History of Computational Neuroscience

Grace Lindsay
Imbizo 2020

What is computational neuroscience?

What is computational neuroscience?

- Understanding the *computations* of the brain
- Building mathematical models of the brain
- Building computational tools to process neuroscience data
- Any use of mathematics to understand the brain

History of Neuroscience
~2000 BCE - 0AD

History of Neuroscience ~2000 BCE - 0AD

- Ingesting things (poppies, alcohol)
- Observing naturally occurring disorders (epilepsy)
- Medical practitioners/dissection
- Effects of brain injury

History of Neuroscience
~2000 BCE - 0AD

“Edwin Smith”

Surgical Papyrus

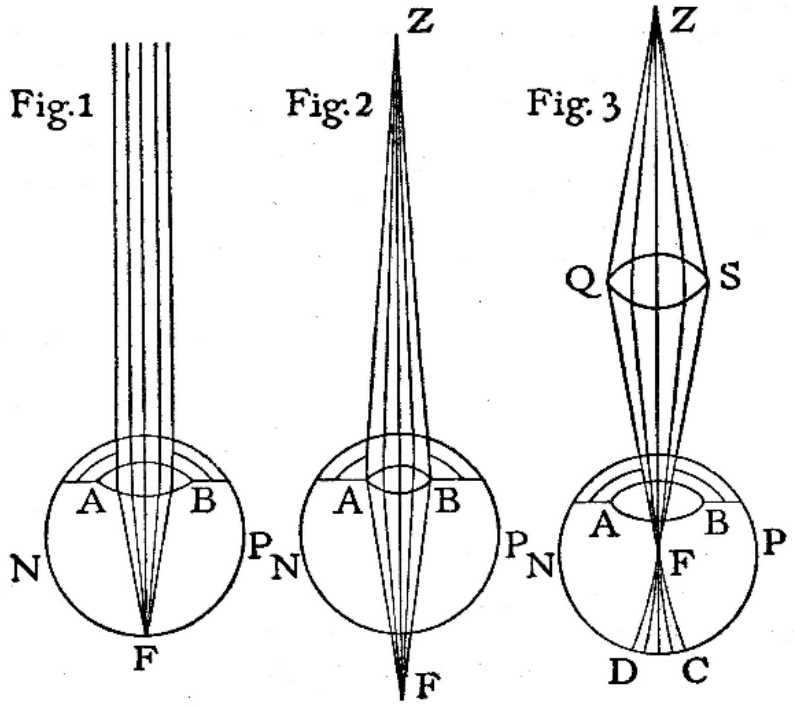
~1700 BCE

https://faculty.washington.edu/chudler/papy.html

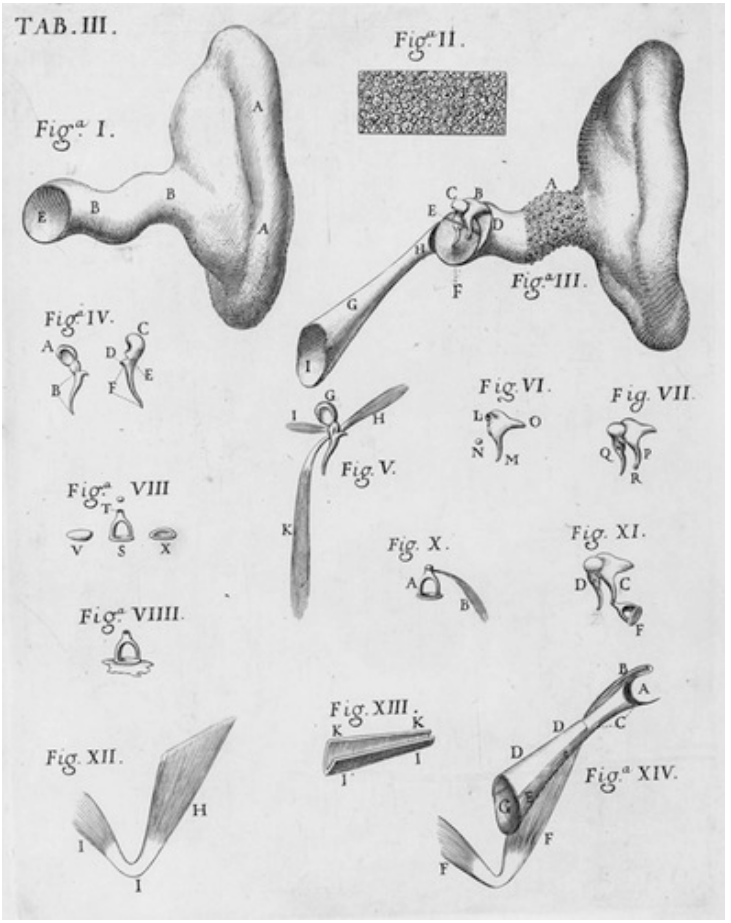
Neuroscience is a history of debates….

- The ancient Egyptians preserved the heart and other internal organs when mummifying, but discarded the brain
- Hippocrates (~400 BCE) states that the brain is involved with sensation and is the seat of intelligence
- Aristotle (~300 BCE) says heart is seat of mental process
- Galen (~100 AD) says the brain controls all the functions and the activities of the human body.

1700-1710 – Sensory Anatomy and Function



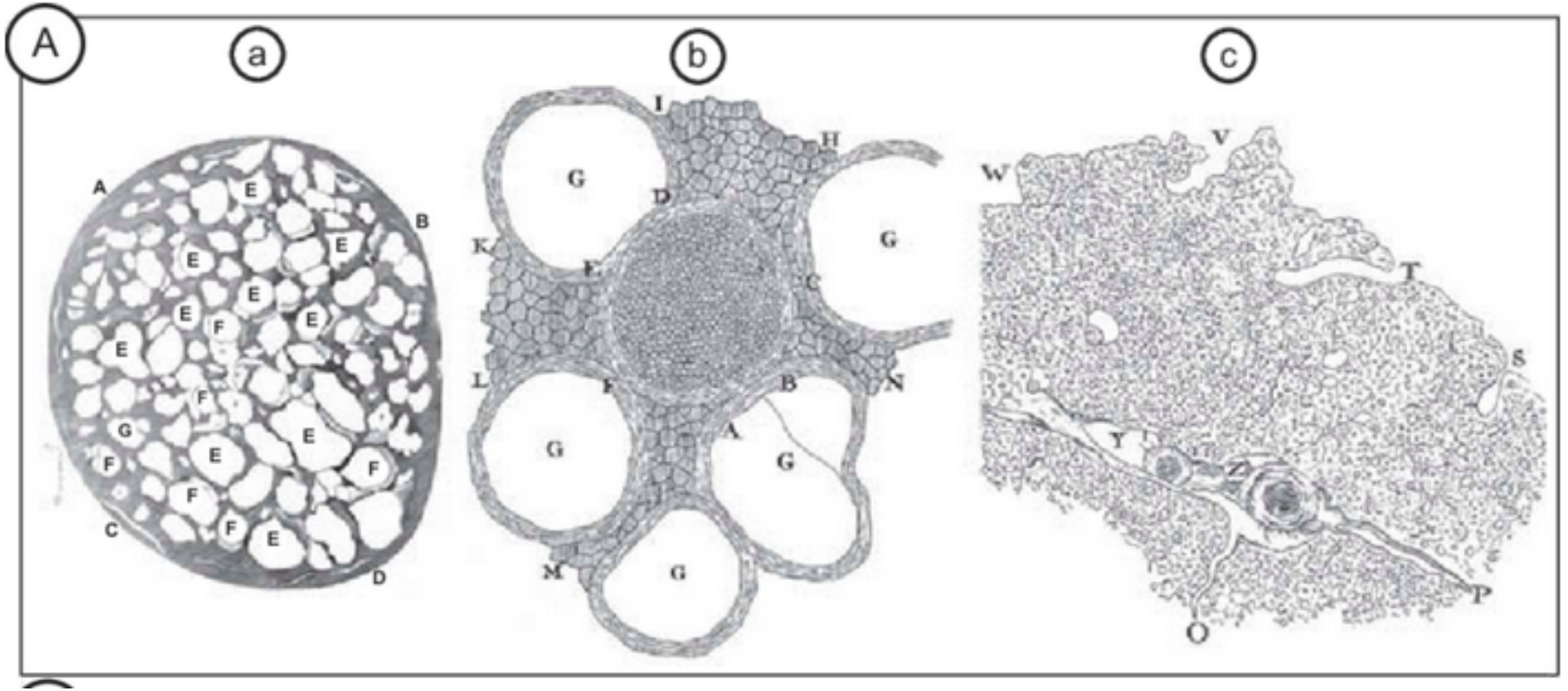
George Berkeley, *A New Theory of Vision*



Antonio Valsalva, *On the Human Ear*

1717 - Antoni van Leeuwenhoek

- Describes cross section of nerve fibers

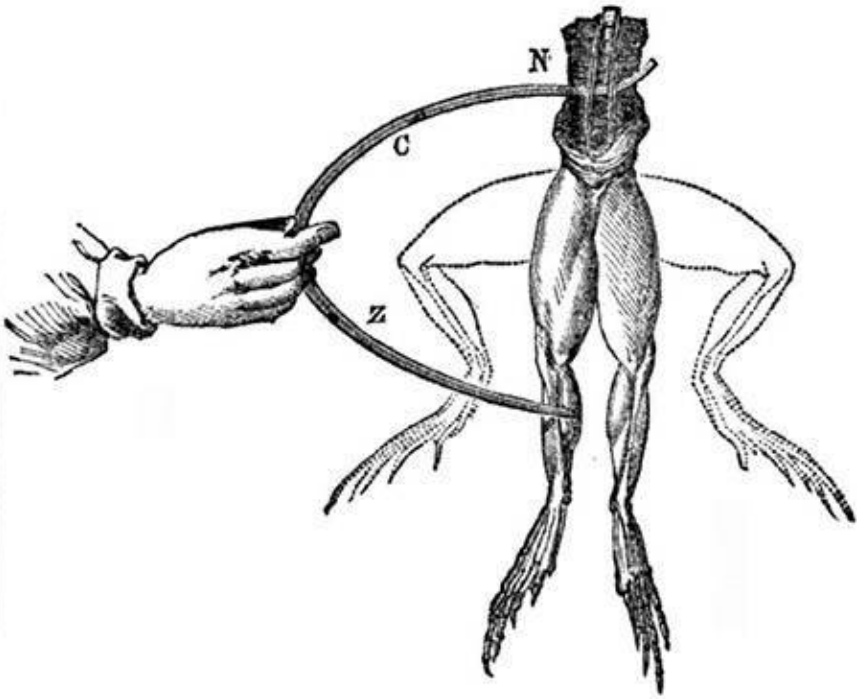


Chvátal, 2015

1791 - Luigi Galvani

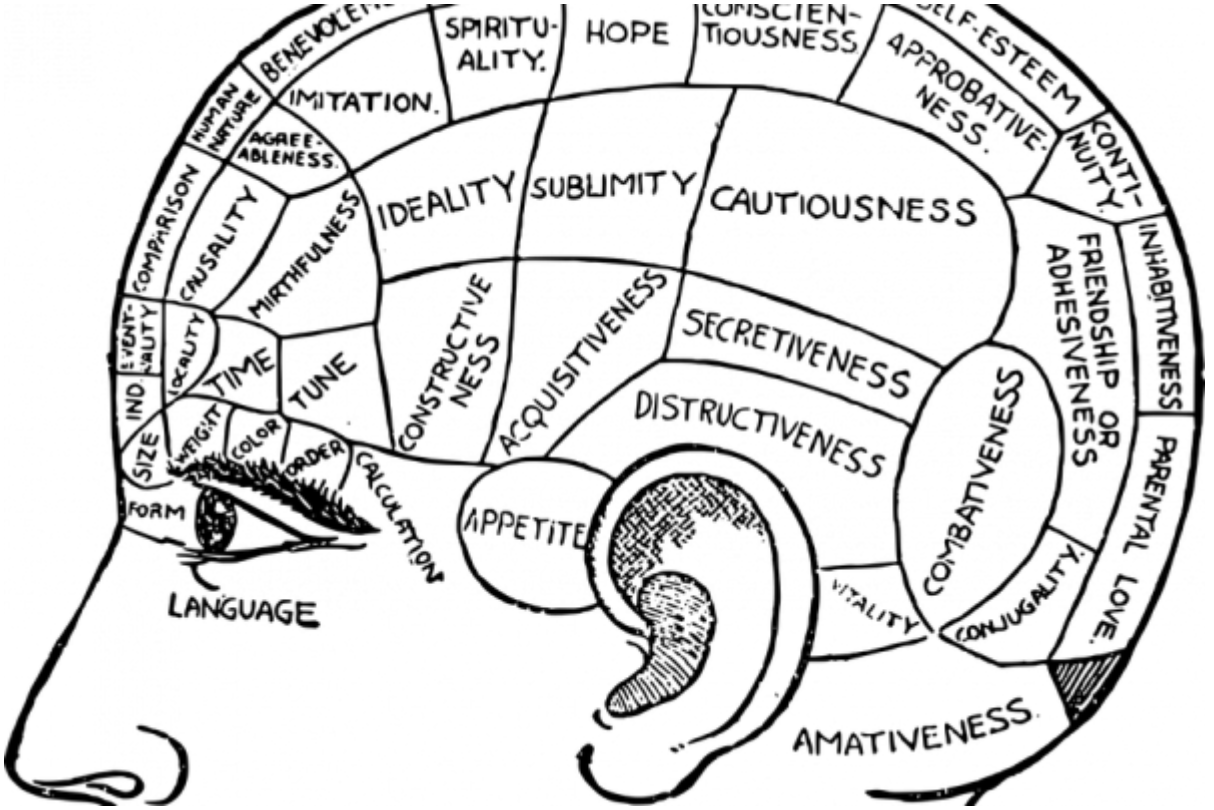
- Discovers electrical stimulation in frog nerves

  (Starts fight with Volta et el.)



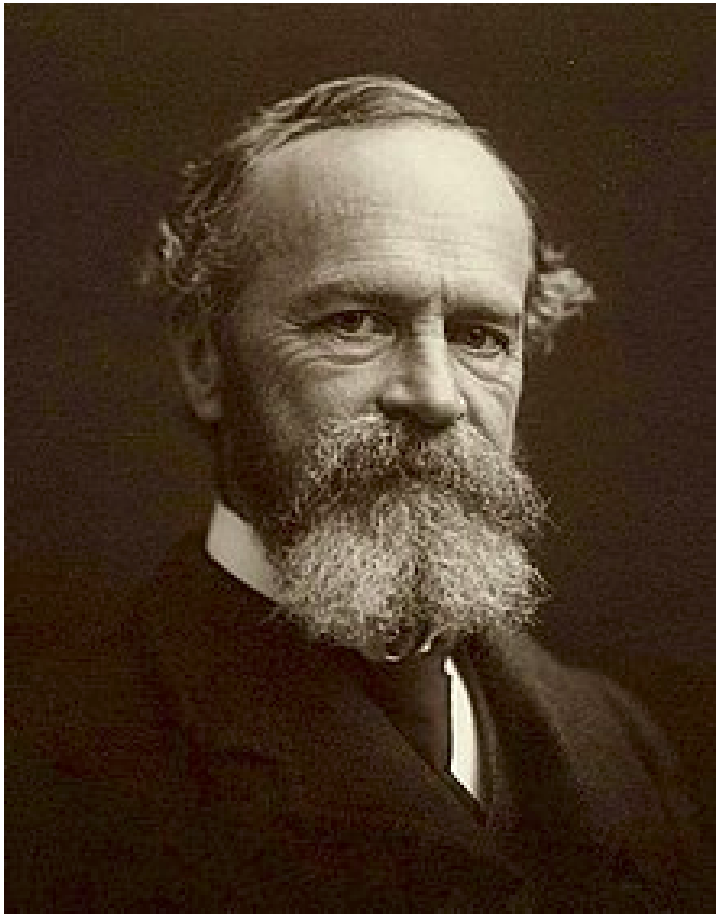
1808 – Franz Joseph Gall

- Popularizes localization of function, phrenology



1890 – William James

- Publishes *Principles of Psychology*



How did math get into the mix?

In the early days, math came into the study of the brain mainly through people who were trained jointly in mathematics and biology...

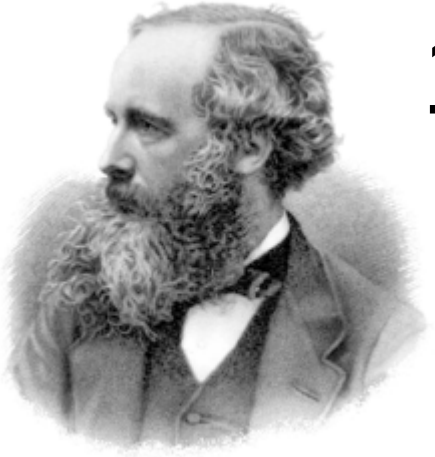
- Hermann von Helmholtz (August 31, 1821 – September 8, 1894)
- Physician, Physicist, Philosopher

Hermann von Helmholtz

- Applied conservation of energy to muscle movement
- Calculated speed of nervous transmission
- Studied auditory and visual psychophysics and wrote treatises on optics and acoustics

- Ernst Mach (18 February 1838 – 19 February 1916)

- James Clerk Maxwell (13 June 1831 – 5 November 1879)



Other sources of mathematical and computational thinking in the study of the brain...

- Artificial Intelligence
- Computer Science
- Statistics/Probability

Rev. Thomas Bayes (c. 1701 – 7 April 1761)

An Essay towards solving a Problem in the Doctrine of Chances, 1763

PROP. 2.

If a perſon has an expectation depending on the happening of an event, the probability of the event is to the probability of its failure as his loſs if it fails to his gain if it happens.

Suppoſe a perſon has an expectation of receiving N, depending on an event the probability of which

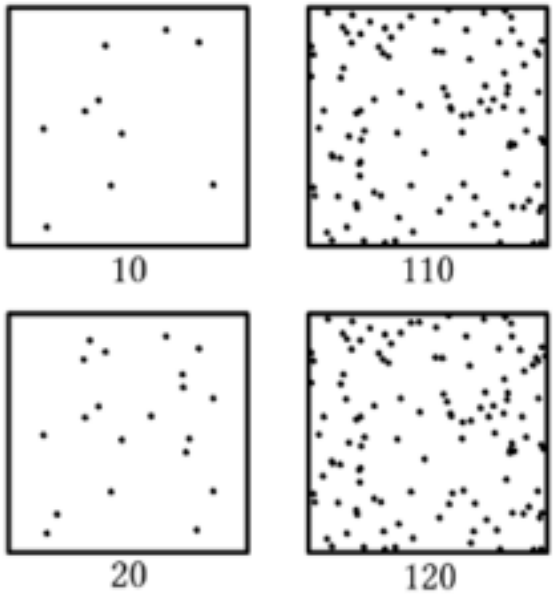
Ada Lovelace (10 December 1815 – 27 November 1852)

- Early computer scientist
- Wanted to create a mathematical model for how the brain gives rise to thoughts and nerves to feelings ("a calculus of the nervous system")

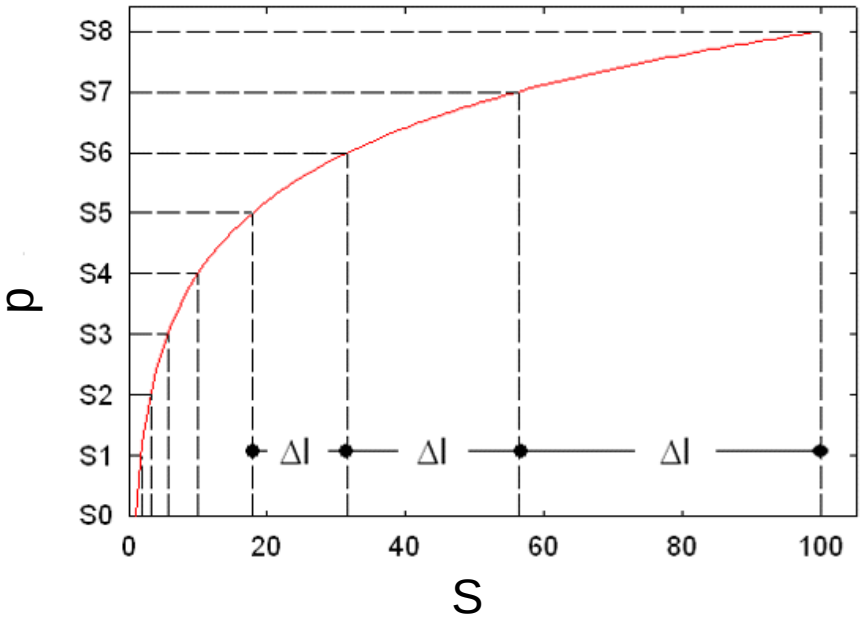
Mathematics of behavior

Mathematics of behavior

- Gustav Fechner (19 April 1801 – 18 November 1887)



