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Adoption of a Uniform Programming Platform in an Undergraduate Biomedical Engineering Program

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ABSTRACT: *In the United States, the Accreditation Board for Engineering and Technology (ABET) requires programs to demonstrate that their graduates have "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice." Additionally, biomedical engineering programs in particular must also demonstrate that their graduates have "…the capability to apply advanced mathematics (including differential equations and statistics)…to solve problems at the interface of engineering and biology." In this talk I describe efforts at the University of Rochester to adopt a uniform programming language, Matlab, throughout the undergraduate biomedical engineering program. One particular course in our program, BME 221: Biomedical Computation, utilizes Matlab extensively and aims to provide students with a working knowledge of biostatistics. Biomedical Computation teaches fundamental concepts in numerical computation and structured programming, and the application of these methods to solve biomedical problems. This is a MATLAB-based course that emphasizes problems in biotransport phenomena. The theoretical framework for selected issues that arise in numerical computation are covered (stability and error analysis, matrix conditioning), as the students develop a toolbox of techniques that they can use in later courses and their eventual careers. Key techniques that are covered include: matrix inversion, linear regression and error propagation, nonlinear root finding and optimization, numerical quadrature, finite difference, and finite elements. Course objectives for BME 221 are threefold:*

1. *Teach fundamentals of numerical computing in engineering;*
2. *Give students exposure to problems in biomedical transport phenomena;*
3. *Develop students' proficiency in writing efficient MATLAB programs.*

Other courses in our program that have successfully adopted the Matlab programming language include: Introduction to Biomechanics, Biomedical Instrumentation and Measurements, and Quantitative Physiology. The historical development of computational tools in the UR BME curriculum, as well as instructor assessment of how well the various course objectives have been satisfied, will be discussed.

1 HISTORICAL DEVELOPMENT

The University of Rochester, located in Rochester, New York, USA, is a private research university established in 1850. Rochester has a relatively long history in biomedical engineering education, and was one of the original recipients of a biomedical engineering training grant from the National Institutes of Health in 1961. In 1997 students became formally enrolled in both the doctorate and undergraduate degree programs in the newly formed Department of Biomedical Engineering (BME). Growth of the BME Department has been supported by Special Opportunity and Leadership-Development Awards from the Whitaker Foundation. In 2000, it was determined by the Undergraduate Curriculum Committee of BME that one of our educational outcomes at the undergraduate level would be to ensure that our students:

> *Demonstrate ability to use computational tools (e.g., spreadsheets, structured programming languages, analysis and data acquisition software, and simulation software) and to write logical algorithms.*

This outcome is consistent with one of the eleven criteria specificed by the Accreditation Board for Engineering and Technology (ABET), that graduates have "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice." To best achieve the outcome related to computational tools, we have decided to adopt the Matlab programming language as a uniform programming platform across several core courses in the biomedical engineering curriculum. In this paper we discuss the process and assessment of this effort to introduce programming into a new undergraduate engineering program.

2.1 PROGRAMMING IN THE CURRICULUM

We have opted to teach programming to our BME students in several engineering courses distributed throughout the curriculum, rather than require a single programming course. The expectation is that biomedical engineering students will appreciate the role of computer programming in engineering analysis, and the application to real world problems, when presented in the context of other topics. Students are introduced to the Matlab programming environment in the spring semester of their sophomore year, in the half-semester lab course "BME 201L: Matlab for Biomechanics." This course supports a core BME course called "BME 201: Introduction to Biomechanics." In BME 201L, students learn the general concepts of structured computer programming, and a toolbox of commands specific to the Matlab language. In eight laboratory sessions, students work individually to complete specific programming tasks. The programming tasks increase in complexity throughout the semester, and build a foundation for the final project in BME 201.

In the fall semester of junior year students use Matlab extensively in weekly programming assignments for numerical computation, data analysis, and graphical presentation of data. Programming concepts such as input/output, flow control, global vs. local environments, and intrinsic vs. user-defined functions, are reinforced through experience-building repetition. In the weekly 75 min. computer laboratory, students complete portions of the weekly assignment while interacting with the instructor and teaching assistants. Specific examples of Matlab use in BME 221 are given below in Section 3.

In the spring semester of the junior year, students use Matlab to analyze, process, and interpret data sets collected in the experimental laboratory course "BME 230: Biomedical Instrumentation and Measurements."

