Introduction to Neural Networks

Johns Hopkins University
Engineering for Professionals Program
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Module 1.1: Course Overview

My Brain

The Hemispheres of the Brain

- Brain lateralization: certain functions seem to be specialized into one hemisphere. Some interesting symmetries!

LEFT BRAIN FUNCTIONS	RIGHT BRAIN FUNCTIONS
Small Picture	Big Picture
Verbal Communication	Nonverbal Communication
Small Muscle Control	Large Muscle Control
Intelligence Quotient	Emotional Quotient
Word Reading	Comprehension
Math Calculations	Math Reasoning
Processing Information	Interpreting Information
Conscious Actions	Unconscious Actions
Positive Emotions	Negative Emotions
Receiving Auditory Input	Interpreting Auditory Input
Linear and Logical Thinking	Gets Abstract Concepts
Curious and Impulsive Actions	Cautious and Safe Actions
Like Routine/Sameness	Likes Newness, Novelty
Activates Immunity	Suppresses Immunity

What are Neural Networks?

- Originated as mathematical models of biological neurons.
- Evolved into large scale, massively parallel collections of computing entities.
- Single neurons are *relatively* simple.
- Many interconnected neurons are complex.
- Simple computation.
- Complex computation.

A bit of History

- McCulloch and Pitts (1943) devised neural network models in the context of automata and computation;
- Donald Hebb (1940) established concepts now referred to as *Hebbian learning* covered later in the course.
- Alan Turing (1940) developed the foundation of computing theory with his Turing machine.
- John von Neumann (1940) devised other computing paradigms.
- Stanislaw Ulam (1940) worked on cellular automata and computing theory.
- Developments in electronics, nuclear science, radar, computers and cryptanalysis.

A great deal of intellectual ferment during World War II.

What are Neural Networks?

- Neural networks are an attempt to mimic the behavior, in some respects, of the brain—a network of nerve tissues.
- Neural networks are mathematical models inspired by biological neurons.
- Each nerve or neuron is considered to be a relatively simple device.
- When combined with other similar neurons in a network, they become an exceedingly complex system that seem to give rise to ‘emergent’ behavior.
- Mathematical capabilities to perform logic.
- Mathematical properties of dynamical systems.

Why do people study them?

- Curiosity about how brains work.
- Curiosity about consciousness, thinking and computing.
- Curiosity about ‘complex systems’ and ‘emergent’ behavior.
- Many recent advances and insights into ‘network theory’.
    - Keywords: clustering, network analysis, pathways, degrees of contact, data-mining, complexity theory …
    - Maximal Information-based Nonparametric Exploration---data mining.

But, What are Neural Networks?!

- Essentially, they are simple, mathematical models of neurons.
- Have roots in
  - Neuroscience
  - Mathematics and statistics
  - Physics
  - Computer science
  - Engineering
- Requires use of mathematical tools to study and analyze them and gain insights into what they CAN and CANNOT do.
  - Linear algebra, Calculus, Vector Calculus, metric spaces and dynamical systems, optimization methods.

Application Areas

- Modeling systems.
- Time series processing.
  - Forecasting, prediction.
- Signal processing.
  - Filtering, noise reduction…
- Pattern recognition.
  - Speech recognition,
  - Natural language processing,
  - Biometrics,
  - Classification
- Control system engineering.

From Simple to Complex

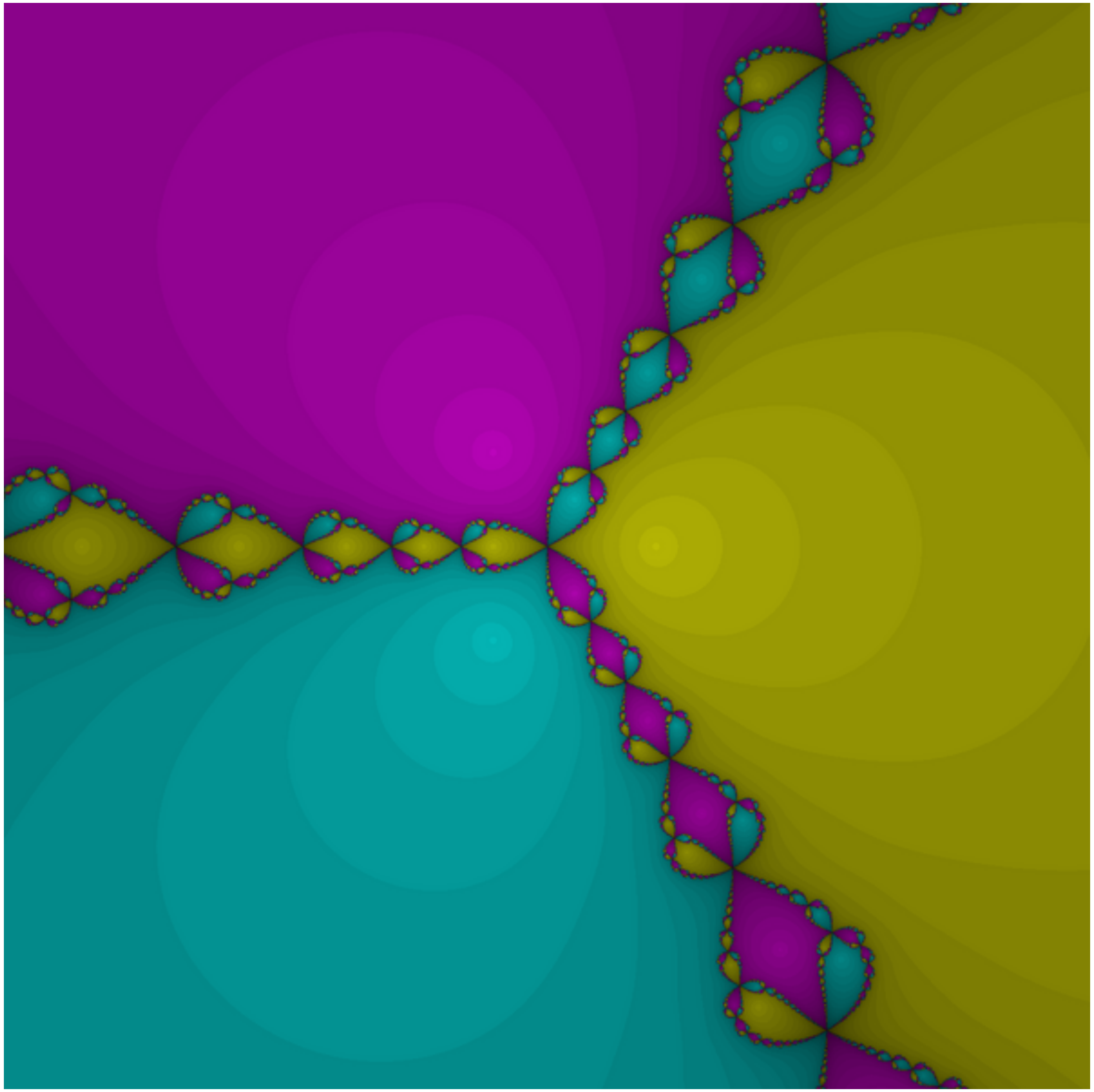
- Let's start with a simple polynomial --- how complex can that be? $f(z) = z^3 - 1$

- Let's explore something where a mathematical quantity changes over time according to some formula.

Newton's Method

- In complex plane, what are the roots of:

$$f(z) = z^3 - 1$$



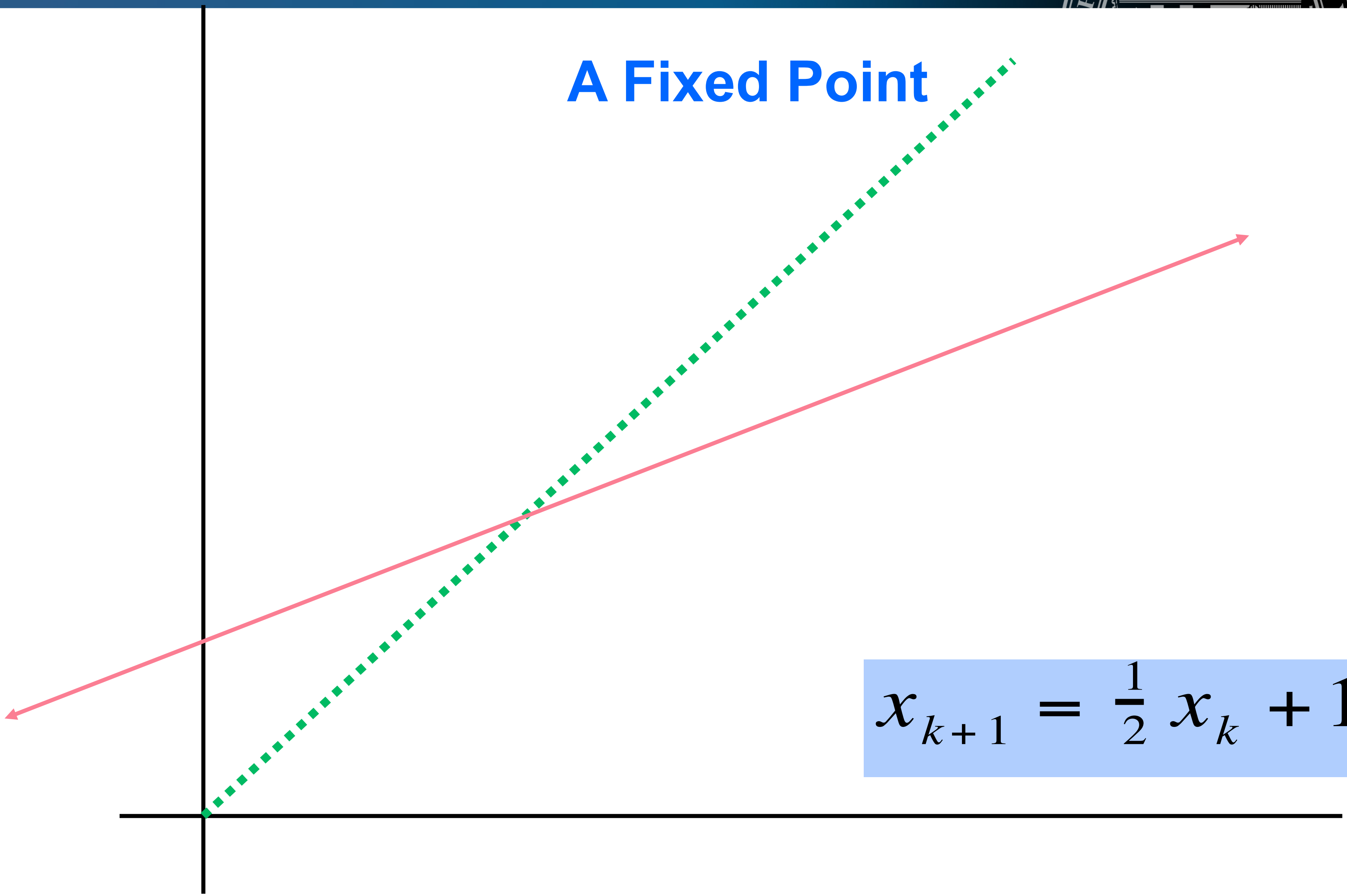
A Simple Dynamical System

$$x_{k+1} = f(x_k)$$

$$\lim_{k \to \infty} x_k = x^* \quad \Rightarrow \quad x^* = f(x^*)$$

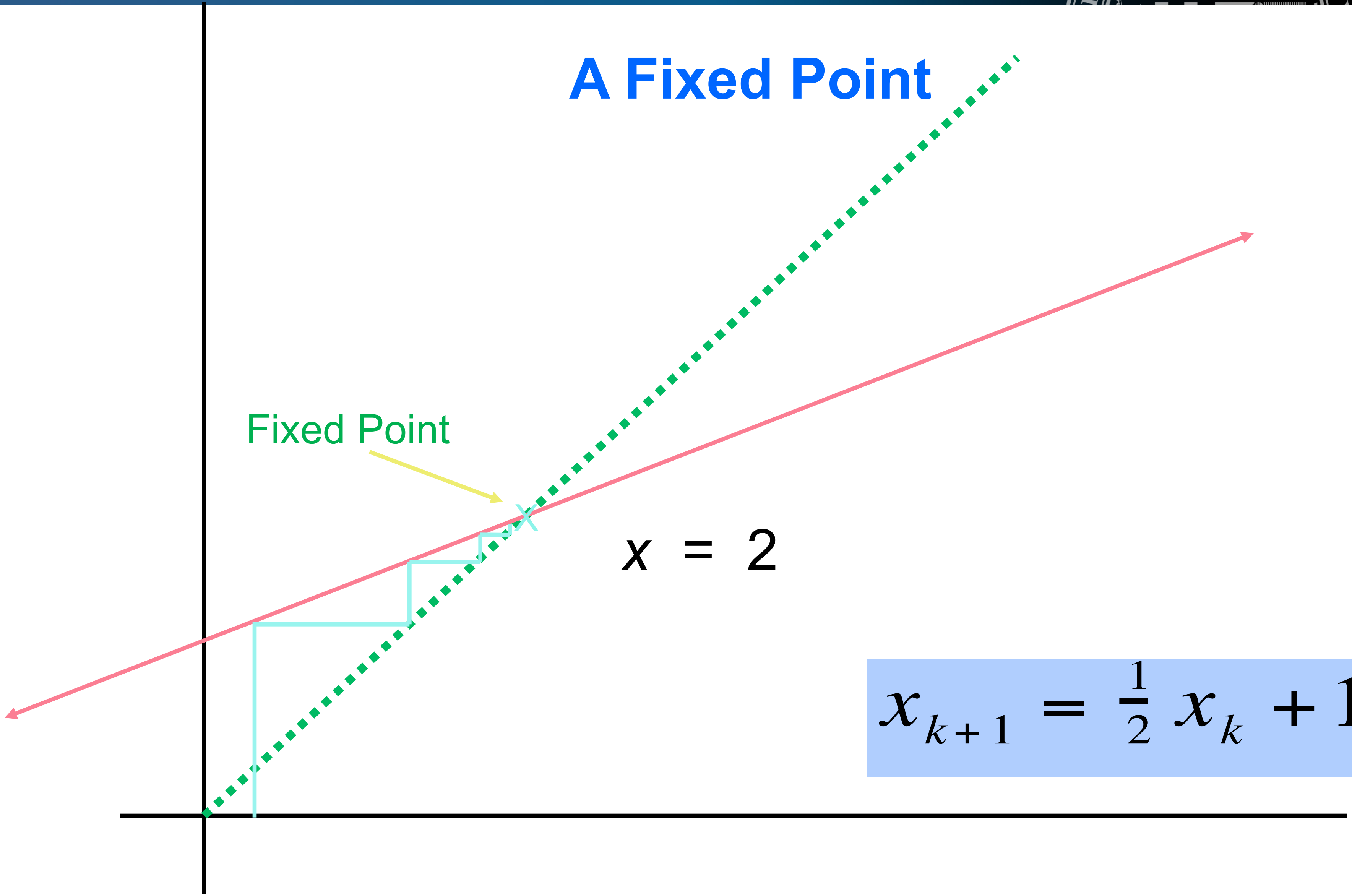
A Fixed-Point

A Fixed Point



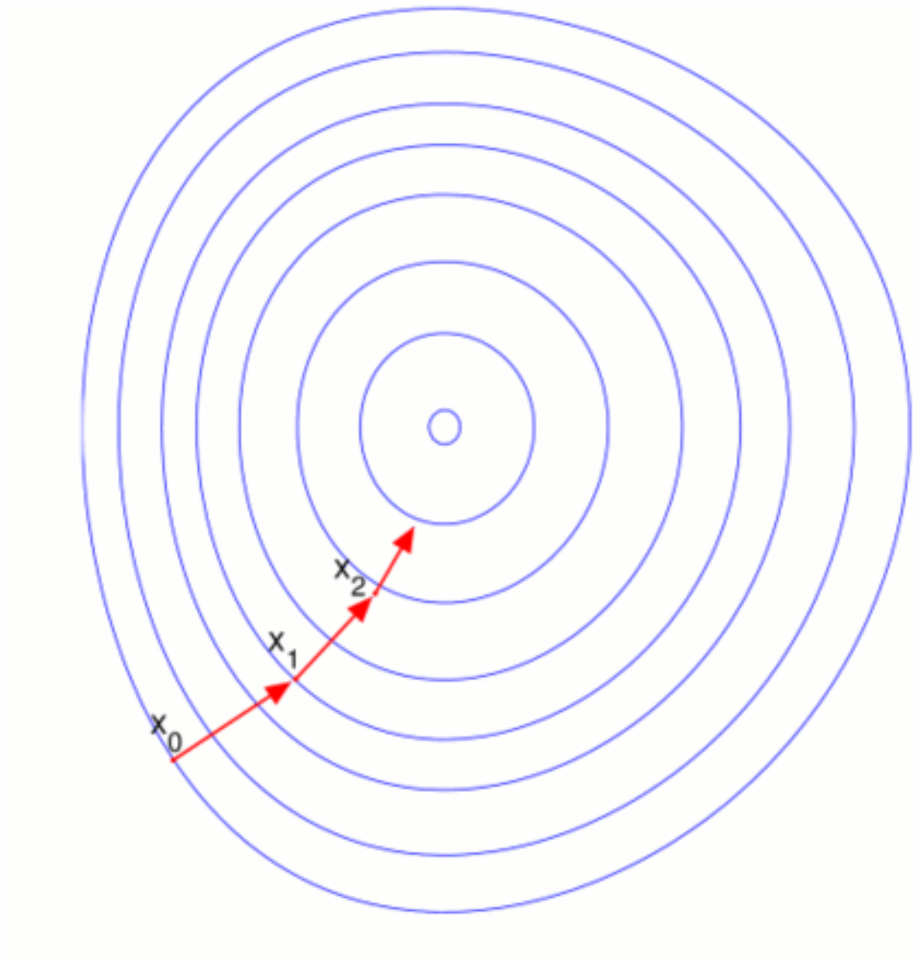
$$x_{k+1} = \frac{1}{2} x_k + 1$$

A Fixed Point

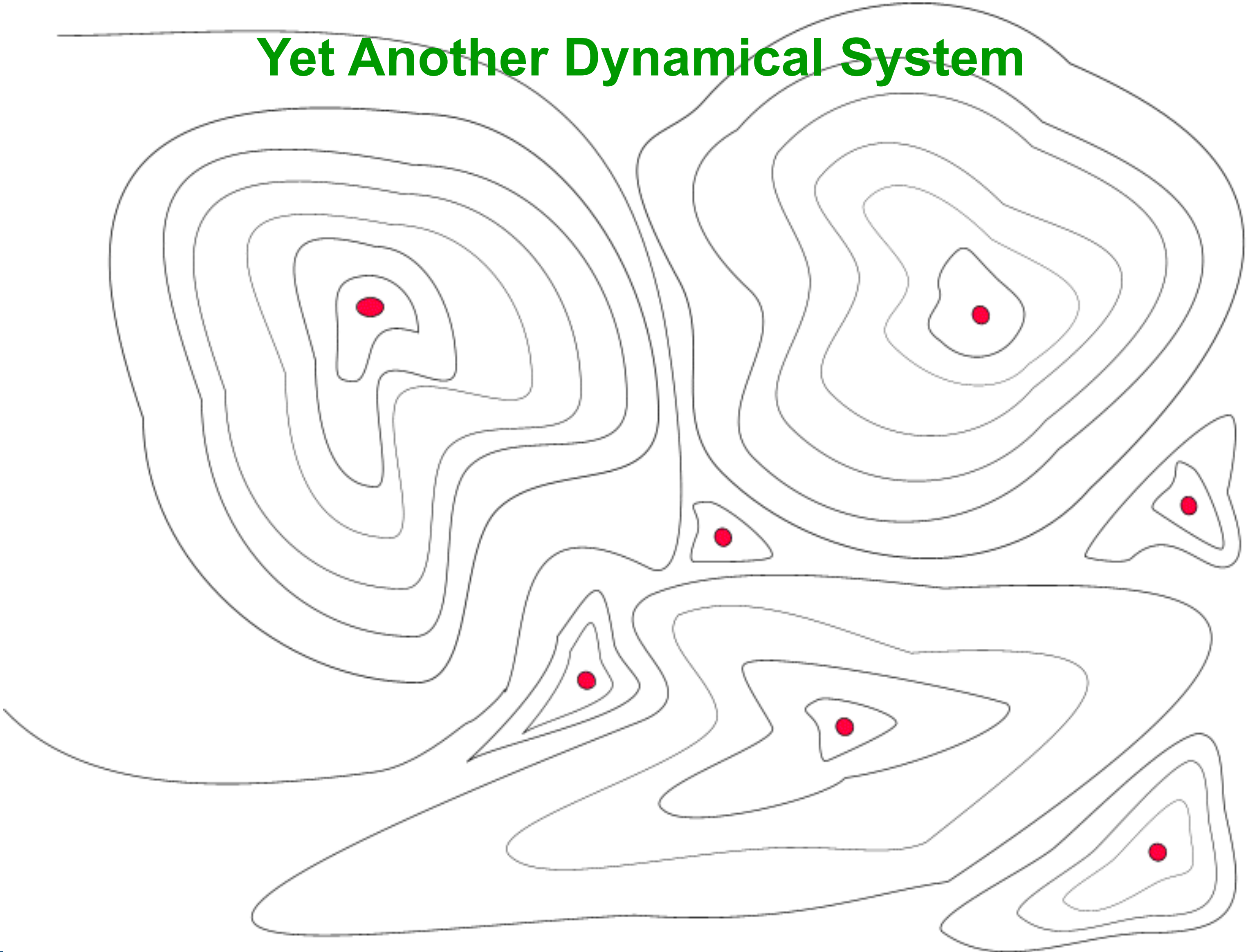


$$x_{k+1} = \frac{1}{2} x_k + 1$$

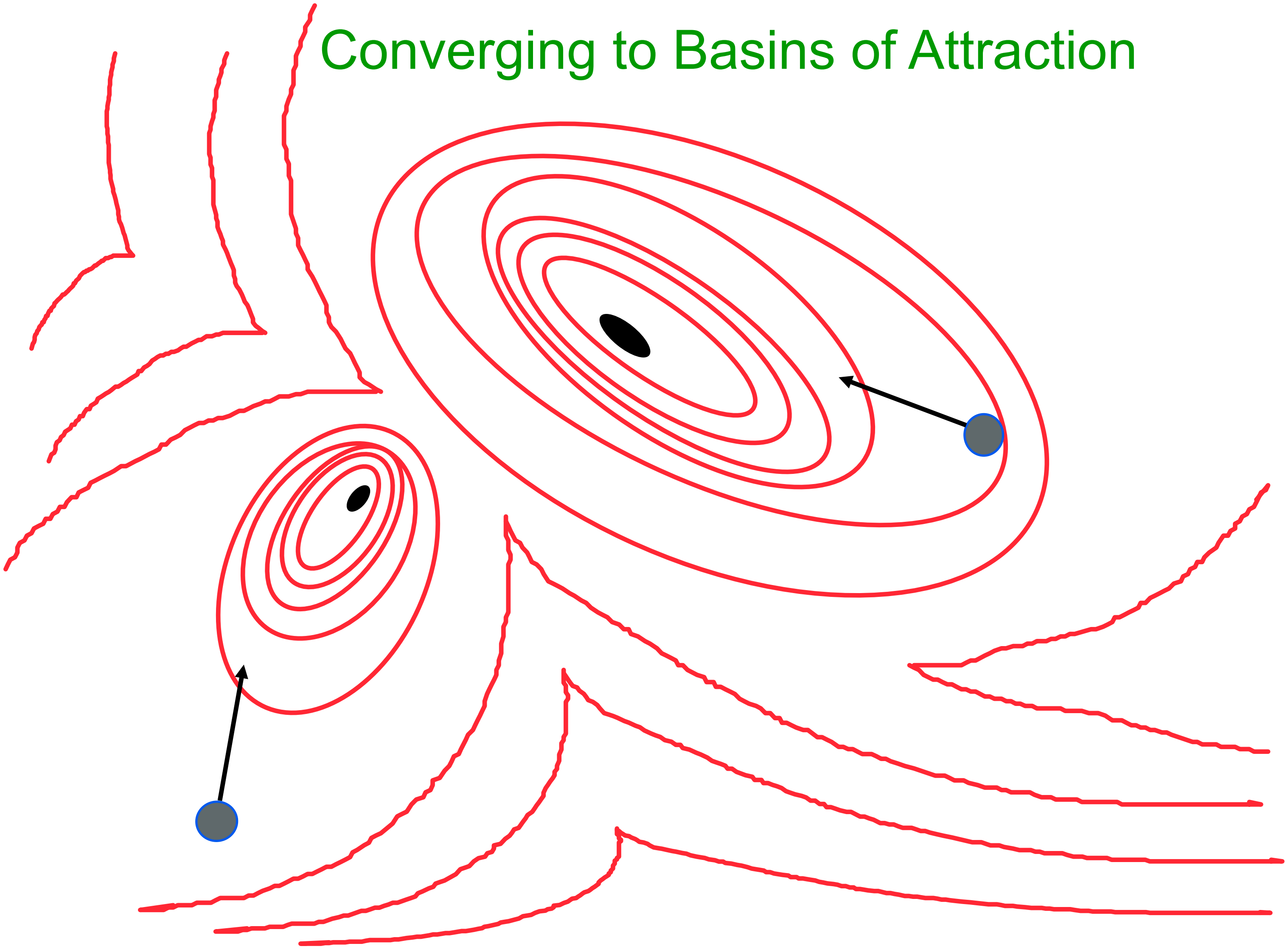
Another Dynamical System



Yet Another Dynamical System

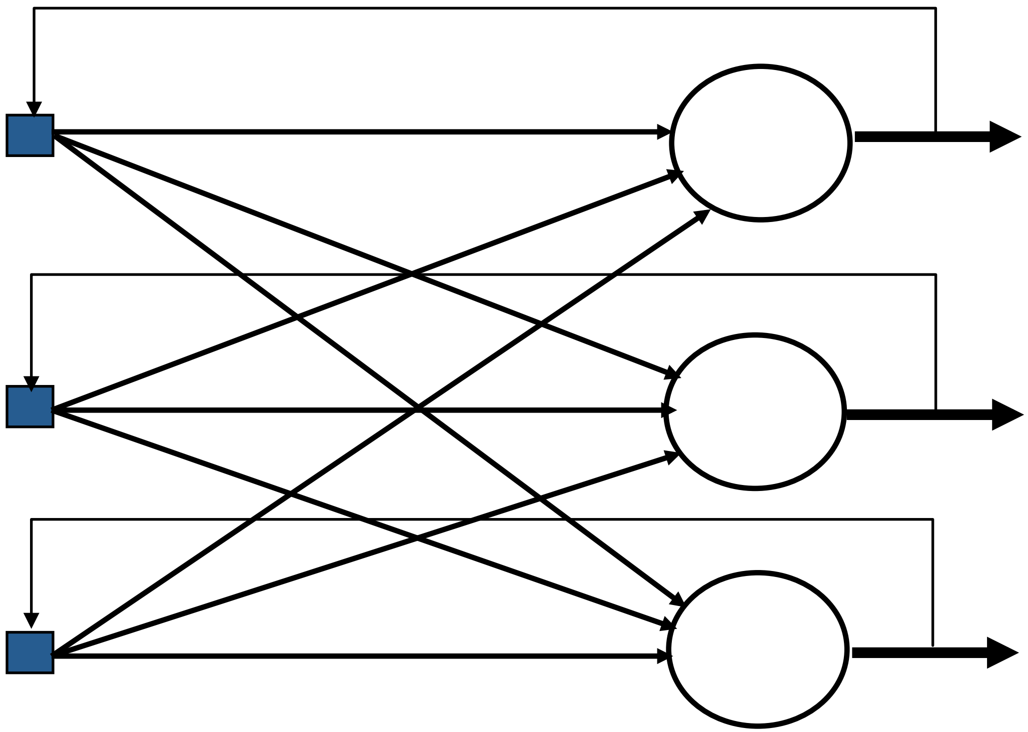


Converging to Basins of Attraction



Attractor Neural Nets

Hopfield Net



Some topics we'll cover:

- Simple mathematical relationships and theory
- Some 'systems' theory
- Some numerical methods and algorithms
