Doing Cool Research Projects in Simulating Biochemical Reactors on Computers by a Layperson: MATLAB and R Codes, and Instruction Videos

Zuyi (Jacky) Huang
Villanova University
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>1</td>
</tr>
<tr>
<td>Chapter 1. Overview of the Book ..................................................</td>
<td>4</td>
</tr>
<tr>
<td>1.1 Introduction of biochemical models studied in this book ...............</td>
<td>4</td>
</tr>
<tr>
<td>1.2 Introduction of MATLAB, Simulink and R ....................................</td>
<td>6</td>
</tr>
<tr>
<td>1.3 Installation of MATLAB ............................................................</td>
<td>7</td>
</tr>
<tr>
<td>Chapter 2. Introduction of Ordinary Differential Equations and Simulink</td>
<td>11</td>
</tr>
<tr>
<td>2.1 Ordinary differential equations (ODE): a running car example .........</td>
<td>11</td>
</tr>
<tr>
<td>2.2 Introduction of MATLAB and data representation in figures ............</td>
<td>14</td>
</tr>
<tr>
<td>2.3 Introduction of MATLAB Simulink: a Lego-building platform for modeling</td>
<td>19</td>
</tr>
<tr>
<td>2.4 Simulation of a running car in Simulink ....................................</td>
<td>22</td>
</tr>
<tr>
<td>2.5 Simulation of the water level in a leaking tank in Simulink ..........</td>
<td>28</td>
</tr>
<tr>
<td>2.6 Practice exercise .........................................................................</td>
<td>32</td>
</tr>
<tr>
<td>Chapter 3. Simulation of a Fed-Batch Bioreactor in Simulink .................</td>
<td>33</td>
</tr>
<tr>
<td>3.1 Introduction of chemical kinetics: an enzymatic reaction example ......</td>
<td>33</td>
</tr>
<tr>
<td>3.2 Simulation of an enzymatic reaction model in Simulink ..................</td>
<td>36</td>
</tr>
<tr>
<td>3.3 Introduction of the ODE model for a fed-batch bioreactor ...............</td>
<td>40</td>
</tr>
<tr>
<td>3.4 Simulation of a fed-batch bioreactor in Simulink ..........................</td>
<td>43</td>
</tr>
<tr>
<td>3.5 Practice exercise .........................................................................</td>
<td>49</td>
</tr>
<tr>
<td>Chapter 4. Simulation of a Microbial Fuel Cell in Simulink ..................</td>
<td>50</td>
</tr>
<tr>
<td>4.1 Introduction of microbial fuel cells ...........................................</td>
<td>50</td>
</tr>
<tr>
<td>4.2 The components of microbial fuel cells ........................................</td>
<td>51</td>
</tr>
<tr>
<td>4.3 Application examples of microbial fuel cells ..................................</td>
<td>53</td>
</tr>
<tr>
<td>4.4 Introduction of a MFC ODE model ................................................</td>
<td>54</td>
</tr>
<tr>
<td>4.5 Simulation of a MFC ODE model in Simulink ...................................</td>
<td>59</td>
</tr>
<tr>
<td>4.6 Practice exercise .........................................................................</td>
<td>69</td>
</tr>
<tr>
<td>Chapter 5. Simulation of Biochemical Models in the R language ...............</td>
<td>70</td>
</tr>
<tr>
<td>5.1 Installation of the R language ....................................................</td>
<td>70</td>
</tr>
<tr>
<td>5.2 General introduction of the R language .........................................</td>
<td>71</td>
</tr>
<tr>
<td>5.3 Introduction of functions and scripts in R: a running car example ....</td>
<td>78</td>
</tr>
<tr>
<td>5.4 Simulation of the water tank model in R ........................................</td>
<td>82</td>
</tr>
<tr>
<td>5.5 Simulation of the enzymatic reaction model in R .............................</td>
<td>84</td>
</tr>
<tr>
<td>5.6 Simulation of the fed-batch bioreactor in R ..................................</td>
<td>87</td>
</tr>
<tr>
<td>5.7 Simulation of the MFC ODE model in R ..........................................</td>
<td>91</td>
</tr>
<tr>
<td>5.8 Practice exercise .........................................................................</td>
<td>96</td>
</tr>
<tr>
<td>Chapter 6. Mini-Projects for Modeling Human Diseases ............................</td>
<td>97</td>
</tr>
<tr>
<td>6.1 Overview of existing mathematical bio-models ..................................</td>
<td>97</td>
</tr>
<tr>
<td>6.2 Mini-project 1: HIV infection of CD4+ T-cells ..................................</td>
<td>98</td>
</tr>
<tr>
<td>6.3 Mini-project 2: Cell-Mediated Immune Response to Tumor Growth ........</td>
<td>100</td>
</tr>
<tr>
<td>Index .................................................................................................</td>
<td>103</td>
</tr>
<tr>
<td>Reference ............................................................................................</td>
<td>104</td>
</tr>
<tr>
<td>Appendix 1: Instruction to access the recorded videos for the modeling examples</td>
<td>106</td>
</tr>
<tr>
<td>Appendix 2: Testimonials from previous readers ....................................</td>
<td>107</td>
</tr>
</tbody>
</table>
Preface

