the overall results of its investments in CUREs, REUs and other similar programs. Once the NSF is able to objectively evaluate the educational value of those CURE and REU programs which it has funded, the NSF will be able to make decisions about the extent to which the program should be refunded. The goal of this project was to evaluate the effectiveness of CUREs by identifying the qualities that make an undergraduate research program successful.

Our objectives were as follows:

1. Identify what the NSF values in an undergraduate research program
2. Define the outcomes of the NSF funded CURE and REU programs
3. Formulate recommendations for ideal implementations of CUREs

For our first objective, we conducted semi-structured interviews with NSF officials. To define the research program outcomes, we mainly conducted archival research through database searching on the Education Resources Information Center (ERIC) and the Computerized Version of Engineering Index (COMPENDEX). We also conducted interviews with students who participated in NSF-sponsored REUs in the summer of 2014 in order to allow a comparison between CUREs and REUs to be performed, which was a minor goal in our project. Finally, we provided recommendations for ideal implementations of CUREs. We begin this chapter with detailed descriptions of both the pilot interviews and the methodology strategies for each objective.
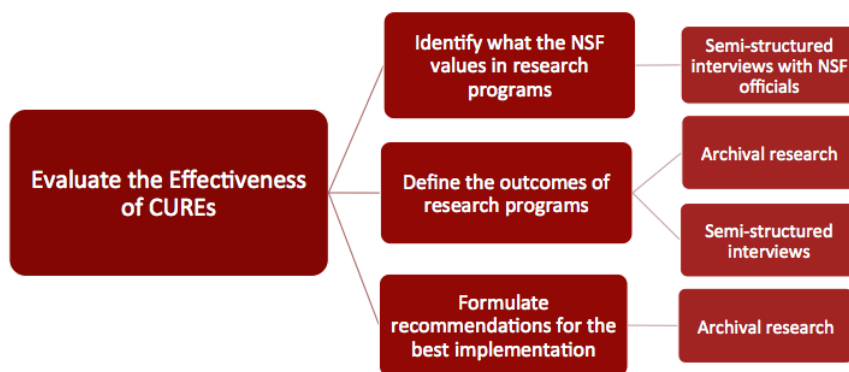

Figure 2: Outline of Goal, Objectives, and Methods. In order to evaluate how effective CUREs are, we identified what parts of research programs the NSF values, defined research program outcomes, and then recommended how to best implement CUREs. Our methods include semi-structured interviews and archival research.

3.1 PILOT INTERVIEWS

We began our research in Washington, D.C. by conducting sixteen interviews to students who presented their NSF-sponsored REU projects at an NSF symposium on October 27th, 2014. The goal of these interviews was to give directions to what outcomes should be looked for during the archival search as well as to allow a comparison between CURE and REU to be performed. The audio of all the responses was recorded for analysis at a later time. Students were asked about the length of the programs and the mentorship style they had. Also, students were asked about the top three benefits they obtained from their research experience. In addition, students were asked about their expectations about their REU experiences before they entered it. Finally, students were asked to provide recommendations on how to improve REUs in the future.

3.2 OBJECTIVE ONE: *Identify what the NSF values in an undergraduate research program*

We used semi-structured interviews to understand how NSF officials approach approval of the projects, and what they expect out of those ones they approve. We also asked them about how they believe these programs could be improved. These methods helped us understand what the NSF values in CUREs and REUs and what outcomes it anticipates from those programs. Sample interview questions can be found in Appendix B.

3.3 OBJECTIVE TWO: *Define the outcomes of the NSF funded CURE and REU programs*

In order to find the actual outcomes of programs such as CUREs and REUs, we first determined what the outcomes have been in the past and what to look for in interviews and publications. These pilot interviews helped to serve as guidance during our search for program outcomes and characteristics. In addition, we extracted how the students' future careers developed after their program via archival review of longitudinal studies devoted to following students' long-term progress. We reviewed the list of references provided by the NSF. We also came up with search terms to search in databases such as the educational database, ERIC, and the engineering database, COMPENDEX. We looked for studies by searching for those publications that best matched the following criteria: included implementations that matched the definition of a CURE, had assessments of students, and was in STEM fields. Each team member reviewed

the abstracts of the results and collected the publications that were relevant to our research topic based on the previously stated criteria. The search keywords, the title, the authors, and the abstract were collected for every selected publication. The team member repeated these steps several times with different keyword terms. We then compiled all the papers we had found, including those that were not read, in an excel file.

In addition to archival review, we used semi-structured interviews to engage with professors who have had involvement in programs similar to CUREs and REUs. Semi-structured interviews are open-ended and allow the interviewee to share his/her experience without any restrictions (Arksey, 1999). The purpose of these interviews was to get professors' viewpoints on the importance and effectiveness of researched-based learning programs on undergraduate education, and on the best way to provide the largest number of students with a meaningful experience and on how to enhance existing programs. Sample questions can be found in Appendix A.

3.4 OBJECTIVE THREE: *Formulate recommendations for ideal implementations of CUREs.*

After we met the first and second objective, we were able to identify the factors that lie behind the success of a CURE. We were able to identify the strengths of CUREs as well as the most common impediments that may stand on the way of implementing a successful CURE. As a consequence, based on the features and obstacles of CUREs, we provided six recommendations that, based on our meta-analysis of 41 papers of CUREs, might improve the effectiveness of future CUREs.

CHAPTER FOUR: FINDINGS

4.1 ELABORATION OF CLAIMS

We formulated six main claims, defined as follows:

1. CUREs are good complements to REUs since authentic research or design can be integrated into traditional lecture-based classrooms, providing students with experiences similar to those of professionals.

