12.009 Theoretical Environmental Analysis

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Catalog description

Analysis of cooperative processes that shape the natural environment, now and in the geologic past. Emphasizes the development of theoretical models that relate the physical and biological worlds, the comparison of theory to observational data, and associated mathematical methods. Topics include carbon cycle dynamics; ecosystem structure, stability and complexity; mass extinctions; biosphere-geosphere coevolution; climate change. Employs techniques including stability analysis; scaling; null model construction; time series and network analysis.

Objectives

The principal objectives of this course are twofold. First, it provides students with an understanding of the mechanisms that underly the organization of the natural environment; i.e., how nature works. Second, it introduces students to methods of quantitative analysis that are useful for investigating how any system works. The course teaches students how to identify fundamental phenomena, how to formulate theoretical models, and how to quantitatively test models by comparison to observations. Students are provided with real datasets so that they can engage in these processes independently and creatively.

A secondary but no less important objective is to provide students with a unified view of environmental science. The unification is made possible by emphasizing aspects of earth, atmospheric, and planetary sciences that collectively act to create the natural environment, both physical and biological. We feature several of the great advances of 20th-century science (e.g., plate tectonics, climate cycles, and chaos theory) and introduce modern mathematical models of complex phenomena that remain to be understood. In so doing, we teach methods of analysis that are applicable throughout science and engineering.

Prerequisite and corequisite

The course requires elementary physical reasoning, and therefore 8.01 is a prerequisite. The course also requires mathematical experience at the level of ordinary differential equations (18.03). However, because all relevant 18.03-type concepts will also be developed here, 18.03 is a co-requisite rather than a pre-requisite.

Requirements

There are quasi-weekly problem sets, a take-home midterm exam, and a final project due on the last day of classes. Whereas the problem sets will be directed towards developing specific skills, the mid-term and final project will ask that you use tools developed previously to perform independent analyses of your own design.
During final exam week, on a day to be determined, we will ask that each student meet individually with the instructor and TA for a 15-minute oral exam, during which time the student will be asked to defend their analysis.

Students are welcome to collaborate on weekly problem sets but, if you do so, we ask that you list the names of the students you have collaborated with along with your own name. The take-home midterm and final project must, however, be individual work.

Grades will be determined \textit{approximately} as follows: 50\% from the problem sets, 15\% from the midterm, and 35\% from the final project + oral exam.

\section*{Materials}

There is no textbook. However detailed lecture notes, including references for further reading, will be posted on the web.

\section*{Office hours and website}

Chris Follett: Tuesdays and Wednesdays, 5:00–7:00 pm.
Prof. Rothman: Thursdays, 2:00–4:00 pm.
More info: \url{http://stellar.mit.edu/S/course/12/sp11/12.009}

\section*{Tentative syllabus}

The first part of the course (topics 1–3) is loosely organized around Earth’s carbon cycle: the injection of CO$_2$ into the atmosphere and oceans by volcanos and other tectonic processes, the exchange CO$_2$ between the atmosphere and oceans, and the runoff of dissolved carbon from rivers into the oceans. In each case, we emphasize the role of diffusion, perhaps the simplest and most important mode of transport in the natural environment.

In the second part of the course (topics 4–5) we focus on climate cycles, their foundation in orbital dynamics, and methods for the analysis of periodic phenomena in general. We learn how to compute and interpret power spectra, one of the most important tools used in the analysis of any system that evolves with time.

In the final part of the course (topics 6–8) we discuss the physical basis of ecological organization, the dynamics of ecological communities, and nonlinear dynamics in general. Here we meet concepts of scaling, stability, and the geometry of natural networks. The course ends with an introduction to the greatest intellectual achievement arising from the study of environmental dynamics: the theory of chaos.

0. Introduction.

(a) Themes, objectives, and expectations.
(b) The biological and geological carbon cycles.
(c) Climate cycles.
(d) Ecological organization and dynamics.
1. Plate tectonics.
   (a) Volcanism as a long-term CO$_2$ source.
   (b) Thermal convection within the Earth; the Rayleigh number.
   (c) Seafloor heat flux, topography, and thermal diffusion.
   (d) Diffusive scaling.

2. Short-term evolution atmospheric CO$_2$.
   (a) The Keeling curve.
   (b) The radiocarbon bomb spike as an impulse response.
   (c) Microscopic (random-walk) model of molecular diffusion.
   (d) Diffusive exchange with the oceans.

3. Scaling laws for rivers and runoff.
   (a) Fluvial transport as a sink for CO$_2$.
   (b) The geometry of river basins.
   (c) Power laws, fractals, allometry, and scale invariance.
   (d) Random-walk model, null models, and universality.

   (a) Ice-core records of climate change.
   (b) Milankovitch cycles.
   (c) Precession, obliquity, eccentricity, and insolation.
   (d) Enigmatic significance of the eccentricity time scale.
   (e) Enigmatic correlation of climate and CO$_2$.

5. Quantitative analysis of periodic phenomena.
   (a) Discrete Fourier transform.
   (b) Power spectrum and autocorrelation function.
   (c) Power spectra of periodic signals and white noise.
   (d) Null hypotheses and statistical significance of spectral peaks.

6. Ecological organization.
   (a) Energetic limits on the length of food chains.
   (b) Food webs and scale-free networks.
   (c) Body size and the allometric scaling of metabolism.
   (d) Ecological equipartition.
7. Stability and complexity of ecosystems.
   (a) Predator-prey models and Lotka-Volterra cycles.
   (b) Dynamical stability.
   (c) Stability vs. diversity.
   (d) Fossil record of biodiversity and mass extinctions.
   (e) Long-term climatic stability (the weathering “thermostat”).

8. Chaos and the Lorenz model.
   (a) Thermal convection in a loop; ordinary differential equations.
   (b) Rayleigh number, stability, and the transition to turbulence.
   (c) Strange attractors; sensitive dependence to initial conditions.
   (d) Deterministic unpredictability.
   (e) Routes to chaos.