2006-1874: KEVIN BACON, TACTICAL WARFARE, AND PROTEIN NETWORKS - AN INTERACTIVE ONLINE QUANTITATIVE CELLULAR BIOLOGY LEARNING MODULE

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Kevin Bacon, Tactical Warfare, and Protein Networks - An Interactive Online Quantitative Cellular Biology Learning Module

Abstract

BIOL 295F – Introductory Quantitative Cellular Biology was first offered at a Midwest US Research I institution during the fall 2004 semester. An online learning module on protein networks was designed and implemented for the second offering of the course during the fall 2005 semester. The overarching design goal was to create an online module to help students develop a large scale mental model of biomolecule interactions as a formal network. The application of network theory to biochemical networks provides a new view on cell function and stands to make a significant contribution to future advances in systems and computational biology. By taking advantage of advances in technology, the online module was developed to provide both visual representations of networks, so as to help engineering students best learn using their preferred learning style, and interactive learning features to engage students in the necessary higher-level critical thinking.

This paper will highlight the design, implementation, and assessment of the new online learning module. Student learning gains were assessed using pre-post quiz questions focused on concepts presented in the online learning module. In addition, students' actual use of the tool and their perceptions of the interactive online learning modules versus other modes of instruction were evaluated through the use of an attitudinal survey.

Introduction

Bioengineering includes the study of biological phenomena using the fundamental principles of engineering. Despite the rapid growth of bioengineering as a field of study for undergraduate students, the development of educational materials for bioengineering instructors has failed to keep pace. Until only a few years ago, the subject of bioengineering was predominantly limited to graduate level coursework and research labs. Only in recent years, due in part to the burgeoning of interdisciplinary research and the general increased growth of technology, has bioengineering found its way into the undergraduate curriculum. Despite the proliferation into undergraduate coursework, most instructors are limited to professional journal articles or complex tools aimed at those working in the field. Many of the textbooks covering bioengineering topics are outdated before they even arrive in bookstores and are rarely targeted towards teaching introductory material[1]. In a report on the progress of bioengineering as an independent field of study, Johnson[2] explicitly states, "We have yet to develop texts and other teaching materials in biological engineering." Moreover, because of the scale, complexity, and interdisciplinary nature of the study of most bioengineering phenomena, the development and implementation of hands-on experiments can be both costly and challenging at the early undergraduate level.

Though the growth of the internet has led to a general increase in web-based tools, those available to students for learning introductory cellular biology are still severely deficient in a number of areas. First, the majority of engineering students are classified as visual learners. In a validation study of the Felder-Soloman Index of Learning Style, Zywno[3] summarized the results of 6 studies, finding that between 69% and 88% of engineering students are classified as learning material best when presented visually. Though most engineers are visual learners, the vast majority of instruction is still done using textual explanations and static images of complex phenomena, making it exceedingly difficult for students to develop a sound conceptual understanding.

The second problem that has plagued the available web-based tools is that they often lack the interactivity necessary to better engage students in the learning process. In the same validation study, Zywno[3] found that between 55% and 69% of students were classified as active learners. "Active learners do not learn much in situations that require them to be passive (such as most lectures)"[4]. Many of the learning modules currently available do not require any response from the user, outside of the occasional "press here to continue" or multiple-choice question. These modules are often no better than traditional paper textbooks. This phenomenon of electronic versions of static textbooks is most likely due in part to the tremendous amount of time and effort required to develop course materials that take advantage of capabilities new technology has to offer[5]. The time commitment needed to create an electronic textbook is much less than that needed to create dynamic educational materials. Educators who are looking to utilize technology in their classrooms are more likely to choose the less time consuming option. The idea that students learn best when they are more involved in the learning process is not a new concept, but in the face of new technology, is often a forgotten concept.

An online learning module about protein networks was specifically designed to resolve these two major problems, namely a lack of instruction that is both interactive and visually based. This paper discusses the design, implementation, and assessment of an online learning module aimed at introducing undergraduate engineering students to the properties and structure of protein networks. Student learning gains are assessed using pre-post quizzes focused on concepts presented in the learning module. In addition, students' perceptions of the interactive learning module are assessed.

Protein Networks Learning Module

BIOL 295F, Quantitative Biology of the Living Cell, is a 1-credit hour computer lab based course developed at a Midwest US Research I institution targeted at engineering students studying bioengineering or related fields. Offered for the second time during the Fall 2005 semester, the course met once each week for 110 minutes in a computer lab. The objective of the course is to examine traditional cellular biology topics, but place them in an engineering context, identifying the fundamental engineering concepts that underlie many biological processes. This course is designed to be a co-requisite to BIOL 295E, Biology of the Living Cell, an existing 3-credit hour traditional introduction to cellular biology for engineering students.

The course developer, as part of the course creation process, envisioned seven topics, each with corresponding online learning modules. To allow for more rapid development and prototyping, Macromedia Flash MX 2004 was selected as the development environment of the modules and their associated architecture. To help with the data collection process, a PHP/MySQL database was connected to the Flash architecture. For the first iteration of the course, three online learning modules were developed. Ion transport[6], phylogenetic relationships of organisms[7], and dynamic gene regulation[8] were the topics selected for initial module development. These three topics were selected as they each require a fundamentally different type of interactivity; therefore, each topic provides a unique computer-based learning experience for the user. For example, the phylogenetic relationships topic allows for students to emulate one of the pioneering studies in organism classification. The gene regulation topic requires a simulation tool that allows students to interpret the results of changing specified input parameters to a system of differential equations; the emphasis being placed on cause and effect relationships between the input and output parameters. Though both provide an interactive component, they are fundamentally different in how they allow the user to interact with the module.

While repetition has long been viewed as advantageous for student learning, one of the significant problems is the memorization effect, where students become better at the specific problem type they are repeating but fail to learn the underlying concepts. By utilizing computer-based instruction, more randomization can be built into the system, allowing for unique problem generation with each iteration. This approach was used in the development of the online learning module. Whenever possible, randomization was employed to change the problem. Incorporation of randomization allowed for more repetition while virtually eliminating the "memorize-and-regurgitate" response.

Network theory appears across numerous disciplines and is the foundation for a wide variety of theoretical constructs. Network theory is the basis for the internet, provides a mathematical basis for tactical warfare decisions, and has made appearance within popular culture as "The Six Degrees of Kevin Bacon."[9]. The protein networks module has student calculating network properties and building networks to represent protein reactions. The module provides an interface that allows students to both interact with existing networks to calculate common network properties as well as build their own networks to meet specified requirements.