CUREs provide bona-fide research experiences for a larger number of students than REUs before graduation. If the program is designed well, and the mentorship is of good quality, students feel that they have experienced authentic research. Unlike a traditional lab, which has predetermined experimental results and outcomes, an authentic research experience involves research activities with open-ended results, similar to scientific research in the real world. With bona-fide research experiences, students are able to establish their scientific identity, which includes understanding how to design experiments, how to conduct reproducible, responsible, and ethical research, and how to think like scientists. A genuine research experience fosters students' understanding of the nature of science, which deals with how science is created; starting from observing a certain phenomenon, to proposing a hypothesis, to testing it through experiments, and to finally confirming the hypothesis and forming a scientific theory (Lederman, 1992).

Traditional classroom environments usually include a traditional laboratory component with predesigned experiments and preordained outcomes. No open-ended laboratory activities are usually performed in such pedagogy. This is not necessarily detrimental, but it is also not the best way to undertake scientific training. One study found that traditional laboratory environments have harmful effects on how women perceive their abilities, while it did not significantly affect men's perception or performance (Laursen *et al.,* 2014). Women experienced a significant decline in their intention to pursue mathematics further, while men had only slight decreases in future pursuit of mathematical studies. Women placed in inquiry-based classes had improved attitudes and intent to take more math classes, plus they became more confident in their mathematical skills and teaching abilities. They rated their collaborative gains as significantly higher than men did (Laursen *et al.,* 2014). Conversely, CUREs involve research or design experiences that have both lecture and lab sections. The lab sections often act as the

primary source of knowledge and the lecture sections are utilized to provide basic background knowledge, to enhance the lab experience, to address problems that students face in the lab, and to instruct students in how to overcome typical problems (Panchal *et al.,* 2012; Levis-Fitzgerald *et al ,* 2005).

CUREs can also involve visits to active work sites in order to give students insight into what they could work on when they graduate. In order to enhance the students' learning outcomes about the research or design on which they are working, some CUREs include trips to a nearby company or industry (Durfee, 2007; Dekhane, & Price, 2014). In such visits, students can come to understand that the work they are doing is, indeed, a real-life experience. Also, students have the chance to interact with the employees of a company or industry and ask questions related to their research or design project. Students are often asked to write a report about their visit and reflect on how it has helped them. In some cases, students have also experienced the opportunity to actually work at a local company or industry through a partnership with their respective institutions (Durfee, 2007; Dekhane, & Price, 2014). Such collaborations between universities and industries are important as they enrich the student's undergraduate experience and demonstrate the role of the industry in society.

CUREs are perfect preparations for students before they enter into a REU or a similar experience. Students who enter REUs typically already have more lab experience than students who enter CUREs. That difference arises because professors in REUs often do not have time to teach students basic laboratory skills or techniques. Professors want students to understand basic research techniques such as how to clean glassware, keep a hood sterile, dispose of hazardous waste, pipette, measure pH, and use a centrifuge. Therefore, the professors select the students with more experience, whether it is from a course or another program outside of class. These students are less likely to make mistakes simply because they are experienced with everyday lab techniques. CUREs provide the students the opportunities to learn these techniques. CUREs are a valuable experience for beginners since they are specifically designed to teach students about research, even if students have had no prior research experience. Professors or mentors in CUREs have the opportunity to teach and train students so that they can meaningfully participate in gathering new data for scientific research. Students undergoing CURE training are more

likely than non-CURE trained students to become future scientists after participating in high-quality CUREs (Levis-Fitzgerald *et al*., 2005; Spell, 2014).

As a result of being immersed in the culture of research, students are exposed to the demands and expectations of graduate school. CUREs expose students to how authentic research is conducted. This gives the students the opportunity to immerse themselves in the culture of research, which encompasses reading, learning and searching on their own, seeking help from their mentors when needed, and overcoming problems. All of these experiences, and more, provide the students with a clear understanding about the nature of graduate school, a setting in which students work assisting faculty members in gathering data and conducting real research (Rust, 2013). CUREs provide a similar research environment to that of graduate school and foster the abilities needed to participate actively in a professor's research, such as analyzing data and running experiments. Since students get to experience the research culture in a specific discipline, they can make better decisions on both whether they want to go to graduate schools and what discipline they prefer. As a result, such research experiences may increase the interest of students to pursue scientific studies, fulfilling one of the crucial goals of CUREs (Russell & Weaver, 2011; Szteinberg & Weaver, 2013).

2. CUREs emphasize the importance of teamwork.

Students in CUREs work in teams in order to solve a problem or implement a design, and learn how to handle conflicts and obstacles as a team. CUREs provide the opportunity for students to be able to work in groups; students who participate in a CURE can more easily work in a collaborative environment since they have begun to develop the skills necessary to work in such an environment. Teamwork can help students to realize what they are naturally good at. In a group, it is best to work with students' strengths. Students in CUREs learned "group skills, time management, being able to communicate technically at a high level, both orally and in a weekly progress report" (McLaughlin, 2013).

However, if not accounted for in the project design, such collaboration may lead to one student doing one task and not learning much about other aspects of the project. Each member in the team should be aware of, and knowledgeable about, what other team members are doing. This sharing of knowledge is imperative since it prevents certain tasks from being performed twice, which in turn results in wasting time the team may desperately need, and also implies

20

poorly established communication among group members. The existence of good communication within the team facilitates the progress of the research or the design project and also fosters team spirit. This may encompass listening to what each team member has to say, and resolving problems among the team members when such problems occur. Therefore, not only does teamwork mean that participants work together to accomplish a specific job, but it also means that teammates have to come to a compromise whenever an issue of potential disagreement arises (Nurmi, R, 1996; Stevens & Campion, 1994).

