Modeling and Control of Biomolecular Machines
EML 6934 Sections MCBM, 2FED, 1FE2
Fall 2023, M W F, 7th Period, 1:55 PM – 2:45 PM
CSE E122

Modifications to this syllabus may be required during the semester. Any changes that are made will be reflected in a posted version of the syllabus and announced in class.

Instructor

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WERT 489
Please contact through the Canvas website https://elearning.ufl.edu
Any emails to ufl email address must include EML 6934 in the subject line

Office Hours

- M F, 3:00 PM – 4:00 PM, WERT 489
- Or via confirmed written appointment

Course Description

Course Catalog: "Overview of biomolecular systems engineering. Introduction to cell processes, biochemical kinetics, models of biological macromolecules, analyses of biomolecular dynamics, simulation of stochastic behaviors, common gene regulatory network motifs, and the design of synthetic biology circuits." (Credits: 3)

Course Pre-Requisites

Undergraduate course in ordinary differential equations (e.g., MAP 2302) with a minimum grade of C, or instructor permission.

Course Objectives

By the end of EGM4585 and EML 6934, you should be able to do the following:

- Use kinetic and thermodynamic concepts to describe biomolecular machine behaviors;
- Construct phenomenological and mechanistic models of these behaviors and machine interactions; and
- Understand analysis and design tools from dynamical systems theory and control to predict the dynamics of biomolecular and cellular networks.

By the end of EML 6934, you should **also** be able to do the following:

- Recognize the state-of-the-art in biomolecular control systems, and identify the next research steps that will advance the field; and
- Deploy models, analysis, and design tools from dynamical systems theory and control to alter the predicted dynamics of biomolecular and cellular networks, in simulation.

These objectives will be achieved through lectures and homework and reading assignments. The additional graduate course learning objectives will be achieved through a semester-long project.

Materials and Supply Fees

None.

Required Textbooks, Software, and Hardware

- Lecture notes and reading materials will be provided by the instructor.
- MATLAB (MathWorks), any recent release.
- Scientific calculator (not your phone).

Reference Textbooks (Alphabetical)

- Uri Alon, *An Introduction to Systems Biology: Design Principles of Biological Circuits*, 2nd Ed., 2020
- Geoff Baldwin et al., *Synthetic Biology - A Primer (Revised Edition)*, 2016
- Carlo Cosentino and Declan Bates, *An Introduction to Feedback Control in Systems Biology*, 2012
- Domitilla Del Vecchio and Richard M. Murray, *Biomolecular Feedback Systems*, 2015
- Leah Edelstein-Keshet, *Mathematical Models in Biology*, 2005
- Terrell Hill, *Free Energy Transduction and Biochemical Cycle Kinetics*, 2004
- Pablo Iglesias and Brian Ingalls, *Control Theory and Systems Biology*, 2010
- Brian Ingalls, *Mathematical Modelling in Systems Biology: An Introduction*, 2013
- Eric Klavins, *BioCircuits: A Systems Approach to Synthetic Biology,* 2019
- John Kuriyan et al., *The Molecules of Life: Physical and Chemical Principles*, 2013
- J. D. Murray, *Mathematical Biology*, Vols. I and II, 3rd Ed., 2007
- Rob Phillips et al., *Physical Biology of the Cell*, 2nd Ed., 2013
- Steven Strogatz, *Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry, and Engineering*, 2nd Ed., 2015

Important Dates

- Classes Begin: Aug 23 (Wednesday)
- Holidays/Reading Days: Sep 4 (Monday), Oct 6 (Friday), Nov 10 (Friday), Nov 22 – 24 (Wednesday – Friday), Dec 7, 8 (Thursday, Friday)
- Classes End: Dec 6 (Wednesday)
- Classes Canceled: Sep 11, 13, 15 (Monday, Wednesday, Friday)
- Homework dates stated in this syllabus will be confirmed in class
- Final Exam Project Presentations: Dec 14 (Thursday) 10:00 AM – 12:00 PM

Requirements for class attendance and make-up exams, assignments, and other work in this course are consistent with university policies. Click here to read the university attendance policies: https://gradcatalog.ufl.edu/graduate/regulations/

Attendance Policy

- Students are expected to attend all lectures and final project presentations.
- Absences may be excused with appropriate documentation.
- **Make-up Policy:** Instructor notifications are required in all circumstances. See https://care.dso.ufl.edu/instructor-notifications. Note that, "Instructors have the right to accept or reject the Instructor Notification."

