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Undergraduate Research and Curricular Redesign of IPLS Laboratory Courses

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Introduction

The University of Detroit Mercy is a recent recipient of a National Institutes of Health (NIH) BUILD (BUilding Infrastructure Leading to Diversity) grant aimed at creating a career pipeline with the goal of increasing the participation of under-represented minorities (URM) in biomedical sciences research. Steep declines in the presence of these populations[1,2] within the biomedical research sector have caused sufficient alarm that the NIH has tasked grantee institutions "to implement and study innovative approaches to engaging and retaining students from diverse backgrounds in biomedical research, potentially helping them on the pathway to become future contributors to the NIH-funded research enterprise."[3] The institutions involved in our grant have identified a number of barriers and opportunities to enhance the success of URM students at the undergraduate level within the biomedical pipeline. Chief among the challenges faced are the integration of authentic research experiences within the undergraduate curriculum. Studies show that student participation in undergraduate research is correlated with the success of all students in STEM careers.[4] In particular, the early introduction of mentored research that complements student coursework has been shown to improve retention rates of URM students by enhancing their academic skills, self-esteem, motivation to overcome barriers and knowledge of post-graduate career paths.[5,6] Implementing these findings requires reforming the foundational undergraduate science curriculum and providing students with meaningful research experiences, especially in laboratory settings.

The goals of the BUILD grant dovetail well with intensive efforts within the physics community to transform and enhance the Introductory Physics for Life Sciences (IPLS) course sequence in ways that more fully integrate the foundational principles in physics with the education of biologists and life scientists.[7,8,9] The undergraduate introductory physics sequence remains a source of frustration for students of biology and the life sciences. The disconnect between the topics students learn in introductory physics lecture and laboratory and the changing nature of the biological sciences has only grown worse in recent decades. Students do not see the relevance of what they learn in their physics courses to either their ongoing education in biology or their future careers in the life sciences. Yet, biomedical researchers and medical practitioners are acutely aware of the critical role of physics in the study of living systems from the macroscopic to the cellular scales. The recognition that physics laboratories provide an ideal space to teach modeling, computational tools and modern technology, while training students in the concepts needed for the study of living systems, have energized efforts to redesign the laboratory course.[10]

This paper outlines a project that integrates the undergraduate research goals of the BUILD grant within a framework that promotes the curricular redesign of the introductory physics for life science (IPLS) laboratory courses. We briefly discuss the literature on the importance of the goals, design and assessment of student research projects followed by a description of our physics REU (Research Experience for Undergraduates) model. We present data and analysis from a biologically-relevant interdisciplinary research project that involves Newton's Law of Cooling. The research was conducted by a BUILD scholar who is currently a junior biochemistry major at the university, and is listed as the first author of this paper. We conclude by evaluating the benefits and weaknesses of our REU model based on the student's perception of the project and provide other examples of experiments suitable for use in this context.

Goals of Undergraduate Research

While the importance of engaging undergraduate students in authentic research projects has been extensively discussed in the literature,[11,12,13] the evaluation of various research strategies and goals has not received much attention.[14,15] The typical modes of undergraduate research revolve around summer internships, faculty-mentored projects that last one or more semesters, and research-based curricula incorporated into lower or upper division courses.[16] Unfortunately, most research projects involve topics that are too advanced for beginning undergraduates or that have little to no structured integration with student coursework[15]. In part, this stems from a continuing emphasis on what Ernest Boyer identified as the *scholarship of discovery* which prioritizes fundamental research that advances human knowledge[17]. This emphasis, prevalent at research universities, and frequently adopted at predominantly undergraduate institutions (PUIs), is succinctly described by the following statement from the 1998 Boyer Commission report: "In the sciences and social sciences, undergraduates can become junior members of the research teams that now engage professors and graduate students."[18] Unfortunately, this model suffers from a serious epistemological weakness:

