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A New Undergraduate Curriculum on Mathematical Biology at University of Dayton

Muhammad Usman
University of Dayton, musman1@udayton.edu

Amit Singh
University of Dayton, asingh1@udayton.edu

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Muhammad Usman and Amit Singh*
University of Dayton

Abstract

The beginning of modern science is marked by efforts of pioneers to understand the natural world using a quantitative approach. As Galileo wrote, "the book of nature is written in the language of mathematics." The traditional undergraduate course curriculum is heavily focused on individual disciplines like biology, physics, chemistry, and mathematics with lesser emphasis on interdisciplinary courses. This fragmented teaching of sciences in the majority of universities leaves biology outside the quantitative and mathematical approaches and vice versa. The landscape of biomedical science has transformed dramatically with advances in high-throughput experimental approaches, which has led to the generation of an enormous amount of data. The best possible approach to using this huge amount of data to generate insights into biological problems is to employ the strength of mathematics. Since professionals trained in either biology or mathematics alone will not be as helpful in this pursuit, there is a great demand to prepare a future workforce trained in the interdisciplinary field of mathematical biology. With this aim, we have developed a four hundred-level interdisciplinary undergraduate course in mathematical biology at the University of Dayton. This course was offered for the first time in the spring of 2010. This course focuses on mathematical modeling of three important facets of biology including the nervous system, growth regulation, and diseases of the immune system. The results from exit surveys of students who enrolled in the course are promising. They strongly felt that their experience was conducive to learning, and that it strongly evoked their interest in the mathematical biology discipline. Here we present the details of the course and its outcome on student inquiry and learning habits.

Keywords:
Mathematical Biology, undergraduate course curriculum, STEM education, interdisciplinary courses

Introduction

Many universities and schools all over the world offer individual mathematics and biology undergraduate programs. This may be due to the pre-existing concept that the research focuses of mathematics and biology fields did not overlap very often (Blanton, 2008; Taraban & Blanton, 2008). However, with advancements in the biomedical field and new forays into computational applications, it has become essential to explore relatively newer areas like mathematical biology (Newell, 1994). The majority of biology students lack thorough training in mathematics as most of them are scared of mathematics (or do not understand it); the converse also holds equally true (Reed, 2004). Despite this divide, recent advances in biomedical and mathematical research make it essential for us to foresee a new class of trained professionals and researchers that can work at the interface of mathematics and biology (Steen, 2005; Miller & Walston, 2010).

In order to train students in this newly emerging field there is a need to direct these efforts at the grassroots level of undergraduate education (Russell, 2008; Nadelson et al., 2010). It is an established fact that undergraduate education serves as the foundation for higher education. Recently, there has been great emphasis on initiatives towards developing and introducing interdisciplinary teaching and projects for undergraduate course-curricula that involve a research experience (Bialek & Botstein, 2004; Farrior et al., 2007; Blanton, 2008; Seymour et al., 2003; Miller & Walston, 2010; Nadelson et al., 2010). Based on this ideology, we have developed a course that was designed to introduce the discipline of mathematical biology at the University of Dayton. Since it was difficult to teach this course content individually, we planned a team taught course involving faculty from both the Biology and Mathematics departments. This four hundred-level undergraduate course, which was offered for the first time in the spring 2010 semester, focuses on training students (including juniors and seniors) at the interface of mathematics and biology. It involved: (i) providing students with the necessary insight into topics in specific areas of mathematical biology (the nervous system, growth regulation and disease, and disease of the immune system); (ii) introducing them to current research in the field; (iii) training them in basic research skills, such as designing a hypothesis and then testing it; (iv) teaching them how to

* Corresponding Author
amit.singh@notes.udayton.edu

perform bibliographic searches, and reading and summarizing research articles; (v) providing them input toward preparing presentations of their work for critical evaluations from their peers via a poster or oral presentation; and finally (vi) teaching them how to write these projects as research papers/reports.

In the next section, we will discuss the rationale and purpose of introducing such a course. We will follow it up with a section that deals with the challenges in teaching the course, and finally, we will present our conclusions from this work in the last section.

Why should we introduce mathematical biology?