Class Expectations

- The student is solely responsible for their education. The instructor is the guide to their understanding of the field.
- Cell phones, laptops, etc.: **under no circumstances will disruptions from electronic devices be tolerated. Students are expected to take either handwritten notes with pen/pencil and paper, or electronic notes with stylus and tablet.**
- Respect and disruption: the instructor and students will be always respectful. Classroom disruption of any kind will not be tolerated.
- **The principles of the Honor Code must be always adhered to.** Individual effort is required on homework assignments, quizzes, and exams. Groups will be treated as individuals for projects. UF students are bound by the Honor Pledge which states, "We, the members of the University of Florida community, pledge to hold ourselves and our peers to the highest standards of honor and integrity by abiding by the Honor Code." On all work submitted for credit, the following statement is either required or implied:

On my honor, I have neither given nor received unauthorized aid in doing this homework/quiz/report/exam.

The Conduct Code (https://sccr.dso.ufl.edu/process/student-conduct-code/) specifies behaviors that are in violation of this code and the possible sanctions. You are obligated to report any academic misconduct to appropriate personnel. If you have any questions or concerns, please consult with the instructor or TA.

Course Zero-Tolerance Policy: *Any* violation or suspected violation of the Honor Code by a student may result in that student receiving a grade of E for the course.

Homework

The purpose of homework is to learn and understand the material. **Students are responsible for performing and understanding the homework problems and solutions on their own.**

Software and Copyrighted Material Use

All faculty, staff, and students of the University are required and expected to obey the laws and legal agreements governing the use of software and the use of copyrighted material. Failure to do so can lead to monetary damages and/or criminal penalties for the individual violator. Because such violations are also against University policies and rules, disciplinary action will be taken as appropriate. We, the members of the UF community, pledge to uphold ourselves and our peers to the highest standards of honesty and integrity.

Exams

Honorlock: Consistent with UF policy, Honorlock may be used for course assessments and will be confirmed by the instructor in advance. Please see https://distance.ufl.edu/proctoring/ for more information.

Students Requiring Accommodations

Students with disabilities who experience learning barriers and would like to request academic accommodations should connect with the Disability Resource Center (https://disability.ufl.edu/students/get-started/). Students should share their accommodation letter with their instructor and discuss their access needs as early as possible in the semester.

Commitment to a Safe and Inclusive Learning Environment

The Herbert Wertheim College of Engineering values varied perspectives and lived experiences within our community and is committed to supporting the University's core values, including the elimination of discrimination. It is expected that every person in this class will treat one another with dignity and respect regardless of race, creed, color, religion, age, disability, sex, sexual orientation, gender identity and expression, marital status, national origin, political opinions or affiliations, genetic information, and veteran status.

If you feel like your performance in class is being impacted by discrimination or harassment of any kind, please contact your instructor or any of the following:

- Your academic advisor or Graduate Program Coordinator
- HWCOE Human Resources, 352-392-0904, student-support-hr@eng.ufl.edu
- Curtis Taylor, Associate Dean of Student Affairs, 352-392-2177, taylor@eng.ufl.edu
- Toshikazu Nishida, Associate Dean of Academic Affairs, 352-392-0943, nishida@eng.ufl.edu

Student Privacy

There are federal laws protecting your privacy with regards to grades earned in courses and on individual assignments. For more information, please see: https://registrar.ufl.edu/ferpa.html

Instructor-Initiated Course Recording

Lectures and office hours may be audio visually recorded by the instructor or TA for students who are unable to attend live, and for student reference. Online students who participate with their camera engaged or who utilize a profile image are agreeing to have their video or image recorded. If you are unwilling to have your video or profile image recorded, ensure that your camera is off and that you do not use a profile image.