> The standard model of undergraduate research is the apprenticeship model in which students are transported across this divide with little cognitive or practical preparation. Sinking or swimming, the student is then presented with a problem or project, shown the basics of how to solve the problem, and allowed to give it his/her best shot. This effort frequently takes place under the guidance of graduate students and/or research associates who themselves have little cognitive or practical preparation for this role. This research experience most often takes place late in the student's course of study and is usually pedagogically and epistemologically distinct from his/her course of study.[19]

An alternative model better suited to beginning and advanced undergraduates combines Boyer's *scholarship of teaching* and *scholarship of integration* with the goal of "transforming and extending" the student's knowledge by encouraging critical thinking and multidisciplinary understanding in carefully structured research projects that relate directly to the student's curriculum. Studies have shown that such an approach can "expand opportunities for undergraduate research, develop new curricula, reinvigorate existing curricula, and support innovation within the existing course structure."[18] An important feature of this model is an initial emphasis on the independent reproduction of results from prior research presented in peer-reviewed journals. While traditional laboratory curricula emphasize the reproducibility standard inherent in the scientific method, they often do so in cookbook-fashion with faculty-created manuals that stifle independent thought and creativity. Even reformed curricula suffer from the over-structuring inherent in credit-based schedules and course grades. For beginning undergraduate researchers, however, the task of independently reproducing the results of prior research provides the appropriate scaffolding to train them in designing and implementing experiments to investigate specific scientific questions. Students learn the importance of research protocols, error analysis and quantitative modeling in the design process. These skills are then utilized when students test original hypotheses that are extensions of the original research. The appropriate standard for these research questions continues to be their worthiness for publication or presentation, thus training the writing and speaking skills of students.

Our REU Model

At the University of Detroit Mercy, we designed a pilot project based on this model. An undergraduate student researcher was tasked with reproducing and extending a physics laboratory experiment published within the pages of *The Physics Teacher* or the *American Journal of Physics*. These journals have well-deserved reputations within the physics community for peer-reviewed, research-based innovations in undergraduate teaching and research. They contain a wealth of ideas and experiments aimed at audiences of college-level students and faculty that have been scrutinized for rigor and correctness. Articles from these journals were chosen for research projects based on the following criteria: (1) the central concepts in the article should be accessible, and typically taught, to students in an IPLS course; (2) the experiment should involve qualitative and quantitative modeling of physical phenomena in a biologically-relevant context; (3) the paper should provide an optimal level of information and guidance to the student researcher, requiring them to make independent research decisions while reproducing the experimental results in the paper; and (4) the topic should provide sufficient opportunity for the student to conduct original research. The standards for this latter criterion were a balance between publication-worthiness and usefulness for an IPLS laboratory course. Consequently, the student was required to create a laboratory manual that could be implemented in such a course. Table 1 below lists some articles from the pages of *The Physics Teacher* and the *American Journal of Physics* that are suitable as research projects for freshman or sophomore undergraduate students.

IPLS Concept	Article Title	Citation
Resistors; bioelectricity	Bridging Physics and Biology Using Resistance and Axons	https://doi.org/10.1119/1.4897581
Optics; scattering of light	Simple laser scattering experiment for biology-oriented physics labs	https://doi.org/10.1119/1.11792
Mechanics; sound; bioelectricity; fluid flow	Some experiments with biological applications for the elementary laboratory	https://doi.org/10.1119/1.9800

Elasticity; speed of sound	Interdisciplinary cantilever physics: Elasticity of carrot, celery, and plasticware	https://doi.org/10.1119/1.4826190
Electrical conduction; drag forces; fluid friction	Undergraduate physics laboratory: Electrophoresis in chromatography paper	https://doi.org/10.1119/1.4932546
Kinematics; forces; torque	The indirect measurement of biomechanical forces in the moving human body	https://doi.org/10.1119/1.2149868
Optics; interference; spectroscopy	Investigating thin film interference with a digital camera	https://doi.org/10.1119/1.3490011
Fluid Pressure; error analysis	Kitchen Physics: Lessons in Fluid Pressure and Error Analysis	https://doi.org/10.1119/1.4974119
Diffraction; optics	How Rosalind Franklin Discovered the Helical Structure of DNA: Experiments in Diffraction	https://doi.org/10.1119/1.3555496
Drag forces; mechanics;	Measuring Drag Force in Newtonian Liquids	https://doi.org/10.1119/1.3685119
Thermodynamics; elasticity	Laboratory Activity: Specific Heat by Change in Internal Energy of Silly Putty	https://doi.org/10.1119/1.3661107