- Some optimization methods

The Principle Theme

- **Using computers to perform experiments, investigate ideas and develop and test new theories!**

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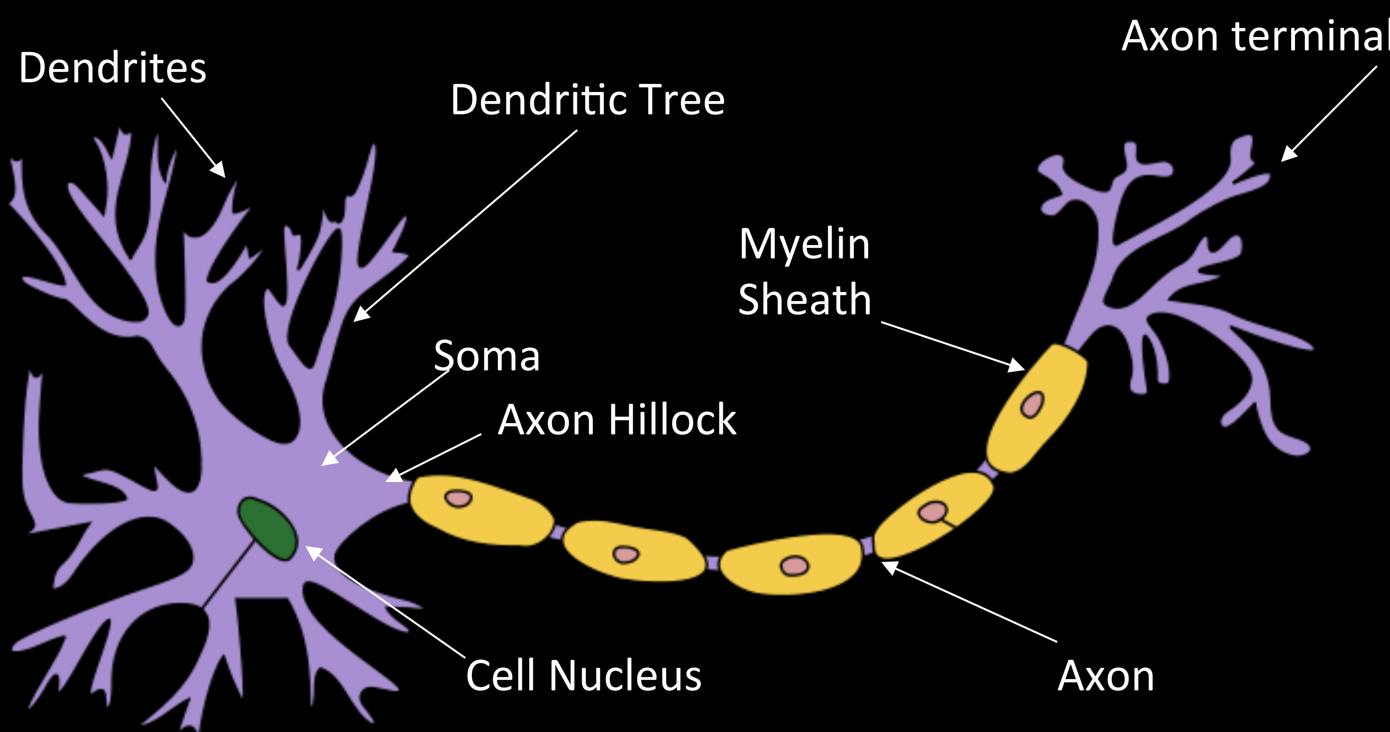
Module 1.2: The Biological Neuron

This Sub-Module Covers …

- The basic elements/components of biological neurons and serves as the foundation of our modeling efforts. We will cover:
  - The basic structure of the biological neuron.
  - Some of the electro-chemical properties of the neuron.
  - Mechanisms for signaling between and among neurons.
  - Mechanisms associated with neuronal excitation and inhibition.
- This sub-module is then followed by a short quiz.

A Biological Neuron

Nature's Communication Mechanism



From Wikipedia.

The Ion Pump

- A basic mechnism of a living neuron.
- ‘Pumps out’ sodium ions from inside of cell, pumps in potassium ions.
- 3:2 --- 3 out for every 2 in.
- Results in a net positive charge on the outside of the cell membrane.
- Some ions randomly cross membrane.
- Ion movement attempts to neutralize charge.
- Various types of ‘channels’ that are open or close and let ions move through the membrane more easily.

Neuronal Connections

- Axon terminals have 'synaptic buttons' at a 'synapse'.
- The synapse 'connects' to dendrites of other cells and so one cell can connect to many other cells.
- The length of the axon is relatively long compared to the dimensions of the cell body --- long distance communication!

So how do the cells 'communicate'?

Open the Flood Gates!

