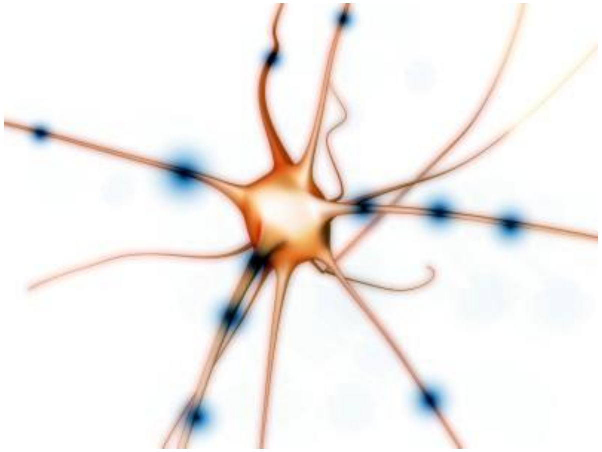


Introduction

Computational Approaches to Neuroscience (NSCI 850)

Gunnar Blohm

Some facts

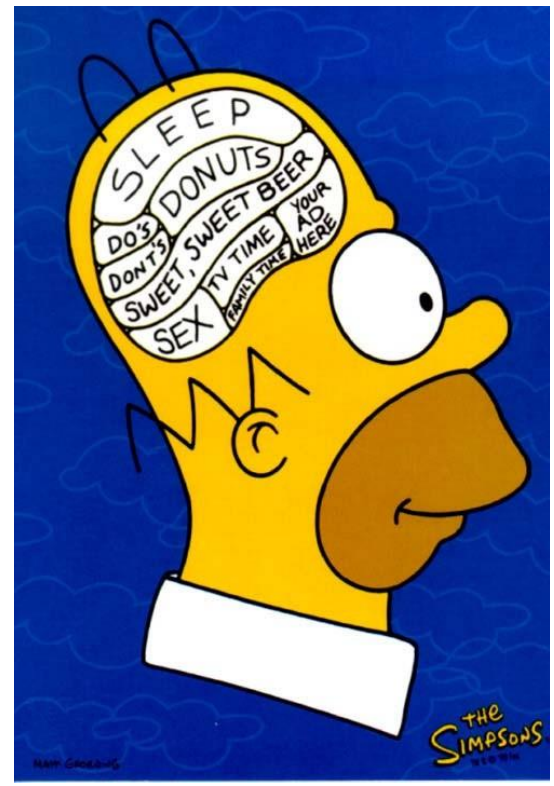
- The human brain = the most complex device on this planet
  - 10^{10} neurons
  - 10^{14} synapses
  - 100,000 miles of dendrites
  - # different potential pathways: $1^{\text{followed by 7 million miles of typewritten 0s}}$
  - Our brain is capable of having more ideas than there is atoms in the universe

- Question:
  - What are the computational principles of this device that produce our cognitive and behavioural abilities?

Outline

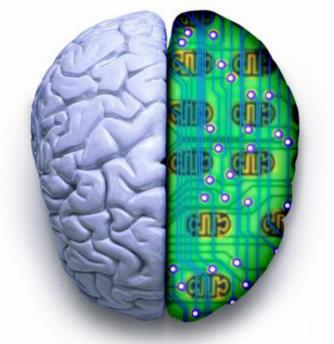
- What's computational neuroscience?
- Goals
- Why modeling of the brain?

