

Introduction to Computational Neuroscience

Lecture I: Introduction

Objectives of the course

- get an idea of the common approaches to study the brain

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- get an idea of the common approaches to study the brain
- understand the differences between how brains and computers process information

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- get an idea of the common approaches to study the brain
- understand the differences between how brains and computers process information
- develop a critical thinking about neuroscience news and literature

Organization of the course

<https://courses.cs.ut.ee/2016/neuro>

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Raul Vicente raulvicente@gmail.com

Ardi Tampuu arditampuu@gmail.com

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Raul Vicente raulvicente@gmail.com

Ardi Tampuu arditampuu@gmail.com

Group of Computational Neuroscience

[Ulikooli 17: room 208](#)

Schedule of the course

- 14 Lectures (Monday 14:15 @ room 110)
- 7 Practical (Thursday 12:15 @ room 102)

Schedule of the course

- Excursion to the Experimental Psychology lab



Lesson	Title	
1	Introduction	Basics
2	Structure and Function of the NS	Analyses
3	Windows to the Brain	
4	Data analysis	
5	Single neuron models	
6	Network models	Models
7	Artificial neural networks	
8	Artificial intelligence	
9	Learning and memory	Cognitive
10	Perception	
11	Attention & decision making	
12	Brain-Computer interface	Applications
13	Neuroscience and society	
14	Future and outlook	
15	Projects presentations	
16	Projects presentations	

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Homework

Project

Grading system

Differentiated: A-F

- Exam (30%)
- Homework (35%)
- Project (35%)

You can collect up to 110 points,
90+ will give you A, 80+ B, 70+ C
and so on.

50% for each component to get a final assessment

Bonus exercises (up to 10%)

Exam

- 20 questions
- 2-3 paragraphs
- lecture/practice material

Structure and function

Q₂ : The nervous system (NS) of vertebrates is divided in central and peripheral parts. Name a few characteristics of the central NS and of the peripheral NS. You can consider characteristics of each division regarding both its structure/anatomy and function.

Q₃ : Name the two main types of cells found in a nervous system and describe their main roles.

Q₄ : Describe what is a synapse and what happens at the synapse when an action potential (spike) reaches the end of an axon.

Windows to the brain

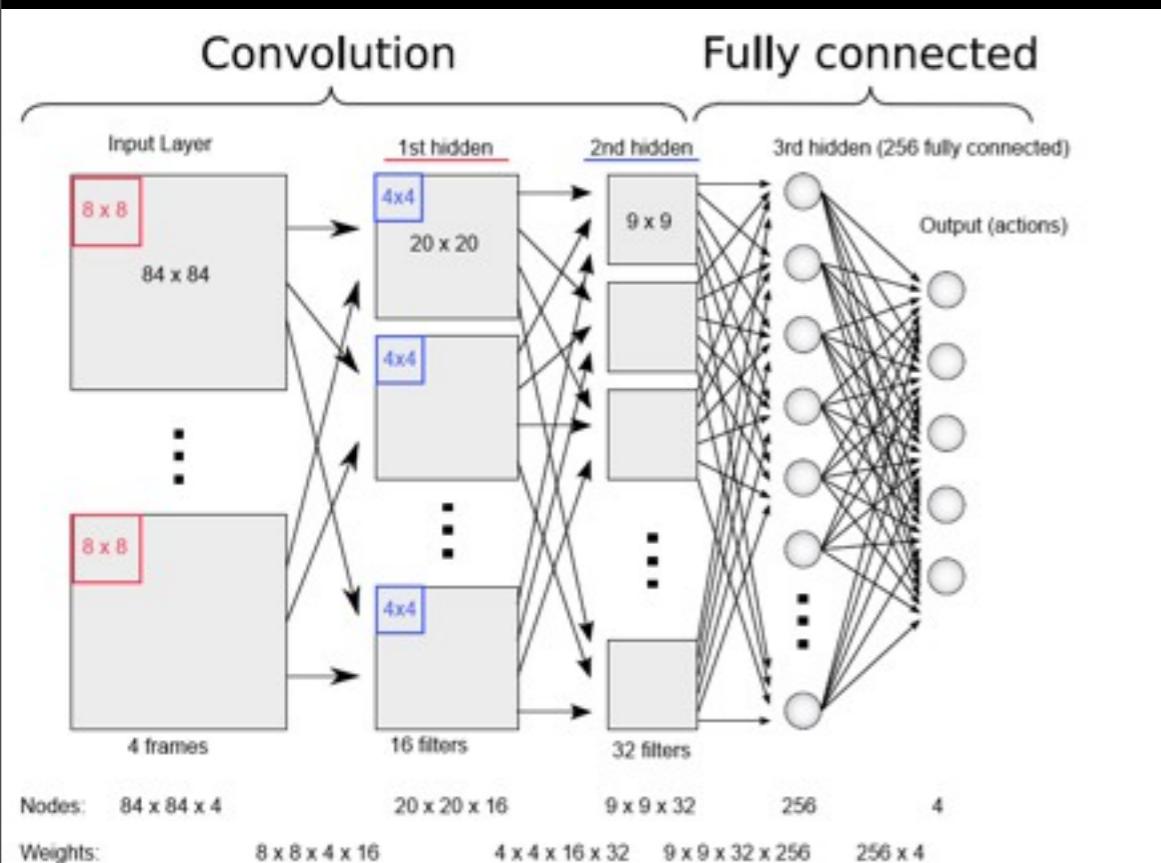
Q₅ : What is the main goal of structural brain imaging? What is the main goal of functional brain imaging?

Q₆ : Describe what is the typical neuronal signal one obtains from an extracellular recording? Which is the neuronal signal typically obtained from intracellular recordings?

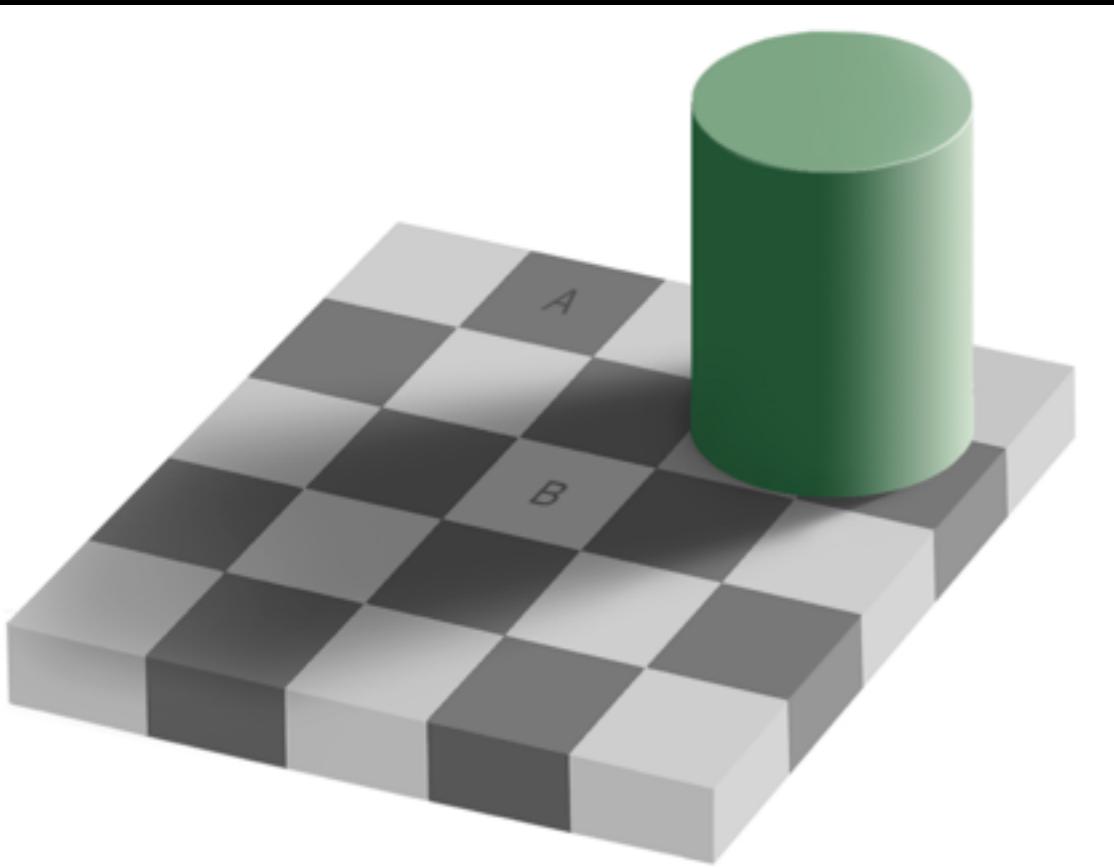
Project

- 2-4 people
- 15 pages
- small research (data collection, data analysis, model, essay...)
- presentation

Project (ANN playing Atari)



Project (visual illusions)



- N = 238
- 10, 15 ... 1 rpm = 134
- 10, 5 ... 15 rpm = 104
- Gender:
 - Males: 63
 - Females: 175
- Age: group from 20-29 = 172
- Education:
 - Secondary school = 88
 - Bachelor degree = 80
- Country of origin: 30 countries (Estonia, Latvia, Syria, Israel, Australia, etc.)

