2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #39458

Board 15: Work in Progress: Cultivating Growth of Systems Thinking Habit of Mind over a Five Course Fundamental Sequence

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Introduction

Biomedical engineering as a discipline is a diverse field; yet a central tenant is problem solving skills leveraging a strong foundation in mathematics, engineering, and biology to create new solutions to existing challenges in human health [1]. Problem solving skills are developed through a series of courses that teach the foundational knowledge while developing engineering "Habits of Mind" [2], which are defined as modes of thinking in which STEM students develop strategies to transfer their existing knowledge to new contexts. The breadth of biomedical engineering demands nimble, systematic problem-solving strategies, a core component of Engineering "Habits of Mind."

Here, we present a plan using a fading scaffold between five core interconnected biomedical engineering courses during the middle years of a traditional biomedical engineering curriculum: three traditional lecture-based courses and two laboratory-based courses (**Figure 1**). The two laboratory-based courses are hands-on discovery and implementation of general accounting principles of mass, energy, and momentum of biomedical systems taught in BEN 201 and 202. The core junior lecture-based course (BEN 401) focuses on characterizing the dynamics of biological systems using both analytical and numerical solution strategies connecting critical concepts from biology, physics, chemistry, and engineering to describe 'generalized variables' for efficient problem solving. In this WIP, we hypothesize that the redesign of several class activities (2 example activities in Appendices B and C) within this core sequence will improve the development of student's Engineering "Habits of Mind" specifically in the following categories defined by Boutin et. al. [4]: 1) Computation and Estimation, 2) Mathematical Rigor, 3) Critical Response Skills, and 4) Values and Attributes. As the critical core concepts of these sequenced courses build upon each other, we anticipate that assessment of these Engineering Habits of Mind via the redesigned activities will demonstrate improvements in each of the categories.

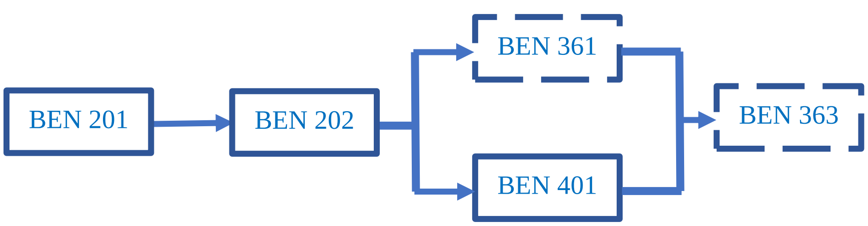

Figure 1. Diagram displaying how the multicourse biomedical engineering courses are linked. Courses with a dashed border are laboratory-based courses while solid borders are lecture based classes.

Methods

A single course activity was examined in both BEN 201 (Fundamentals of Biomedical Engineering) and BEN 401 (Dynamic Biomedical Systems) as approved by an IRB protocol #2023-04-02. Both problem statements were written using realistic real-world backstories and were influenced by the shortages of the ongoing tripledemic pandemic to further engage students [3]. A rubric (Appendix A) adapted from Boutin's [4] was used in both course activities to evaluate student's: 1) Computation and Estimation, 2) Mathematical Rigor, 3) Critical Response Skills, 4) Value and Attributes.

BEN 201: Fundamentals of Biomedical Engineering Problem Statement
Twenty students in BEN 201 were tasked with written assignment confirming a consultant's work for the design of a new three-stage manufacturing process for 0.7mol% acetic acid. The full problem statement is in Appendix B. Students were provided with a detailed process flow diagram with mole and mass fractions of relevant molecular species (i.e., glucose, water, ethanol, and acetic acid) entering and leaving each unit of the three-stage process. Students were asked to: 1) Identify and correct any errors found in the process flow diagram, 2) Justify your answer, and 3) Correct the process flow diagram. Simple calculation and incorrect stoichiometry were considered minor. More rigorous analyses revealed errors within the volumetric flowrate of air entering the second bioreactor, a subtle error as this is not necessary to correct mass balance. The most comprehensive error necessitated the redesign of the last unit of process to dilute the final product. All errors and proposed altered solutions required complete justification targeting their critical response and communication skills.