During the pre-module lecture, students are told about network theory using two major analogies. The first analogy is a classical problem known as the Seven Bridges of Königsberg, which was first studied by Euler during the early 18th century. The problem depicts a set of four landmasses connected by seven bridges and asks if it is possible to cross every bridge once and only once. Using this problem as an example, the course instructor explained the concept of nodes, edges[1], directionality, and connectivity. From here, the instructor moved on to using the Six Degrees of Kevin Bacon game to explain the concept of shortest path length. The general concept behind the game is to connect other actors or actresses to actor Kevin Bacon using movies, where the actors/actresses is a node in the network and the films they have appeared in represent the edges of the network. One example given to the class was Cameron Diaz, who was in Vanilla Sky with Tom Cruise, who was in A Few Good Men with Kevin Bacon. In this case, the path between Kevin Bacon and Cameron Diaz is of length two. If Kevin Bacon and Cameron Diaz appear in a movie together, then the path between them is of length one. The shortest path is, as the name implies, the length of the path between any two nodes that is of the shortest length. While its significance is beyond the scope of this paper, the accessibility of this

[1] The terms "node" and "edge" are used throughout the remainder of this paper. Depending on the application, other terms may also be used interchangeably. The other commonly used name for a node is a "vertex". Other common names for edges are "arcs" or "connections".

example may have been more difficult for some of the international students as the Six Degrees of Kevin Bacon game is a highly American cultural reference.

After covering these two analogies, the focus of the discussion shifted to biochemical networks and using network theory to explain relationships between various types of cellular interactions. This shift in focus allowed for two other concepts to be explained, that of the clustering coefficient and that of random versus directed attacks. The clustering coefficient is a measure of how heavily connected a node is within the network.

The pre-module lecture helped provide a background for the activities being done throughout the module. The first module activity (Figure 1) has students calculating the connectivity, shortest path length, and clustering coefficient for a single node. All three questions include a required textbox asking the student to explain their response. Upon answering all three questions, the students are given automated feedback on the correctness of their numerical answers. In the event that any of their responses are incorrect, they are given a new random network and must calculate all three values for the new network. They are not allowed to advance to the next activity until they correctly calculate all three values for a network.

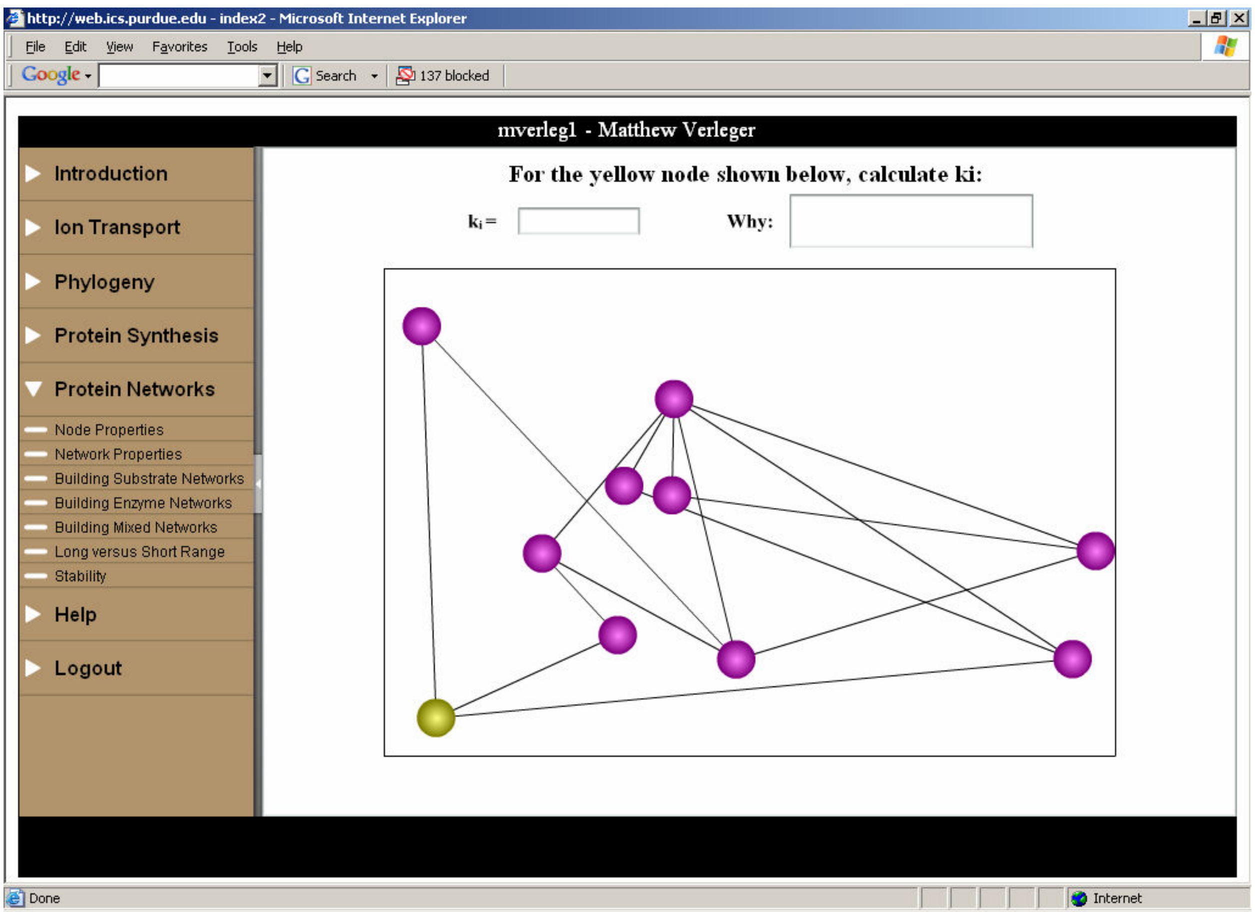

Figure 1. Node Properties Activity

The second activity (Figure 2) is similar to the first in that the students are presented with a random network. Here, students are asked to calculate the average connectivity, average shortest path length, and average clustering coefficient. Because all three calculations can be time intensive, the size of the network was limited to 6 nodes. Again, students are given feedback and required to obtain mastery of the calculations before advancing.