Team members usually come from different backgrounds and have different personalities. Therefore, team dynamics are seldom perfectly functional. When issues arise, as they usually do, teams must confront them and compromise on a solution in order to make positive progress arises (Nurmi, R, 1996; Stevens & Campion, 1994). Students learn such skills when they have the chance to constantly work in teams (McLaughlin, 2013). Nevertheless, sometimes students may realize that they can't work with specific students, and they know that because they might have worked with those students and noticed that they had irreconcilable differences. In order to not harm the team dynamics as the project evolves, students may have the choice to bring matters of disagreement to their instructor early in the course of a project in order to find another team to join. Students learn how to make such decisions when they are constantly exposed to working in teams.

CUREs promote synergy between students; they feel responsible for their part of the group work, and at the same time, they learn to trust others to complete their portion of work. The idea of ownership fosters a sense of responsibility (Zilberberg, 2010). Students, who feel this sense of ownership and responsibility, realize that if they do their part well, then their team has a better chance of succeeding. However, if one student fails, his or her team has a weak link for which other team members will need to compensate (Hanauer *et al.*, 2012). There is an example of this scenario happening in an aerospace program at Pennsylvania State University, but the program will be improved with better supervision for the next round of courses (McLaughlin, 2013). In a post-course survey, one student suggested that team members look out for each other because any mistake could influence the whole research experiment (Levis-Fitzgerald *et al.*, 2005). This watchfulness might be also due to the fact that most professors tend to grade the students as a team, not individuals.

Many programs replace the traditional exams with papers and oral presentations, since it is difficult for professors to evaluate individuals' performances based on grades in the exams (Levis-Fitzgerald *et al.*, 2005). Knowledge-based quizzes may still be implemented in some CUREs programs to measure the retention of the disciplinary knowledge after the course is over (Liang & Camesano, 2011). Since most of the course activities, such as presentations, posters, final reports, and labs, are done in teams, students' grades depend on the whole team's performance as well as on each student's contribution according to teammate's evaluation. This type of policy makes team members pay close attention to others' performance and try to help each other successfully complete the project, which escalates the level of synergy among team members. However, it happens sometimes that some students do not fully pull their weight in the project; such behavior may impact the team's performance and may translate, unfairly, into a bad grade for the whole team.

3. Mentorship plays a significant role in CUREs program.

Different levels of mentorship in CUREs facilitate the learning process for students. Students feel that they can take their questions to the graduate students more frequently; they ask professors the more complex questions. Our pilot interviews results showed that students who were involved in NSF-sponsored REU programs over the summer of 2014 noted that they felt more comfortable with the graduate students. They worked with the graduate students on a more frequent basis and thus would go to the graduate students if they had questions. They then turned to the professor for questions that the graduate students could not answer or for those that affected the project in a complex way. This setup helps with prioritizing professors' valuable and often limited time. Professors usually require that the graduate students monitor the progress of the undergraduate students in their research, which in turn provides a better teaching and mentoring experience for the graduate students (Levis-Fitzgerald *et al.*, 2005; McLaughlin, 2013).

Professors have their own research, meetings, classes, and other commitments; therefore, they often find difficulties having time to track the status of students and the work done inside the lab. Having graduate students around to monitor undergraduate students' progress and help them with any problems they encounter lightens the professor's workload. It also helps the graduate students gain valuable mentorship experience. Graduate students learn how to handle

students' questions and how to guide undergraduate students in the right direction. In one of the studies, students in CUREs appreciated the course organization of having faculty members as the main people in charge and the graduate students as more direct, everyday contacts. The students thought that the group meeting was a productive way to share feedback and information (McLaughlin, 2013).

However, some undergraduate students had difficulty working with the graduate students. Sometimes the graduate students would not leave many tasks for the undergraduates, preferring instead to do the tasks themselves. The graduate students were usually the ones who worked the most with undergraduate students and faculty. Some students felt that this hierarchy "got in the way sometimes… but that's real-world kind of stuff" (McLaughlin, 2013). In order for this type of setup to work, the instructors have to be conscious of how the groups are working with each other, and whether any students are not doing their fair share of the work, whether the workload is too much or too little (Levis-Fitzgerald *et al*., 2005). The biggest challenge for the instructors is to build and continuously monitor the organizational structure illustrated in *Figure 3*. As the course progresses, students show different levels of understanding on the topics even if they started at the same level at the beginning. Some students tend to lead the team and some students tend to follow others. Professors should evaluate the team dynamics at some point of the course and balance the uneven team dynamics so that students are able to collaborate in a fair and efficient way. (McLaughlin, 2013)

As the lack of mentorship is a problem, too much mentorship involvement could also be detrimental to project progress. Once the students became more confident in their abilities, they enjoyed being able to do their work without close supervision, and then bring their results to the professors (Levis-Fitzgerald *et al.*, 2005). They felt reassured since they could ask the graduate student or professor questions about problems. One of the students, in our pilot interviews, mentioned that he had to meet three hours daily with his professor discussing the project progress. The student was not satisfied and felt he had no freedom in the work he was doing.
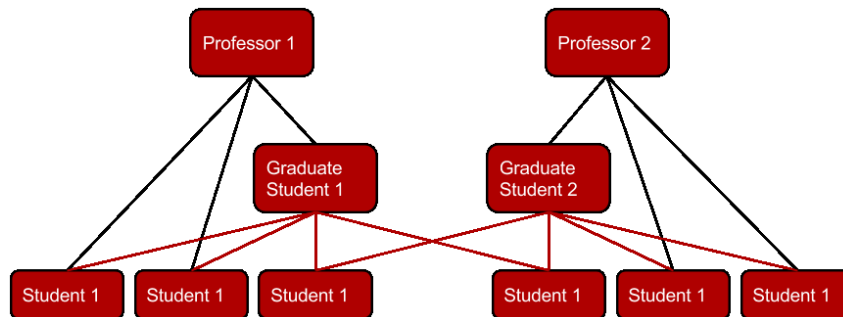
Figure 3: Class Module. This figure provides an example of a model class structure with more than four mentors to a varied number of students.