BEN 401: Dynamic Biomedical Systems Problem Statement:
Twenty-eight students in BEN 401 were tasked with developing a 3-compartment model of the diffusion process of antibiotics to treat a common ear infection. The problem statement is found in Appendix C. Students were given 24 hours to solve the problem and upload their solutions and justification to a learning management software. The students were individually scheduled for 10-minute technical meetings with the instructor simulating a progress update in an industrial COOP setting. Students presented a system diagram, identified all assumptions, and presented graphs clearly depicting the results of their numerical solution model to assess student's mathematical rigor and computation and estimation. To further evaluate computation and estimation, students were asked to consider various perturbations to the system and qualitatively describe the system response. The course instructor did provide guiding questions as needed if additional direction was needed and the types of guiding questions and student responses were considered while evaluating student's communication skills, critical response skills, and values and attributes.

Preliminary Results and Discussion

BEN 201: Fundamentals of Biomedical Engineering

The students demonstrated an ability to follow a clearly laid out procedure; however, students faltered once deeper analyses requiring extrapolation were needed. This can be seen in Figure 2 by the high scores in computation and estimation but low in mathematic rigor. For example, students easily found simple errors; yet the error in the volumetric flow was undetected. The volumetric flow rate required students to assume growth conditions of the organism in the bioreactor demonstrating limited understanding of entire system and was a dominant factor in the low mathematical rigor scores. Since this is the first course in the sequence this limitation is not

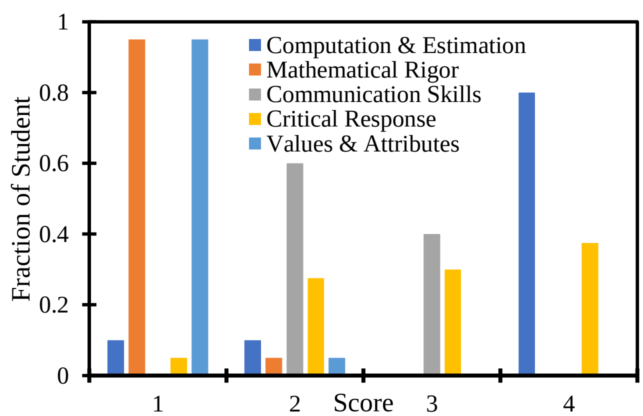

Figure 2. Breakdown of student scores from BEN 201

surprising. Overall, student work submitted was difficult to follow and frequently had limited explanation driving factors in the low assessment of student values and attributes towards their own work.

BEN 401: Dynamic Biomedical Systems
Overall, 50% of the students consistently scored as proficient or advanced within each element. This was not surprising as this was a final assessment of the junior semester in which much of the instruction time focused on active learning in small groups solving similar types of problems. The high percentage of students scoring in the advanced and proficient ranges of all elements within the Engineering Habits of Mind may also be contributed to the involvement of metacognition reflection habits as part of the course curriculum following a class-wide poor performance on a low-stakes quiz earlier in the semester. After the poor performance, the instructor streamed the Skillful Learning, "Reflecting on Our Thinking" YouTube video [5] and offered students an opportunity to repeat the quiz to earn up to 50% of lost points. Interestingly, students were similarly weak in both computation and estimation (57% scored as proficient or advanced) and with mathematical rigor (60% scored as proficient or advanced) (**Figure 3**). Over 80% of the students scored as proficient or advanced in both their communication and critical response skills (**Figure 3**). Furthermore, 78% of the students scored proficient or advanced in values and attributes (**Figure 3**).