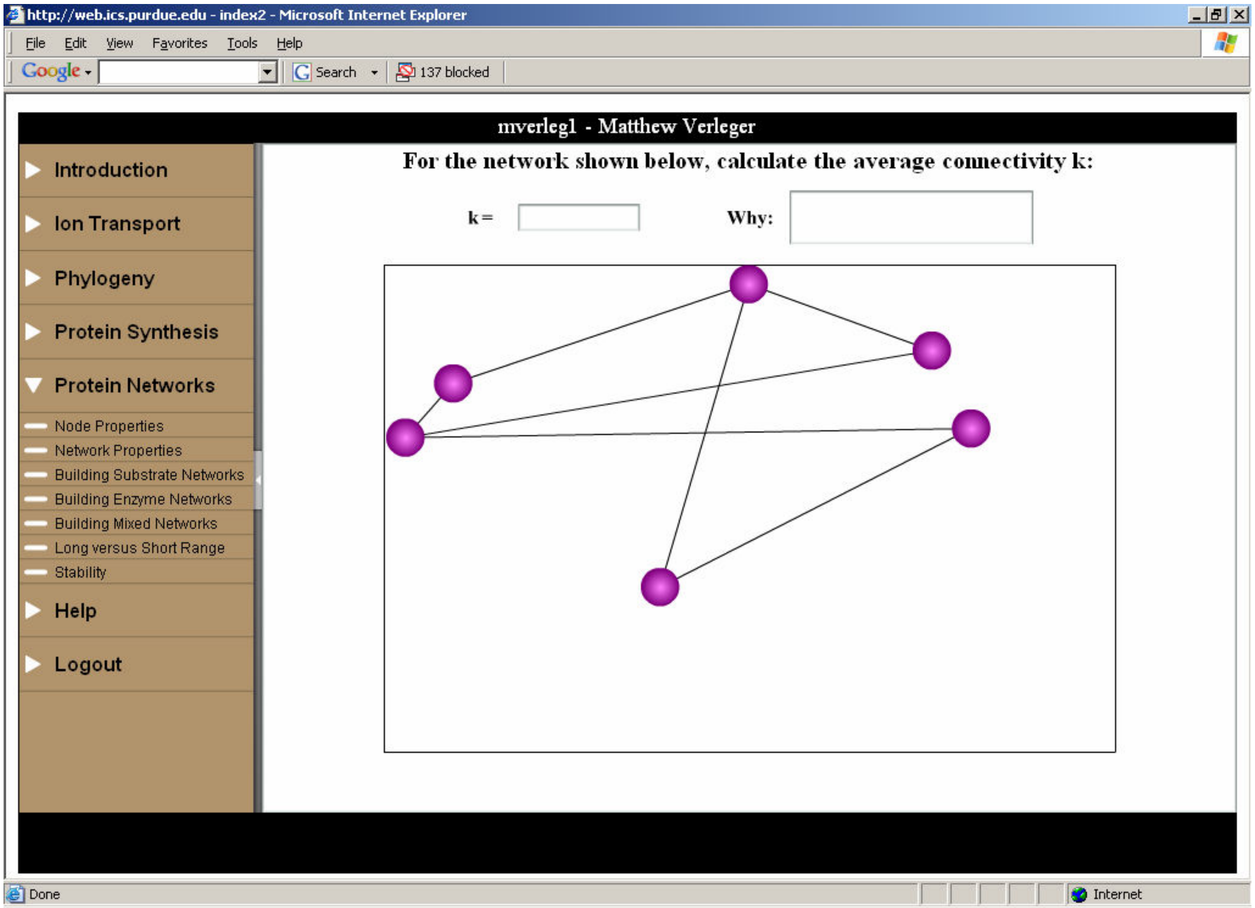

Figure 2. Network Properties Activity

The third (Figure 3), fourth, and fifth activities are similar in design with subtle differences in the question being asked. Students are given the chemical reaction sequence shown in Figure 4 and asked to create various networks to represent different aspects of the reactions. Activity 3 has students create a substrate network, activity 4 has them create an enzyme network, and activity 5 has them create a directed mixed enzyme-substrate network. Students are given a tool to build a network. Using the tool, students can place nodes, label the nodes, and connect the nodes with edges. Upon the completion of a network, students are given feedback about the correctness of their network. It was decided that each student would have the same reaction sequence, allowing for better feedback to be written. An example of the feedback a student might receive is “You are missing a connection between G6P and NADP+”.

