Computational Neuroscience: I

Lecture 3

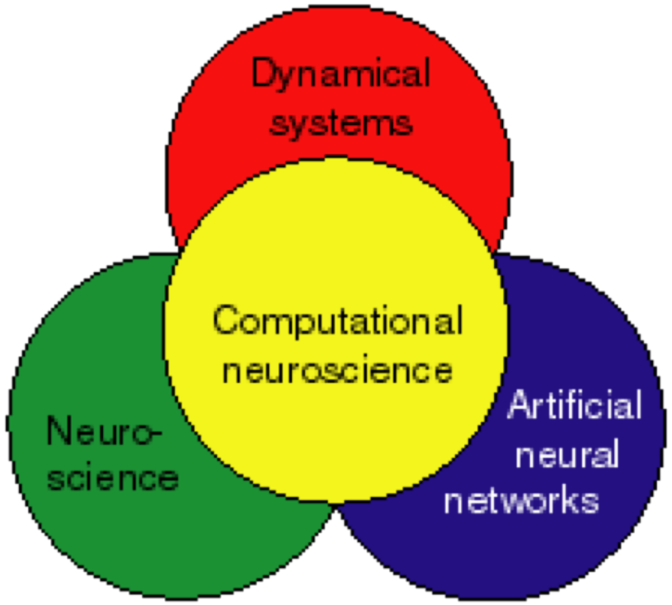
Outline

- What is Computational Neuroscience?
- Approaches to understanding the brain
- Computational models classification
- Basic concepts of computational neuroscience
- Turning curves

What is **Computational Neuroscience**?

- Using computers to simulate and model brain function
- Applying techniques from computational fields (math, physics, engineering, machine learning) to understand the brain
- Trying to understand the computations performed by the brain

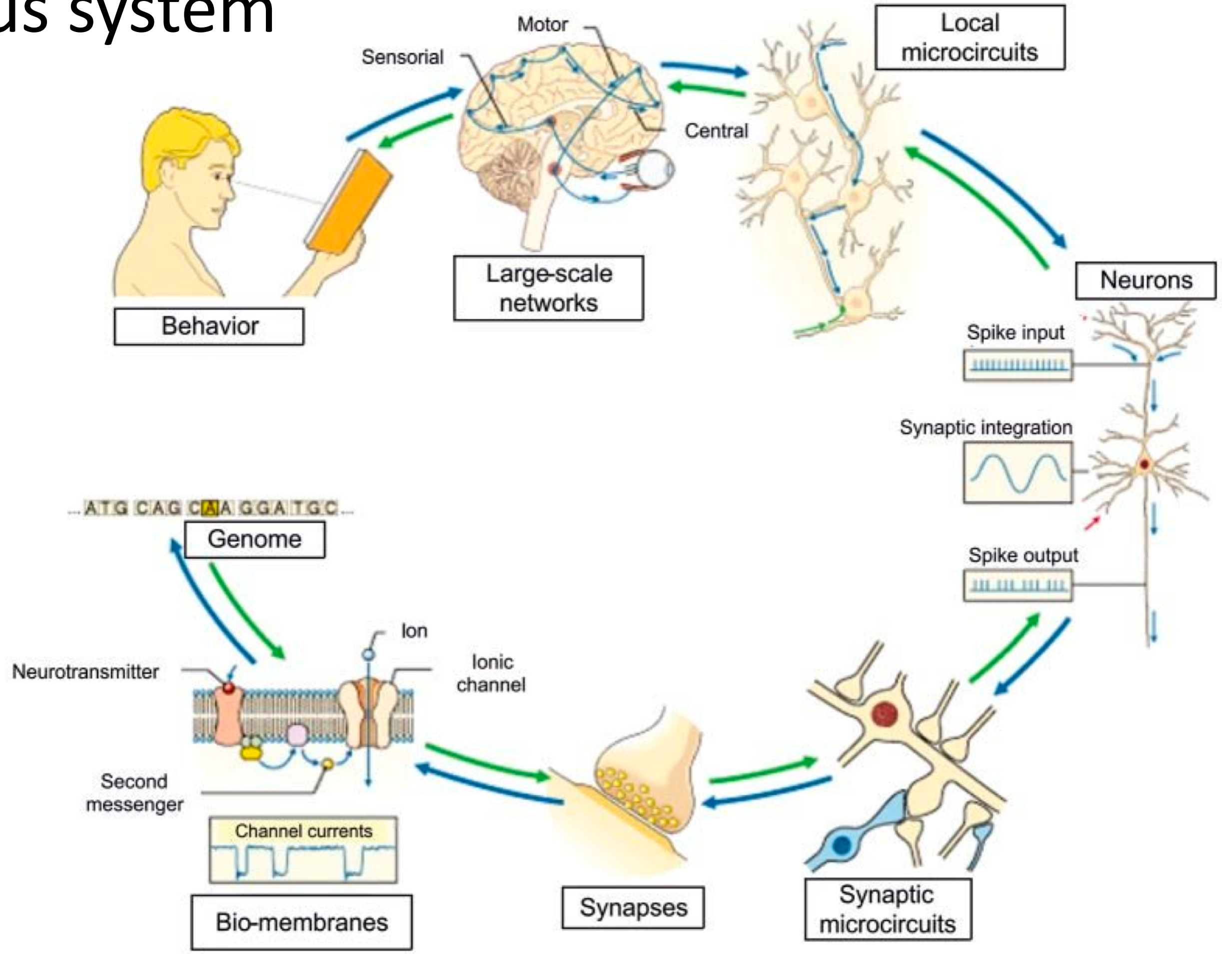
- Interdisciplinary field that tries to uncover the principles and mechanisms that guide the nervous system's



Approaches to understanding the brain

- The term computational neuroscience covers a dizzying array of approaches to understanding the nervous system

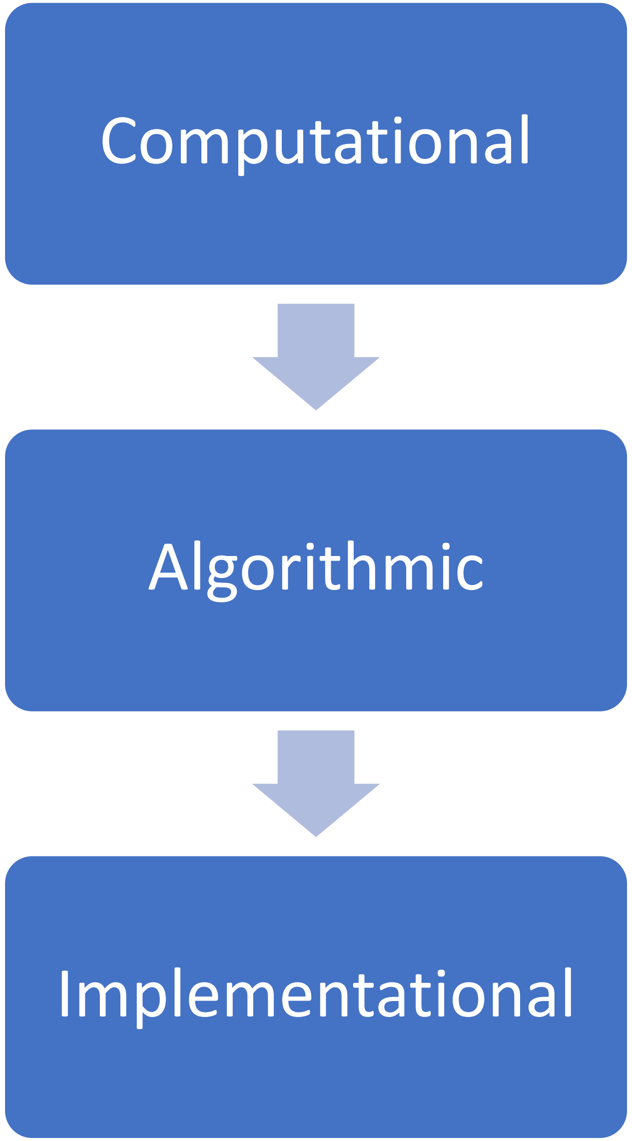
- One division according to level of analysis is **biological**: the brain can be studied at a hierarchy of scales ranging from the cellular and molecular level to the level of small localized circuits in the brain to the level of large-scale brain circuits involving multiple neural subsystems



