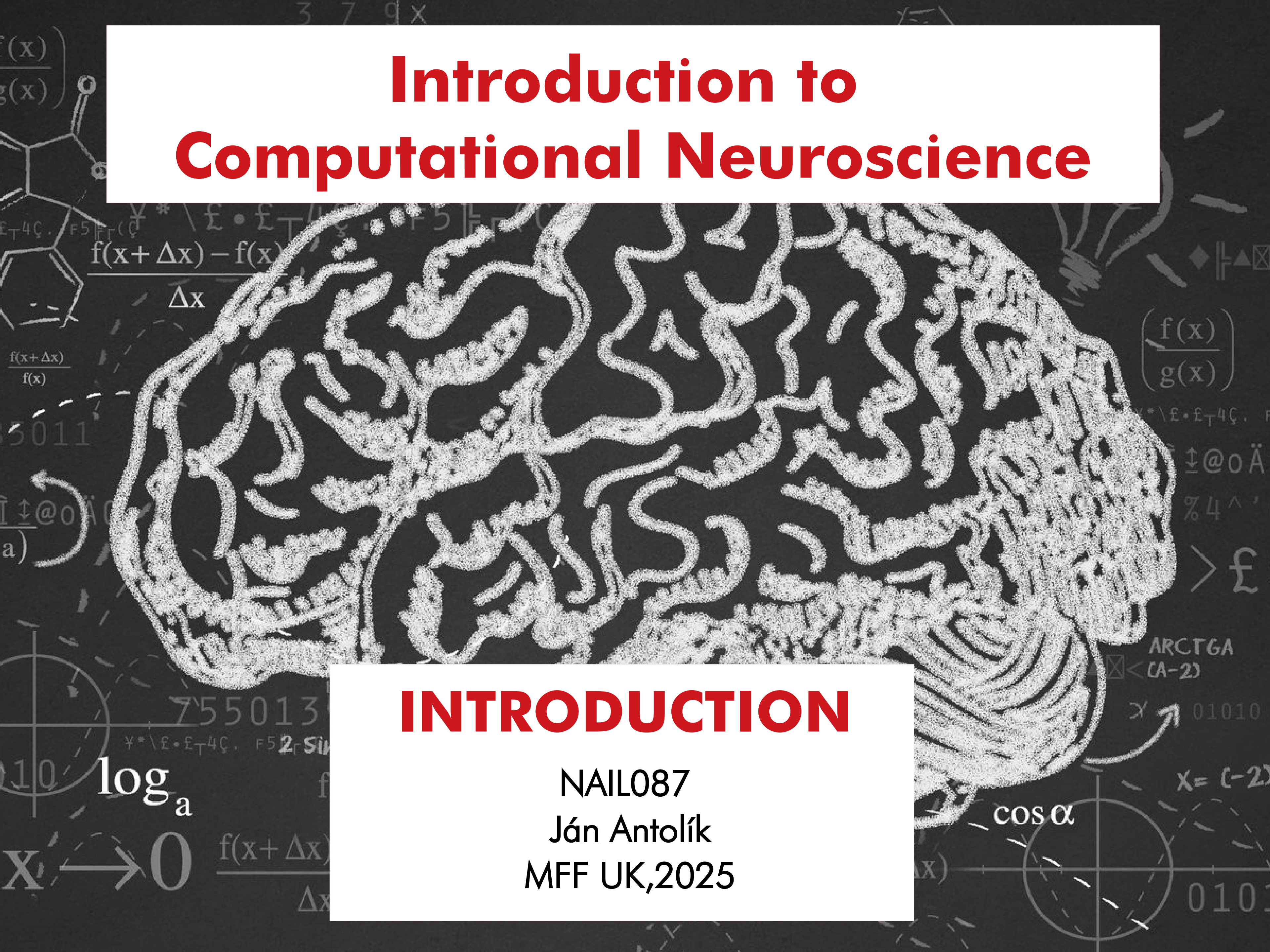
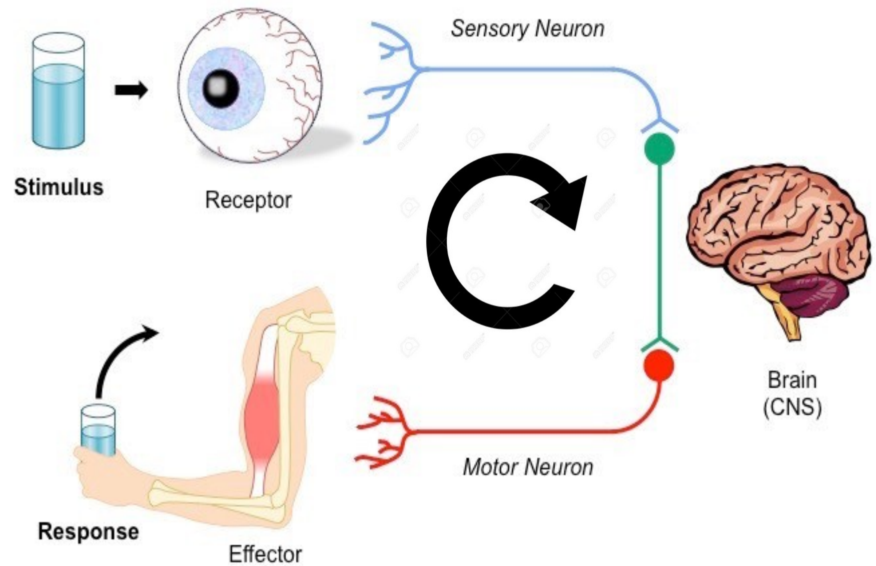
Introduction to Computational Neuroscience



INTRODUCTION

NAIL087
Ján Antolík
MFF UK,2025

Brain as information processing machine



Cognition can be simplified as an infinite sensory-motor loop:

1) Environment influences our senses
2) Brain processes this information and activates motor system
3) Our muscles exert influence on the environment (GOTO 1)

‘our muscles exert influence on the environment’

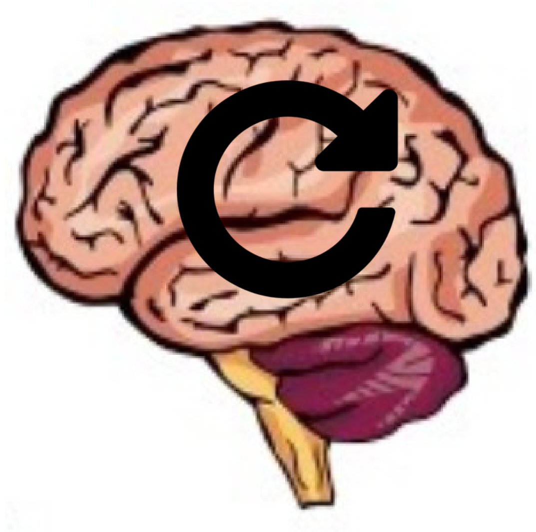
Did I miss something?

Brain as sensory motor loop

?

Is it a oversimplification?

In this lecture we will take the reducionist mechanistic view:

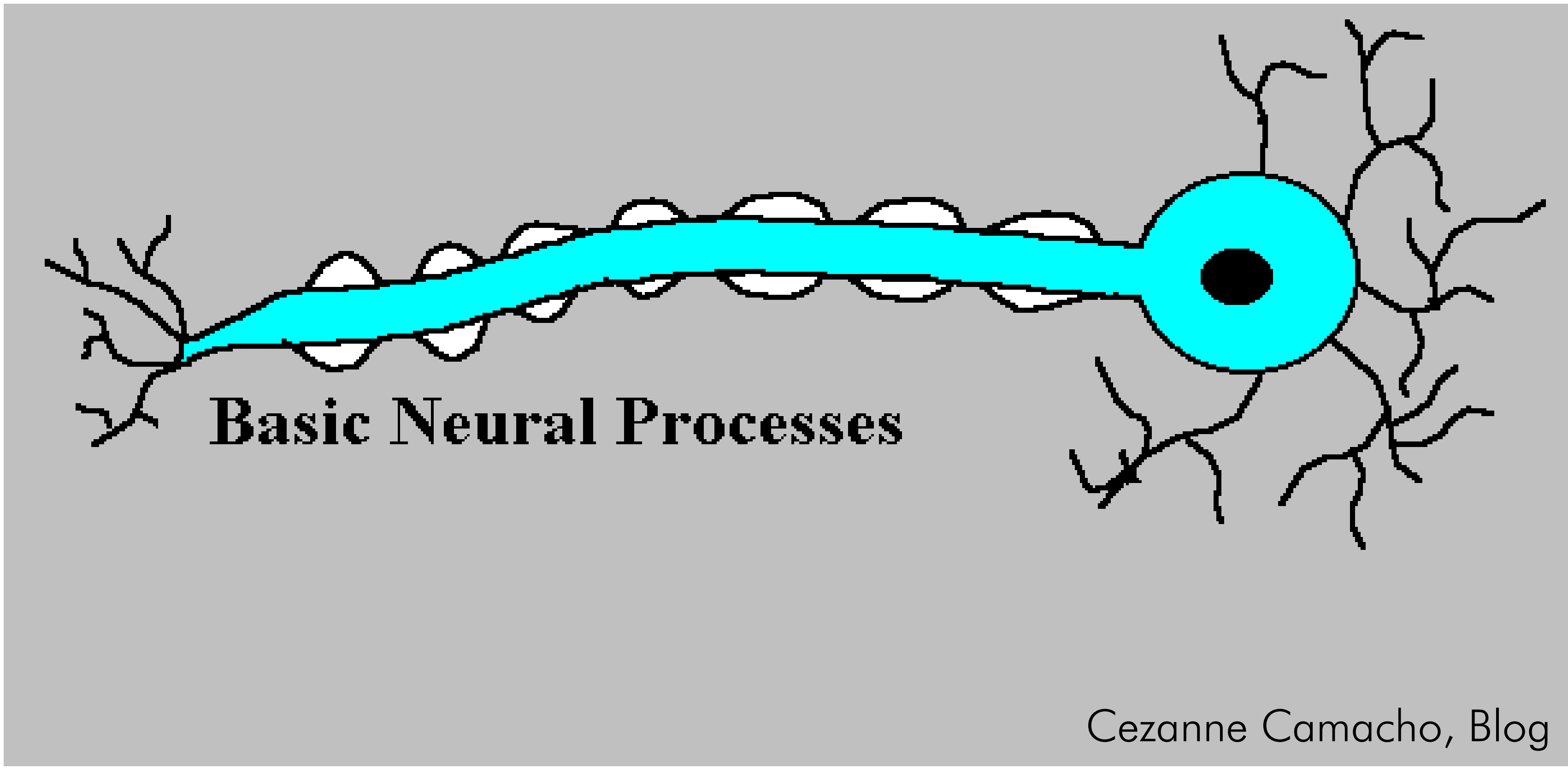


Cognition = computations that transform sensory input into motor action

Reductions view

What is the elementary unit of computation in the brain?