4. Even though CUREs are valuable experiences for undergraduate students, time usually is a common obstacle when it comes to implementation.

The limitation of time to provide an authentic experience to students sometimes adversely affects the design and implementation of CUREs. A huge barrier to implementation of authentic research in a laboratory course is the amount of time it takes to develop a new research experience or a design (Beck, 2014). Professors may feel constrained when designing CUREs if they are more familiar with REU structures. Since REUs typically take place in the summer, the student can dedicate a substantial amount of time to research. There is more time during a REU to compensate for mistakes made since there is a larger amount and more flexible lab time. However, during a CURE, the lab facilities have to be scheduled since there are other classes taking place in the same semester. Also, laboratories have limited capacity, and if a class is large, there will have to be different sections for the class groups.

Students may need to master essential material before being able to do work that contributes towards the project goal. Exposing students to a research or a design project often means that students are about to learn concepts to which they have not previously been exposed because, in general, research concentrates on a narrow topic in a specific sub-discipline. For example, in one of the studies we examined, students conducted research on genomics and, more specifically, in sequencing a microbial genome (Levis-Fitzgerald *et al.*, 2005). Sequencing the genome included preparing a genomic library, isolating DNA from the library, preparing the DNA for sequencing, sequencing the DNA, performing bioinformatics analysis of the DNA sequence, and, finally, building a curated genome sequence database (Levis-Fitzgerald *et al.*, 2005). As a result, students had to read and learn more about sequencing on their own. Genomic

research is an area that requires reading and digesting significant supplementary materials (Levis-Fitzgerald *et al*., 2005).

Also, design projects require students to understand some material with which they might not have previously dealt. For instance, in a mechanical engineering class, students had the opportunity to work in collaboration with a local industry (Durfee, 2007). The students reported that they enjoyed their experience and also were able to successfully accomplish the goal of their project. However, students had also to read and learn about the background of their design on their own. That was a problem for some students since they also had commitments to other classes.

Students in the examples mentioned above also had work commitment from other classes; thus, it was challenging for them to allot their time between the work in the lab, outside the lab, and the work from other classes. These examples illuminate how time can be an issue in the implementation of CUREs. Students should not be expected to know much about research as CUREs are originally designed to introduce them to research. However, a study offered by Harrison discussed an implementation of a one-year long program offered in freshman year that did not require much educational background about the project (Harrison, 2011). The first semester was designed to introduce the students to the culture of research and to the research background information. When the students started working on the actual research, which took place during the second semester, the students were able to immerse themselves into the actual research project with facing any major obstacles (Harrison, 2011).

5. Students feel more involved in research if they generate solutions themselves.

Ownership of a project fosters a sense of responsibility. Students who feel that they have ownership of their project, or a part of it, also have a desire to see it succeed (Auchincloss *et al.,* 2014; Shaffer *et al*., 2014). Hence, they put more effort into the work needed to get results. If students are provided the opportunity, they likely will be willing to continue working on the research even after the course ends. The students' willingness to go beyond basic requirements may be directly related to their acquiring sense of ownership in the project.

6. Ill-structured problems promote original thinking and self-direction in students.

In order for CUREs to achieve their goals of increasing students' interests in STEM and providing real-life experience before graduation, program designers should employ ill-structured problems (Zilberg, Pierrakos, & Thompson *et al.,* 2010). Such problems do not usually have well-defined goals or methods, and even their end state or solution is not explicitly stated (Ertmer *et al.,* 2008). These types of problems are usually the ones encountered by professionals. Exposing students to such problems early in their undergraduate education promotes developing critical thinking and problem solving skills. Such problems force students to think harder and to collaborate with their teammates in order to find well-thought-out methods that lead to the best solutions available. Students who have not yet experienced research may initially feel uncomfortable with CUREs. Although more is asked of them than in a typical course (if they have not yet had a research experience) and the research activity may be out of their comfort zone, students eventually become accustomed to being challenged academically and even grow to like being challenged in the CURE environment (Levis-Fitzgerald *et al*., 2005). Students mentioned that having this type of experience on a resume makes them a better job candidate since it shows that they have research experience and can talk extensively about it (McLaughlin, 2013).

