EE 123 / BME 123: Bioelectricity
Fall 2022

Class meeting time: Mon/Wed 3:00-4:15
Instructor: Joel Grodstein. Office hours: by appointment.
Teaching assistant: none.

Prerequisites: see below

***Bioelectricity is medicine*:**

We humans are biological creatures – but much of our body runs on electricity. In the not too distant future, it may be as common to attack disease by altering our bioelectrical system as it is today to take a medication.

Our nervous system contains almost 100 billion neurons, which conduct electrical impulses known as action potentials. These action potentials let us sense our surroundings, think about what we've observed, and control our muscles. In fact, they control almost every aspect of our body's functioning – from our blood pressure to our sensation of pain – with the result that we are becoming more and more able to control these functions bioelectrically.

Our heart is a bioelectrical oscillator. It is built from billions of error-prone small cells that, as a whole, function incredibly reliably over the course of an entire lifetime. When the oscillator does malfunction, we've learned to fix it in a hospital with pacemakers, or in the field with defibrillators.

Finally, in fact nearly every cell in our body creates its own bioelectrical voltage. Unlike neurons, these voltages change quite slowly. While we do not fully understand the purpose of all these voltages, there is a growing belief that they form an intricate signaling web that not only coordinates normal growth, but whose malfunction can be involved in abnormal growth such as cancer.

What we will cover:

We will start with reviews of basic physics (electrostatics), of basic circuit theory (resistors, capacitors, voltage and current sources), and of biology. We will assume some background in physics and circuits, but little or no background in biology. With those basics in hand, we will learn the physics of bioelectricity – ions, ion channels and cells – and how to analyze them at a higher level with electrical equivalent circuits.

We will then cover our three main target areas: neurons and the brain; the heart; and bioelectrical signaling to control growth. Each area will require its own specific biology background and will typically involve extending our physics-based and electrical models.
We will have common themes in all areas:

- Biology can be overwhelmingly full of detail. We will try to use engineering analyses to abstract away the detail and focus on the big picture.
- We will learn the medical usage of bioelectricity in each of our areas.

***Course Objectives*:**

Upon completion of the course, students will be familiar with:

1. How bioelectricity works; basic physics and modeling

2. How bioelectricity is used in neurons and in the heart.
3. How bioelectricity may control body shape.
4. The use of bioelectrical interventions in medicine (sometimes called *electroceuticals*)

Electrical medicine: the past, the future and the potential

- Electrical medicine (e.g., cardiac pacemakers, and drugs to control cardiac ion channels) has been around for some time. However, the intersection of biology, computing and engineering may be poised for transformative applications, in medicine and elsewhere. Scores of startups are focusing on electrical medicine, along with venture-capital firms specializing in the area.
- Morphogenesis is one of the black mysteries of biology; we know very little about how an embryo grows into a full body, and how the body can repair itself. The course will cover, in some detail, one particular hypothesis that is being worked at the Tufts Allen Discovery Center. This hypothesis, which is supported by growing evidence, has by no means reached the status of fact.

Rough course sequence

1. Introduction to bioelectricity: how a cell creates a voltage inside of itself and controls that voltage. Neurons and the brain. Synapses and gap junctions – how cells communicate bioelectrically (3 weeks).
2. Neurons and medicine: myoelectric prostheses, electrical pain relief (spinal-cord stimulation and peripheral-nerve stimulation), electroceuticals. EMG lab. (3 weeks).
3. Cardiac bioelectricity: how the heart's electrical system works. How cardiac pacemaker cells coordinate to all oscillate at the same frequency. How electrical impulses are transmitted through the heart. Biological and human-engineered fail-safe systems for robustness when pacemaker-cell oscillations are blocked. Physics and practice of ECG measurements for heart waveforms. ECG lab to measure and understand our own electrical fields (3 weeks).
4. Morphogenesis: how we progress from a single cell to fully-formed bodies. The magic of planaria (an organism that regenerates itself so well that it is essentially immortal). Building patterns and coordinate systems from bioelectricity, so that we know where to put different organs. (3 weeks).

Workload:

- We will have roughly 5 programming labs (using a Python-based bioelectric simulator) and 3 real labs (2 that measure your body's electrical fields and one that illustrates diffusion). Each group should hand in only one official lab report; we will then discuss the report during one of our group meetings. You need do only 7 of the 8 labs; pick your favorite one to skip.
- The course is divided into 4 units. Each unit will start with a current-events topic related to that unit. Your job is to learn a bit about the topic. Current events don't always align themselves nicely to our knowledge level – some of the topics will be too hard for us to really understand, but hopefully interesting anyway! Typically, we will talk about it in one of the group meetings. However, if you're particularly interested, you can learn more about the topic and turn it into the quiz for that unit.
- Each unit has an oral quiz. The quiz questions are available in advance. There is nothing to hand in – the quizzes are oral and will take place during our group meetings. Why? It can be difficult to argue that a traditional test – where you have one hour to do something and cannot work with other people – is an accurate reflection of how we solve problems in real life. However, working

with other people to figure out harder problems and then having interactive technical conversations about them is a skill that is quite useful in life (and in job interviews!).

- There is a final project (with presentations during the final-exam slot). There is no midterm or final exam.