Pre-requisites

- Basic programming (e.g. Matlab, Python)
- Not be scared of small data analysis or a simple equation
- Understand that this is an interdisciplinary topic

What is computational neuroscience?

What is neuroscience?

What is neuroscience?

Scientific effort to understand how the brain works

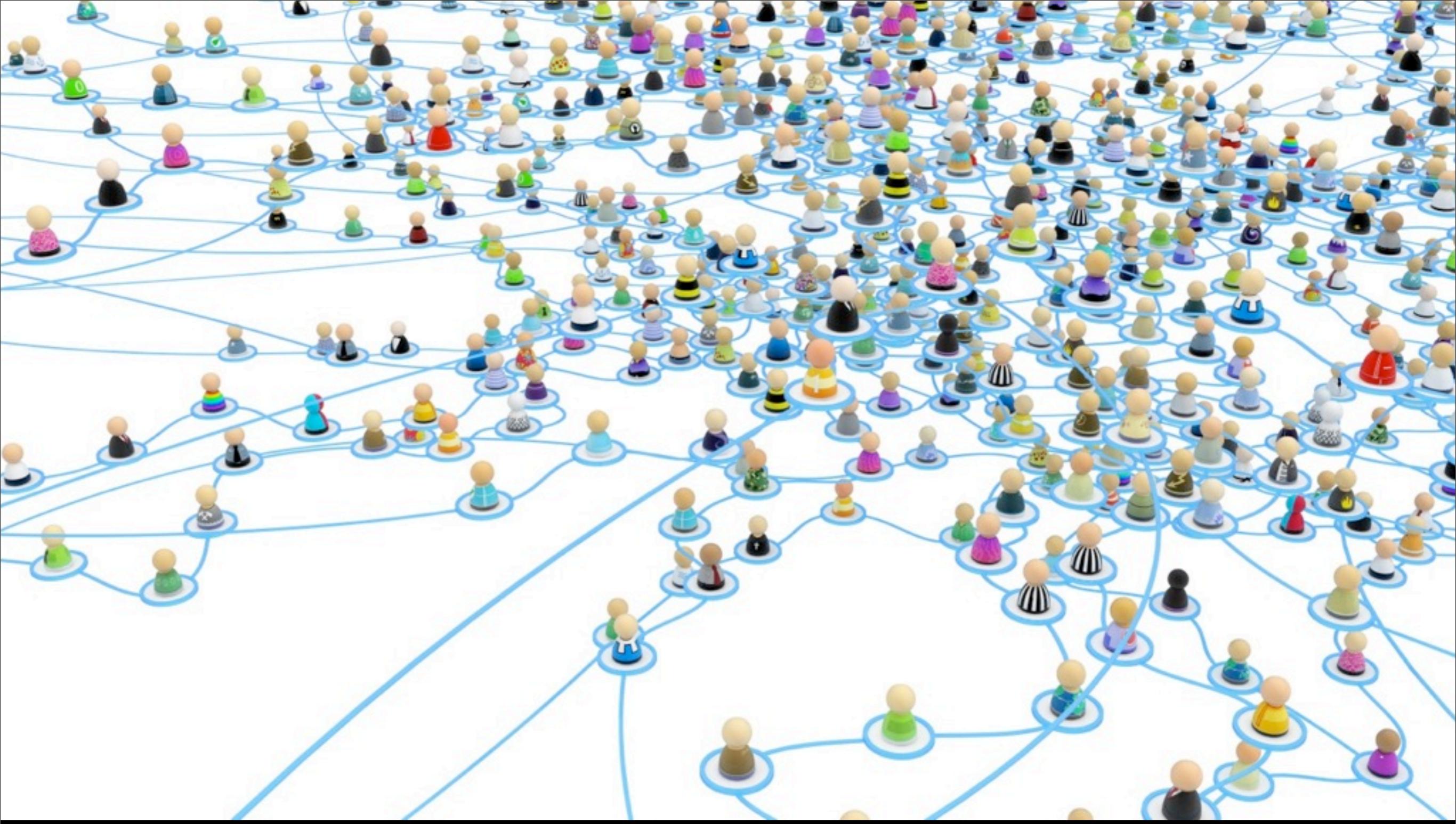




>30000 scientists attended the last SfN meeting

Why?

- your brain (a spongy, 1.5 kg of tissue) is the most complex structure we know



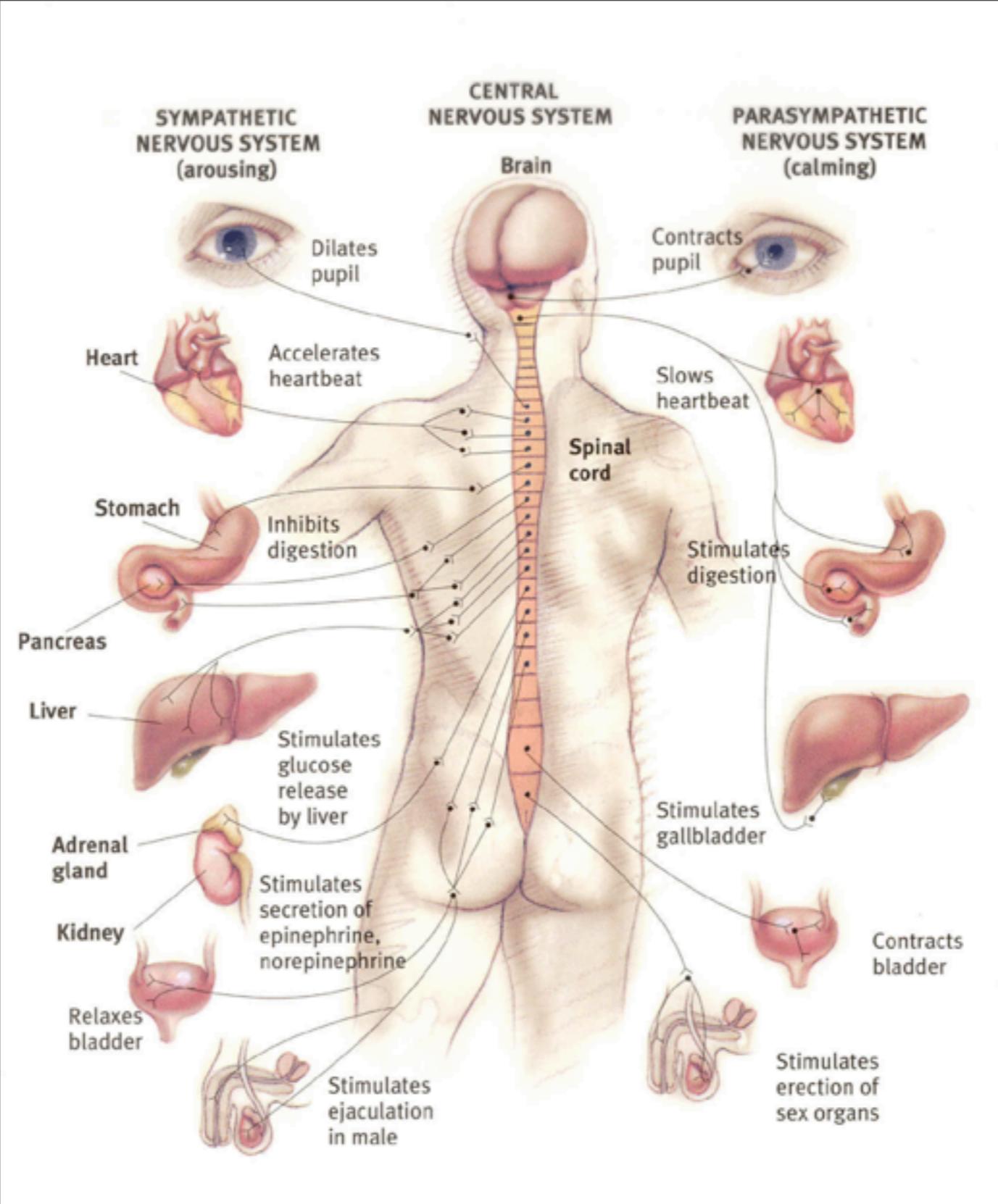
Network more complex than any social network



100 billion neurons & 100 trillion synapses

Why?