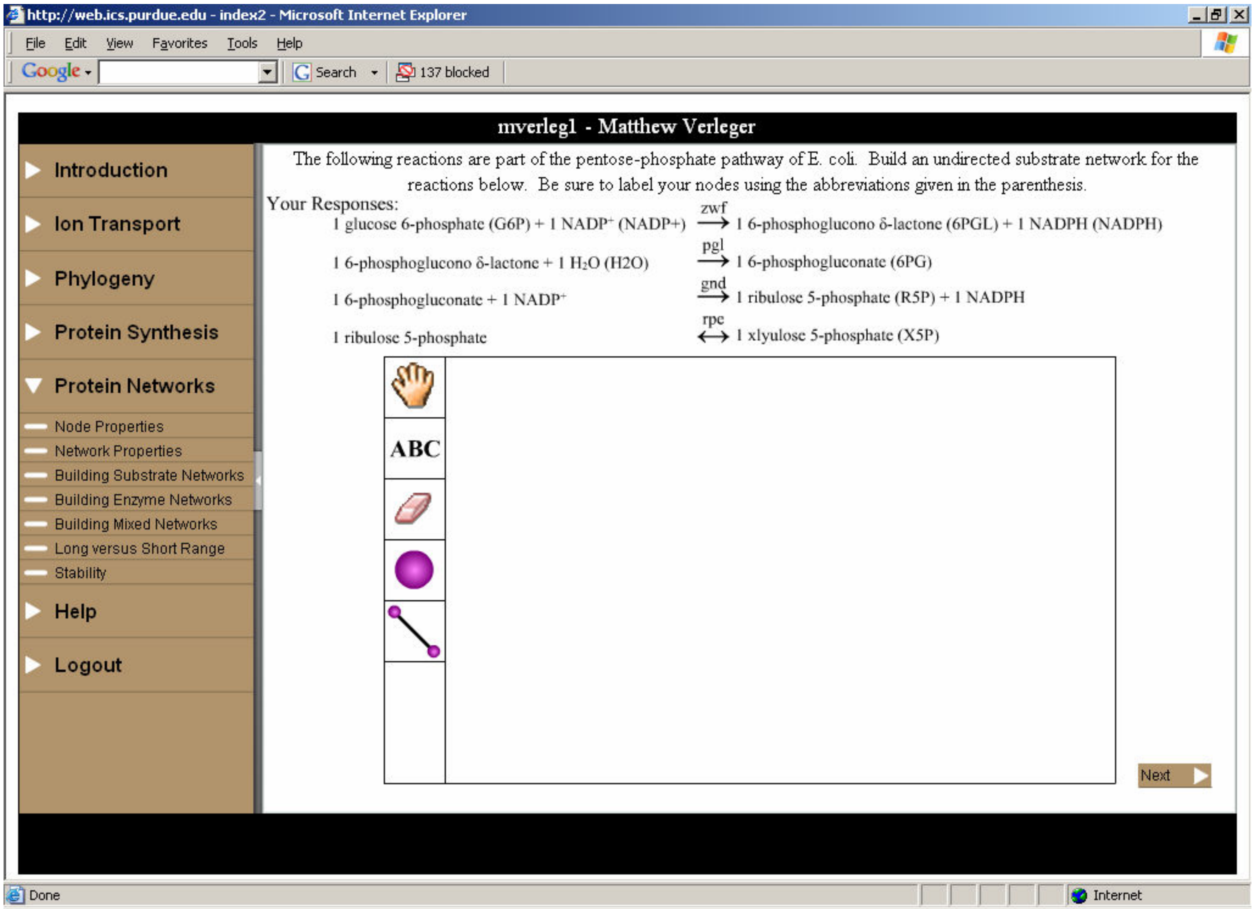

Figure 3. Building Networks Activities

1 glucose 6-phosphate (G6P) + 1 NADP$^+$ (NADP+) $\xrightarrow{\text{zwf}}$ 1 6-phosphoglucono δ-lactone (6PGL) + 1 NADPH (NADPH)

1 6-phosphoglucono δ-lactone + 1 H_2O (H2O) $\xrightarrow{\text{pgl}}$ 1 6-phosphogluconate (6PG)

1 6-phosphogluconate + 1 NADP$^+$ $\xrightarrow{\text{gnd}}$ 1 ribulose 5-phosphate (R5P) + 1 NADPH

1 ribulose 5-phosphate $\xleftrightarrow{\text{rpe}}$ 1 xlyulose 5-phosphate (X5P)

Figure 4. Reaction Sequence for Building Networks Activities

The sixth activity (Figure 5) has students examine the affect of long range connections between nodes on the shortest path length. Given a network where each node is only connected to its nearest physical neighbors, students are asked to calculate a few of the shortest path lengths. Students are then asked to add two long range edges, connecting any two nodes that currently have at least a shortest path length of four or more. After adding the edges, students are asked to calculate the same shortest path lengths. Students are then shown their original and new answers side-by-side and asked to speculate on the differences and the affect of the long range connections.

