Carnegie Mellon University

# 33-767 Biophysics
## From Basic Concepts to Current Research

**Meeting Days, Times, Location:** WF 14:20-15:40, DH A200

**Semester:** Spring **Year:** 2021

**Units:** 12

### Instructor information

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| **Name** | Prof. Shiladitya Banerjee |
| **Contact Info** | shiladtb@andrew.cmu.edu |
| **Office location** | Wean 6301. Zoom Meeting ID: 924 0870 7146 [Passcode: 931492] |
| **Office hours** | By appointment |

### Prerequisites

It is recommended but not mandatory that students have taken courses on Undergraduate Thermal Physics (33-341 or equivalent) and/or Statistical Mechanics (33-765). The required concepts in statistical mechanics will be (re-)introduced in the course. No prior knowledge of biology is needed (beyond some very basics).

### Course Aim

The course will provide students with insights into the physical concepts of some of the most fascinating processes that have been discovered in the last decades — those underpinning the molecular machineries of living cells and organisms. These concepts will be introduced and illustrated by a wide range of phenomena and processes in the cell, including cell cycle, biomolecular structure, DNA packing in the genome, mechanics of the cytoskeleton, molecular motors and neural signalling.

The aim of the course is therefore to provide students with:

- Knowledge and understanding of physical concepts which are relevant for understanding biological phenomena from the molecular (nm) to cellular (μm) scales.
- Knowledge and understanding of how these concepts are applied to model various physical processes in the biological cell.

### Objectives

After completing this course, students should be able to:

- Give a physical description of the biological cell and its contents and describe the quantitative models underpinning cellular life cycle.
- Use the concepts of free energy, entropy and Boltzmann distribution to explain cellular organisation and energy transduction.

- Describe two-state kinetic processes in cells using statistical mechanical models.
- Describe DNA structure and organisation from the viewpoint of polymer physics and random walk.
- Describe the energetics of DNA bending and Cytoskeletal deformation using elasticity theory. Explain how such models are relevant for understanding the mechanics of cells.
- Use fluid dynamics models to describe motion in biological environment.
- Describe diffusion in biological systems and their consequences for molecular transport.
- Explain the concepts of rate equations for chemical reactions and apply them to macromolecular systems.
- Explain the emergence of biological patterns using reaction-diffusion models.
- Describe the physical concepts involved in the dynamics of molecular motors and apply them to derive quantitative models of motor-driven motion and force generation within the cell.
- Describe neural signalling in terms of propagating action potentials in brain cells.
- Link the materials in the course to specific examples of research in the recent scientific literature.

## Learning Resources

- The course will make use of the book - *Physical Biology of the Cell*, R. Phillips et. al., parts of which will be obligatory reading material. However, some lectures will be based on current research materials.
- Lecture slides and notes to be made available after every lecture.
- Selected research articles.
- Other books (optional) which may be useful include the following. They cover more material than is in the syllabus.
  - *Biological Physics*, 1st Edition, Philip Nelson, W.H. Freeman, 2004
  - *Mechanics of Motor Proteins and the Cytoskeleton*, 1st Edition, J. Howard, Sinauer Associates, 2001
  - *Protein Physics*, 1st Edition, A.V. Finkelstein and O.B. Ptitsyn, Academic Press, 2002
  - *Molecular Driving Forces*, 1st Edition, K.A. Dill and S. Bromberg, Garland Science, 2003

## Assessments

The final course grade will be calculated using the following categories:

| Assessment | Percentage of Final Grade |
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| Homework | 40% |
| Mid-term exam | 30% |
| Final exam | 30% |

- **Assignments:** Weekly homework assignments will constitute 40% of the grade. Assignments will be due in 7 days, and should be handed in by the end of class.
- **Late-work policy**: 1 working day late – no penalty; 2-5 working days late – half credit. Homework may not be graded at all if handed in after 5 working days without valid excuse.
- **Attendance**: If you miss class, it is your responsibility to find out what you missed.
- **Mid-term exam**: Take home.
- **Final exam**: Take home.

- **Grades**: Students will be assigned the following final letter grades, based on calculations coming from the course assessment section.

| Grade | Percentage Interval |
|---|---|
| A+ | 96-100% |
| A | 92-95% |
| A- | 88-91% |
| B+ | 84-87% |
| B | 80-83% |
| B- | 75-79% |
| Fail | 74% and below |