Levels of analysis

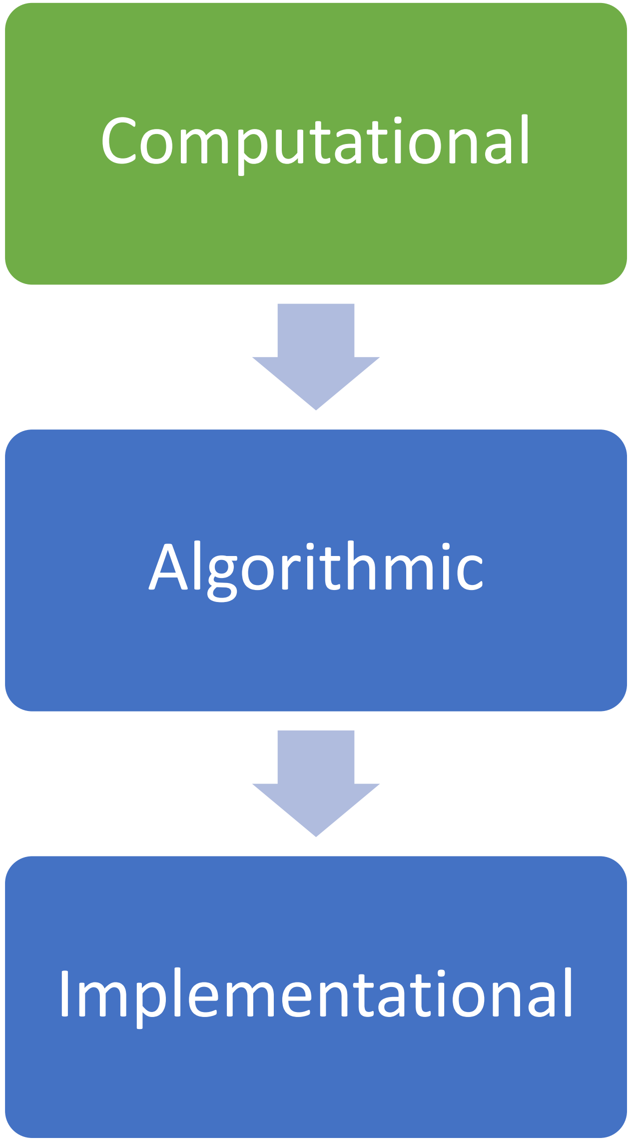
- David Marr (1982): integration results from psychology, artificial intelligence, and neurophysiology into new models of visual processing.

- Marr was making computer models of visual perception, and made the distinction between three levels of analysis →



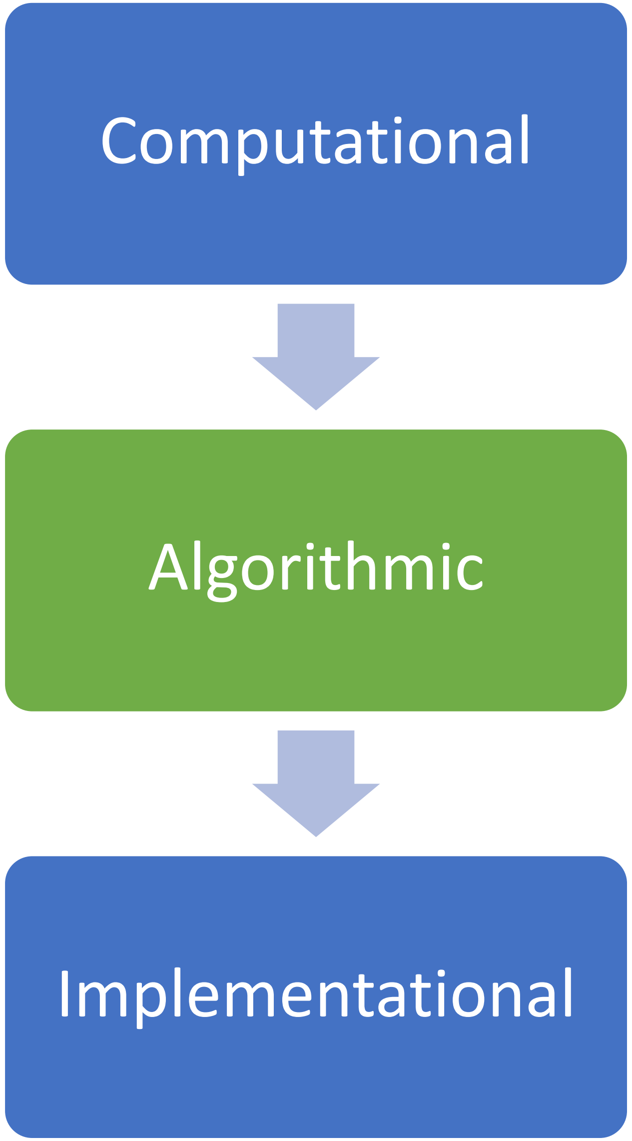
Levels of analysis

- The computational level is the most abstract and concerns itself with a description of the problem to be solved, i.e. what is the computation that is being performed.
- Here the object of study are the high-level computational principles involved such as optimality, modularity, etc



Levels of analysis

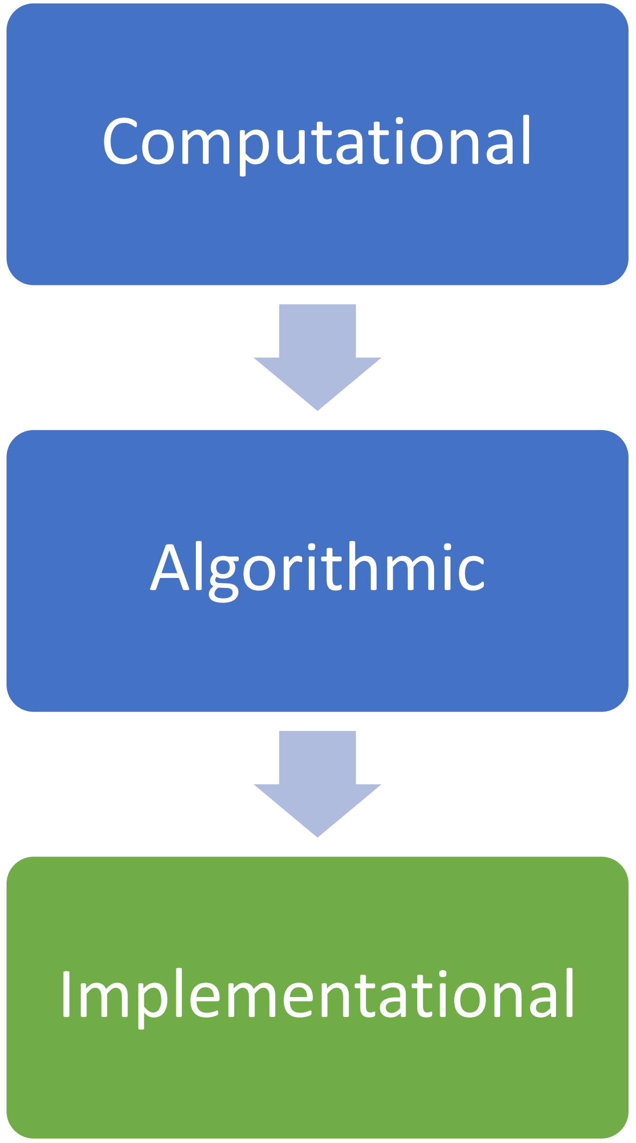
- The algorithmic level of description concerns itself with the structure of the solution, e.g. the nature of the subroutines used to perform the calculation



Levels of analysis

- The algorithmic level of description concerns itself with the structure of the solution, e.g. the nature of the subroutines used to perform the calculation

- The implementational level concerns how this algorithm is actually implemented in a biological object.