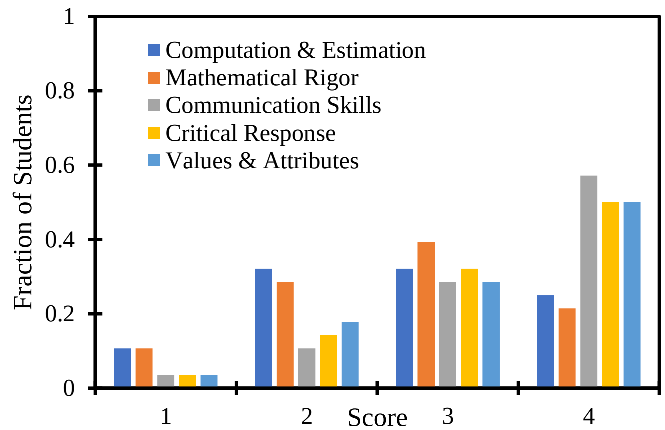

Figure 3. Breakdown of student scores from BEN 401

Future Modifications
At this point, comparing the student scores between the two courses is not a simple direct comparison due to significant differences in the final work product. The acetic acid manufacturing process was primarily focused on finding and justifying the errors, tasks that are heavily focused on critical response. Alternatively, the 3-compartment antibiotic model required students to assemble the entire procedure requiring a holistic assessment of all categories within the Engineering Habits of Mind rubric. Furthermore, the modes of assessment were different, one was oral whereas the other was a written task. During the oral assessment, the instructor did ask guiding questions, potentially redirecting the student response limiting the direct growth comparison from the written sophomore assessment. Yet we do anticipate a growth in students' "Engineering Habits of Mind" between the two years.

As this work is expanded to incorporate all five courses in the sequence, additional focus will be on creating assignments that are targeted to assess 1-2 "Engineering Habits of Mind" rather than attempting to create a single assessment of categories simultaneously for each of the courses. The collective growth of student cohorts will be tracked for each activity.

Works Cited

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[2] B. Lucas and J. Hanson, "Thinking Like an Engineer: Using Engineering Habits of Mind and Signature Pedagogies to Redesign Engineering Education," *International Journal of Engineering Pedagogy (iJEP)*, vol. 6, no. 2, p. 4, May 2016, doi: https://doi.org/10.3991/ijep.v6i2.5366.

[3] AMD NextGen Engineer and National Academy of Engineering, *Infusing Real World Experiences into Engineering Education*. National Academies Press, 2012.

[4] T. Yellamraju, A. J. Magana, and M. Boutin, "Investigating students' habits of mind in a course on digital signal processing," *IEEE Transactions on Education*, vol. 62, no. 4, pp. 312–324, 2019.

[5] Skillful Learning, "3 - Reflecting On Our Thinking," *YouTube*. Jan. 29, 2019. Accessed: Nov. 17, 2022. [Online]. Available: https://www.youtube.com/watch?v=3exsUBpz2OI

Appendix A: Rubric used for Assessment (Adapted from Boutin et. al. [4])