Motivation of writing this book

As an educator in biochemical engineering, I was surprised to find U.S. college students do not thrive in Math compared to many other countries in the world. While the U.S. is a competitive, influential powerful country in the world, the mean score in math in PISA 2015 for U.S. high school students was below the OECD average [1]. Even as U.S. high school students are falling behind their peers from other countries in their math performance, few existing STEM outreach activities are designed specifically for mathematical modeling education. Most students in the United States have not encountered engineering education [2], with typical K-12 math and science classrooms rarely providing students the chance to engage in authentic problem-based or design learning [3].

This lack of opportunity in the math classroom is exacerbated by some of the memorizing ways that math has traditionally been taught. While great strides have been made to increase students’ ability to conceptualize and be creative in solving math problems, many students still see math as boring and challenging. In my partnerships with several high school and college researchers, I learned that many lost their interest in math and preferred veering toward business and other careers. In this time when the United States is seeking an increased STEM workforce, this is a shame. We need to create new approaches to educate U.S. students about math related techniques. In this book, I aim to provide a solution to provide a layperson to do affordable research projects at anytime from anywhere, with the hope that the hands-on research experience convinces readers to develop careers in the STEM areas.

While I planned to design a project suitable for high school students, I first took action during the summer of 2014. In that summer, Clement Ekaputra, a local junior high school student, successfully built a mathematical model of a microbial fuel cell in MATLAB Simulink. Microbial fuel cells can convert the organic compounds in waste streams into electricity. That project was originally designed for senior college students. It convinced me that using a Lego-building platform (e.g., Simulink) to solve a real-world engineering problem (e.g., microbial fuel cell design) may be a good solution to inspire high school students’ interest in modeling techniques [4]. In order to attract more students to the microbial fuel cell (MFC) modeling project, I further recorded videos so that students were able to finish the project by watching lecture videos. This idea was proved successful by several high school student volunteers and presented in a regional ASEE conference [5]. While MATLAB offers a free trial version for 30 days and some high schools have it installed in their students’ computers, MATLAB is not free. This may prevent students from low-income families in participating in the designed MFC modeling project. I thus implemented the MFC model in the free R language. Five local high school students built the MFC mathematical models in both Simulink and R. High school students were able to build the MFC models in the script windows of R, although they preferred the Lego-building platform of Simulink [6].

Most of high school students participating in the aforementioned projects selected STEM majors in their college applications. Some students were accepted by top schools, including but not limited to, Princeton University, the University of Pennsylvania, Cornell University, the University of Michigan, the University of Pittsburgh, and the University of California, Los Angeles. This proves that the designed projects did well in inspiring students to pursue careers in STEM fields. This also finally motivates me to write this book so that I can inspire and convince more students to learn and use modeling skills to solve real-world problems.

Who will benefit from reading this book

This book takes the approach of introducing math to a broad audience in the hopes of increasing enthusiasm for all of the exciting applications that a foundation in math will allow. I attempt to address a range of enthusiasts, from high school students who want to explore potential disciplines for further study and high school teachers looking to supplement their standard course materials with additional classroom and extracurricular activities, to scholars in fields for whom math is a related discipline. I
assume each reader is a layperson who does not have a strong academic knowledge in mathematical modeling, engineering, electrochemistry, or microbiology. Therefore, I cover the necessary background information in this book for such readers. High school students and teachers, college students, or continuing education students who would like to know more about modeling and have interest in working in STEM fields should benefit the most from this book.