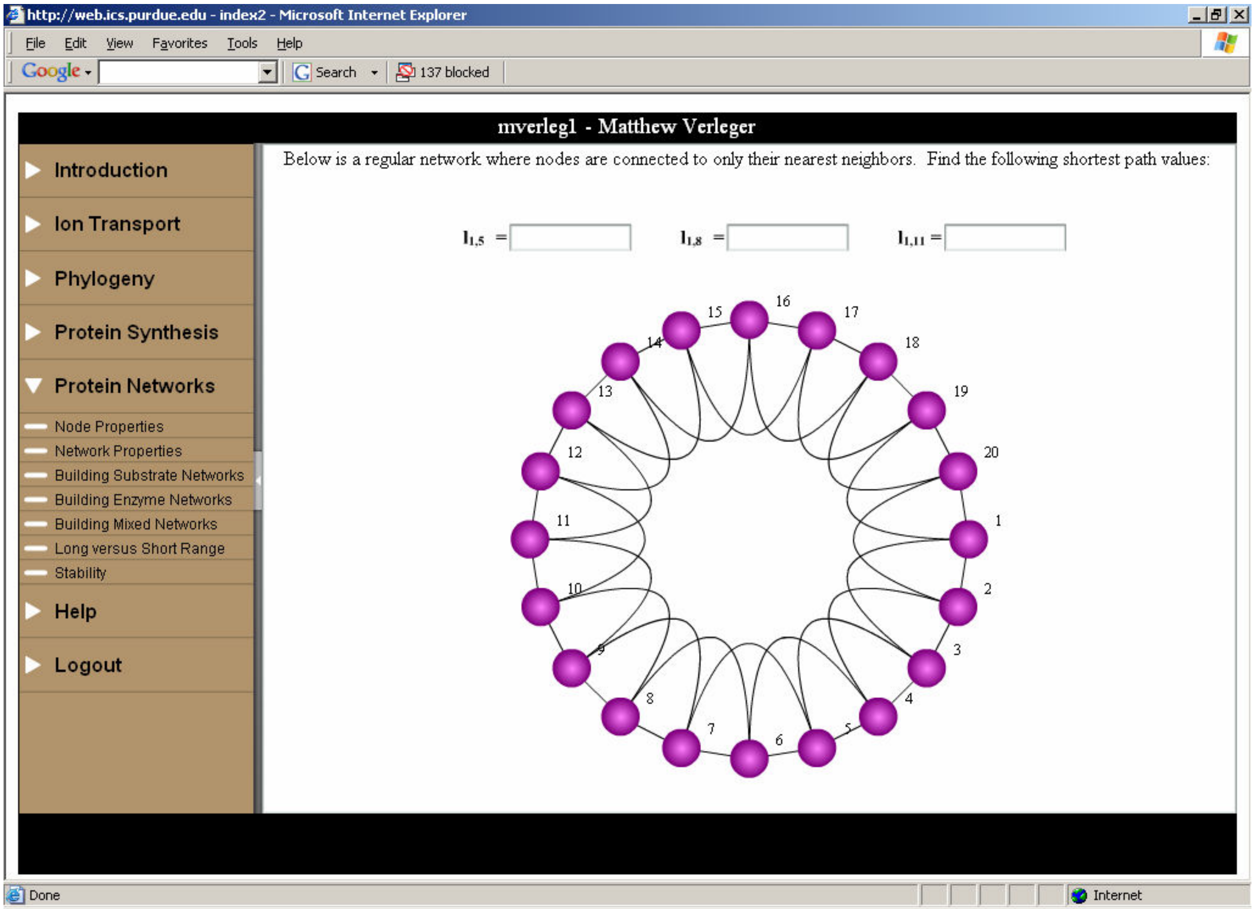

Figure 5. Long versus Short Range Activity

Finally, in the seventh task (Figure 6), students are given a network and asked to erase three specific nodes from the network. These nodes are the three most highly connected nodes. They are then asked to erase any three other nodes. Finally, they are asked to speculate what happens to the network in each case. The goal is to show that the targeted destruction of the highly connected nodes reduces the stability of a network more than randomly destroying nodes. Conceptually, this was explained during the pre-module lecture using the analogy of tactical warfare. A bomber will cause more damage by bombing targets of high importance than by attacking random locations which may or may not be important.

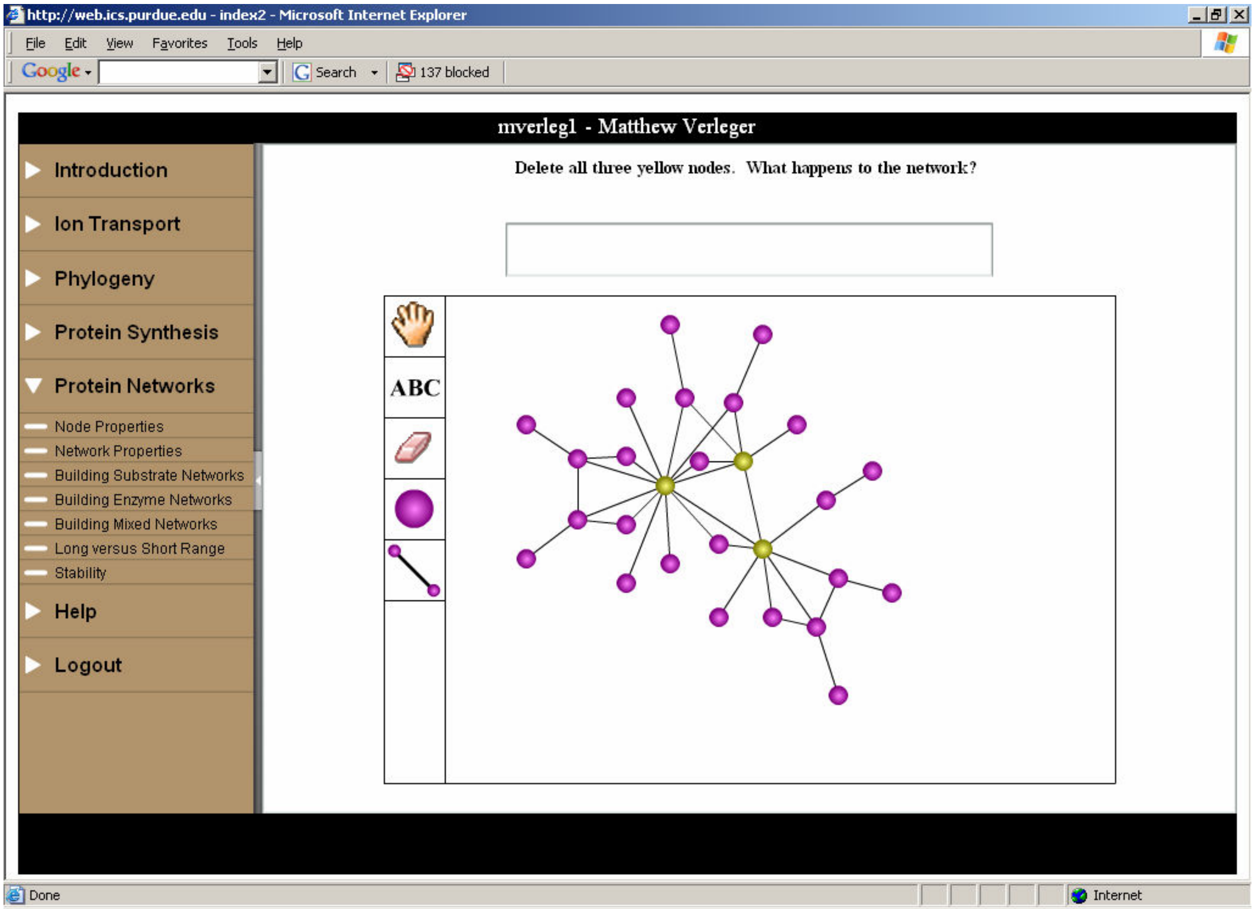

Figure 6. Network Stability

Technical Problems

While every effort was made to test the modules under a variety of conditions, a number of problems afflicted this module. Unfortunately, during the third, fourth, and fifth activities, due to a couple of mathematical errors in the building tool, students were not always able to connect some nodes, and correctly built networks were sometimes being marked as incorrect, requiring that students unnecessarily repeat the problem. While the problems were frustrating, they did not prevent anyone from being able to work through the third and fourth activities. The errors did prevent students from completing the fifth activity where they were building directed networks.

The final task related to network stability also contained an error which prevented any students from advancing past the initial question. This error resulted primarily from a last minute change that went improperly tested and consequently crashed the code. When these problems were identified by the students, attempts were made to resolve the problems as quickly as possible. When the problems could not be resolved quickly, the menu items were released, allowing students to skip the afflicted activities and move on to the next activity. All of these errors have since been repaired.

Implementation

Though the course is required for agricultural and biological engineering students, BIOL 295F was made available to any student concurrently enrolled in BIOL 295E, providing the potential for a cross-section of students from a variety of disciplines. In total, 12 students registered for the course from three different fields of study. Eight students were pursuing degrees in Agricultural and Biological Engineering. The remaining students were pursuing pre-pharmacy or medicinal chemistry degrees.

The protein networks lesson began during the 15th week of the semester with an instructor led discussion. This was the fourth online learning module students were participating in this semester, with all four modules having similar designs and timelines. The first three modules were Ion Transport[6], Phylogeny[7], and Gene Regulation[8]. The modules were not designed to be complete stand-alone learning modules independent of other instruction, but more as an extension to a more traditional instructional package. The pre-module lecture provided the background material necessary to begin using the online learning module. It also provided a brief introduction to the topics found in the module so as to give students a starting point. Over the course of two weeks, students took a pre-quiz, worked through the online module, took a post-quiz and completed an attitudinal survey. A full timeline can be seen in Table I.