Mathematics and biology are considered two different and distinct branches of science (Steen, 2005; Taraban & Blanton, 2008). The concepts of mathematical biology have been designed by similar logic as those of biophysics, which has been used to understand the physical concepts related to biological phenomenon, and thereby works at the interface of physics and biology. By the same token, mathematical biology employs mathematical logic to understand biological phenomena (Lonning et al., 1998).

For a long time it was considered that theory and experimentation are two independent methods for scientific discovery (Figure 1). Recent developments in the biomedical field have raised a need for interdisciplinary approaches (Newell, 1994; Steen, 2005; Farrior et al., 2007). Rapid growth in biomedical sciences has led to the generation of an enormous amount of data. Most often, biologists lack the skills and insights to extrapolate the data, and thus have trouble interpreting it. The best approach would be to create algorithms for scientific computation that are user-friendly for biologists. Mathematicians, on the other hand, have the tools and expertise to compute and extrapolate information that makes sense of the biological datasets (Reed, 2004). However, mathematicians lack the fundamental knowledge of biology. Thus, biologists who understand the system they are studying, but lack the necessary tools to properly analyze the huge amount of data they have produced, need an infusion of mathematics to get better insights into their data (Rossi et al., 2004). These issues definitely hold true for clinical research, too. Therefore, in order to develop new tools, both mathematicians/statisticians and biologists are needed. The recognition of the above-mentioned issues has led to the

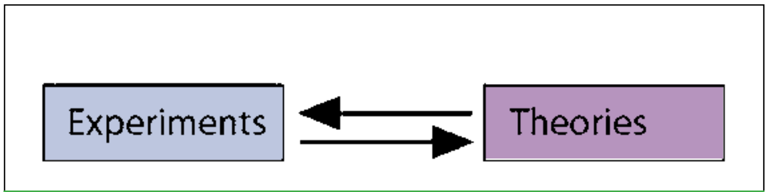

Figure 1.

emergence of a new field of mathematical modeling to understand how life in all its diversity and detail works.

Today, experimentation, theory, scientific computation, and mathematical modeling are considered as a new synergistic approach to scientific discovery (Figure 2). Mathematical modeling and numerical simulation enable us to study complex natural phenomena that would otherwise be difficult or even impossible (Reed, 2004). Thus, the new field of mathematical modeling can be instrumental in developing quantitative skills among biology students, and developing an understanding of biological phenomenon among the mathematics students (Laursen et al., 2010; Miller & Watson, 2010; Nadelson et al., 2010).

It is a well known fact that there is an immense shortage of quality teachers in the K–12 system in STEM (**S**cience, **T**echnology, **E**ngineering, and **M**athematics) disciplines (Hailey et al., 2005: Laursen et al., 2007; 2010). These types of courses at the undergraduate level will allow training of new generations of teachers who can interact across the disciplines, and thereby help to improve the quality of interdisciplinary curricula at various levels in our education system. Thus, interdisciplinary courses such as mathematical biology will provide great impetus to education and applications of mathematics in real life problems.

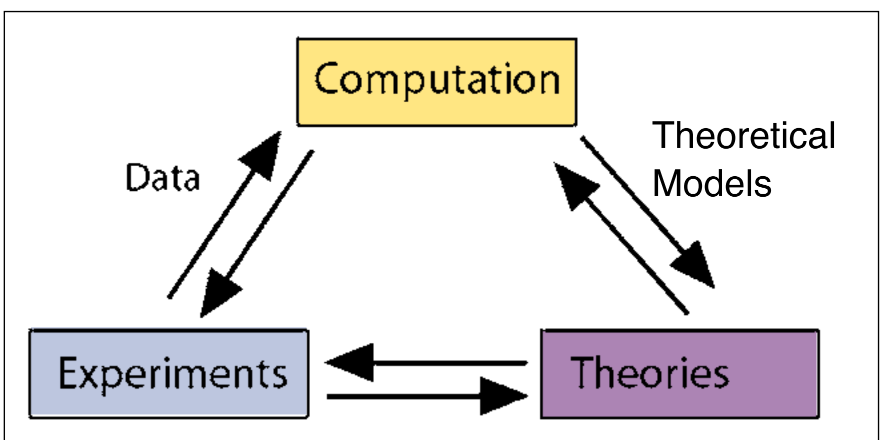

Figure 2.