Suggestions for reading this book

The biochemical reactors covered in this book include an enzymatic reaction that describes a catalyst like enzyme for accelerating chemical reactions, a fed-batch reactor in which cells are grown to uptake substrate to produce the specific product (e.g., antibodies), and a microbial fuel cell. A car model that describes the driving distance over time, along with a water tank model that quantifies the water level in a leaking tank, is also used to introduce ordinary differential equations (ODE) and MATLAB Simulink. Although these two models are not real biochemical reactors, they are included to make the introduced concepts more related to readers’ daily life.

Readers should read the first three chapters first, as they cover the basic skills that are essential for doing the modeling projects shown in Chapters 4 to 6. For example, basic concepts, such as ordinary differential equations, chemical kinetics and microbial growth kinetics, are introduced in Chapters 1-3. Simulink is also introduced along with several practice examples in Chapters 1-3. The first half of Chapter 4 introduces microbial fuel cells and an ODE model for a general microbial fuel cell. This is followed by the implementation of the MFC ODE model in Simulink. Chapters 1-4 are essential sections of this book. Simulink provides a platform in which readers can build mathematical models by linking modules that are provided in Simulink. This is similar to building Lego by putting pieces (i.e., math modules) together. Simulink is thus easier to learn, but it is faster to build the model by typing the equations in the MATLAB or R command windows. Readers who have finished all the examples in the first four chapters are encouraged to try the command-window platforms for solving ODE models in R (Chapter 5). Chapter 6 introduces ODE models for two human diseases, one for HIV infections and the other for cancer growth. This offers readers a chance to explore the application of modeling in human diseases. Chapter 6 only shows the ODE models without MATLAB/R programs. This gives readers a chance to do mini research projects and practice their modeling skills. An overview of existing mathematical models for bio-processes/reactors is also given in Chapter 6. Readers who like to do more research in biomodelling may find existing models for the problems they like to investigate.

The trial version of MATLAB is free within 30 days, while R is totally free. Readers are encouraged to finish the first four chapters in 30 days. Readers should also check with their schools, as certain high schools offer an educational license for their students.

Organization of each chapter

Each chapter will provide an explanation of the theoretical background. Then, it will be followed by examples in which readers are asked to follow instructions to reproduce the simulations. These are assignments in each chapter for readers to practice their modeling skills.

Resources and follow-up of the project

In order to facilitate readers’ learning, I record lecture videos for each modeling example, including the instruction on installing MATLAB and R, and a general introduction for both MATLAB and R. Readers can follow the videos step by step to reproduce the programs shown in the book. While this is a book, I try to make it as a standalone and affordable mini-course. I also try to make the book short enough to cover all necessary information so that readers can pick up the modeling skills introduced in the book in a short time. This is in line with my purpose of writing this book for STEM outreach.

As an incentive for readers to finish at least the first four Chapters of the book, I will select one reader from the waiting list every week, evaluate his/her programs, and provide a letter to prove that he/she has finished the corresponding programs introduced in the book. Since I am busy with my work
and my kids, I can only evaluate the work of four readers in a month. Only those readers finishing the programs introduced in the first four chapters (the MATLAB section) or Chapter 5 (the R section) of the book should enter the waiting list. The link for entering the waiting list can be found on the website https://www.ivy-stem-outreach.com. The rule of “first come, first served” is used to select readers from the waiting list. Similar to what most book authors do, I may not have time to answer questions from every reader. Feedback from readers to further improve the book will be appreciated. I also like to work with high school teachers to implement the projects shown in the book in their classrooms.

Author’s Biography

I am an Associate Professor in the Department of Chemical and Biological Engineering at Villanova University, a top 50 national university in U.S. I received both my bachelor’s and master’s degrees from Tsinghua University, the top engineering school in China. I came to U.S. in 2005 to pursue my Ph.D. research in chemical engineering at Texas A&M University. Since then, I have been working in biological systems modeling. I joined Villanova University in 2011 and developed the Biological & Environmental Systems Engineering Lab (BESEL) at Villanova University. My current research is focused on developing advanced modeling and systems analysis techniques to manipulate microbial biological systems for combating biofilm-associated pathogens or generating biofuels from waste streams. I also study T cell metabolism to enhance T cell growth and reduce side-effect of T cell therapy for cancer treatment. The third on-going project in my lab is applying big-data analysis techniques to extract useful information from existing bio-databases (e.g., NCBI Pathogen Detection Isolates Browser). I have published 39 journal papers and two book chapters from my research so far.