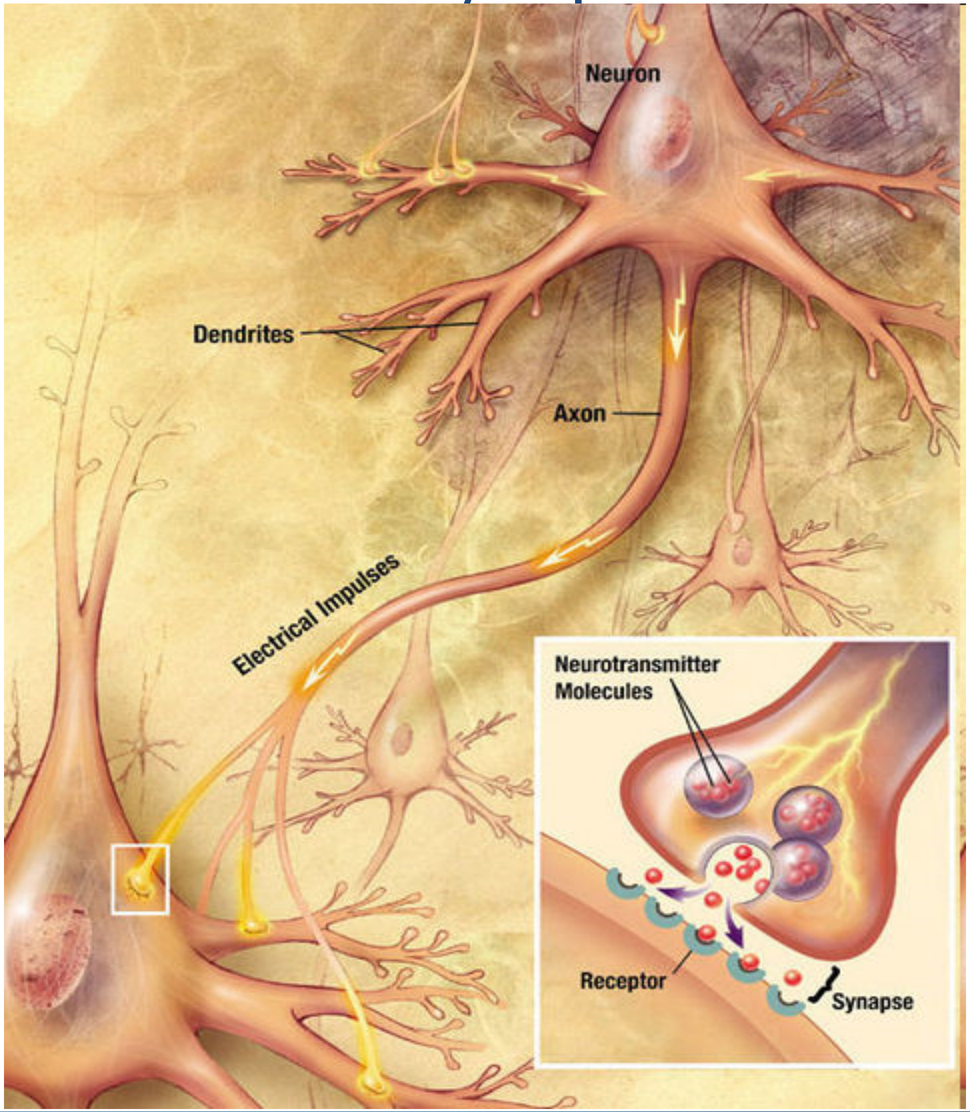
- Sometimes a channel is opened causing sodium ions to flood into the cell. E.g., ligand-gated channels near synapses. Causes local depolarization.
- This can cause nearby sodium channels to open. E.g., voltage-gated channels. Causes further depolarization.

The Action Potential

A simplified view

- The 'action potential' is essentially a pulse of electric charge that travels down an axon.
- It cascades down the axon changing the state of channels which cause an electric wavefront to expand causing further channels to change, etc. Just like dominoes.
- This pulse is triggered by electrical changes in the cell body.
- Inputs at synapses, affected by release of neuro-transmitters, trigger electrical changes (increase/decrease electric charge) in the neuron by changing the number of ions in the cell.
- These changes affect voltage dependent sodium channels through which ions can enter or leave a cell.

The Synapse

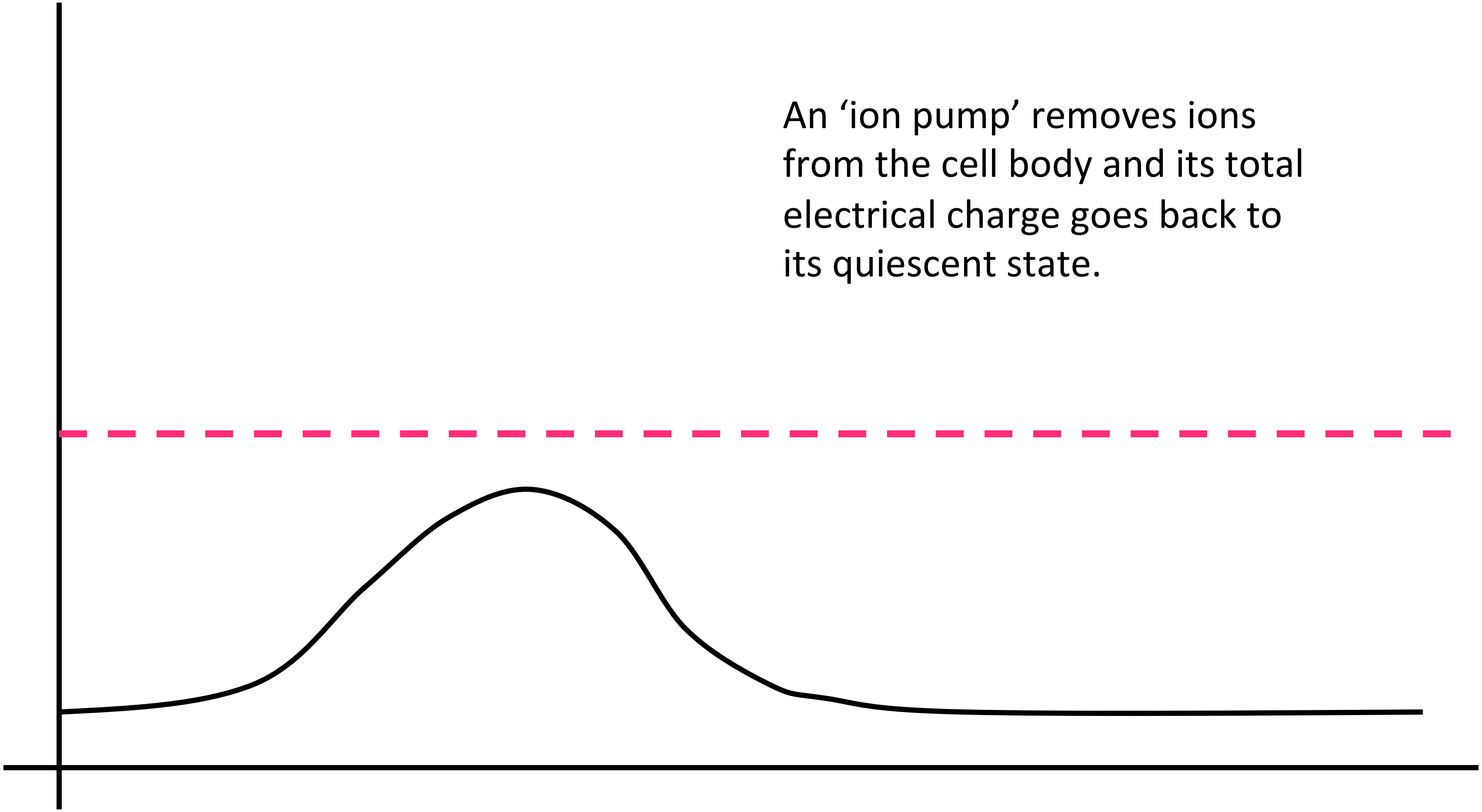


From Wikipedia

The Action Potential

- Charge builds up and/or decays in a neuron.
- If the charge continues to build up and reaches a threshold value, the cell begins to discharge… i.e., the action potential is triggered.