4.2 PILOT INTERVIEW RESULTS

We used pie charts to present the results of our pilot interviews. The numbers inside the charts represent the number of students responded to a certain question. These numbers correspond with the answers the students provided, which are listed on the right side of the charts. The pie diagrams and tables are shown below in *Figure 4*.
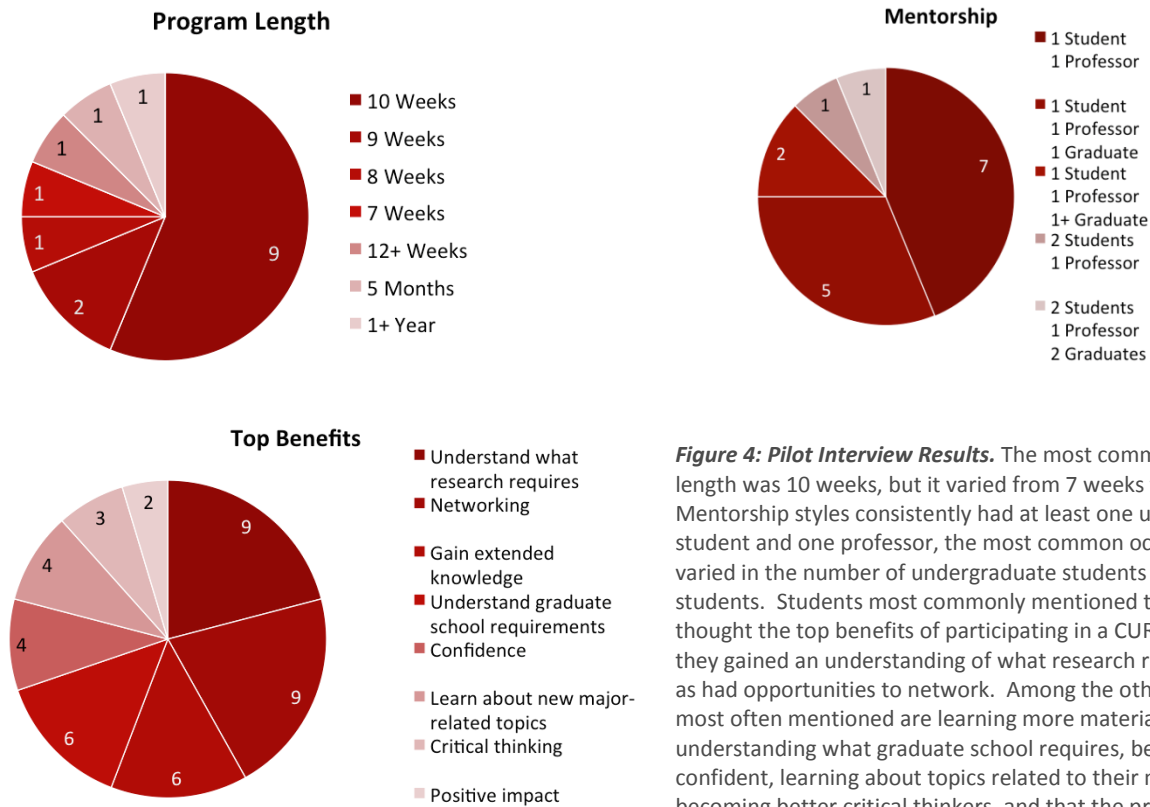
Program Length

- 10 Weeks
- 9 Weeks
- 8 Weeks
- 7 Weeks
- 12+ Weeks
- 5 Months
- 1+ Year

Mentorship

- 1 Student
  1 Professor
- 1 Student
  1 Professor
  1 Graduate
- 1 Student
  1 Professor
  1+ Graduate
- 2 Students
  1 Professor
- 2 Students
  1 Professor
  2 Graduates

Top Benefits

- Understand what research requires
- Networking
- Gain extended knowledge
- Understand graduate school requirements
- Confidence
- Learn about new major-related topics
- Critical thinking
- Positive impact

Figure 4: Pilot Interview Results. The most common program length was 10 weeks, but it varied from 7 weeks to over a year. Mentorship styles consistently had at least one undergraduate student and one professor, the most common occurrence, but varied in the number of undergraduate students or graduate students. Students most commonly mentioned that they thought the top benefits of participating in a CURE were that they gained an understanding of what research required, as well as had opportunities to network. Among the other top benefits most often mentioned are learning more material, understanding what graduate school requires, becoming more confident, learning about topics related to their major, becoming better critical thinkers, and that the project had a positive impact on them.

Expectations	Recommendations
Be introduced to the culture of research	Allot time to learn about the background
Gain experience	Increase students awareness of the existence of the REUs
The REU would be very different experience than any other experiences in undergraduate	Make REUs accessible to a large number of students
The REU would be just like other experiences in which students forget about the material over time	Change mentorship (more or less monitoring)
Networking	Period of research is not enough
No expectations	Everything was perfect

Table 3: Pilot Interview Results. Students were asked what their expectations were prior to entering the REUs, as well as what ideas they had to improve their program.

4.3 CURE AND REU COMPARISON

We used the results from the interviews and the archival search to perform a comprehensive comparison between REUs and CUREs, which was a minor goal in our project. We compared the properties of both programs such as the goal, length and collaboration style. We also compared the outcomes of both programs. The table and Venn diagram below represent the results of this comparison.

Description	CUREs	REUs
Purpose	Introduce students to scientific research	Introduce students to scientific research
Expected Research Background	Not required	Basic techniques
Length	Depends on the program	7-10 weeks
Collaboration Style	Always team-structured	Independent / team-structured
Mentorship	Usually a professor & multiple graduate students	Usually a professor & a graduate student
Availability	All students	High-performing students

Table 4: Comparing and Contrasting CUREs & REUs. The purpose, expected research background, program length, collaboration style, mentorship, and availability of CUREs and REUs is compared.
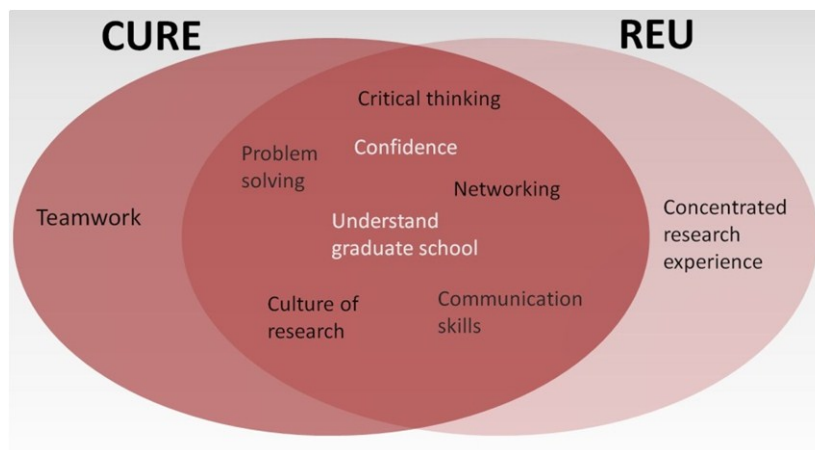

Figure 5: Outcome Comparison. CUREs and REUs share many outcomes; Teamwork is emphasized more in CUREs, while REUs provide a more concentrated research experience.