While I enjoy doing research with my graduate students, I also like to inspire both high-school and college students to learn and apply modeling techniques to solve real-life engineering problems. As mentioned above, I introduced a mathematical model of a microbial fuel cell (MFC) to several high school students in the past few years. Their works were either presented in American Society for Engineering Education (ASEE) conferences [4, 5] or published in decent journals [6]. I love to use innovative teaching approaches to facilitate students in learning modeling techniques. For example, I developed the first flipped-classroom modules to teach senior students MATLAB in my Chemical Process Control class at Villanova University. Since these modules were published in 2017 [7], they have been well cited and requested by faculty worldwide. My colleagues at Villanova and I were awarded the prestigious 2016 ASEE Joseph J. Martin Award [8] for our effort in promoting video-based teaching.

Acknowledgement

I would like to thank high school students who worked with me in previous projects. I received lots of meaningful feedback from them for writing this book. I am very lucky get the book proofread by the following volunteer students: Amy Yinmin Chen (Episcopal Academy, Newtown Square, PA – now at U Penn), Matthew Fan (Conestoga High School, Berwyn, PA), Jonathan Huang (Episcopal Academy, Newtown Square, PA – now at U Penn), Tobey Le (Radnor High School, Wayne, PA), Owen Boran Li (Methacton High School, Eagleville, PA), Ethan Wang (Central Bucks High School South, Warrington, PA – now at Georgia Tech), and Michael Hu Wang (Methacton High School, Eagleville, PA). Without the support and patience from my wife Ivy Jia, my sons Cody Huang and Carlo Huang, I could not have finished this book.

Zuyi (Jacky) Huang
zuyi.huang@villanova.edu
August 14, 2019
Chapter 1. Overview of the Book

The contents of the chapters that follow support the goal of making math accessible to a broad audience. We begin with a race car example that illustrates the differential equation that describes driving distance over time in Chapter 2. The other model in that chapter presents a water tank with a leaking valve to depict the mathematical understanding of how the water level changes in a measurable container. These models which are familiar to the nontechnical reader serve as a foundation to the ways math is useful in their homes and daily routines. Readers can connect the math equation with their daily lives. The following chapters proceed through similarly familiar models but get increasingly more specialized in biochemical reactors and human diseases. In this way, readers reach the end of the book with well-developed knowledge of how math is applied across disciplines. First, however, this introductory chapter sets up the reader to know the models used throughout the book as well as how to install the modeling tool, MATLAB, so that readers can build the models themselves at home. The equations of those biochemical reactions will be provided. The instruction for the installation of R will be provided in Chapter 5.

1.1 Introduction of the biochemical models studied in this book

While a car is not a biochemical reactor, it is first used in this book to illustrate the concept of an ordinary differential equation in Chapter 2. In particular, a race car shown in Figure 1.1A is used to illustrate an ordinary differential equation model that quantifies the distance \( x \) of the car driving in the time period \( t \) at a varying speed of \( V \). A more complicated water tank model shown in Figure 1.1B is further used to illustrate the principle of mass balance, which describes the accumulation of mass in a container with inlet and outlet mass streams. This model predicts the water level \( h \) in a tank with water flowing in at an inlet flowrate \( q_{in} \) and flowing out through an opened outlet valve.

\[
\frac{dh}{dt} = \frac{1}{A}(q_{in} - K_v \sqrt{h})
\]

Figure 1.1, (A) model used to predict the driving distance \( x \) of a race car over time; (B) model used to quantify the water level \( h \) in a water tank.

