Computational Neuroscience

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Computational Neuroscience (Lecture 1, 2022/2023)

Outline of Lecture

- Course outline and formalities
- Motivation and introduction to computational neuroscience
- Q and A

Welcome to CNS

- Goal of CNS: Understand how the brain works, including biophysics of neurons, how the nervous system processes information and performs computations, how these computations generate perception, cognition and behaviour

- Highly interdisciplinary field: Combines ideas from computer science, maths, physics, biology, psychology, artificial intelligence, machine learning, etc.

- Learning outcomes: understand computational models of brain function, think critically about how to model aspects of brain function, implement models in code and analyse them mathematically

Is CNS for You?

- CNS is a course about the brain and computation in the nervous system
- We make *extensive* use of mathematics and computational/numerical techniques to build and interpret models of brain function
- CNS is **not** a course that is widely useful for industry or applications (such as AI/ML)
- Problems in CNS are often open-ended with no correct answer, the biology is messy, the brain is too complex to modelled exactly – you need to be comfortable with vagueness and uncertainty, and willing to do a lot of independent reading!
- Computational neuroscience is an extremely interesting and exciting field!

Relationship to Other Courses

- Computational Cognitive Neuroscience (CCN: Semester 2) – stronger focus on cognition and on the field of computational psychiatry. CNS is great preparation for CCN

- Computational Cognitive Science (CCS: UG3) – less focus on biology/brain, more cognitive and algorithmic

Previous/extinct courses:

- Neural Computation (NC) focused on biophysical models of neurons
- Neural Information Processing (NIP) focused on AI-inspired theories of brain function
- Computational Neuroscience of Vision (CNV) focused exclusively on the visual system

- CNS covers elements of both NC and NIP, but often in less depth. We will also cover some visual neuroscience.

Requirements for this Course - Maths

- **You need to know:** calculus, linear algebra, probability theory, differential equations

- Not very advanced but used extensively. Solving equations and performing analytical derivations is required for the tutorials, assignment, and exam

- Examples: linear first order ODE, Poisson process, matrix/vector algebra, Taylor expansion, limits of functions for small or large arguments, Dirac delta function

- Mathematics is the primary tool we use to study the brain in this course - if you do not enjoy studying model systems mathematically in order to gain insight into their behaviour, you will not enjoy this course!

Requirements for this Course - Coding

- **Coding:** Numerical computing, to implement models and investigate their properties
- The computer labs assume Python, but you are free to use another language if you prefer (e.g., Julia, Matlab)
- You will need to solve differential equations numerically, plot the results, etc.
- Coding is never the end goal/learning outcome in this course, it is used only as a means to study models of the brain. Correctness of code is required but the primary goal is to critically interpret your findings in the context of biology. Code is never assessed.

Requirements for this Course - Biology

- We will cover a lot of biology in this course, be prepared!
- No formal knowledge of neurobiology is required (but much to be learned in a short space of time)
- Some background reading is highly recommended (see Learn for basic resources)
- We aim to provide the bare minimum of biology needed to understand the key concepts, but there is a whole world of messy biological details out there!

Requirements for this Course - Physics

- Many models in computational neuroscience involve tools and knowledge of physics
- We will cover some basic physics concepts (capacitance, conductance, voltage, etc.)
- No prerequisites, but often challenging for students, and may require some independent study!
- The physics concepts we cover are roughly at advanced high school level

Assessment

- 25% assessed coursework, 75% exam

- 1x assignment (25%). Implement a model in Python. Simulate, critically evaluate, and discuss your findings. May also involve some mathematical analysis. Some questions may be open-ended and might not have a single definitive answer.

- **Deadlines:**

 - Assignment 1 (due 25th November 12pm) [25%]

 - Exam (date tbd) [75%]

Lectures

- Lectures delivered **in person** – recordings and slides will be available on Learn
- Lecture times: 3.10pm Tuesday in 50 G.06 George Square and 3.10pm Friday in room 2.12 Appleton Tower
- Please interrupt and ask questions during lectures, especially if something was unclear or too fast. Interactions are encouraged!

Computer Labs

- Labs every two weeks (Week 1, 3, 5, 7, 9, 11). 2 hours each, in Appleton Tower 4.12.

- Three lab groups: Monday 12.10pm, Wednesday 2.10pm, Friday 11.10am. Labs are "Drop-In" (i.e. you can attend any of them)

- Format of labs: coding and implementation of models in Python.

Labs are good practice for the assignment! The TAs will also provide additional derivations/extensions of material covered in lectures.

- Lab this week: learn to solve ordinary differential equations in Python, make scientific plots, etc. Please attend!

Virtual Office Hours, Discussion, etc.