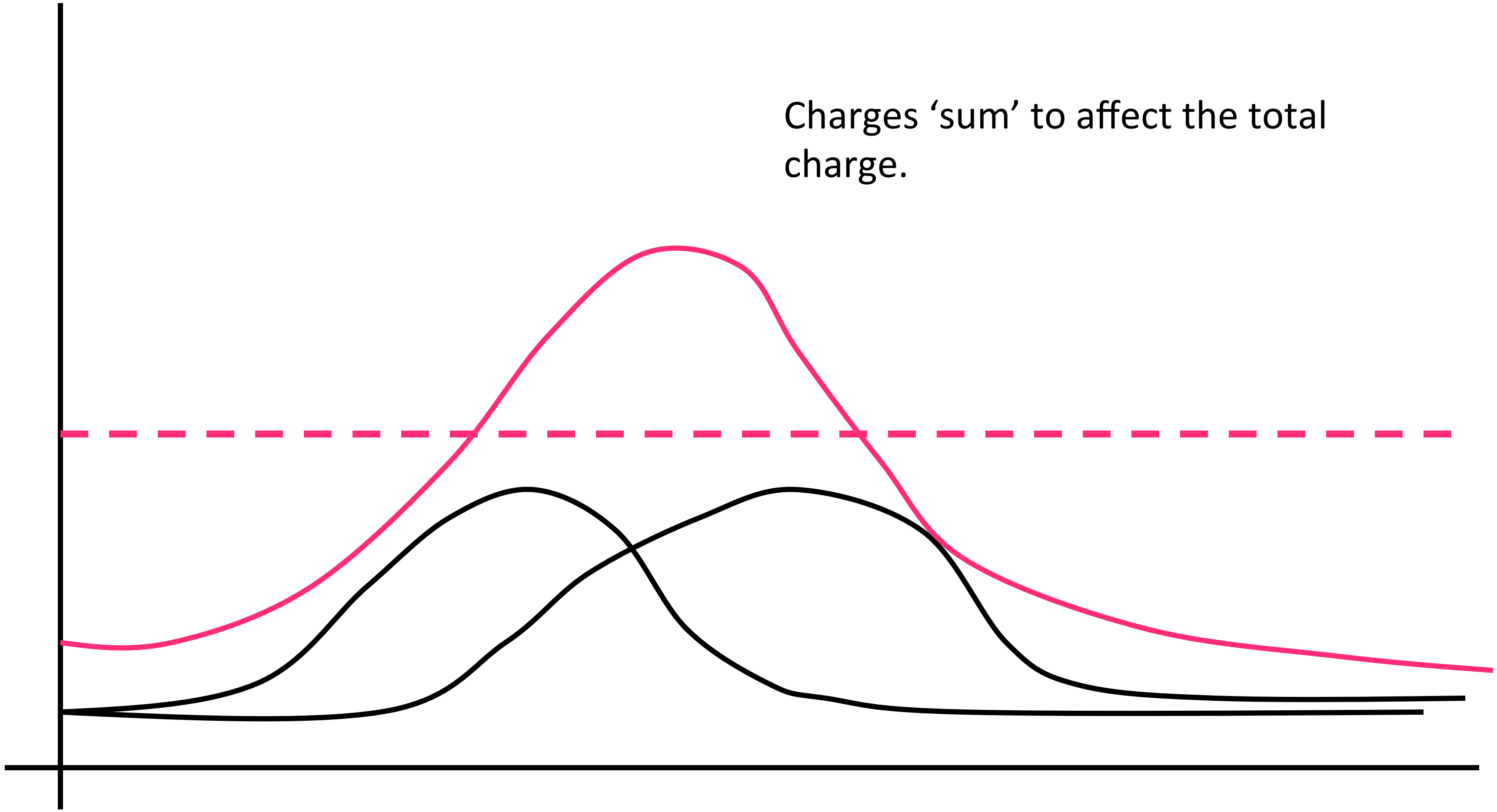
The Action Potential



An ‘ion pump’ removes ions from the cell body and its total electrical charge goes back to its quiescent state.

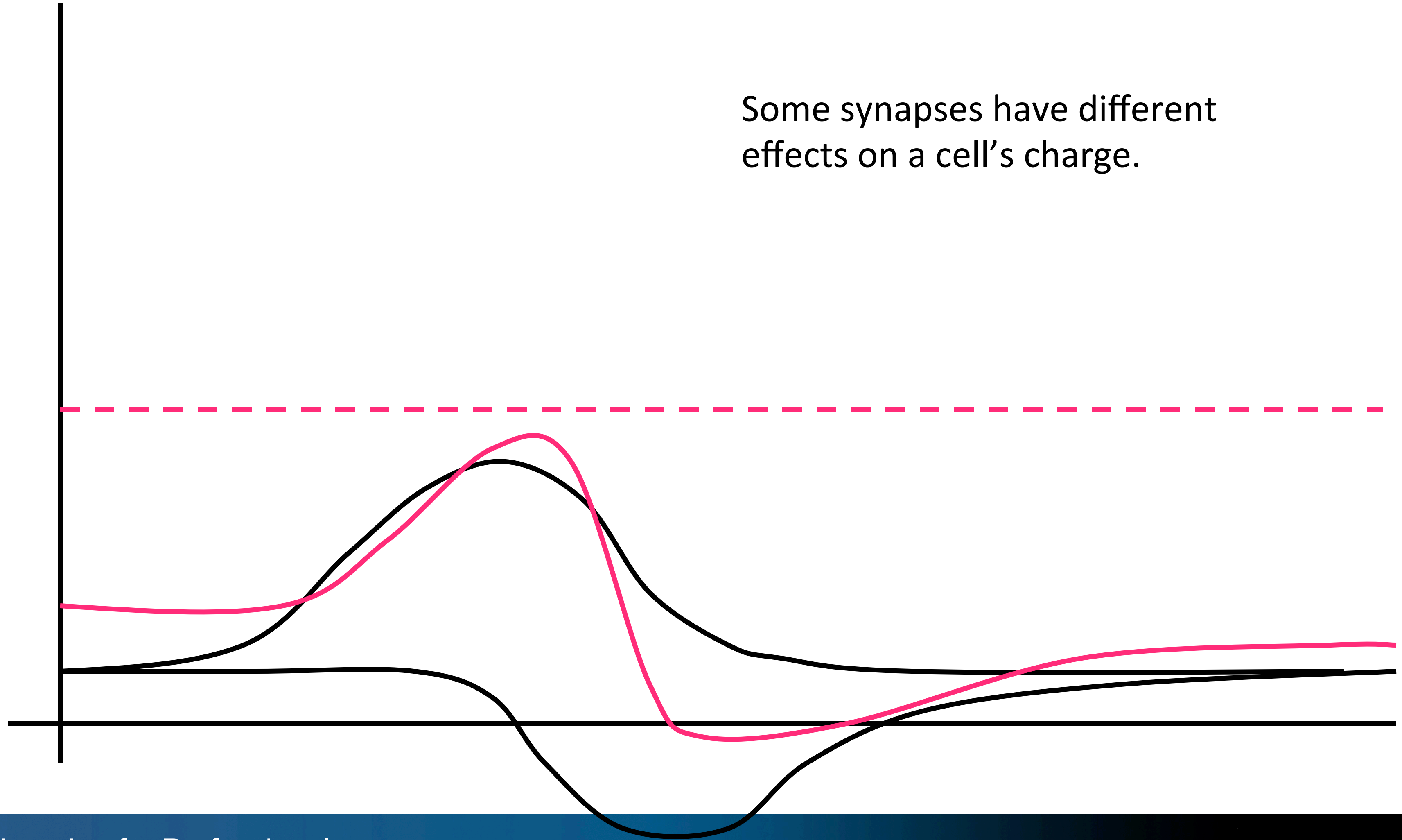
The Action Potential

Charges 'sum' to affect the total charge.



The Action Potential

Some synapses have different effects on a cell's charge.



The Meaning of the Action Potential

- What does it ‘mean’ when it ‘fires’? What good is that?
- Think in terms of evolution.
- What does it mean when several action potential impinge on a given neuron?
- What does the fact that the effect of an action potential ‘decays’?

In the next sub-module…

- We will cover some of the issues surrounding the art and science of modeling.
- Before viewing the next sub-module, take the online quiz using the link following this presentation in the Module Content page.

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Module 1.3: Modeling Considerations