BME students take another course, "BME 260: Quantitative Physiology" in the fall semester of their senior year. In BME 260 students use Simulink, the graphical user interface of Matlab, to perform computer simulations of neuronal function. Additionally, Matlab is used as a computational graphing tool as in previous courses.

In the BME 295/296 Senior Design sequence, students are not specifically required to use Matlab, but are encouraged to select and use the computational tool most appropriate for their individual design projects. Over the past two years in which BME 221 has been offered, there has been an increase in the numbers of students voluntarily choosing to use Matlab for calculations and numerical simulations associated with the Senior Design sequence.

2.2 PROCESS FOR CONTINUAL IMPROVEMENT

The BME department has several mechanisms in place to continually improve the program and our ability to meet the educational objectives that have been established. The ~10 primary faculty in BME meet for six hours in a Semiannual Curriculum Review, which constitutes a major internal review of the objectives, outcomes, and assessment data conducted by the faculty soon after the conclusion of each semester. Each instructor presents the a summary of their course and the entire faculty discuss and debate the relation of each course to the overall program. Several significant improvements to individual courses have resulted from these review meetings. Results of the Semiannual Curriculum Review are further refined in the monthly meetings of the Undergraduate Curriculum Committee (UGC). Of course, proposals for improvement of the program can be brought to the UGC at any time of the year. An ad hoc ABET committee has also been instrumental in defining the educational objectives and process for improvement as well. Several other sources of information are used to help improve the BME program. These include an annual meeting with the External Advisory Board, comprised of leaders from industry and academia. Although our young BME department has a relatively small group of graduates so far, an annual alumni survey has been implemented to obtain critical feedback regarding our program objectives and outcomes. Finally, surveys of current students and senior exit interviews are used to further refine our educational approaches.

3 BME 221: BIOMEDICAL COMPUTATION

We now present several specific examples of course material from a new numerical methods course developed by the author, BME 221: Biomedical Computation. Figure 1 below shows a representative example of graphical output generated in Matlab.

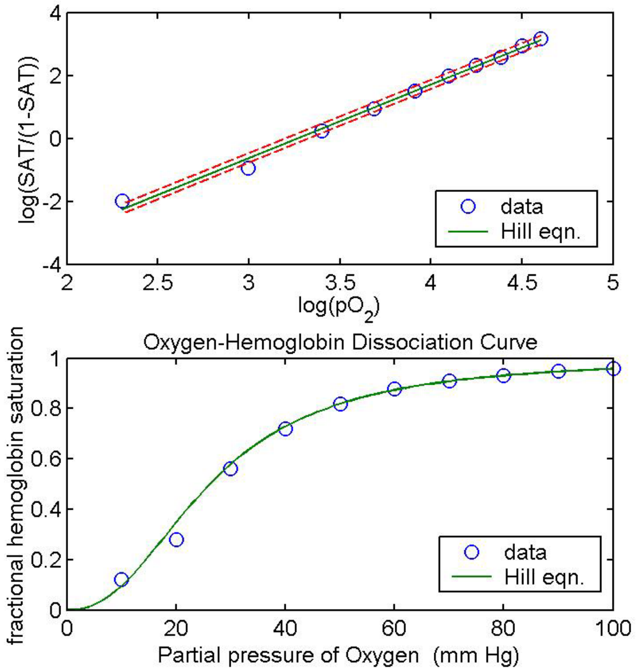

Figure 1 – Linear regression using the normal equations.

One example of a Matlab programming assignment in BME 221 is to perform a linear regression using the normal equations, of the Hill model for oxygen-hemoglobin dissociation. Students demonstrate that simple transformations of the data produce models that are linear in the modelling parameters. Rather than using “polyfit” or other built-in regression functions, students regress data using the normal equations. For a given linear model

$$\mathbf{Ax}=\mathbf{b},$$

the modelling parameters are equal to

$$\mathbf{x}=\left[\mathbf{A}^T\mathbf{A}\right]^{-1}\mathbf{A}^T\mathbf{b}\quad\left(=\mathbf{Kb}\right).$$

In the above expressions, **A** represents the matrix of modelling functions, and **b** is a column vector containing a set of measured data points. This yields a simple expression for the covariance matrix of the regression parameters,

$$\Sigma_{\mathbf{x}}^2=\mathbf{K}\Sigma_{\mathbf{b}}^2\mathbf{K}^T.$$

Weighted linear regression, where the variance of individual data points is not assumed to be equal, is an optional topic also covered in the course and is a straightforward extension of the above development.