- **Office Hour:** catch me after lectures or talk to one of the TAs in a computer lab
- **On Piazza:** Post questions/discussion about the course. Will be monitored by lecturer and TAs

Course Contacts

- First point of contact should always be Piazza! Post a private question if it is confidential, you should only email the lecturer in exceptional circumstances (e.g., can’t gain access to Piazza)

- **Lecturer/Course Organiser:** Angus Chadwick (angus.chadwick@ed.ac.uk)

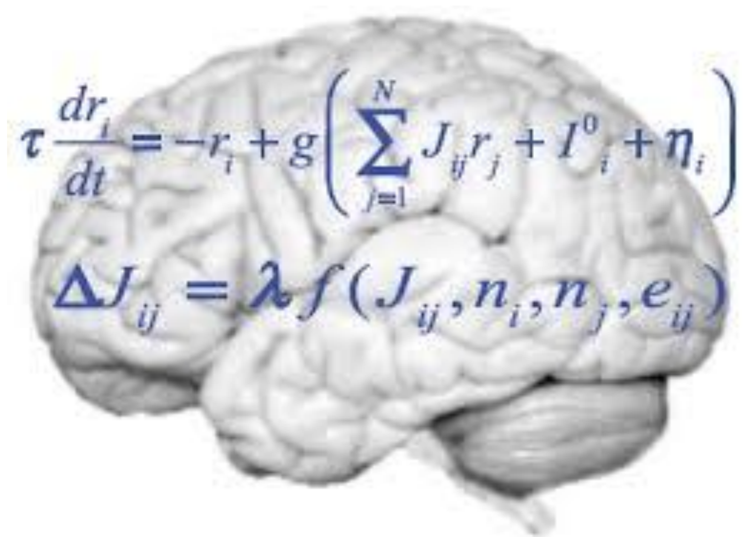
- **TAs:** Isabel Cornacchia and Arthur Pellegrino (isabel.cornacchia@ed.ac.uk, arthur.pellegrino@ed.ac.uk)

- **Markers:** Isabel Cornacchia and Arthur Pellegrino

What is Computational Neuroscience?

"Computational neuroscience is the field of study in which mathematical tools and theories are used to investigate brain function. It can also incorporate diverse approaches from electrical engineering, computer science and physics in order to understand how the nervous system processes information."

Nature (academic journal)



What is Science? [Philosophical Interlude]

- Broadly speaking, scientists attempt to explain things about the world using theories

- Theories are usually a set of equations, and the behaviour of the equations is compared to experimental measurements of the system in question

- A good theory should have explanatory power: it should generalise across situations, it should explain disparate observations in terms of a smaller set of underlying principles, and it should offer satisfying conceptual insight ("understanding")

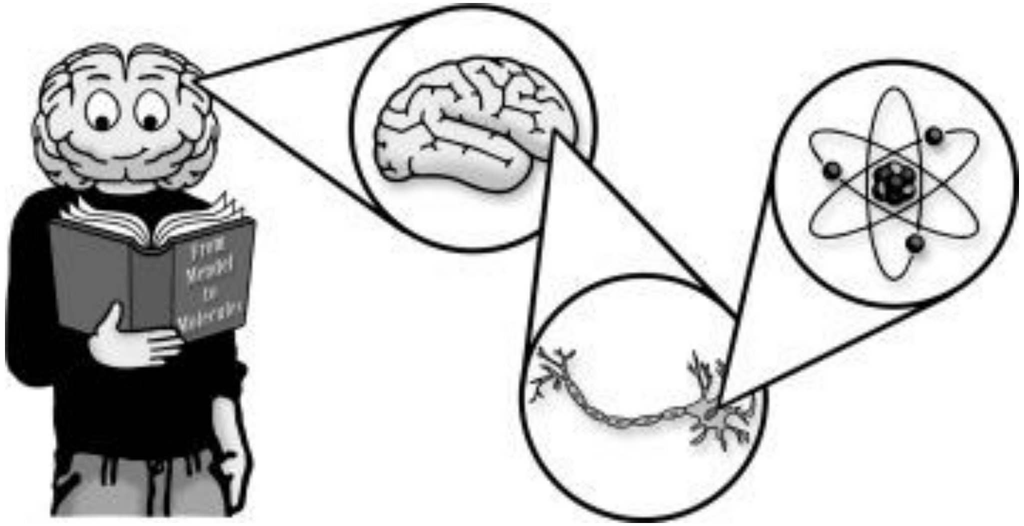
- Theories are always approximations/abstractions - they have a domain of application and break down when assumptions are violated

- In most cases, scientists proceed by breaking a problem down into simpler manageable subproblems, solving those, and hoping that that these simpler problems give insight into the real world (i.e., reductionism)

Why is Understanding the Brain Hard?