- your brain (a spongy, 1.5 kg of tissue) is the most complex structure we know
- single organ that controls the body (CEO + data scientist of your body)



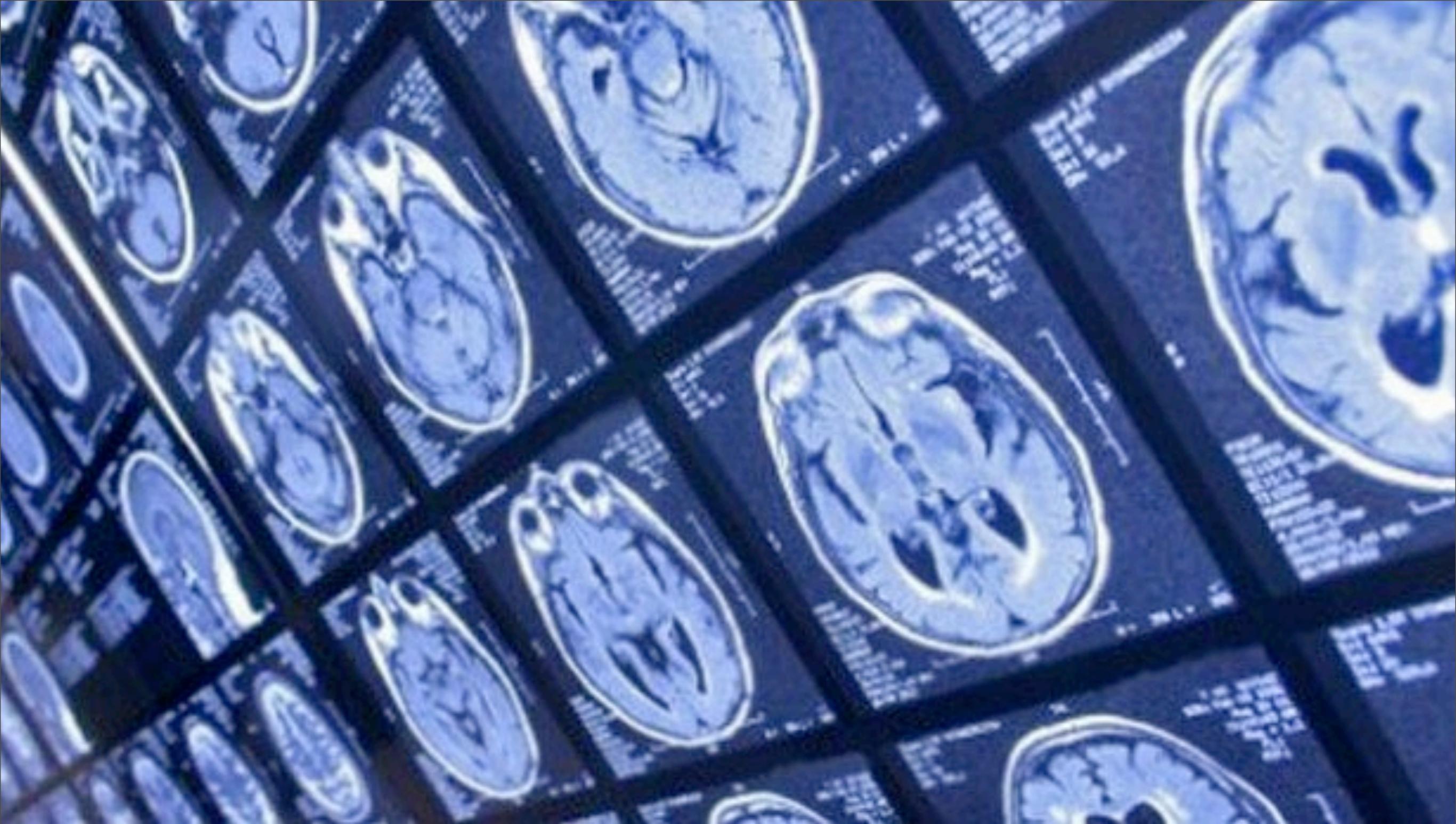
Heart rate, temperature, pressure, sleep,...



Coordinated movement of muscles and glands

Why?

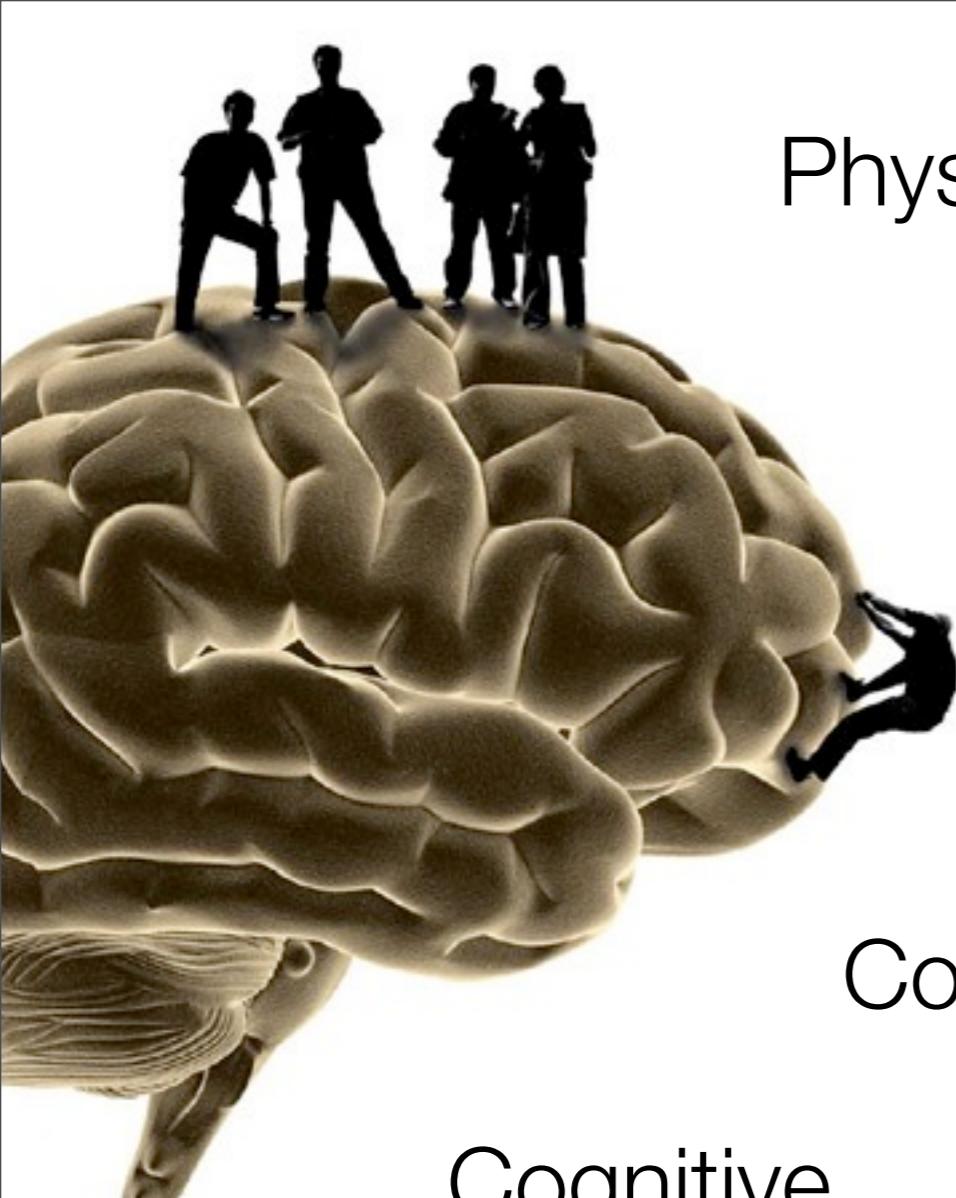
- your brain (a spongy, 1.5 kg of tissue) is the most complex structure we know
- single organ that controls the body (CEO + data scientist of your body)
- >1000 disorders of the brain and the NS



Parkinson, Alzheimer, autism, multiple sclerosis, depression,
schizophrenia, addiction,...



Parkinson tested from phone call... with >95% accuracy!