## Course Schedule

| Date | Theme | Topics | Assignments |
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| 2/3 | Physics of the cell I – basic principles | How does a cell grow? Divide? Measure size? Measure time? | |
| 2/5 | Physics of the cell II – molecules of life | Self-reproducing machines; Central Dogma of Molecular Biology - DNA, RNA, and Proteins; DNA replication; Translation. | Homework 1 - set |
| 2/10 | Statistical Physics of cellular processes I | Deterministic versus Thermal Forces; Equilibrium models of cellular processes; Free-energy minimization and Entropy; Liquid-liquid phase separation and organelle formation. | |
| 2/12 | Statistical Physics of cellular processes II | Statistical microstates, Boltzmann distribution and Partition Function; Ligand-receptor binding and Ion Channel Gating. | Homework 1 – due<br>Homework 2 - set |
| 2/17 | Two-state biological systems I | Macromolecules with multiple states; Ion channel gating; RNA hairpin folding-unfolding transitions. | |
| 2/19 | Two-state biological systems II | Gibbs distribution; Chemical Potential; Phosphorylation; Cooperative binding. | Homework 2 – due<br>Homework 3 - set |
| 2/24 | Structure of Macromolecules I | Random walk models of polymers; Entropy, Elastic properties and Persistence length of polymers. | |
| 2/26 | Structure of Macromolecules II | Chromosome Organization; DNA looping; Single-molecule mechanics; Force-extension relation of random walk polymers. | Homework 3 – due<br>Homework 4 - set |

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| 3/3 | Mechanics of biopolymers I | Elasticity theory of beam deformation and the worm-like chain model of stiff polymers. | |
| 3/5 | Mechanics of biopolymers II | Beam theory applied to the mechanics of DNA and the Cytoskeletal Filaments; Buckling of biopolymers. | Homework 4 – due<br>Homework 5 - set |
| 3/10 | Biological Fluid Dynamics I | Navier-Stokes Equation; Viscosity and Reynolds number in cells; Fluid Dynamics of Blood. | |
| 3/12 | Biological Fluid Dynamics II | Low Reynolds number regime in biology; Stokes Flow; Swimming of microorganisms; The Scallop Theorem. | Homework 5 - due |
| 3/17 | | Mid-term exam | |
| 3/19 | | NO CLASS – mid semester break | |
| 3/24 | Diffusion in cells I | Active vs Passive Transport in Cells; Fick's Law for diffusive transport; Diffusion equation and its applications | Homework 6 - set |
| 3/26 | Diffusion in cells II | Driven diffusion, Smoluchowski equation and the Einstein Relation; Diffusion-limited capture. | |
| 3/31 | Chemical Reactions in cells I | Actin-based cell motility; Polymerization dynamics of cytoskeletal filaments. | Homework 6 - due<br>Homework 7 - set |
| 4/2 | Chemical Reactions in cells II | Kinetic models for intracellular self-assembly | |
| 4/7 | Molecular Motors I | Types of motors; Mechanics of muscle contraction; Stepping dynamics of motors; Rectified Brownian motion; Driven diffusion model for molecular motors. | Homework 7 – due<br>Homework 8 - set |
| 4/9 | Molecular Motors II | Energy states and two-state model for molecular motors; Force generation by polymerization. | |
| 4/14 | Neural Signaling I | Charge state of the cell; Electrochemical equilibrium and Nernst Potential; Two-state model for ion channels; Cell membrane as an electrical circuit; | Homework 8 – due |
| 4/16 | | NO CLASS – Spring carnival | |
| 4/21 | Neural Signaling II | Dynamics of membrane voltage. Cable theory. | Homework 9 - set |
| 4/23 | Neural Signaling III | Hodgkin-Huxley model for the propagation of action potentials. | |
| 4/28 | Biological Pattern Formation I | Morphogen gradients and pattern scaling in development | Homework 9 – due |
| 4/30 | Biological Pattern Formation II | Reaction-diffusion and Turing Patterns | Homework 10 – set |
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| 5/5 | Population Dynamics I | Predator-prey models; Lotka-Volterra model. | |
| 5/7 | Population Dynamics II | Spreading of infectious disease; SIR model; applications to COVID-19 | Homework 10 – due |
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**We must treat every individual with respect.**

We are diverse in many ways, and this diversity is fundamental to building and maintaining an equitable and inclusive campus community. Diversity can refer to multiple ways that we identify ourselves, including but not limited to race, color, national origin, language, sex, disability, age, sexual orientation, gender identity, religion, creed, ancestry, belief, veteran status, or genetic information. Each of these diverse identities, along with many others not mentioned here, shape the perspectives our students, faculty, and staff bring to our campus. We, at CMU, will work to promote diversity, equity and inclusion not only because diversity fuels excellence and innovation, but because we want to pursue justice. We acknowledge our imperfections while we also fully commit to the work, inside and outside of our classrooms, of building and sustaining a campus community that increasingly embraces these core values.

Each of us is responsible for creating a safer, more inclusive environment.

Unfortunately, incidents of bias or discrimination do occur, whether intentional or unintentional. They contribute to creating an unwelcoming environment for individuals and groups at the university. Therefore, the university encourages anyone who experiences or observes unfair or hostile treatment on the basis of identity to speak out for justice and support, within the moment of the incident or after the incident has passed. Anyone can share these experiences using the following resources:

**Center for Student Diversity and Inclusion:** csdi@andrew.cmu.edu, (412) 268-2150
**Report-It online anonymous reporting platform:** reportit.net username**:** *tartans* password**:** *plaid*

All reports will be documented and deliberated to determine if there should be any following actions. Regardless of incident type, the university will use all shared experiences to transform our campus climate to be more equitable and just.