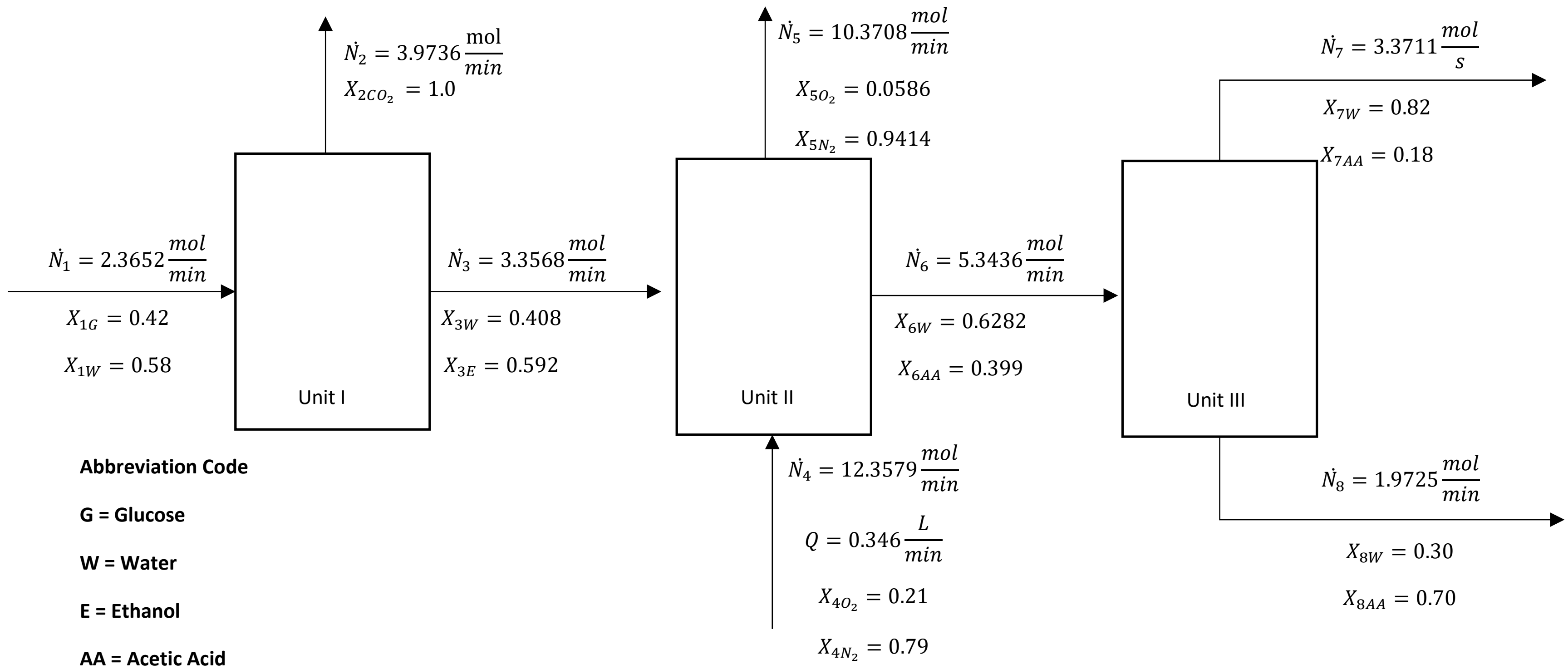
Element	Definition	Below Basic: 1	Basic: 2	Proficient: 3	Advanced: 4
Computation and Estimation	Ability to select appropriate computation method & perform mathematics accurately	Incorrect method selection.	Correct method selected but incorrect solution.	Correct method selected and correct solution but method selection was poorly justified.	Correct method selection and correct solution with clearly justified method selection.
Mathematical Rigor	Demonstrates mathematical rigor and details of definition	No mathematical rigor.	Some mathematical rigor but major errors.	Some mathematical rigor but minor errors.	Significant mathematical rigor and no error.
Communication Skills	Ability to communicate ideas effectively	Unclear and unjustified procedure	Procedure presented but was not justified	Procedure clearly presented with reasonable justification	Procedure clearly presented with detailed justification based on theory or principles.
Critical Response Skills	Ability to detect doubtful solutions, assertions, and arguments in own work.	Unable to identify incorrect procedural error. No procedure identified to validate solution.	Procedural error identified but not corrected. No procedure identified to validate solution.	Procedural error identified and corrected. No procedure identified to validate solution	Procedural errors identified and corrected OR no procedural errors present. Clearly presented procedure to validate solution(s).
Value and Attributes	Student attitude toward their own work	Indifferent or negative comments about their own work.	Generic comments that do not provide any insight.	Good comments providing insight and reasonable critique.	Excellent comments, correcting mistakes with insight critique.

Appendix B: BEN 201 Assessment Example

On the following page, there is a process flow diagram created as a preliminary design of a three-stage process of manufacturing acetic acid at 0.7 mol% aqueous solution to be used as an aseptic for wound care. This process consists of two bioreactors and a distillation column.

Unit I consist of a bioreactor containing *Saccharomyces cerevisiae* which will produce ethanol. Due to global shortages, it is more efficient to manufacture ethanol in house versus importing the chemical. The ethanol is then fed into Unit II, which is a packed bed bioreactor with *Acetobacter aceti* which will aerobically generate acetic acid used in the final product. The effluent of this bioreactor needs to be concentrated using a distillation column. The bottoms product will enter the bottle division of the plant to be processed before being shipped to customers.