Table 1.
Undergraduate research project ideas from the pages of *The Physics Teacher* and the *American Journal of Physics*

Forensic Applications of Newton's Law of Cooling

The September 2015 issue of *The Physics Teacher* contained an article[20] describing numerous experiments at the intersection of biology and physics suitable for an IPLS course. One example described in the article involved the use of a store-bought bratwurst as a model for a human cadaver. The bratwurst, which was heated and then allowed to cool, was used to study the concept of heat transfer inherent in Newton's law of cooling. This allows for an estimation of the "time of death" of the bratwurst in a manner similar to that conducted on human corpses by medical examiners and forensic scientists. This article was selected for the RUE pilot using the criteria listed above, and serves as an interesting example of biologically-relevant physics.

As described in numerous texts and articles[21], Newton's law of cooling is an empirically-derived result that states the rate at which an object's temperature changes over time is proportional to the difference in temperature between the object and its surroundings,

$$T(t) - T_s = (T_0 - T_s)e^{-kt}$$

Here, $T(t)$ is equal to the temperature of the object at a given time, T_s is the temperature of the surroundings, T_0 is the original or starting temperature of the object, and k is a constant whose inverse serves as a time-constant for the exponential decrease in the temperature-difference. The value of the time-constant depends on numerous physical properties of the object, including its mass, specific heat capacity and surface area.

I: Reproduction of experiment: In the lab exercise described in the article, students were provided with a 90-gram bratwurst heated to approximately 45°C and then submerged in a 410-gram water bath at approximately 2°C. In our experiment, we used a bratwurst with a mass of 108-grams which was heated to an initial temperature of 39.8°C (as measured longitudinally along its center) and submerged in a 375-gram water bath at a temperature of 2.8°C The temperature changes of both the water and the bratwurst were recorded at regular time-intervals and show an exponential decay for the temperature difference between the bratwurst and water as a function of time, as shown in Figure 1 below.

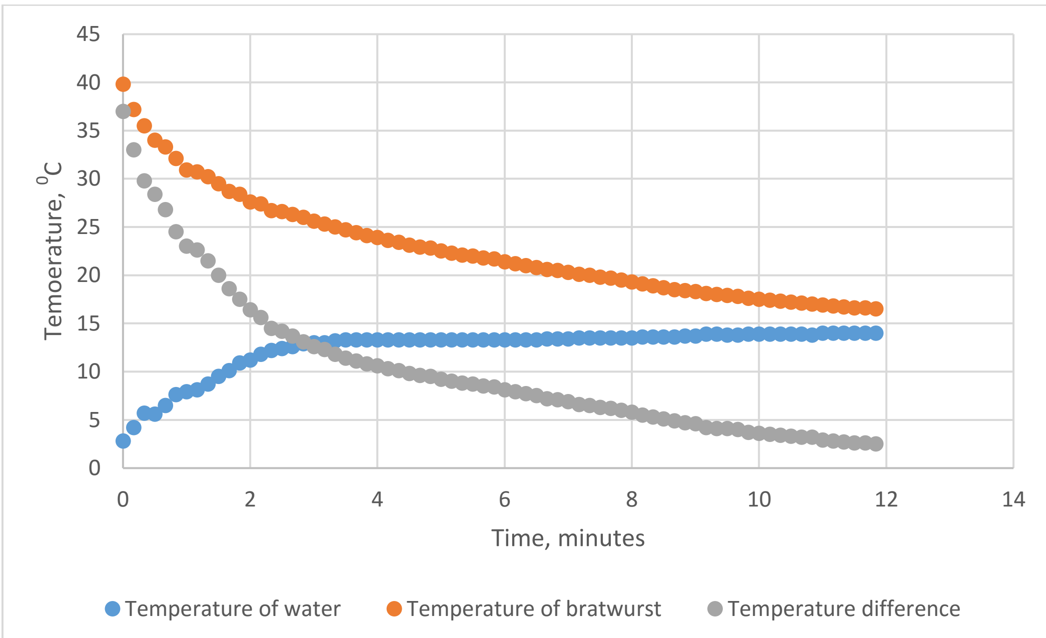


Fig. 1
Temperature changes in the bratwurst and water as a function of time. The orange dots show the difference in temperatures plotted against time.