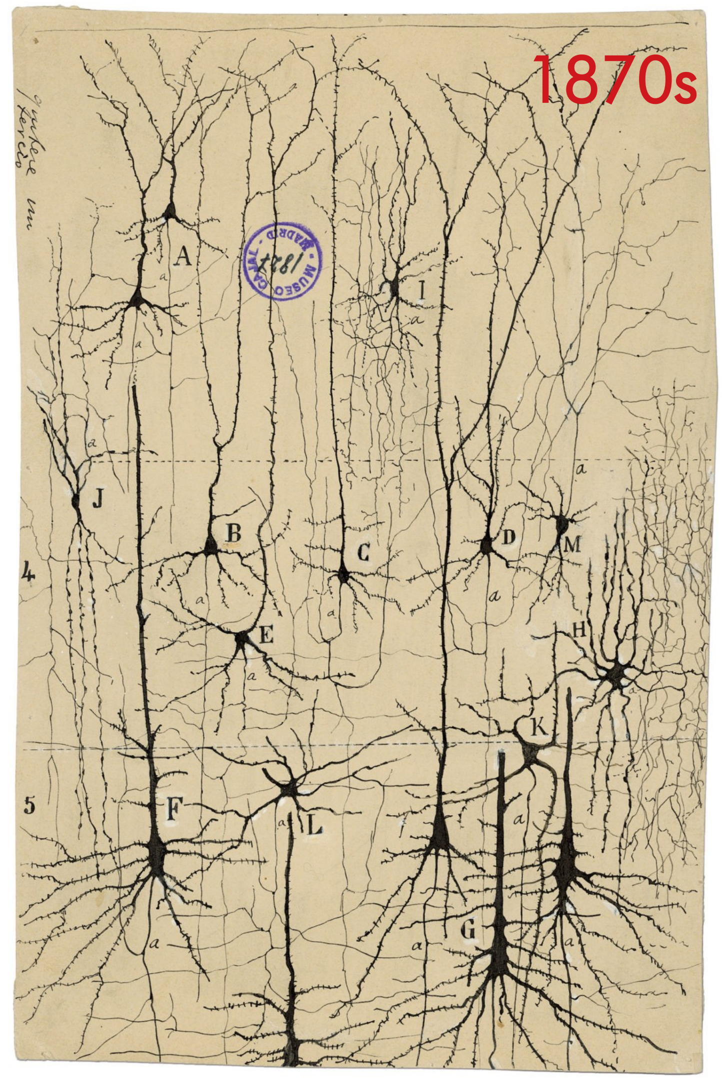
Neuron as information integrator



Neuron is a specialized cell, capable of receiving, processing, transmitting and responding to electrical or chemical signals.

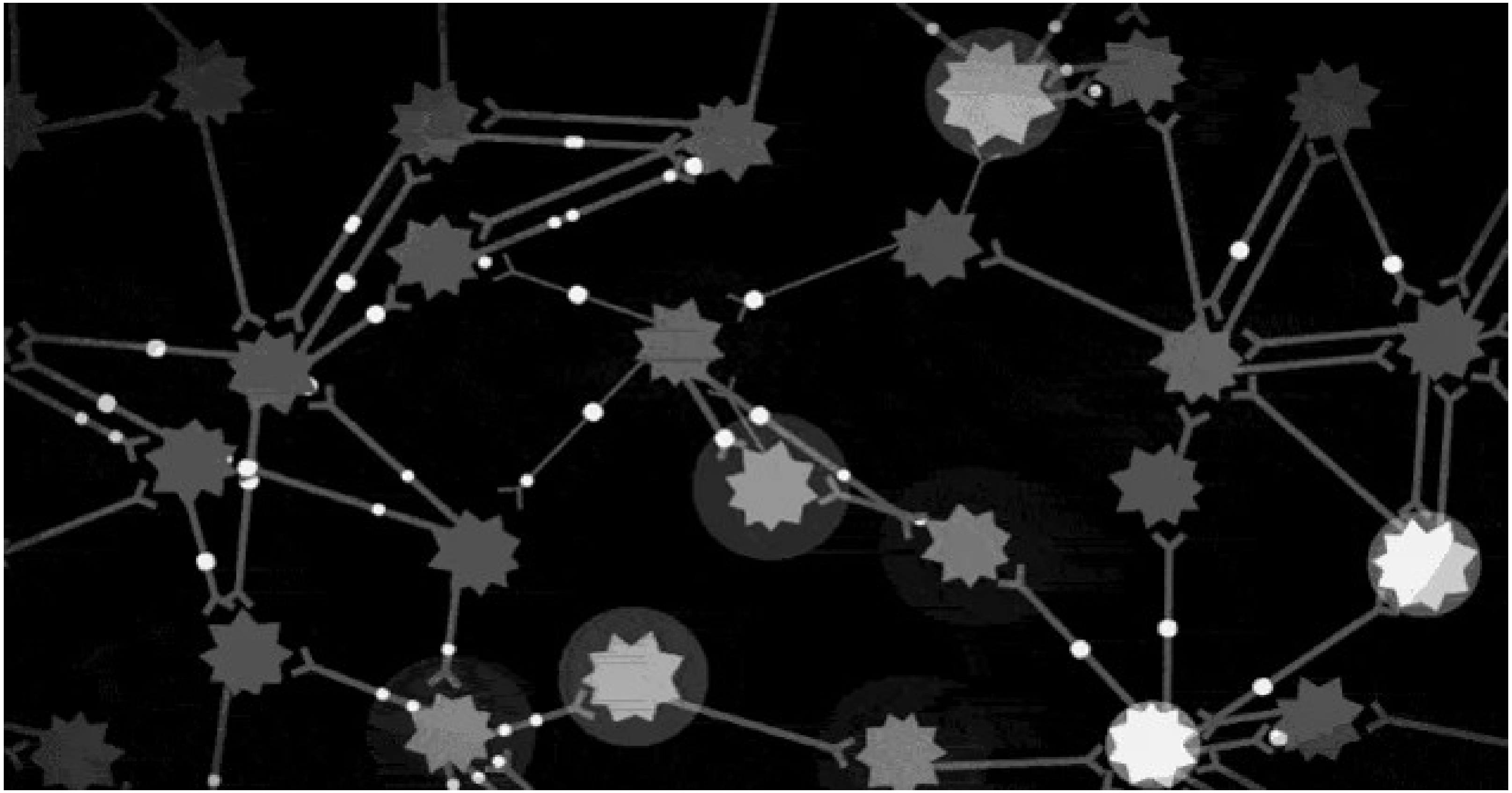
Neural substrate

- How to look at neurons:
  - Golgi's method of silver staining
  - S.R. Cajal stainings of neurons
- 1 mm^3 contains 3km of wires

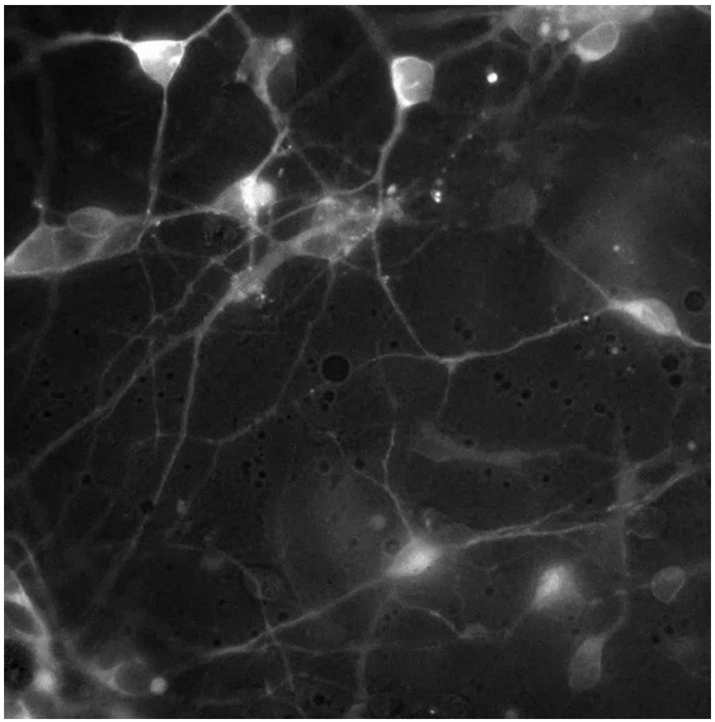


Santiago Ramón y Cajal

Neurons are nice, but it's all about the network

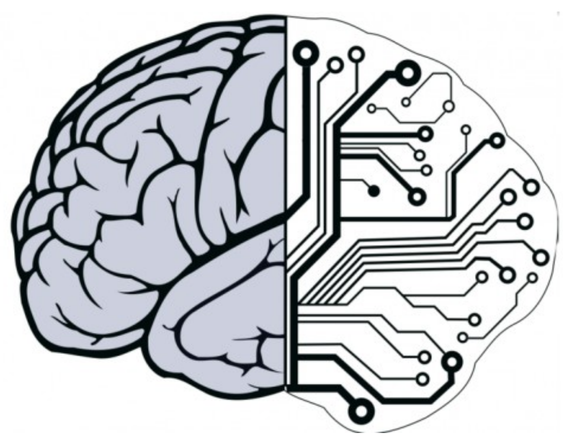


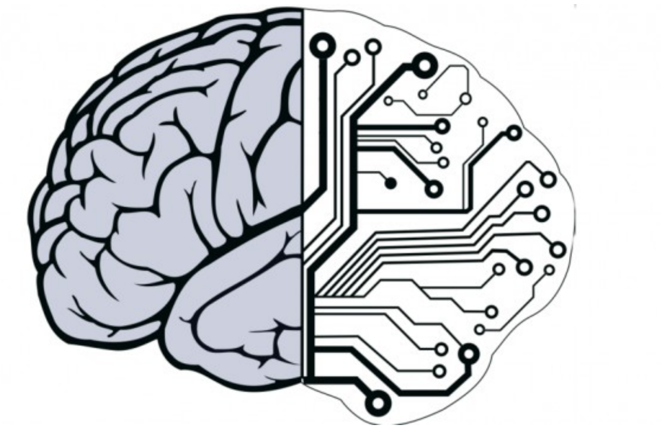
Behold, living neural tissue



- Small volume of cortex view under two-photon imaging
- Two-photon imaging: technique that allows to visualize activity in living neural tissue