- The brain is a highly complex system, with collective and emergent behaviour

- Breaking the brain down into parts is possible (e.g., we can study neurons), but the whole is more than the sum of its parts (networks of neurons behave differently to isolated neurons) – reductionism doesn’t work!



- We can simulate complex models of the brain, but simulations don’t give understanding (e.g., why did this simulation behave this way, how does the qualitative behaviour depend on the parameters?)

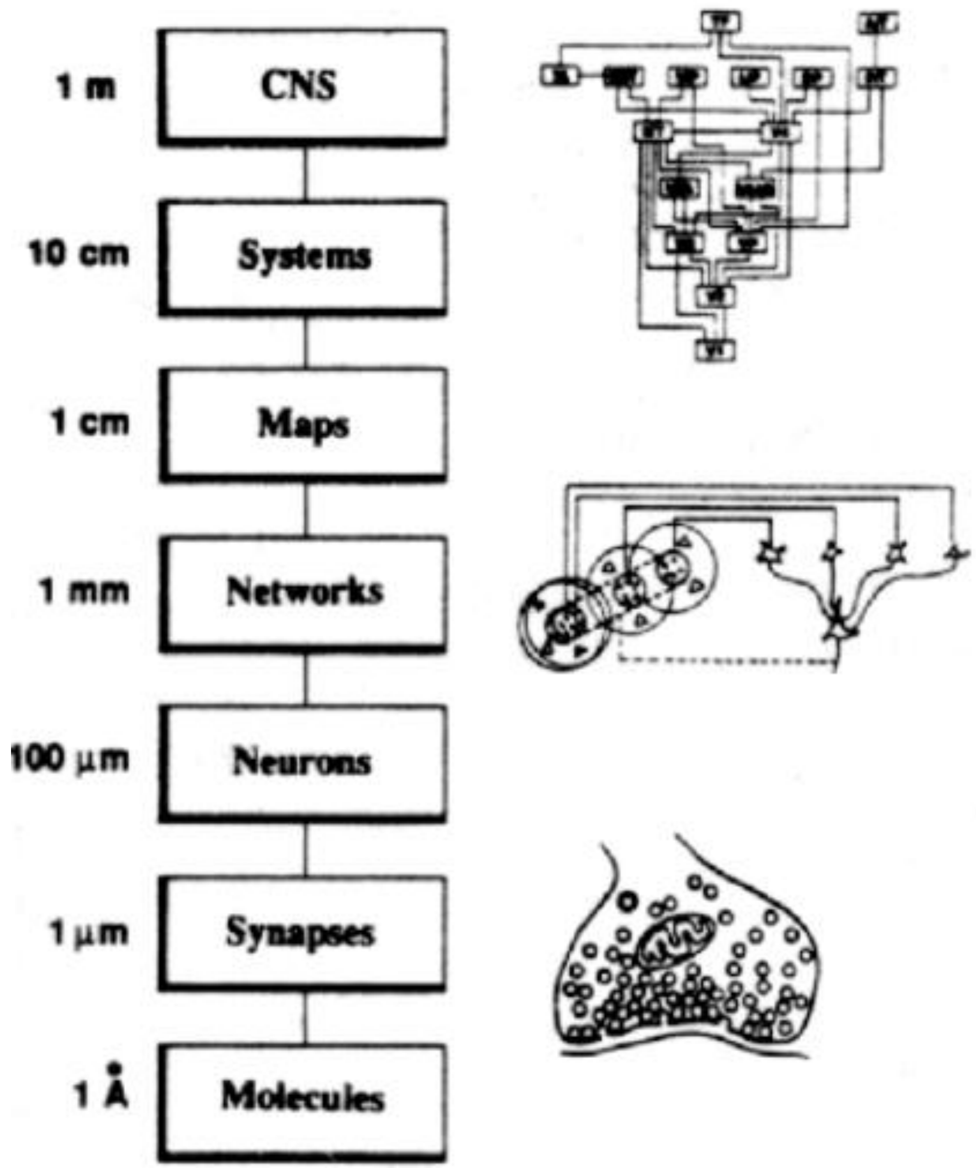
What Do(n’t) We Know About the Brain?

- We have collected many facts about the brain, but have no coherent understanding of how it works

- We also don’t know how to find out how the brain works… (e.g., if we can’t even understand a deep network, how can we hope to understand the brain?)

- In this course you will learn many interesting facts about the brain, but the deepest and most interesting questions will remain unanswered

The Scales of Neurobiology



The brain is a complex system spanning multiple spatial and temporal scales
(molecular to behavioural, milliseconds to years)

To understand the brain we need:

- models/theories that address each scale

- organising principles which span these scales

- theories of various kinds (what, why, how?)