- Course content
- Deliverables & evaluation
- Organization



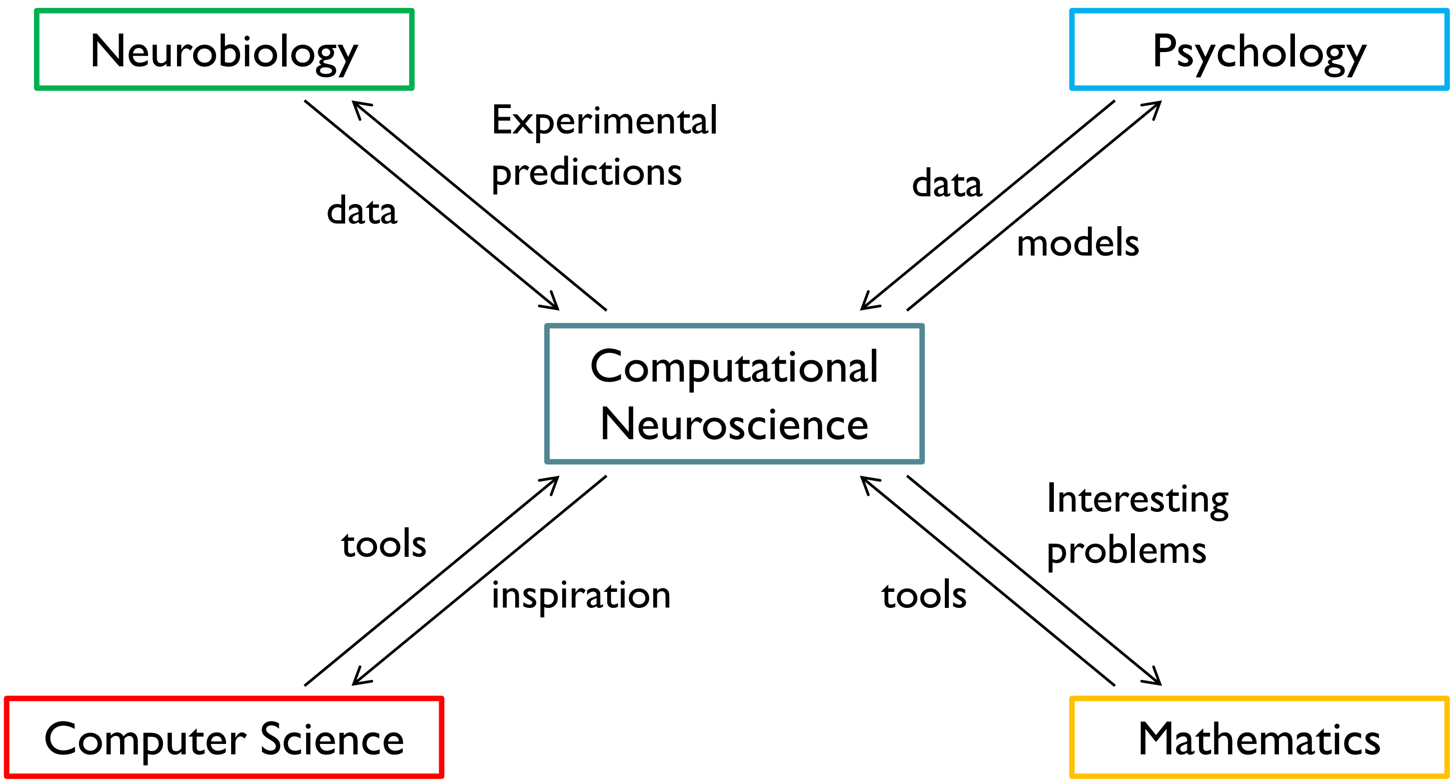
What is computational neuroscience?

- It is the use of mathematical, engineering and computer science tools to attempt answering neuroscience questions.
- Builds mathematical models describing computations in the brain that give rise to mental abilities
- A way to put "word models" into mathematical language and to analyze the result
  - Identify hidden assumptions
  - Explain observations
  - Make predictions



- Interdisciplinary: neuroscience, cognitive science, psychology, electrical engineering, computer science, physics, mathematics, life science, health science, medicine, etc…

Computational vs. Neuroscience



Goals

- Gain complete understanding of some experimental phenomenon
- Identify hypotheses, assumptions, unknowns
- Make quantitative predictions
- Build a theoretical brain as a model of the real brain (stroke lesions etc)
- Inspire new technologies
- Models of neurological diseases to help treatment, rehabilitation, quality of life
- Guidance in designing useful experiments (i.e. animal research)