To ensure that the decay is indeed exponential, a log-linear plot of the temperature difference as a function of time was plotted and is shown in Figure 2. As expected, the data was reasonably fit with a linear trendline, with a slope value equal to 0.0866 min^{-1}. A quick calculation reveals a value of $k = 0.20$ min^{-1} which compares quite favorably with the value of $\lambda = 0.17$ min^{-1} quoted in the TPT article for the decay constant.

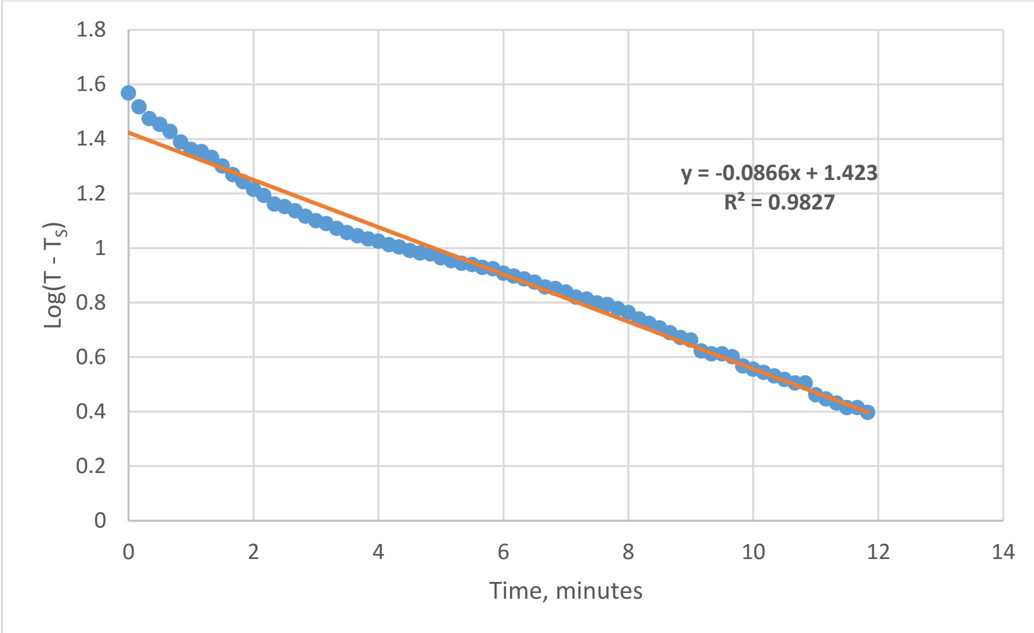


Fig. 2
Log-linear plot of the temperature difference between the bratwurst and water plotted against time.
A linear trendline provides a good fit to the data as expected for exponential decay.

II: Research-based extension of project: Forensic analysis of post-mortem cooling has a long history. In 1868, Scottish physician H. Rainy applied Newton's law of cooling to decipher the "length of time since death" of the deceased.[22] In these and subsequent experiments, the analysis was conducted in scenarios where the body was exposed to a relatively constant ambient room temperature. After completing a literature search that provided an interesting historical and scientific timeline of forensic research, the student decided to conduct a second experiment in which the bratwurst was left to cool in air as would be expected for a human corpse in a real-world situation.

A similar experimental procedure was followed, except that the temperature of the air was measured to remain constant at approximately 24 °C. Figure 3 shows the results of a log-linear plot of the temperature difference between the bratwurst and ambient air as a function of time, which is tracked very well by a linear-regression fit. The slope value equals to 0.031 min^{-1}, corresponding to a value of $k = 0.07\ min^{-1}$, which is about a third of the rate in the water experiment, reflecting both, the smaller temperature differential as well as the differing conductivities of the water versus air pockets adjacent to the bratwurst.