Table I
Timeline of Protein Networks Lesson

Week	Activity
15	Lecture
16	Pre-Quiz Module work
17	Post-Quiz Attitudinal Survey

The pre-quiz and post-quiz were paper-based multiple-choice and short answer quizzes (Appendix). Every question that appeared on the pre-quiz had a corresponding variant on the post-quiz. As the questions were written to investigate the learning effects of the activities found in the online learning module, the results of these question pairs are analyzed below.

After students had completed the lesson, they were given an attitudinal survey to assess their perceptions of the online learning module. The survey was broken into four sections. The first section consisted of questions asking how students felt the module related to the course and learning the course material. The second section asked students how they felt the problems in the module affected their ability to learn the material. The third section asked students to compare the online learning module to other forms of instruction, including traditional lectures and live demonstrations. Finally, students were asked to rate the usability of the learning module. Questions in each section were rated using a 5-point Likert scale. Open-ended questions followed the first three sections asking students to explain their responses.

As participants work through the learning module, their responses to the questions are being stored to a database for later review by the course instructor. At the same time, a number of time-based measurements are collected, including how long a student spends on any particular problem. Though both of these pieces of data were collected over the three-week period, their analysis is outside the scope of this paper.

Data Analysis

Due to the relatively small class size (N = 12), no statistical analysis was performed beyond simple counts. One student failed to attend the final two weeks, resulting in no pre or post quiz data as well as no attitudinal survey for this student. One student also failed to attend the final week, resulting in no post quiz or attitudinal survey. Data for these two students was removed from the study, resulting in an N of 10 students for all presented data.

Pre-Post Quiz Results and Discussion

Table II contains a question pair breakdown of pre-quiz to post-quiz performance. For example, for question pair 5, four participants answered both the pre and post quiz questions correctly, while one student answered the pre-quiz correctly but missed the corresponding post-quiz question. Question pairs 3 and 4 did have partial credit associated with them, though the numbers described in Table II refer only to the total correctness of the problem. A more detailed analysis of the partial credit appears below.

TABLE II
Performance on Pre-Post Quiz Question Pairs

Pre-Quiz Answer	Post-Quiz Answer	Question Pair						
		1A	1B	1C	2	3	4	5
Correct	Correct	10	8	8	10	3	4	4
Correct	Incorrect	0	0	0	0	0	2	1
Incorrect	Correct	0	2	2	0	4	0	4
Incorrect	Incorrect	0	0	0	0	3	4	1

Question Pair 1A, 1B, & 1C – Module Activity 1 (Node Properties)

Question pair 1 presented students with a network and asked them to calculate the connectivity (1A), shortest path length (1B), and clustering coefficient (1C) for a specific node (or pair of nodes in the case of shortest path). Performance on this question was positive, with all students getting all three parts correct on the post-quiz. One of the two students who missed the pre-quiz question 1B clearly understood the shortest path problem, however missed the problem because instead of stating the length of the shortest path as requested, wrote down the correct sequence of nodes on that path. The two students who missed question 1C, based on their work, were confused on what the variables in the clustering coefficient represented.

Question Pair 2 – Module Activity 1 (Node Properties)

Question pair 2 had students answering a multiple choice question defining the connectivity of a node. All students answered this question correctly in both the pre and post quizzes, indicating that this content is very clearly being conveyed as part of the lecture.

Question Pair 3 – Module Activity 3 (Building Substrate Networks)

The third question pair provided students with a chemical reaction sequence and asked them to draw the undirected substrate network where the nodes were the reactants and products and the edges are the reactions. Performance on this question dramatically improved between the pre and post-quizzes. Taking into account partial credit (Appendix C), the average score jumped from 3.60/5.00 to 4.50/5.00 from the pre to the post quiz. On the pre-quiz, three students had perfect networks. Of the remaining seven students, one student had an extra edge, one student was missing only one edge, and five had two or more missing edges. The missing edges were not consistent between students, indicating that students generally misunderstood how to solve the problem as opposed to the problem being deceptive. On the post-quiz, seven students had perfect networks. One student added an additional node and duplicated a label, however did have all the correct edges present. The remaining two students were missing one and three edges respectively. Overall, despite the technical problems encountered during this activity, students did seem to learn the mechanics of constructing a substrate network from the module.

Question Pair 4 – Module Activity 4 (Building Enzyme Networks)

The fourth question pair required students to draw the undirected enzyme network for the same chemical reaction sequence as in question pair 3, where the nodes were now the catalyzing enzymes in the sequence and the edges were the shared products or reactants. Despite the technical errors in the tool, nine of the ten students were able to create the correct enzyme network in the module activity however these results are not reflected in the post-quiz scores. Overall, the average on the pre-quiz was 3.70, but was reduced significantly by two students who failed to attempt the problem and thus received no partial credit. The average of the remaining eight students on the pre-quiz was 4.63. The average score on the post-quiz of those same eight students was only 4.13/5.00. One possible explanation is that the network given as part of the module activity was easier than the network found on both the pre and post quizzes, containing only four nodes and four edges, whereas the pre-quiz contained six nodes and eight edges and the post quiz contained six nodes and ten edges. This difficulty disparity was not present with Question Pair 3, indicating that perhaps more difficulty is needed in the module activity related to building enzyme networks.

Question Pair 5 – Module Activity 6 (Long versus Short Range)

Here, students were asked to identify the properties of long and short range connections in a network. Performance on this question increased with only two students getting the incorrect answer on the post-quiz. When asked to explain why they chose the answer they did, the two students who missed the question on the post-quiz gave proper explanations that were inconsistent with the multiple choice answer selected. This may indicate that they did understand what was being asked but were confused by the language used in the multiple choice response options.

Attitudinal Survey Results & Discussion

Attitudinal Survey – Relation to Course Material

Table III contains the responses for the two questions on the attitudinal survey about how the online learning module relates to the course material. In general, participants felt the module was well related to the course material, ranking it positively in both its benefit towards learning and its relation to the course objectives. One student noted that "It is appropriate because it uses interactive learning module instead of just reading from hand out." Another pointed out that "it followed the lecture and provided hands-on learning by doing exercises."