Likewise, online students who un-mute themselves to orally participate during class are agreeing to have their voices recorded. If you are unwilling to have your voice recorded, ensure that your mute button is activated and that you communicate exclusively using the "chat" feature, which allows students to type questions and comments live. The chat will not be recorded or shared. Similar to the above, in-class students who orally participate are also agreeing to have their voices recorded.

In-Class Recording

Students are allowed to record video or audio of class lectures. However, the purposes for which these recordings may be used are strictly controlled. The only allowable purposes are (1) for personal educational use, (2) in connection with a complaint to the university, or (3) as evidence in, or in preparation for, a criminal or civil proceeding. All other purposes are prohibited. Specifically, students may not publish recorded lectures without the written consent of the instructor.

A "class lecture" is an educational presentation intended to inform or teach enrolled students about a particular subject, including any instructor-led discussions that form part of the presentation, and delivered by any instructor hired or appointed by the University, or by a guest instructor, as part of a University of Florida course. A class lecture does not include lab sessions, student presentations, clinical presentations such as patient history, academic exercises involving solely student participation, assessments (quizzes, tests, exams), field trips, private conversations between students in the class or between a student and the faculty or lecturer during a class session.

Publication without permission of the instructor is prohibited. To "publish" means to share, transmit, circulate, distribute, or provide access to a recording, regardless of format or medium, to another person (or persons), including but not limited to another student within the same class section. Additionally, a recording, or transcript of a recording, is considered published if it is posted on or uploaded to, in whole or in part, any media platform, including but not limited to social media, book, magazine, newspaper, leaflet, or third-party note/tutoring services. A student who publishes a recording without written consent may be subject to a civil cause of action instituted by a person injured by the publication and/or discipline under UF Regulation 4.040 Student Honor Code and Student Conduct Code.

Health and Wellness

U Matter, We Care

Your well-being is important to UF. The U Matter, We Care initiative is committed to creating a culture of care on our campus by encouraging members of our community to look out for one another and to reach out for help if a member of our community is in need. If you or a friend is in distress, please contact umatter@ufl.edu so that the U Matter, We Care Team can reach out to the student in distress. A nighttime and weekend crisis counselor is available by phone at 352-392-1575. The U Matter, We Care Team can help connect students to the many other helping resources available including, but not limited to, Victim Advocates, Housing Staff, and the Counseling and Wellness Center. Please remember that asking for help is a sign of strength. In case of emergency, call 9-1-1.

COVID-19, Cold, Flu, and Other Contagious Respiratory Illnesses

- You are expected to follow guidance from the Centers for Disease Control and Prevention (CDC) regarding the wearing of approved face coverings during class and within buildings even if you are vaccinated.

- If you are sick, stay home and self-quarantine. Please call your primary care provider if you are ill and need immediate care or the UF Student Health Care Center at 352-392-1161 to be evaluated for testing and to receive further instructions.
- Please continue to follow healthy habits, including best practices like frequent hand washing. Following these practices is our responsibility as Gators.

Counseling and Wellness Center

https://counseling.ufl.edu/, and 352-392-1575; and the University Police Department: 352-392-1111 or 9-1-1 for emergencies.

Sexual Discrimination, Harassment, Assault, or Violence

If you or a friend has been subjected to sexual discrimination, sexual harassment, sexual assault, or violence contact the Office of Title IX Compliance (https://titleix.ufl.edu/), located at Yon Hall Room 427, 1908 Stadium Road, 352-273-1094, title-ix@ufl.edu

Sexual Assault Recovery Services (SARS)

Student Health Care Center, 352-392-1161.