The graph shows an interesting effect in that the cooling in the earliest stages do not follow the exponential decay expected from Newton's law of cooling. A search of the research literature revealed that this is known as a "plateau effect" in forensic analysis.[23] In the initial stages, temperatures in the center of the bratwurst cool less rapidly due to the poor conductivity of the tissues and possible continuing heat production in those same tissues, leading to a slower rate.

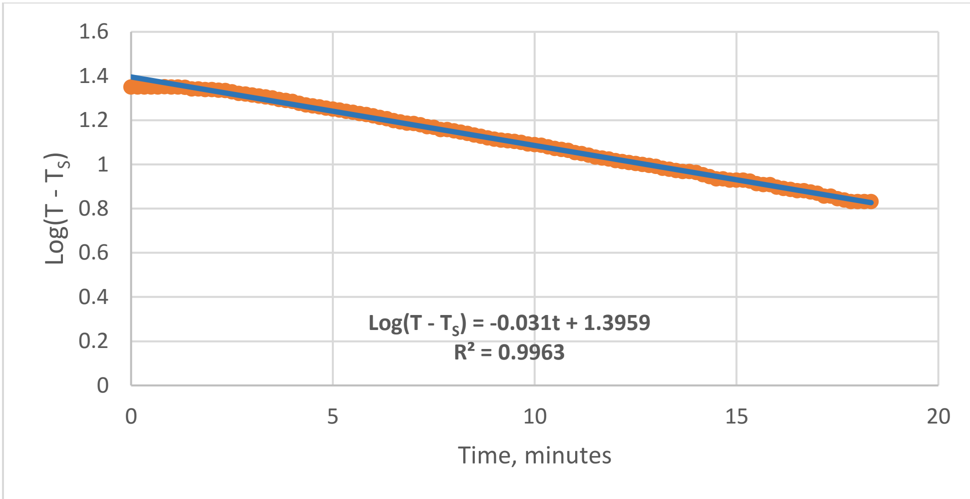


Fig. 3
Log-linear plot of the temperature difference between the bratwurst and surrounding air plotted against time. A linear trendline provides a good fit to the data as expected for exponential decay.

Evaluation of REU Model and Benefits from Research

In recent years, there has been a spate of articles attempting to "determine an empirically established set of benefits generated by undergraduate research experiences in the sciences."[24] Survey instruments designed to evaluate these outcomes have recently been developed. [25] One of the more widely accepted surveys is the URSSA (Undergraduate Research Student Self-Assessment) instrument. Among the various research gains surveyed in URSSA are "skills such as lab work and communication", "conceptual knowledge and linkages" in the field of research,, and "deeper understanding of the intellectual and practical work of science".[26] While the instrument was not designed for surveying individual students, it is quickly becoming the standard questionnaire to evaluate the gains in undergraduate research. A copy of the full survey can be found on the website of the Ethnography and Evaluation Research unit at the University of Colorado, Boulder.[27] The student was therefore required to fill out a modified version of the survey with questions that were relevant to the current REU model and to follow-up with a personal narrative of his research experience based on survey questions.

Table 2 below shows a summary of scale results from some of categories surveyed in the URSSA. The full results of the URSSA survey is available on request. As can be seen from the table, the student perceived the benefits of the research experience across multiple categories as ranging from "moderate" to "great" gain, with one exception in the "overall research experience" category which involved a question about interactions with scientists "from outside your school" and was not a part of our REU model.