Both the car model and the water tank model contain only one differential equation. Multiple differential equation models are further introduced in a general two-step enzymatic reaction. A chemical reaction describes the conversion of the reactants (e.g., the items on the left-hand side of Equation 1-1) to the products (e.g., the items on the right-hand side of Equation 1-1). Equations 1-1 and 1-2 show the enzymatic reactions that commonly take place in bioreactors (e.g., bacteria and mammalian cells). Enzymatic reactions also take place in our daily lives. For example, sucrose (referred to as S, the substrate) in food is converted to glucose and fructose (referred to as P, the product) in the enzymatic reactions catalyzed by the enzyme sucrase (referred to as E, the enzyme) in the following figure. In another example, Amylase (i.e., E) in the saliva of humans catalyzes the hydrolysis of starch (i.e., S) into sugars such as maltose and maltotriose (i.e., P). The enzyme is one type of the most commonly used catalysts which are known for their role in accelerating chemical reactions (e.g., the conversion rate from the substrate S to the product P). The catalyst (e.g., E) is not consumed in one reaction cycle.
Thus, it can be re-used to accelerate another reaction cycle. Developing good enzymes is essential for improving the performance of bioreactors. The enzymatic reaction is used to introduce the concept of chemical kinetics that can quantify the reaction rate on the basis of the reactant concentrations and the availability of catalyst (i.e., enzyme in biological reactions).

\[
E + S \xrightleftharpoons{K_{f_1}}^k_{2} ES \quad (1.1)
\]

\[
ES \xrightarrow{k_2} E + P \quad (1.2)
\]

*Figure 1.2*, the enzymatic reactions for converting the substrate S to the product P catalyzed by the enzyme E. One such example is given: the conversation of sucrose to glucose that is catalyzed by sucrase.

While the enzymatic reactions shown in Figure 1.2A mainly describe the reactions in the cell scale, a fed-batch bioreactor (Figure 1.3) is further introduced to quantify the growth of cells and production of a product (e.g., an antibody) on a larger scale. A substrate such as glucose is fed into the reactor in which cells grow on the substrate and in turn produce the target product (e.g., an antibody). In the fed-batch mode, the product stays in the reactor until the end of the run. Since this model can be generally applied in fed-batch bioreactors for producing antibodies and therapeutic proteins, the cell and antibody are not specified in this book. The cell growth kinetic, which describes the cell growth rate, is introduced in this model. The concepts of mass balance and chemical kinetic are also reinforced in this model.

*Figure 1.3*, the fed-batch bioreactor in which the cells uptake the feeding substrate to produce the product P.

The fed-batch bioreactor model provides a smooth transition to the more complicated model of a microbial fuel cell (MFC). The major electrochemical processes of MFC can be generally described as shown in Figure 1.4: 1) anodophilic bacteria (also called exoelectrogenic bacteria) form a biofilm on the surface of the anode electrode; 2) anodophilic bacteria uptake organic compounds (acetate in this work) from the waste stream (like waste water) and produce electrons, protons, and CO\(_2\); 3) intracellular mediators (e.g., cytochrome proteins) transfer electrons from bacteria to the anode electrode surface, and electrons then translocate to the cathode electrode via an external electrical circuit; 4) the protons diffuse through the cation exchange membrane and react with O\(_2\) on the surface of the cathode electrode; 5) the electrons are accepted by O\(_2\) to form water. This model introduces readers to some basic concepts of electrochemistry and a bioreactor with multiple species of bacteria.
MATLAB and R programs are provided to take readers step by step through the process of building the aforementioned models in the following two platforms: 1) MATLAB Simulink and 2) R command windows. While mini research projects for HIV infection of T-cells and cell-mediated immune response to tumor growth are introduced in Chapter 6, the models in these projects are not developed further; readers can follow up on these models, if they wish, to build their own programs.

1.2 Introduction of MATLAB, Simulink, and R

Most mathematical models built in STEM fields are implemented via the following tools: MathCAD, Maple, Mathematica, MATLAB, R, Python, and C++/C#. Each of these tools has advantages. Maple is good for a symbolic math operation, for example. Mathematica has good computational efficiency. R is good for statistical data analysis. After comparing all of the aforementioned tools, I prefer MATLAB for solving ODE models for the following reasons:

1) It offers a Lego-building platform (i.e., Simulink) that can make building ODE models more attractive;
2) It is generally easier to pick up than other tools (e.g., C++/C#), as it doesn’t impose strict syntax;
3) It offers excellent function libraries that cover most STEM fields; this significantly accelerates the modeling work;
4) MATLAB is one of the most commonly-used programming softwares in industry [9];
5) Students can get it from their schools or get the trial version for free for 30 days. MATLAB also offers a student license at the price of $49 (as shown on MathWorks’ webpage in July 2019). MATLAB is more affordable than some other tools (e.g., MathCAD, Maple, and Mathematica)

In addition to MATLAB, R language is also introduced in this book, as it is totally free. R language is also easy to pick up and has good function library. In addition, R is the most widely used free tool for statistical data analysis in the biopharma industry, finance, and economics. While this book doesn’t cover the application of R in statistical data analysis, it introduces some basic skills that helps readers learn more advanced R modeling techniques. Python is another widely used high-level programming language in engineering [10, 11]. It is regarded as one of the best alternatives to the commercial MATLAB. In addition, some high schools offer AP courses on C and C++ to their students [12]. These programming tools are not included in this book so as to avoid overwhelming readers. The experience of learning MATLAB and R should be helpful for readers to learn other programming tools.

As mentioned above, programs for the five mathematical models shown in Figures 1.1-1.4 will be introduced in detail in Chapters 2 to 5. The programs are implemented in Simulink, and the R command window. For example, the enzymatic model shown in Figure 1.2 can be implemented in these two platforms as shown in Figures 1.5-1.6. Simulink library provides existing components for math operations involved in the model, such as add, subtract, multiply, divide, and integrate (Figure 1.5). Simulink also provides components to assign the model inputs and record the output profiles for plotting. Identifying the components in the model and connecting them together are the major steps for building models in Simulink. Unlike building with Legos, model builders in Simulink do not have an existing

![Microbial Fuel Cell System](image)

**Figure 1.4**, the diagram of electrochemical processes for a microbial fuel cell (left) and its ordinary differential equation model (right)

$$\begin{align*}
\frac{dS}{dt} &= -q_x x_a - q_y x_b + D(S - S) \\
\frac{dS}{dt} &= -\mu x_a - K x_a x - \alpha D x \\
\frac{dS}{dt} &= -\mu x_a - K x_a x - \alpha D x \\
\frac{dM}{dt} &= -y_1 + \frac{I_{sec} 1}{mT Vx} \\
I_{sec} &= \frac{E_{soc} - M_{soc}}{R_{soc} + R_{m} i + M_{red}}
\end{align*}$$
step-by-step instruction. They create their own step-by-step procedure to build the model and they can change the model easily without totally breaking the built “Lego” apart.

While Simulink is easy to learn, it is typically used for building simple models consisting of only a few equations (e.g., less than 10 differential equations). When the model becomes more complicated, there are a larger number of lines to connect math components in the Simulink model. This makes debugging the program (i.e., identifying issues or errors in the program) challenging. Representing ODE models with subscript functions in the R command window (Figure 1.6) is a faster way of building complicated models. As shown in Figure 1.6, the equations can be typed in subscript functions. It is also easier to check the model and modify the model in subscript functions. While building ODE models in the R command window has several of the aforementioned benefits, there are some challenges: learning how to write the program in subscript functions, assigning model parameter values, defining the setting for the ODE solver, and presenting the results in figures. These procedures are more challenging than with Simulink. Therefore, Simulink is introduced first in this book, as it provides a more friendly interface for beginning modelers. After readers build the microbial fuel cell model in Simulink, they can take on the challenge of using Simulink to build more complicated ODE models. Building models in the R command window is then introduced to readers.

![Figure 1.5](image1.png)

*Figure 1.5.* the Simulink model built for the enzymatic reaction shown in Figure 1.2 by connecting math operation components provided in Simulink.

![Figure 1.6](image2.png)

*Figure 1.6.* model built for the enzymatic reactions shown in Figure 1.2 in the command window of R.

1.3 Installation of MATLAB

MATLAB is owned by MathWorks. Schools, especially colleges, may provide their students with a MATLAB license. Readers should check with their schools on this first, to see if they can take advantage of a school subscription. Readers can also order the student version of MATLAB. It costs $49 (as shown in July 2019). The free trial version is available for 30 days. The step-by-step procedure to install the trial version of MATLAB is shown below. The procedure to install the standard/student version of MATLAB is similar. **All the codes provided in this book are developed in the version of**
Step 1: Google the keywords “MATLAB”, “trial”, and “installation” to find the webpage for downloading the trial version of MATLAB. On that webpage, users can check their campus license or type in their emails to register a new account (Figure 1.7).

