AM/PHY 230: Active Matter
Instructor: L. Mahadevan (SEAS, Physics, OEB)

Term: Spring 2023.

Time: Fridays 1200- 1445**.**

Place: Pierce 209.

Lectures, homeworks, exams and grading: Early on, there will be regular lectures. Later parts of the course will involve active discussions of current problems in the field, driven by readings including a few guest lecturers. There will be 5 problem sets (75%), due every couple of weeks, and a longer project (25%), that will involve working individually or in small groups of 2-3 students. Instead of a final exam, students will present their project and submit a written report that is somewhere between a proposal, a tutorial and a research paper.

Homework grading is intended to show you how well you are progressing in learning the course material. You are *encouraged* to seek advice or help from other students and/or to work in study groups. However, the work that is turned in must be your own.

Course description: Active matter describes out of equilibrium systems that consume energy to do work and become functional. Understanding their behavior and function has implications for biology and complex systems across scales, from cells to ecosystems, e.g. morphogenesis, collective behavior of flocks and herds, neurodynamics of locomotion etc. The tools and concepts needed range from non-equilibrium statistical mechanics, kinetic theory, soft matter, and hydrodynamics, and methods for the analysis of the models that range from scaling, coarse-graining, dimensional reduction and computational algorithms. This course will provide an introduction to the questions, techniques and successes of this exploding field that cuts across the physical and biological sciences.

Textbooks and Reference Materials: There is no single textbook given that this is a young rapidly developing subject. However, the lectures will be supplemented by various readings/reviews from the literature that spans biology, physics, engineering and mathematics. Two non-technical books that you might dip into as a prelude are:

Collective animal behavior by David Sumpter, Princeton, 2010.
Self-organization in biological systems, ed. Camazine et al*.,* Princeton, 2003.

Learning outcomes: Students will learn to (i) formulate and analyze models of active matter starting from experimental observations (e.g. bacteria, cells, morphogenesis, neurodynamics, collective behavior of organisms, …) using analytic and computational approaches, (ii) read and critique the literature on the subject that will lead to a final project that generalizes existing models, (iii) communicate their findings in a final paper that addresses a specific biological problem, and the general mathematical/physical framework that allows for its abstraction and analysis.

Syllabus (tentative/approximate!):

Weeks 1-2: *Active matter across scales in natural and synthetic settings*.

Week 1: Jan 27 – Examples of active matter: collective behavior of cells, neurons, social insects, worms, animals, animats; tissue morphogenesis; neurodynamics and motor control. How to study them. Watch 2022 Loeb Lectures by Cristina Marchetti.

Week 2: Feb 3 - Experimental probes of active matter – characterizing patterns in space-time using order parameters (scalar, vector, tensor). Correlations in space-time patterns, fluctuation-dissipation relations and their breakdown. Dynamical systems approaches for structure. Computational methods for active matter – algorithms and packages e.g. Espresso, Lampps, ….

Weeks 3-8: *Statistical and continuum dynamics.*

Week 3: Feb 10 – Passive and Active Brownian Particles: from Langevin dynamics to Fokker-Planck formalism. Computational algorithms. ABP, RTP, AOUP, and other animals from the zoo. How to track a gradient: from sperm to dung beetles. HW#1.

Week 4; Feb 17 – Statistical and continuum mechanics of a scalar swarm. Motility-Induced Phase Separation – mean field and fluctuation dynamics. Connection to phase separation. Bacterial and colloidal experimental systems. Guest lecture: Aparna Baskaran, Brandeis.

Week 5; Feb 24 - Linear stability and pattern formation. Basic methods for bifurcation analysis and pattern formation. Weakly nonlinear analysis, similarity and singularity. HW#2

Week 6; Mar 3 - Active polar swarms and Toner-Tu equations. Microscopic and symmetry-based derivations. Waves and instabilities. Simplified models for porous analog of T-T equations. Boundary layers and singularities. Experimental analogs. Guest Lecture: Craig Reynolds, Independent.

Week 7; Mar 10 – Active nematodynamics. Stability, instability and patterns. Turbulence. Wet active matter and multi-phase models for complex active fluids. Active poroelasticity, viscoelasticity. Odd elasticity and odd viscosity. Guest Lecture: Sean Megason, Harvard. HW#3

Weeks 8-9: *Geometry, topology and morphodynamics.*

Week 8; Mar 24 - Why geometry matters. Differential geometry and mechanics of growth. Elastic instabilities due to growth. Morphogenesis of tissues – guts, brains, shoots, leaves, flowers. Asymptotic approaches for long wavelength theories. Guest Lecture : Nikta Fakhri, MIT. HW#4

Week 9; Mar 31 – Topological defects, localized patterns, order-disorder transitions. Scalar, polar and nematic active matter in low dimensions. Active filaments, membranes and shells. Guest Lecture : Jorn Dunkel, MIT.

Weeks 10-12: *Neurodynamics, sociodynamics and control.*

Week 10; Apr 7 - Neuronal excitability. Phase dynamics and Kuramoto oscillators. Synchronization and coordination in active matter – oscillators and swarmalators. Wilson-Cowan dynamics. Neurodynamics of motor systems and active matter. Proprioception and locomotion. Worms, guts and tentacles. Guest Lecture: Dan Needleman, Harvard. HW#5

Week 11; Apr 14 – Sociodynamics. Breaking down the living/non-living boundary. Brain-body-environment interactions. Social insects, and robots– morphotectonics and physical intelligence. Patlak-Keller-Segel model for chemotaxis and its generalizations. Stigmergy, rheomergy, and other physico-chemical communication channels.

Week 12; Apr 21 - Optimization and control – Pontryagin-maximum-principle, Hamilton-Jacobi-Bellman equation. Simple examples e.g. navigation. Optimal transport of active matter. Projection-based methods for low-dimensional control. Control of active drops, flocks, and tissues.

Week 13; April 28 – Discussion of project presentations.

Week 14; May 3 – Final (group) presentations.
