EvoSysBio: Modeling in Evolutionary Systems Biology

Genetics 677-11   410B Wendt Commons   Fall 2017
Genetics 546   (upcoming course number)

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Office Hours
Tue 5:15pm-6:00pm
(or by appointment)

Course Times
Lecture: Tue 4:00pm-5:15pm
Lab: Thr 4:00pm-6:00pm

Class Numbers
Genetics 61566
Medical Genetics 61707

Course website: https://evosysbio-course.discovery.wisc.edu/
Mailing List: genetics677-11-f17@lists.wisc.edu (only for EvoSysBio Students)

Goal: To help you to build your own model of a small part of biology, incorporating aspects of the EvoSysBio perspective and using Evolvix, a programming language designed to make it easy to describe biological systems in mathematically accurate terms.

Overview and Purpose

Models are the maps of modern biology. Here you will learn to read and create them.
This course is about the bigger picture. We will build models to make connections that traverse the scale of organic life. Your interest and creativity will define the modeling possibilities, which may range from *molecules in cells* to *individuals in ecosystems* to *long-term evolution* itself.

You name it. You model it. You map it.

Evolutionary systems biology operates at the cutting edge of computational modeling, and building your own map of a small part of biology will develop your science skills like little else. By the course's conclusion, you will harness substantial analytical power, broadly transferable across scientific disciplines.

Course Description

This 3 credit course with a 2-hour *in silico* lab component helps you to connect to the bigger picture by helping you to build good models in systems biology and evolution. You will learn how to use Evolvix, a model description language with associated simulation tools that make it easy to implement certain types of biological models into computable simulations. This frees you from the complexities of low-level coding tasks and allows you to focus on the bigger question of what you want to have in your model and how it's biology is supposed to work. You will work on a group project where you will get real-life experiences in modeling a biological system in the computer. You can select the system you model or use one given to you. This interdisciplinary course is half lab, half lecture and will help you learn to work with students from different disciplines. There are no formal prerequisites other than the interest to contribute directly or indirectly to modeling in some field of biology. Ideal for advanced undergraduates who have found their field or graduate students who aim to write an NSF graduate research fellowship proposal in their first year.
Topics: Overviews of molecular systems biology, evolution, modeling in both, approaches to EvoSysBio, connecting models to real data and more (see time-table at end and course website at: http://evosysbio-course.discovery.wisc.edu). For a 10 slide introduction to EvoSysBio, please see: https://figshare.com/articles/EvoSysBio_in_10_Slides/1427128

Learning Outcomes

- Hone your problem-solving skills in an active problem-based learning environment
- Form your own interdisciplinary student group and research topic
- Model a system of your choice, exploring its predictive power and limits
- Learn to use *Evolvix* to describe biological models with mathematical accuracy
- Learn how to ask for and receive individual help from an expert in biological modeling
- Learn how to explain your findings to your peers in weekly writings
- Improve writing skills for research grant proposals and peer reviews
- Develop a habit of learning for life instead of learning for an exam
- Collaborate across diverse levels of experience and background
- **Graduate students** will contribute to and build on more detailed modeling questions.

Take this course if you like …

- to learn in a problem-based way on real problems (no answer known)
- to connect to new disciplines and learn how they see the world and talk about it
- to get a taste of real-world research without having to redirect your career
- to think about the deep, inner meaning of things in order to make connections and achieve understandings that few others see
- to hone your writing abilities to become more skilled as a writer
  (as some say, it takes 10,000 hours of practice to become really good at something, so you might as well get started in a course that emphasizes scientific writing)
- to learn a tool that helps you learn how to model Continuous Time Markov Chains (CTMCs)
- to take your first steps into a new field in relative privacy (taking this course is much a safer way to dive into the vast ocean of scientific reality than starting a PhD program, only to decide that it wasn't a good idea after all)

Do not take this course if you …

- prefer memorizing facts
- are uncomfortable with "the unknown" (and prefer to keep it that way)
- expect the instructor to always know the answer
- dislike peer reviewing and getting peer reviewed