Step 2: Register a MathWorks account with an email address (Figure 1.8A). Students should use their school emails in their registrations, in case their schools provide a MATLAB license (Figure 1.8B).

Step 3: Verify the email address and finalize the MathWorks account (Figure 1.9). Users should specify their first and last name, their school name (e.g., college or high school name), their school location, and their major/department (or future major/department).

Step 4: Download the control systems packaged trial options (Figure 1.10). Make sure to pick the control systems package, as it contains the Simulink toolbox. MATLAB provides installers for Windows, macOS, or Linux operation systems.

Step 5: install MATLAB by running the downloaded installer. Users may be required to log in to MathWorks using their accounts and select their trial license during the installation (Figure 1.11A). In addition, users can also see what toolboxes are included in the installed MATLAB (Figure 1.11B). Simulink should be seen as one of the selected toolboxes. Once the toolboxes are selected, the installation begins and lasts for around 30 minutes (depending on the user’s computer). Once the installation is done, a window pops up for activating the installed MATLAB. Users just need to click on it, as they are authorized to use MATLAB with the trial license. After the activation is done, users can use MATLAB for 30 trial days.

Figure 1.7, the webpage for registering a new account to download the trial version of MATLAB
Chapter 1. Overview of the Book

(B) **Figure 1.8**, (A) the webpage for registering a new account to download the trial version of MATLAB; (B) users are allowed to change their email addresses to their school emails.

---

**Figure 1.9**, the step to verify the user’s email and finalize the user’s MathWorks account
Figure 1.10. download the MATLAB trial version and install the Control Systems package. This package contains the Simulink toolbox.

Figure 1.11, (A) log in to MathWorks using the registered account; (B) select the toolboxes installed in MATLAB (make sure MATLAB and Simulink are selected); (C) activate the MATLAB trial version
Testimonial from Frederick Qiu

Dear Future Readers,

This is Frederick Qiu, a senior of Central Bucks High School East (Doylestown, PA). Although I was an outstanding student academically and participated in a variety of extracurricular and leadership activities, I am certain that the research I conducted as a result of this book was one of the key pieces of my application which got me accepted to Princeton University. Here I would like to share with you my experience in reading this book and trying the programs provided in it.

The age-old complaint one might hear from a disgruntled math student comes in many forms: “How is this ever going to be helpful? Why do we have to learn this? When am I ever going to use this?”

The student that asks these questions is right, in a sense; what matters in a math class is not what you’re doing directly, but how you apply what you learn. In that regard, one of the purest ways to apply mathematics is through research. When you think of research, you might think of adults in lab coats, operating expensive equipment. In reality, research can be as simple as working on your computer at home, manipulating data sets to draw conclusions and create models. This book contains the tools you need to conduct your own statistical analyses with powerful coding languages like R and MATLAB.

After following the videos provided in the book, I was able to conduct my own research regarding pollution and popular perception of it, which was published in a science journal (MDPI) and accepted for presentation at an annual conference (AIChE), all while I was only in high school. I cannot recommend this book enough, as getting a head start into the material will deepen your interest in mathematics and give you a skillset that allows you to be able to conduct your own research and glimpse into what a future career in the field might look like. And, as a note from one student to another, having hands on experience like research never hurts in something like a college application, where you need to truly distinguish yourself from the heavy competition.

Sincerely,

Frederick Qiu

A senior from Central Bucks HS East

July 3th, 2019
To Whom It May Concern,

My name is Peibo Guo and I am a senior at Conestoga High School. I plan to major in Environmental Sciences/Materials Science Engineering/Biochemistry in college and I participated in this project this past summer, to learn more about the field. Through it I learned that microbial fuel cells produced clean bioenergy through a reduction-oxidation process using microbes, and that they also cleaned water systems through a desalination process. I also found that MFCs collected and formed masses of precious materials from the whole reaction as a byproduct. In addition to their processes, I also learned how to construct microbial fuel cells so that I could construct one and study its functions even further.