Challenges in teaching interdisciplinary courses

Mathematics and biology have a cultural divide as the science of biology is descriptive, whereas pure mathematics is relatively abstract in nature. Biology and mathematics differ from each other in terms of both presentation and dissemination of research results. Furthermore, some of the biological concepts are difficult to understand for the mathematics students and vice versa. Another challenge is the limited mathematical background of most biologists, as is evident from biology textbooks and curricula (Reed, 2004). By the same token, mathematicians lack exposure to the latest concepts in the fast-changing field of biology. Added to this, the fact that mathematics is an abstract science presents problems when trying to conceptually integrate it with real-life biological problems. Thus, development of interdisciplinary courses will help reduce the gap and will help develop a new synergy between these two different disciplines of science.

With these issues in mind we developed a mathematical biology course, with the hope that this type of course will help to reduce the information gap that is known to exist between mathematics and biology (Reed, 2004; Steen, 2005; Nikitina, 2006). We expected that the interdisciplinary course would also stimulate interactions between the two disciplines both on the teaching and the research fronts. The most important aspect of the course was how to deliver the subject material effectively. We designed the course in such a way that the students were first apprised of a biological concept by a biology faculty member, and this was followed by mathematical modeling and simulations in the computer laboratory by a mathematics faculty member.

It should be noted that we encouraged students to learn and take initiatives to apply mathematics to a biological phenomenon, and not to solely depend on the inputs and guidance of the faculty. The idea was to inculcate independent analytical thinking among the students in order to extrapolate the biological concept to a mathematical algorithm (Hunter et al., 2006; Russell et al., 2007; Buck et al., 2008). Our rationale was that these training exercises would provide the students with opportunities to test their knowledge by addressing some hypothesis, or to apply their ideas to develop some models/applications (Hunter et al., 2006).

Course outline

This course is an interdisciplinary course intended for students from different science majors with a background in mathematics (precalculus level) and biology (basic introductory biology level); no programming skills were required. The course was divided into three different modules that focus on three different aspects of biology and mathematical modeling associated with it.

Module I

Communication between Parts of an Organism: The Neuron/Nerve Cells

- Introduction to the nervous system
- Ion transport through the membrane (channels and ion pumps)
- Action potential generation
- Electrochemical potentials and thermodynamic equilibrium across the membrane
- Hodgkin-Huxley Model
- FitzHugh-Nagumo model

Module II

Growth Regulation

- Biology of Cancer
- Growth Regulation by pathways controlling Cell Proliferation and Cell Death
- Mathematical Model of Tumors

Module III

Immune System and Disease

- The Immune System: HIV and AIDS
- Mathematical Approach to HIV and AIDS
- Biology of Infectious Disease
- Dynamic Models of Infectious Diseases

Evaluation

We evaluated the students using two different levels of classroom-based pedagogy: (i) in class assessments and computer laboratory based generation of data and (ii) presentation of project in the form of a poster in the Brother Joseph J. Stander Symposium, an annual undergraduate research symposium at the University of Dayton.

Technology

We used Microsoft Excel (Microsoft Office 2007), MAPLE 14 and MATLAB software for this course. Excel is a Microsoft Office product used for plotting data and for curve fitting. MA-

PLE 14 (www.maplesoft.com/) is a computer algebra system used to handle symbolic manipulation and numerical computation. MATLAB (http://www.mathworks.com/products/matlab/) stands for **Mat**rix **Lab**oratory, and is a fourth-generation programming language developed by Math Works for numerical computing environments. MATLAB is an interactive environment for algorithm development, matrix manipulations, data visualization, data analysis, and numeric and scientific computation. The University of Dayton has site licenses for all these software programs. Other freely available software (freeware) used were "dfield and pplane" (http://math.rice.edu/~dfield/index.html) developed by John Polking at Rice University. The programs are written in MATLAB and serve as useful tools for qualitative analysis of mathematical models (Polking, 2004). A java version is also available (http://math.rice.edu/~dfield/dfpp.html). These tools are used for visual displays of certain characteristics of differential equations and have proved to be user-friendly.