Weber-Fechner Law

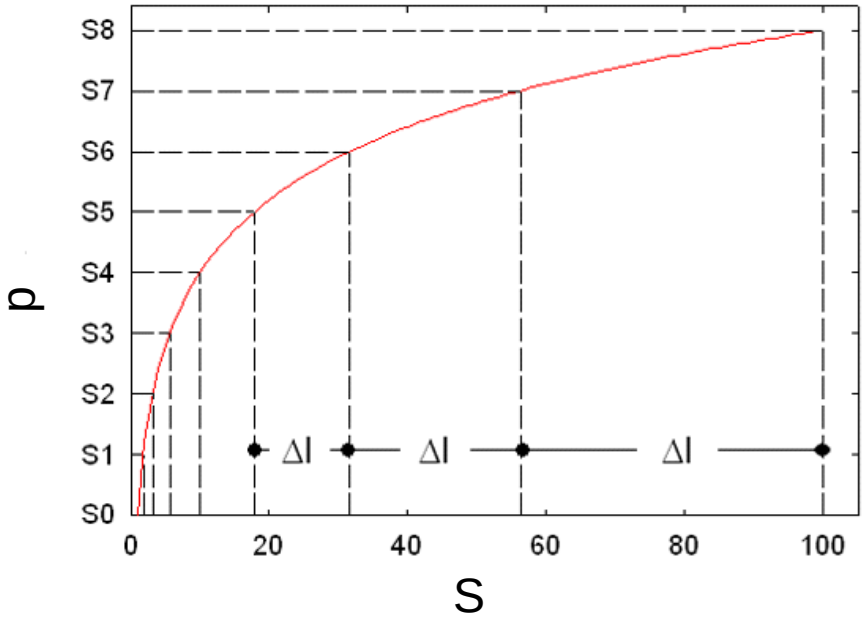


$$p = k \ln \frac{S}{S_0}$$

Mathematics of behavior

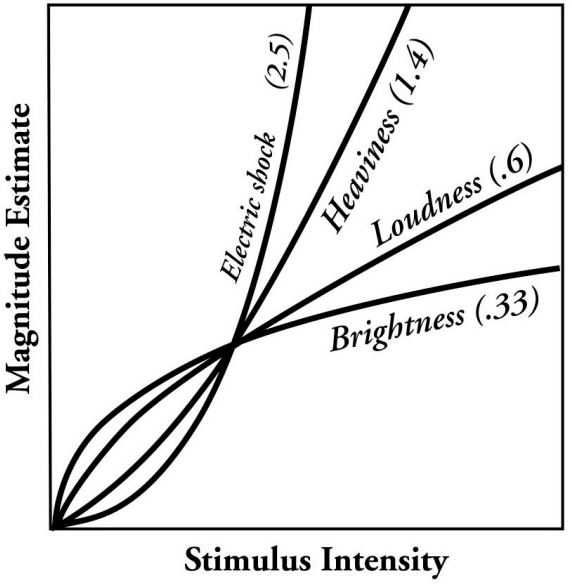
- Stanley Smith Stevens (November 4, 1906 – January 18, 1973)

Weber-Fechner Law



$$p = k \ln \frac{S}{S_0}$$

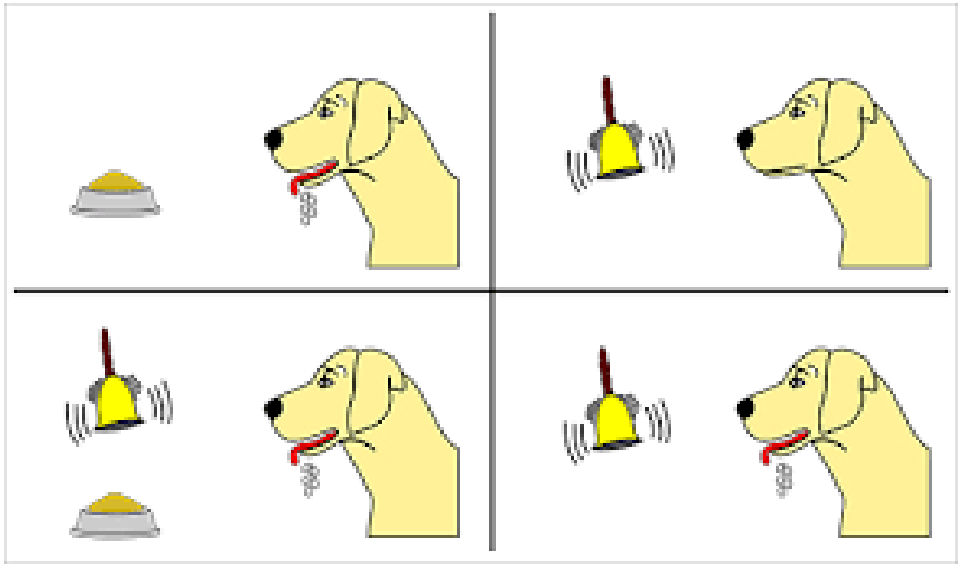
Stevens Law



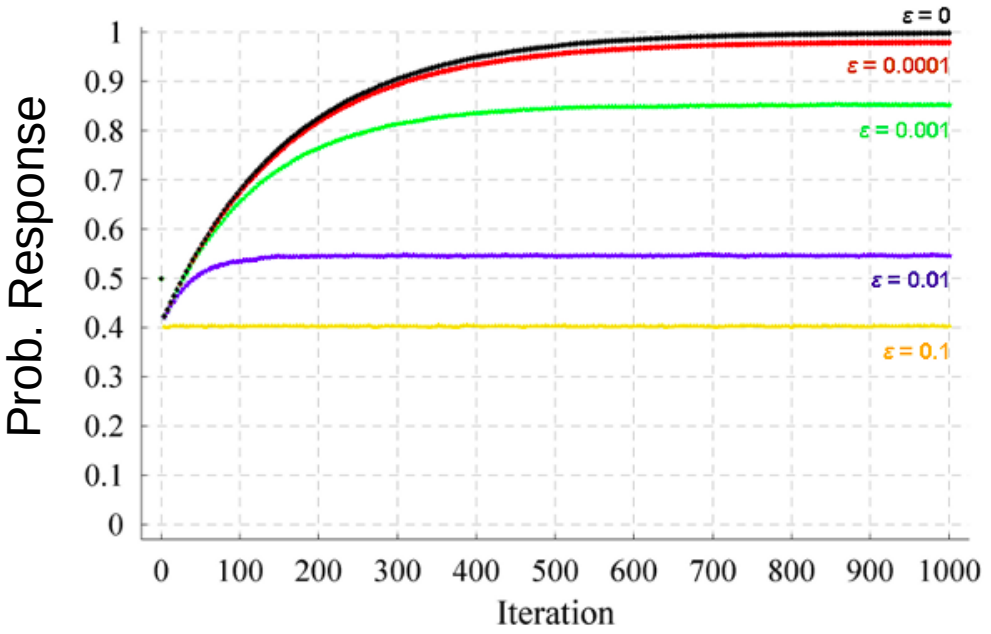
$$p = k\left(S - S_0\right)^n$$

Mathematics of behavior

- Robert R Bush (physicist, 1920 – 1972)
- Frederick Mosteller (statistician, 1916 – 2006)

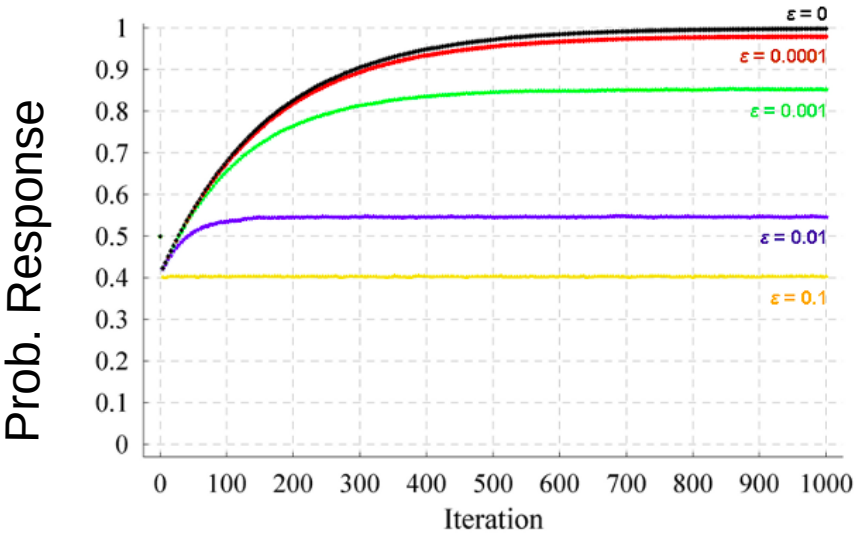


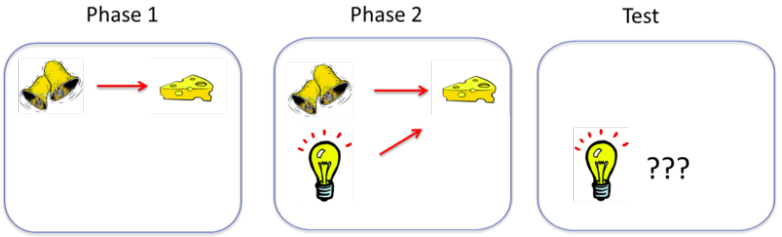
Pavlov's Dogs



Mathematics of behavior

Bush-Mosteller model





Rescorla-Wagner model (1972)

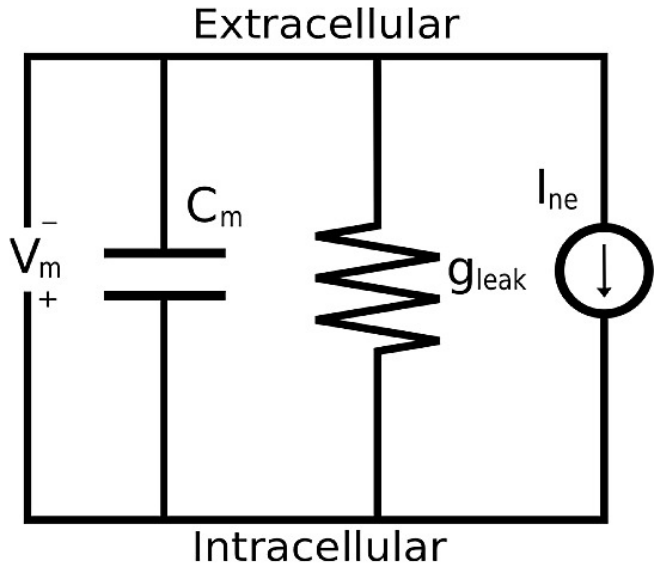
Temporal Difference Learning (Sutton, 1988)

Reinforcement Learning

Mathematics of electrophysiology

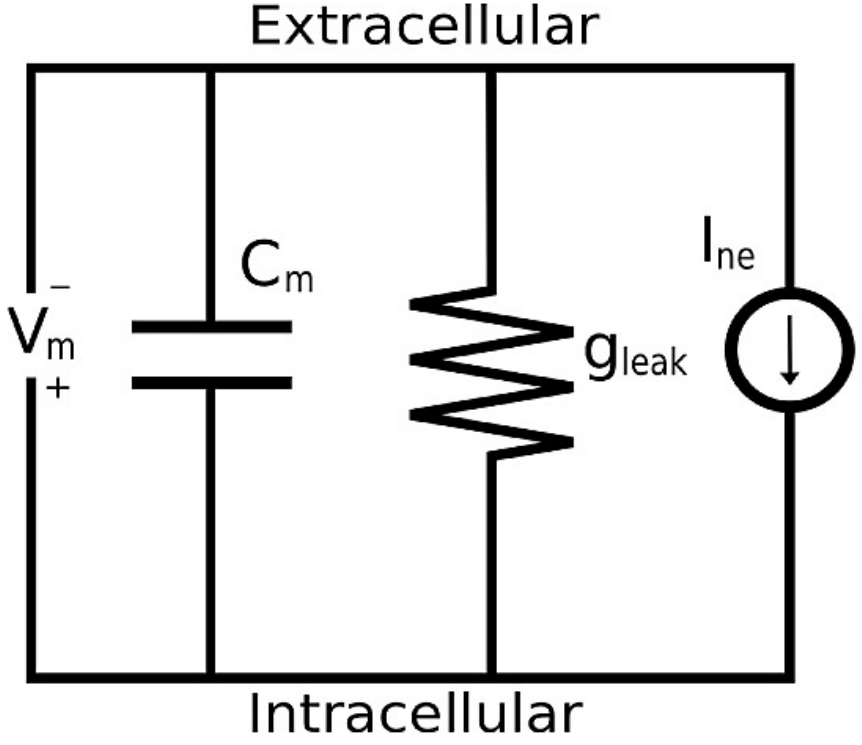
Mathematics of electrophysiology

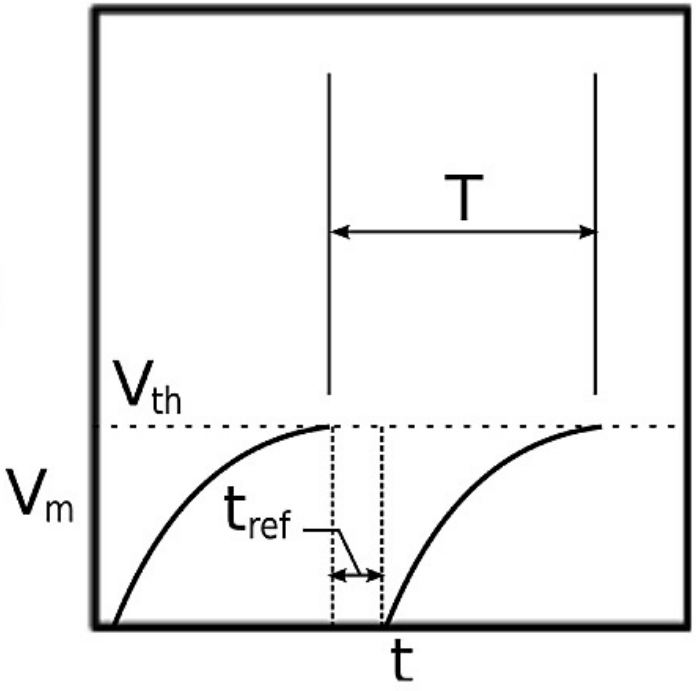
- Louis (1866-1952) and Marcelle (1873–1960) Lapicque
- Compared the nerve to an “equivalent circuit”



Mathematics of electrophysiology

- The equivalent circuit set the groundwork for the “leaky integrate and fire” model





$$C_m \frac{dV_m}{dt} = I_{ne} - g_{leak} V_m,$$

Mahdi et al, 2013

Mathematics of electrophysiology

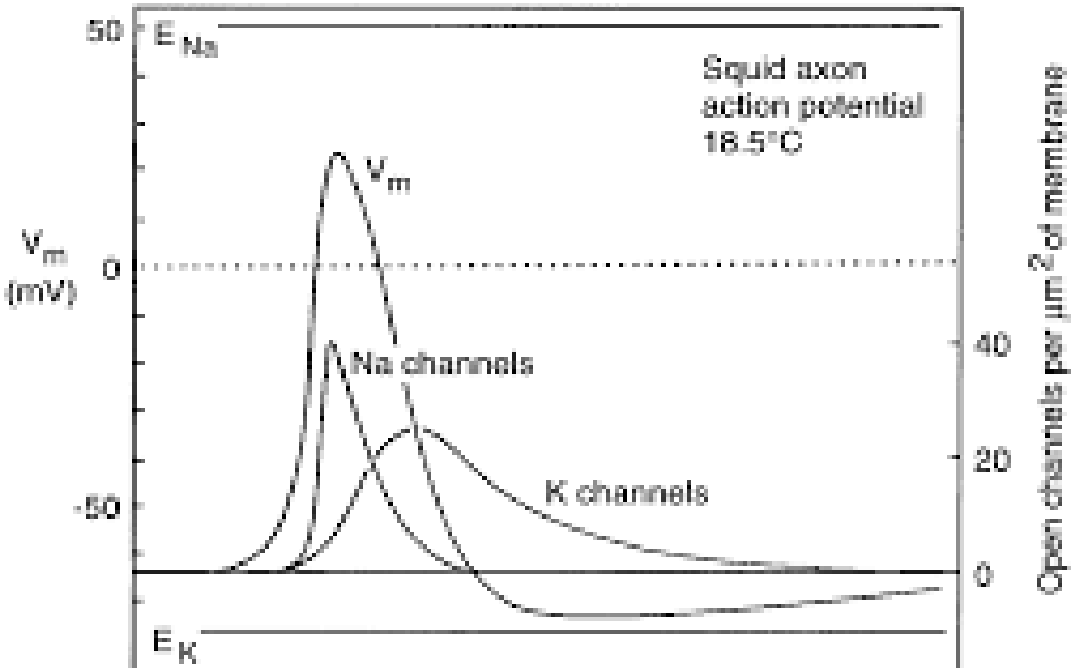
- Alan Hodgkin (5 February 1914 – 20 December 1998)
- Andrew Huxley (22 November 1917 – 30 May 2012)

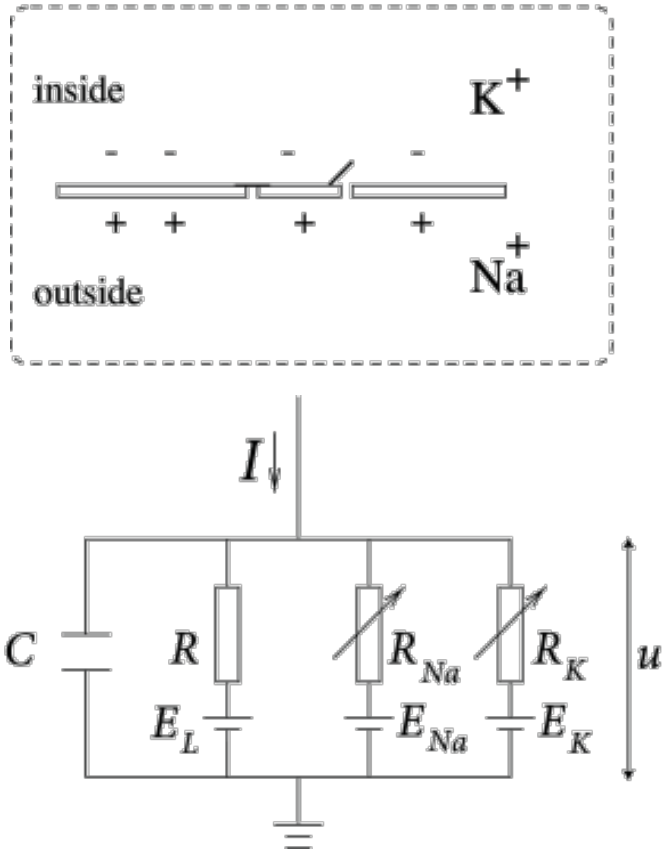
NERVE-CELL ENIGMA SOLVED

The British scientists, A. L. Hodgkin and A. F. Huxley, experimenting with the nerve fibers of squids and lobsters.