Relationship to other courses at UW-Madison

This course does not duplicate content of any other course. It offers a starting point for exploring the fascinating world of modeling in biology at a pace that is manageable for typical 'non-computing' biology students. Adopting a 'systems' perspective from engineering, students will learn how to draw reasonable boundaries around their modeling systems and how to explore how various parts interact with each other. Students in mathematics, statistics, computer science, or engineering can learn use this course to (i) learn about and model some aspects of biology, (ii) how to collaborate with biologists, and/or (iii) identify challenging problems from their respective disciplines, which the instructor has been collecting. These problems can range from 'good challenging homework' to 'beyond the current horizon of research in the field'. Students who know what they are doing are welcome to explore these as part of their research in the course, but should not expect worked out solutions for every problem that presents itself. This course engages with problem-based learning and we use real or realistic research problems, just as in real life, where problems also do not carry a label about their difficulty and come with a guarantee that they can be solved in a reasonable way. Typical hard problems include concurrency, combinatorics, probability, modeling formalisms, syntax design, semantics, naming, network theory, multi-dimensional spaces, optimization, simulation, calculus, logic, and many more.

Prerequisites and Required Materials

Prerequisites

An interest in interdisciplinary approaches to modeling in biology.

This is the central prerequisite for the course! Otherwise, enrollment is open. All undergraduate and graduate students are welcome from any field related to Biology, Medicine, Chemistry, Physics, Philosophy, Math, Stats, Computer Science, or Engineering.

Perhaps you are wondering why there are no prerequisites beyond being interested. How can one class accommodate such a wide range of students? Well….

- EvoSysBio builds on knowledge from diverse disciplines, but everything required from them will be covered in the course. EvoSysBio (and many other fields) depends on your willingness to interact with and learn from researchers in other disciplines. You do not need to master all disciplines to benefit from them or this course!
- Quantitative modeling is integral to EvoSysBio. In the course we will explore a very powerful standard modeling approach (known as Continuous Time Markov Chains, or 'CTMCs'), which is not only essential to EvoSysBio but also highly relevant to many disciplines. Centrally, students learn in this course how to turn the intuitive verbal models that often result from experimental work into computable models to predict time series which can be relevant in disciplines from biochemistry to ecology.
- The Evolvix[1] modeling language used in the course provides an *easy*, user-friendly entry point for such modeling. Students can use Evolvix without needing to understand the details of its inner working, just as we can drive a car responsibly without knowing how to build one. This course will teach students how to 'drive' a CTMC model implemented in Evolvix to help them understand some aspects of a biological system[2].
- Finally, previously acquired disciplinary expertise is relevant to the precise modeling questions chosen for the group project and the ReLog entries, both of which are integral to this course. In short, your diverse disciplinary backgrounds will make our questions, writing, and discussions more interesting and analytically rigorous!

The topics and skills learned in this course are highly relevant for understanding how many models are built in biology. The basics are not difficult to learn and are immensely valuable for exploring what it may mean to propose that a certain interaction exists.

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[1] Evolvix is a model description language that is being developed in the Evolutionary Systems Biology Group at the Laboratory of Genetics and the Wisconsin Institute for Discovery, UW-Madison. It is being designed by the course instructor for providing a reliable, research-quality platform that makes it easy to describe biological models in mathematically accurate terms. Evolvix drives a number of innovative modeling applications that are currently under development in the Loewe Lab.

[2] This course does not focus on the math, statistics, and computer science required for simulation. Students with the quantitative and formal expertise are welcome to employ their skills by extending Evolvix in a way that better meets the needs of their group project. Non-bio students are expected to learn some basic biology, just as bio students are expected to learn some basics about formal models – everyone is expected to contribute expertise to our interdisciplinary dialogue.

Required Materials

- You will need a notebook computer in class each Thursday
- You will need a computer with an operating system capable of running Evolvix models:
  - Windows 7 – 10
  - Mac OSX 10.9 – 10.11
  - Linux (RedHat, Fedora, Ubuntu)
  - See http://evolvix.org for downloads and further details; if in doubt, ask instructor.
- You must be able to:
  - Run Evolvix models on your own (at home or in the library)
  - Exchange modeling data within your research group (emails or USB stick); this will be essential during Thursday labs and to take group progress home for your own modeling work
  - Post to the group website (you will receive login information soon)

If you anticipate difficulty meeting these material requirements, you can work with another student and bring your data on a USB stick (or use some other work around).
Please ask the instructor about your arrangement to ensure that it will work, as details may vary.
You might also consider borrowing a computer from a campus library.

Course Website

We will rely heavily on the course website

> https://evosysbio-course.discovery.wisc.edu

and thus some elements require explanation before you get full access.