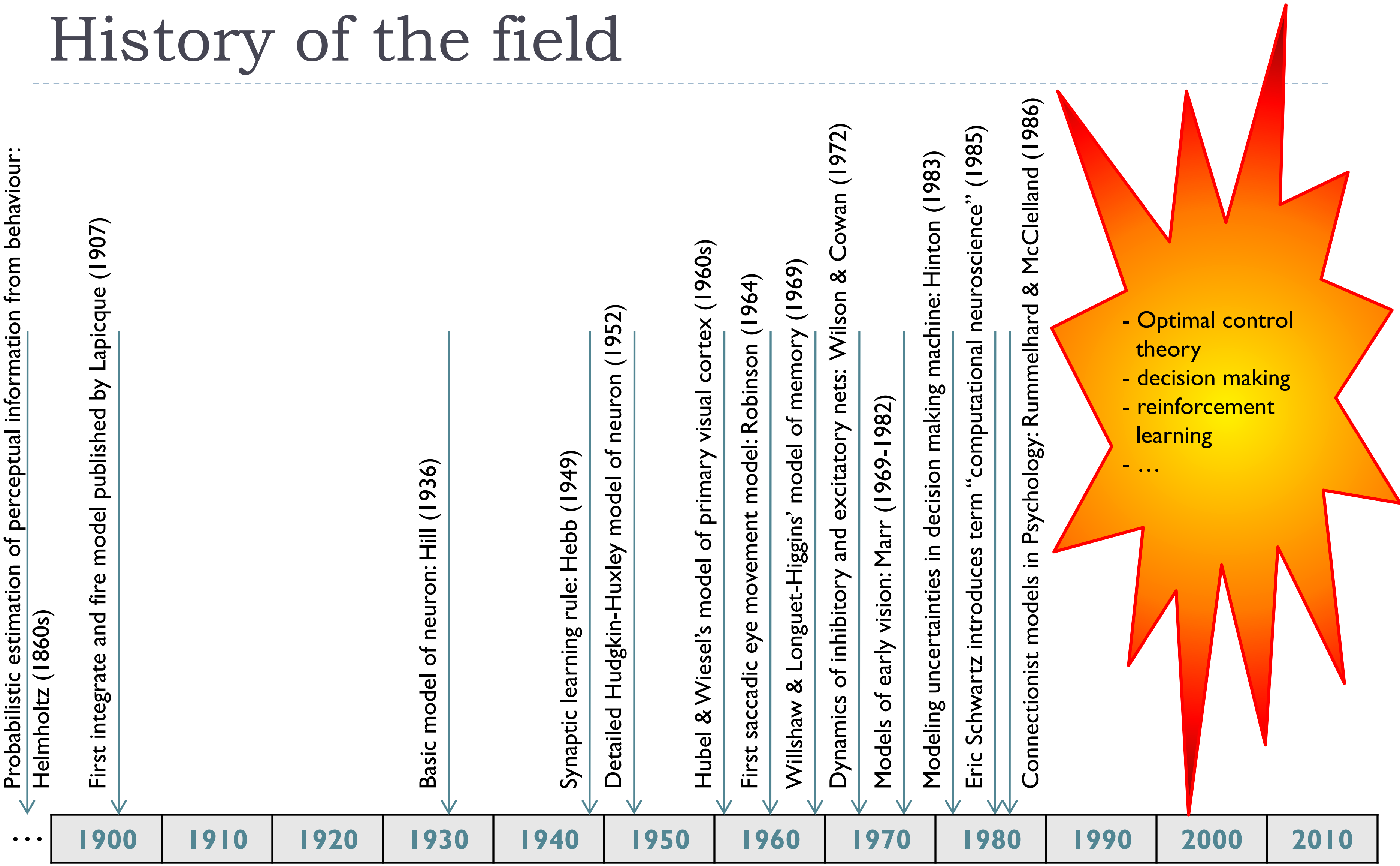
Why model brain function?

- Models help answering three potential types of questions about the brain (Dayan & Abbott, 2001)
  - Descriptive = What?
    - Compact summary of large amounts of data
  - Mechanistic = How?
    - Show how neural circuits perform complex function
  - Interpretive = Why?
    - Computations in the brain are usually performed in an optimal or nearly optimal way
    - Understanding optimal algorithms and their implementation to explain why the brain is designed the way it is

Why model brain function?