Grading

The course grade will be computed roughly as follows:

- 7 labs (choose any 7 from the 5 programming labs and 3 real labs) = 60% of the total grade
- walking quizzes = 25%
- final project = 15%

Late Assignments:

Late assignments will be penalized by 10% per day. Any extensions due to extenuating circumstances (illness or family emergencies) must be arranged ahead of time with the instructor before the original due date.

Resources:

- The best introduction to bioelectricity I've found is *"Biological Physics: Energy, Information, Life"* by Philip Nelson. It's the textbook for PHYS 25, and so the bookstore may have some copies left. Tisch has two copies (one of which I've placed on reserve).
- *Lippincott's Illustrated Reviews: Physiology, 2nd edition* is available online at Tisch. Its chapters on cardiac physiology (both the plumbing and the electrical sides) are quite readable.
- *Modeling Planarian Regeneration: A Primer for Reverse-engineering the worm*, Lobo and Levin 2012. A very readable overview of the computational problems that planaria seem to solve effortlessly as they regenerate themselves.
- *Gap junctional blockade stochastically induces different species-specific head anatomies in genetically wild-type Girardia dorotocephala flatworms*, Emmons-Bell 2015. Another paper describing the wild and wooly feats that planaria are capable of.
- There are numerous books on Python programming. Two that are available free online are
  - http://greenteapress.com/thinkpython2/thinkpython2.pdf
  - https://automatetheboringstuff.com
- *An Introduction to Systems Biology: Design Principles of Biological Circuits*, Uri Alon. An excellent introduction to the field of systems biology, with a bit of synthetic biology and morphogenesis thrown in. It doesn't really cover the material that we do – but it's such a nice book that I still recommend it!

Popular and entry-level literature on electroceuticals:

- *Why It's Time to Take Electrified Medicine Seriously*, Time Nov 2019
- https://galvani.bio/news-archive/
- https://spectrum.ieee.org/topic/biomedical/

Prerequisites

- This is an extremely interdisciplinary course, covering parts of biology, physics, computing, electrical engineering and programming. It is expected that very few people will enter the course being competent in all of these areas, and we thus are not being strict about prerequisites. Obviously, the more areas you have to learn, the more work you will have. With that in mind…

- While we will cover a fair amount of biology, the course is intended to be self-contained in that respect; we will cover all of the biology that we absolutely need. Of course, you will find it easier if you already have some biology background. Nonetheless, my expectation is that only perhaps one third of the class will be in this category.
- We will be doing a relatively small amount of programming in Python. In all cases, you will be given an existing simulation framework and you will "merely" need to write enough code to use it. If you're reasonably competent in Python, you will have no trouble. If you're competent in a similar language (e.g., Matlab), you should be able to pick up enough Python without much trouble. If you've never done any programming at all, then this may not be the class for you unless you're willing to put in some work catching up.
- We will be learning about bioelectricity and about using electrical circuits to analyze it. We require at least one of PHYS 12 or ES3 as a prerequisite. Having both (or their equivalents) would be even better. We will have self-study review material and flipped-classroom lectures to refresh your memory if this material is rusty for you.
- One semester of differential equations is listed as a prerequisite.

Collaboration policy

Learning is a creative process. Individuals must understand problems and discover paths to their solutions. During this time, discussions with friends and colleagues are encouraged—you will do much better in the course, and at Tufts, if you find people with whom you regularly discuss problems. But those discussions should take place in English, not in code. If you start communicating in code, you're breaking the rules. When you reach the coding stage, therefore, group discussions are no longer appropriate. Each program, unless explicitly assigned as a pair problem, must be entirely your own work. Do not, under any circumstances, permit any other student to see any part of your program, and do not permit yourself to see any part of another student's program. In particular, you may not test or debug another student's code, nor may you have another student test or debug your code. (If you can't get code to work, consult a teaching assistant or the instructor.) Using another's code in any form or writing code for use by another violates the University's academic regulations. Do not, under any circumstances, post a public question to Piazza that contains any part of your code. Private questions directed to the instructors are OK. Suspected violations will be reported to the University's Judicial Officer for investigation and adjudication. Be careful! As described in the handbook on academic integrity, the penalties for violation can be severe. A single bad decision made in a moment of weakness could lead to a permanent blot on your academic record. The same standards apply to all homework assignments; work you submit under your name must be entirely your own work. Always acknowledge those with whom you discuss problems! Suspected violations will be reported to the University's Judicial Officer for investigation and adjudication. Again, be careful.

Additional resources

Tufts University values the diversity of our students, staff, and faculty, and recognizes the important contribution each student makes to our unique community. Tufts is committed to providing equal access and support to all qualified students through the provision of reasonable accommodations so that each student may fully participate in the Tufts experience. If you have a disability that requires reasonable accommodations, please contact the Student Accessibility Services office at

Accessibility@tufts.edu or 617-627-4539 to make an appointment with an SAS representative to determine appropriate accommodations. Please be aware that accommodations cannot be enacted retroactively, making timeliness a critical aspect for their provision. Tufts and the teaching staff strive to create a learning environment that is welcoming to students of all backgrounds. If you feel unwelcome for any reason, please let us know so we can work to make things better. You can let us know by talking to anyone on the teaching staff. If you feel uncomfortable talking to members of the teaching staff, consider reaching out to your academic advisor, the department chair, or your dean.