Login: You can only access the full website by logging in. The instructor will provide you with two user names at the beginning of the semester: (1) the "KnownName" acknowledges your identity and you will use it to post ReLog entries; (2) the "ReviewerName" is anonymous and you will use it to peer review your colleagues' written work. After establishing your user names, you will need to create two, distinct passwords. Since this site houses sensitive content, maintaining web security is essential. **Please ensure that you use https, rather than http, in the web address, and be sure that your passwords are at least 12 characters long and include at least one number and one symbol.** It is often helpful to use "passphrases" instead of passwords. For guidance on effective password creation refer to:

> https://evosysbio-course.discovery.wisc.edu/how-to/choose-good-passwords

Course Tab: This page is the gateway to a series of explanations and descriptions that are more details than was possible in this syllabus. Some relevant resources include: the instructor's teaching philosophy, the course's learning goals, information on grading, expectations, and deadlines, and instructions for how to complete various course assignments. **Be sure to read and sign the Entry Agreement, which is a condition of enrollment.**

Timetable Tab: This page displays the course's progression, including deadlines.

How-To Tab: Refer to this page for assistance with the website, course assignments, and Evolvix.

Projects Tab: This is where you will develop your project proposal.

ReLogs and Feedback Tabs: These two pages are where you will develop your ReLogs and provide your peer reviews. Be sure to become acquainted with them early – much of your graded work will be developed on this page.

Readings

Students will read a number of articles relevant to their project. **Graduate students are expected to complete a larger and/or more complex reading load than undergraduates**, reflecting their greater expertise. The instructor will usually find out quickly, if you are actually engaging with other disciplines in your research and actually broaden your horizon (goal of the course, no matter what you already know) or if you are simply rehashing what you already know.

The quality of your work and the broadening of your trans-disciplinary horizon (and therefore your grade) will hinge on an earnest engagement with scientific literature from disciplines that go beyond your horizon. If you plan to avoid difficulties posed by the unknown, well…is this course for you?

There is no required book, though reading systems biology textbooks will help you navigate this course with greater ease. To explore a useful mix of topics in systems biology you may consider:

> *Klipp, E., et al. (2009)* **Systems Biology: A Textbook.** *Wiley-Blackwell-VCH.*

For a high-level overview, core definitions, and various links between disciplines that are important for EvoSysBio, this open access paper will help you to get the big picture:

> Loewe L (2016) "**Systems in Evolutionary Systems Biology**", pp. 297-318, vol. 4, in *Encyclopedia of Evolutionary Biology*, eds.: Richard M. Kliman (Chief Ed.) & Hiroshi Akashi (Section Ed. for *Molecular and Genome Evolution*), Oxford, UK, Academic Press.
> URL: http://evolutionarysystemsbiology.org/ref/Loewe-2016F-frame-EvoSysBio-Def.pdf

You are expected to read the above paper at some point during the course in order to be able to link your own modeling work to the broader context of this course.
If you prefer to start with a brief 10 slide introduction, you can start here:

> URL: https://figshare.com/articles/EvoSysBio_in_10_Slides/1427128

Evaluation and Grading

Evaluation

Evaluation in this course is intended to reflect research engagement, not memorization. What counts is the quality of: (1) your weekly independently written ReLog entries; (2) your peer reviews (of your colleagues' ReLogs and project proposals); and (3) your contributions to the group project. In your group, you will write a research grant application using preliminary modeling data to justify the theoretical or experimental work you propose.

This course is designed to provide a taste of what is important in the life of researchers (who do not take exams and, therefore, neither do you). Instead, **your grades will be based on how well you continually engage in your research through the course's duration**.

In a nutshell, there are three big tasks that you must make steady progress on:

1) Write (or re-write) a 250 - 500-word entry for your ReLog each week

2) Peer review two ReLog entries each week

3) **Group project:** In your group, write a draft and two revisions of a grant application while adhering to the "Group Work" due dates listed in the Timetable Overview. The application's text should range between 3,000 and 10,000 words, though **concise prose** should take precedence over length. *Avoid the fluff and make every word count!*

Group project topics

The group project is the core of this course, so choose it wisely in an area you are really interested in. If you already know your area of interest, inform the instructor as soon as possible. The aim is to help you to find a team of collaborators who share your interest. If you are unsure about your area of interest, you can always choose one of the available preselected topics or join a group led by someone who could use some help. Some project titles from previous groups:

> "*The Stag Hunt Game with Shirking: An Articulation, Analysis, and Application of a Model of Collective Action that Helps to Explain the Evolutionary Dynamics of Cooperation in Teams*"

> "*Modeling the Process of Switching-On Alcohol Dehydrogenase in the Human Liver*"

> "*Construction of a Comprehensive Colon Cancer Signaling Network*"

You will only have about two (2) weeks for your first pass at finding your group and your project topic, so **please start searching for your team and project options immediately**. Decisions on group composition and rough research area will need to be near final by the end of **Week 3** and are as good as locked in with the brief presentation made by you and your group at the end of **Week 4**. Bigger changes after that date need separate instructor consent, aiming to ensure that you have enough time to find and read relevant studies, build a model and analyze some simulation results before writing your part of your grant proposal. **Note that the first week can be extremely short.**

Writing help

Everything you write for this course will appear in the shared Google Drive, and these entries will be the basis for your grades. Keep in mind that your texts are only visible to others in the course. Consider taking your drafts to UW's Writing Center, where trained professionals offer free editorial services:

The Writing Center, phone (608) 263-2992, http://www.writing.wisc.edu/

With your colleagues, you will exchange peer reviews that assess the quality of written work while providing **constructive** criticism. While these assessments are part of the learning experience (both for you and the reviewers), they are not your grades and only reflect how your fellow researchers see your work. **The instructor may or may not agree, and will grade your work independently.**

Grading

Your **final course grade** will be based on the instructor's assessment of your overall performance as a researcher in your role of author, collaborator, and reviewer. Your major and previous expertise will be taken into account when evaluating the quality of your work in your main area, as well as the effort you invest into connecting to other disciplines.

The final grade breakdown is:
- 30%   ReLog entries
- 20%   Peer reviews
- 40%   Group project
- 10%   Group collaboration

Letter grades are determined as follows:
- A   90% - 100%
- AB   85% - <90%
- B   75% - <85%
- BC   70% - <75%
- C   60% - <70%
- D   50% - <60%
- F   <50%

If you have questions, please ask the instructor.

Attention Graduate Students:

Graduate students (particularly PhD students) will be held to **higher standards**. Both your quality of work and reading loads will be greater than those of your undergraduate peers.

Extra essay on crossing disciplinary boundaries. Graduate students are required to write a ca 2000-word essay, due before the last meeting of the course. In your essay you describe your personal observations about engaging one or more other disciplines in a trans-disciplinary research environment. Assess everything you perceive as challenge and/or strengths of trans-disciplinary research and experiences that helped you to communicate across disciplines. At the end use your observations to recommend strategies to overcome these problems in your graduate research and beyond. You can draw on observations in the course and outside of the course.

Diversity and your blind spot

Diversity is a source of strength, creativity, and innovation. While true of research in general, this is particularly true of this trans-disciplinary course. Often other disciplines than one's own have an unfamiliar culture that can be difficult to understand at first (you need to 'move' intellectually). However, once you have moved a new perspective becomes available. This perspective often helps to understand others and can hold the key to surprisingly innovative solutions to problems that might otherwise seem impossible to solve. Many have found repeatedly, that the cost of exploring new perspectives is small compared to the rewards for those who engage in this process. After some initial confusion, a new point of view opens up and it brings one of the most valuable gifts: a glimpse of what would otherwise remain well-hidden at your blind spot.

This observation can be made about various scientific disciplinary cultures, as well as other types of human cultures and perspectives, whether related to ethnic, religious, life-style, status, gender, various orientations or other.

In this class, we value the contributions of each student and respect the profound ways in which this course and the university are enriched by every student's unique identity, culture, background, experience, status, abilities, and opinion. This course is committed to integrating the diversity of its students into excellent opportunities for learning, teaching, research-project initiation, training in mental agility and outstanding communication skills.

We welcome your point of view as an important perspective on how you model the world. We strive to integrate your perspective with those of other students and relevant scientific evidence as we seek to best serve the various challenging needs of our time.

For more on the many facets of diversity see: https://stemdiversity.wisc.edu

Students with disabilities

Students that require learning support or have disabilities should contact the instructor as early as possible to explore options for reasonable accommodations. For more information regarding reasonable accommodations see: https://mcburney.wisc.edu

NSF Synergy

Students who plan to apply to the prestigious NSF Graduate Research Fellowship Program should alert the instructor early on to explore ways to integrate their research agenda in this course with their goals for the fellowship application. Doing so will take some experimenting, but students taking this course may benefit from discussions with an instructor who has secured an NSF award.