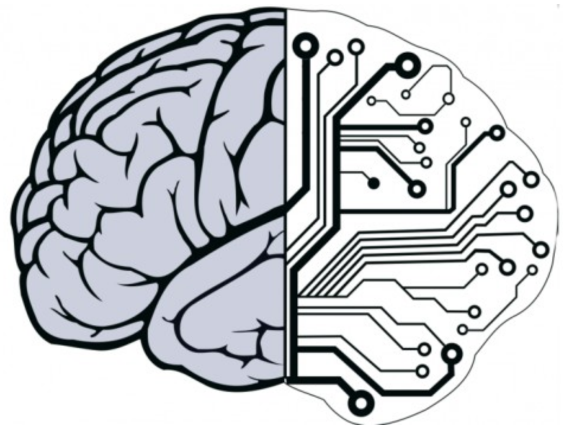
As computer scientists, let’s put brain into perspective by comparing it to computers.



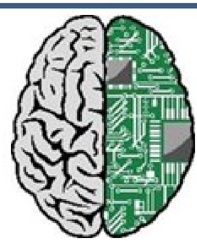


THE SPECS
Computer vs. Brain

	BRAIN	COMPUTER
# elements	10^{10}-10^{12} neurons	10^{7}-10^{8} transistors
# connections/element	10^{3}-10^{4}	10
clocking	10^{3} Hz	10^{9} Hz
energy/operation	10^{-16}J	10^{-6}J
power consumption	10 Watt	100-500 Watt
reliability of elements	low	reasonable
reliability of system	high	reasonable
memory vs. cpu	multiplexed	separate
processing architecture	parallel	serial

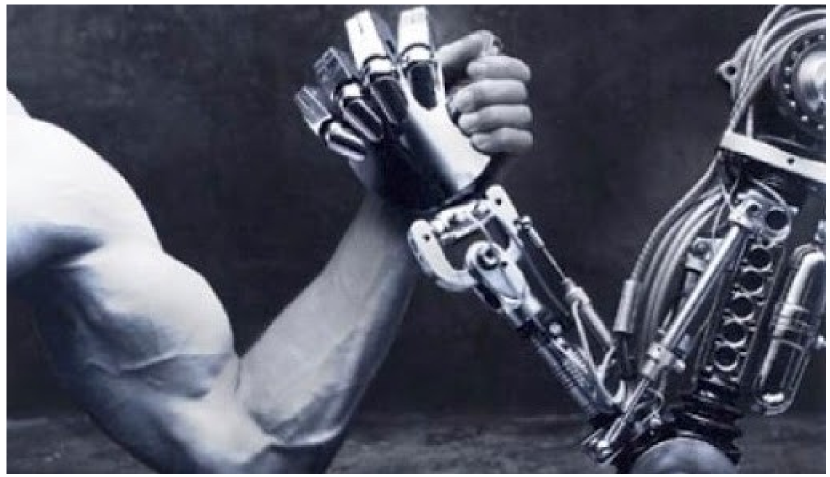


Computer vs. Brain (CAPABILITY)

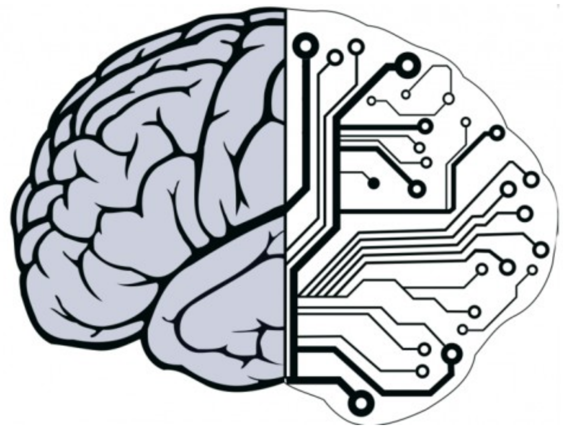
	Computing wins	• Input and output • Information processing and memory
	Closely matched	• Complex movement • Vision • Language • Structured problem solving
	Brain still wins	• Creativity • Emotion and Empathy • Planning and Executive Function • Consciousness

http://becominghuman.ai

Man vs. machine



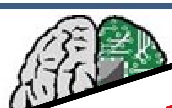
Where do you think human brain still surpasses modern AI?



Computer vs. Brain (CAPABILITY)

Computing wins

- Input and out
- Infor



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Structured problem solving

Brain still wins

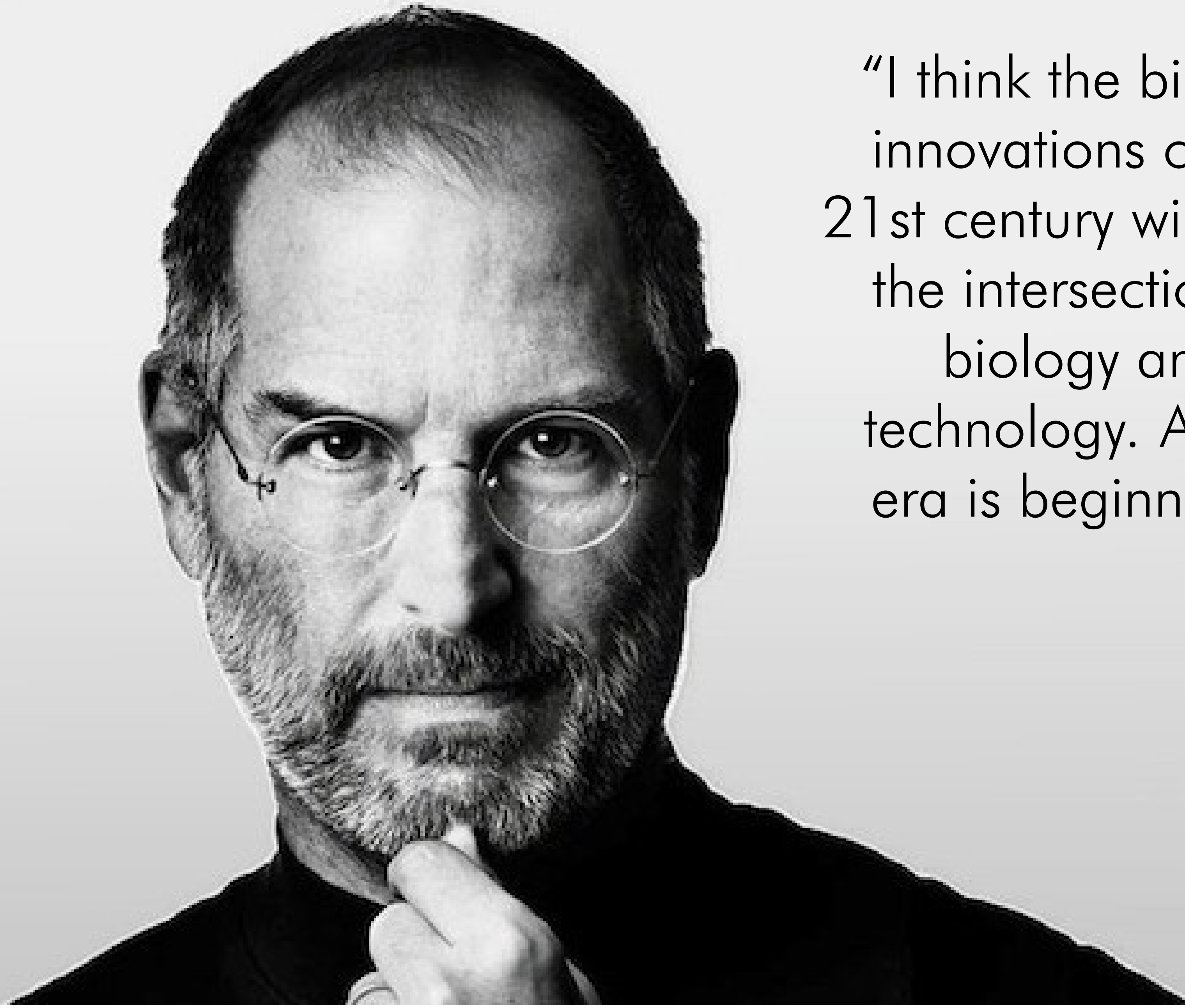
- Creativity
- Emotion and Empathy
- Planning and Executive Function
- Consciousness

GENERALIZATION
LEARNING FROM FEW EXAMPLES
FLEXIBILITY

http://becominghuman.ai

Why to follow this course?

- **Learn critical thinking about neuroscience**
- Gain inspiration for artificial intelligence systems or artificial agents
- Learn about applications in industry
  - Neuro-prosthetics
  - Neuro-morphic engineering
  - Medical imaging
  - Cognitive Mechanisms in DNNs
  - Brain-computer interface
  - …



"I think the biggest innovations of the 21st century will be at the intersection of biology and technology. A new era is beginning."