Physiology

Anatomy

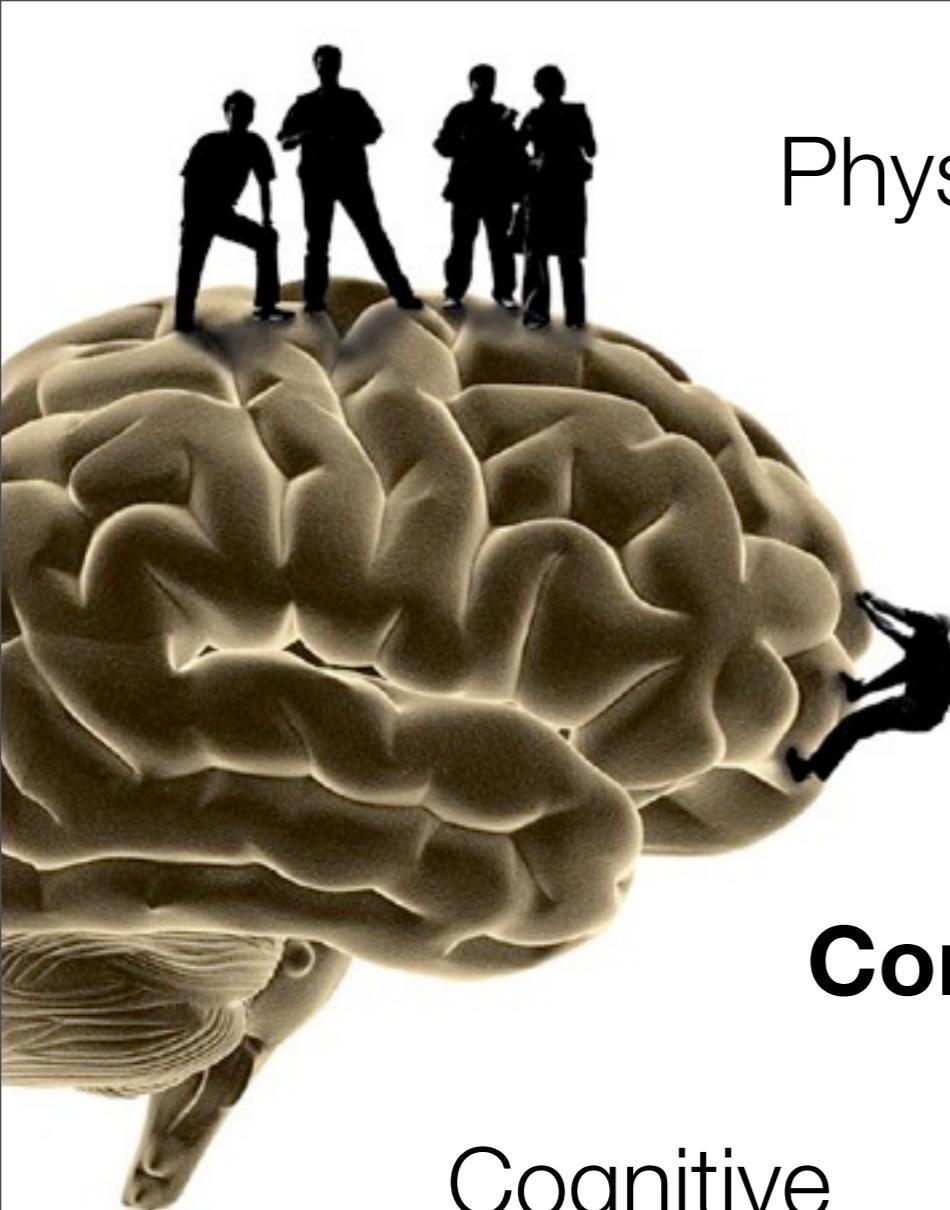
Clinical

Computational

Cognitive

Behavioral

Cellular, Molecular, Developmental, Evolutionary,...



Physiology

Anatomy

Clinical

Computational → **Information
processing**

Cognitive

Behavioral

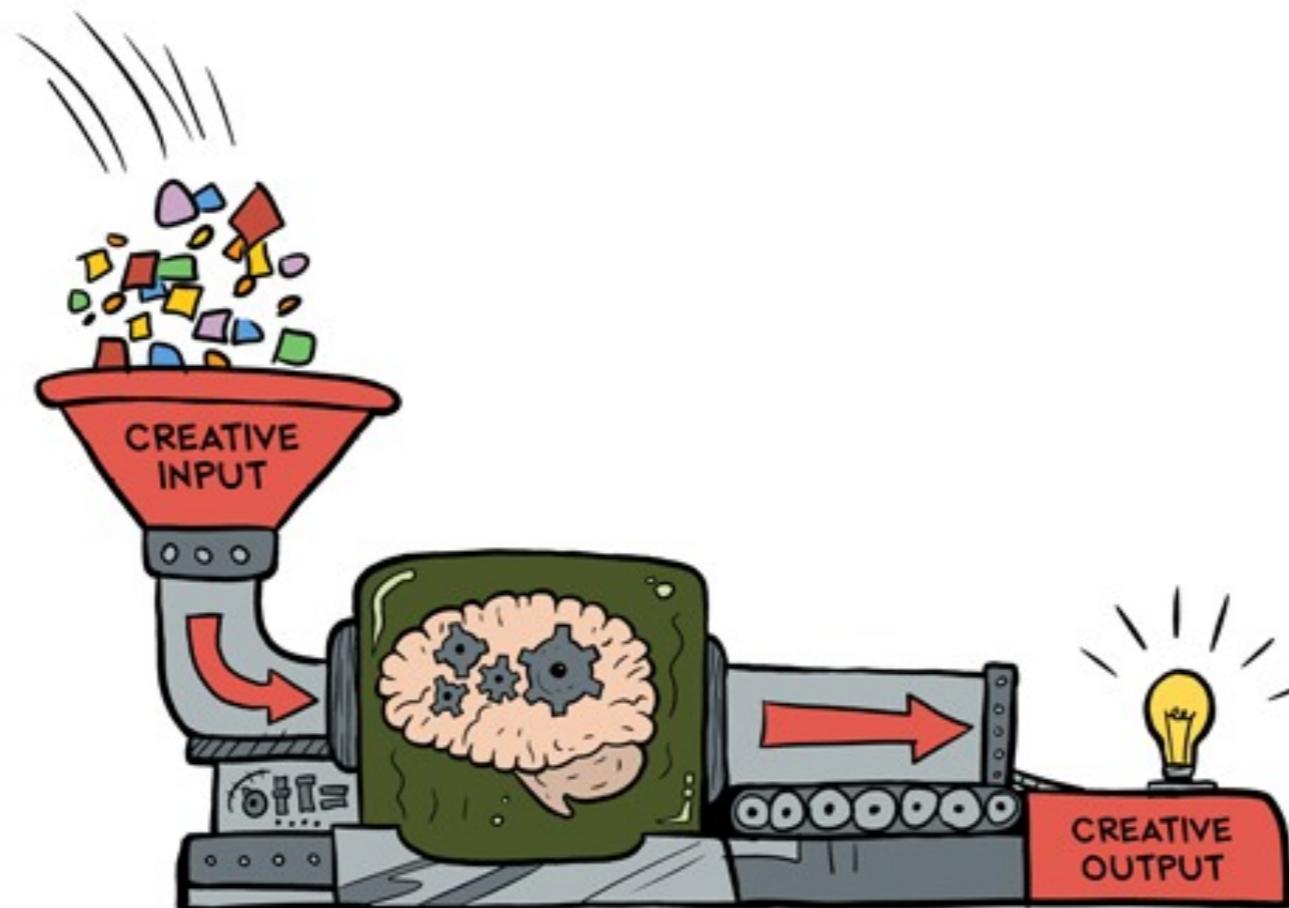
Cellular, Molecular, Developmental, Evolutionary,...