NSF Deadlines are in the 2nd half of October this year and depend on your discipline:

> https://www.nsfgrfp.org/applicants/important_dates

Think about it. We will work something out if you are interested…

What prior students have said …

"*It is precisely the way I think a college course should be taught: You allow students to articulate what they find interesting, then they pursue those projects, with assistance and instruction from you, the expert(s)*."

"*When we first got this project I thought it would be easy and then 2 months later I thought it would be impossible. Finally getting over the hurdles in this project was very empowering*."

"*I got a pretty good view on how a problem was approached in different manners from different mindsets. This meant that I expanded my vocabulary on words that I did not know had alternative meanings that are interpreted differently in different disciplines*."

"*[I enjoyed] Working with people from different disciplines and getting across the jargon barrier*."

"*This course developed my critical thinking skills in that I was challenged to think of a problem outside of my general science based approach. Having a small group of other disciplines made me think a bit differently than useful which was helpful*."

"*I was introduced to, and learned a good deal about, mathematical techniques that will greatly enhance work in game theory that interests me*."

"*Professor Loewe spent a lot of time working with us individually, was quick to respond to emails, and mentored us through the project. I have never had a class where I have gotten this much mentoring*."

"*Learning more about how different disciplines approach a problem was definitely the number one thing I learned this semester*."

"*I think going over parameter estimation was really helpful. It definitely put some things into perspective and made me understand biology a bit more from a mathematical point of view and let me see that everything is not as structured as it is made out in textbooks to be*."

"*The research that I did for my project increased my understanding of cancer theories*."

"*Going over deterministic and stochastic relationships also helped me to understand how random systems can be and how we can best model them to our particular needs*."

"*The things that developed my critical thinking skills the most, were hitting roadblocks and getting swamped in papers that didn't have the data we needed. This forced me to be creative with my solutions and try new approaches*."

"*This course made me think hard about modeling and its relationship to reality. I greatly enjoyed learning about stochasticity and, above all else, nonlinear dynamics*."

"*It was also useful to do more coding as I do not have a lot of computer science background so any experience is helpful*."

"*[I was inspired] when Prof Loewe was talking about how things can frustrate you because you don't know how to describe them. Once you are able to describe the thing you aren't as bothered by it, you understand it. I find this is really true in many areas of life not just modeling systems biology*."

Fall 2017 Timetable Overview

The **"Group Work" column** specifies key events in developing your research grant application. You need to gather enough background references and preliminary simulation results to show that you propose something new and that is actually doable. This roadmap helps you to front-load, so you get to a better proposal in the end. Use your **ReLogs** (ResearchLogs) to work for your grant.

Deadlines are TBD, see course website. The final grant application deadline will be strict.

Week Day	Date	Topic	Group Work
1 **Thur**	Lect 9/7	**Course overview. Why EvoSysBio?** Why trans-disciplinarity? Why problem-based learning? Why is modeling important for biology?	Meet fellow students.
1 **Thur**	Lab 9/7	Explanation of ReLogs, peer review, group projects. Bring your laptops each Thursday! Discussion of potential group projects starts early.	**Start to form your research group** *Many…*
2 **Tue**	Lect 9/12	**Intro to abstract populations, individuals, and actions:** from molecules in cells to organisms in ecosystems. *Reflect on the work of linking abstract math and messy biological reality by understandable names and InfoBlocks*	ReLog: explore topics for the group project; write about potential research questions.
2 Thur	Lab 9/14	Put your first ReLog on the course website. Install and run the Evolvix demo model on your laptop. In all labs: **Re-run and explore models from lectures as needed.**	**Form your research group; find topics** *…small steps…*
3 **Tue**	Lect 9/19	**Simple growing populations of bacteria** in Evolvix as 'zerodice' (deterministic) or 'manydice' (stochastic) models *Reflection on the roles of chance and necessity.*	ReLog: explore topics for your group project
3 Thur	Lab 9/21	**All Labs: bring your computer; sit with your group.** Work on your model(s) for group project, alone or in group; ask other students or instructor for help as needed. Explain your project idea and where you need help.	**Decide to use your own or a default topic for the project?** *…very slowly…*
4 **Tue**	Lect 9/26	**Decaying population of radioactive material** recorded in Evolvix as a time series until amounts vanish. *Reflection on work with analytic and simulation models.*	**Finalize group.** ReLog on your part in the project.
4 Thur	Lab 9/28	Lab: Continue working on group project. **Today:** Groups present 2-3 min overview; adjust scope as needed after brief discussion in class.	**Present group area,** topics, rough plans. *…building on…*
5 **Tue**	Lect 10/3	**Birth, death, and extinction in cancer cell populations,** recorded by Evolvix as time series in a given time window. *Reflect on randomness and mean expectation in cancer.*	ReLog on your role in project. **Group submit title and work plan.**
5	10/5	Lab: Continue working on group project.	**Group research start!** *…top of each…*
6 **Tue**	Lect 10/10	**Reaction chains, waiting time & biopolymer synthesis,** recorded by Evolvix as time series of selected parts only. *Reflection on waiting, big data, and questions in models.*	ReLog on a question from your group work
6	10/12	Lab: Continue working on group project.	*… other can …*
7 **Tue**	Lect 10/17	**How carrying capacity limits can stabilize populations** in ecosystems, recorded in Evolvix as changes of density-dependent deaths over time. *Reflections on dynamic changes, differential equations and the secret language of mathematics*	ReLog on a question from your group work
7	10/19	Lab: Continue working on group project.	*… result in …*