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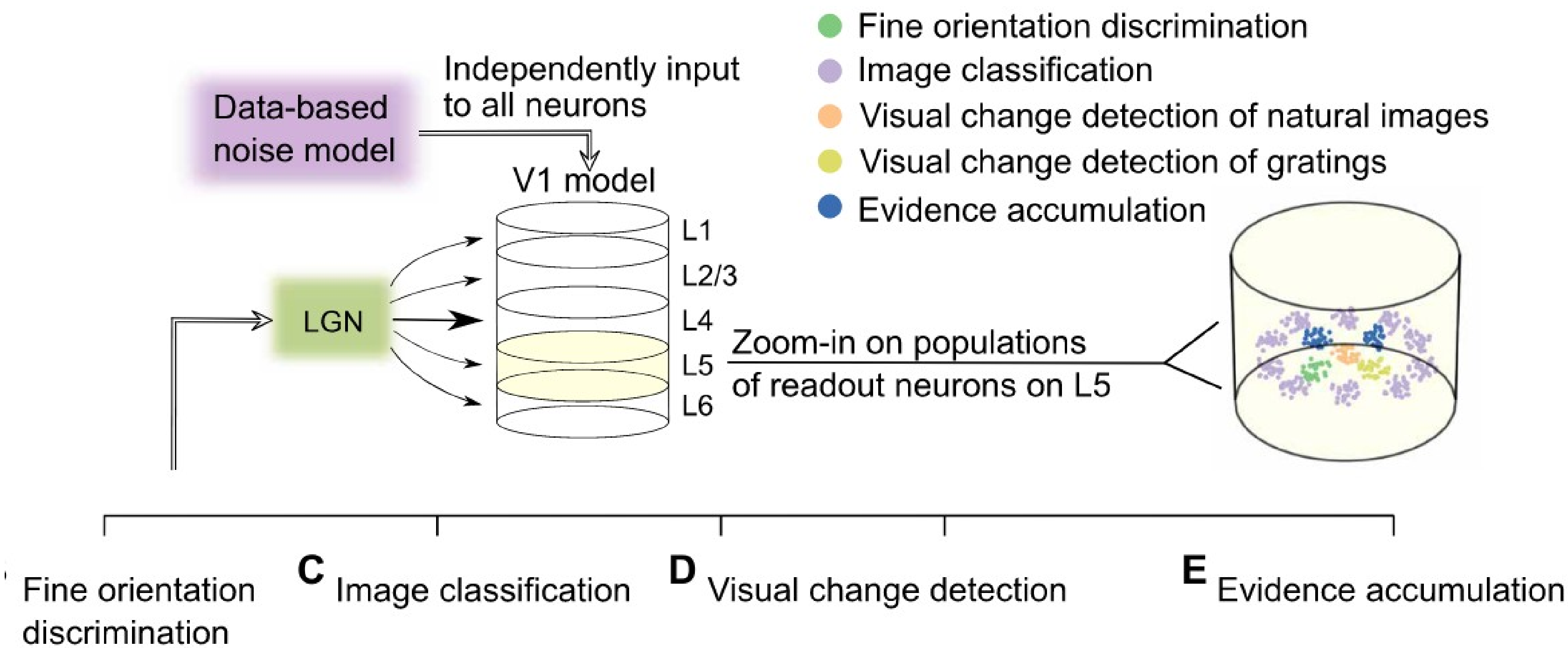
  - Brain-computer interface
  - …

Biological-like spiking networks are more robust

(Chen et al. 2022)



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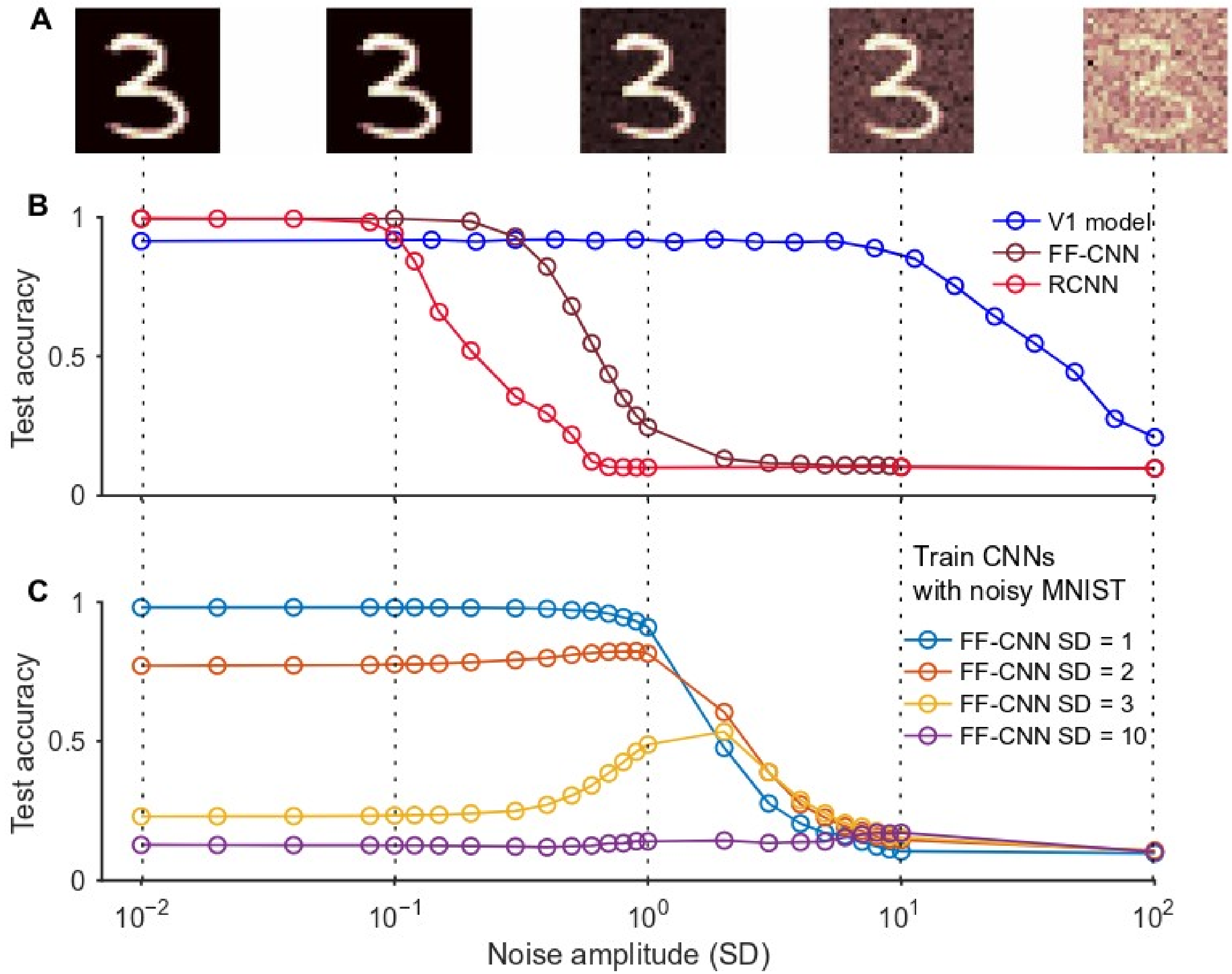

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  - …

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  - **Neuro-prosthetics**
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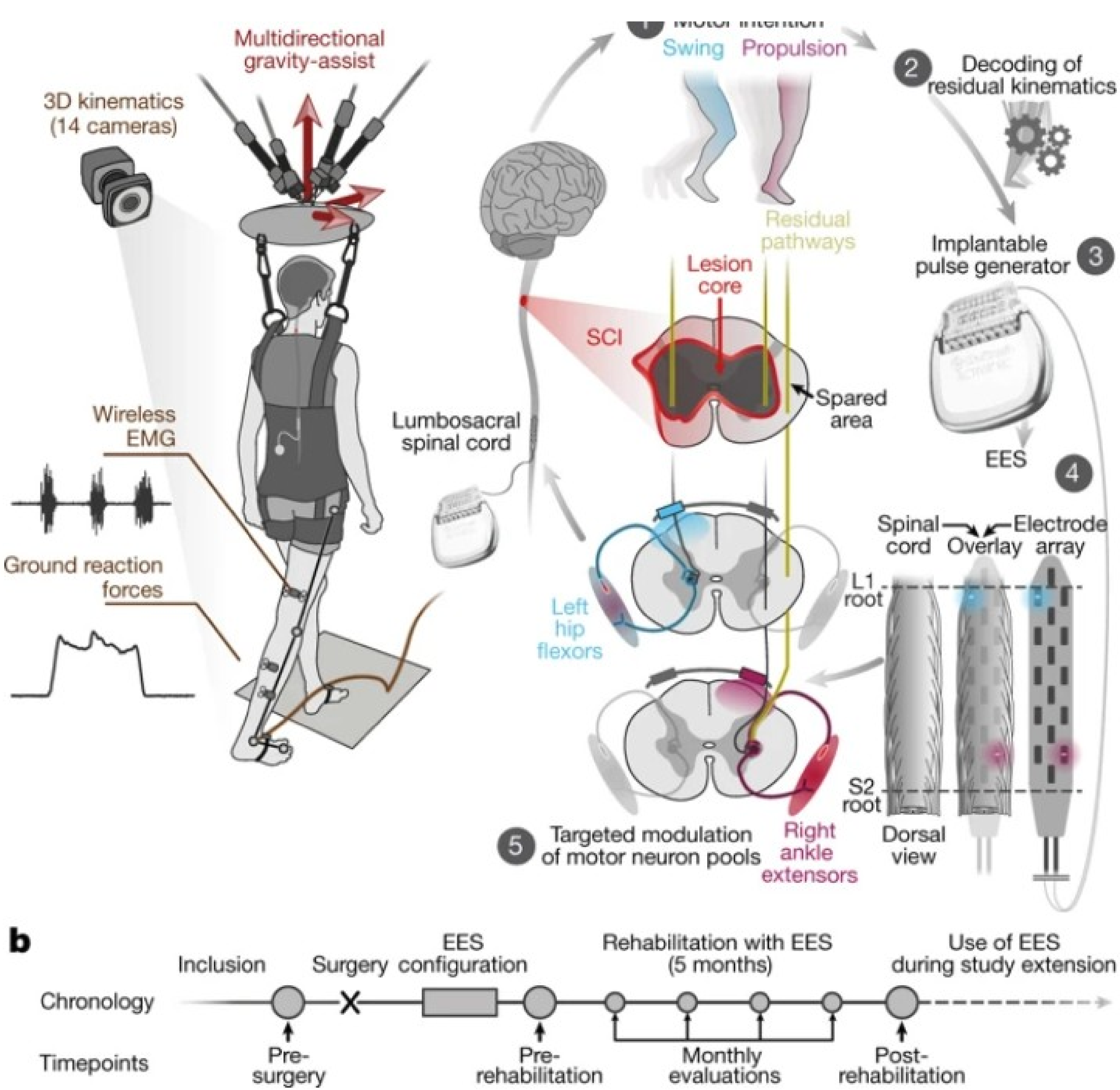
Multidirectional gravity-assist
3D kinematics (14 cameras)
Wireless EMG
Ground reaction forces
Swing
Propulsion
2 Decoding of residual kinematics
Residual pathways
Lesion core
SCI
Spared area
Lumbosacral spinal cord
Implantable pulse generator 3
EES
4
Spinal cord
Overlay
Electrode array
L1 root
S2 root
Dorsal view
Left hip flexors
5 Targeted modulation of motor neuron pools
Right ankle extensors
b
Inclusion
Surgery
EES configuration
Rehabilitation with EES (5 months)
Use of EES during study extension
Chronology
Timepoints
Pre-surgery
Pre-rehabilitation
Monthly evaluations
Post-rehabilitation