Top-down and bottom-up approaches

- A top-down approach starts at the level of cognitive phenomena and tries to reach “down” to connect these phenomena to specific events taking place in the brain.

- The bottom-up approach starts with biological knowledge about brain cells and circuits and tries to determine how these mechanisms support complex mental phenomena.

Computational models classification

- **Mechanistic models** concern themselves with how nervous systems operate based on known anatomy and physiology.
- **Descriptive models** summarize large amounts of experimental data, accurately describing and quantifying the behavior of neurons and neural circuits or brain as whole.
- **Interpretive models** explore the behavioral and cognitive significance of nervous system function, often connecting explaining experimental data in terms of certain theoretical principles.

Two main traditions in neuroscience

- A truly complete survey of computational neuroscience would treat two separate clusters of ideas:
- The first tradition traces its roots back to by far the most successful model in all of neuroscience: the Hodgkin-Huxley model (1952). The formalism embodied in their model laid the groundwork for how we understand the electro-chemical events at the heart of how neurons transmit and transform information.
- The other cluster of ideas is somewhat more diffuse, and includes behavioral and cognitive level models of brain function. One tradition that is has particular prominence here is the field known as neural networks.

Two basic mathematical approaches

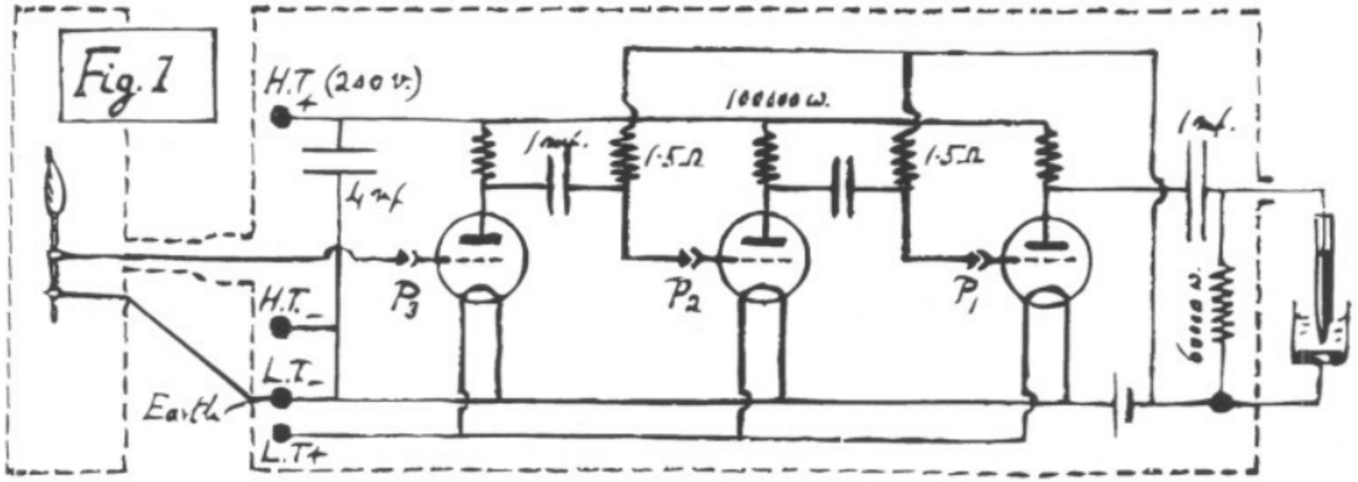
- The first centers around concepts of probability theory. These concepts are crucial to making progress in understanding how the brain encodes, performs computations on, and then decodes information gathered from the world outside the cranium.
- The second approach centers around the idea of a state space. This is a somewhat abstract notion in which a list of the many variables describing a given neural system are viewed as a single point in some (usually large dimensional) space.

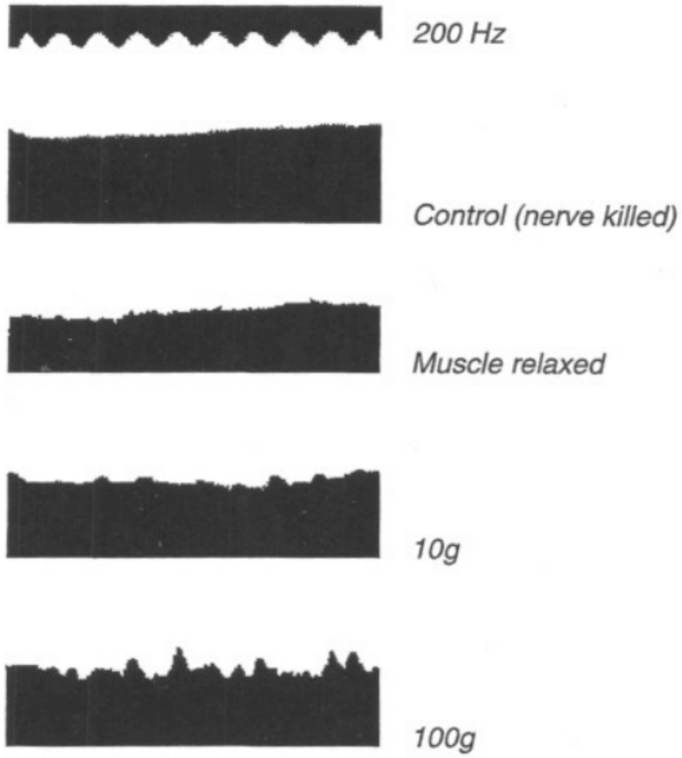
Basic concepts

- The ground breaking experiments in neuroscience were carried out in the 1920’s by E.D. (Lord) Adrian
- Adrian was the first to employ instruments sensitive enough to record from single axons of sensory receptor neurons (previous recordings were from nerve bundles). The first neurons that he recorded from were stretch receptors in the muscle of the frog **(Nobel prize-winning results (1932))**

E.D. (Lord) Adrian (1891-1977)