Our understanding of the brain is still rudimentary

Questions of Computational Neuroscience

Computational neuroscience:

Emphasises understanding how *computations* are performed in the brain. Cognition and behaviour are the result of such computations

Central question:

How does the brain work? How are perception, learning, memory, decision making, language, etc. generated by the concerted action of billions of neurons?

Tools of Computational Neuroscience

Computational Neuroscience: uses computational/mathematical tools to understand the brain, by developing:

- Theories about the brain (using maths)
- Computer simulations (“in silico” experiments)
- Data analysis methods (e.g., machine learning)

Try to answer:

What? Descriptive/phenomenological/statistical explanation

Why? “Teleological”/functional/normative explanation (in terms of *optimality*, i.e. evolution)

How? “Mechanistic” explanation, i.e. *causal* or *physical* explanation in terms of biology

The Data of Neuroscience

Human and animal studies: primates, cats, rodents, birds, insects, etc.

Measurements of behaviour: e.g., psychophysics, memory, linguistic tasks

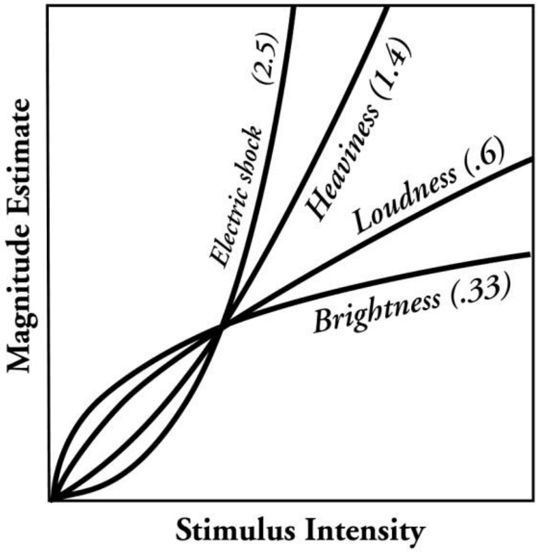
Measurements of neural activity: e.g., EEG, fMRI, intracellular recordings, many more…

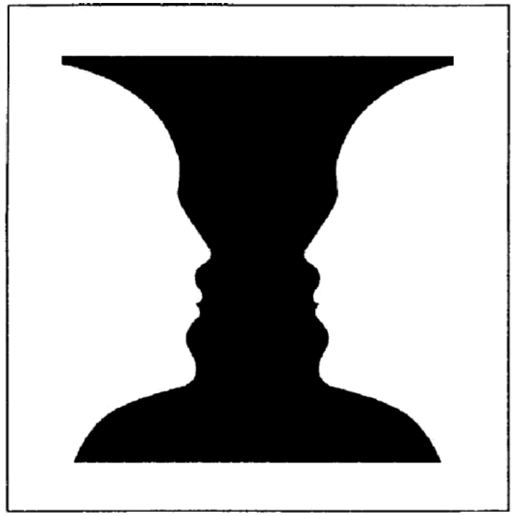
Perturbations of neural activity or behaviour: e.g., pharmacological, electrical, optical

Lesion studies: e.g., accidental injuries (gunshot wounds, WW1), result of brain disease, result of corrective surgery (e.g., split brain patients)

Case studies: neurological disorders (blindsight, hemispatial neglect, face blindness…)