Stimuli

Photons

Pressure

Chemicals

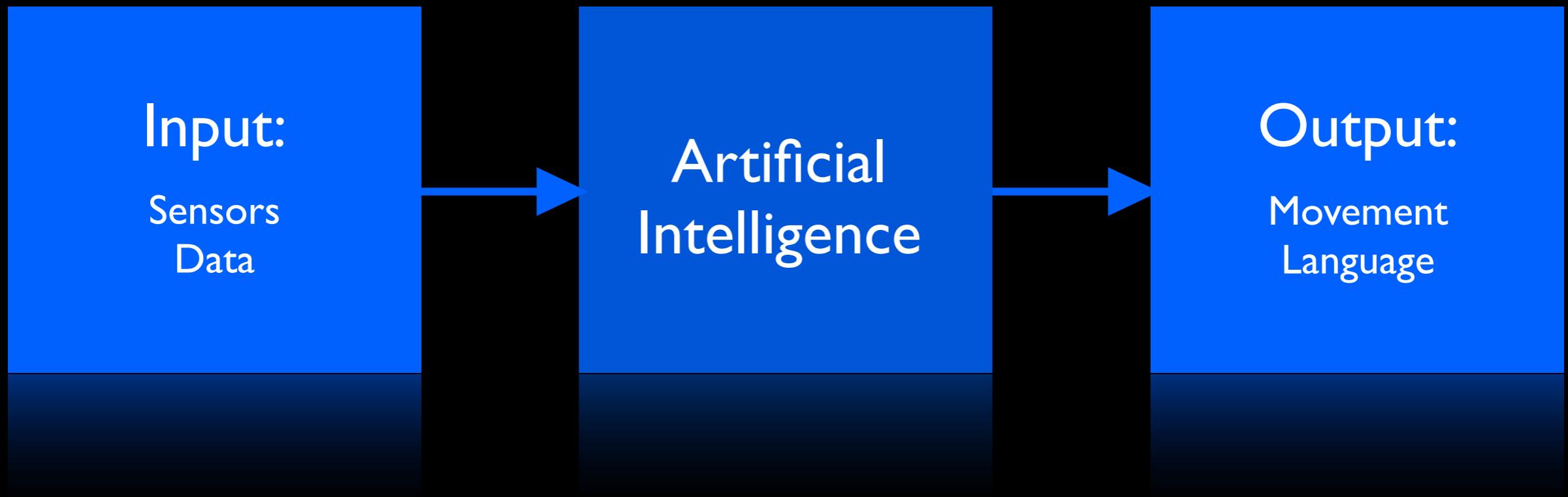


Behavior

Movement

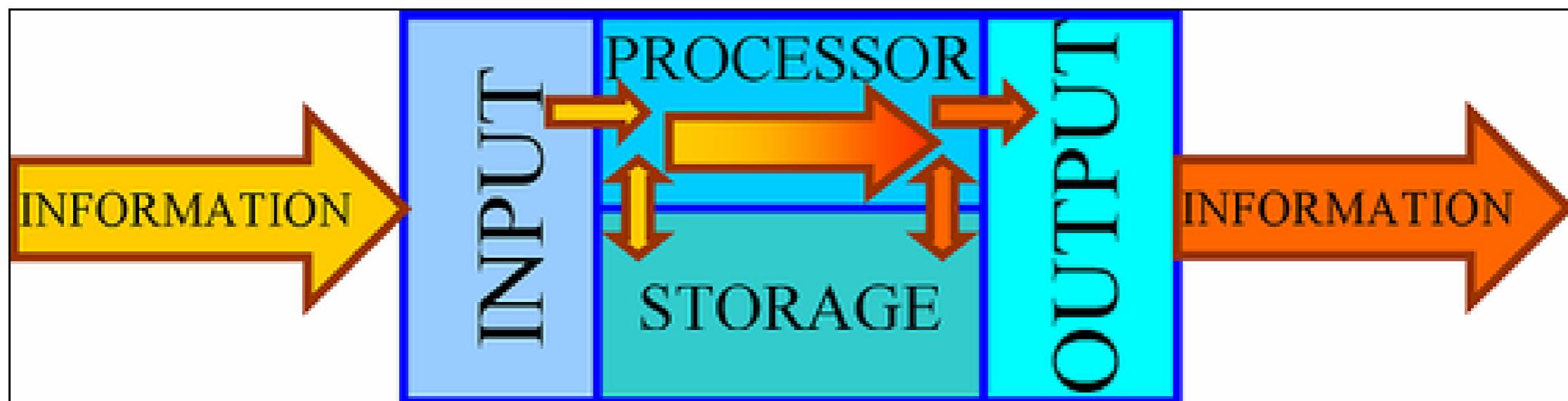
Language

Intelligent agents



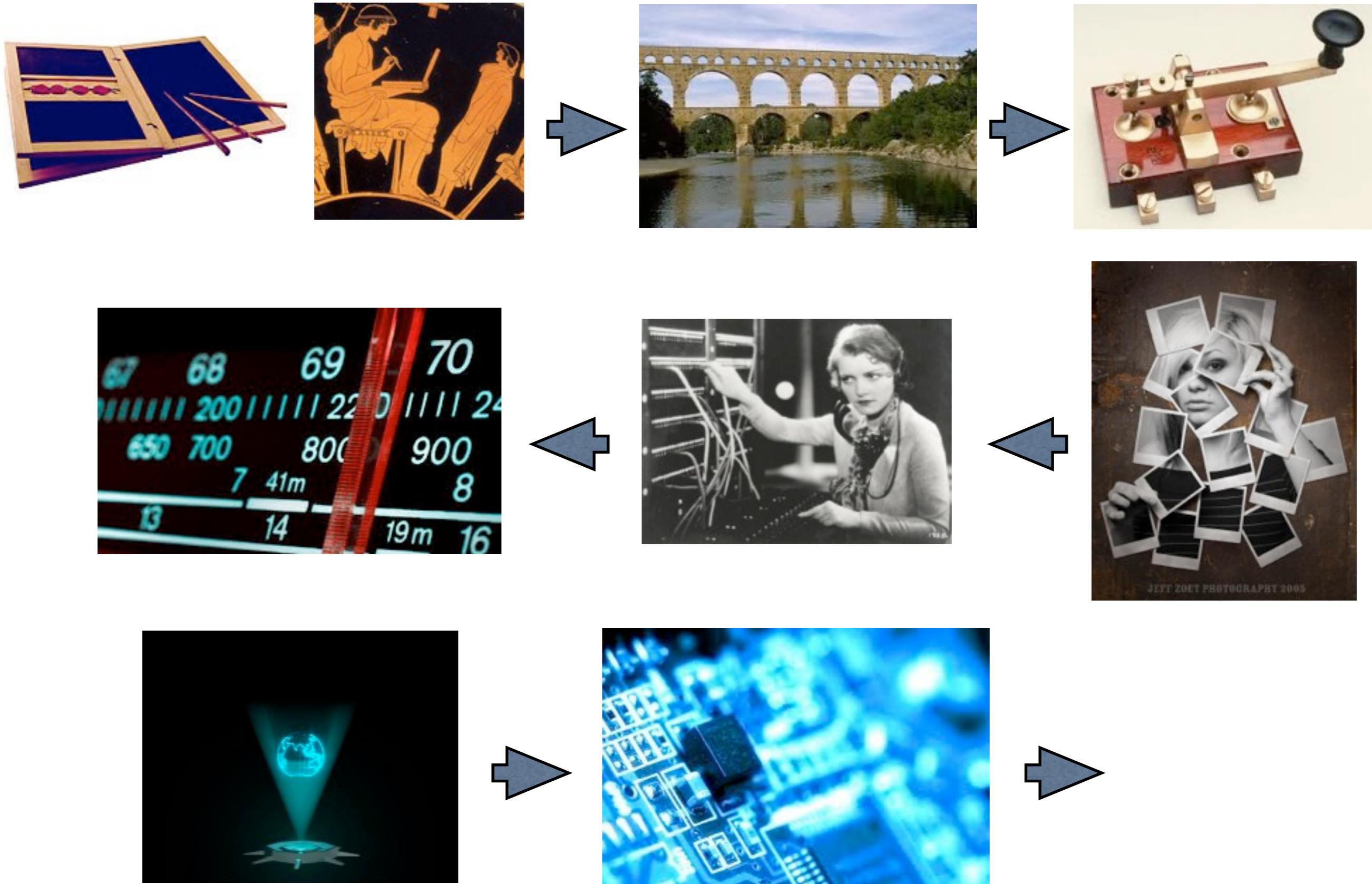
What is computational neuroscience?

to understand how the brain “computes” or processes information



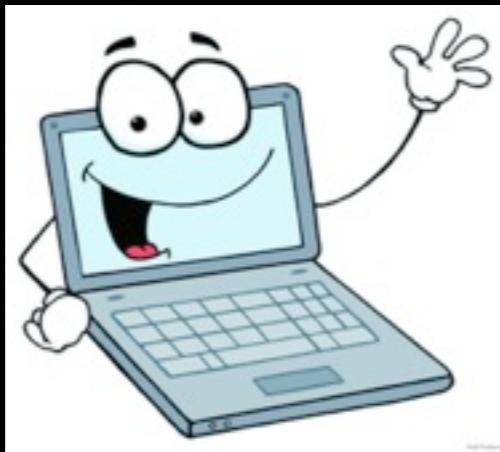
i.e., how neuronal circuits implement input-output relations

Brain as metaphors of current technology...

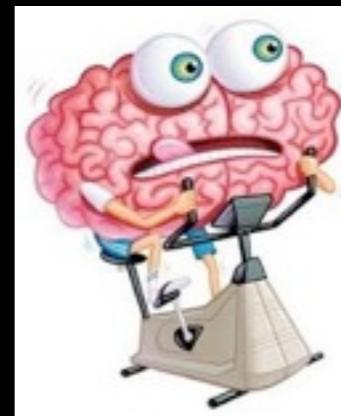


Computational
Neuroscience
uses the computer as a
tool and as analogy

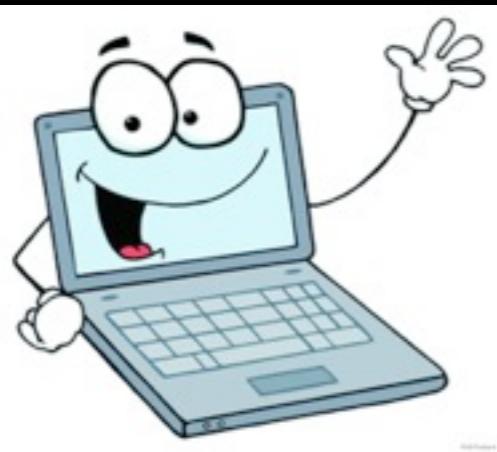
Machines vs Brains



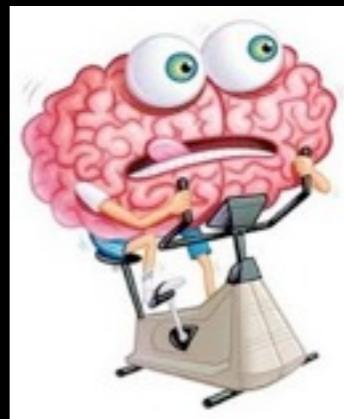
VS.