Adam’s experiment

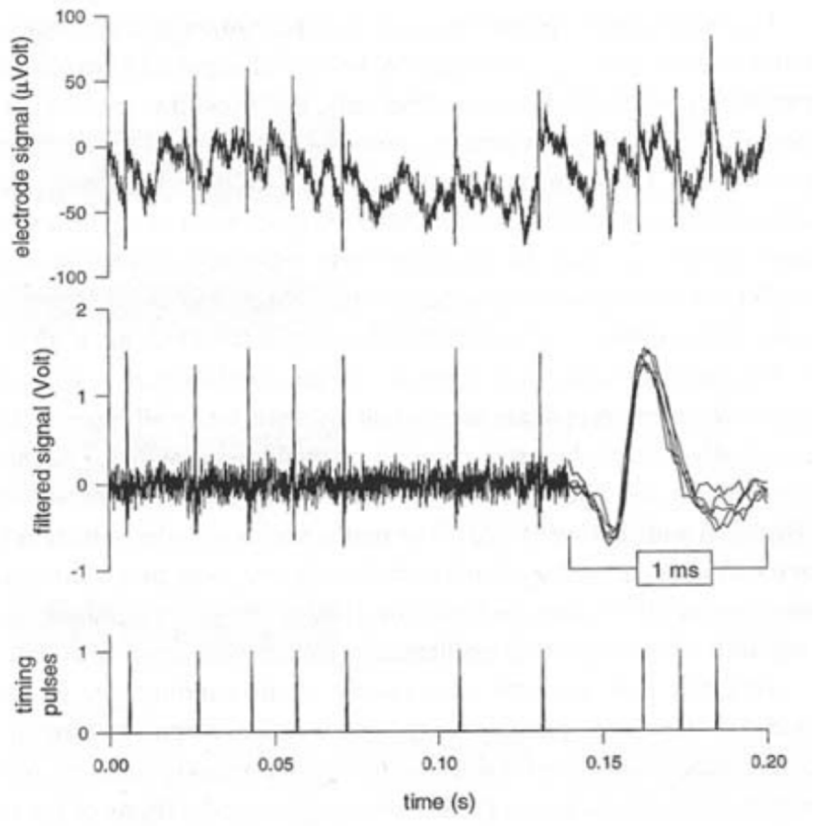




- Schematic of Adrian's apparatus for recording the electrical activity in a nerve fiber. The fiber itself is at the far left. Adrian placed the fiber across two electrodes and measured the difference in the voltage at these two points along the axon. The signal was amplified and used to control a mercury column, at the far right. Records were obtained by scanning a piece of film behind the mercury column

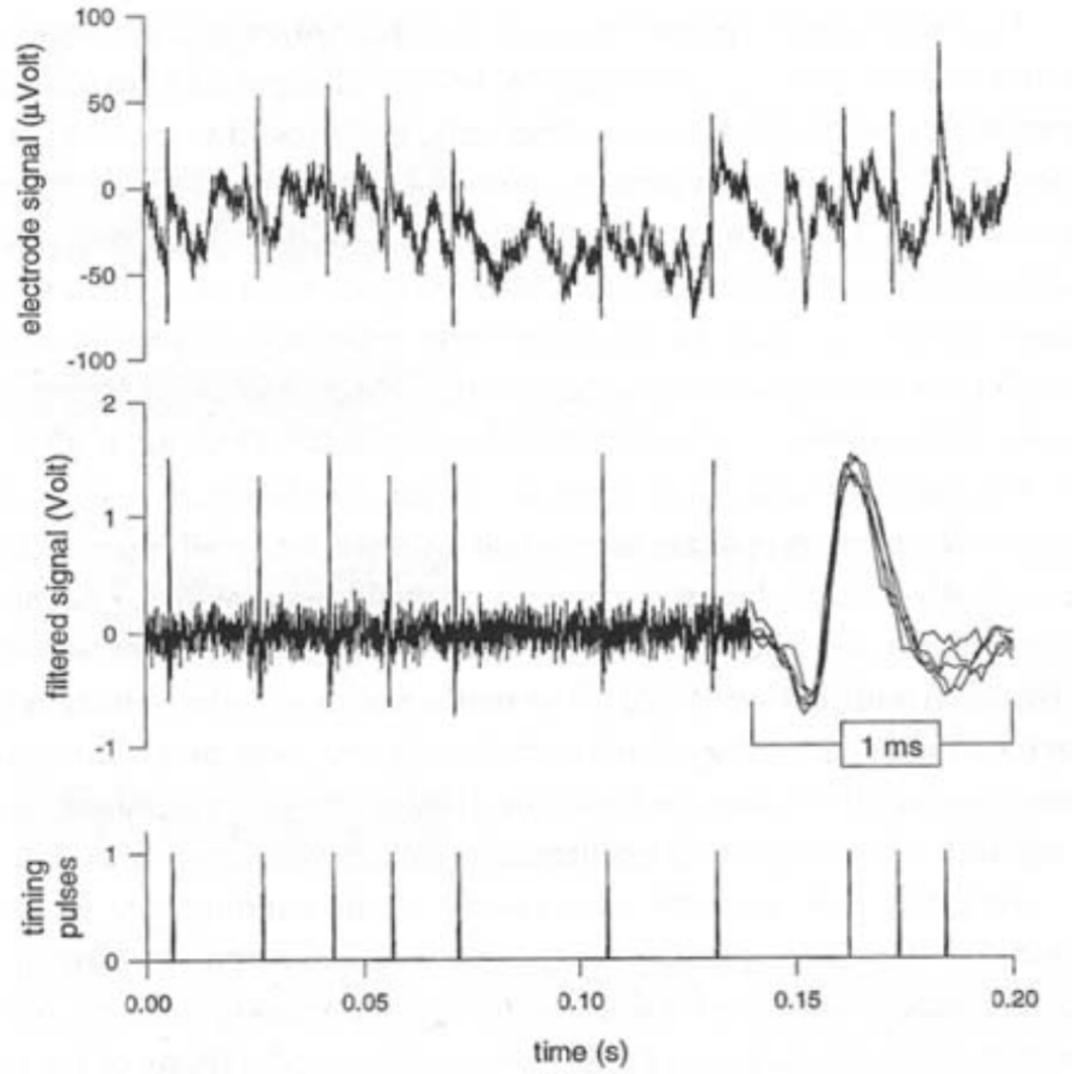
Basic concepts

- First and foremost, Adrian demonstrated that information about the world enters the nervous system as a series of pulses, whose size and shape depended only on the local conditions in the axon.
- Therefore, information is carried only by the temporal pattern of impulses, rather than the type or shape of the impulses themselves.



Basic concepts

All-or-none cording by action potentials
Each action potential generated by cell has a similar shape