Your company has asked you to double check the work of the engineering consultant firm that they have hired. If you identify any errors in the process flow diagram, please explain your reasoning, and justify it. Also, correct the process flow diagram.



Abbreviation Code

G = Glucose

W = Water

E = Ethanol

AA = Acetic Acid

Appendix C: BEN 401 Dynamic Biomedical Systems Assessment Example

During the Fall of 2022, a resurgence of various viral and bacterial infections has plagued the global pediatric population. Your friend Thomas has a 5-year-old who was recently diagnosed with an ear infection and prescribed an antibiotic for treatment. Thomas is asking you how critical it is to space the doses of the antibiotic out throughout the day, so you decide to collect pieces of information from trusted sources (peer-reviewed articles) to create a model to help explain to Thomas why it was suggested that he give his son the antibiotics (350 mg/dose) twice daily spaced approximately 8 hours (hint round up to 500 minutes for easier modeling of the input drug). Thomas tells you that his son gulps the liquid antibiotics very quickly. After some searching you find the following information:

- Gut volume of average 5-year old: 100 mL
- Average blood volume of 5-year old: 5.8L
- Volume of Ear Canal: 1.2 mL
- Rate of exchange of antibiotic from the gut to the blood: 8.75 mL/hr
- Rate of exchange of antibiotic from the blood to the ear canal via capillaries: 3.15 mL/min
- Rate of antibiotic excretion from the blood (renal physiology) into urine: 0.035 mL/min
- Rate of antibiotic consumption by the bacteria found in the ear: 0.005 mL/min

After some additional reading, you find that antibiotics are rarely toxic; however, the gut can become upset if the local concentration in the gut exceeds 3.52 mg/mL. Furthermore, within the ear canal, you calculate that the minimum concentration of the antibiotic must be 3µg/mL.

Armed with this critical information, you go about creating a model to help Thomas understand the dynamics of the antibiotic using a 3-compartment model comprised of the gut, blood (consider this the plasma), and the ear canal.

Hint: Set the Solver type to the following: Type: Fixed-step, Solver: Auto (automatic solver selection) to avoid long solving times.

1. Draw a schematic of the system, include all relevant information.
2. Draw a system input/output diagram.
3. Write the model equations using state variable format. Classify the system in terms of the following: (full credit requires justification)
    a. Dynamic Order
    b. Linear or Nonlinear
    c. Time Invariant or Time Varying
    d. Autonomous or Non-autonomous
4. Identify the state variables of the system.

5. Create a Simulink file to solve the dynamic model.

a. What sort of input function is most appropriate to model the oral ingestion of the antibiotic? Describe how you created this input function. Be sure to specify the unit of time.
b. Provide plots of the concentration of the antibiotic in each of the modeled compartments with a single dose. Describe the relationship between the concentration between the modeled compartments.

6. What happens if Thomas gives his son the 2nd dose after 200 minutes rather than the suggested 500 minutes? (Full credit will include graphs of 2-dose sequence at both 200 and 500-min of relevant body compartments).

7. Before you go ahead and report your results to Thomas, you want to consider the sensitivity of your calculated concentration of antibiotic in the ear canal if the following perturbations relative to the nominal conditions simulated in question 5. Valid responses are: increased, decreased, unchanged, or insufficient information.

Perturbation(s)	Initial Value: $A_{EA}(t)$ at t →0 (g/mL)	Peak Value of $A_{EA}(t)$ (g/mL)	Final Value $A_{EA}(t)$ at t →∞ (g/mL)	Final Rate $dA_{EA}(t)$ at t →∞ (g/mL·hr)
1. ↑ear canal volume				
2. ↓ Gut volume, ↑ Antibiotic dose				
3. ↓ antibiotic consumption				
4. ↑ rate of antibiotic exchange between gut and blood				
5. ↓rate of antibiotic exchange from blood to the ear canal				