Mathematics of electrophysiology

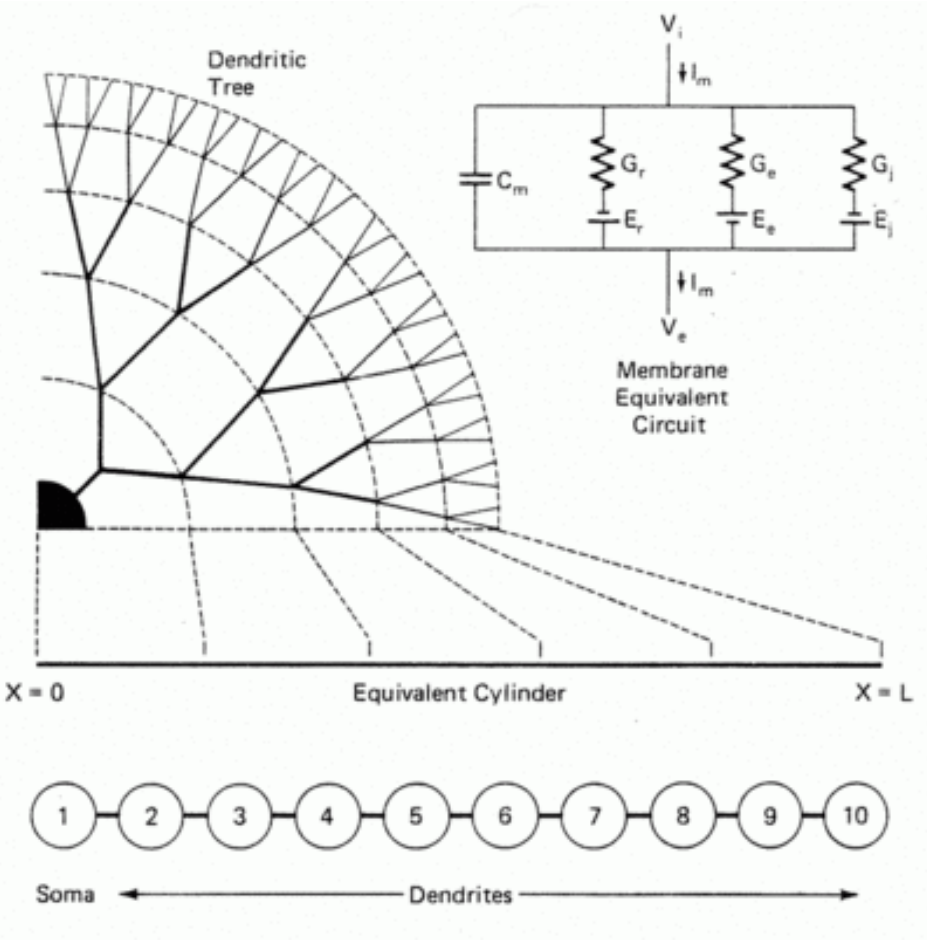
- Hodgkin-Huxley model expanded the “equivalent circuit” to explain the shape of the action potential





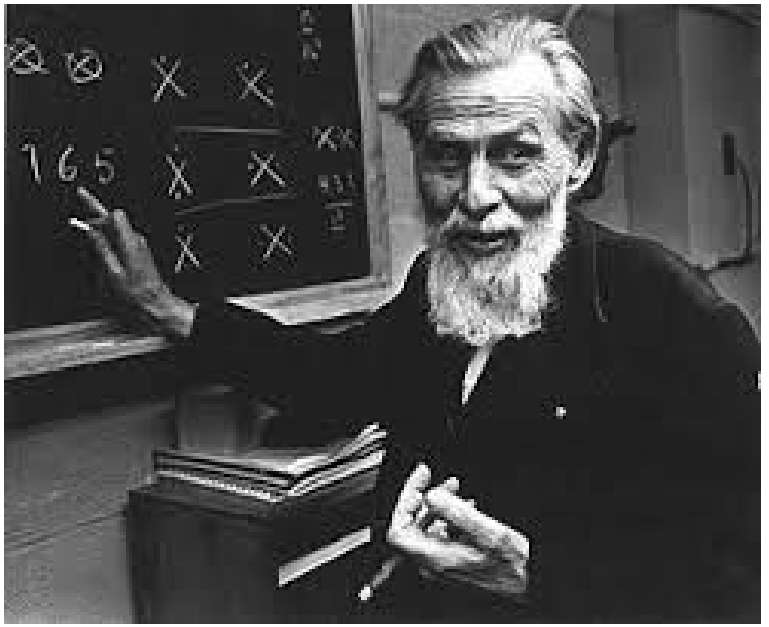
Mathematics of electrophysiology

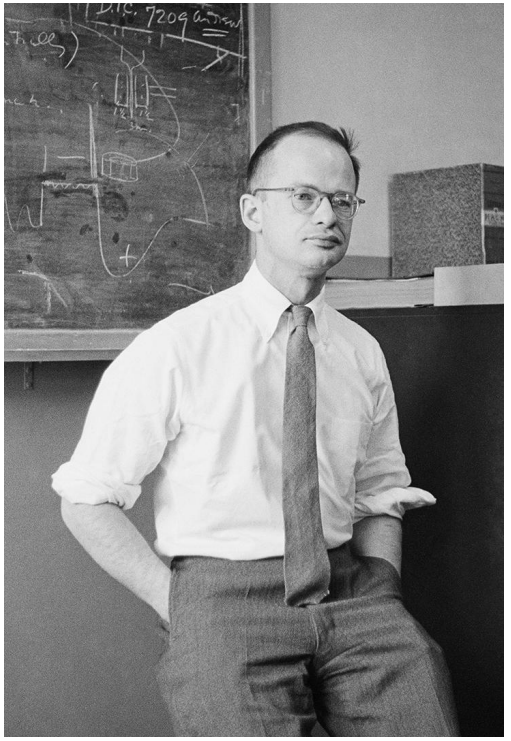
- Wilfrid Rall (August 29, 1922 - April 1, 2018)
- Extended the equivalent circuit model to include dendrite morphology



Mathematics of Artifical Neural Networks (ANNs)

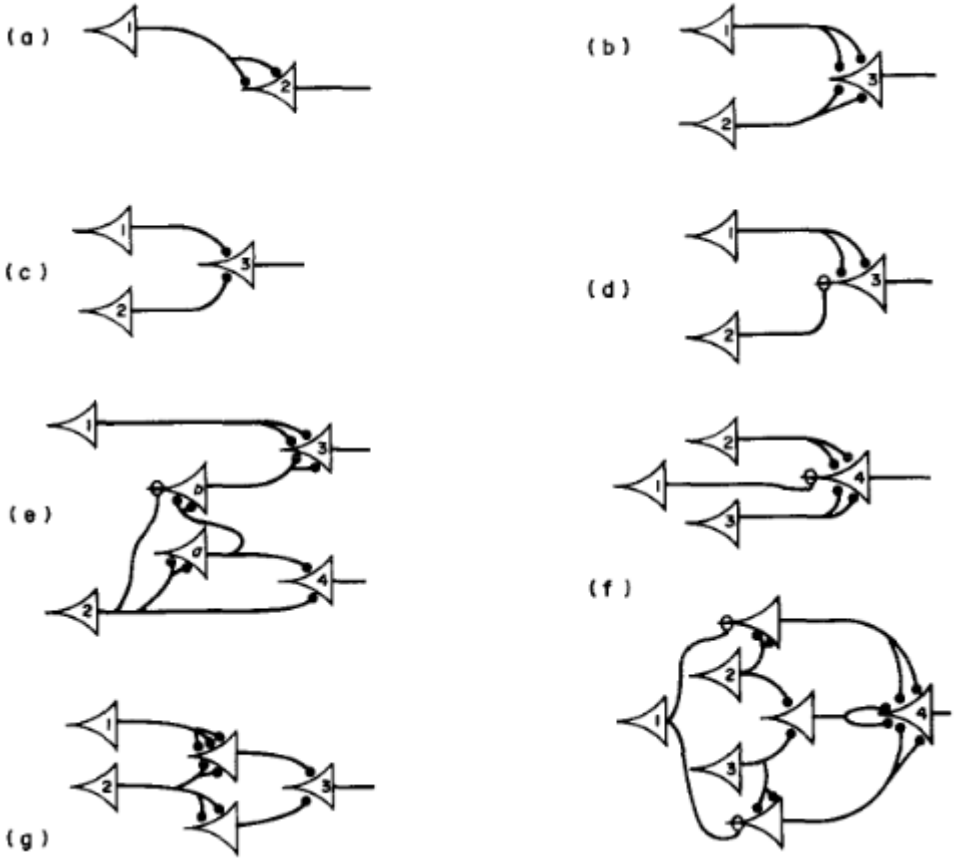
Mathematics of ANNs





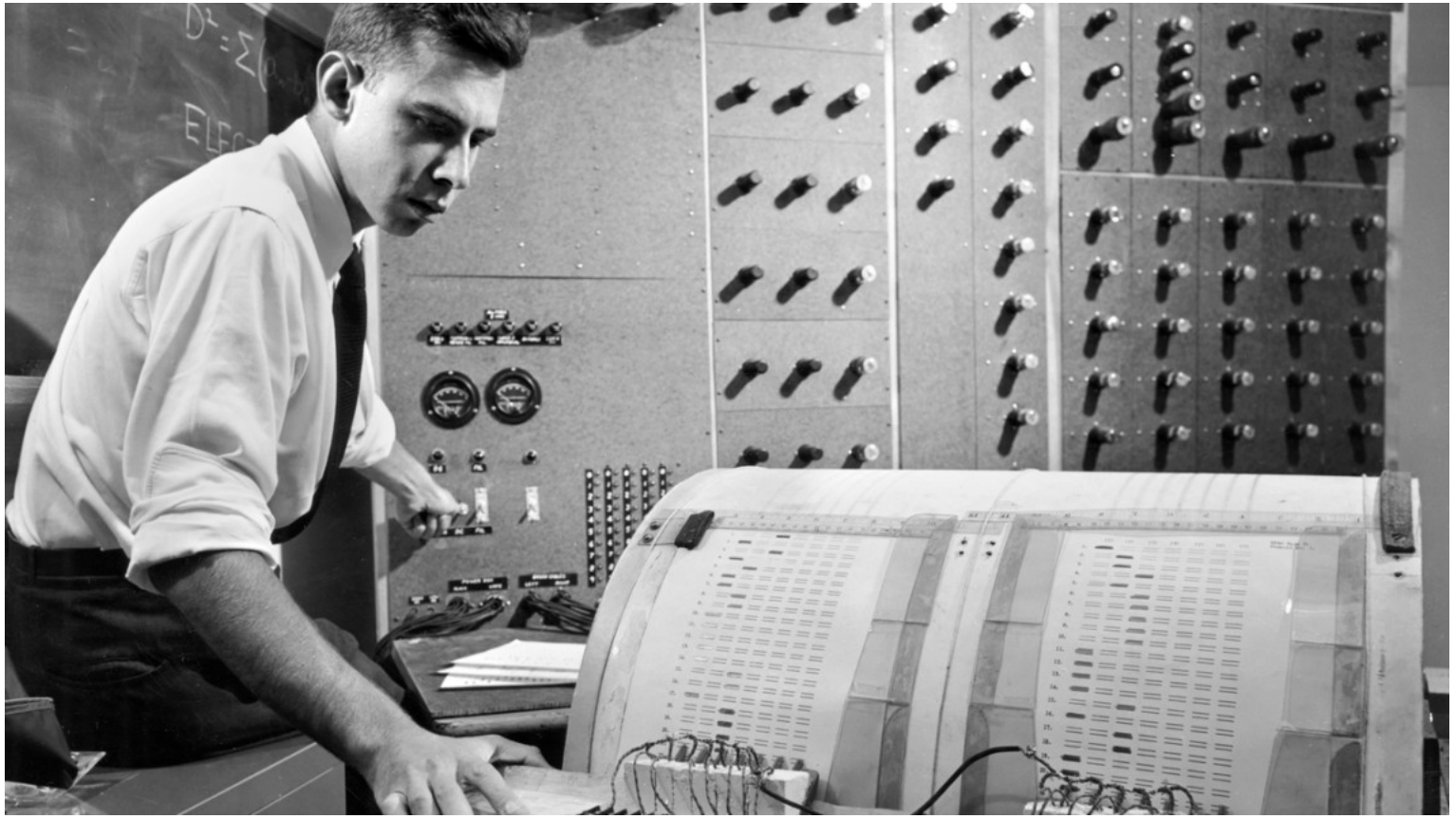
- Warren McCulloch (1898 –1969)
- Walter Pitts (1923-1969)

Mathematics of ANNs



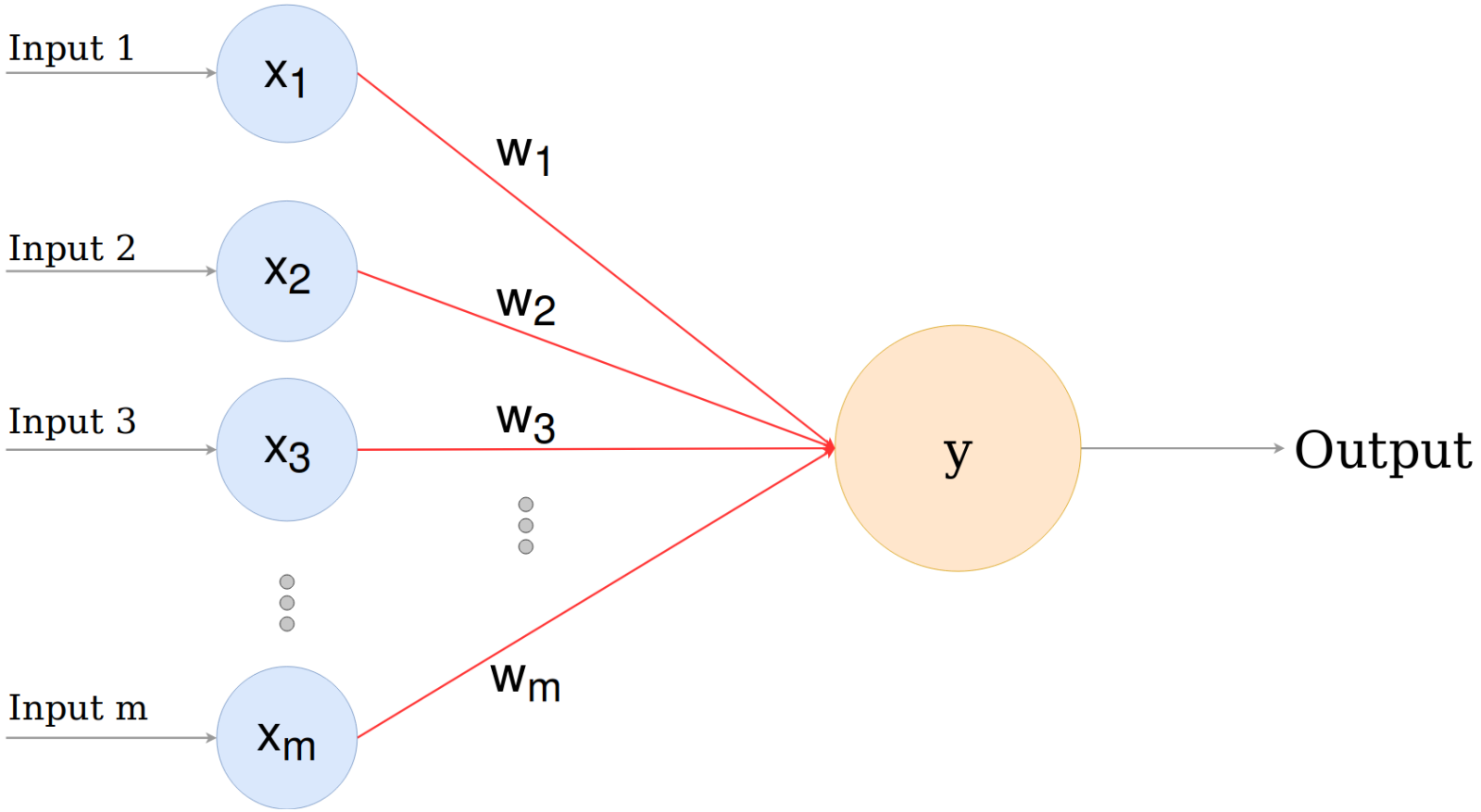
A LOGICAL CALCULUS OF THE IDEAS IMMANENT IN NERVOUS ACTIVITY (1943)

Mathematics of ANNs



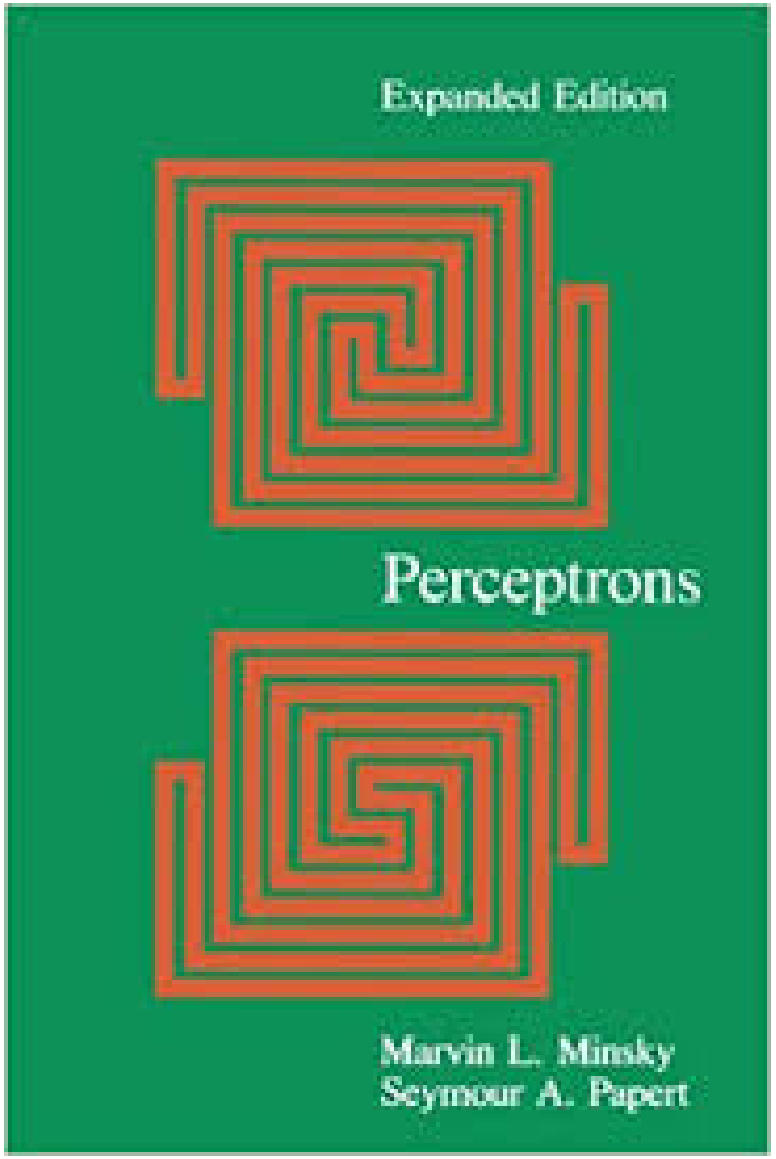
Frank Rosenblatt’s Perceptron (1958)