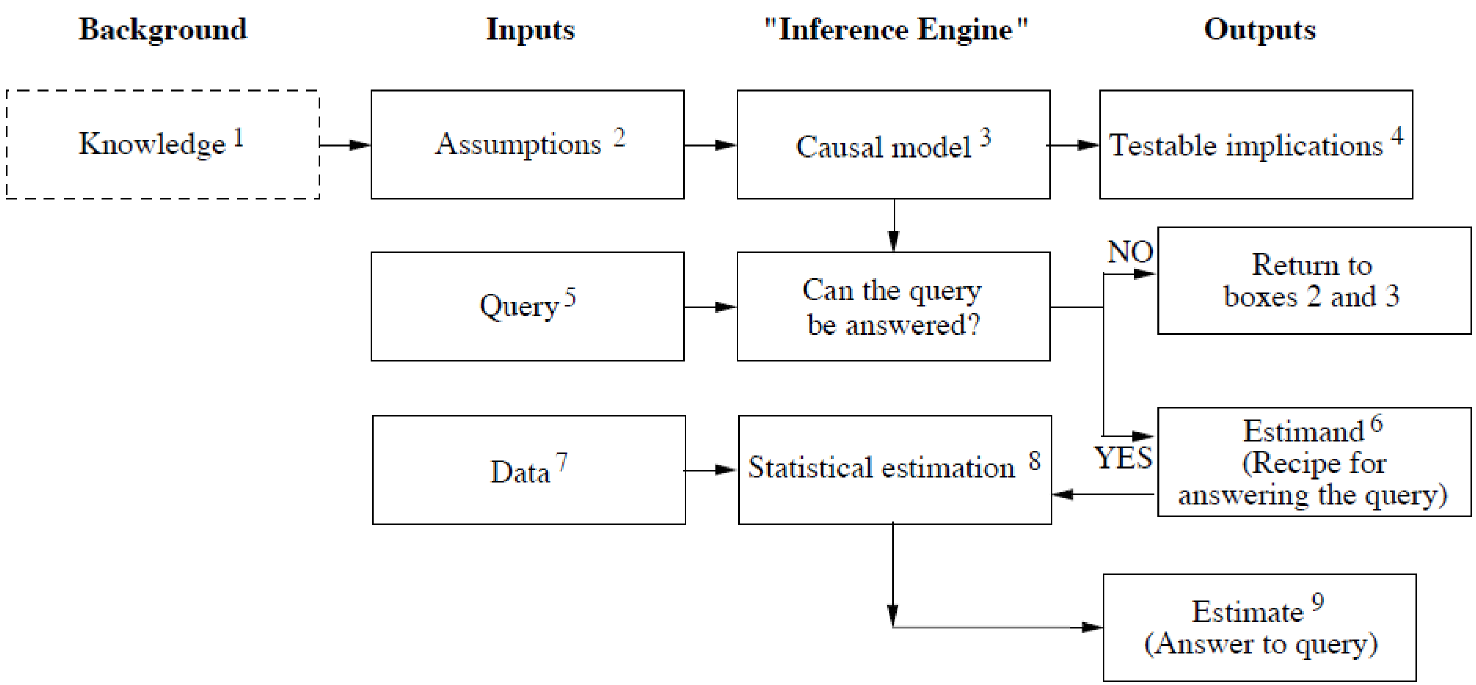
- To inspire new technologies
  - Nature has always inspired technological advances
    - E.g. Leonardo Da Vinci
  - Artificial intelligence
    - Neural networks inspired machine learning (1984)
    - Learning algorithms are often not biologically plausible
    - Many open questions remain (e.g. language, autonomy, creativity)
  - Transferable skills from computational neuroscience
    - Mathematical formulation and simulation of complex dynamical systems
    - Understanding and analysis of dynamical systems
    - Signal processing

History of the field



Models vs. AI

- Data alone cannot lead to generalization
- Models are needed for that!



Pearl & Mackenzie, "The book of why", 2018

Course organization

Course info

- http://www.compneurosci.com/NSCI850.html
- Access to documents on web site:
  - Username: NSCI
  - Password: NNet

Computational anatomy of the brain

- Learning approach
  - Low-level approaches
    - Spiking low-level approach: class 2-3
    - Intermediate-scale rate-based networks: class 4-5
    - High-levels systems approach: class 6
  - Transcendental approaches
    - The Bayesian brain: class 7
    - Optimal control theory: class 8
    - Reinforcement learning: class 9
  - Specific models: class 10-11

Organization

- Specific models
  - Goal: hands-on modelling experience
  - Approach:
    - Chose topic of interest
    - Develop your own model:
      - Model background (physiology, experimental finding etc)
      - Model equations
      - Model implementation
      - Model simulations
      - Model discussion
    - OR reproduce existing model:
      - Model background
      - Model implementation & simulations (reproduce results)
      - **New** model results / predictions / analyses / etc
      - Critical model discussion & suggestions for improvements + implementation of at least one improvement
  - Product: 30-45 min lecture on model (including questions)