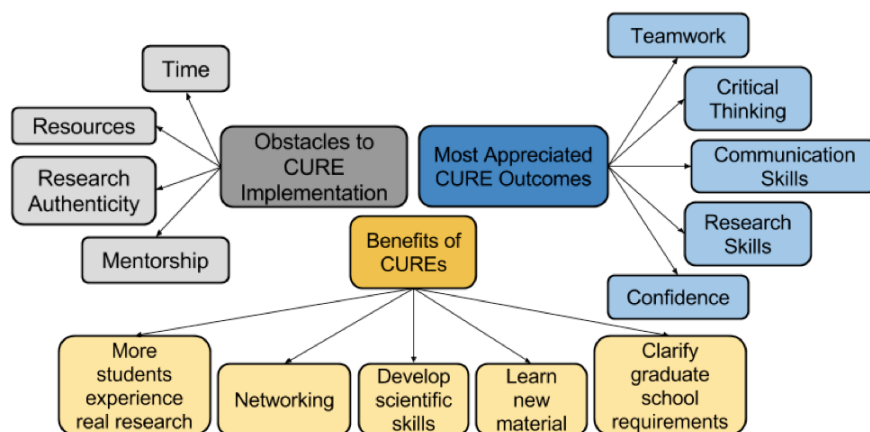# CHAPTER FIVE: CONCLUSIONS & RECOMMENDATIONS

5.1 CONCLUSIONS

Figure 6: Obstacles, Outcomes, and Benefits. Overcoming obstacles referenced here will result in better outcomes and benefits.

It is becoming more widely known that undergraduate research experiences have broad benefits for students involved. However, program designers do not have many good references for designing such research experiences (Hanson, 2013). A meta-analysis of 41 published articles, additional archival research, and semi-structured interviews identified multiple benefits of CUREs, including their introducing more students to research. The main questions that we addressed included what the NSF values most in a research experience as well as what the outcomes of such experiences were. We wanted to guide program designers so they can review what has worked in the past in order to design new successful research experiences.

Our research showed that CUREs are beneficial as they bring research to more students to the culture of research. They provide networking opportunities and ways to improve scientific skills while learning new material. In order for CURE to be authentic, it should encompass ill-structured problems, which do not usually have explicit goals, methods and even end states. Such problems are the ones faced by professionals. Students leave CUREs with a better understanding of the demands and expectations of graduate school. CUREs lead to the development of teamwork and critical thinking. Students also improve their research and communication skills. These outcomes all contribute to boosting students' confidence.

Our research showed that the availability of resources is the biggest obstacle that stands on the way of a perfect CURE (Pantoya *et al.,* 2013). We found that many studies reported that the lack of equipment and space were large impediments when incorporating CUREs at their respective universities. In some cases, the implementations of CUREs were not fully successful due to faculty members' lack of experience in embedding a research project into an undergraduate course. Most of these studies discussed the implementations of CUREs for the first time in their respective institutions. Moreover, our analysis also showed that the quality of mentorship has a considerable impact on the success of CUREs (Beck *et al.,* 2014). That is, when working with larger groups of students, incorporating different levels of mentorship, such as mixing a few graduate students with one or two professors, is beneficial. Students feel that they can take their everyday questions and problems to the graduate students and reserve their hard questions and bigger problems for the typically more limited time with their professor (Levis-Fitzgerald *et al*., 2005; McLaughlin *et al.,* 2013). As a consequence, CUREs also provides benefits for the graduate students since the undergraduate students also ask them questions, which might compel the graduate students to solidify their understanding about the research project and improve their mentoring skills (Levis-Fitzgerald *et al*., 2005; McLaughlin *et al.,* 2013)**.** Finally**,** we want to make it possible for students to be motivated by research, and we believe that following our recommendations will inspire generations of students to CURE our world.

5.2 RECOMMENDATIONS

We formulated six recommendations, as defined below:

1. CUREs should be integrated into first- and second-year courses to allow students to experience a clearer transition from high school to college.

The integration of CUREs earlier in undergraduate education will help increase the interest of students in STEM fields, a change which might reduce the number of students quitting STEM fields during freshmen and sophomore year (Tobias, 1990). Students will be able to perceive their majors better if they have research experience earlier, specifically, during their first and second year in college. As a result, introducing research early in undergraduate education might not only minimize the number of students who quit STEM fields, but it also might encourage students to consider attending graduate school. Most research-based programs are currently offered during junior and senior year. By this time, many students who, if they had

been provided with a research experience like CURE, would have been more interested in STEM fields might have already left STEM fields.

2. Program designers should incorporate activities in which students of diverse expertise work in teams.

Students of all skill levels will benefit from such an experience. Less experienced students are able to ask questions while more experienced students have an opportunity to become better mentors. By forming teams of students with various levels of experience, beginner students can discover motivation in finding something new that they excel at, while older students can improve their ability to teach others (Moore, 2014).

3. Faculty directors of CURE programs should assess, then take into account the ways that their particular students learn.

For example, Felder and Silverman describe learning and teaching styles that capture the various ways students can absorb material (Felder, 1993). A survey similar to theirs could be distributed to assist program directors in understanding their students better learning styles before committing to one style of teaching.