University Police Department

352-392-1111 (or 9-1-1 for emergencies), or http://www.police.ufl.edu/.

Academic Resources

E-learning Technical Support

352-392-4357 (select option 2) or e-mail to Learning-support@ufl.edu. https://lss.at.ufl.edu/help.shtml

Career Connections Center

Reitz Union, 352-392-1601. Career assistance and counseling. https://career.ufl.edu/

Library Support

http://cms.uflib.ufl.edu/ask. Various ways to receive assistance with respect to using the libraries or finding resources.

Teaching Center

Broward Hall, 352-392-2010 or 352-392-6420. General study skills and tutoring. https://teachingcenter.ufl.edu/

Writing Studio

302 Tigert Hall, 352-846-1138. Help brainstorming, formatting, and writing papers. https://writing.ufl.edu/writing-studio/.

Students Complaints: On-Campus

https://ombuds.ufl.edu/student/

Students Complaints: Distance Learning

https://distance.ufl.edu/state-authorization-status/#student-complaint

Course Evaluation

Students are expected to provide professional and respectful feedback on the quality of instruction in this course by completing course evaluations online via GatorEvals. Guidance on how to give feedback in a professional and respectful manner is available at https://gatorevals.aa.ufl.edu/students/. Students will be notified when the evaluation period opens, and can complete evaluations through the email they receive from GatorEvals, in their Canvas course menu under GatorEvals, or via https://ufl.bluera.com/ufl/. Summaries of course evaluation results are available to students at https://gatorevals.aa.ufl.edu/public-results/.

Evaluation of Grades and Grading Policy

Information on the UF grading policy is available at
https://gradcatalog.ufl.edu/graduate/regulations/

Evaluation Mechanism on a Percent Basis

Homeworks (6, total of 35 problems, graded on completion)	70%
Final Project, Attendance of Final Project Presentations	30%

Homework

Students will submit solutions of the homework problems only via the course website. Students who turn in homework before the due date and time will have their homework graded. Not all homework problems will be graded; instead, a selection of problems will be randomly chosen for grading after the homework due date and time. **Grading will be on completeness, not correctness.** Submitted homework that is partially- or fully-missing solutions to chosen problems will not be eligible for full credit for those problems, even if other non-chosen homework problems were completed.

Chosen problems will be scored with a "2" if a complete solution exists for all parts of a problem, even though the solution may be incorrect. A chosen problem's score will be "1" if any part of that problem has a solution that is incomplete. A chosen problem's score will be "0" if no problem parts have a solution. It is the student's responsibility to check their solutions against posted homework solutions.

Exams

All students are expected to undertake the final project and present in the final exam slot. If a student is unable to take this exam for unforeseeable reasons, then the other assignments will count toward the percentage of the grade that makes up the exam if an appropriate DSO instructor notification is accepted.

Final Grade

Final grades may be calculated by the following table. For example, if a student earns 86.60% (Percent Grade Earned %GE = 86.60) then their grade point will be 3.33 (B+). %GE are rounded to the hundredths decimal place. For example, if a student earns 77.995% (Percent Grade Earned %GE = 77.995) it will be rounded up to 78.00%, and their grade point will be 2.67 (B-). Shifts in the grading table are at the discretion of the instructor.

Table 1. Grading Table. *%GE = Percent Grade Earned.*

Percentage Range	Grade Point
$92.00 \leq$ %GE $< 100.00 \Longrightarrow$ A	4.00
$88.00 \leq$ %GE $< 92.00 \Longrightarrow$ A-	3.67
$85.00 \leq$ %GE $< 88.00 \Longrightarrow$ B+	3.33
$81.00 \leq$ %GE $< 85.00 \Longrightarrow$ B	3.00
$78.00 \leq$ %GE $< 81.00 \Longrightarrow$ B-	2.67
$74.00 \leq$ %GE $< 78.00 \Longrightarrow$ C+	2.33
$71.00 \leq$ %GE $< 74.00 \Longrightarrow$ C	2.00
$67.00 \leq$ %GE $< 71.00 \Longrightarrow$ C-	1.67
$64.00 \leq$ %GE $< 67.00 \Longrightarrow$ D+	1.33
$61.00 \leq$ %GE $< 64.00 \Longrightarrow$ D	1.00
$60.00 \leq$ %GE $< 61.00 \Longrightarrow$ D-	0.67
$00.00 \leq$ %GE $< 60.00 \Longrightarrow$ E	0.00