Machines vs Brains



VS.



precise, symbolic data

low resolution, ambiguous data

memory / computation

memory & computation

centralized processing

distributed processing

sequential

parallel

programming

learn

clock-driven

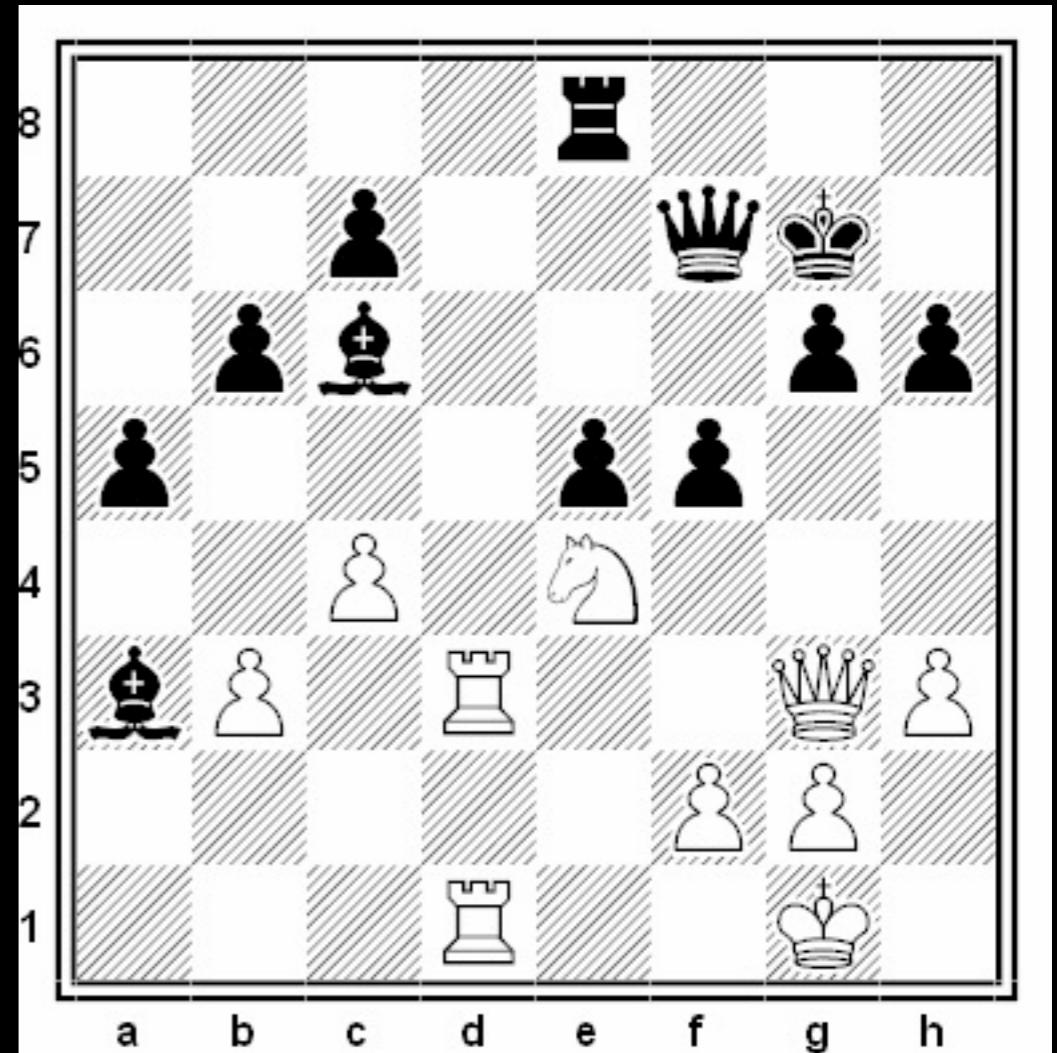
event-driven

fast & hot

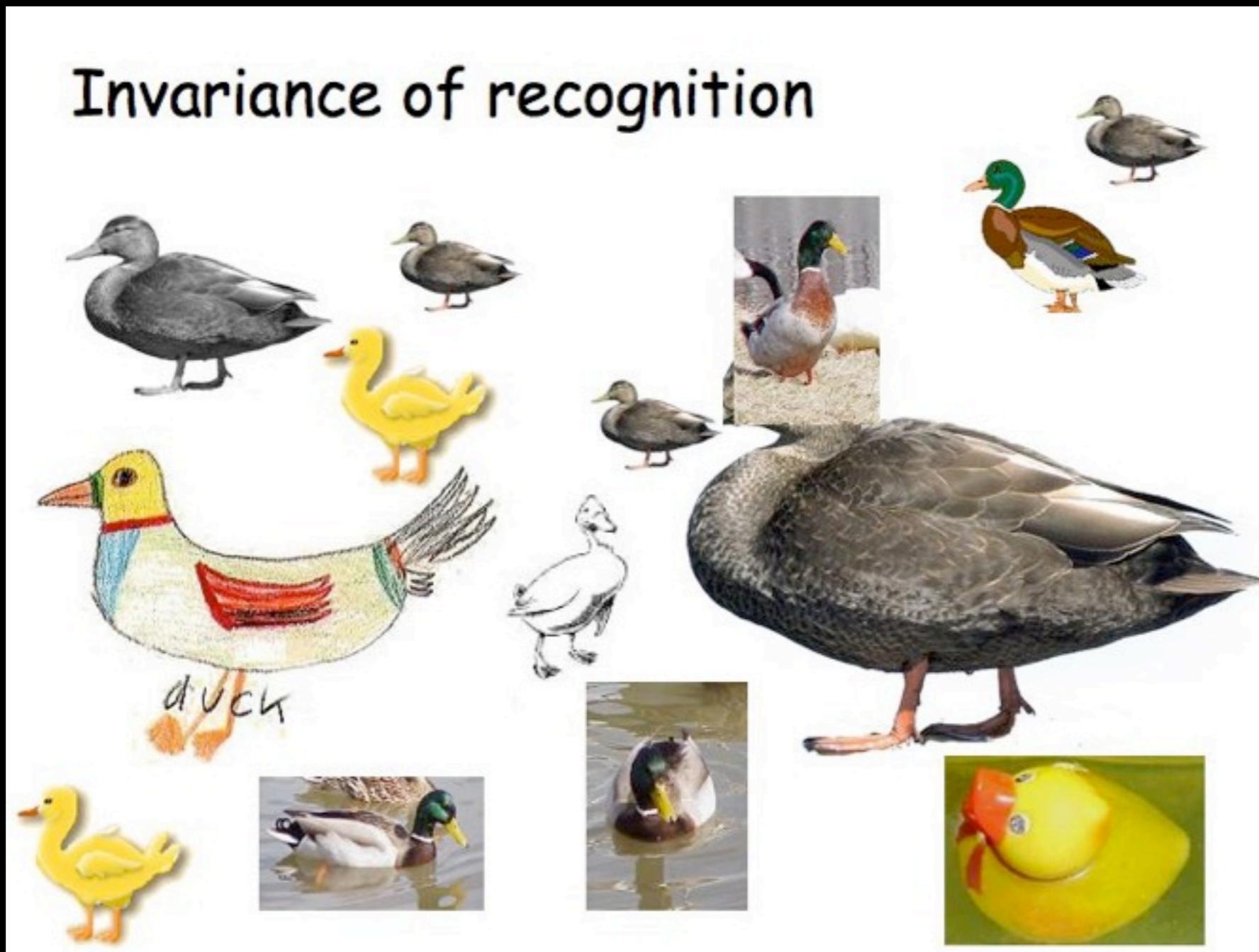
slow & cool

Computer wins by KO

What is the prime factorization of
238434728?



Brain wins by KO



- Try to program a computer to do the same...

Brain wins by KO

Novel examples need to be recognized...



- Try to program a computer to do the same...