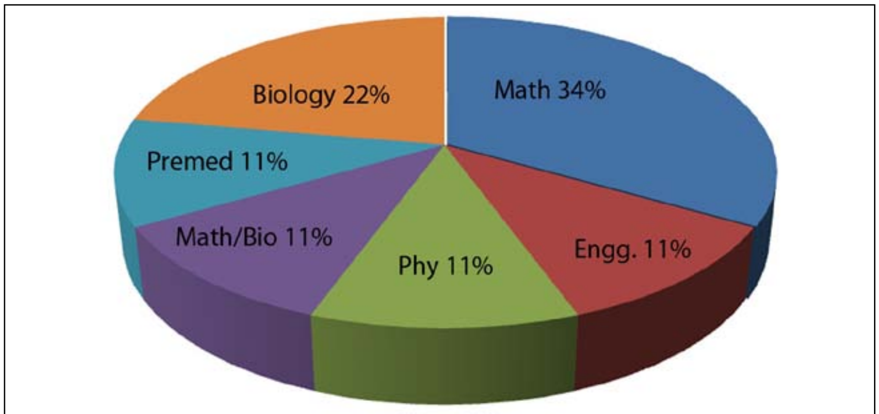

Figure 3. Major distribution of students in the Mathematical Biology course (Math-445/ Bio-422) during the Spring 2010 semester. Note that students from diverse backgrounds of Biology, Premedicine (PreMed), Mathematics and Biology double major (Math/Bio), Mathematics (Math), Physics (Phy), and Engineering (Engg) enrolled in this course.

Individual projects and computer labs

The course was offered for the first time in Spring 2010 and students from different science majors enrolled in the course (Figure 3). To teach some basic mathematical skills, as well as computer algebra systems like MAPLE and MATLAB, we started weekly programming assignments in the beginning of the course. These assignments included individual small projects based on classroom demonstrations of programming software. These programming projects were supplemented with hands-on computer labs that helped the students in learning the scientific inquiry component of the course; such as learning how to write codes and then use them for computational mathematics. For example, we assigned each student a comprehensive project to numerically solve: (i) first order ordinary differential equations, and (ii) a system of first order differential equations using the explicit Euler, implicit Euler, and Runge-Kutta methods (Bradie, 2005; Burden & Faires, 2010; Jones et al., 2010). Students wrote their own codes to solve these problems and compared their solutions with the MATLAB ordinary differential equation solvers for accuracy and efficiency of their codes. These individual projects provided the mathematical background for students to work on their group projects. Furthermore, it also helped to enhance their proficiency in programming with MATLAB.

Groups Projects

We also provided some group projects to the class. We divided the class into smaller groups/cohorts to encourage working as a team and to complement their specializations. We were inspired by the collaborative research model employed by the University of Oregon for undergraduate teaching (http://tep.uoregon.edu/resources/crmodel/index.html). The Collaborative Research Model promotes collaborative student research in coursework across the curriculum. The strength of this model stems from its support of students working together towards a common research problem to develop critical thinking and cooperative learning skills.

Numerous studies have shown that hands-on activities result in the best learning experience with maximum retention rate (McKeachie et al., 1986; Svinicki & McKeachie; 2005). Therefore, we proposed group projects on three different topics in mathematical biology (see details in subsequent sections). Students were allowed to form their groups depending upon their interests and work as a team to carry out a project. We replaced a midterm examination with these group research projects. Students worked on their projects (as a team) in the computer lab with constant input and constructive suggestions from the instructor's end. The idea was to incorporate a curriculum that involves the implementation of three essential elements: research question(s), methodology, and interpretation of results (Schwab, 1962; Herron, 1971; Gibbs, 1988; Seymour et al., 2003; Nadelson et al., 2010).