Grade Corrections

Grade corrections should be submitted promptly in writing within three business days of the grade posting. Include a concise statement of why you believe that there has been an error. The instructor has the final determination in the assigned grade; if a grade change is made, the grade may be lower or higher.

Final Project

There are two components to the final project:

1. A written report on a topic that you choose (sample topics are in the list below). This report should be at least half an IEEE-style double-column conference paper (i.e., 3-4 pages in their style, including figures and references); and
2. A presentation with slides highlighting the findings of your report. Your presentation will take place in a 15-minute timeslot where 12 minutes is for the talk, and 2-3 minutes is for questions and presenter change-over. The goal of the presentation is to educate the class on the topic that you have now become expert in.

Report and presentations are due at the start of our final exam slot, December 14 (Thursday), 10:00 AM. Project topics need to be substantive enough to justify a half-conference paper write-up. There are two options:

Option 1

A literature review on a topic from the list below or some other topic that relates to the modeling and control of biomolecular machines. You must have at least three primary-literature source papers on this topic. Instructor permission for the project topic is required, to ensure topic uniqueness among students. You will need supporting literature on top of your three main papers to write your report and produce explanatory figures. Figures can be produced in MATLAB and confirm published modeling results in new ways, and/or provide sensitivity analyses.

Option 2

Any novel research advance from your ongoing graduate studies, or a design problem that you would like to tackle (sample problems in the list below) that relates to the modeling and control of biomolecular machines, and uses or builds upon class-presented material. Instructor permission for the project topic is required, to ensure topic uniqueness among students. In this option, the project introduction and relevant literature will be on page 1+, theoretical background and advances will be on page 2, results/discussion/conclusions will be on page 3+, and references will be on page 4.

Potential Final Project Topics

- CRISPR-Cas dynamical/biophysical models.
- Resource burden of synthetic biological circuits.
- Detailed models of transcription and/or translation.
- Effects of cell-free experimental systems on dynamical/biophysical biomolecular models.
- Dynamic metabolic engineering.
- Methods to analyze metabolic dynamics (e.g., flux balance analysis, modal analysis).
- Whole-cell models of a cell you choose.
- Evolutionary trade-offs, Pareto optimality, biomolecular multi-objective optimization.
- Fitness landscapes, organism evolution and adaptation in environments, epigenetic inheritance, developmental plasticity, etc., using statistical physics, information theory, and machine learning.
- Design of a biological system that can memorize the order of N inputs.
- Design of a biological system that can self-organize into a two-layer onion structure.
- Design of a bacterial stem cell that "buds" off a daughter in a different physiological state, both terminally, and another that relaxes ultimately back to the same state as the mother cell.
- Development of a parts family for synthetic biology. Argue in favor of your family – is it: Scalable? Designable? Connectable? Composable? Predictable? Functionally homogeneous? Turing complete?
- Creation of the most compact, biologically plausible circuit that can take three environmental inputs and based on their "ON and OFF" values turn on each of eight different response systems. Create the system that is easiest to construct out of known parts that have already been used in synthetic biological circuits or parts that function similarly to these. Compare their operational properties such as speed, signal rectification, susceptibility to intrinsic noise and fluctuations on the input.