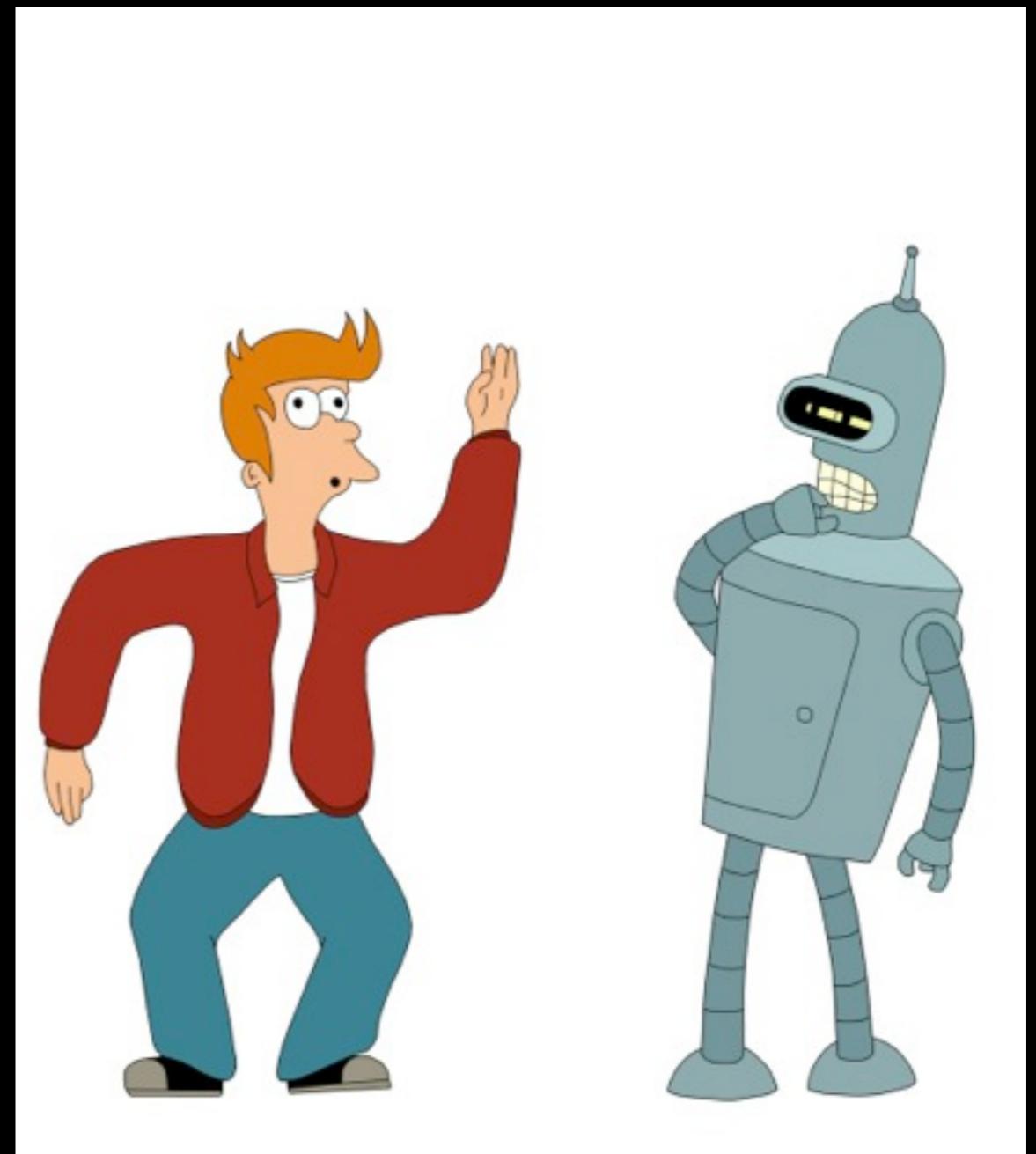
Brain wins by KO

Recognition
when only *part*
of an object is
visible...



- Try to program a computer to do the same...

Brain wins by KO



- Try to program a robot to move smoothly...

https://www.mturk.com/mturk/ — Amazon Mechanical Turk – Welcome

People | ... When will... Society fo... Neurosci... Human Br... Your Nex... For Web I... Robert Bl... sea_squir... Brain - W... How to d... Amazon... +

amazon mechanical turk Artificial Artificial Intelligence

Your Account HITs Qualifications

Already have an account?
Sign in as a [Worker](#) | [Requester](#)

Introduction | Dashboard | Status | Account Settings

Mechanical Turk is a marketplace for work.
We give businesses and developers access to an on-demand, scalable workforce.
Workers select from thousands of tasks and work whenever it's convenient.

270,946 HITs available. [View them now.](#)

Make Money
by working on HITs

HITs - *Human Intelligence Tasks* - are individual tasks that you work on. [Find HITs now.](#)

As a Mechanical Turk Worker you:

- Can work from home
- Choose your own work hours
- Get paid for doing good work

Find an interesting task **Work** **Earn money**

Find HITs Now

Get Results
from Mechanical Turk Workers

Ask workers to complete HITs - *Human Intelligence Tasks* - and get results using Mechanical Turk. [Register Now](#)

As a Mechanical Turk Requester you:

- Have access to a global, on-demand, 24 x 7 workforce
- Get thousands of HITs completed in minutes
- Pay only when you're satisfied with the results

Fund your account **Load your tasks** **Get results**

Get Started

The screenshot shows the Amazon Mechanical Turk homepage. At the top, there's a navigation bar with various links like 'People | ...', 'When will...', 'Society fo...', etc. Below the navigation is the 'amazon mechanical turk' logo with 'Artificial Artificial Intelligence' underneath. There are three main tabs: 'Your Account' (selected), 'HITs', and 'Qualifications'. To the right, there's a link for 'Already have an account? Sign in as a [Worker](#) | [Requester](#)'. Below the tabs, there's a menu with 'Introduction', 'Dashboard', 'Status', and 'Account Settings'. The main content area has a yellow gradient background. It starts with a statement about Mechanical Turk being a marketplace for work, followed by two paragraphs about workers and requesters. A large red text '270,946 HITs available.' is followed by a blue link 'View them now.'. On the left, under 'Make Money', there's a section for workers with a list of benefits and a flowchart: 'Find an interesting task' (with a circular icon containing text about scenarios and tasks), 'Work' (with a circular icon containing gears), and 'Earn money' (with a circular icon containing a dollar sign). A blue button at the bottom says 'Find HITs Now'. On the right, under 'Get Results', there's a section for requesters with a list of benefits and a flowchart: 'Fund your account' (with a circular icon containing a plus sign), 'Load your tasks' (with a circular icon containing a document icon), and 'Get results' (with a circular icon containing a star). A blue button at the bottom says 'Get Started'.

- Amazon mechanical turks for human intelligence

Approaches to computational neuroscience?

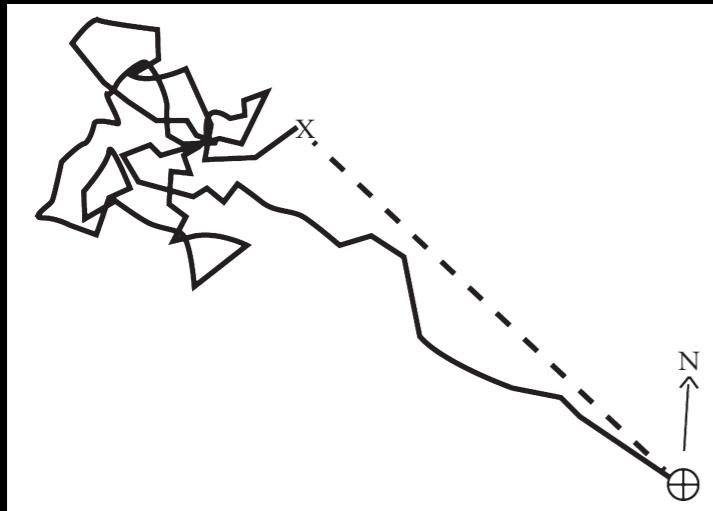
Bottom-up approach (bio)

A reductionist approach:

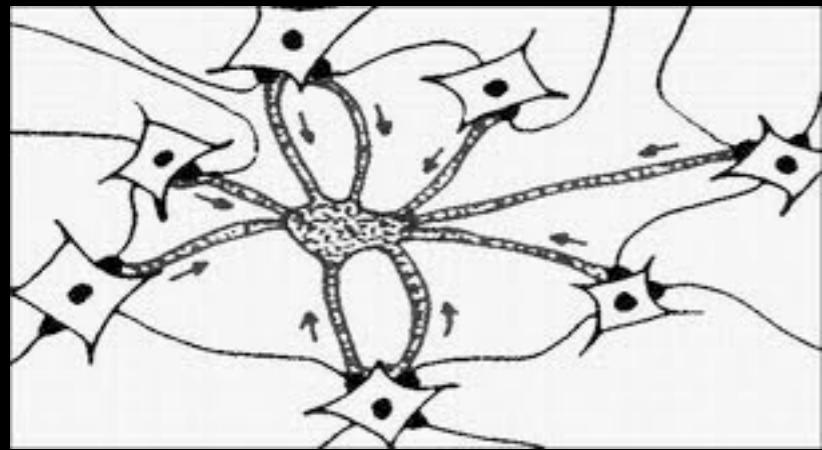
Collect data, organize it, and see what behavior emerges at the next level!

study method	object of study
physics	ions
chemistry	transmitters and receptors
cell biology	neurons
computer science	networks
neurology	systems
psychology	behavior or thought

Top-down approach (eng)