4. Each program should have more than one faculty member so that students receive more mentoring from professors.

One of the most important barriers to implementation of CUREs is lack of time for faculty members to develop new research experiences (Spell, 2014). With only a single professor involved, undergraduate students could find it difficult for all of them to get help from or to arrange a meeting with the professor.

5. Program designers should initially break down the research activity into small tasks or steps; program designers should also consider how to fit small tasks or steps into the course's scheduled lab times.

Students struggle with formulating open-ended problems but have an easier time attacking well-defined problems (Koo *et al*., 2003). Once students have a defined problem, they are better able to come up with a workable solution. If the professor chooses to begin his course with a more defined procedure, the students should eventually be tasked with learning how to break down the research activities into achievable goals on their own. If the students are

provided with a general problem and given some initial guidance, they will be able to navigate the research process from formulating a hypothesis to interpreting results (Shaffer *et al*., 2014). If a course schedule is too intense, students might fail to complete one specific task and thereby delay the progress of the entire research project.

6. Course faculty should encourage students to share all of their ideas and encourage students to lead weekly meetings and lab activities.

Students are more likely to come up with good ideas if their mentors have expressed sincere interest in hearing what ideas they have, even if they are unusual or seemingly unfeasible. Running weekly meetings would help confirm the importance of students' collaborative role working with the mentors or professors in the project, instead of just following orders (Koo *et al.*, 2003). Assuming such responsibilities might also help increase students' sense of ownership of their research.

Our investigation of published reports of course-based research experiences was necessarily time-limited. The conclusions reported here are based on those papers, which are listed in the bibliography of this report. In the Suggested Reading List at the end of this chapter, we have also provided a list of additional papers that might be reviewed by a follow-up project.

We recommend that the NSF utilize our recommendations for the ideal implementation of CUREs when preparing materials for distribution to program designers in NSF's call for proposals. This will help to ensure that applicants have access to recommendations regarding what the NSF values in a paper.

5.3 FUTURE RESEARCH

Relation of discipline to course design: There is another main area we found that needs further research in order to make more conclusive recommendations. There may be a relationship between course discipline and design (Singer *et al.,* 2012). We define research as using existing procedures to develop new scientific theories, while design is using existing knowledge to combine and tailor existing methods to a new problem. Our light research into this topic revealed that research projects are more likely to be implemented in science, and mathematics disciplines, while design projects are more suited to technology. Depending on the specific subdiscipline, design and research projects can be successfully implemented in engineering.

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APPENDIX A: PILOT INTERVIEW QUESTIONS

STUDENTS:

1. Describe your undergraduate research experience's length of time and supervision level.
2. What are the top three benefits you believe you gained from this experience?
3. What did you expect before you began your experience?
4. How could your experience have been improved?
5. Did you have the opportunity to publish a paper?
6. Where can additional information about your project be found?

PROFESSOR:

1. What makes your program different from others?
2. What do you think makes a program successful?
3. How do you expect students to change as a result of participating in an REU?
4. How do you think having a graduate student to assist you affects your program?
5. What is your view on including community college or 2-year college students in REUs or CUREs?

APPENDIX B: WPI PROFESSOR INTERVIEW QUESTIONS

1. What skills do you want students to develop as a result of your research program?
2. Have you taught in more than one learning environment?
3. Which environment do you see the highest student improvement in?
4. What types of improvements do you see in each environment?
5. What types of improvements do you think could be made to the program with regards to:
    1. Helping more students learn better?
    2. Motivating students to pursue careers in science?
2. How important do you believe an undergraduate research experience is in preparing students for the real world as a scientist, if they choose this career option?
3. How can we help a larger number of students gain a better understanding of the material?
4. How would you define a CURE?
5. How would you define a URE?
6. How would you measure the success of a program?
7. What is your view on including community college or 2-year college students in REUs or CUREs?
8. What factors can make an undergraduate program unsuccessful?
9. What obstacles that are usually encountered in the implementation of CUREs?

APPENDIX C: NSF OFFICIALS INTERVIEW QUESTIONS

1. What skills do you want students to develop as a result of participating in the research programs you approve?

2. What are the criteria you use to approve a proposal?

3. From the proposals that you have read, can you think of any missing elements or common elements that could be improved upon?

4. What do you believe is the main goal of UREs? of CUREs?

5. What is your view on including community college or 2-year college students in REUs or CUREs?

6. How would you measure the success of a program?

APPENDIX D:

RUBRIC OF ESSENTIAL AND DESIRABLE CHARACTERISTICS OF CUREs

| Essential Characteristics of CUREs (Goals of CUREs)		
Provide a large number of students with bona-fide research	*Increase the students' interest in STEM fields*	*Provide an authentic experience*
The research project should : 1. Generate new knowledge 2. Include ill-structured problems (check rubric 2)	Integrate CURE in freshmen and sophomore year	Integrate design projects
Team-structured		Plan visits to local industries
Employ graduate students as mentors to provide adequate mentorship for the large number of undergraduate students		Contact a company that deals with material in the discipline & have them 'employ' students to research a solution for a company problem

Rubric 1: Essential Characteristics of a CURE.

Classification of a problem's complexity			
Type of the problem	Well-structured	Moderately-structured	Ill-structured
Goals	Well defined	Well defined	Undefined
Beginning State	Well defined	Well defined	Well defined
Actions	Well defined	Many possible actions	Undefined
End State	Well defined	Well defined	Undefined
Constraints	Well defined	Well defined	Usually not well defined
Example	Starting a car	Fixing a car	Designing a car GWAPA MI

Rubric 2: Classification of problems' complexity

Desirable Characteristics of CURE
(Design of CURE)

Program designers should incorporate activities in which students of diverse expertise work in teams.