The students presented their final work in the forms of a poster presentation at the Brother Joseph J. Stander Symposium (http://stander.udayton.edu). The symposium served as a prestigious platform for them to hone their skills in public speaking and presentation. It also instilled a sense of achievement among the students. Here is the list of the projects pursued by the students:

Project 1: A Computational Study of the FitzHugh-Nagumo Action Potential System

The brain is made up of many cells, including neurons and glial cells. Of these, neurons are cells that send and receive electro-chemical signals to and from the brain and nervous system. There are about 100 billion neurons in the brain. There are many more glial cells; they provide support functions for the neurons. Action potentials are the electrical signals transmitted by nerve cells that relay information throughout the body. They can be observed as spikes in voltage across a cell's membrane. Alan Hodgkin and Andrew Huxley (1952a, b) developed the first quantitative model of propagation of the action potential along a squid giant axon. Many models of action potential generation in neurons have since been proposed by researchers, including the Integrate-and-fire, Morris-Lecar, and FitzHugh-Nagumo models (Nagumo et al., 1964; Keener and Sneyd 1998, Hoppensteadt & Peskin, 2002; Allen, 2007; Shonkwiler & Herod, 2009). The FitzHugh-Nagumo system of equations is used to model the characteristic electrical behavior of a nerve cell action potential (Nagumo et al., 1964; Shonkwiler & Herod, 2009). In this project, students explored the qualitative properties of the FitzHugh-Nagumo model, a simplified model for action potential generation in neurons. Unlike the Hodgkin-Huxley, which has four dynamical variables, the FitzHugh-Nagumo model has only two variables. Therefore, the FitzHugh-Nagumo model was a relatively easy way to explore the dynamics of action potential generation. They solved the system numerically to simulate the traveling waves of action potential across a neuron using MATLAB. Furthermore, the students employed the "pplane," a MATLAB utility developed by Rice University, to explore the dynamical properties of the model.

(http://academic.udayton.edu muhammadusman /2010Stander/FNModel.pdf)

Project 2: Mathematical Modeling of Infectious Diseases

The discovery of the microscope in the 17th century caused a revolution in biology by revealing what was otherwise considered "invisible." Mathematics is broadly referred to as a "non-optical microscope" as it improves the information content of the biological data (Cohen, 2004). Study of infectious diseases (Shonkwiler & Herod, 2009, Logan & Wolesensky, 2009) has become more important with increased global connectivity and personal contact. Mathematical models can help us understand the dynamics of how an infectious disease can spread in a population. These models can also predict how many people may get infected, and what part of the infected population may show recovery by resistance to reoccurrence of infection. In this group project, students studied the infectious disease models qualitatively (Logan & Wolesensky 2009). They studied the seasonal fluctuation of infectious diseases like the flu in a population using parameters such as rate of transmission and rate of recovery estimated by the data from the Center for Disease Control (CDC). These mathematical models were solved numerically using MATLAB. However, these models need further validation from the data generated from biomedical studies.

(http://academic.udayton.edu/muhammadusman/2010Stander/georgekm-MTH445.pdf)

Project 3: Mathematical Modeling of H1N1 Flu

Mathematical models have been used to understand the dynamics of infectious diseases and to predict the future outbreak of epidemics or pandemics. In 2009, a new strain of the influenza A (H1N1) virus spread rapidly throughout the world. This "swine flu," as it is commonly known, increased to what is considered an epidemic in a matter of months. In order to understand the spread of this virus and similar patterns in future outbreaks, students studied a simplified **S**usceptible, **I**nfectious and **R**ecovered (**SIR**) mathematical model (Murray; 2002, Allen, 2007, Logan & Wolesensky, 2009, Shonkwiler, & Herod, 2009) to answer some epidemiological questions. The SIR model gets its name from three variables/compartments viz., S (for susceptible), I (for infectious) and R (for recovered). They solved the model numerically and also studied the qualitative properties of the model to answer the question of whether there would be an outbreak or whether it would be contained within a population. Students used the data from the Center for Disease Control (CDC) and estimated the two parameters of rate of transmission and rate of recovery in the mathematical model by curve fitting (Bradie, 2005). (http://academic.udayton.edu/muhammadusman/2010Stander/H1N1.pdf)