This project really helped me because as a student who was under 18 at the time, it was extremely hard to find internship/experience due to a revision of the Pennsylvania Law on minors in July of 2016. Therefore, this project gives opportunities to students who are passionate about environmental sciences and want to gain experience but are under 18 (especially Pennsylvanian students). Personally, I really enjoyed this project because I gained experience outside of the classroom and it related to the major that I was pursuing in college. Moreover, the project gave me a direction of the kind of research I wanted to focus on in college: biomass materials. During this project, I learned that the material costs of microbial fuel cells outweighed their energy benefits. To overcome this financial barrier, I will plan to study under a materials science engineer/environmental sciences major to research and further develop biomaterials.

The skills I gained were the usage of MATLAB, which is a popular program used by engineering departments. This project also allowed me to improve my time management skills since I had to develop a strict schedule to meet the deadlines for this project in addition to maintaining my involvement with schoolwork, sports, and extracurricular activities.

In my college supplements, I mentioned the project in every single essay for each college to show that I am indeed interested in the major that I am pursuing, and it allowed me to shine above other applicants, who lack the same experience.
Overall I enjoyed the project because it is not difficult to complete, and the project itself is not time-consuming. I also liked how it educated me on microbial fuel cells well and that it gave me a real experience of what researching renewable resources was like. I learned copious amounts of information on the structure, function, and processes within microbial fuel cells which validated my major and helped me in the college process.

Peibo Guo
Testimonial from Clement Ekaputra

To future readers,

My name is Clement Ekaputra. I am 21 years old, going into my final year at the University of Pittsburgh with a major in materials science and engineering, and minors in mathematics and French.

When I was in my junior year at Great Valley High School in Malvern, Pennsylvania, I had the opportunity to do my first research project with Dr. Zuyi Huang at Villanova University. Under his guidance, I learned about microbial fuel cells, devices which harness the natural metabolisms of bacteria to simultaneously purify wastewater and generate electricity. We modelled the effect of nutrient flow rates on the bacterial populations and power generation of the fuel cell using MATLAB Simulink, a graphical modelling tool. I was fortunate to be able to present this work at the 2015 Mid-Atlantic ASEE Conference, and had a paper published in the conference proceedings.

Because of this opportunity, I have gained many benefits that have helped me throughout my academic career. For a start, having research opportunities like this is uncommon among high school students. This helped me to focus my college essays, which certainly helped me to get into the University of Pittsburgh with an academic scholarship. And having work experience, a presentation, and publication doesn’t hurt either!

The skills I learned in research have also helped me to succeed in classes. Because research involves working in an open space where not all the information is readily available, I gained a lot of practice in learning independently and seeking out knowledge to solve problems. When in a classroom setting, the material as a result comes much more naturally, connections between different ideas become more apparent, and doing problems for homework or for exams became easier.

Moreover, it helped me to focus my efforts while in college. Because of this project, I learned that I really enjoyed doing research. I was learning something new every day, whether it was about how microbial fuel cells work, or how to model systems using differential equations, or about controller design – none of which I had ever learned before, but were made accessible with close mentorship from Dr. Huang and tools like MATLAB Simulink. I enjoyed problem solving, thinking critically about real-world needs and overcoming challenges to fulfill them.

Because I worked on this project, I knew I wanted to do more research in school, and I pursued many other opportunities – computational and experimental, in academia and industry, domestically and abroad. Currently, I am a materials research intern at Mine Safety Appliances, a company which develops safety products for workers in hazardous conditions all over the world. I also was selected for a summer research program at MIT, where I am working to develop novel methods of 3D printing. What gave me the technical knowledge, analytical skills, and confidence to pursue these opportunities was simply having research experience, which began with the microbial fuel cell project during that junior year summer of high school.

Now, as I apply to graduate school, hoping to one day develop materials for aerospace applications, I think about what enabled me to pursue this career path. What helped me get more and more opportunities to do research, learn a variety of skills with wide benefits, and have confidence in the face
of huge problems, was the help I got from all those I have worked with, and especially Dr. Huang. I am very thankful for his mentorship and for the opportunity to conduct research on microbial fuel cells with him. This book written by Dr. Huang includes all the detail of the microbial fuel cell project. I believe it will offer many other students similar opportunities to build a good foundation for their academic career.

Sincerely,

Clement Ekaputra

July 30, 2019