Mathematics of ANNs

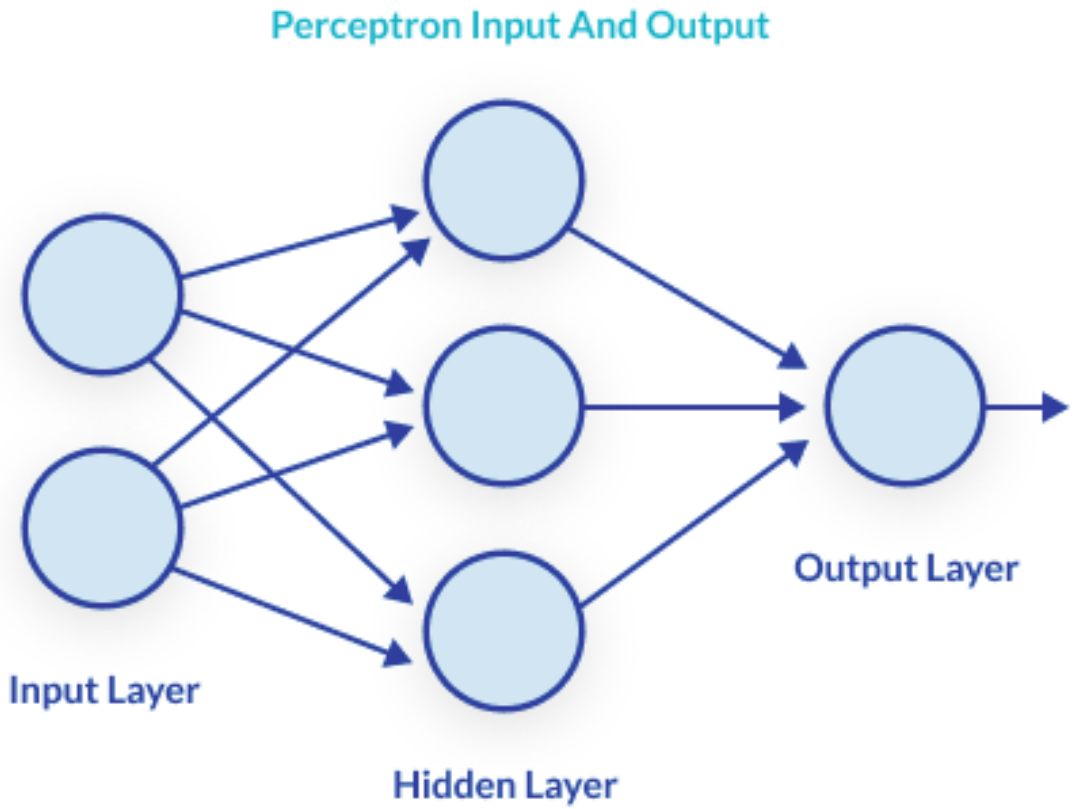


Perceptron Algorithm

Mathematics of ANNs



Mathematics of ANNs



Multi-layer Perceptrons and Back-Propagation

Mathematics of information

Mathematics of information

- Claude Shannon published “A Mathematical Theory of Communication” in 1948

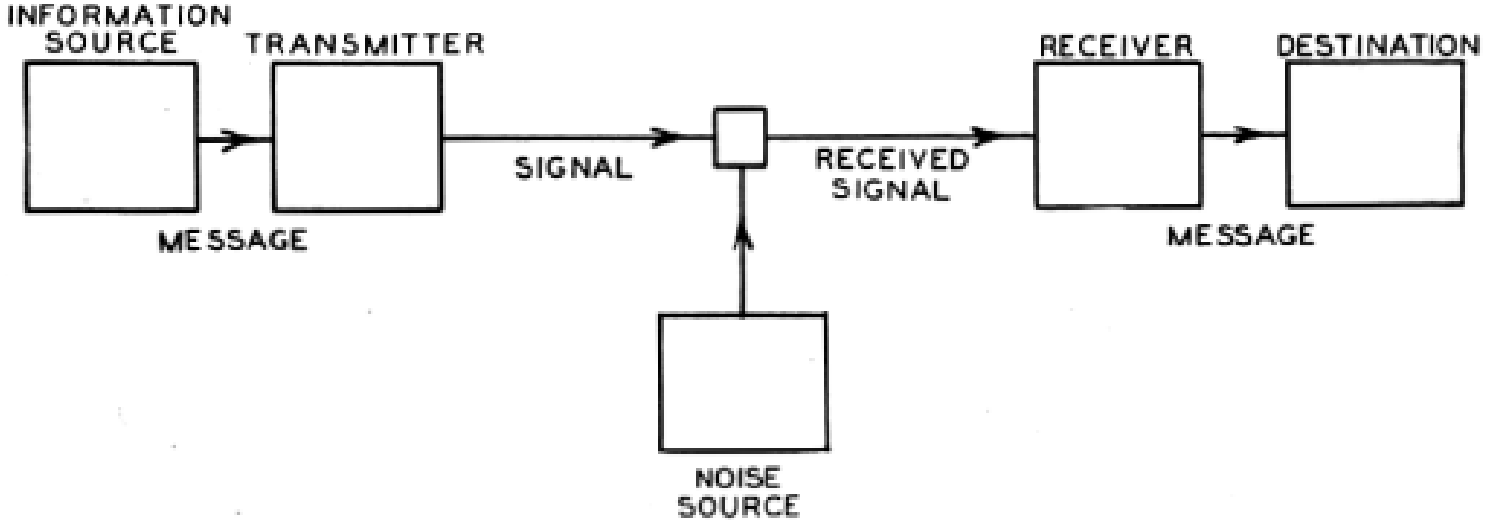
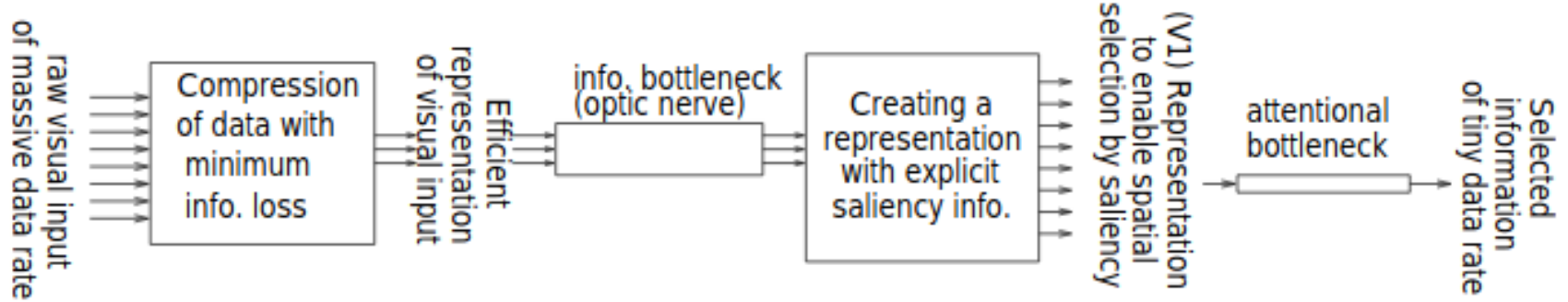


Fig. 1—Schematic diagram of a general communication system.

Mathematics of information

- In 1961, Horace Barlow introduces what is known as the “efficient coding hypothesis”



Li Zhaoping, 2006

The separation of math from the study of the brain

The separation of math from the study of the brain

“[A] schism of major scientific importance occurred towards the end of the nineteenth century. Scientists whose work was previously greatly energized by interdisciplinary investigations of physics and psychology were rapidly replaced by scientists who rarely had even a rudimentary knowledge of the other field.”

-Stephen Grossberg, 1988

The separation of math from the study of the brain

“A major approach-avoidance paradigm was hereby established in the practice of theoretical science. Theoretical physicists abandoned psychology and neurobiology to rapidly fashion theories about the external world that could be quantitatively supported by available mathematical concepts and methods. Psychologists and neurobiologists returned the favor by abandoning physical concepts and mathematics that seemed irrelevant to their data and, over time, by also eschewing and even denigrating theoretical and mathematical training in general.”

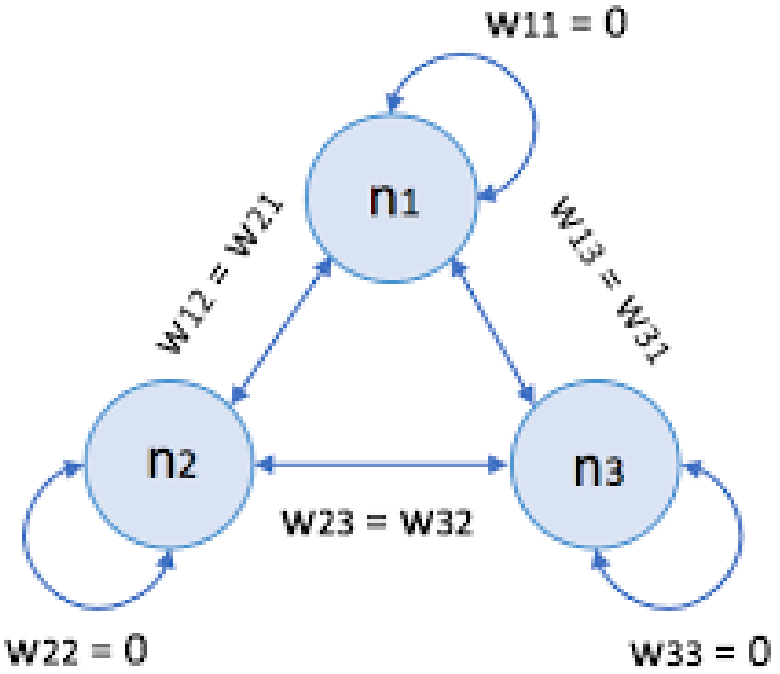
-Stephen Grossberg, 1988

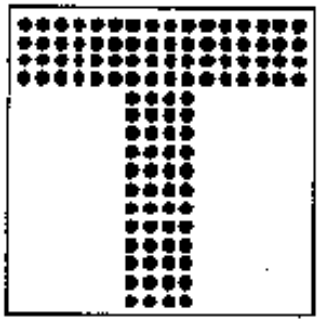
A shift happened around the 1980s...

A shift happened around the 1980s...

- John Hopfield
- Condensed matter physicist that got interested in biology

Hopfield Network





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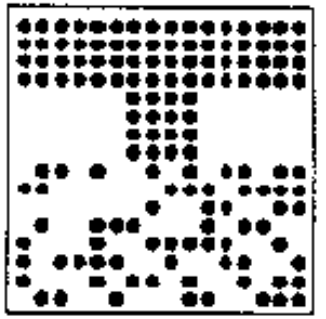


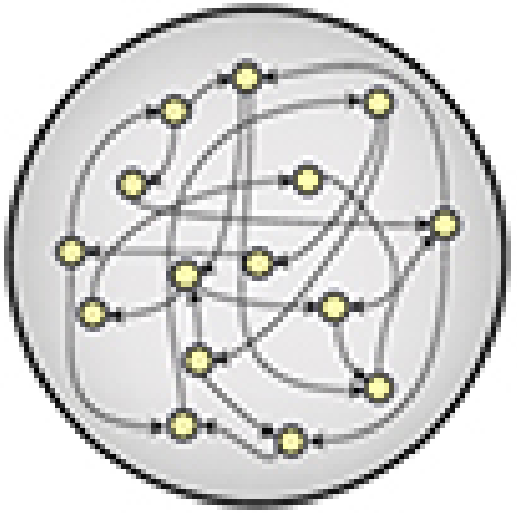
half of image corrupted by noise

“The sheer beauty of this calculation drew a large batch of physicists into the field. These new immigrants entered with high confidence-to-knowledge ratios that, hopefully, have been reduced through large growth in the denominators and more modest adjustments of the numerators.”

-Larry Abbott

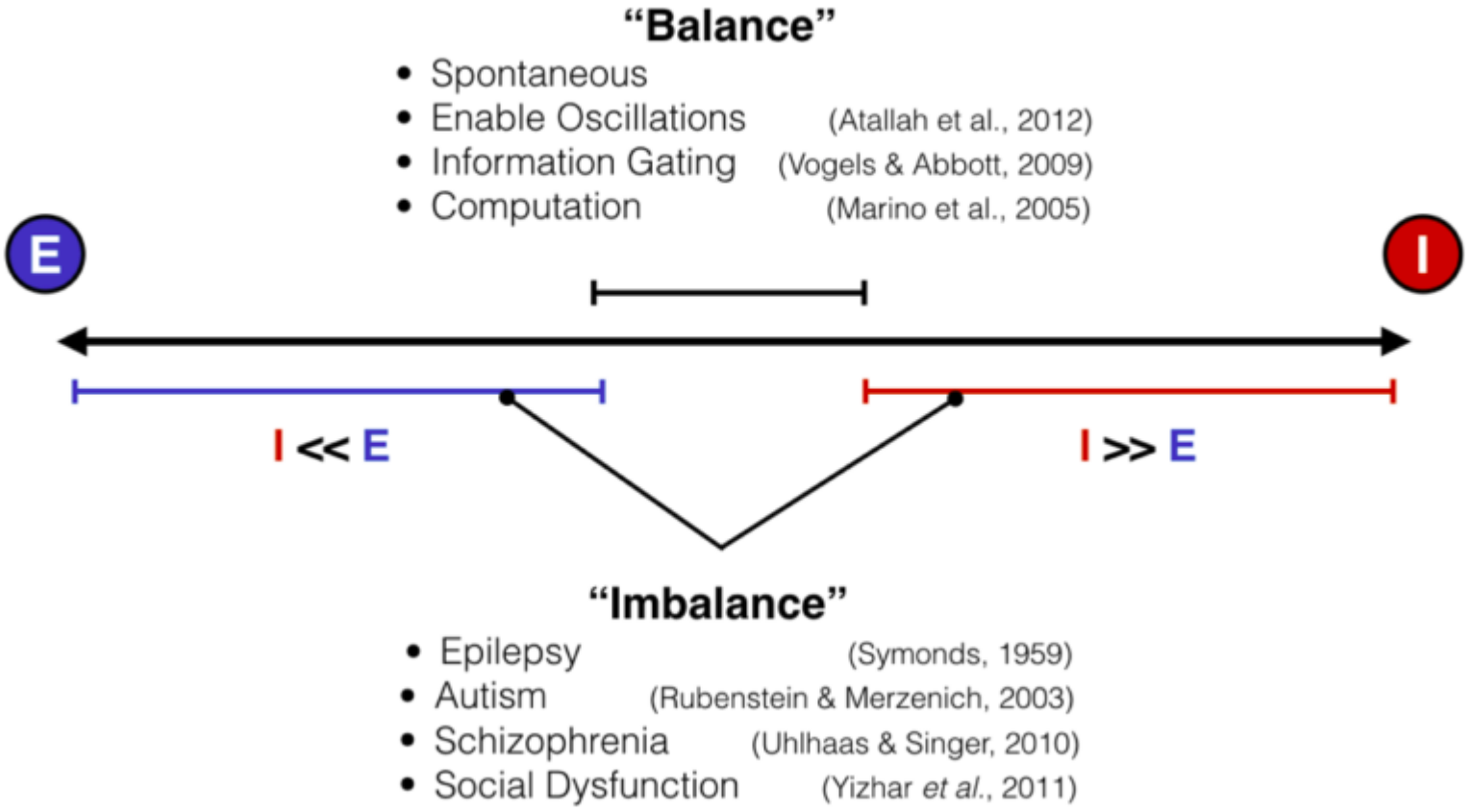
Applying statistical physics to neuroscience

- Haim Sompolinsky

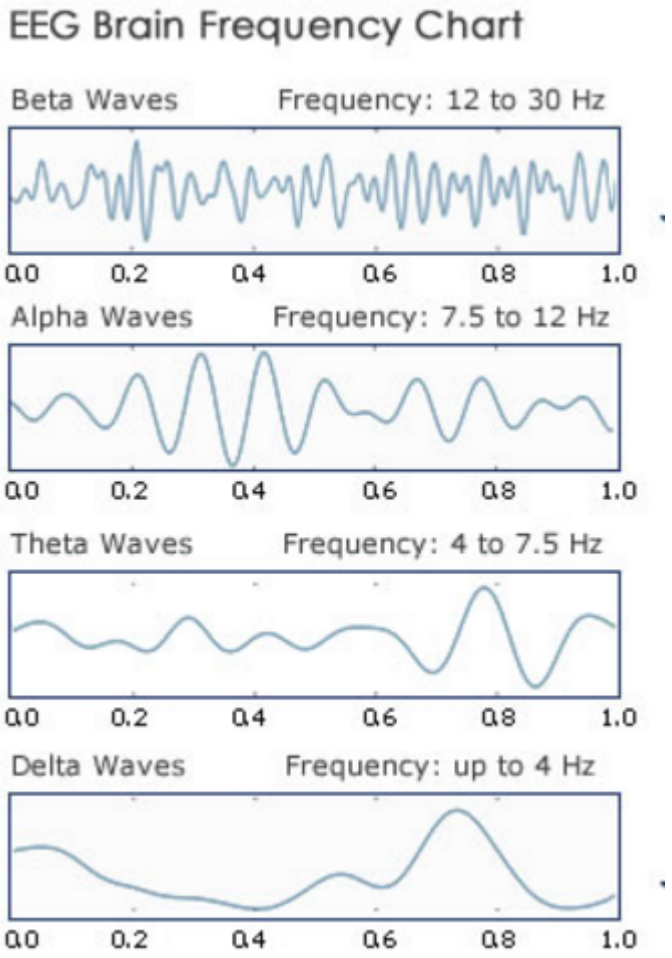


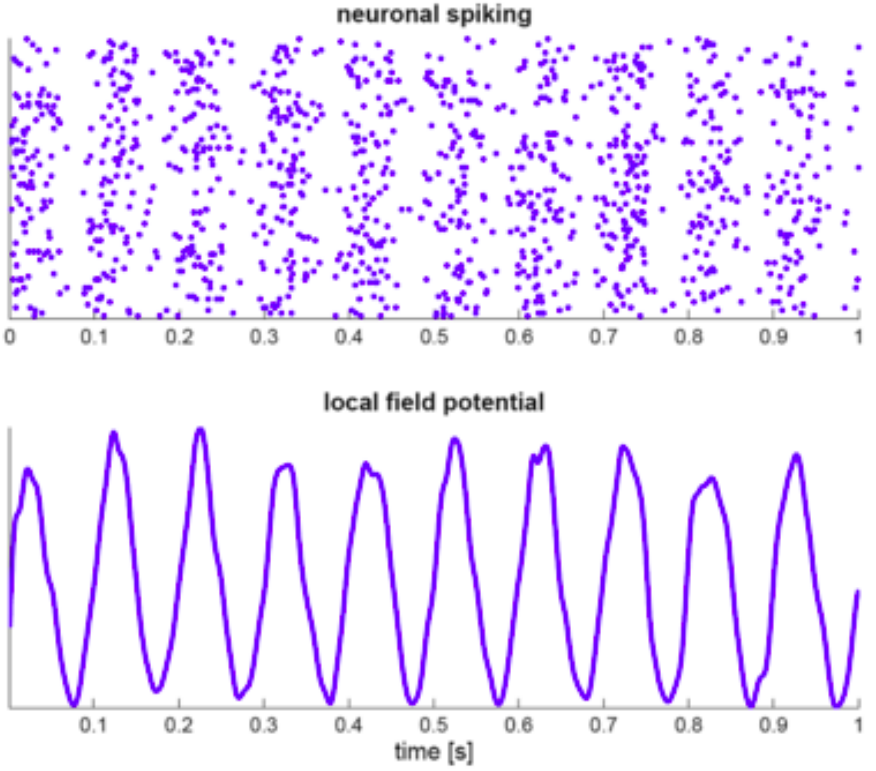
Applying statistical physics to neuroscience

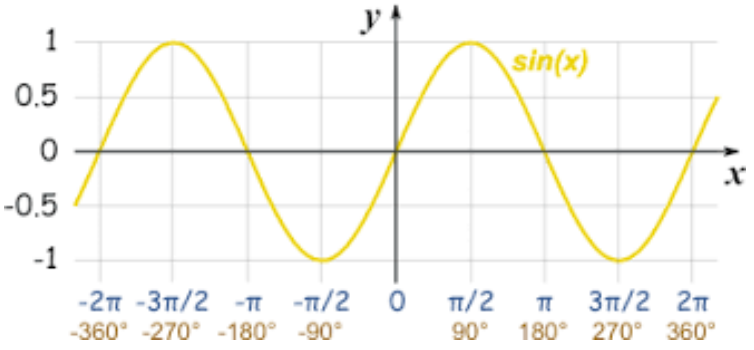
- EI balance



Oscillations

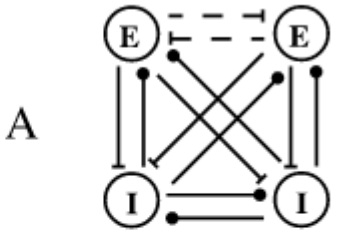


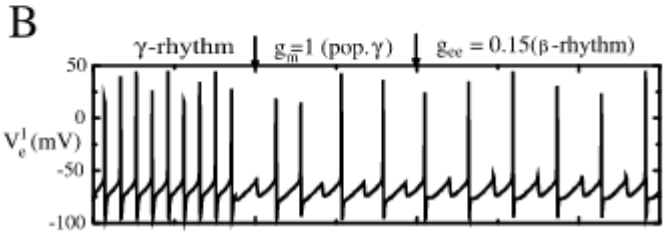




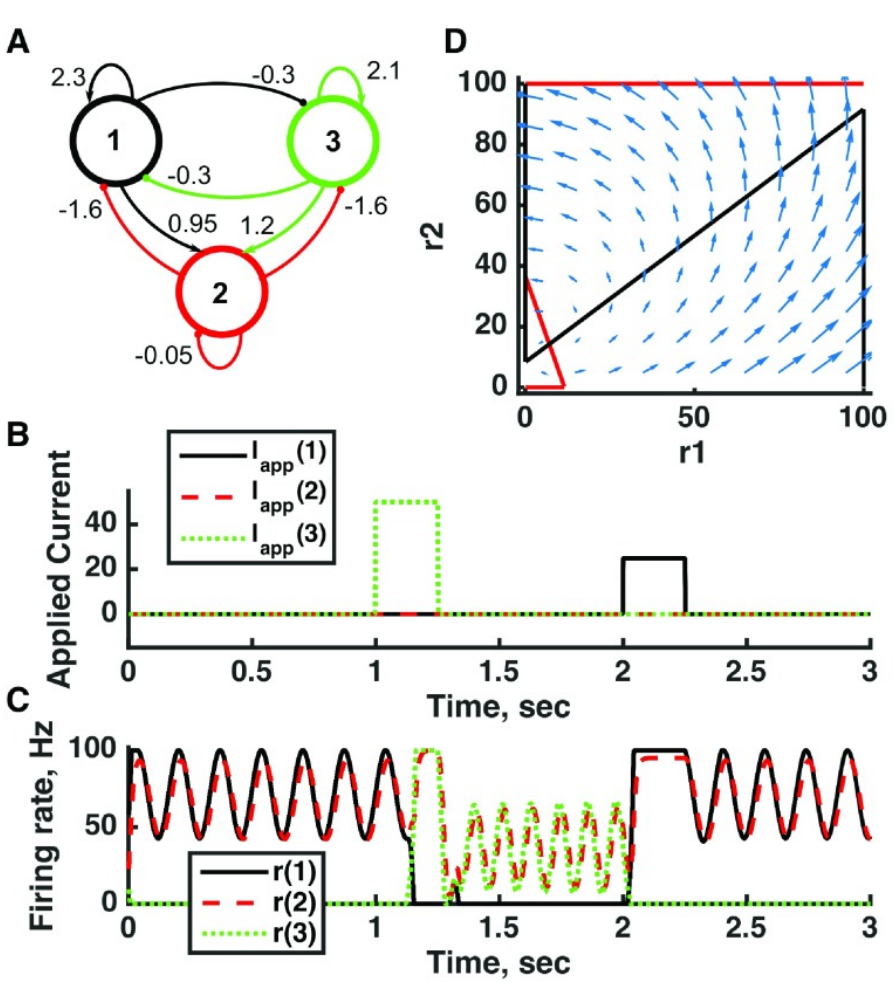
Nancy Kopell

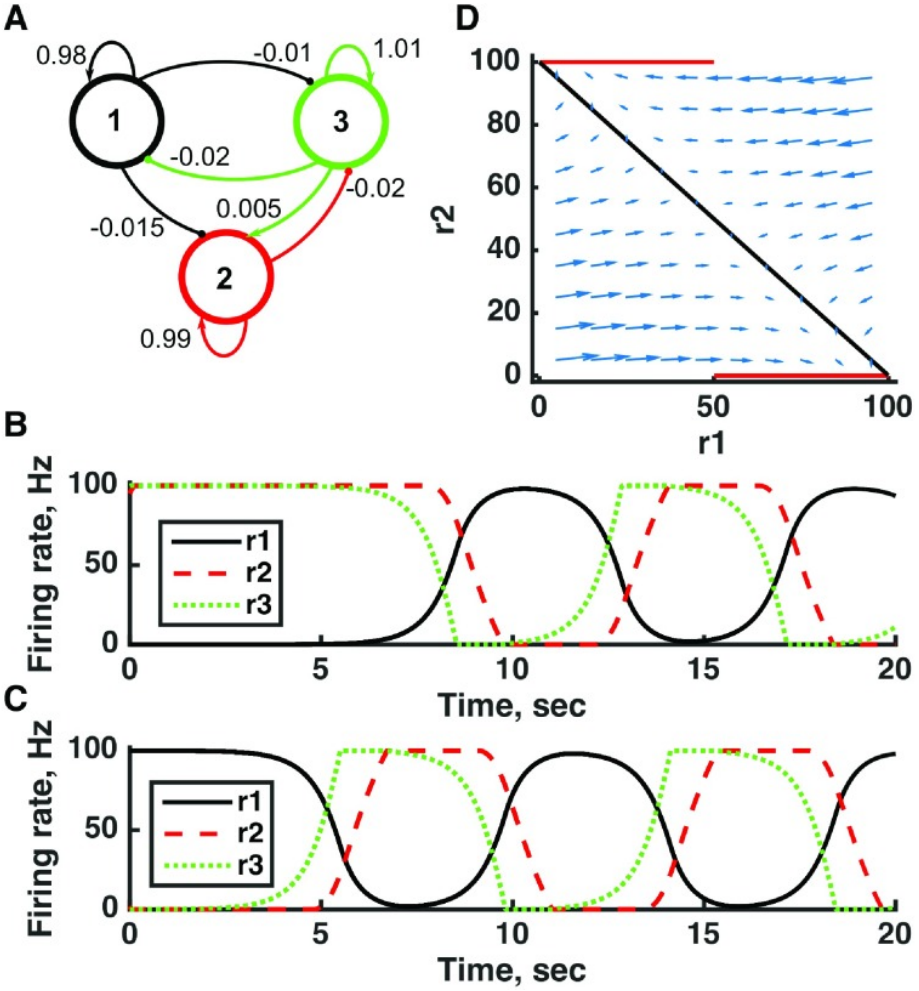
- Mathematician
- Extensive work on building oscillatory models and understanding their role