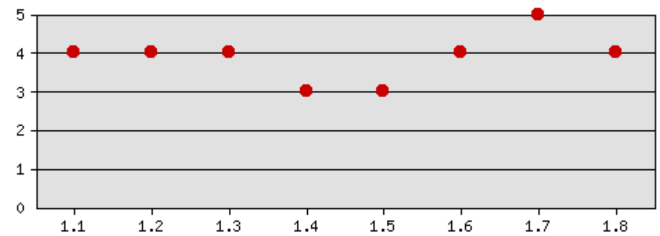
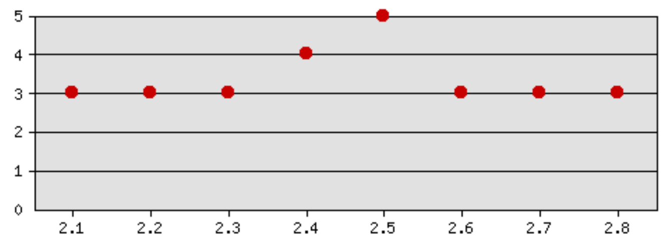
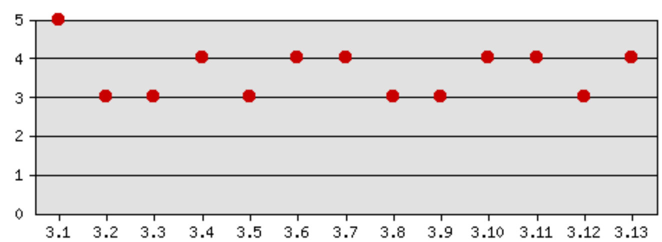
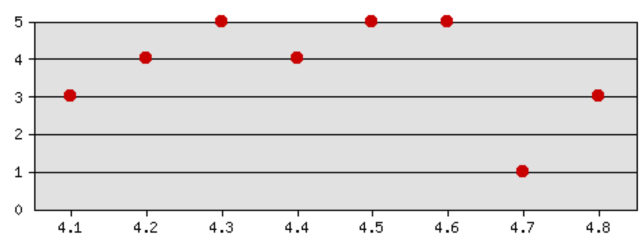
Research Gains	**Graphical Summary of Scale Results**
1=no gain; 2=a little gain; 3=moderate gain; 4=good gain; 5=great gain	
Thinking and working like a scientist: application of knowledge to research work	
Personal gains related to research work	
Skills	
Overall research experience and about any changes in attitudes or behaviors as a researcher	

Table 2.
Summary of partial survey results of the URSSA questionnaire

A summary of the student's personal narrative on the research experience substantiates and expands on the survey:

> The most immediately apparent benefit of the REU model was a much clearer biological connection. The relevance of the physics concepts taught in the lab to biological systems is spelled out, facilitating much of the relational learning for me up front. Reorganizing the instruction of the physics concepts as not simple standalone ideals, but instead as components of a larger context peaked my curiosity and interest in the work I was performing. This heightened curiosity lead

to numerous intellectual and personal growths over the course of the lab and research experience. These growths may be primarily categorized as a better understanding of the research process including key elements such as problem solving and troubleshooting techniques, how to effectively design and carry out a research project, and understanding the scope and limitations of the research. On a personal level, I developed key skills such as critical reasoning, data analysis techniques, and lab notebook upkeep.

Overall, the student had a very positive experience with the project. Both of us recognized that further training in writing skills would help address a weakness that besets most undergraduate student work. The usefulness of this training would help in producing a well-written laboratory manual for the experiment for use in future IPLS laboratory courses. The student is currently working on this part of the project.

Conclusion

In this paper we have described the results of an experiment involving the forensic application of Newton's law of cooling as an example of biologically-relevant physics concepts suitable for an undergraduate laboratory. The undergraduate research student was tasked with reproducing the results presented in a peer-reviewed article from the pages of *The Physics Teacher*. Having successfully completed this exercise, the student was then required to design and implement the experiment to test a new hypothesis. The final step of the research plan was aimed at training the student in writing skills by requiring him to create an undergraduate laboratory manual for the experiments.

The benefits of this research model include the relevancy and appropriateness of projects for beginning undergraduates in the life sciences; an emphasis on the importance of reproducibility and extension of scientific research using peer-reviewed journal articles as case studies; and training in reading and writing scientific articles that build upon existing concepts in the undergraduate curriculum. The weaknesses in the model stem from the narrow scale of these projects that preclude working in research teams, and the difficulty of extending the research into the scholarship of discovery.

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