Basic concepts

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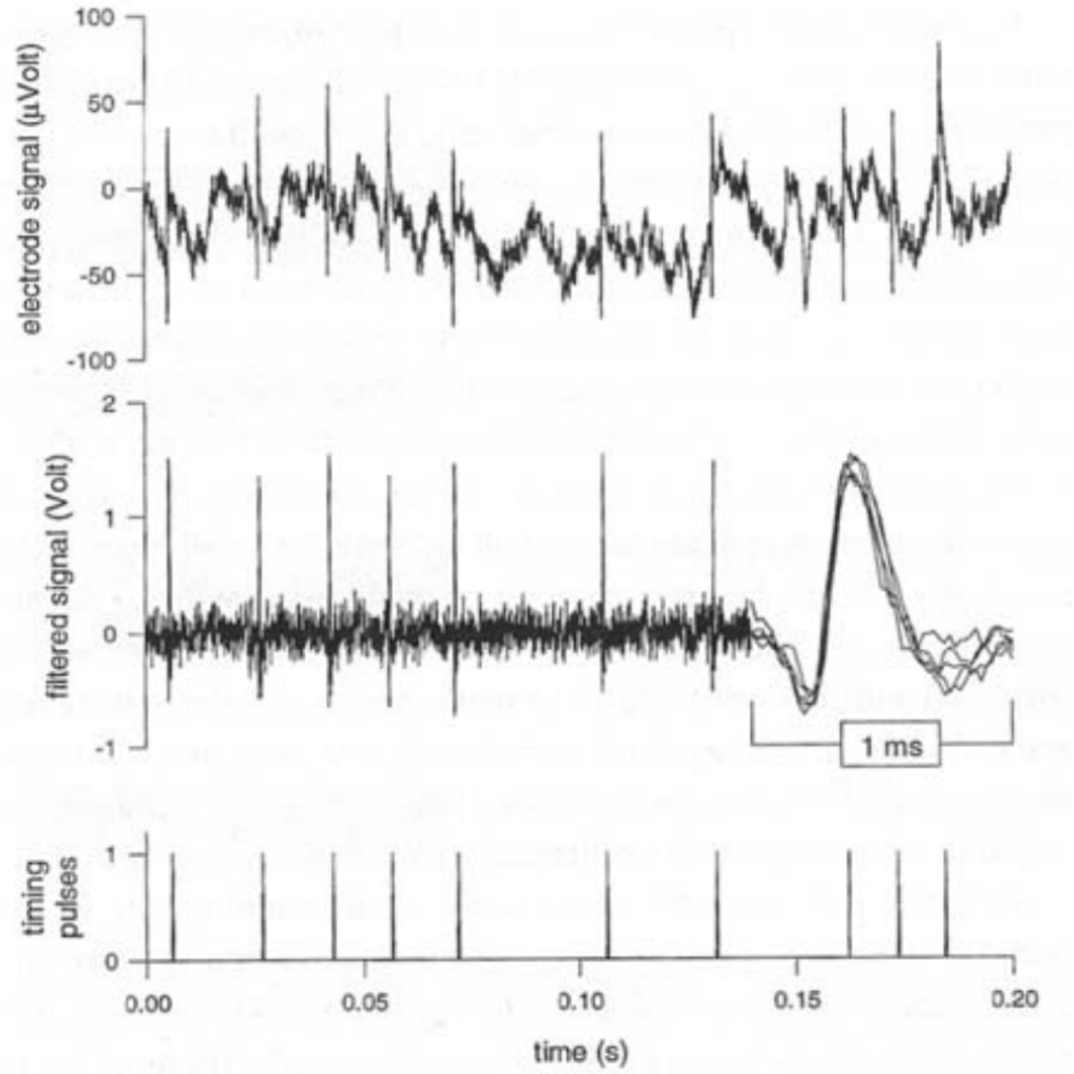
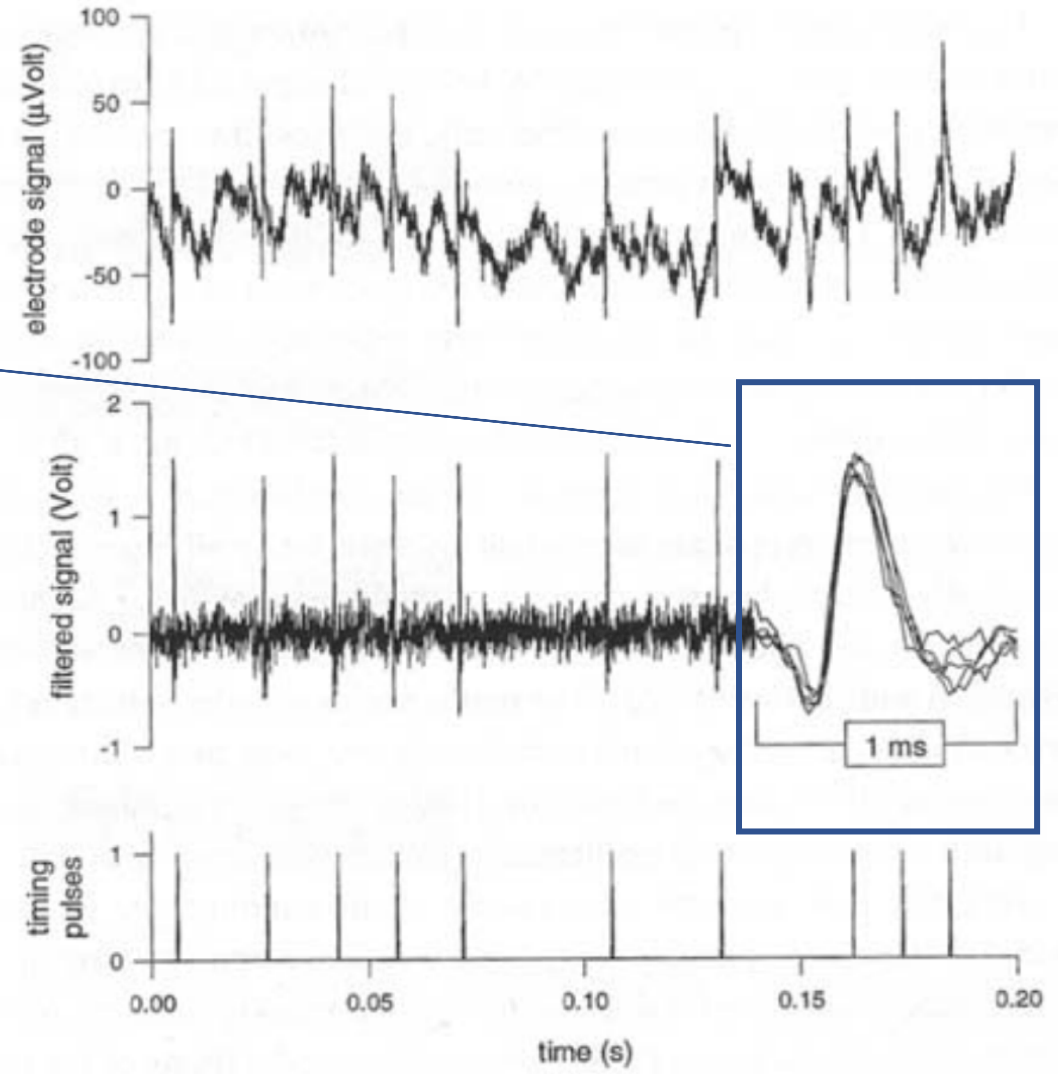
Each action potential generated by cell has a similar shape

The same voltage after band-pass filtering to separate HF components from LF noise. After filtration the shapes of individual spikes are quite similar



Basic concepts

5 action potentials are shown overlaid on an expanded time scale. You see the reproducibility of the sharp