Summary

This course was intended to introduce students to an interdisciplinary subject looking at biological phenomenon from a mathematical perspective. In addition, this course also exposed the students to programming in MATLAB and software applications like MAPLE and EXCEL. Our experience with the first group of students was promising. We collected input from the students by performing anonymous exit surveys at two time points: one at the beginning of the course and the second one just before the completion of the course. In the first survey, one of the major concerns of the students was how the instructors would integrate the dissemination of information from two different disciplines. This concern was addressed by teaching the course in a module format where a biological phenomenon was introduced and was followed by mathematical modeling. This sequential approach for dissemination of the topics covered in the course further facilitated the assimilation of information. Biology students were apprehensive about the mathematics part of the course and vice versa. These concerns were addressed during the first few classes by introducing the students to the basics of programming and essential concepts of biological phenomenon and mathematics. Secondly, teaming students from diverse backgrounds in groups improved their morale and helped them teach each other.

In the second exit survey, the students had two major concerns: (i) A balance was needed in the information disseminated between the two disciplines of biology and mathematics during the course. They found that information provided on the nervous system taught in the first module was more on the biological side, whereas the infectious disease portion dealt with in the third module was heavy on mathematics. (ii) Another concern was regarding the structure of the evaluation as some of the students with prior scientific research experience who excelled in programming did strongly on the second laboratory part. This led to a concern among the other students about their scores as the prerequisites for the course were only precalculus and introductory biology. Both of these concerns will be addressed in the next offering of the course. We have made necessary changes in the content to be taught in Modules I and III so that we can strike a balance between mathematics and biology.

For the second concern, we had some strategies already in place in our course. In the first few classes we will introduce the basic concepts of biology and programming to the students. We evaluated the students based on their efforts in research and their poster presentation. However, we rewarded exemplary performance with extra credit to encourage the students to perform their best. Interestingly, it's a common dilemma faced by instructors in classrooms where we get a mixed population of students with varying degrees of experience and capabilities. In the next offering, we intend to provide more detailed handouts pertaining to basic information so that we can bring all the students to a basic level of understanding before we begin programming projects in class. Furthermore, we found that diversity has a healthy impact in terms of student learning outcomes. We found that the students with some prior experience of scientific research showed a greater confidence and initiative in pursuing the assigned projects and generated major insights into the problem. These students also generated excitement among the students with no prior experience in research. Overall the course was a nice blend of a classroom mode of information dissemination with the computer laboratory-based research simulations of the biological problems.

Our future strategy is to offer this course again in fall of 2011. This course is meant to initiate training of biologists and mathematicians at a grass roots level of undergraduate training to support higher education and research in the newly emerging frontier of mathematical biology. We intend to take the curricular aspect of our course beyond simply offering interdisciplinary mathematical biology course by working on an Academic Affairs Committee (AAC) document for this course, and to get a single joint listing for the course in the college of Arts and Sciences at the University of Dayton. We would like to increase the participation of the faculty from the Departments of Mathematics and Biology by introducing some more topics and to initiate a summer research experience for the students. The outcome of teaming biology and mathematics has great benefits for both departments and or the individuals involved. This course will be the stepping stone to promote more research interactions between the two disciplines within the University of Dayton. The undergraduate curriculum becomes more attractive as faculty begin to think 'outside the box." Furthermore, both departments can participate intellectually in the biological revolution, the greatest revolution of our times.

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Dr. Muhammad Usman is an assistant professor in the Department of Mathematics at the University of Dayton since 2007. Dr. Usman holds Ph.D Mathematics and MS in Nuclear Engineering from the University of Cincinnati. He also holds a graduate degree in Biophysics from Ohio University. Dr. Usman is numerical analyst and other research interest includes mathematical biology and numerical solutions of partial and ordinary differential equations. He has advised many mathematical biology projects and is involved in developing mathematical biology and biomedical interdisciplinary courses.

Amit Singh is an Assistant Professor in the School of Biology, and in Center for Tissue Regeneration and Engineering at Dayton (TREND) at University of Dayton. His research area is using fruit fly Drosophila melanogaster eye as a model to study organogenesis and to understand genetic basis of neurodegeneration in eye. He has been actively engaged in developing interdisciplinary course curriculum on math biology that transcends the border of conventional disciplines of science. He has been instrumental in providing CAPstone research experience opportunities to undergraduates in his laboratory.