A model taken from a published paper (Moore & Teter, 2014).
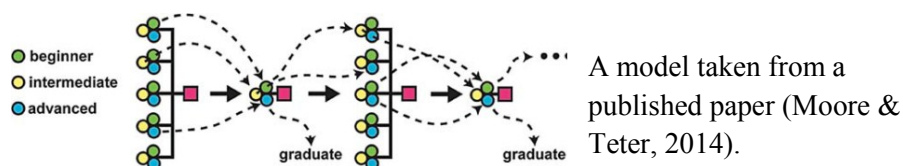
Faculty directors of CURE programs should assess, then take into account the ways that their particular students learn.

Emphasis on Transferrable Skills

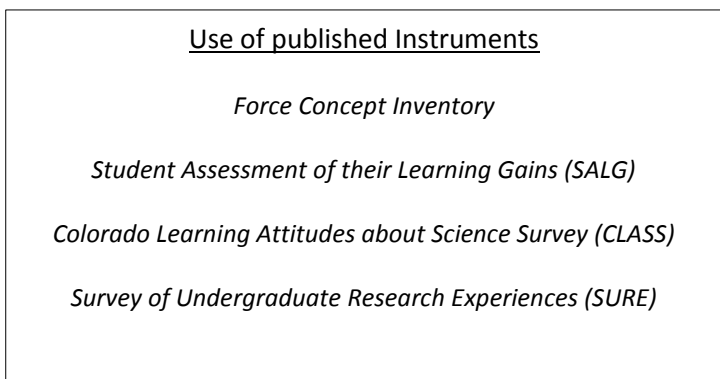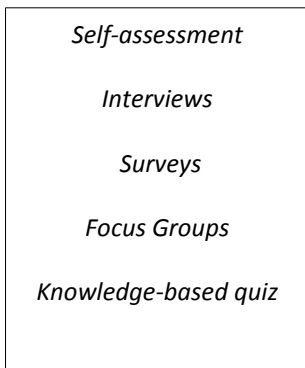| Research Skills	Technical Writing	Constructive critiques	Presentation

Each program should have more than one faculty member so that students receive more mentoring from professors. A model is provided below
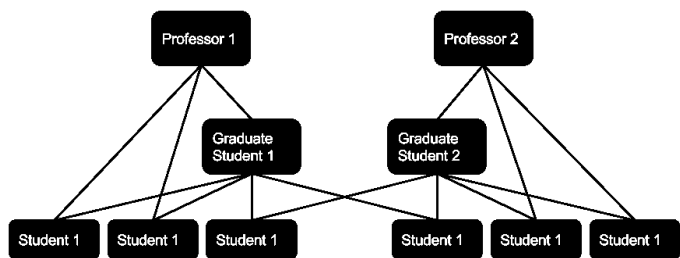
Course faculty should encourage students to share all of their ideas and encourage students to lead weekly meetings and lab activities.

Program designers should initially break down the research activity into small tasks or steps; program designers should also consider how to fit small tasks or steps into the course's scheduled lab times.

Assessment

Self-assessment	Use of published Instruments
Interviews	*Force Concept Inventory*
Surveys	*Student Assessment of their Learning Gains (SALG)*
Focus Groups	*Colorado Learning Attitudes about Science Survey (CLASS)*
Knowledge-based quiz	*Survey of Undergraduate Research Experiences (SURE)*

Rubric 3: Desirable Characteristics of a CURE.

APPENDIX E: SUGGESTED READING LIST

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   a) A paper providing the design and validation of a published survey instrument that has been modified for use in Biology, Chemistry & Physics.

2. American Association for the Advancement of Science (2011). Vision and Change: A Call to Action, Washington, DC.
   b) Further persuasion for using inquiry-based learning

3. Bailey, R., Bischof, H., Kwon, M., Miller, T., and Raj, R. (2011). On Providing Successful Research Experiences for Undergraduates. *ASEE/IEEE Frontiers in Education Conference 41*, T2F-1- T2F-6.
   c) A review by university professors on methods for creating successful Research Experiences for Undergraduates

4. Basey J, Francis C (2011). Design of inquiry-oriented science labs: impacts of student attitudes. *Research in Science & Technology Education 29*, 241–255.
   d) Learn more about the differences between how guided inquiry and project based labs affect students

5. Belanger KD (2009). Using affinity chromatography to investigate novel protein-protein interactions in an undergraduate cell and molecular biology lab course. *CBE Life Sciences Education,*8, 214–225.
   e) Case study across universities using the same laboratory exercise

6. Brownell SE, Tanner KD (2012). Barriers to faculty pedagogical change: lack of training, time, incentives, and tensions with professional identity. *CBE Life Sciences Education,11*, 339–346.
   f) Understand why teachers have been hesitant to change their teaching methods

7. Felder, Richard, (1993)."Reaching the Second Tier: Learning and Teaching Styles in College Science Education." *Journal of College Science Teaching, 23*(5), 286-290
   g) Understand more about how to recruit more students into STEM

8. Hanauer, D., Dolan, E. (2013). The Project Ownership Survey: Measuring Differences in Scientific Inquiry Experiences. *CBE Life Sciences Education 13*(1): 149-158.
   h) Project Ownership Survey – developed, presented and evaulated. Used for larger data sets to measure the extent to which students feel project ownership.

9. Hestenes, D., Wells, M., Swackhamer, G. (1992). Force Concept Inventory. *The Physics Teacher, 30,* 141-158.
   i) Describes the design and results of a survey designed to how well high school and college students understand Newton's concepts regarding force.

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   j) A CURE case study in genetics with an attached assessment. Designed to introduce students to experimental research. Could provide further evidence for positive CURE outcomes.