Table III
Attitudinal Survey - Relation to Course Material

Item	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
This tool was of benefit to me when learning the concepts taught in this module	1	0	1	4	4
This tool was appropriate for meeting the learning objectives for this module	0	0	4	4	2

Attitudinal Survey – Effect of Module Errors

Table IV contains the responses for the two questions on the attitudinal survey regarding how students viewed the tool in light of the technical problems. The majority of students felt that they still learned something from the tool even with the problems, and all students thought that it would be beneficial once the bugs were fixed. "Once the bugs are worked out I think this will be the most helpful of the modules we did."

Table IV
Attitudinal Survey - Effect of Module Errors

Item	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Despite the problems with the Protein Networks tool, I still feel as though it was beneficial to my learning the course material.	0	2	1	4	3
If the problems were fixed, I could see where the Protein Networks tool would be a useful learning tool for learning the course material.	0	0	0	6	4

Attitudinal Survey – Comparison to Other Forms of Instruction

Table V contains responses for the three questions on the attitudinal survey asking students to compare the tool to more traditional forms of instruction. As with the relation to course material, the response towards the module was favorable when compared to other forms of instruction. With regards to independent reading, one student noted, "It is better because we are actually doing the work ourselves rather than just being required to learn by reading." In fact, five of the ten students made some comment with regards to the interactivity helping to elevate it above independent reading. One student said in regards to live demonstration or lab experiments that "live demonstrations wouldn't allow me to pick it apart", acknowledging that the module allowed them to do something that a live demonstration simply would not.

Table V
Attitudinal Survey – Comparison to Other Forms of Instruction

Item*	Significantly Worse	Somewhat Worse	About the Same	Somewhat Better	Significantly Better
Independent Reading such as textbooks and journal articles	0	1	1	4	4
Traditional Lectures	0	1	4	5	0
Live Demo or Lab Experiments	0	2	4	3	1

* i.e. "If given the choice between the Protein Networks tool and Traditional Lectures, I would find using the Protein Networks tool to be:"

Attitudinal Survey - Module Usage

Table VI contains responses for the five questions on the attitudinal survey that asked students about their perceptions of using the module. Positive responses were recorded here as well, with all students agreeing that the tool complimented the course material. Two students commented on the repetition of the module and disliked how the module made them repeat an entire activity if only one question is not correct. One student commented, "The module should not have you start over if you miss only 1 question. It would better to only repeat what you missed because it also saves time."

Table VI
Attitudinal Survey – Module Usage

Item	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Complimented the course materials	0	0	0	6	4
Was relatively easy to use	0	2	2	5	1
Was worth the time spent using it	1	0	1	6	2
There was sufficient support provided to effectively use the tool*	0	1	2	5	1
I learned more in class as a result of using the tool outside of class	1	1	1	3	4

*One student did not mark any response

Conclusion & Next Steps

An interactive online quantitative cellular biology learning module for protein networks was developed for an undergraduate engineering course at a Midwest US Research I institution. Analysis of student performance on the pre-post quiz reveals that the module was moderately successfully in helping students learn about the properties of networks and using them to construct representations of protein networks. Though some improvement is still needed, the majority of the issues seem to be a result of the programming errors within the module which have since been fixed. The most outstanding issue to address is that a number of students disliked having to restart the problems from the beginning when they only missed a small part of the problem. While this was intentionally done to force students to check their work before submitting it, that subtlety was clearly lost on them and must therefore be reevaluated. Based on the attitudinal survey, the students tended to agree that using the module was better than other forms of instruction.

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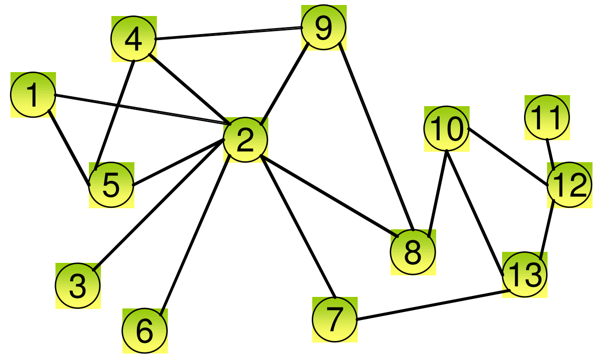
Appendix A – Relevant Pre-Quiz Questions (Correct answers in shown in bold)

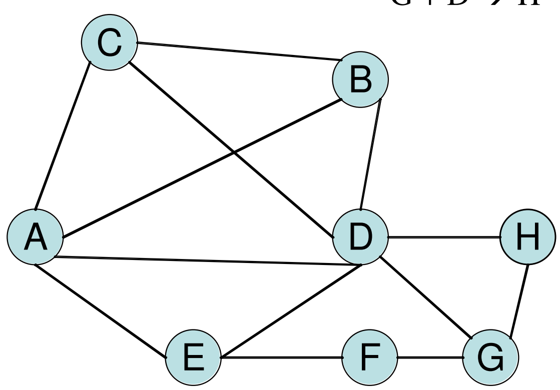
1. For the following network find
   a. The connectivity of node 2 – **8**
   b. The shortest path length between nodes 1 and 12 – **4**
   c. The clustering coefficient for node 2 – **1/7**



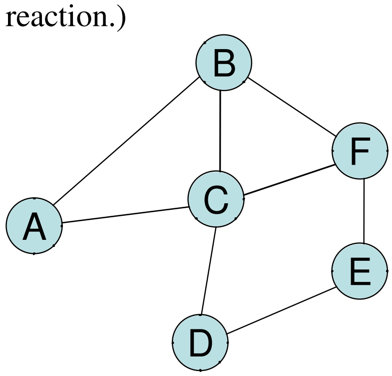
2. The connectivity of a node
   a. is the number of connections that the node makes with other nodes
   b. is the smallest number of connections between that node and another defined node
   c. reflects how connected the neighbors of that node are
   d. depends upon the clustering coefficient
   e. c and d
   f. none of the above

3. For the following set of reactions, draw an undirected substrate network where the nodes are the reactants and products and the connections are the reactions that they participate in.