Basic concepts

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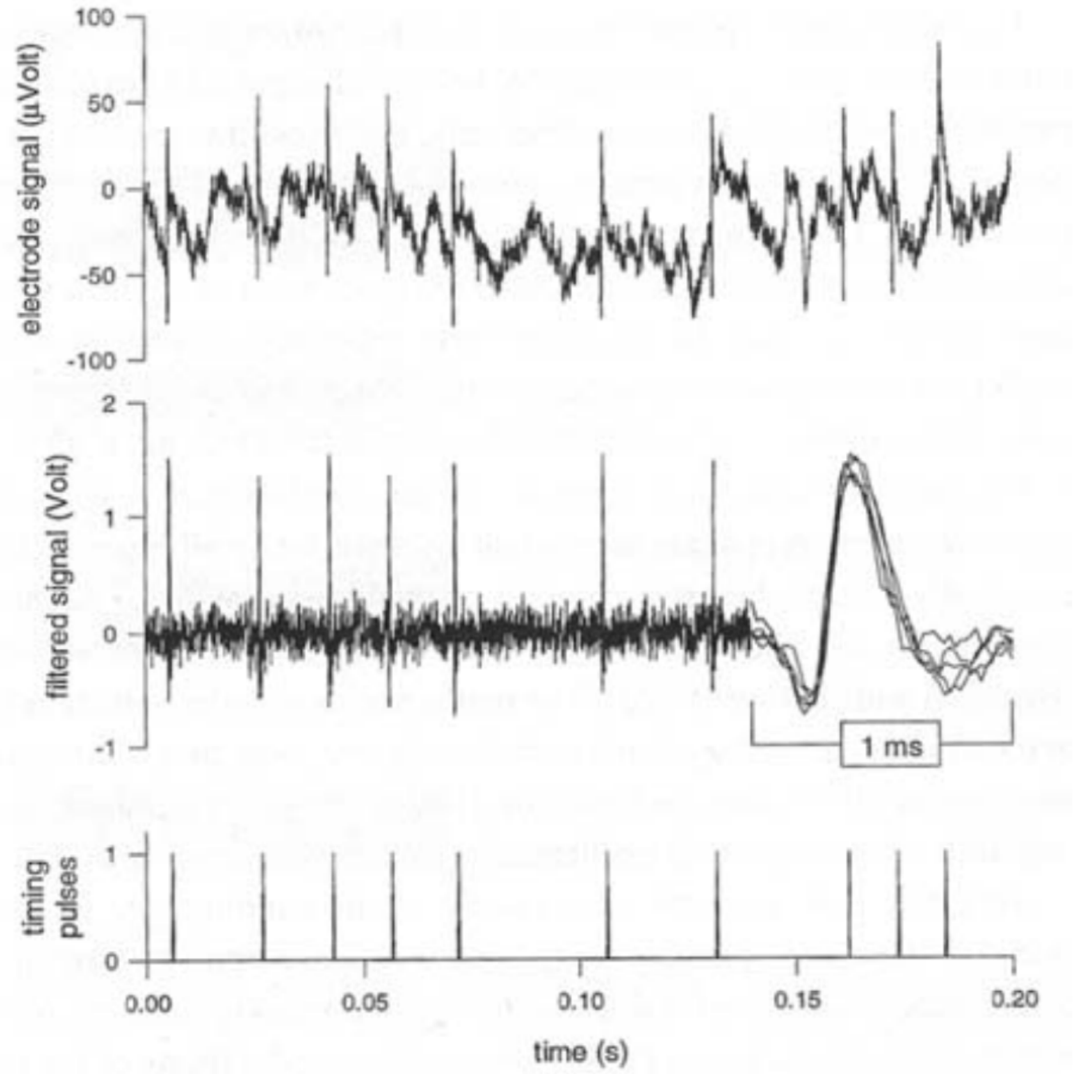
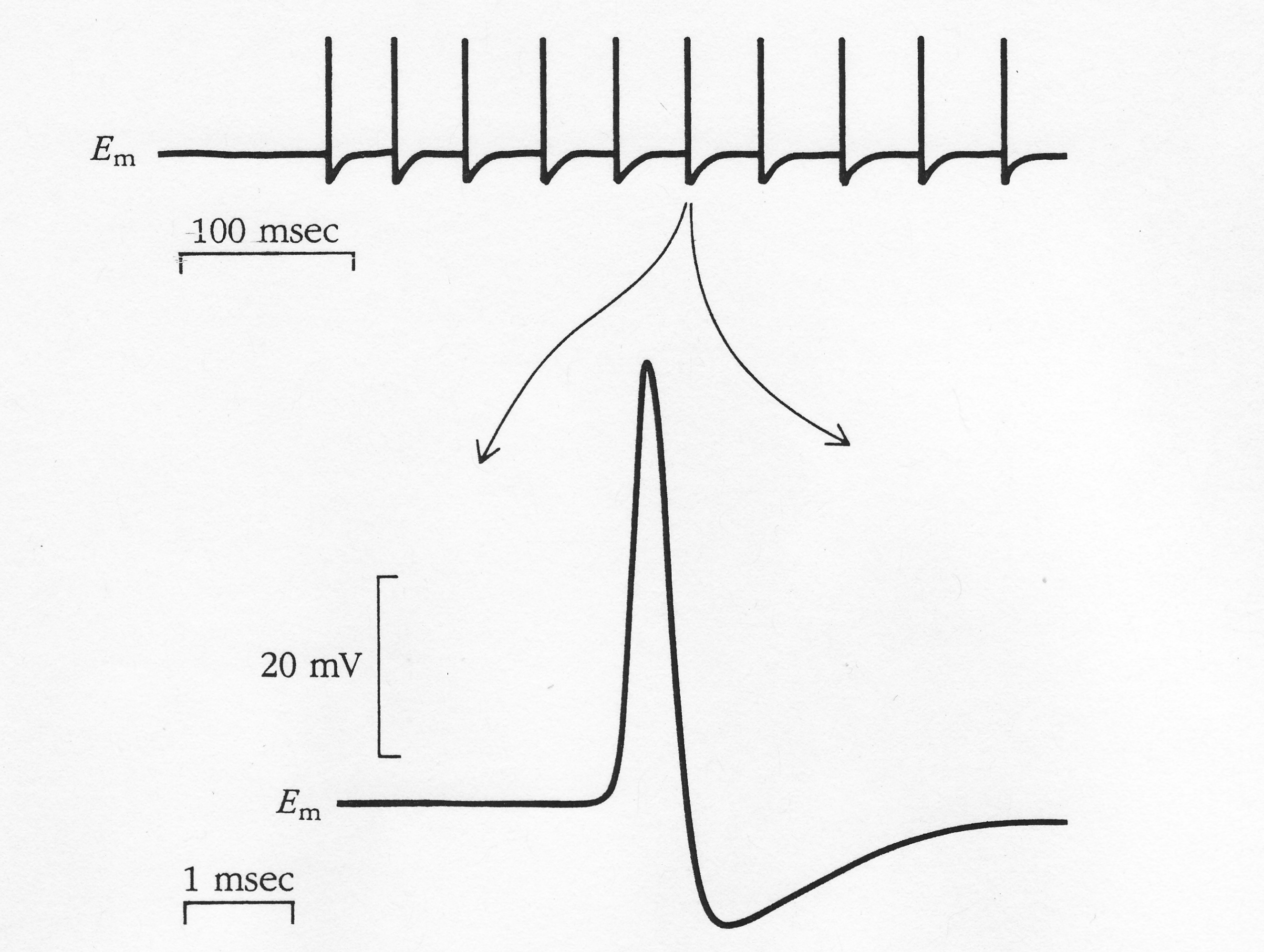
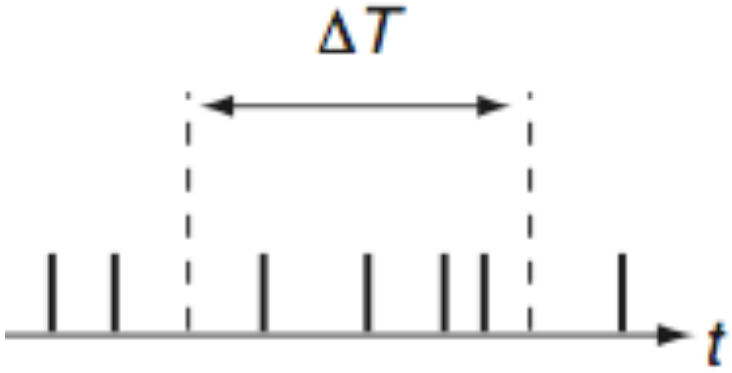
Timing pulses generated automatically by a threshold discriminator circuit