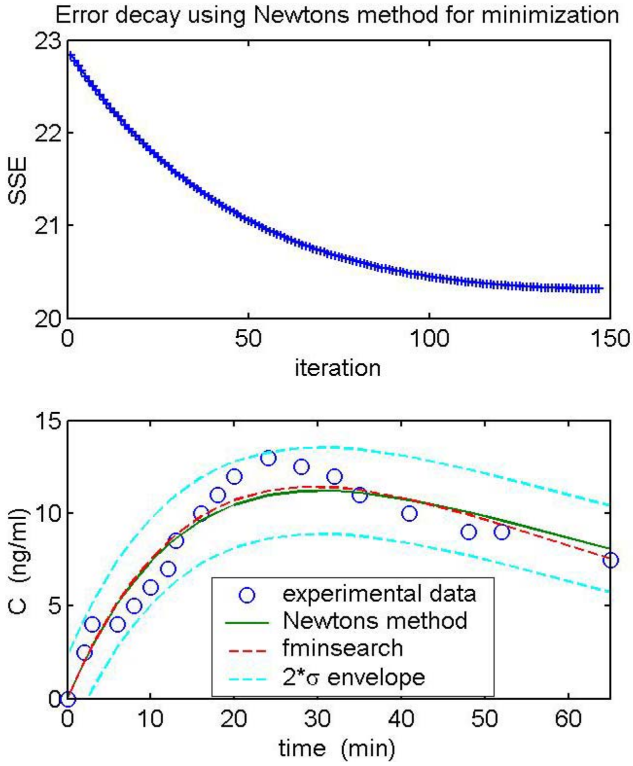

Figure 2 – Nonlinear regression via Newton's method

Students in BME 221 are asked to perform a nonlinear regression via Newton's method, to solve a single-compartment pharmacological model with first-order absorption and elimination terms. The speed, accuracy, and radius of convergence for different methods of nonlinear regression are compared. Students learn to implement their own multidimensional Newton's method for optimization/minimization as

$$\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} - \left[\nabla\nabla F\left(\mathbf{x}^{(k)}\right)\right]^{-1} \nabla F\left(\mathbf{x}^{(k)}\right)$$

The data in Figures 1 and 2 are from Fournier (1999). Students are made aware of the limitations of the convergence of Newton-based methods when the local slope of the function approaches zero. Alternative methods for minimization that are not susceptible to this such as the Golden Search are discussed.