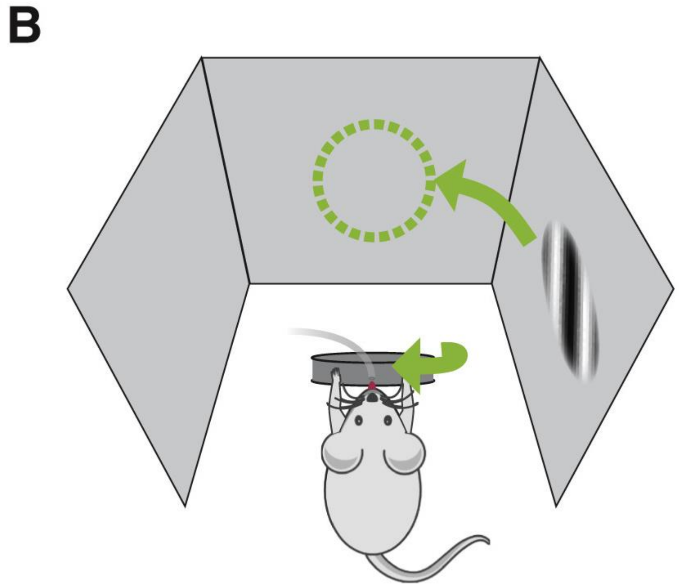
Measuring Behaviour/Perception

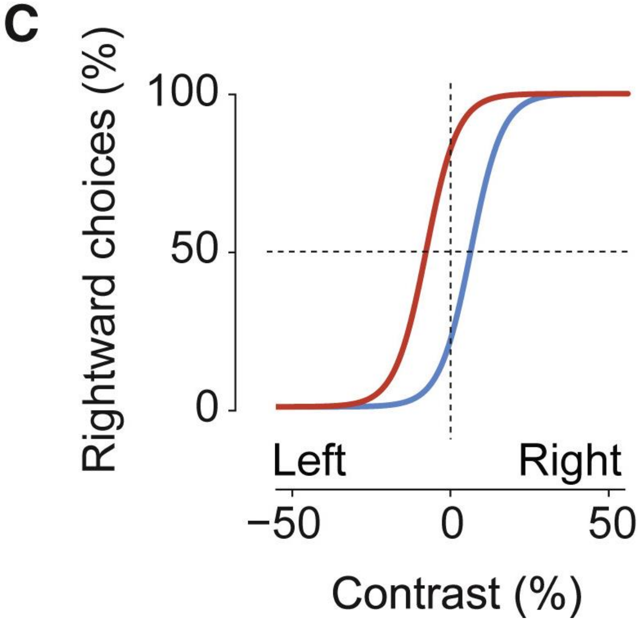




Human Psychophysics:
Behavioural report of perception

Left: How intense? (Fechner's law)
Middle: Faces or vase?
Right: Gustav Fechner

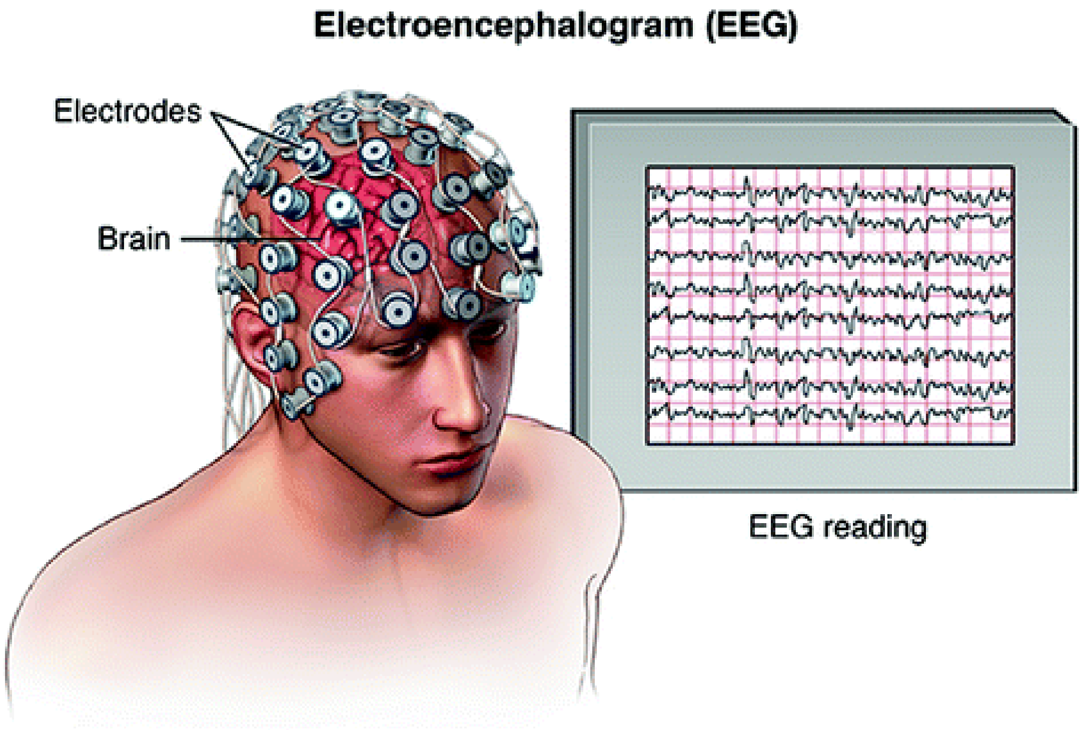




Animal Psychophysics:

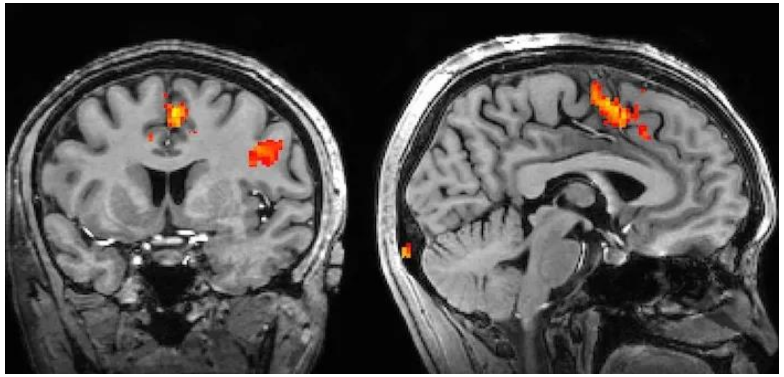
Left: Mouse behavioural task
Right: Measured Psychophysical curves

Measuring Neural Activity – Non-invasive Imaging



EEG – high temporal but low spatial resolution. Noisy, contaminated, indirect measurement of brain's electrical field.

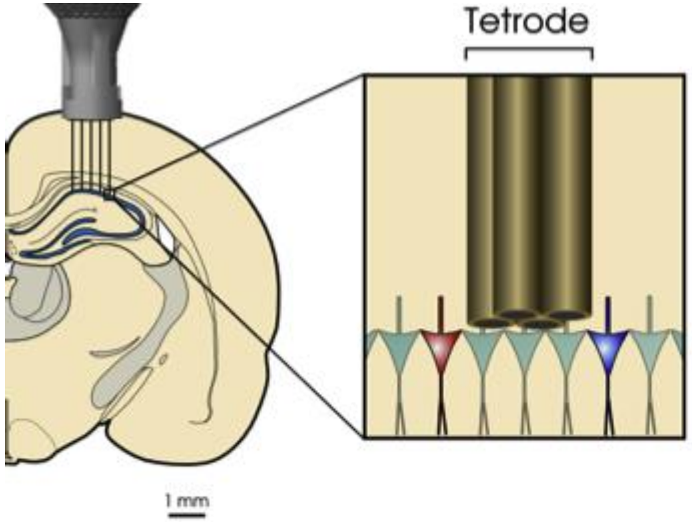
fMRI

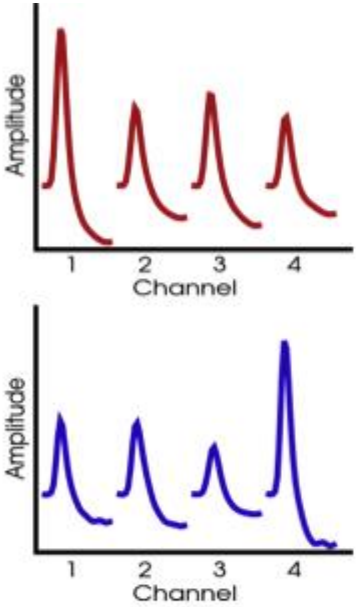


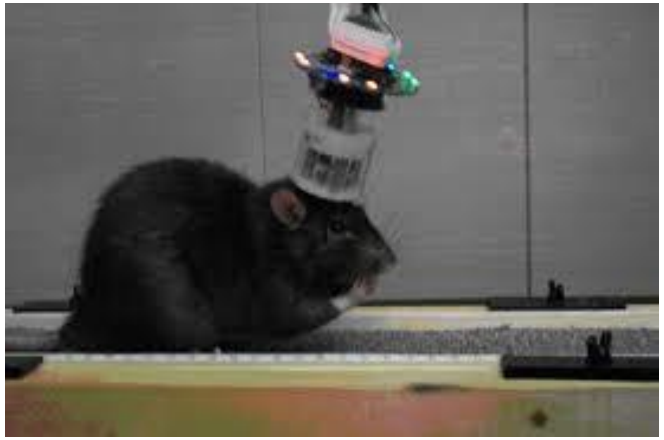
Low temporal but high spatial resolution. Measures BOLD signal (blood flow)

Measuring Neural Activity – Invasive Electrodes

Electrodes: intracellular or extracellular.