Rate Coding



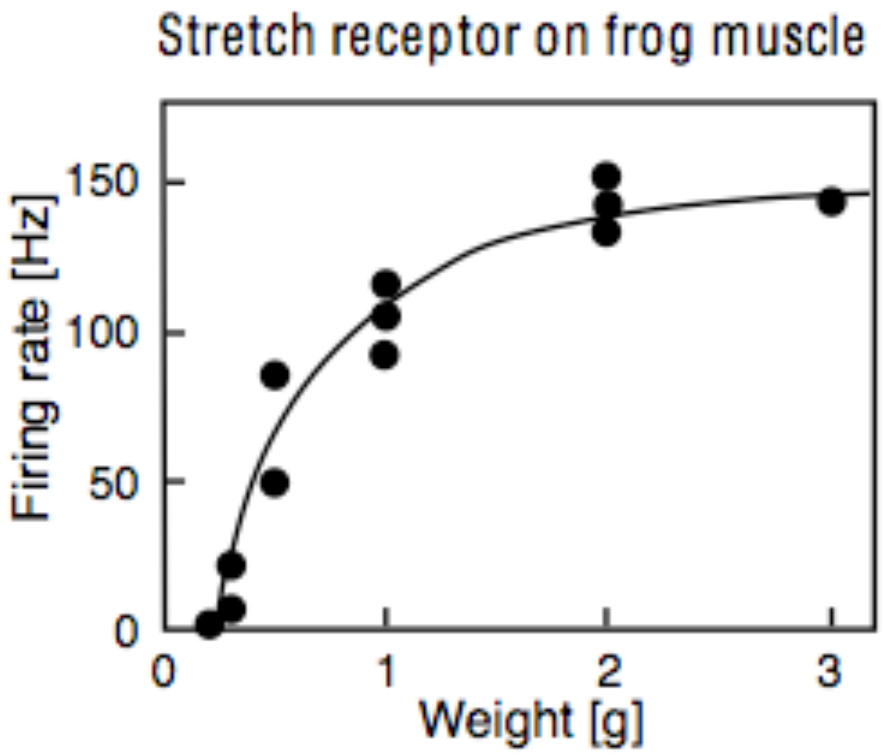
Temporal averaging



$$spike\ rate = \frac{\#\ of\ spikes}{period\ of\ time}$$

Basic concepts

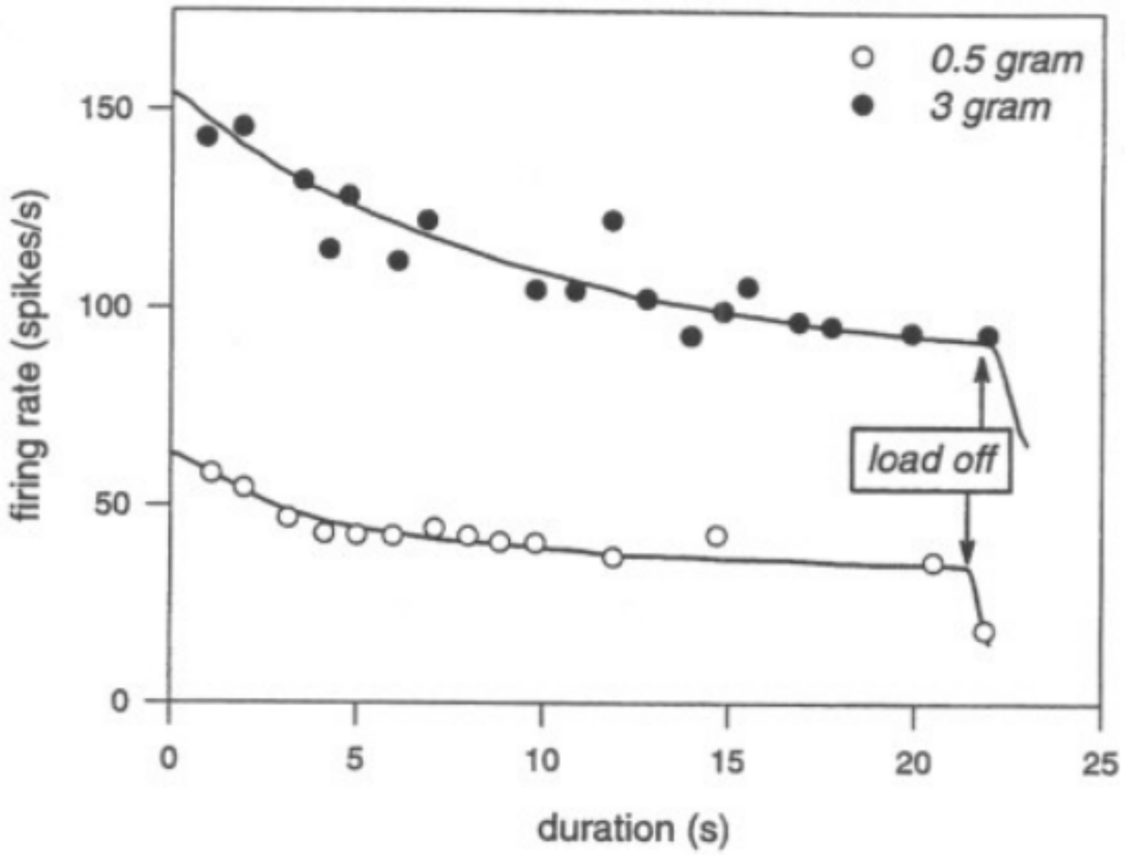
- The shape of the action potential did not appear to carry significant information
- Adrian found that as the magnitude or intensity of stimulation was increased, the sensory neurons produced action potentials at an increasing rate
- The nervous system uses firing rate to encode information about the world.
- However, it is quite possible that information is encoded in the pattern of spike timing rather than (or in addition to) their overall rate of production



Average firing rate of a stretch receptor as a function of the weight applied to the muscle

Basic concepts

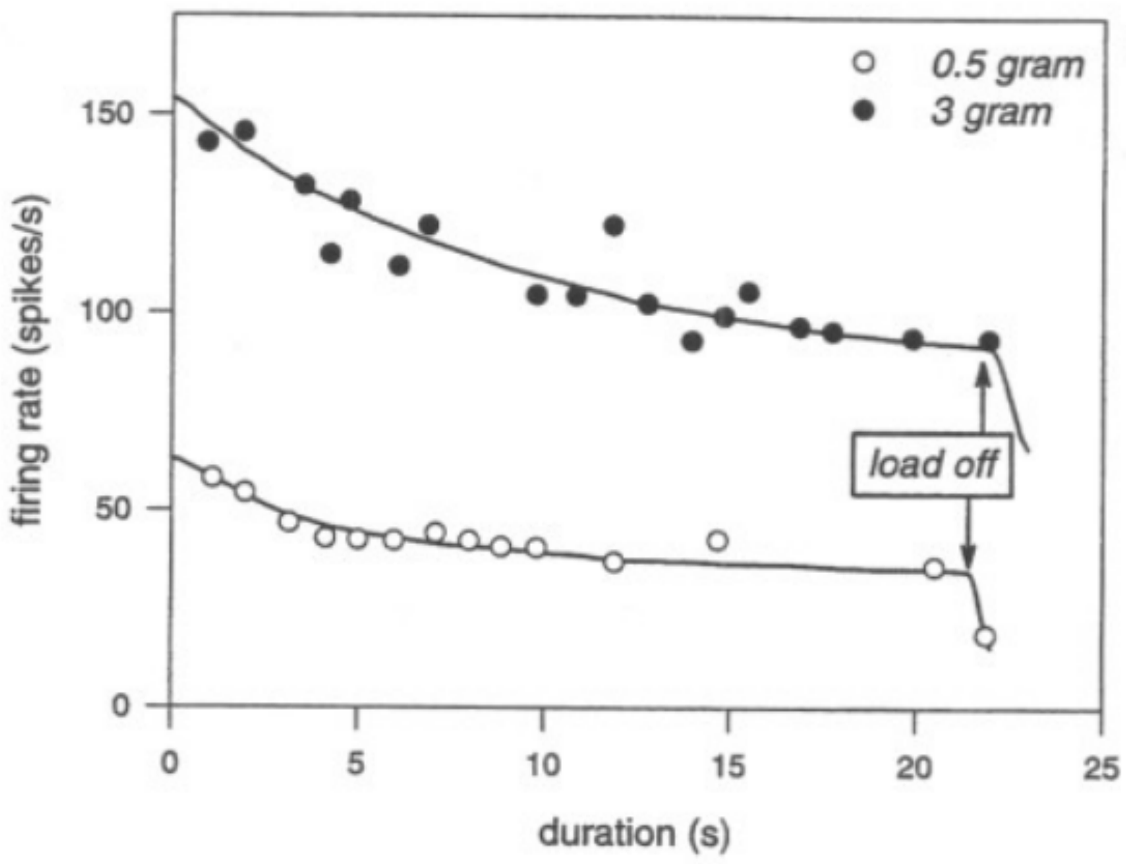
- The neural responses adapt, i.e. the initial presentation of a stimulus causes a neuron to produce spikes at a certain rate, but as the neuron "adapts" to this stimulus its firing rate slows
- The representational power of sensory neurons may be focused on representing changes in the state of the environment, rather than the state of the environment per se