Locomation restoration via neural prosthetics.

VIDEO #1

Why to follow this course?

- Learn critical thinking about neuroscience
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- Applications of neuroscience in industry
  - Neuro-prosthetics
  - **Neuro-morphic engineering**
  - Medical imaging
  - Inspiration for AI
  - Brain-computer interface
  - …

Event–based cameras

VIDEO #2 and #3

Why to follow this course?

- Learn critical thinking about neuroscience
- Gain inspiration for artificial intelligence systems or artificial agents
- Applications of neuroscience in industry
  - Neuro-prosthetics
  - Neuro-morphic engineering
  - **Medical imaging**
  - Inspiration for AI
  - Brain-computer interface
  - …
-

Adversial generative networks for MRI tumor image generation

VIDEO #4

Why to follow this course?

- Learn critical thinking about neuroscience
- Gain inspiration for artificial intelligence systems or artificial agents
- Applications of neuroscience in industry
  - Neuro-prosthetics
  - Neuro-morphic engineering
  - Medical imaging
  - Inspiration for AI
  - **Brain–computer interface**
  - …

Brain–computer–inteface

VIDEO #5

Neuroscience is a vast field

- We have limited time and will thus focus on
  - basic building blocks of neural system
  - principles of neural processing
  - sensory input
  - motor output
- We will focus on how can these biological processes be simulated in the computer.
- We will use **vision** as a glue across the different topics
- There is IKV2 – more topics covered, greater focus on modeling
- Number of experts will teach the different topics

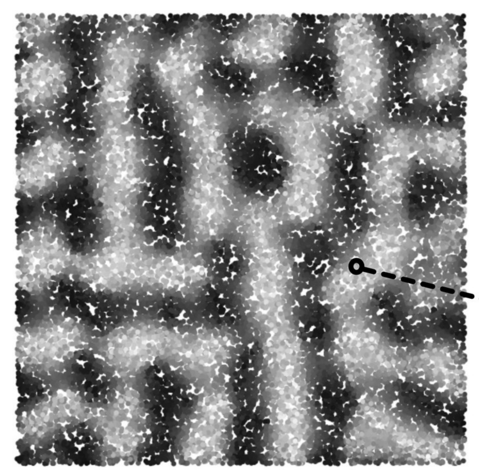
What do you wish to learn in this course

?

WHO

- **Ján Antolík**
- Karolína Korvasová
- Matej Hoffman
- Giulia d'Angelo
- Aitor Morales
- Katarína Studeničová

Computational neuroscience
Visual system modeling
Sensory development modeling
Machine learning in neuroscience



http://antolik.net

WHO

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- Aitor Morales
- Katarína Studeničová

Computational neuroscience
Neural data analysis
Criticality
Oscillations

Excercise sessions

http://csng.mff.cuni.cz/people.html

WHO

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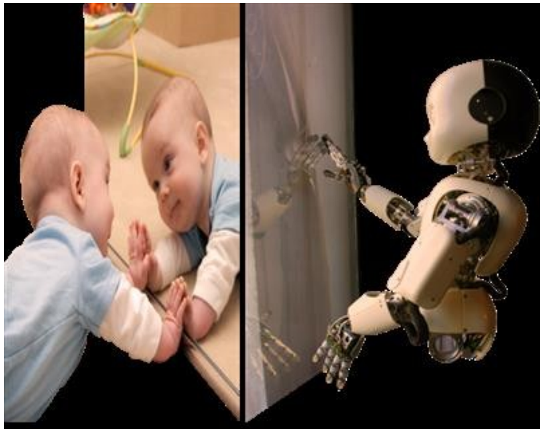
ČVUT
ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

Robotics
Body representations
Embodiment and morphological computation
Minimally cognitive robotics



https://sites.google.com/site/matejhof/home

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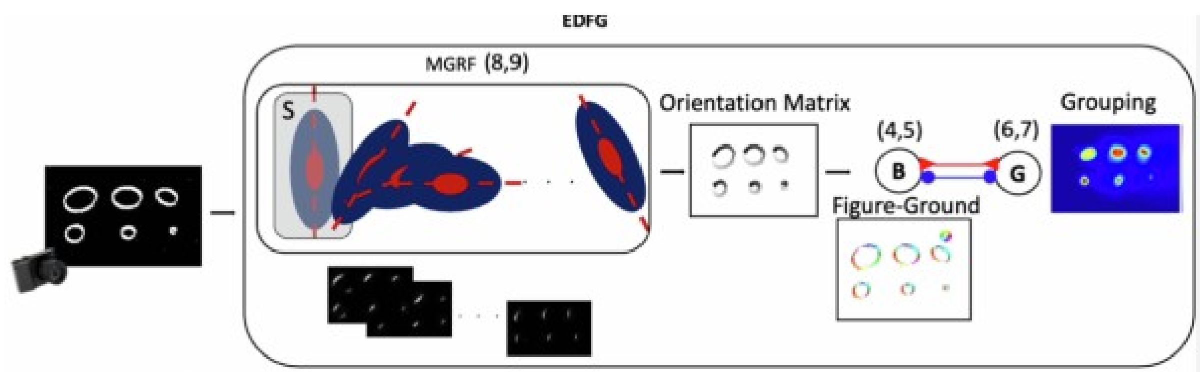
Nueromorphic computing
Robotics
Artificial Vision



https://brainsandmachines.net/

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Requirements

- Test
  - Compulsory readings from Bear book
    - Neuroscience: Exploring the Brain, 3rd Edition (Mark F. Bear, Barry W. Connors, Michael A. Paradiso)
    - If not successful oral exam
- Excercise sessions
    - Computational modeling project

Grading

- For both tasks (test & the report) you will receive a grade
- The final grade is the arithmetic mean of the two partial grades

Let's look at the course website and schedule

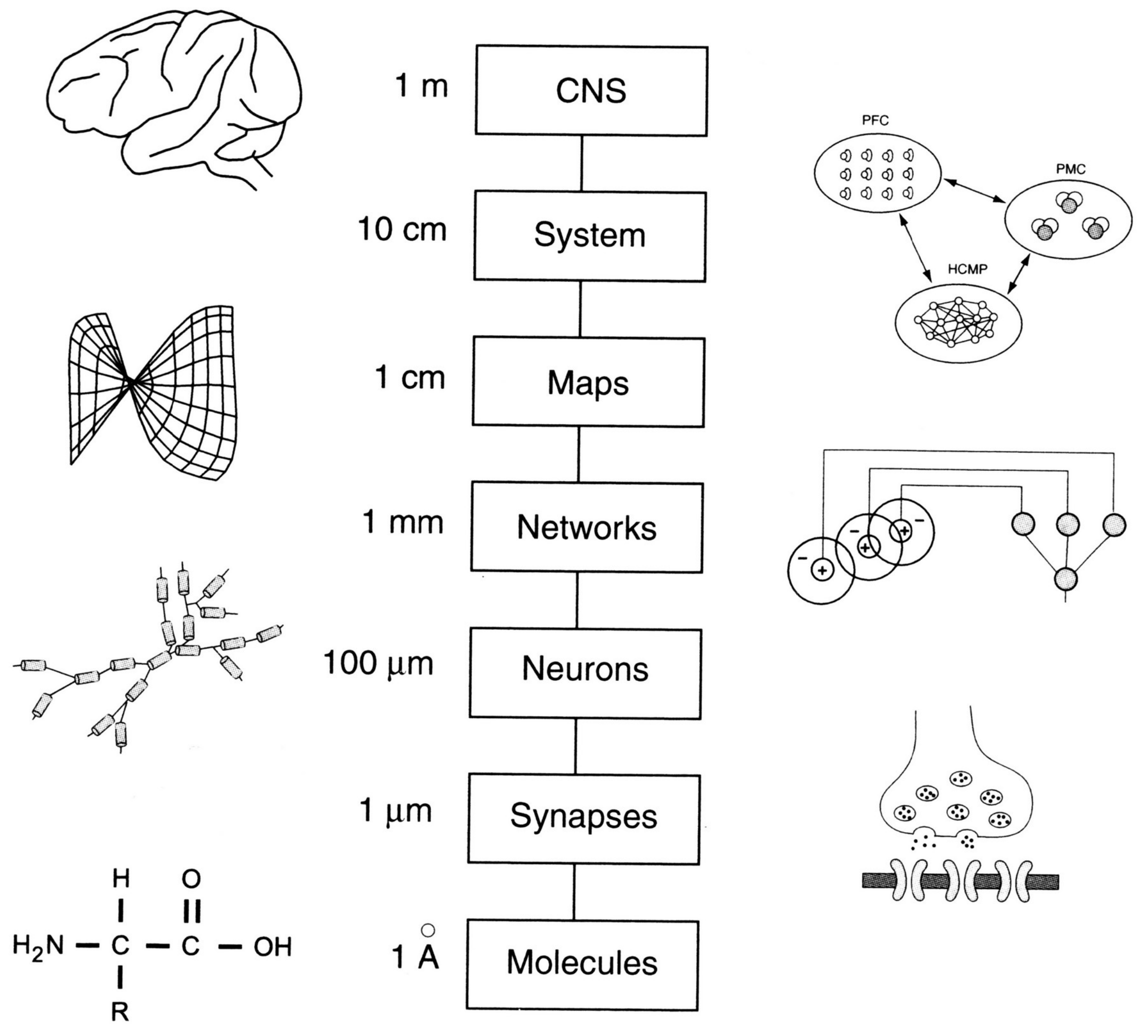
Multiple scales in:

Substrate

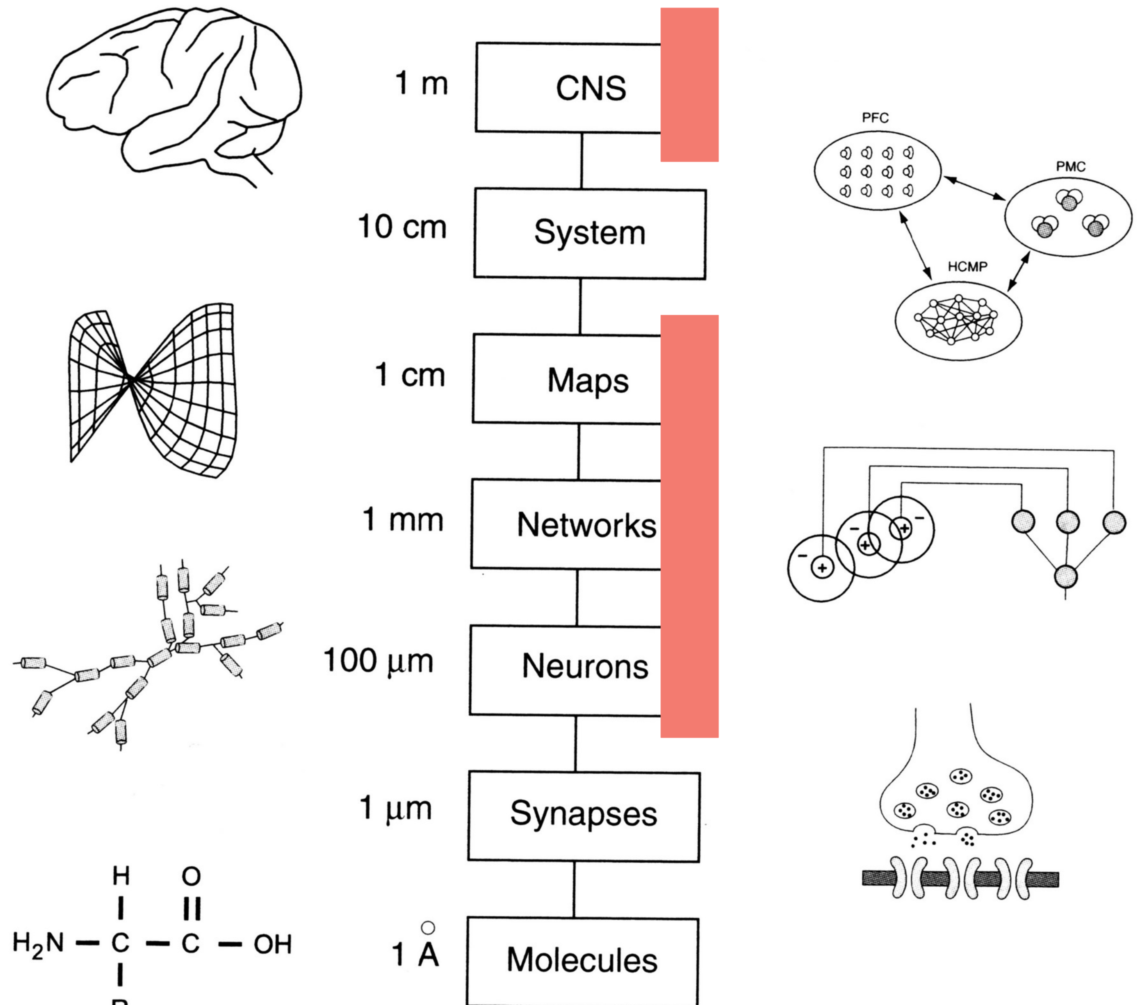
Models

Measurments

Brain as a multi–scale system

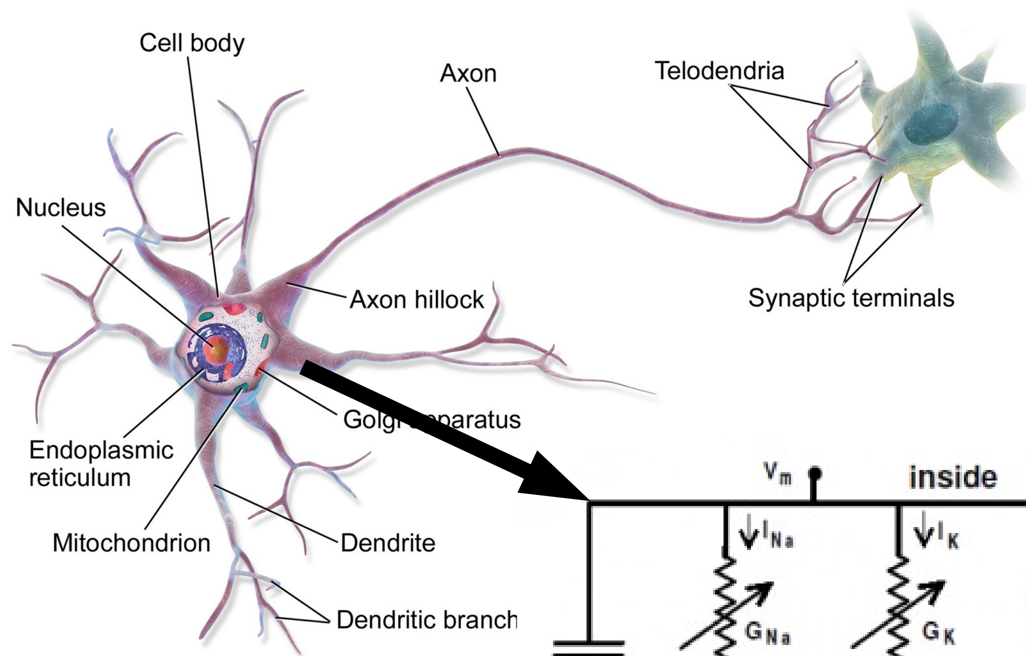


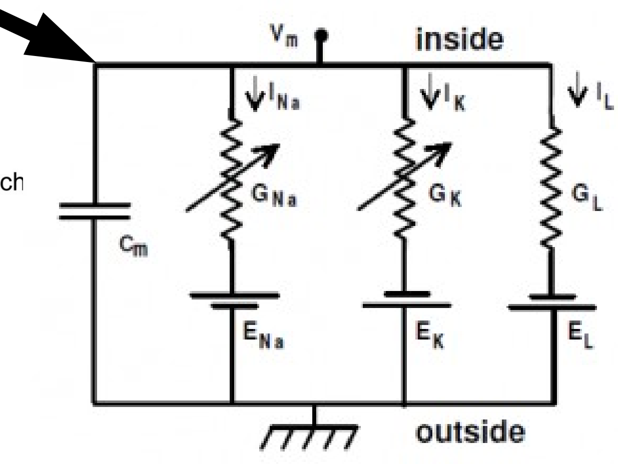
Brain as a multi-scale system



What kind of models?

