Computational Neuroscience Fall 2013
PBS 40; COSC 16

**Introduction to Computational Neuroscience**
Prof. Richard Granger

Readings:
Readings including class handouts and published articles (list attached), to be posted on blackboard
No required textbook for the class.

Course introduction

The mind is what the brain does, and the brain is becoming understood computationally. Just as scientific understanding of physics brings with it the ability to manipulate and alter materials and environments and even to create entirely new physical entities, and scientific understanding of biology has enabled the creation of medicines, cures, and even new biological organisms, so a scientific understanding of the brain will confer the ability not only to describe and characterize the mind, but to modify it, enhance it, diagnose and treat its illnesses, and, eventually, to imitate its operation. Computational neuroscience has as its twin goals the scientific and engineering tasks of understanding of how brain computes mind, and using that understanding to characterize and reconstruct these computations.

Brain circuits are just circuits, albeit highly unusual ones from an engineering standpoint. Enormous advances over the past decade have provided data on brain architecture and mechanism, advancing hypotheses of how thought arises from neural operation, and enabling initial derivation and formal analysis of candidate constituent algorithms carried out by these circuits.

Your brain is composed of low-precision (~ 2 bit), slow (milliseconds per operation), sparsely connected (p(connection) < 0.001) computing elements, yet it far outperforms any extant computer on most complex signal processing tasks that humans and other animals perform readily. Whereas most mammals can recognize complex visual and auditory signals, navigate complex locales and terrains, and perform real-time goal-directed tasks, our ability to construct systems to do so is still surprisingly limited, especially in light of the high level of effort that has been aimed at accomplishing these ends. Indeed, the best current artificial systems that process images or voices, such as face recognition and automated telephone operator systems, are surprisingly limited – yet the only reason that we know that these industrial systems can be outperformed is that humans do so.

This course will introduce concepts of brain circuits including engineering characteristics of cells, anatomical design and organization of telencephalic (mammalian forebrain) circuitry, physiological operating rules of synapses, cells and networks, synaptic long-term potentiation (LTP); and basics of the mathematical field of "neural networks," including the delta rule for single-layer feedforward networks, the generalized delta rule (backpropagation) for multi-layer networks, dynamic and Hopfield nets, unsupervised learning and competitive learning. The class is intended for students from many different backgrounds. Lectures will include brief but self-contained background on all necessary mathematical tools for the class, including tools from statistics, calculus, and linear algebra. Finally, these neural network analyses will be applied to selected telencephalic structures to illustrate candidate emergent computations from these primary mammalian brain circuits.

REQUIREMENTS:
This class integrates knowledge of computer science, engineering, psychology, and neuroscience. The prerequisites are Comp Sci 1 or 4 (or old CS 5), or Engineering 20; or Psych 1 or 6.
Lectures are required; the majority of material for the class will be contained solely in the lectures. There will also be a series of readings from the literature and via handouts. Note that readings do not substitute for the lectures.

GRADING:
There will be three exams (20% each), a programming assignment (20%), and a final project (20%).

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OUTLINE OF KEY TOPICS

Part I. Brain: Neuroscience data and mechanism

- Introduction: Brain. Mind. Intelligence. Artificial intelligence
- Anatomy of cells, synapses, and circuits
- Physiology of excitatory and inhibitory neurons and synapses
- Brain chemistry and pharmacology
- Composition of telencephalic circuits
- Synaptic plasticity; long-term potentiation
- Variants of synaptic plasticity in different circuits

Potentially useful websites containing pointers to background information on neurobiology.

http://www.neuroguide.com
http://brainmuseum.org/circuitry/index.html
http://sig.biostr.washington.edu/projects/da/
http://faculty.washington.edu/chudler/facts.html

Part II. Computational approaches: Artificial neural networks

- Classes of networks and their architectures
- Math of network operations I [Linear Algebra]
- Perceptrons, delta rule, backpropagation
- Math of network operations II [Calculus]
- Recurrent dynamic networks, Hopfield nets
- Competitive learning networks
- Math of network operations III [Statistics]
- Reinforcement & sequence networks

Potentially useful websites with background/review on ANNs

http://www.gc.ssr.upm.es/inves/neural/ann1/anntutorial.html
http://diwww.epfl.ch/mantra/tutorial/english/
http://www.learnartificialneuralnetworks.com/

Part III. Computational neuroscience: Analysis of brain circuits

- Paleocortex and unsupervised clustering
- Striatal complex and reinforcement learning
- Thalamocortical loops and sequence learning
- Cortico-striatal and other loops; allometry of brain growth
- Predictions, extrapolations