Frequency of spikes per second produced by stretching the muscle with constant loading weight

Basic concepts

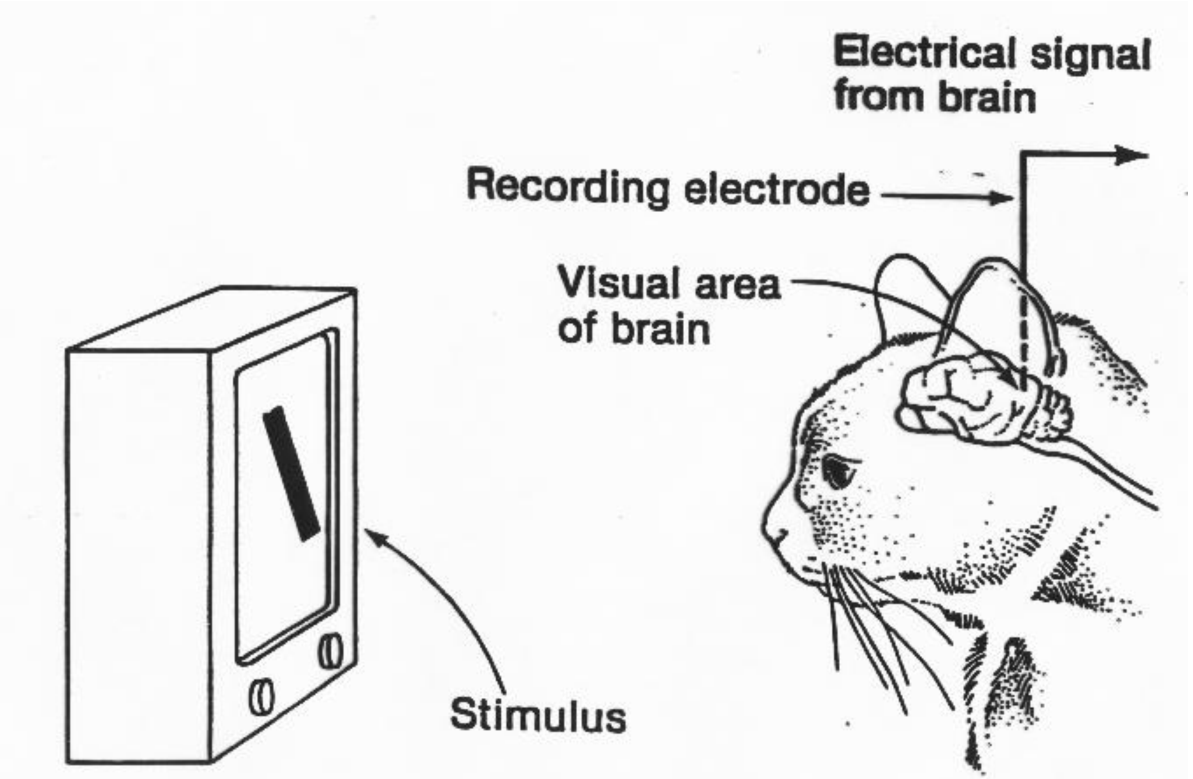
- Adaptation causes a significant complication for the notion of a rate code, because it removes the one-to-one relationship between spike rate and magnitude of the stimulus.
- Thus, stretch receptors cannot be said to use firing rate to represent the weight of an object, at least not using the most direct notion of rate encoding.



Frequency of spikes per second produced by stretching the muscle with constant loading weight

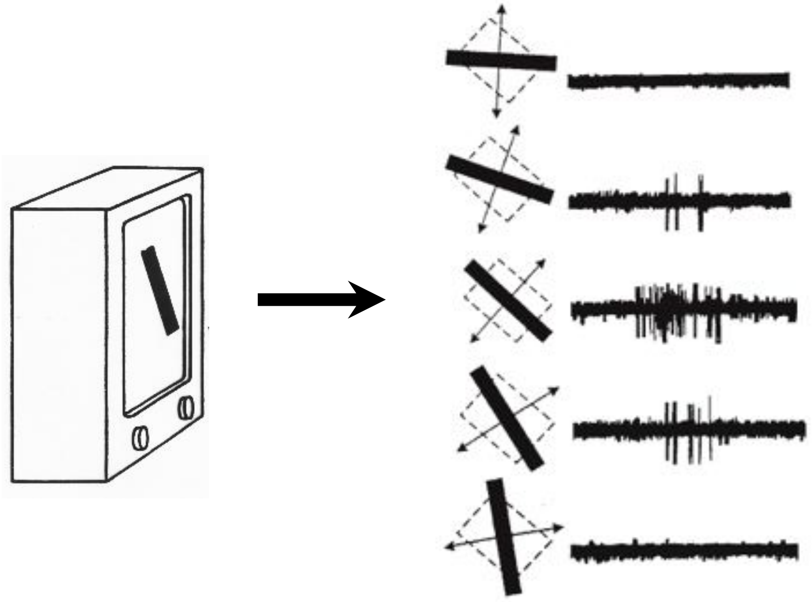
Turning curves

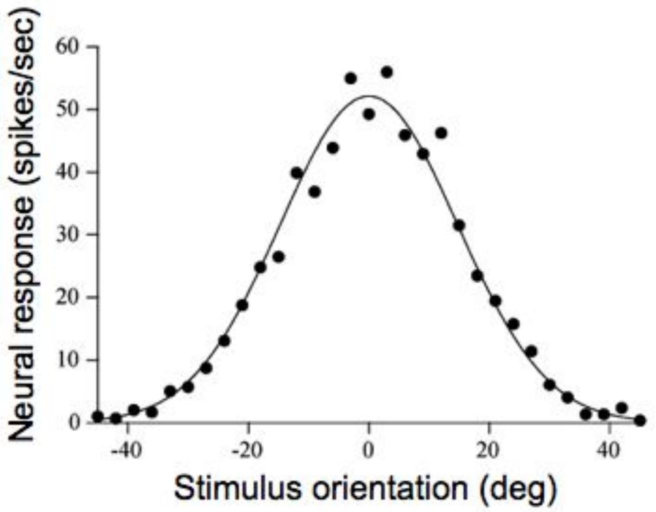
- At the most basic level, all experiments designed to uncover the neural code can be described as presenting a bunch of stimuli (more or less under the control of the experimenter) and recording the neural response.



Turning curves: orientation selectivity

- Tuning curve is a graph of neuronal response (usually measured in action potentials or spikes per unit time) as a function of a continuous stimulus attribute, such as orientation, wavelength, or frequency.





Orientation tuning of neurons in the visual cortex. A shows extracellular recordings in a monkey stimulated by moving bars. B shows the average firing rate of a neuron in the primary visual cortex of the cat as a function of the angle of a light bar stimulus