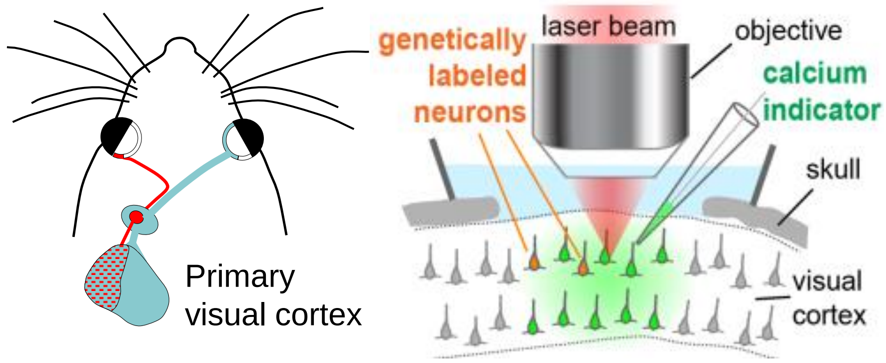


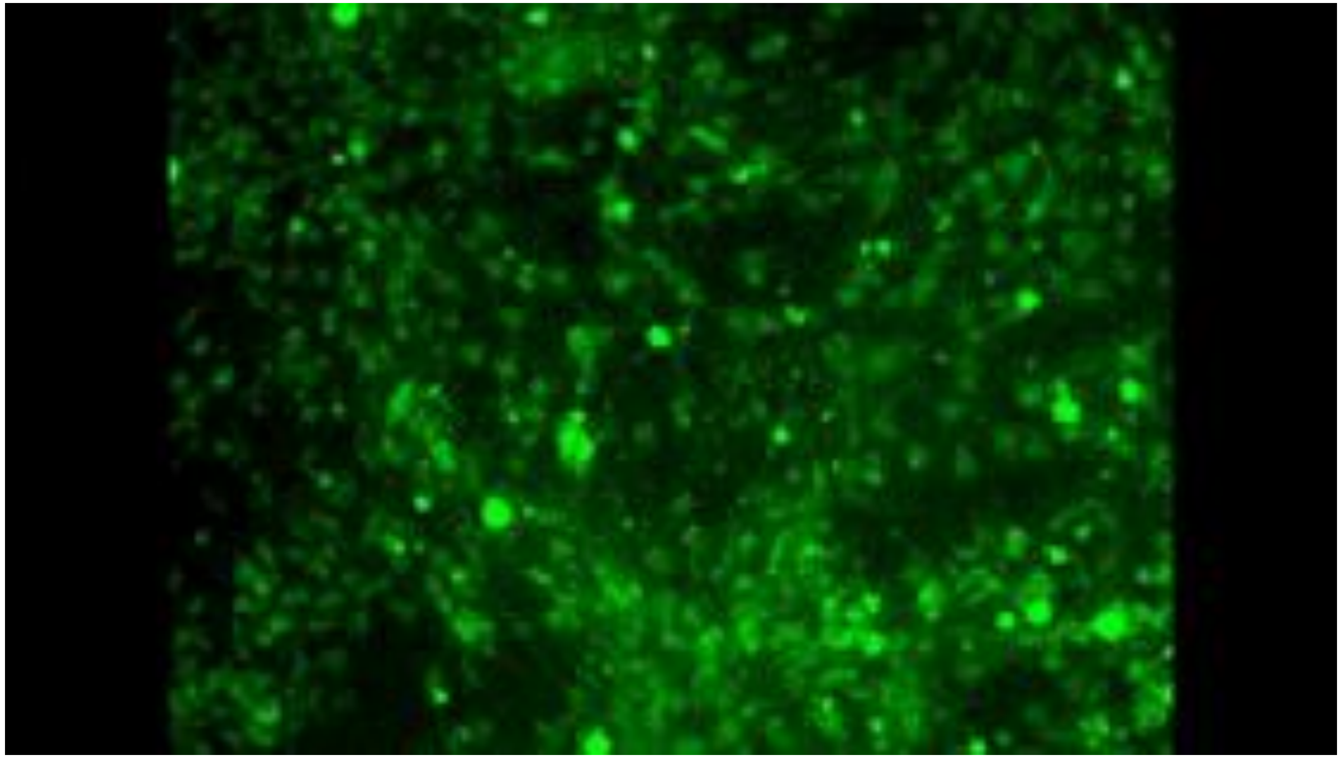


Pros: measure from single neurons at high temporal resolution, measure electrical activity
Cons: Invasive, limited to working with animals, can't record from many cells simultaneously, data pre-processing tricky