- **Descriptive**
- Mechanistic
- Functional
- Normative

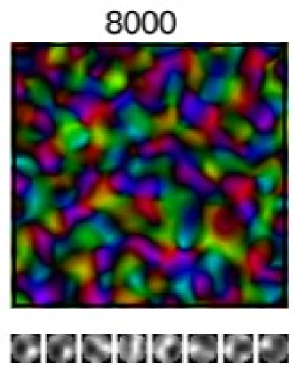


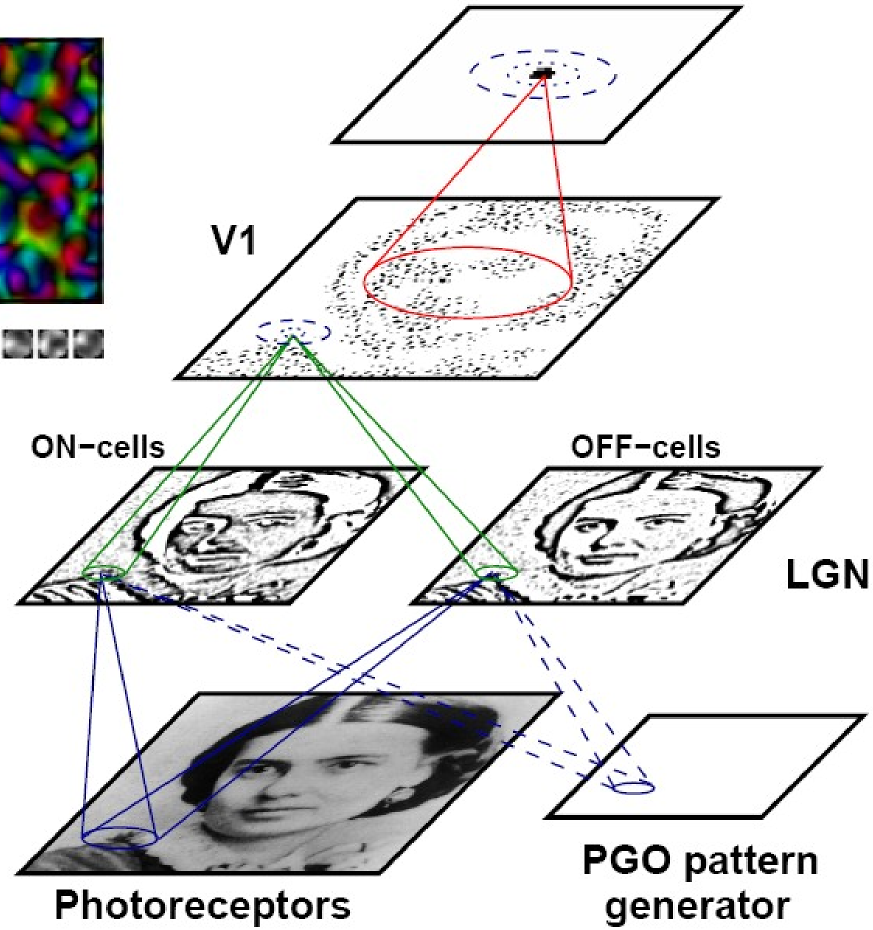


Mathematical fit to behavior. Good model if it is well fit. Simple, amenable to mathematical analysis. Often to over-simplified. Doesn't tell us how is the behavior implemented in the neural substrate.

What kind of models?

- Descriptive
- **Mechanistic**
- Functional
- Normative





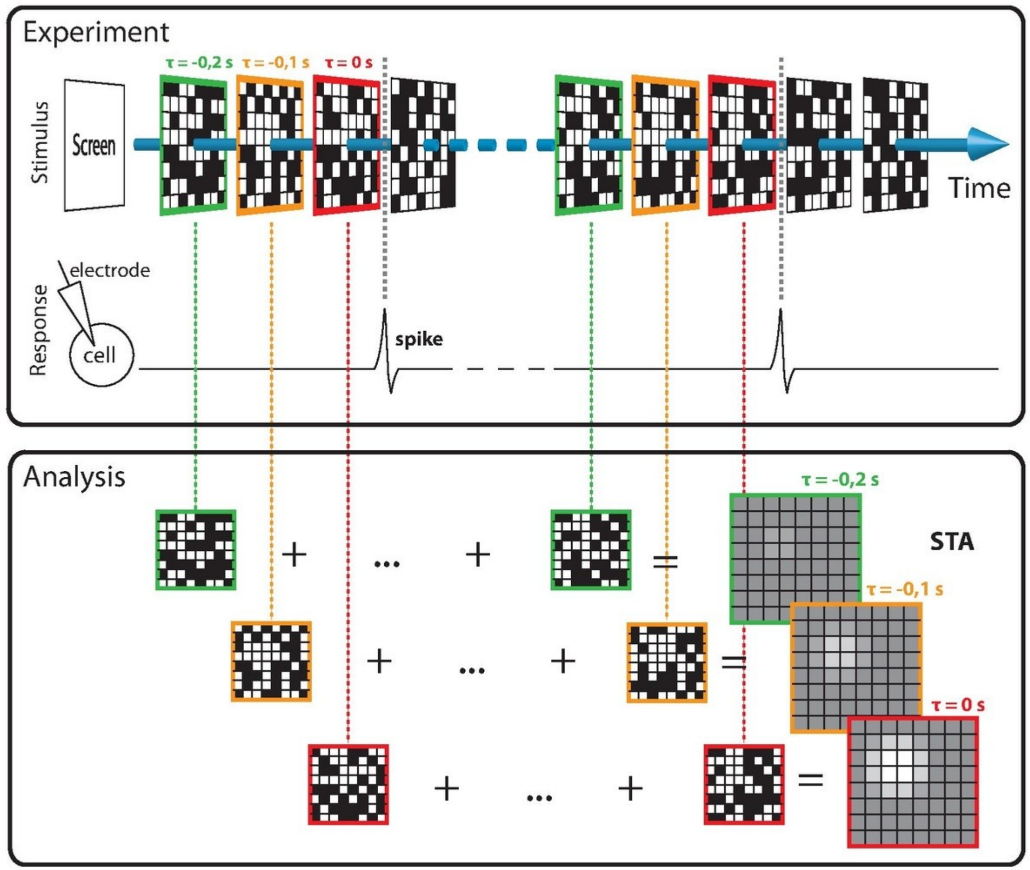
Systematic explanation built on top of a model of elementary computing units (usually neurons). Good if good model of the elementary computing unit, and consistent with anatomy and other neural mechanism Less amenable to systematic mathematical treatment.

What kind of models?

- Descriptive
- Mechanistic
- **Functional**
- Normative

Treats brain as black-box – we observe inputs-outputs, model fits what happens in between. Better fidelity with data than other models. The underlying computation often remains elusive – poor explanatory power. Prone to classic ML weaknesses such as over-fitting.

Spike-triggered average (STA)



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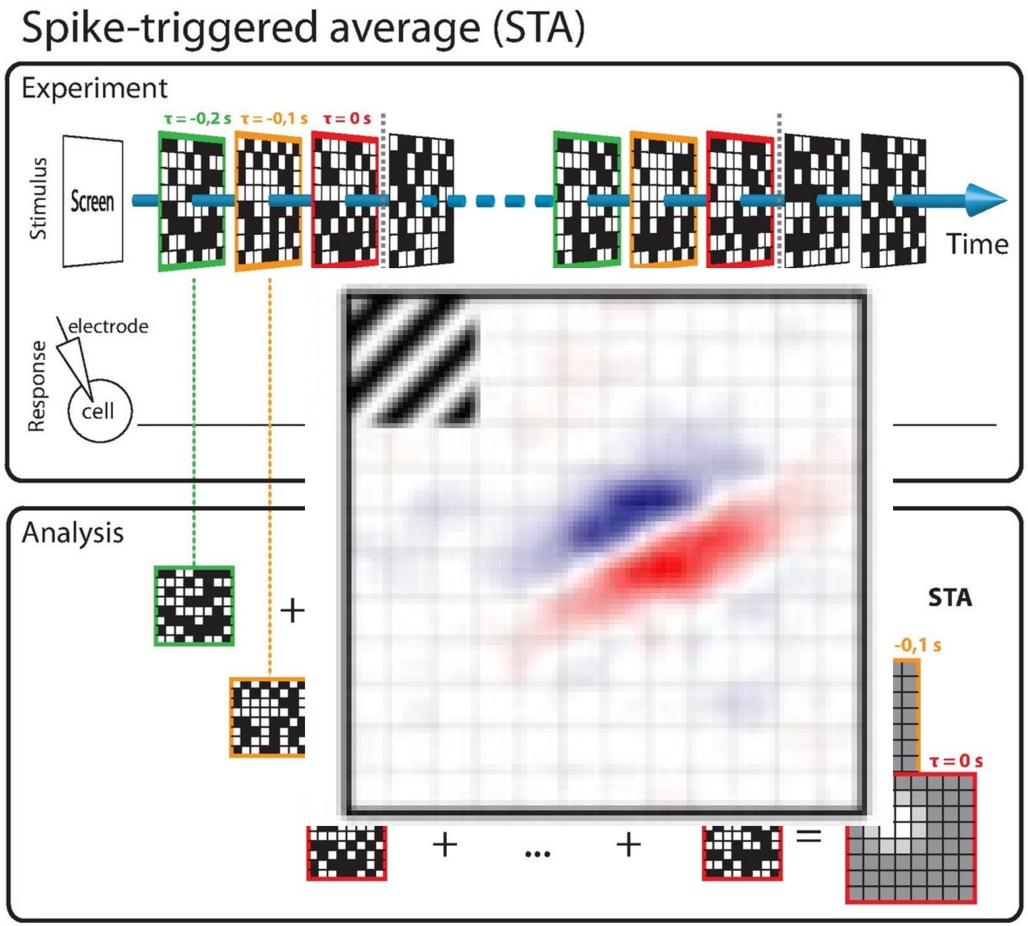