- Design of a biological system in which different cell types search for partner cells and upon encountering the right one irreversibly adheres to it. Make this system "addressable" in that one can "program" a large number of different cell types derived from the same common chassis. Can we do cellular "origami" with this?
- Design of a biological system with a form of simple associative learning.
- Design of a bacterium that can circulate safely in blood, recognize arterial plaque, and degrade it. Ensure that it can survive long enough to have an effect but that it can be cleared from the system on demand.
- Design of a tumor-targeting/tumor-killing bacterium when the presence of a tumor is sensed.
- Design of a biological system to optimize nitrogen fixation for a plant.
- Design of a biological system to sense or record or manipulate a human gut microbiome.
- Analysis of various oscillator designs (single cell and/or population synchronized).
- Spatiotemporal modeling of bacterial quorum sensing, including hysteresis.
- Detailed models of bacterial chemotaxis.
- Modeling segmentation in *Drosophila* embryogenesis.
- Design and spatiotemporal simulation of wave-propagation using BZ reaction-diffusion system (also, investigate propagation only in a particular direction).
- Modeling synthetic emergent pattern formation systems (e.g. stripes and spirals with a Turing system).
- Analysis of Conway's Game of Life: emergence of global patterns from local rules of interaction based on neighborhood density and cell life/death.
- Modeling 3D tissue structuring with a sheet of epithelial cells.
- Analysis of noise propagation for network topologies and transcription factor interactions with DNA / RNAp.
- Modeling DNA computing approach based on gel electrophoresis.
- Modeling DNA self-assembly and tiling that form large scale patterns.
- Design and simulate a system to treat Type I Diabetes: control stem cell to pancreatic beta cell differentiation.
- Design of gene circuit motifs that involve master regulator genes of stem cell differentiation.
- Simulation of a phosphorylation-only toggle switch.
- Design and simulation of an emergent pattern forming system that uses three signals.
- Design and spatiotemporal simulation of a predator-prey ecosystem.
- Design and simulation of a cell division counter.
- Simulation of programmed cell motility (synthesis of chemical attractants and repellants by "leaders" and movement based on these chemicals by "followers") – can be used as a component for modeling injury repair.
- Design of a synthetic biological system that is robust to mutations (as long as they are below a certain threshold) or that kills itself upon mutation occurrence.
- A multiscale Computer Aided Design (CAD) tool "bio-compiler" that translates a program written in a high-level language to a low-level genetic circuit implementing that program.
- Design of a genetic "bandpass filter" – assuming an oscillating input signal, only propagate certain frequencies to output of the genetic circuit.
- Design and spatiotemporal simulation of a multicellular branching system.
- Simulation and analysis of RNAi circuits for cancer therapy.
- Hydrophobic effect strength at high temperatures.
- Myosin walking on actin via a hand-over-hand mechanism.
- How proteins find their recognition sites on DNA: 1D diffusion vs. intrinsic 3D diffusion rate limits.
- Turing's reaction/diffusion mechanism applied to animal morphogenesis.
- Kinetic proofreading to explain how a T-cell discriminates self peptides from non-self peptides.
- Out-of-equilibrium 'proofreading' effects to prevent cross-talk in eukaryotic gene regulation.
- Do effective molarities achieved by enzyme scaffolds approach 10^8 M?
- Is it possible to carry out computation with zero energy input?

- Are the tightest binding affinities that are achievable by a protein for a nucleotide 10^{-23} M?
- Can enzymes achieve k_{cat}/k_m beyond the diffusion-limit of 10^7 $M^{-1}s^{-1}$?
- Is it true that the rate-limiting step is not generally well-defined for an enzyme's free energy diagram?