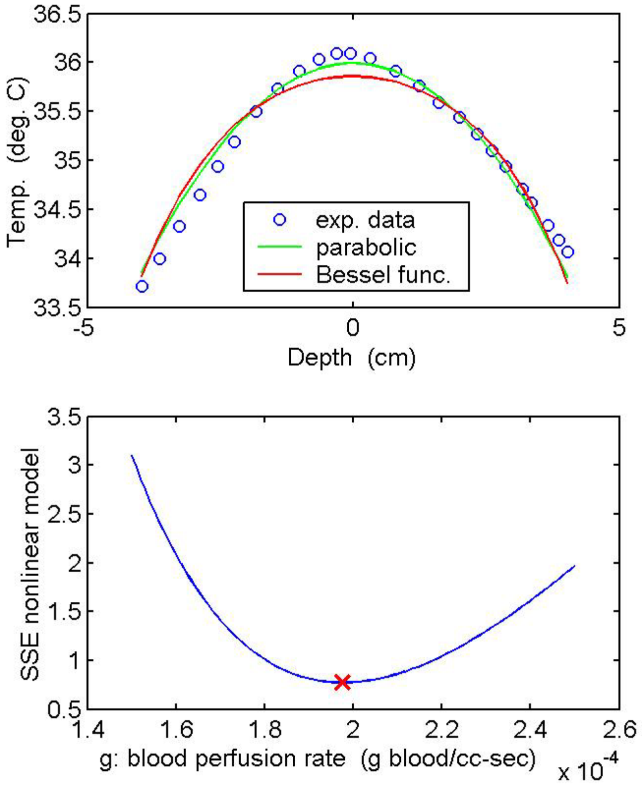

Figure 3 – Nonlinear regression using an intrinsic minimum function

One homework assignment in BME 221 is based on a nonlinear regression using an intrinsic minimization function, to determine the radial temperature distribution in the human arm. The human arm is modelled as a cylinder with uniform metabolic heat generation, and convective and conductive heat transfer. A linear and nonlinear model are compared with the r^2 goodness-of-fit parameter. Students perform a nonlinear regression by defining an SSE function and using the intrinsic Matlab function "min". The data in Figure 3 are from Cooney (1976).

The theoretical underpinnings of numerical methods are tested on pencil-and-paper exams in BME 221. One example problem is: Given $z = f(x,y)$ where x and y are randomly distributed variables, how is the error in x and y propagated into the final result z? The biomedical example used is the sphericity of red blood cells,

$$S = \frac{4\pi}{(4\pi/3)^{2/3}} \cdot \frac{V^{2/3}}{A}$$

Where A and V are the cell area and volume. The answer to this question is obtained by combining the partial derivatives as

$$s_z^2 = \left(\left. \frac{\partial f}{\partial x} \right|_{x,y} \right)^2 s_x^2 + \left(\left. \frac{\partial f}{\partial y} \right|_{x,y} \right)^2 s_y^2 + 2 \left(\left. \frac{\partial f}{\partial x} \right|_{x,y} \right) \left(\left. \frac{\partial f}{\partial y} \right|_{x,y} \right) s_{xy}^2$$

Where s^2 is the sample variance. Another example exam problem is: Determine the eigenvalues and criteria for numerical stability for a set of two coupled ODEs. A biomedical example of such a problem is the FitzHugh-Nagumo model for cell membrane potential. To solve this problem, one must calculate the criterion

$$\left\| \mathbf{I} + h\mathbf{J} \right\| < 1$$

for time step h and Jacobian $\mathbf{J}$. In lecture, the accuracy and stability characteristics of competing finite difference schemes are derived.

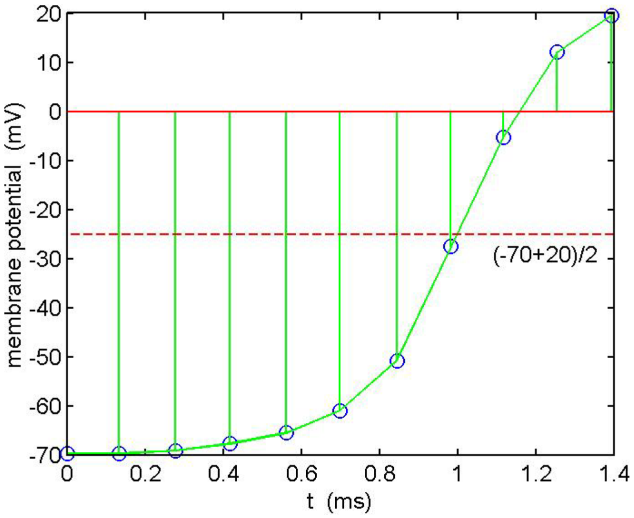

Figure 4 – Numerical quadrature via Simpson's rule

Students in BME 221 use numerical quadature via Simpson's rule to analyze the cell action potential during depolarization and overshoot. A common approximation in this problem is to use the mean of the two endpoints to estimate the average potential, resulting in a large error. The relative error of trapezoidal, Simpson's rule, and Gaussian quadrature methods are compared. Students learn to derive the weights and node placement to achieve integration at a desired order of accuracy. The data in Figure 4 are taken from Carr and Brown (2001).

4 CONCLUSIONS

By all measures, we have successfully developed a programming component in an undergraduate biomedical engineering program, that bridges across several core courses within the discipline. Furthermore, mechanisms are in place to continually improve the elements of the program, by responding to feedback from industrial, government, and academic constituents as the needs for biomedical engineering education and training evolve in time. Due to the excitement among the general public for biomedical engineering, partially fuelled by recent breakthroughs in tissue engineering and the Human Genome Project, enrollment in BME has quickly grown to the highest of any department in the School of Engineering and Applied Sciences at Rochester.

ACKNOWLEDGEMENTS

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