My Brain, Your Brain

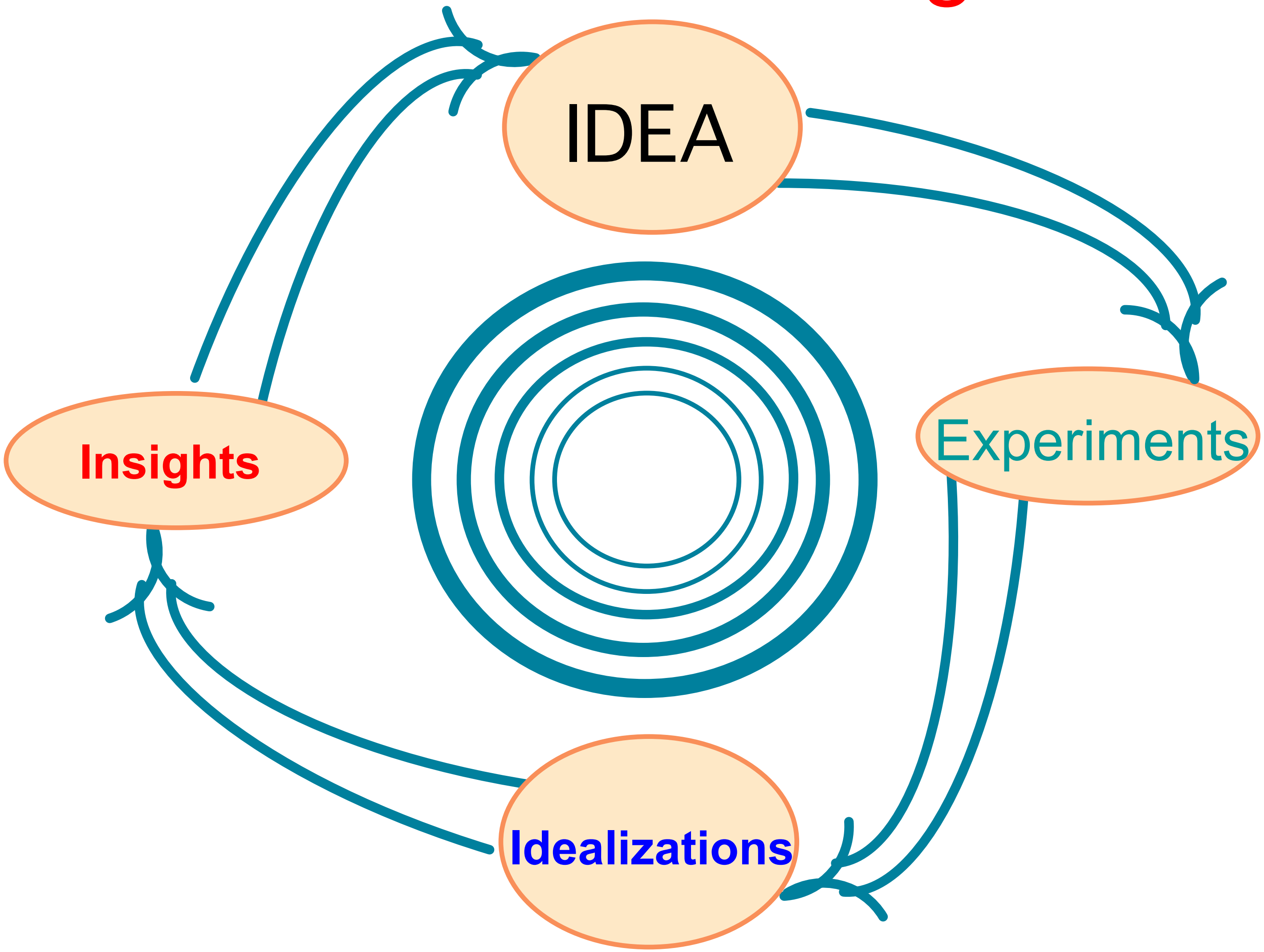
In this sub-module…

- We will cover some of the issues surrounding the art and science of modeling.
- These issues involve a tradeoff between detail and simplicity.
  - Want enough detail to capture important phenomena.
  - Want to keep things simple enough so that we can analyze our model and gain insight.

Modeling Reality

- Can't model all details. Too difficult and misses the mark.
- Don't want it too simple…also misses the mark.
- Have to strike a balance so that some interesting phenomena can be illuminated and possibly analyzed and studied.
- Capture the essential and interesting features.

The Vortex of Progress



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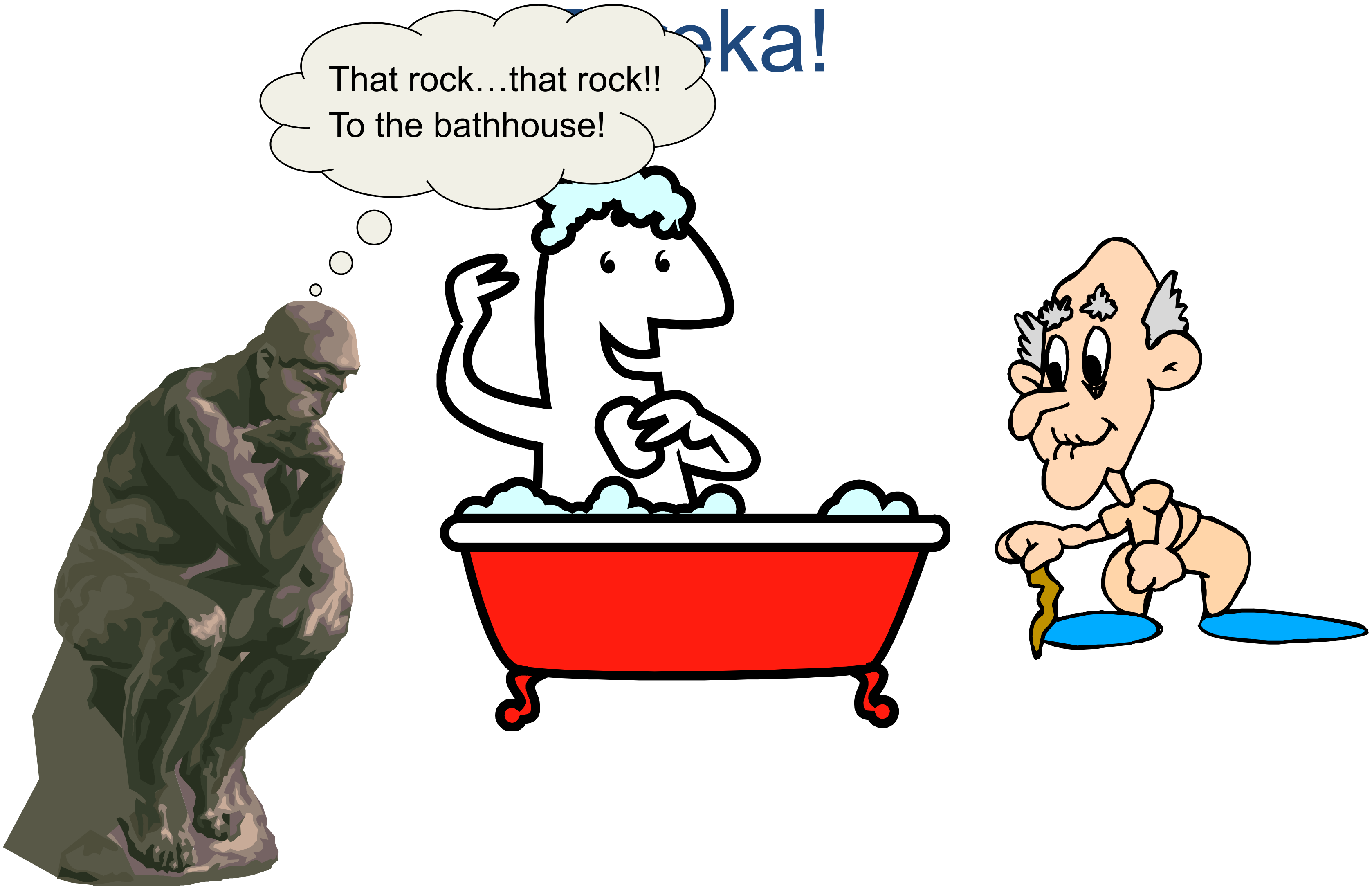
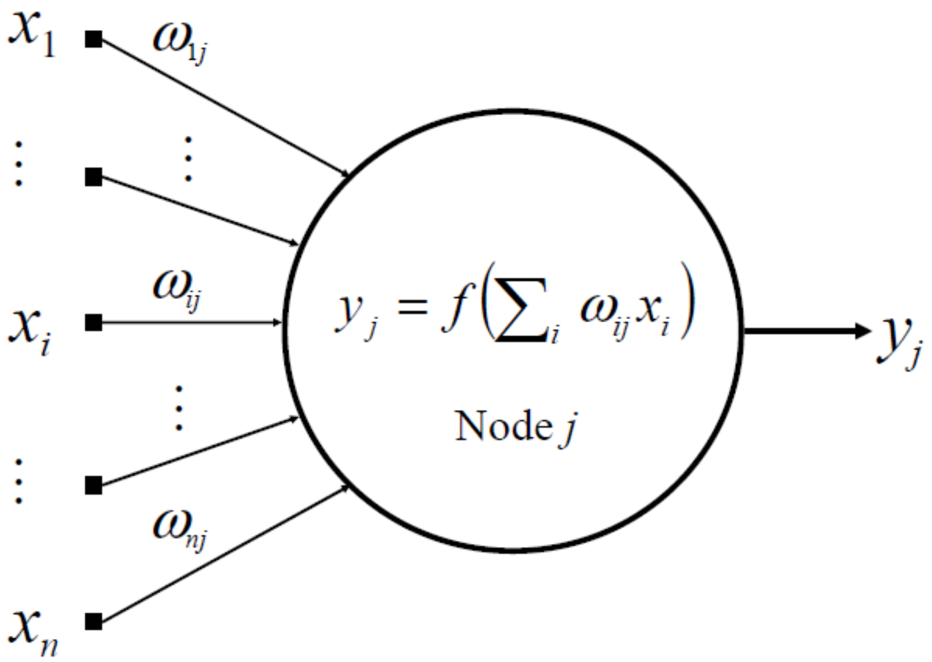
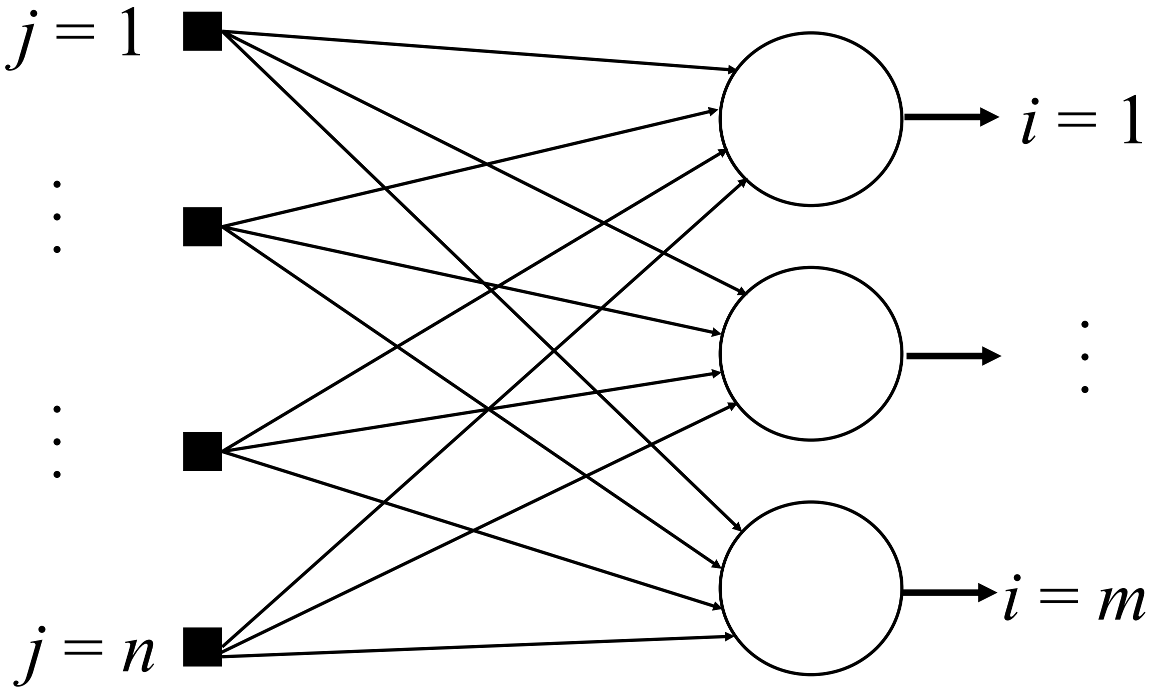