Course Schedule

The course content is approximately:

Lectures 01-13	Deterministic modeling of biomolecular machines (13 lectures)
Lectures 14-19	Stochastic modeling of biomolecular machines (6 lectures)
Lectures 20-32	Dynamical systems theory to control biomolecular machines (13 lectures)
Lectures 33-38	Controlling biomolecular machines (6 lectures)

Course Schedule, Approximately by Lecture Number

1	Aug 23	Systems Biology and Synthetic Biology
2	Aug 25	Biomolecular Systems Modeling
3	Aug 28	Cell Processes
4	Aug 30	Passive and Active Transport, Biological Macromolecules
5	Sep 1	Biological Macromolecules, Bond Potential
6	Sep 6	Angle Potential, Torsion Potential, Intermolecular Forces
Approximate End of Coverage for Homework 1		
7	Sep 8	Cell Process Dynamical Models, Intro to Chemical Reaction Networks (CRNs)
8	Sep 18	CRNs: Conversion, Binding, Binding Isotherm, (Non-)Exponential Decay
Homework 1 Due Sep 18 (Monday), 11:59 PM		
9	Sep 20	CRNs: Stoichiometry, Cooperative Binding and Allostery
10	Sep 22	CRNs: Competitive Binding, Michaelis-Menten
11	Sep 25	CRNs: Quasi-steady-state, Briggs-Haldane, Transcription Regulation
12	Sep 27	CRNs: Translation Regulation, Linear Transforms
13	Sep 29	CRNs: Programming, Population-Level (Monod Kinetics)
Approximate End of Coverage for Homework 2		
14	Oct 2	Statistical Physics, Ligand-Receptor Binding, Microstates, Macrostates
Homework 2 Due Oct 2 (Monday), 11:59 PM		
15	Oct 4	Partition Function, Boltzmann Distribution
16	Oct 9	Thermodynamic Entropy, Gibbs Entropy, Free Energy
17	Oct 11	Boltzmann Distribution with Free Energy, Energy Landscape, Microscopic Rates
18	Oct 13	Chemical Master Equation, Chemical Langevin Equation
19	Oct 16	Monte Carlo Methods, Gillespie Algorithm
Approximate End of Coverage for Homework 3		
20	Oct 18	Metabolism Thermodynamics, Flux Balance Analysis, Metabolic Control Analysis
21	Oct 20	Linear Programming, Whole Cell Models, Glycolysis
Homework 3 Due Oct 20 (Friday), 11:59 PM		
22	Oct 23	Nonlinear Systems (e.g., Lotka-Volterra), Linearization, Stability
23	Oct 25	Phase Portraits, Genetic Toggle Switch
24	Oct 27	Limit Sets, Limit Cycles, Dulac's Criterion, Poincaré-Bendixson Theorem
25	Oct 30	Cyclic Feedback Systems, Repressilator Trajectory Analyses
Approximate End of Coverage for Homework 4		
26	Nov 1	Glycolytic Oscillations
27	Nov 3	Bifurcations
Homework 4 Due Nov 3 (Friday), 11:59 PM		
28	Nov 6	Hopf Bifurcation, Glycolytic Oscillations Revisited, Positive Systems Theory
29	Nov 8	Genetic Circuit Design, Negative Autoregulation
30	Nov 13	Sequestration, Ultrasensitivity, Gate-Matching Principle
31	Nov 15	Digital vs. Analog Genetic Circuits, Positive Autoregulation
Approximate End of Coverage for Homework 5		

32	Nov 17	Ribosome Binding Calculator, Genome Binding/Editing, CRISPR Circuits
33	Nov 20	Noise in Gene Regulatory Networks: Benefits and Mitigation

Homework 5 Due Nov 20 (Monday), 11:59 PM

34	Nov 27	Harnessing Quorum Sensing, Cell Signaling, Turing Patterns
35	Nov 29	Integral Control and Disturbance Rejection, Chemotaxis, Network Motifs
36	Dec 1	Proportional-Integral-Derivative (PID) Control Genetic Circuits
37	Dec 4	Cell Population Control: Gut Microbiome Enhancement, Epidemic Mitigation
38	Dec 6	Cell Population Control Systems: Use of Optogenetics, Model Predictive Control

Approximate End of Coverage for Homework 6
Homework 6 Due Dec 11 (Monday), 11:59 PM

Final Project Presentations on Dec 14 (Thursday), 10:00 AM