Organization

- Specific models
  - Make a choice before Mar 4

  - Suggestions:
    - Visual system (early vision, feature/color selection, stereo vision…)
    - Eye movements (saccades, pursuit, eye-head coordination, VOR, deficits, vergence…)
    - Decision making
    - Disorders (Alzheimer, Schizophrenia, Parkinson, epilepsy…)
    - Attention
    - Motor control (muscles, feedback…)
    - Multi-sensory integration
    - Central pattern generators (swimming, walking etc)
    - Reference frame transformations
    - Learning & memory
    - …

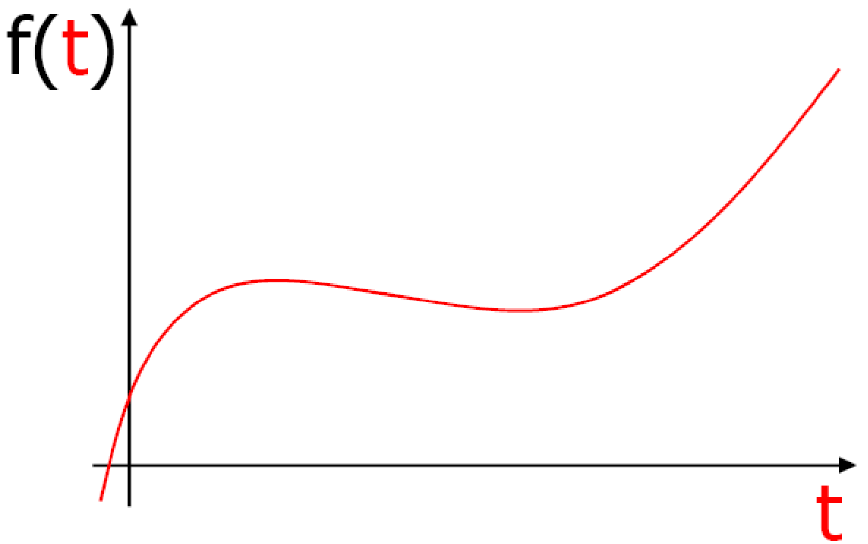
Further readings

- Trappenberg: Fundamentals of Computational Neuroscience. Oxford University Press 2010
- Dayan & Abbott: Theoretical Neuroscience. MIT Press 2001
- http://matrixcookbook.com/
- Wilson: Spikes, Decisions and Actions. Oxford University Press 1999
- Izhikevich: Dynamical systems in Neuroscience. MIT Press 2006
- Wallisch et al.: Matlab for Neuroscientists. Academic Press 2008
- Gerstner & Kistler: Spiking neuron models. Cambridge University Press 2002
- Gupta et al.: Static and dynamic neural networks. Wiley-Interscience 2003
- Shadmehr & Wise: The computational neurobiology of reaching and pointing. MIT Press 2005

Differential calculus and ODE primer

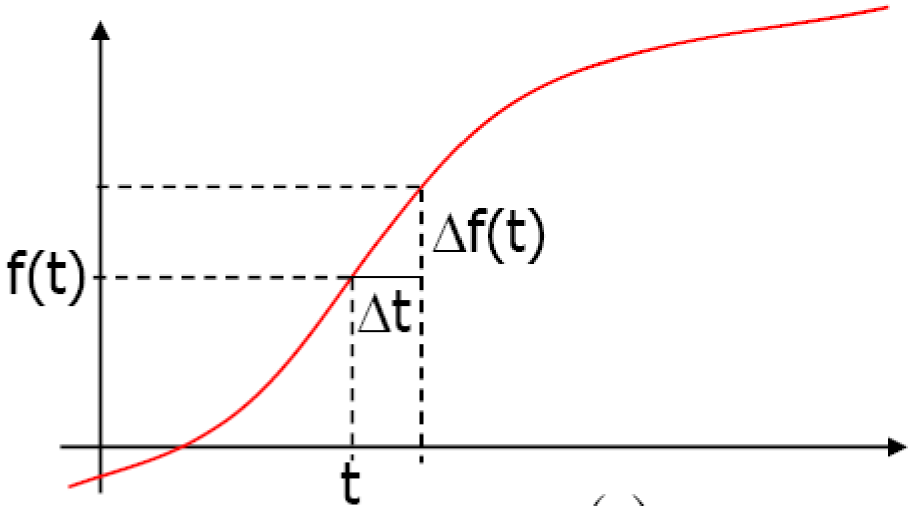
Derivatives

- Consider a function f (e.g. neuronal activity) that changes over time
- f = f(t)