Potentially useful websites with background/review on computational neuroscience

http://home.earthlink.net/~perlewitz/

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**Tentative schedule**

| | | |
|---|---|---|
| PART I: Neuroscience: Data & mechanisms | | |
| | Sept | |
| | 17 | Introduction |
| | | Course outline, goals, requirements |
| | | Multidisciplinary fields |
| | | |
| | 19 | Introduction to neuroanatomy |
| | | Organization of brain structures |
| | | Introduction to telencephalon; brain evolution |
| | | Reading: Striedter (2006); Anatomy handout |
| | | |
| | 24 | Introduction to genomics |
| | | Introduction to biochemistry I |
| | | neurotransmitters and receptors |
| | | Reading: Genomics handout; physiology I |
| | | |
| | 26 | Introduction to biochemistry II |
| | | Physiology & pharmacology: |
| | | excitatory & inhibitory neurons; synapses & local circuits |
| | | Reading: Physiology II |
| | Oct | |
| | 1 | Synaptic plasticity |
| | | Long-term potentiation |
| | | Reading: LTP handout |
| | | Hebb (1949); Intro pp. xi-xix, and Ch. 4. pp 60-78. |
| | | Martinez & Derreck (1996); Lynch (2003) |
| | | |
| | 3 | Review & discussion |
| | | |
| | | |
| | 8 | Exam 1 |
| | | |
| PART II: Computational tools; Artificial neural networks | | |
| | 10 | Introduction to artificial neural networks (ANNs) |
| | | Simulation and modeling; mathematics of ANNs |
| | | Linear algebra I: vectors & matrices |
| | | Reading: Linear algebra handout |
| | | |
| | 15 | Linear algebra II: vector combination; inner product |
| | | Perceptrons; delta learning rule |
| | | Reading: Perceptron handout |
| | | Reading: Matlab handout |
| | | |
| | 17 | Extension of perceptrons to multiple layers |
| | | Extension of delta rule; Backpropagation of error |

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|---|---|
| | Reading: Backpropagation handout; Rumelhart et al. (1986) |
| | Introduction to matlab; neural net simulation; simulating backprop |
| | |
| 22 | Introduction to Hopfield networks |
| | Analysis of dynamical systems |
| | Reading: Hopfield, 1982 |
| | Introduction to unsupervised learning systems |
| | Final project proposal discussion |
| | |
| 24 | Clustering, winner-take-all mechanisms |
| | Competitive networks |
| | Reading: Zipser & Rumelhart, 1985 |
| | |
| 29 | Review and discussion [Final project proposals DUE] |
| | |
| 31 | Exam 2 |
| | |
| PART III: Brain and computation | |
| Nov 5 | Paleocortex; olfactory circuits [Matlab assignment DUE] |
| | Simple telencephalic organization |
| | Reading: Granger 2003 |
| | |
| 7 | Clustering; hierarchical clustering |
| | Computational costs; scaling; predictions & experiments |
| | |
| 12 | Striatal complex / basal ganglia |
| | Reinforcement learning |
| | Reading: Niv 2009 |
| | |
| 14 | Thalamocortical loops |
| | Unsupervised and supervised classification |
| | Reading: Rodriguez et al., 2004; |
| | Reading: Chandrashekar et al., 2012 |
| | Memory storage and retrieval; data structures; capacity |
| | |
| 19 | Implications |
| | Experimental questions for psychology & neuroscience |
| | Applications: software, hardware, robotics, embedded AI |
| | Review & discussion |
| | Reading: Granger 2011 |
| | |
| Exam week | Exam 3 |
| | |
| | [Final projects DUE] |

**Readings:**

Chandrashekar A, Granger R (2012) Derivation of a novel efficient supervised learning algorithm from cortical-subcortical loops. Front. Comp Neuro, 5(50): 1-17. doi: 10.3389/fncom.2011.00050

Granger R (2003) Neural Computation: Olfactory cortex as a model for telencephalic processing. Learning & Memory (J.Byrne, Ed.), pp.445-450.

Granger R (2006) Engines of the brain. AI Magazine 27: 15-32.

Granger R (2011). How brains are built: Principles of computational neuroscience. Cerebrum; The Dana Foundation. http://dana.org/news/cerebrum/detail.aspx?id=30356

Granger R Wiebe S, Taketani M, Lynch G (1996) Distinct circuits composing the hippocampal region Hippocampus 6:567-578.

Hebb D (1949). The organization of behavior. New York: Wiley.

Hopfield, J. (1982). Neural networks and physical systems with emergent collective computational abilities. Proc Natl Acad Sci, 79: 2554-2558.

Lynch (2003) Long-term potentiation in the Eocene. Phil. Trans R. Soc. Lond B 358:625-628.

Martinez & Derreck (1996) Long-term potentiation and learning Ann. Rev. Psych. 47:173-203.

Rodriguez A, Whitson J, Granger R (2004) Derivation and analysis of basic computational operations of thalamocortical circuits J Cog Neurosci., 16:856-877.

Rumelhart D, Zipser D (1985). Feature discovery by competitive learning. Cognitive Sci, 9:75-112.

Rumelhart D, Hinton G, Williams R (1986). Learning internal representation by error propagation. Nature 323: 533-536.

Striedter G (2006) Precis of Principles of Brain Evolution, Behav & Brain Sci, 29:1-36.