$A + B \rightarrow C$	catalyzed by enzyme a
$C + B \rightarrow D$	catalyzed by enzyme b
$A + D \rightarrow E$	catalyzed by enzyme c
$E \rightarrow F$	catalyzed by enzyme d
$F \rightarrow G$	catalyzed by enzyme e
$G + D \rightarrow H$	catalyzed by enzyme f

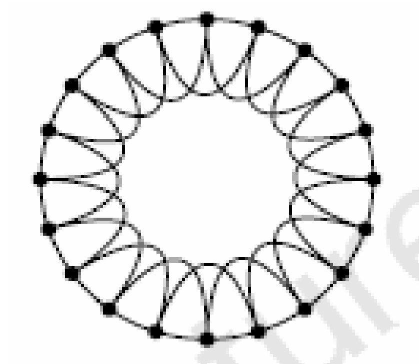


4. For the same reaction set, draw an undirected enzyme network, where each node is an enzyme and the connections represent a sharing of reactants and/or products (for example a reactant of one enzyme reaction may be a reactant or product in the other enzyme reaction.)

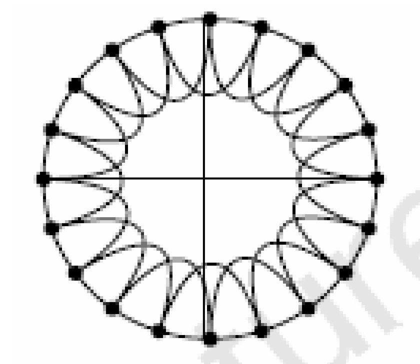


5. For the following two networks which statement is most true?
    a. Network A has long range connections while Network B does not
    b. Network B has short term connections
    c. The average shortest path length for network A is likely to be smaller than that of network B
    d. The average shortest path length for network B is likely to be smaller than that of network A.
    e. Both b and d
    f. Both c and b

A

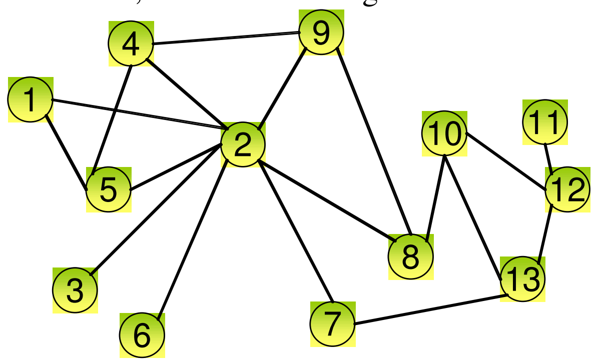


B



Appendix B – Relevant Post-Quiz Questions

1. For the following network find the connectivity for node 9_i the shortest path length between 4 and 11, and the clustering coefficient for node #9_i



Connectivity – 3
Shortest Path – 5
Clustering Coefficient – 2/3

2. The connectivity of a node
   a. is related to how many total nodes are in the network
   b. is the number of connections that the node makes with other nodes
   c. is the smallest number of connections between that node and another defined node
   d. reflects how connected the neighbors of that node are
   e. depends upon the clustering coefficient
   f. b and e

3. For the following set of reactions, draw an undirected substrate network where the nodes are the reactants and products and the connections are the reactions that they participate in.

$$A + E \xrightarrow{alpha} D$$

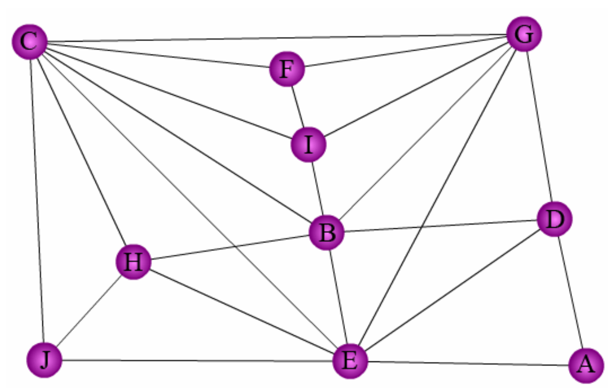
$$D + G \xrightarrow{beta} B + E$$

$$B + C \xrightarrow{gamma} G$$

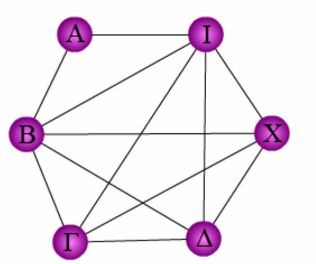
$$G + F \xrightarrow{delta} I + C$$

$$H + I \xrightarrow{chi} B$$

$$C + H \xrightarrow{iota} J + E$$

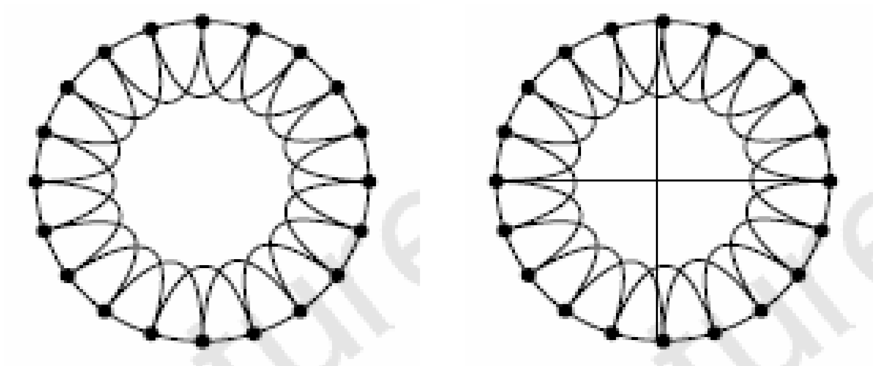


4. For the same reaction set, draw an undirected enzyme network, where each node is an enzyme and the connections represent a sharing of reactants and/or products (i.e. a reactant of one enzyme reaction is a reactant or product in the other enzyme reaction.)



5. For the following two networks which statement is most true?
    a. The average shortest path length for network A is likely to be smaller than that of network B
    b. The average shortest path length for network B is likely to be smaller than that of network A.
    c. Adding long range connections increases the average shortest path length for the networks.
    d. Both a and c
    e. Both c and b

A B



Appendix C – Grading Criteria for Quiz Questions 3 and 4

5 points – Network Drawn Correctly
4 points – Missing 1 Edge
3 points – Missing 2-3 Edges or 1 Extra Edge or Node
2 points – Missing 4 Edges
1 point – Missing more than 4 edges
0 points – Problem not attempted