Derivatives

- Definition of derivative

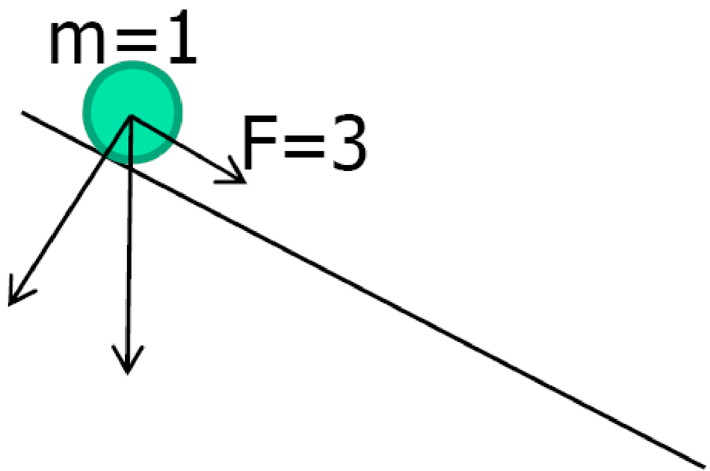


$$\frac{df(t)}{dt} = \lim_{\Delta t \to 0} \frac{\Delta f(t)}{\Delta t}$$

- Other notations $\frac{df(t)}{dt} = f'(t) = \dot{f}$
- Sign of derivative
  - Positive: function increases
  - Negative: function decreases

Example

- How does the velocity of the ball change over time?



- Newton's law: F = m*a
- From the definition of acceleration:

  $a = dv/dt = 3$

Example cont'd

- dv/dt = 3 is a differential equation!
- Differential equations describe how the derivative of a function behaves
- It says that function v(t) is a function whose derivative is equal to 3 at all times
- What is the function that satisfies this equation?
- Is there just one such function or are there many of them?
- There are an infinity of solutions: v(t) = 3*t + c
- Importance of initial conditions

Another common example

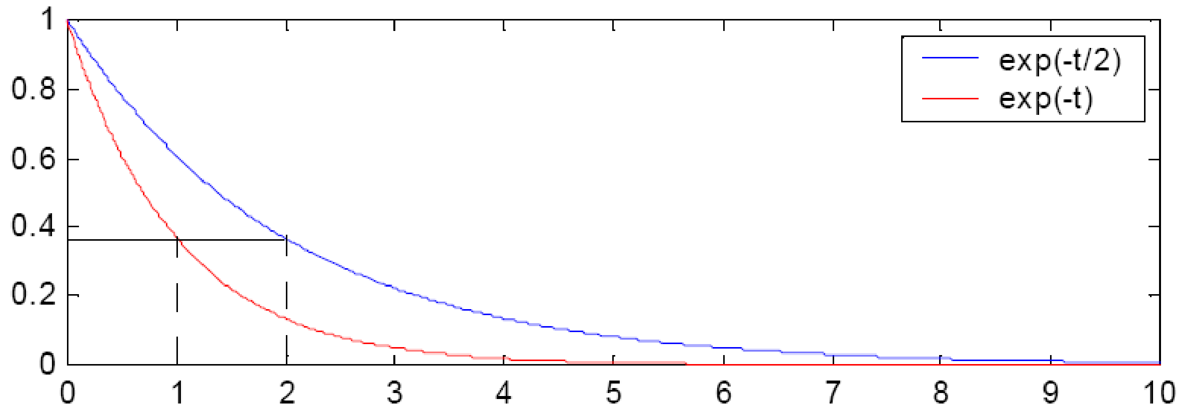
- Let us consider the following ordinary differential equation (ODE)

$$\tau \frac{df(t)}{dt} = -f(t)$$

- What is the solution? Is it unique?
- Solution:

$$f(t) = ce^{-t/\tau}$$

- Parameter tau?



The end

Course material: www.compneurosci.com/NSCI850.html