Measuring Neural Activity – Invasive Imaging

Two-photon calcium imaging



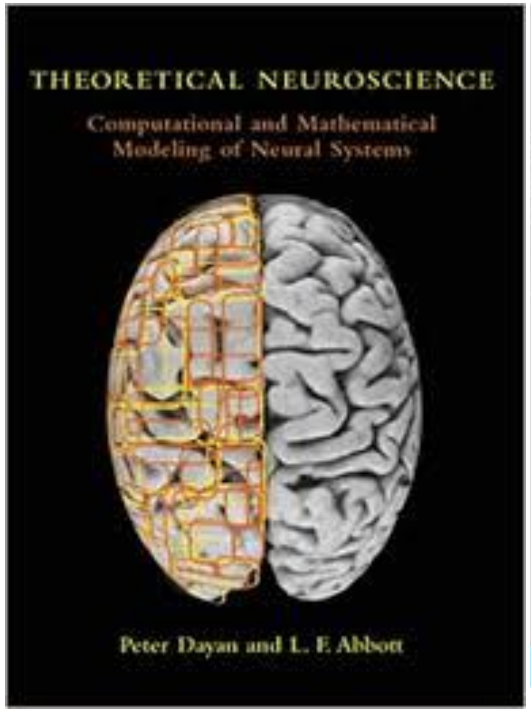


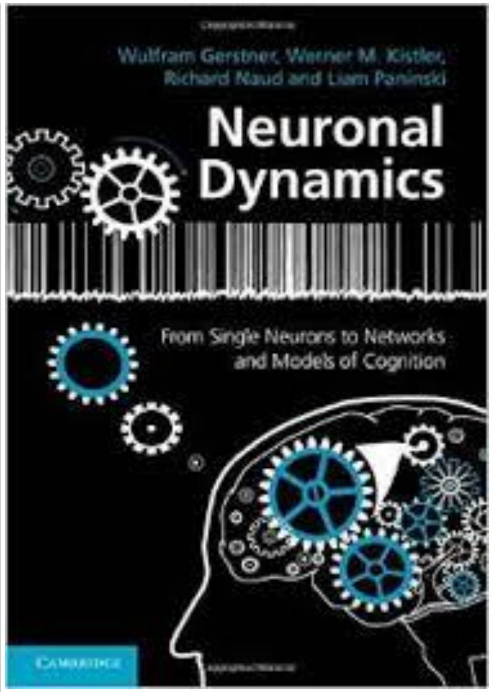
Pros: Image many cells at once, high spatial resolution

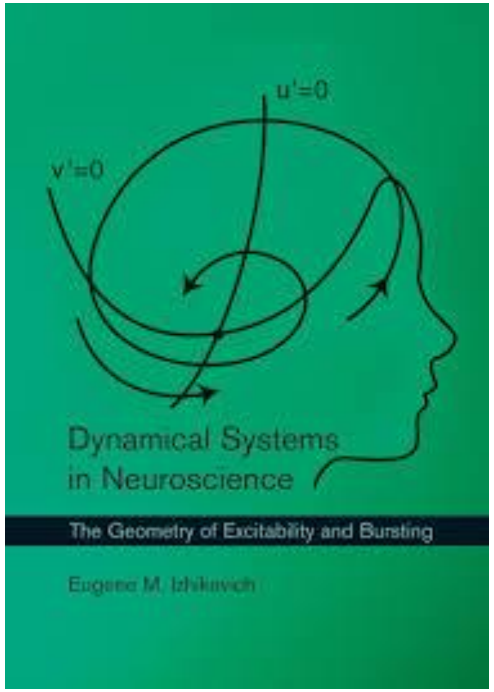
Cons: Invasive, measure only calcium fluorescence, low temporal resolution, data pre-processing tricky

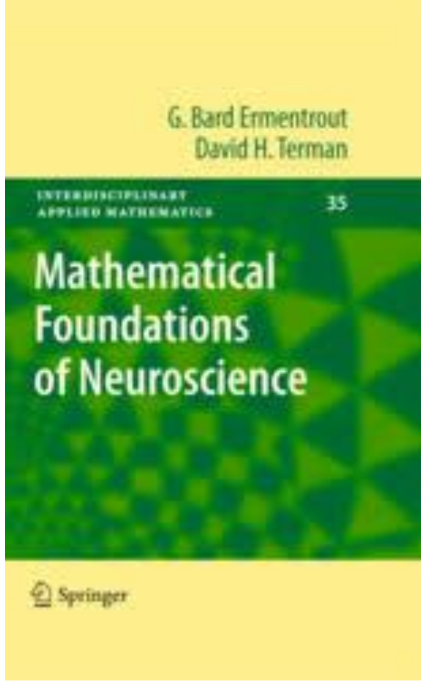
Textbooks

- Much of the lecture material is adapted from these books – some are *free* online (e.g., on the course Learn page). Use these to supplement the lecture material
- We also have detailed lecture notes from a previous course (Neural Computation) that covers much of the material in this course









Overview of Upcoming Lectures

Lecture 2: Overview of (computational) neuroscience

Lectures 3-5: Biophysics of single neurons

Lecture 6: Neural spike statistics

Lecture 7: The visual system

Lectures 8-10: Neural coding

Lectures 11-12: Networks

Lectures 13-15: Plasticity, learning and memory

Lectures 16: Neural data analysis

Questions