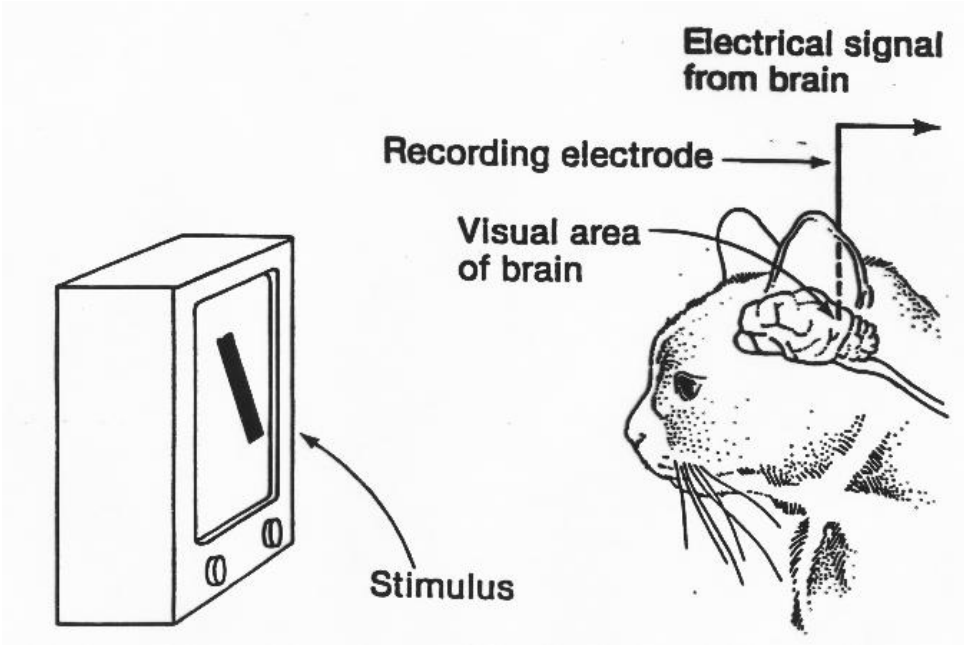
Dynamical systems analysis of neural circuits

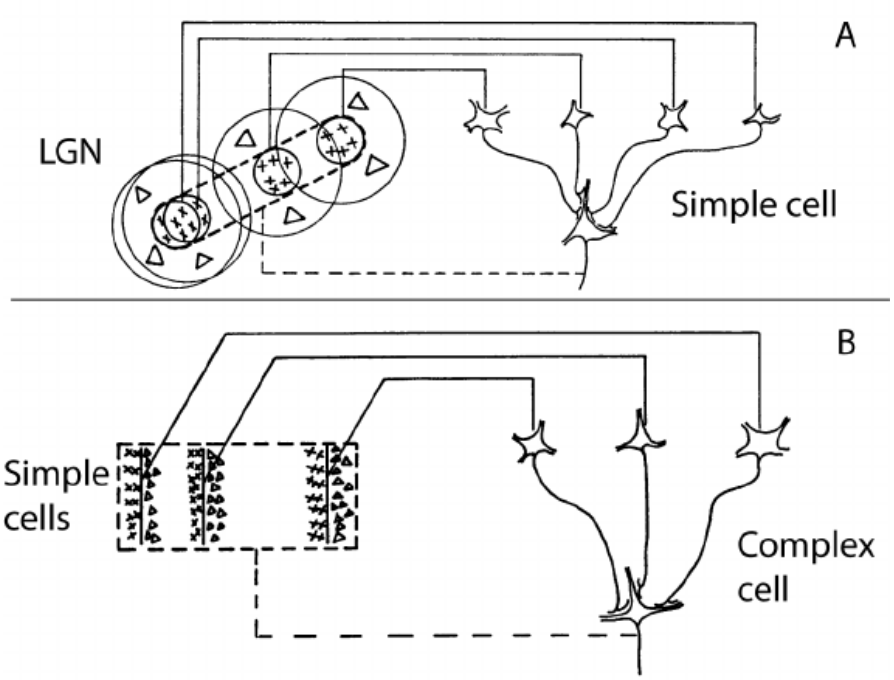




Miller, 2016

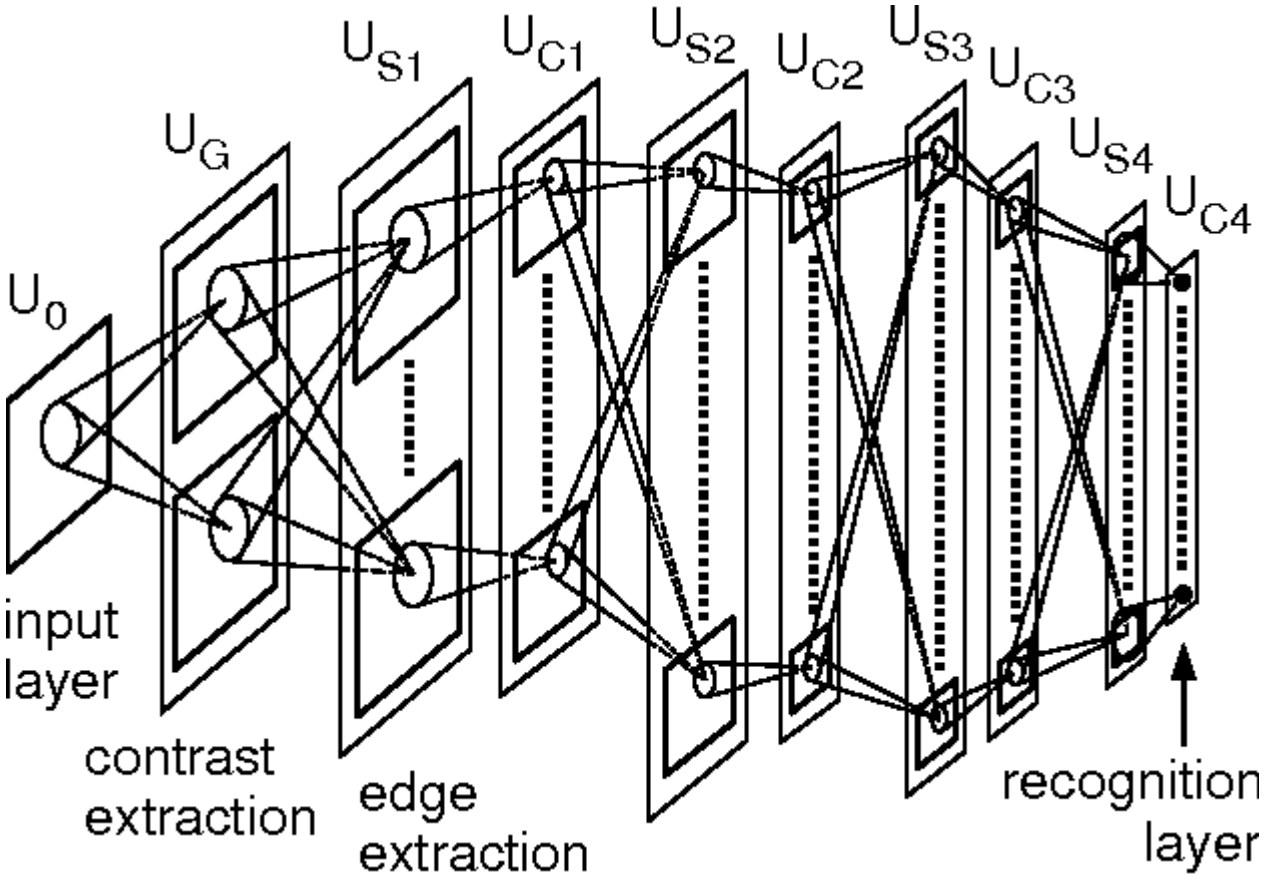
Neocognitron (1980)





Hubel & Wiesel, 1962

Neocognitron (1980)



Fukushima, 1980

Marr's Levels

Computation

constrains

"What is the goal of the computation, why is it appropriate, and what is the logic of the strategy by which it can be carried out?"

Representation and algorithm

constrains

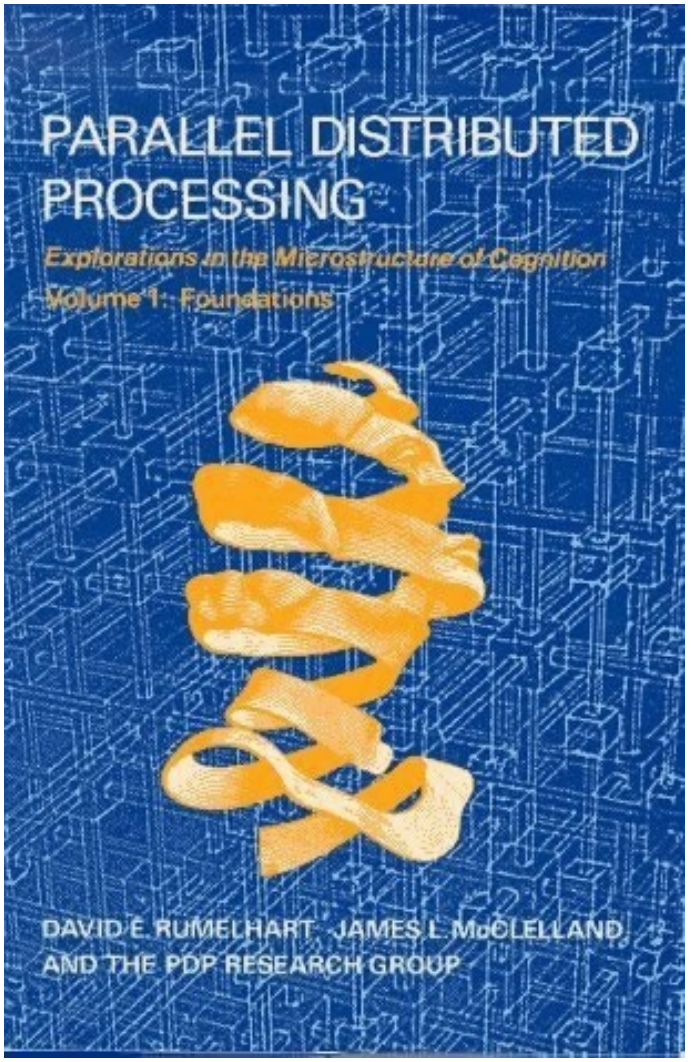
"What is the representation for the input and output, and the algorithm for the transformation?"

Implementation

"How can the representation and algorithm be realized physically?"

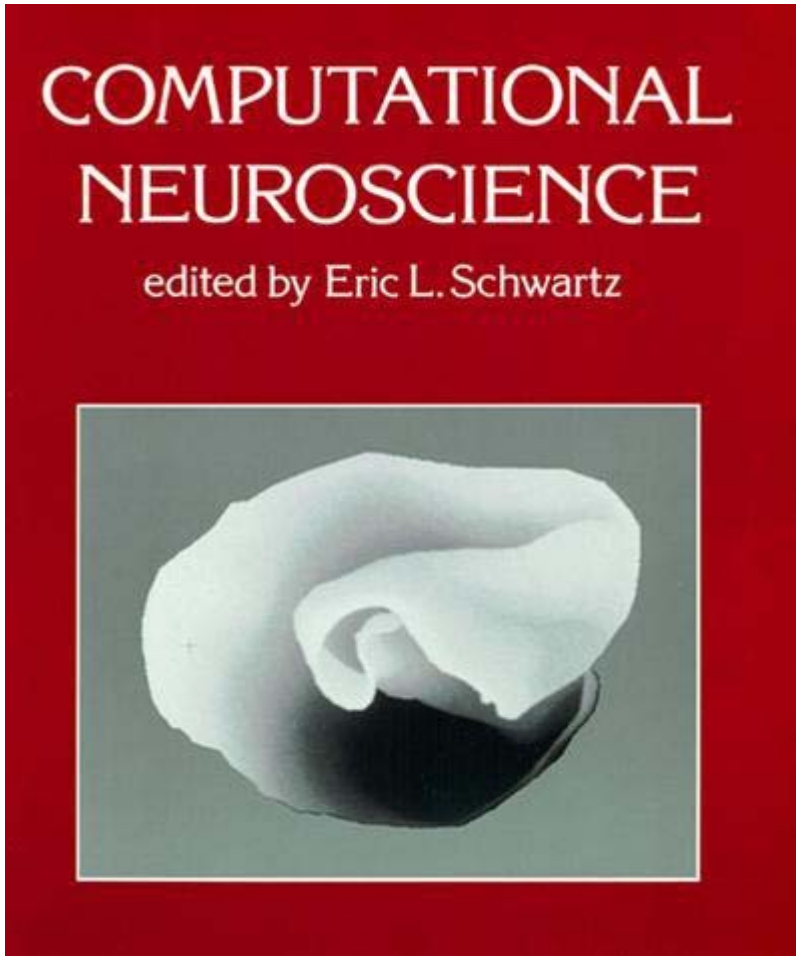
Marr's Book, *Vision*, published in 1982

Parallel Distributed Processing



- Book published in 1986
- Revived artificial neural networks in neuroscience

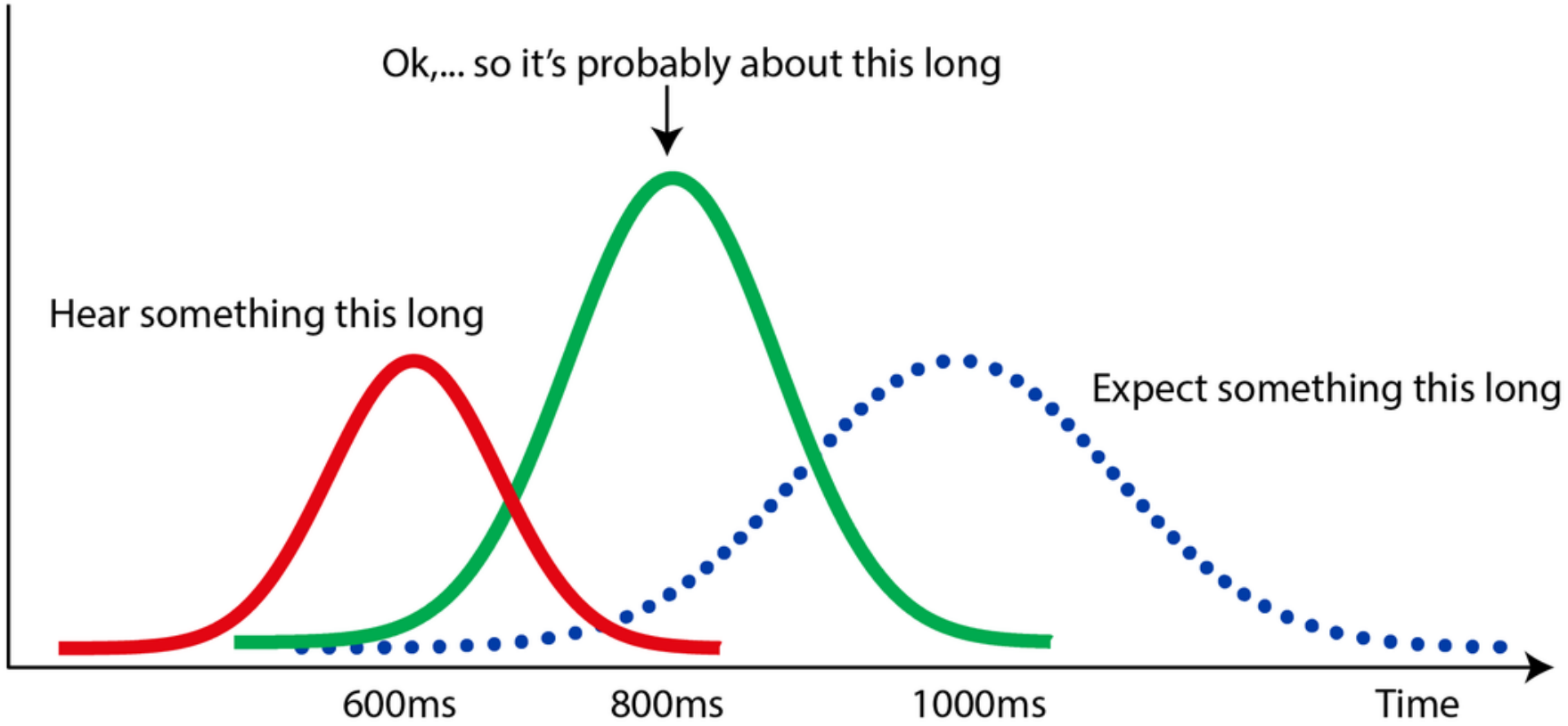
“Computational Neuroscience”



- The term was officially coined at a 1985 conference
- Notes from that conference, including various takes on the definition of the term, were published five years later

Bayes' Rule

- Bayesian Psychology took off in the 1990s



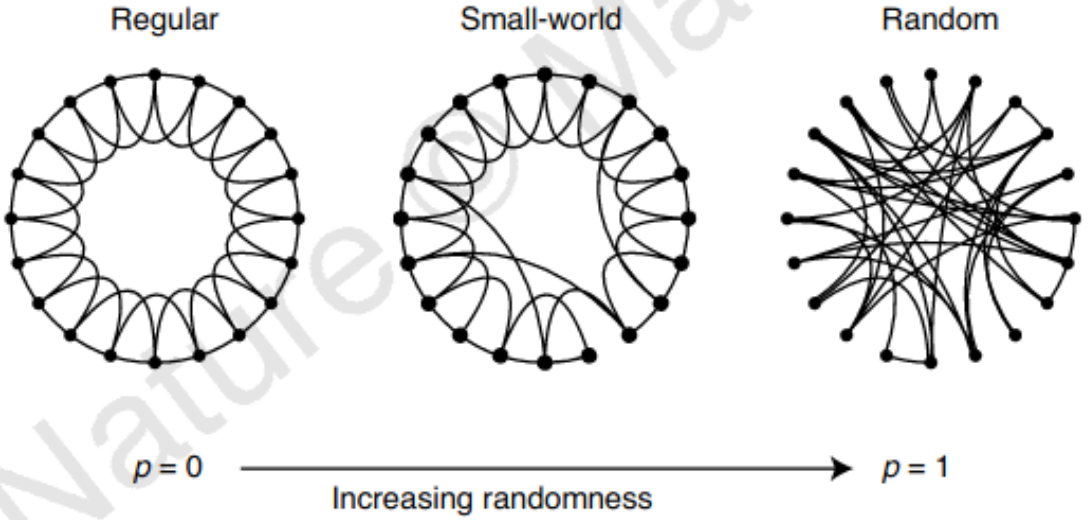
Network Neuroscience

- Discovery that the *C.elegans* connectome is a small world (1998)