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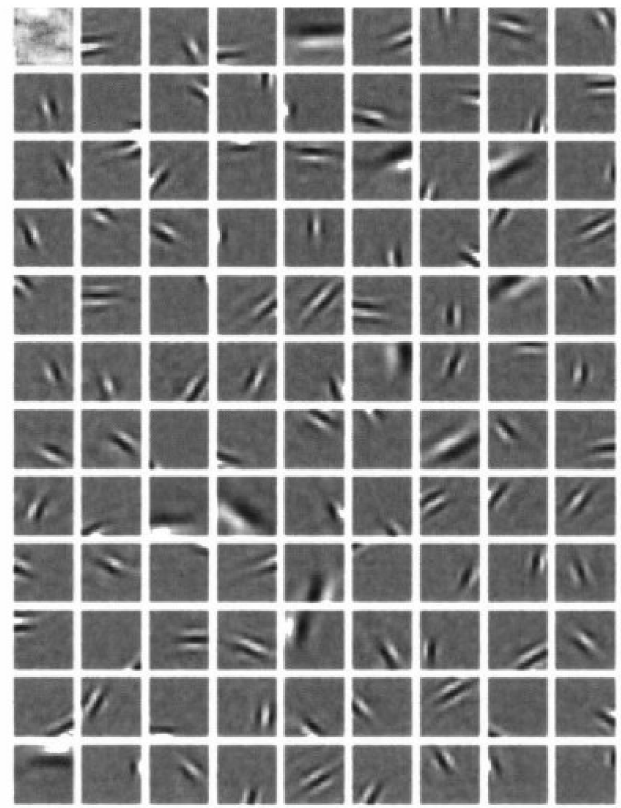
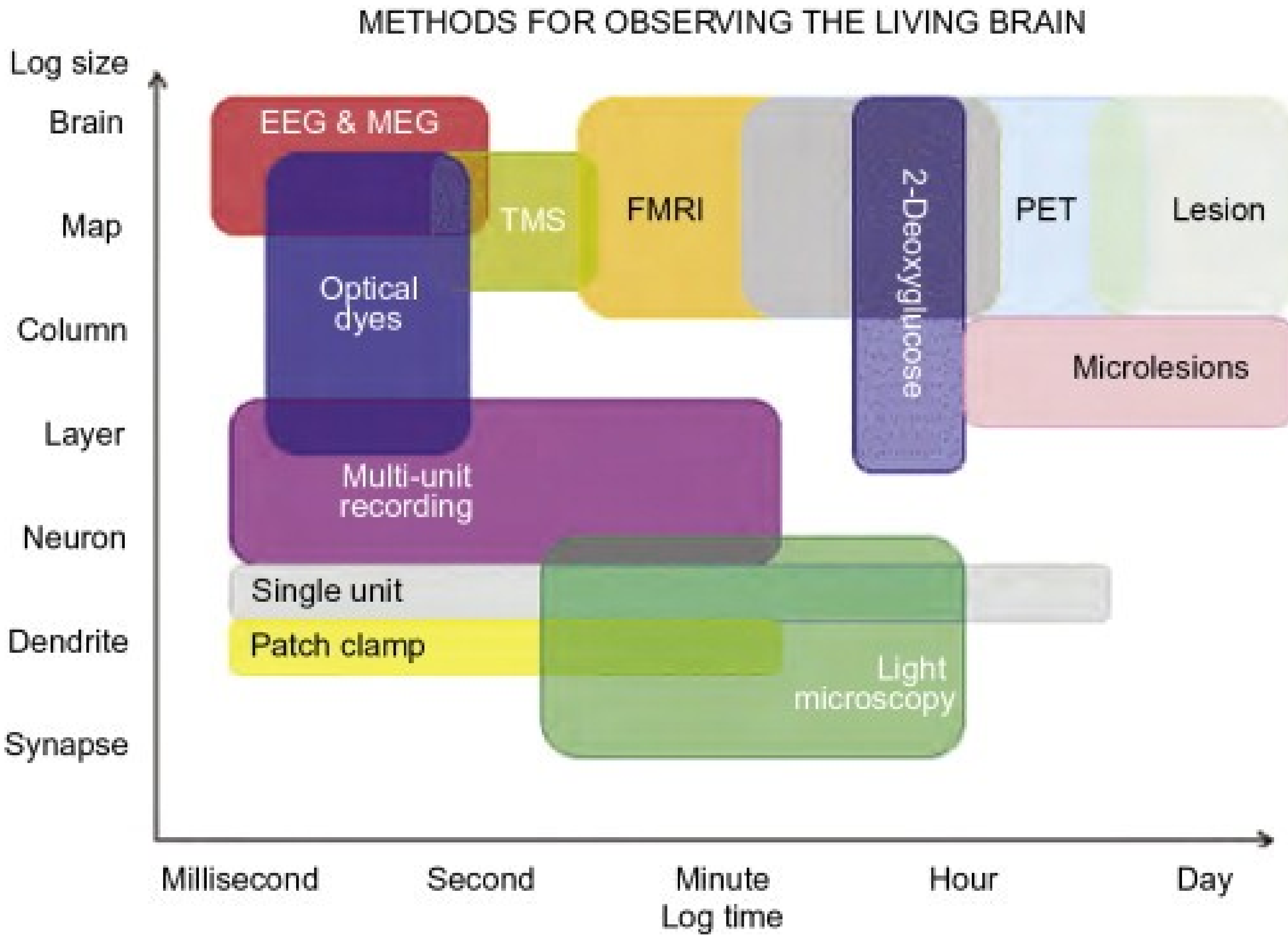


1.Formulate the question Q above brain as an optimization problem P.
2. Obtain solution S of the opti. problem.
3. If S matches experimental findings, conclude that brain is organized as S because it is optimal for solving problem P.
.
Example of P: brain tries to preserve information in the visual input, and represent it sparsely.

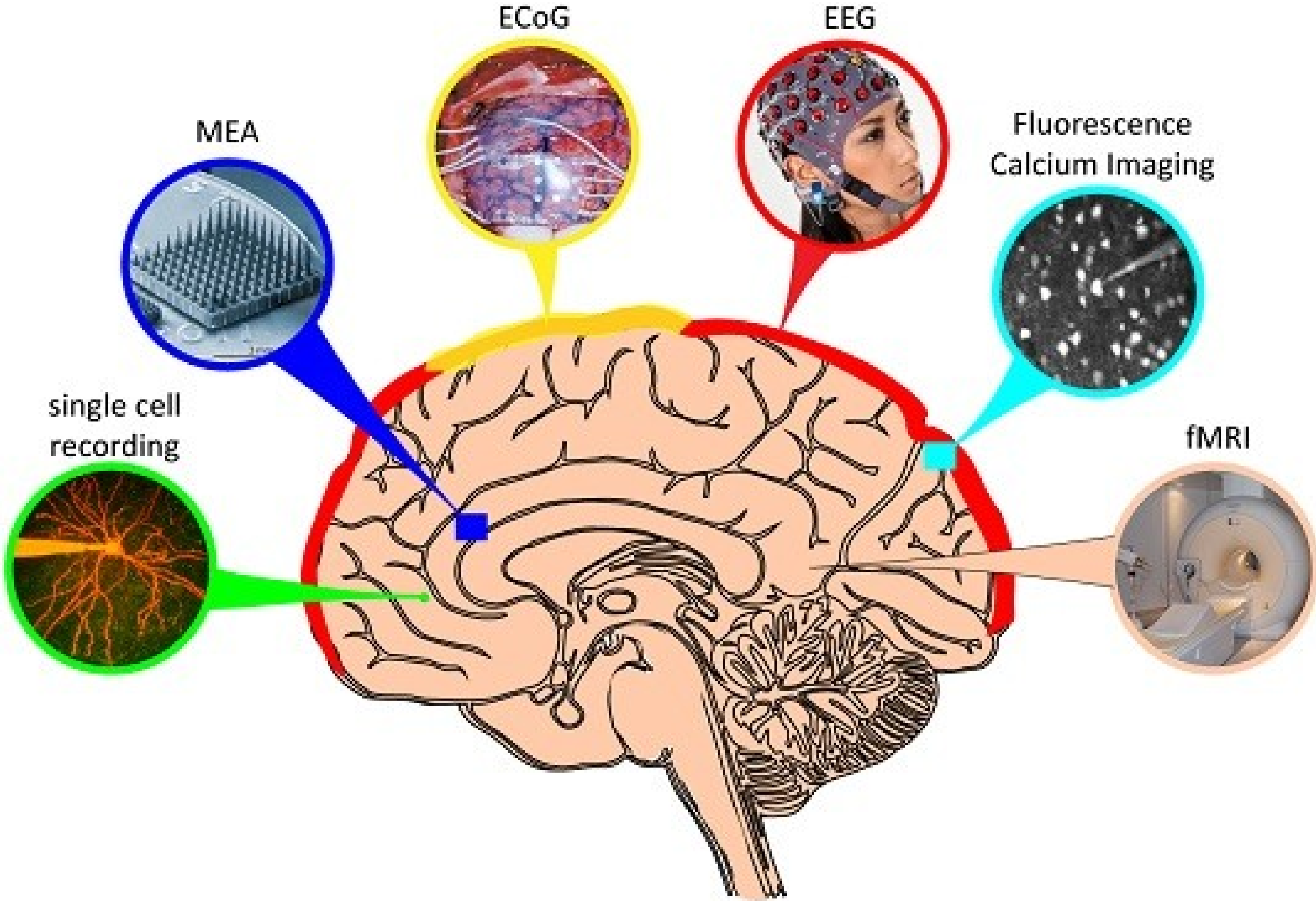
$$[\text{preserve information}] = -\sum_{x,y}\left[I(x,y) - \sum_i a_i\phi_i(x,y)\right]^2$$

$$[\text{sparseness of } a_i] = -\sum_i S\left(\frac{a_i}{\sigma}\right)$$

Measuring brain



Measuring brain



More info about the course on the website of our group

http://csng.mff.cuni.cz/

CHARLES
UNIVERSITY

COMPUTATIONAL SYSTEMS
NEUROSCIENCE GROUP

About Research Software Publications People For students Join us!

- We are a research group interested in **how visual system processes visual information**.
- We do this through combination of
  - Large-scale biologically detailed **spiking neural network** models
  - **Deep neural networ**k approaches applied to neural data
- We also apply our models on the problem of **vision restoration via brain-machine-interface**
- We collaborate with many international teams (e.g. USA, France, Germany Spain…) and use **state-of-the-art data sets** from our partners.

Come chat with us

- If you have deeper interest in the topic of neuroscience of neural engineering come to chat with us at the:

Computation neuroscience seminar
(NAILR128)

Student projects

Available student projects

Would you like to contribute to our research? This is a list of projects available for interested students. Most are designed to be completed within 3 to 6 month, but some can be expanded into longer projects even full PhD scope. If you are interested in working on any of the projects please contact me.

Computational Neuroscience Projects

- Biologically plausible model of body representation development.
- OFF centred thalamic V1 convergence.
- Travelling waves.
- Association field in visual cortex of higher mammals
- Early visual cortex vs Deep Neural Networks.
- Reconciling activity driven development of orientation maps with ON/OFF V1 convergence.
- Unifying retinal mozaik model with activity based development.
- Embedding of detailed compartmental neuron models into large-scale model of V1.
- Local-field potentials (LFP) in a large-scale model of cat primary visual cortex.
- Processing of higher order correlations in early visual cortex: a computational modelling investigation
- Stimulation protocols for cortical visual prosthesis.
- Deep biologically structured system identification approaches for studying primary visual cortex function.

Software engineering projects

- Mozaik data-store module based on object oriented database.
- A model inspection/visualization tool for Mozaik.
- Sumatra integration with Mozaik.

See at:
http://csng.mff.cuni.cz/students.html