The Perceptron



The Multi-perceptron



The Activity Function

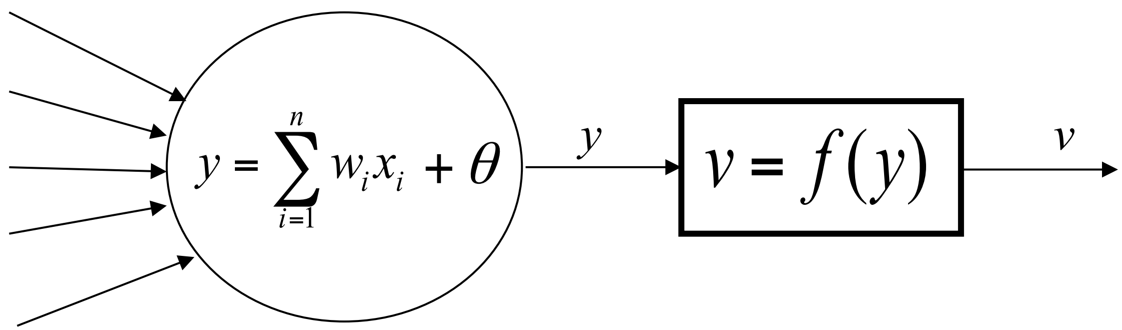
- The output of the Perceptron *y* is given by the equation:

$$y = \sum_{i=1}^{n} w_i x_i + \theta$$

- This Activity Function is sometimes referred to as a *linear basis function*.

The Activation Function

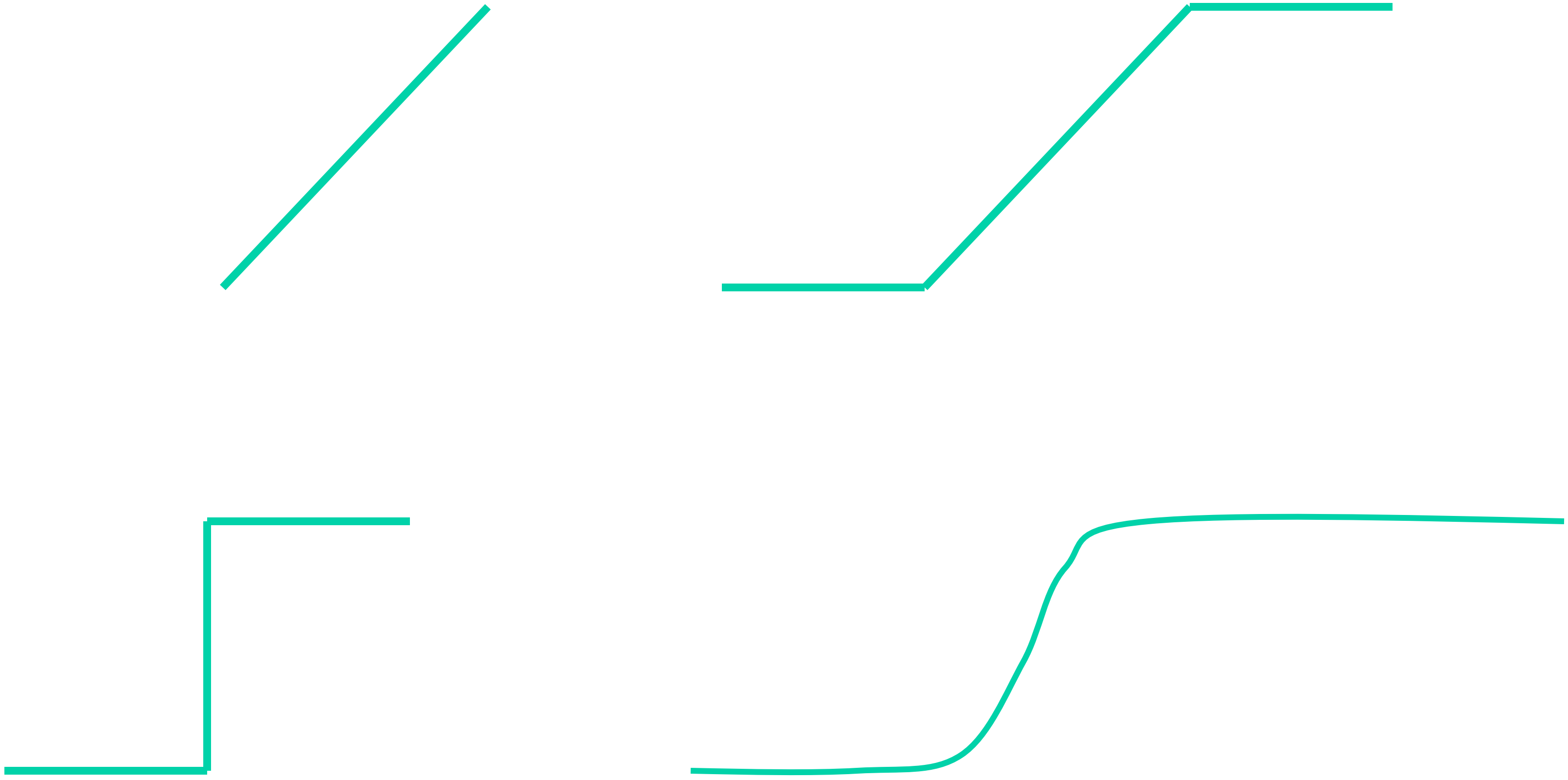
- The Activation Function provides a one to one mapping between the Activity Function as input and some value for the output.
- It attempts to provide further flexibility in modeling biological neurons.



Features of the Perceptron

- Weighted inputs --- correspond to synaptic inputs.
  - Can involve both positive and negative values.
  - Provides an analogy to excitation and inhibition.
- Activation function --- corresponds to action potential.
  - We have great flexibility in choosing the activation function.
  - We choose one that satisfies our needs.

Activation Functions



An Important Activation Function

The Sigmoid Function

$$v = \frac{1}{1+e^{-y}} = \frac{1}{1+e^{-\left(\sum_{i=1}^{n} w_i x_i + \theta\right)}}$$