Collective dynamics of 'small-world' networks

Duncan J. Watts* & Steven H. Strogatz

Department of Theoretical and Applied Mechanics, Kimball Hall, Cornell University, Ithaca, New York 14853, USA



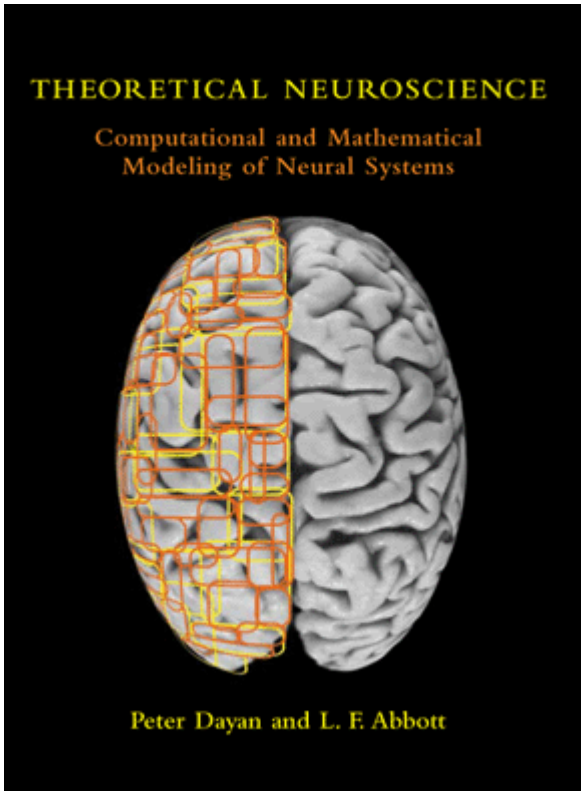
Computational neuroscience conferences got started…

Computational neuroscience conferences got started…

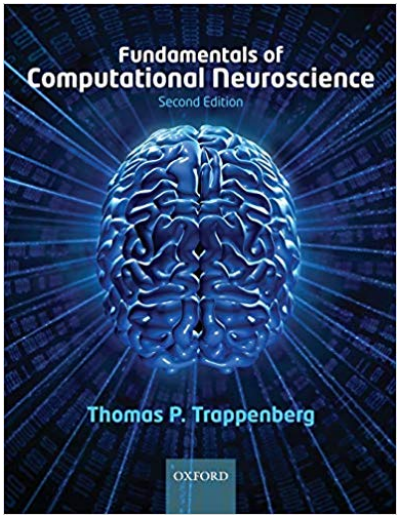
- Neural Information Processing Systems (NIPS/NeurIPS): 1987
- Organization for Computational Neurosciences conference (CNS): 1992
- Computational and Systems Neuroscience conference (COSYNE): 1996/2004
- Bernstein Conference: 2009
- Cognitive Computational Neuroscience conference (CCN): 2017

Books were written…

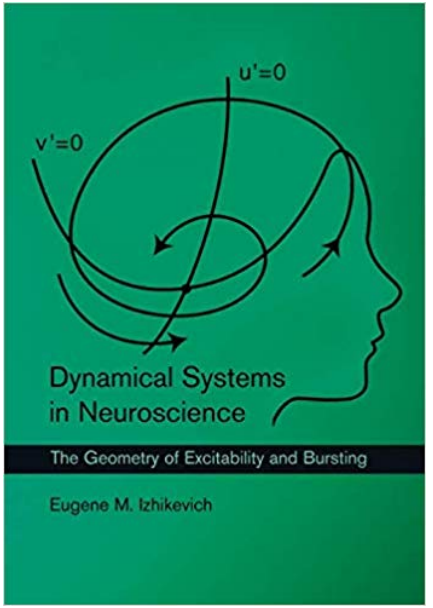
2001



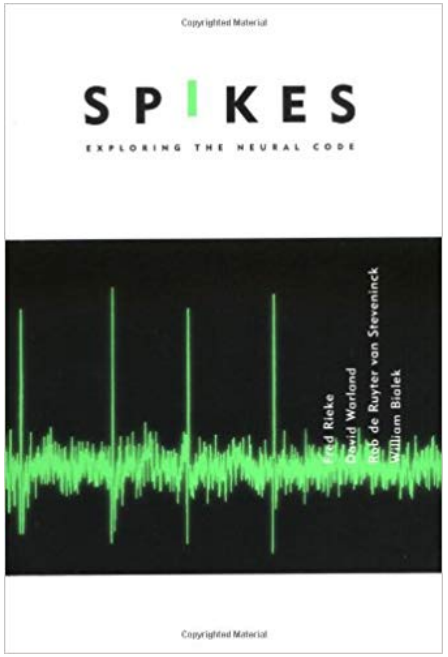
2002



2007



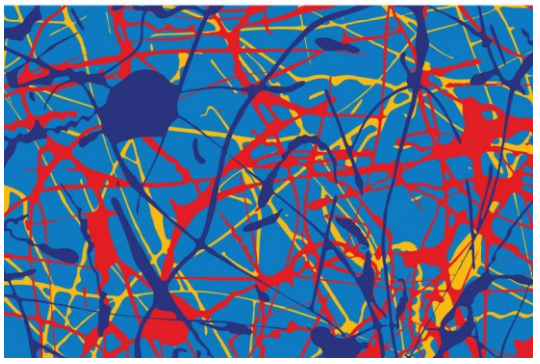
1997



2018

Paul Miller

An Introductory Course in
COMPUTATIONAL NEUROSCIENCE



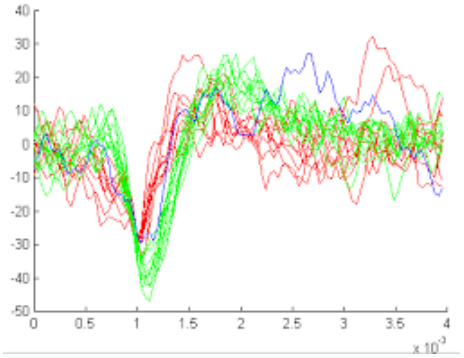
Research centers & PhD programs were born...

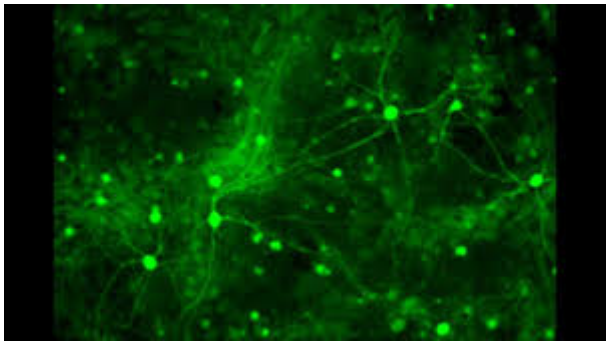
- Gatsby Unit at University College London
- Center for Theoretical Neuroscience at Columbia University
- Bernstein Centers for Computational Neuroscience
- Boston University Computational Neuroscience PhD Program
- Center for Neural Basis of Cognition at Carnegie Mellon and University of Pittsburgh
- Princeton Quantitative and Computational Neuroscience Program
- ...etc.

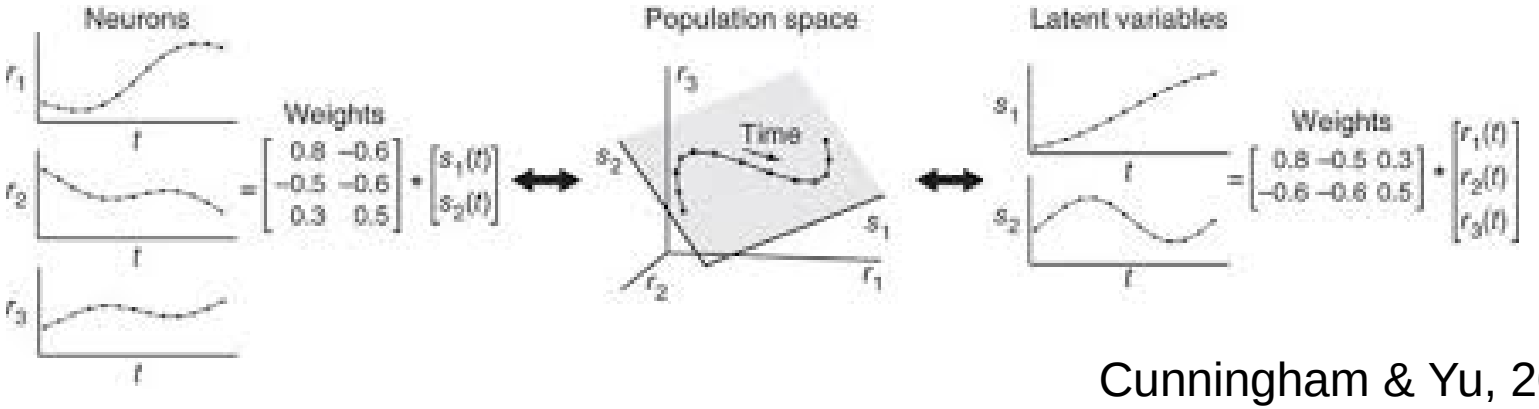
Data Analysis

Data Analysis

- Spike sorting
- Calcium imaging
- fMRI analysis
- Dimensionality Reduction
- Fitting statistical models
- Identifying latent variables

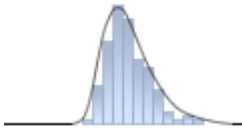






Cunningham & Yu, 2014

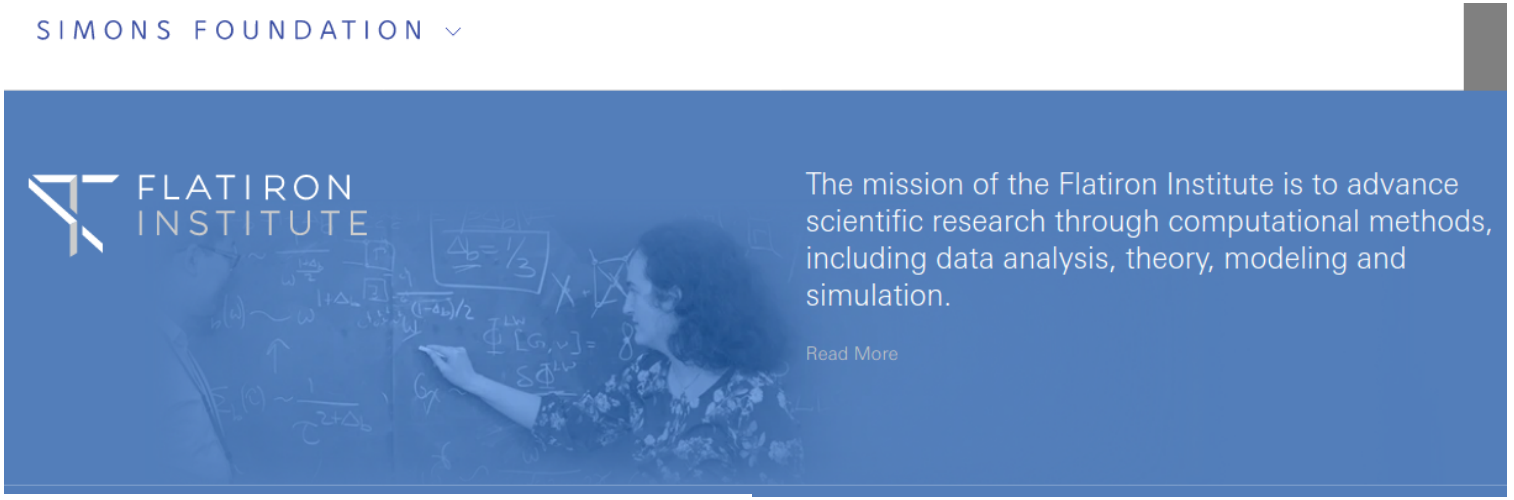
Data Analysis



Grossman Center for the Statistics of Mind

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

SIMONS FOUNDATION



Neural data science: accelerating the experiment-analysis-theory cycle in large-scale neuroscience

L .Paninski [1, 2] ✉, JP Cunningham [1]

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https://doi.org/10.1016/j.conb.2018.04.007

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Though there is still some opposition….

Though there is still some opposition….

"It is common knowledge that the human brain can keep track of only so many variables. It is also common experience that once the number of components in a system reaches a certain threshold, understanding the system without formal analytical tools requires geniuses, who are so rare even outside biology."

Yuri Lazebnik, *Can a biologist fix a radio?*

Though there is still some opposition….

"In engineering, the scarcity of geniuses is compensated, at least in part, by a formal language that successfully unites the efforts of many individuals, thus achieving a desired effect, be that design of a new aircraft or of a computer program. In biology, we use several arguments to convince ourselves that problems that require calculus can be solved with arithmetic if one tries hard enough and does another series of experiments."

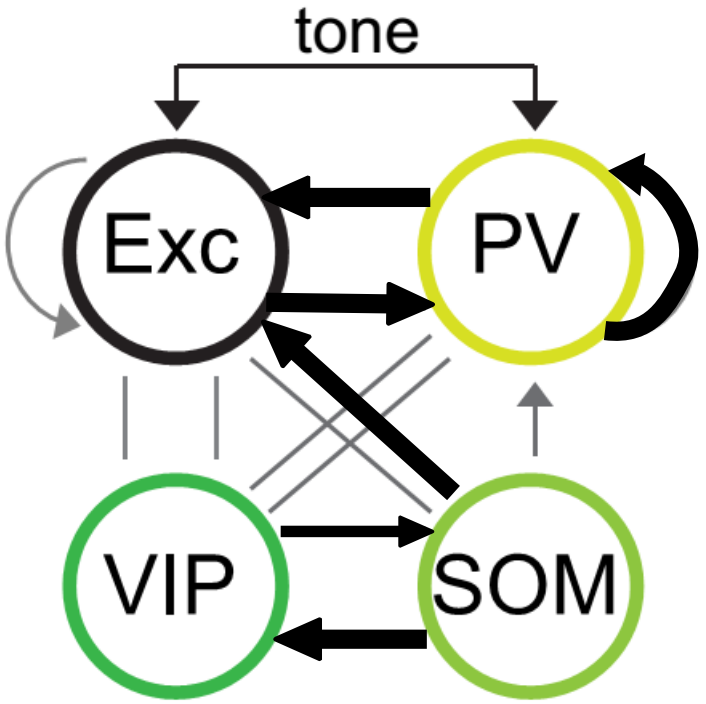
Yuri Lazebnik, *Can a biologist fix a radio?* 2002

Mini-projects!

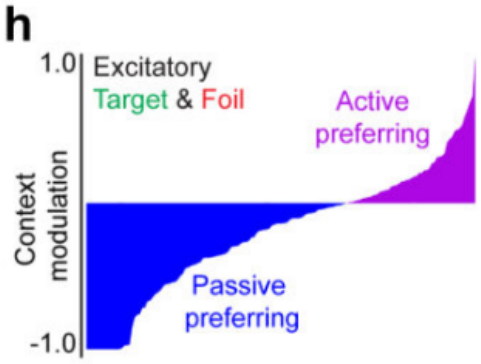
1.) How inhibition impacts a circuit

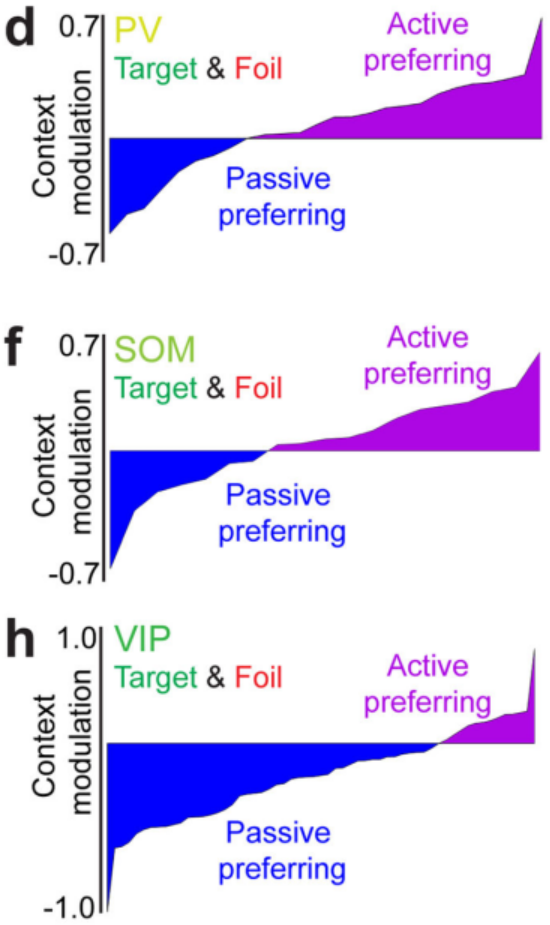
Parallel processing by cortical inhibition enables context-dependent behavior

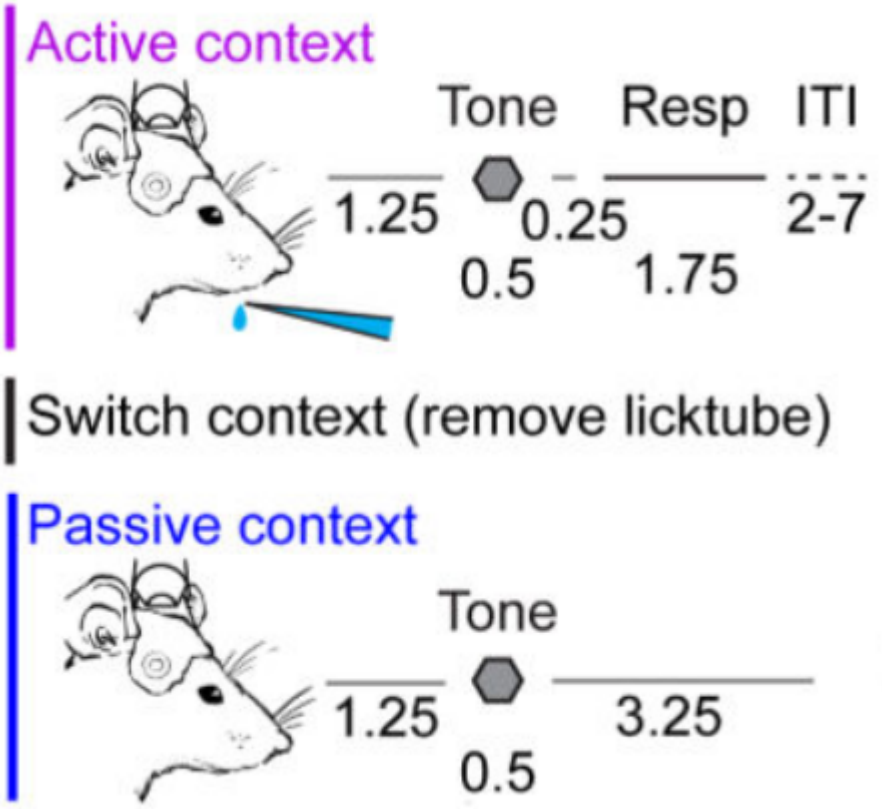
Kishore V. Kuchibhotla[1,2], **Jonathan V. Gill**[1,2], **Grace W. Lindsay**[3], **Eleni S. Papadoyannis**[1,2], **Rachel E. Field**[1,2], **Tom A. Hindmarsh Sten**[1,2], **Kenneth D. Miller**[3], and **Robert C. Froemke**[1,2,*]