Week Day	Date	Topic	Group work
8 Tue	Lect 10/24	**How flux can stabilize populations of metabolites,** recorded in Evolvix as phase diagrams of amounts. *Reflections on dynamics, stationary flux-balance and Occam's razor.*	ReLog on a question from <mark>your group work</mark>
8	10/26	Lab: Continue working on group project.	*... incremental ...*
9 Tue	Lect 10/31	**Oscillations in cell-virus, host-pathogen, predator-prey** simple systems, recorded in Evolvix as phase diagrams of fluxes, or other time series. *Reflection on the meaning of attraction and chaos in non-linear dynamics.*	ReLog on a question from <mark>your group work</mark>
9	11/2	Lab: Continue working on group project.	*... progress ...*
10 Tue	Lect 11/7	**Stimulating and limiting kinetics of Michaelis & Menten** in degrading Alcohol, recorded in Evolvix as time series with varying precision. *Reflections on the differences between counts and concentrations.*	ReLog on a question from <mark>your group work</mark>
10	11/9	Lab: Continue working on group project.	*... that taken ...*
11 Tue	Lect 11/14	**Molecular switches, Hill kinetics, and gene regulation,** recording the speed of a switch in Evolvix using time series. *Reflections on reversibility and irreversibility in biochemistry and ecology.*	ReLog on a question from <mark>your group work</mark>
11	11/16	Lab: Continue working on group project.	*... together can be...*
12 Tue	Lect 11/21	**Summary of Continuous Time Markov Chain** (CTMC) basics as used above, reviewing Evolvix syntax for easy CTMC modeling and clear mapping to math methods. *Reflection on danger analyzing models with only a single method.*	ReLog on a question from <mark>your group work</mark>
12	11/23	Thanksgiving Break: No Lab	*... quite impressive!*
13 Tue	Lect 11/28	**Using CTMCs in diverse areas of biology,** including biochemistry, cell biology, physiology, epidemiology, life-history, ecology, population genetics, and phylogeny. **Directing experiments using sloppy CTMC models** despite unknown parameters with the help of ensemble approaches such as sensitivity analyses or Approximate Bayesian Computation. *Reflection on the semantics of 'nothing', 'unknown' and 'verified' in biology and math.*	ReLog on a question from <mark>your group work</mark>
13	11/30	Lab: Finalize group project.	<mark>Last bits of group work</mark>
		Deadline to be agreed upon early on.	**Submit Grant Now!**
14 Tue	*Talks* 12/5	<mark>**Student presentations of group projects. Discussion.**</mark>	
14 Thur	*Talks* 12/7	<mark>**Student presentations of group projects. Discussion.**</mark>	
15 Tue	*Disc.* 12/12	**Bringing it all together.** Using fitness landscapes, CTMC models, and EvoSysBio to predict aspects of evolution. *Reflections on research, computing, reproducibility, and ways of expressing meaning in future biology.* **Debriefing from your research experience. Feedback on the course. Open Discussion.**	
		No exam. Grades are determined from your ReLogs, grant proposal, reviews, participation and presentation.	