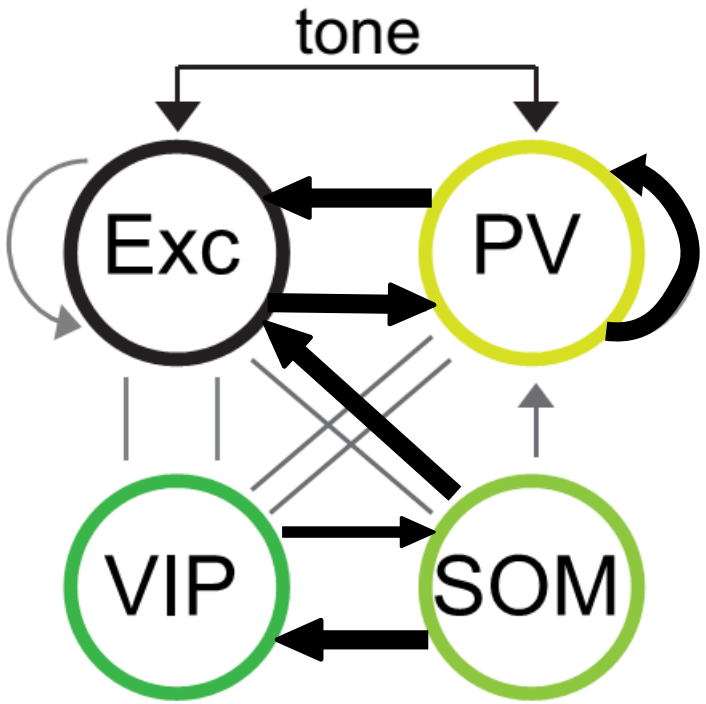
1.) How inhibition impacts a circuit

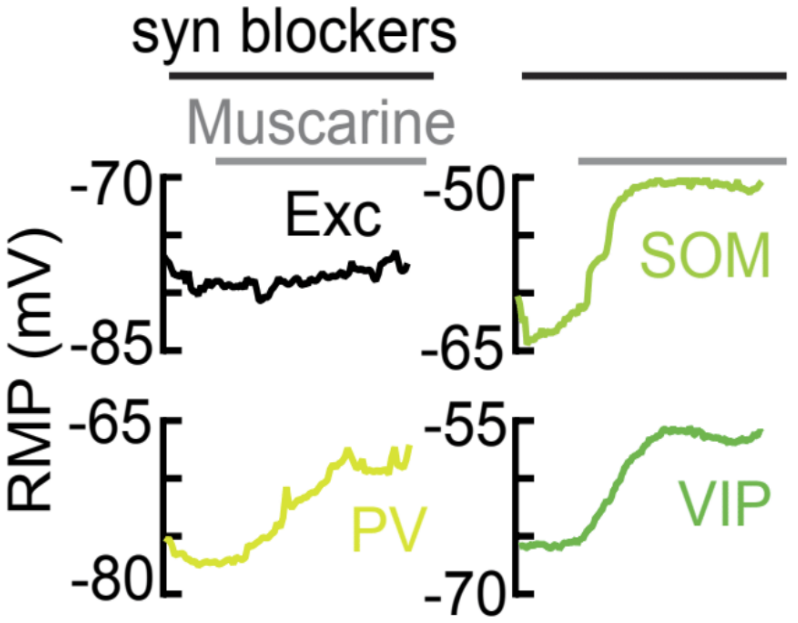




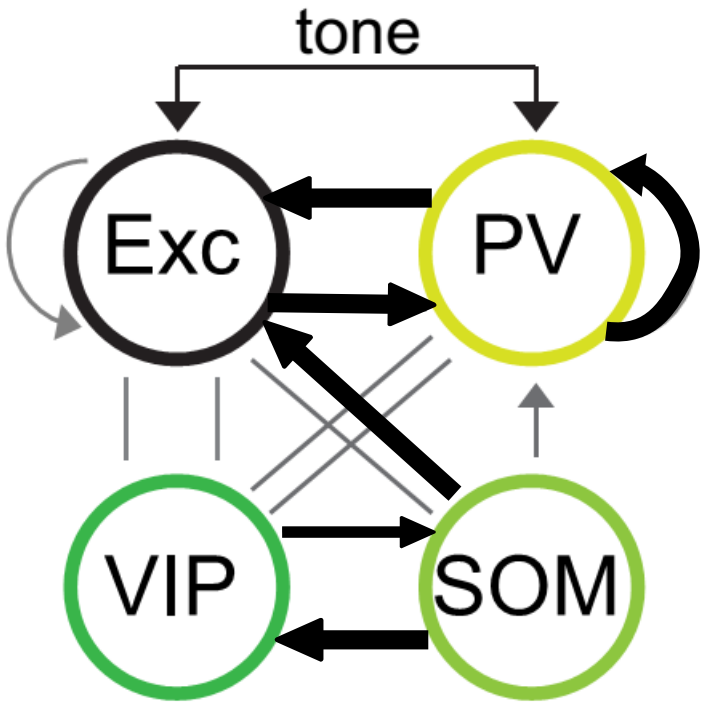


1.) How inhibition impacts a circuit





1.) How inhibition impacts a circuit



Each population (E, PV, VIP, SOM) is represented by a single rate-based equation:

$$\tau_x \frac{dr_x}{dt} = -r_x + f(I_x^{tot})$$

With:

$$I_x^{tot} = \sum_y W_{xy} r_y + I_x^B + I_x^T$$

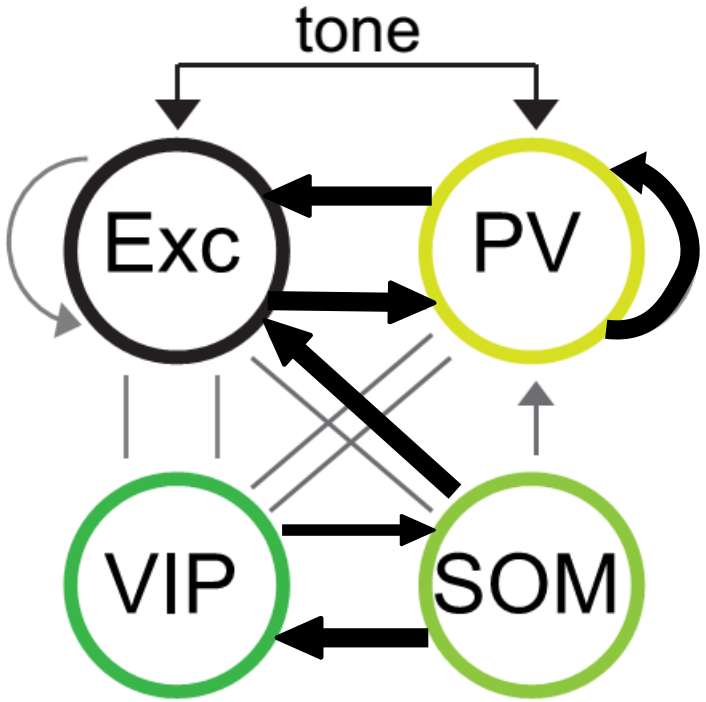
Input from other populations

Background and tone (and Ach)

And:

$$f(I_x^{tot}) = k([I_x^{tot}]_+)^n$$

1.) How inhibition impacts a circuit



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Input from other populations

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And:

$$f(I_x^{tot}) = k([I_x^{tot}]_+)^n$$

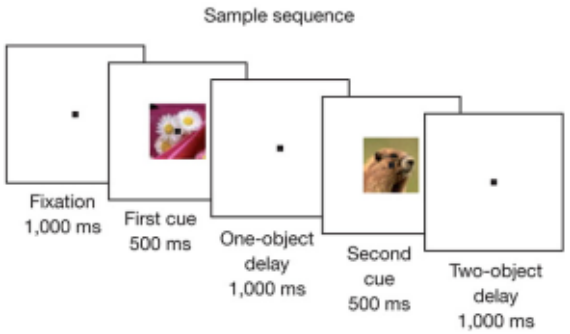
2.) How learning helps with context-dependent tasks

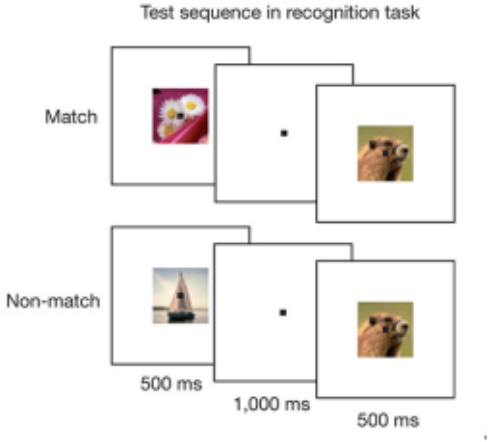
Hebbian Learning in a Random Network Captures Selectivity Properties of the Prefrontal Cortex

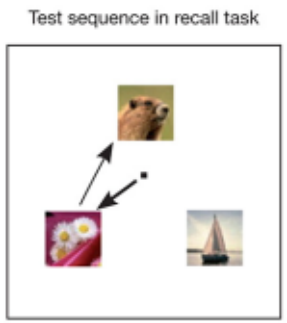
Grace W. Lindsay,[1,2] **Mattia Rigotti,**[1,4] **Melissa R. Warden,**[5,6] **Earl K. Miller,**[6] **and Stefano Fusi**[1,2,3]

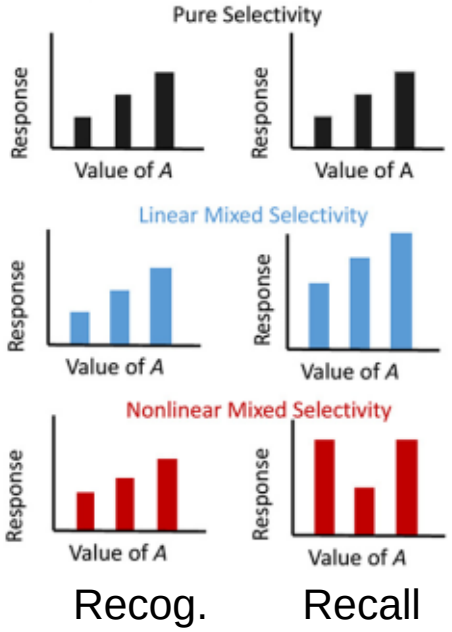
[1]Center for Theoretical Neuroscience, College of Physicians and Surgeons, [2]Mortimer B. Zuckerman Mind Brain Behavior Institute, College of Physicians and Surgeons, and [3]Kavli Institute for Brain Sciences, Columbia University, New York, New York 10027, [4]IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598, [5]Department of Neurobiology and Behavior, College of Agriculture and Life Sciences, Cornell University, Ithaca, New York 14853, and [6]The Picower Institute for Learning and Memory & Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

2.) How learning helps with context-dependent tasks



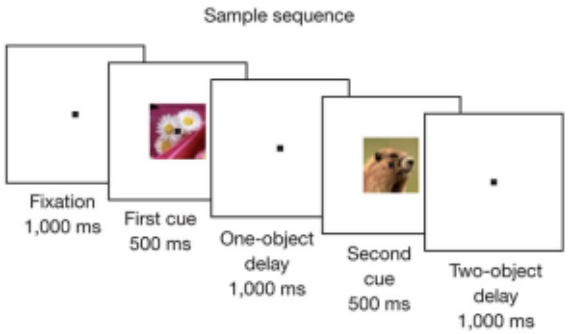


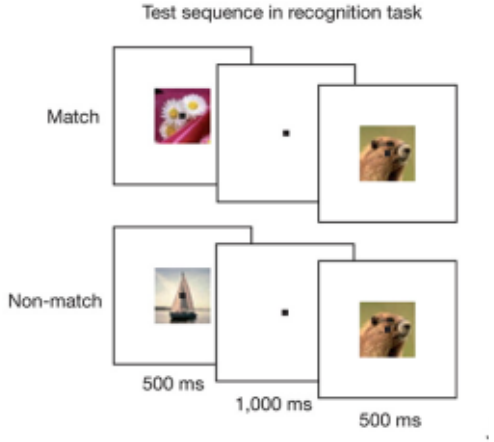


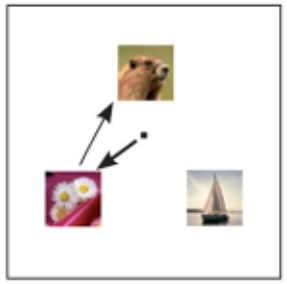


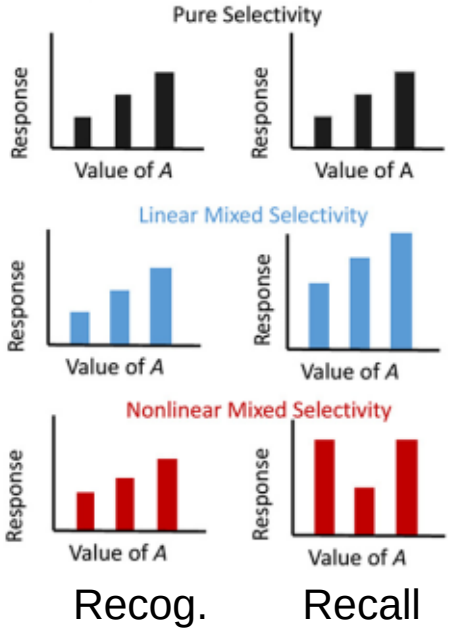
Recog. Recall

2.) How learning helps with context-dependent tasks

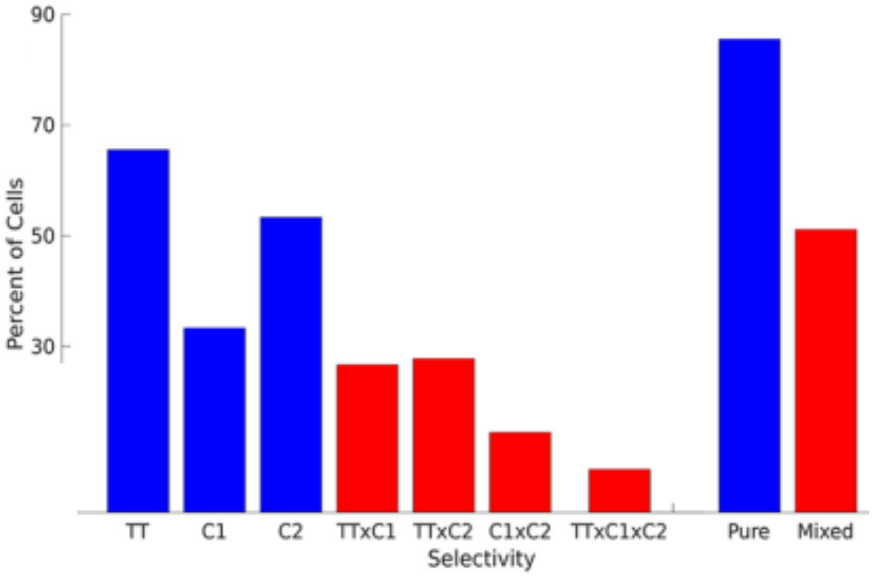






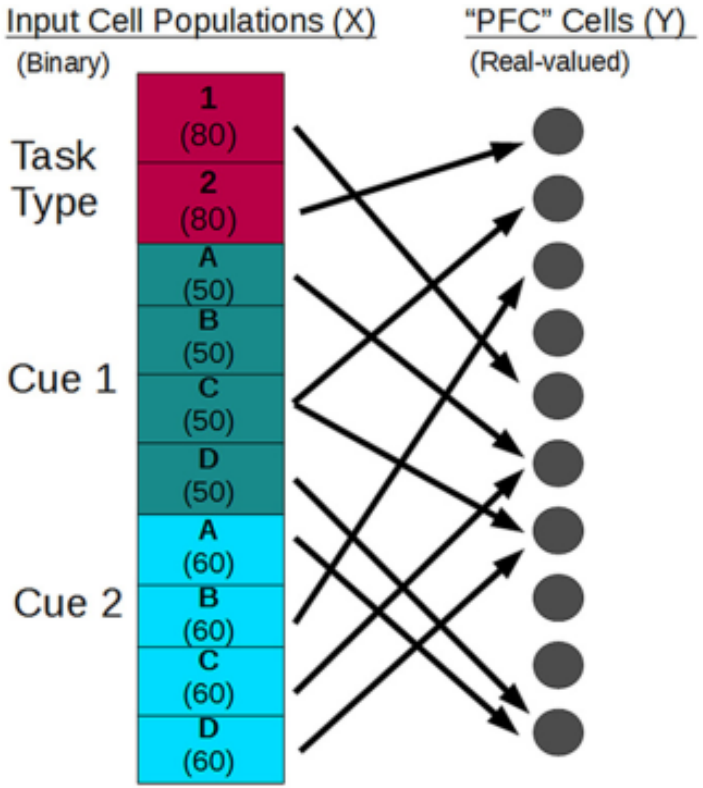


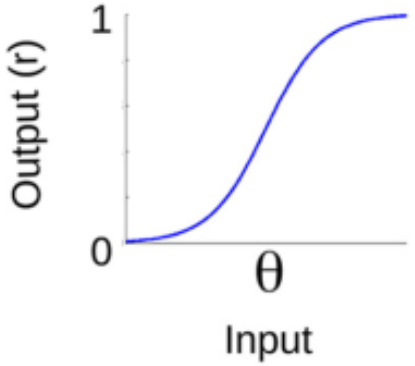
Data from Prefrontal Cortex:



-Nonlinear mixed selectivity can be measured using ANOVA

2.) How learning helps with context-dependent tasks





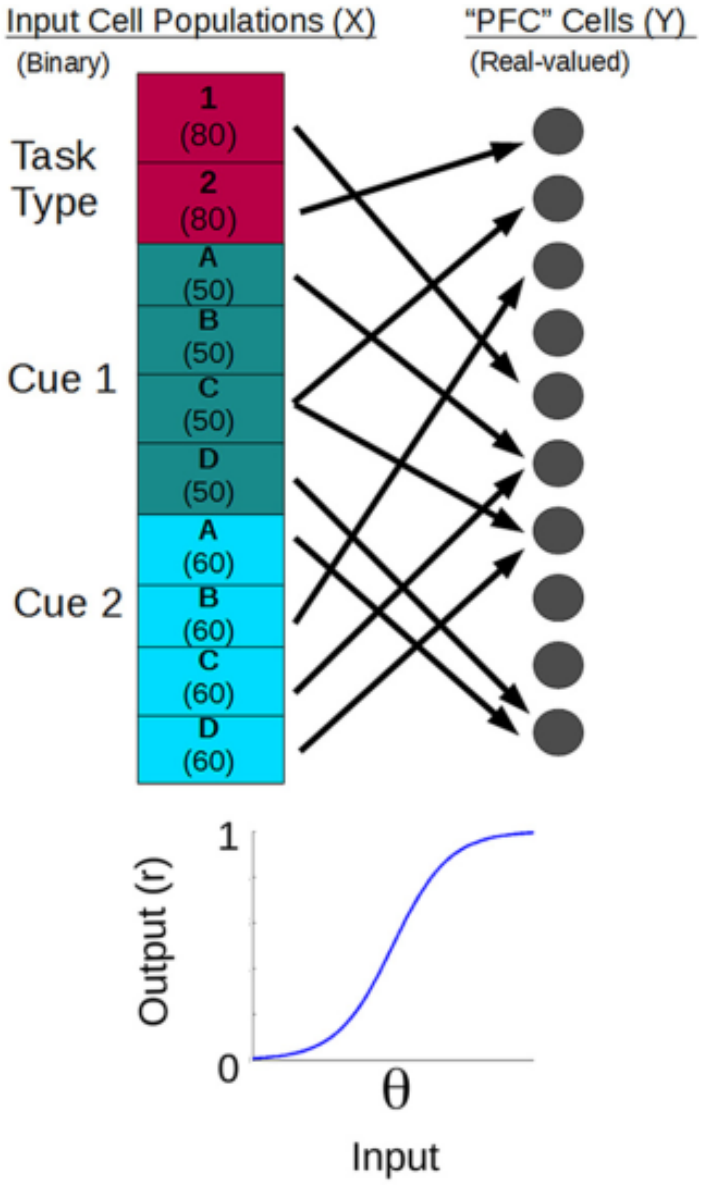
$$r_i^t = k\phi\left(\sum_j w_{ij} x_j^t + \epsilon_A^t - \Theta_i \right)$$

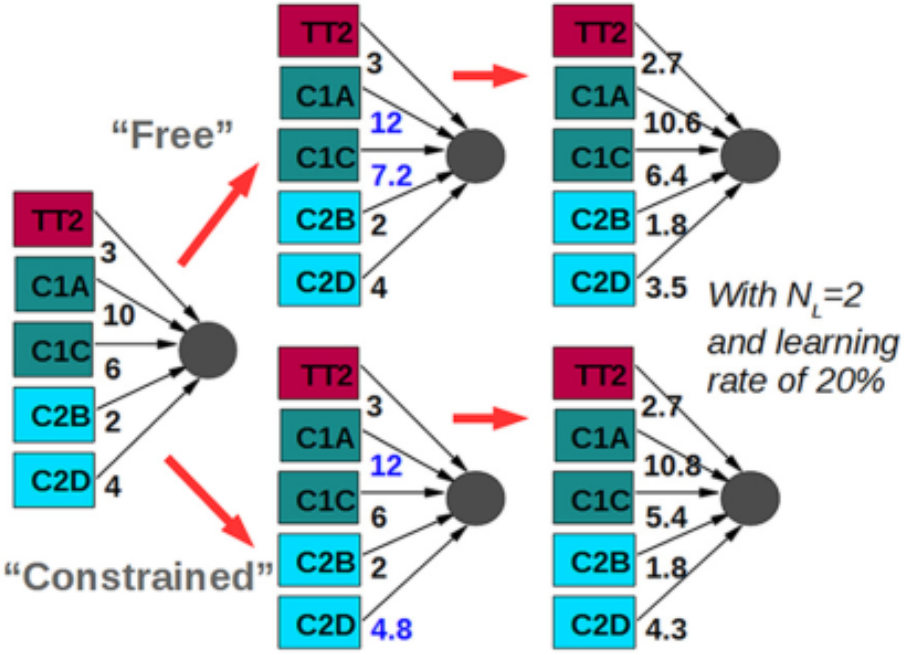
$$\phi(z) = \frac{1}{1 + e^{-z}}$$

$$y_i^t \sim \mathcal{N}(r_i^t,\ \sigma_{M_i}^{t2})$$

$$\sigma_{M_i}^t = m r_i^t$$

2.) How learning helps with context-dependent tasks





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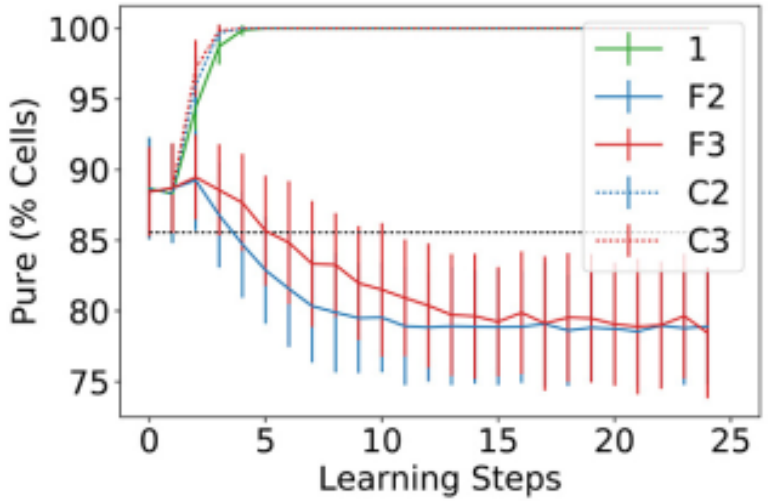
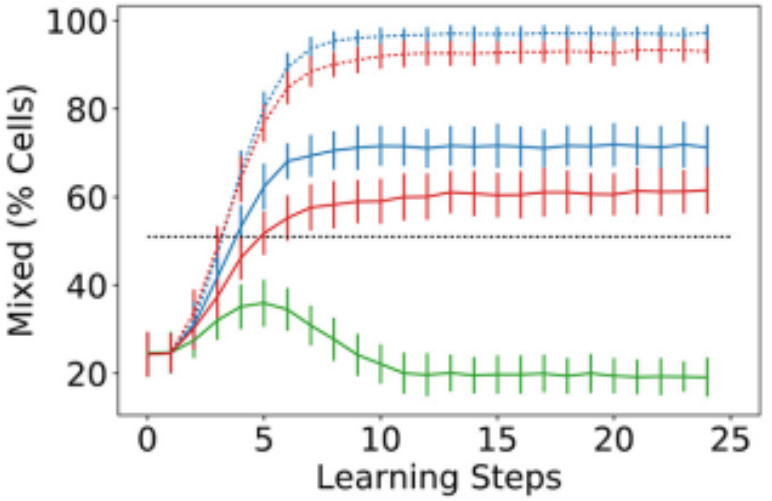
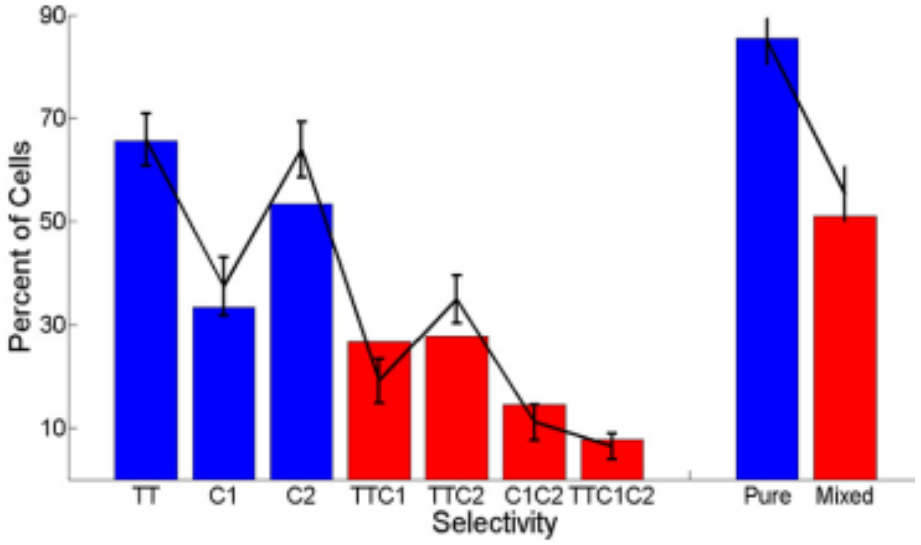




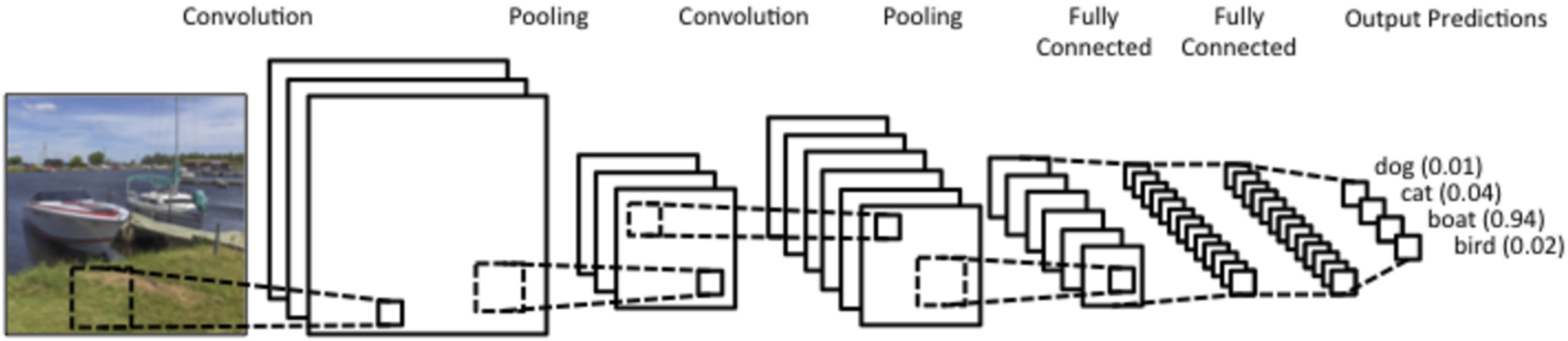


3.) Adding attention to convolutional neural networks

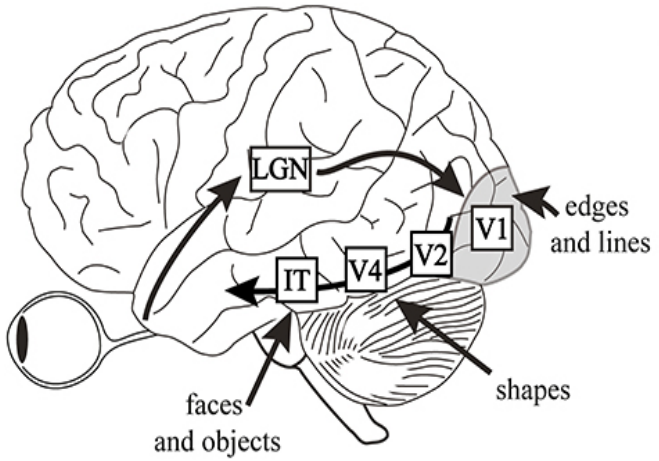
How biological attention mechanisms improve task performance in a large-scale visual system model

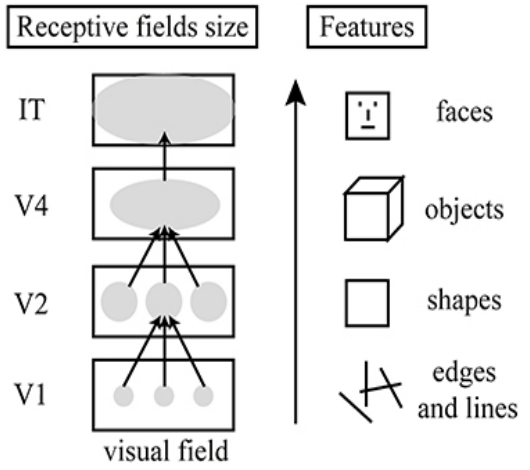
Grace W Lindsay[1,2]*, Kenneth D Miller[1,2,3,4]

3.) Adding attention to convolutional neural networks



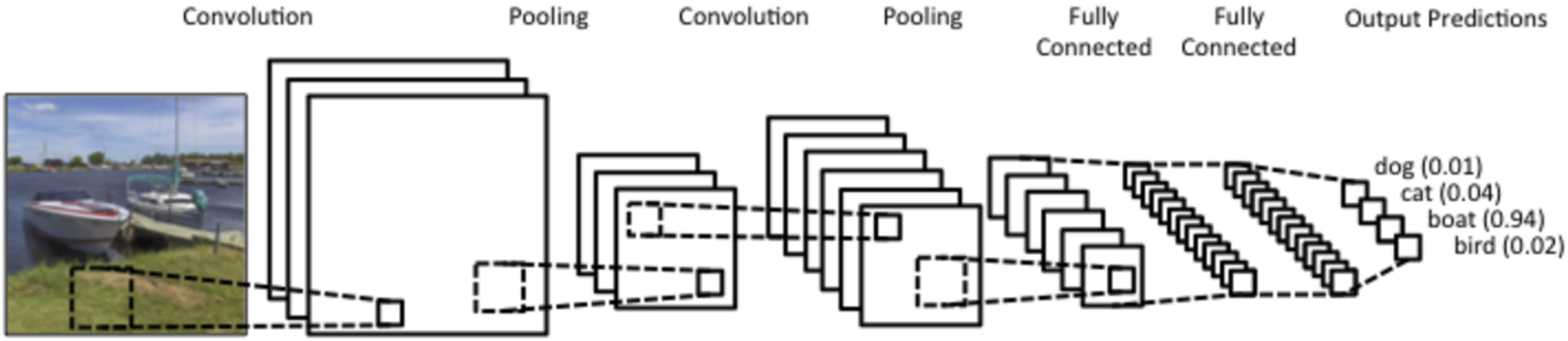
Architecture is inspired by the visual system (spatial layout and hierarchical feature extraction) and responses match data.



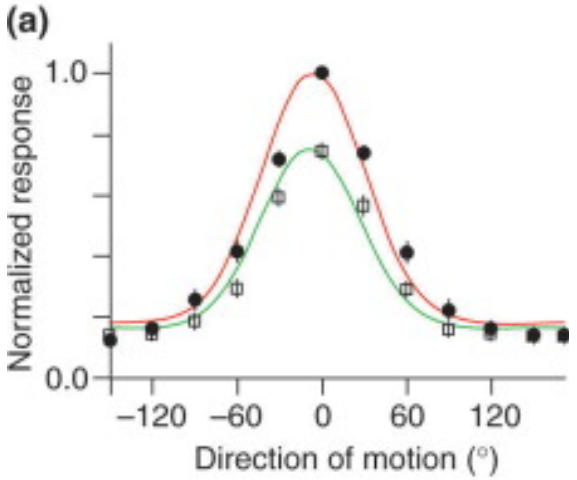


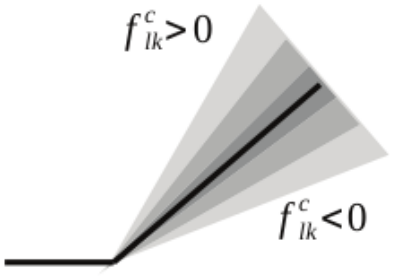
Herzog and Clarke, 2014

3.) Adding attention to convolutional neural networks



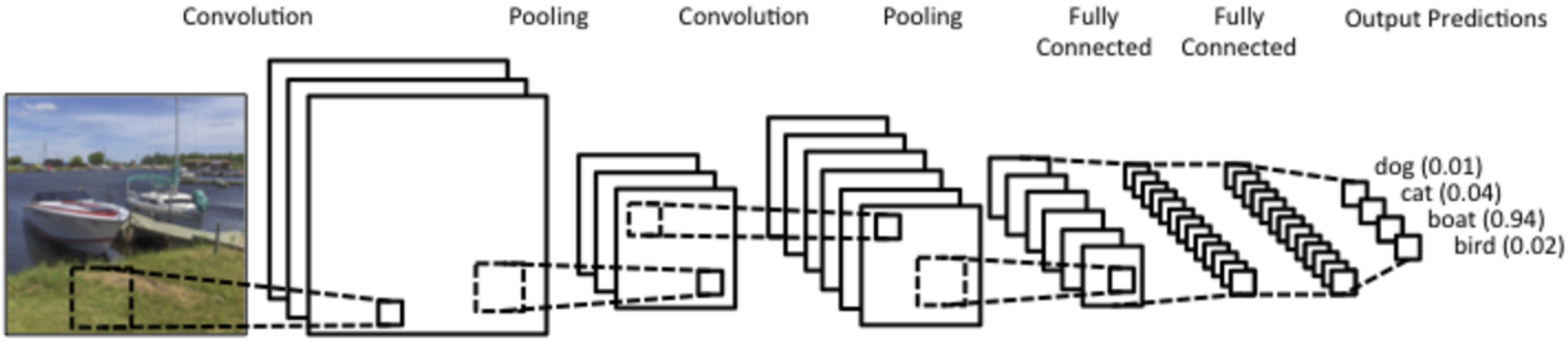
Attention scales activity multiplicatively

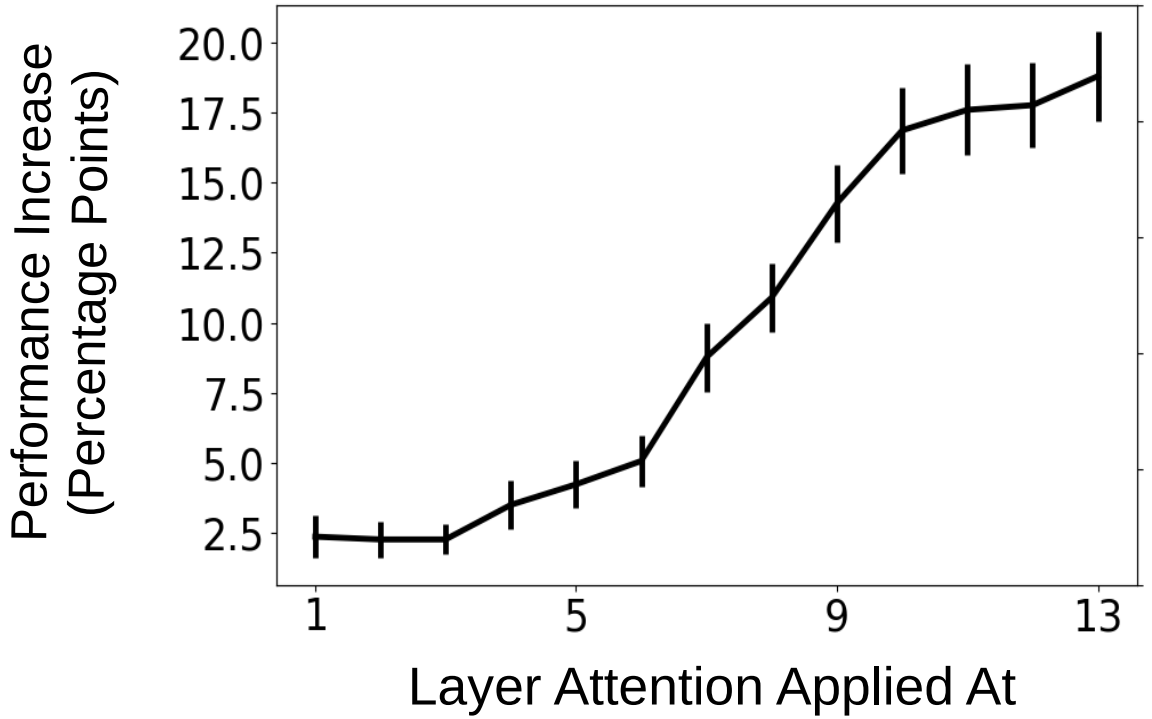




$$x^{ij}_{lk} = \left(1+\beta f^c_{lk}\right)\left[I^{ij}_{lk}\right]_+$$

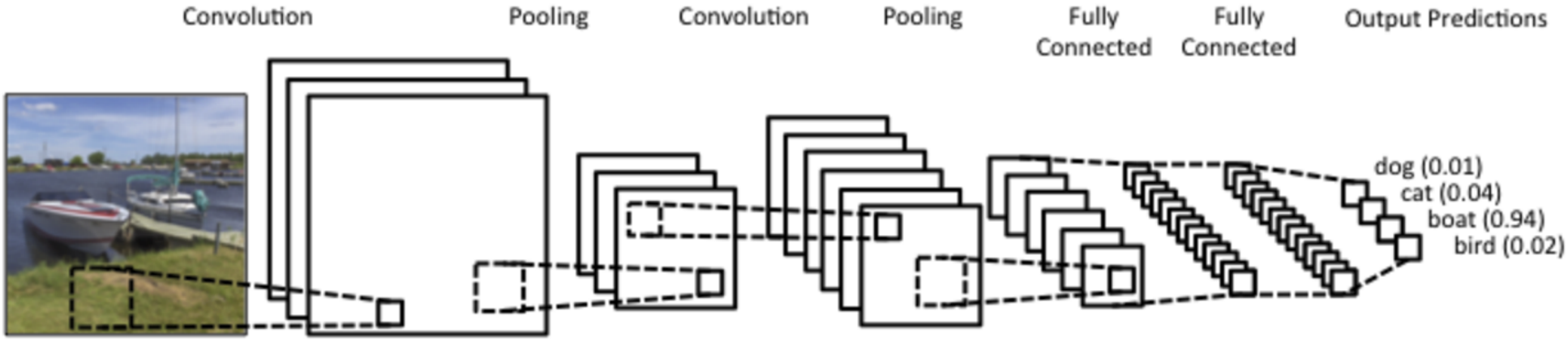
3.) Adding attention to convolutional neural networks

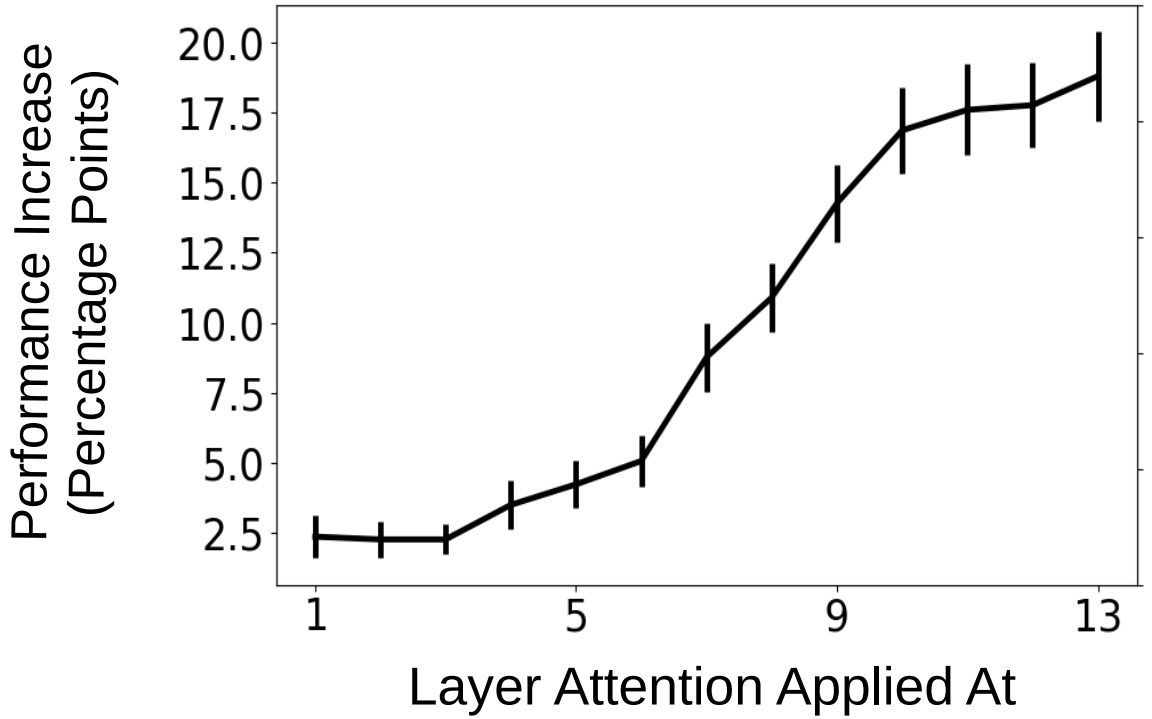




Attention enhances performance on challenging visual tasks

3.) Adding attention to convolutional neural networks





Attention enhances performance on challenging visual tasks

3.) Adding attention to convolutional neural networks