Location =
Sum{velocity(t)*dt}

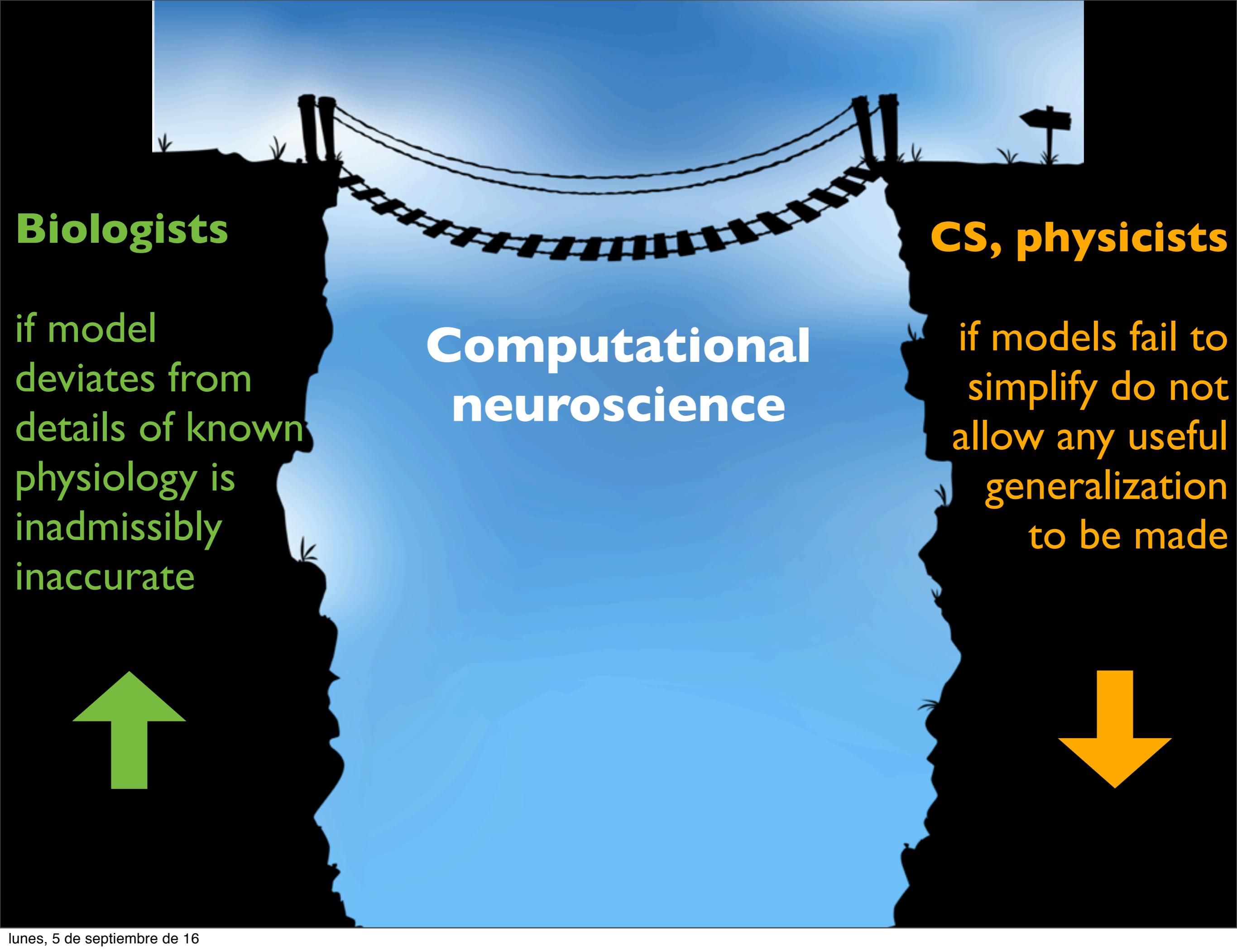


Functional:
What information processing
problem is being solved ?

Algorithm:
What information processing steps
are carried out to solve it ?

(Biophysical) Implementation:
How is the algorithm implemented in
biological hardware ?

David Marr



Biologists

if model
deviates from
details of known
physiology is
inadmissibly
inaccurate

CS, physicists

if models fail to
simplify do not
allow any useful
generalization
to be made

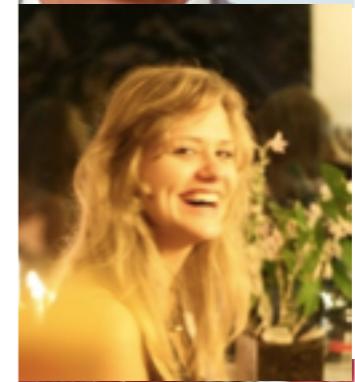
Computational neuroscience



Jaan



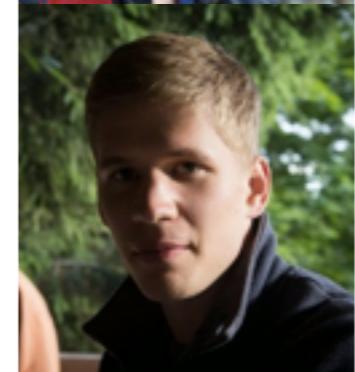
Toomas



Liisa



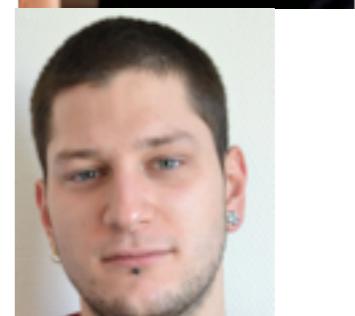
Julius



Sander

Daniel

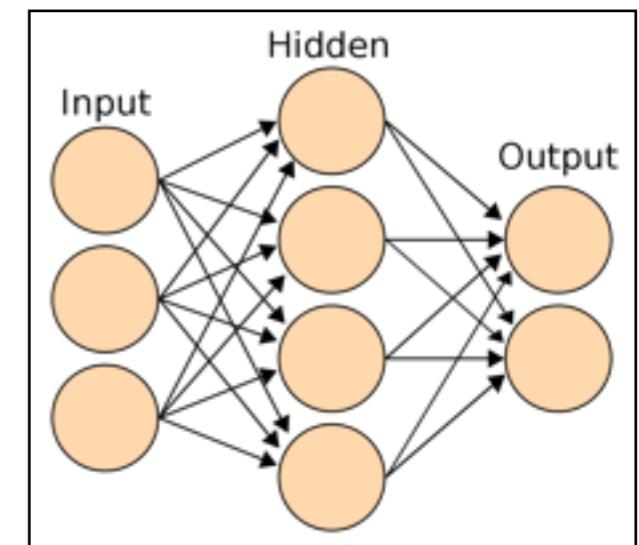
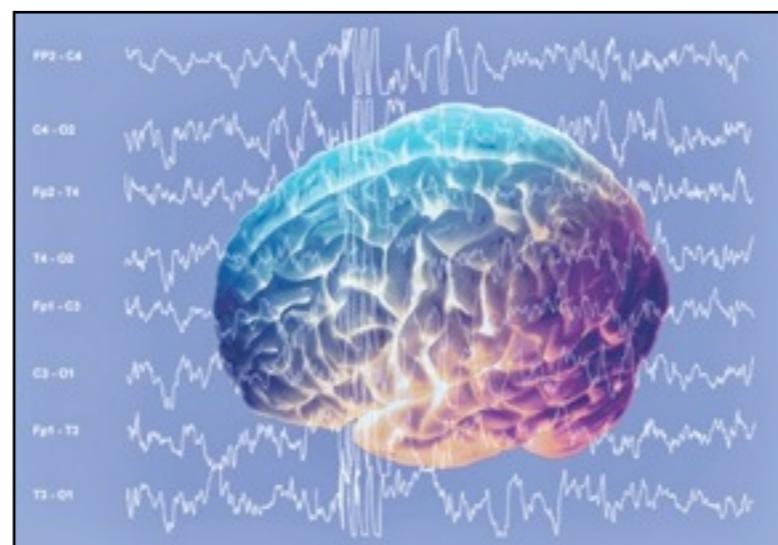
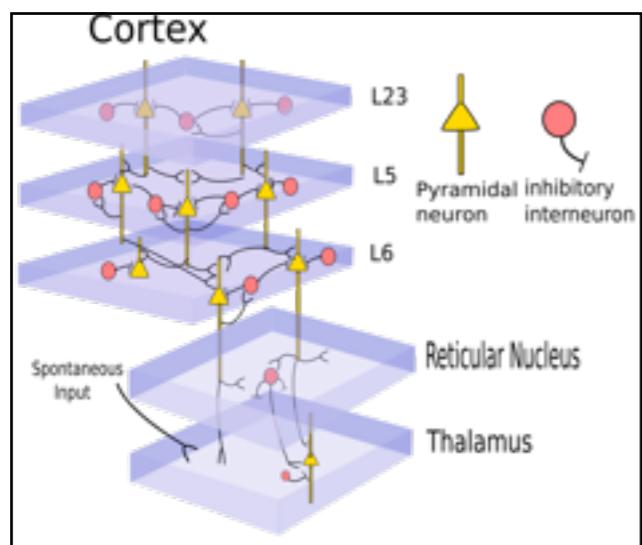
Aqeel



Dorian



3 lines of research from our lab



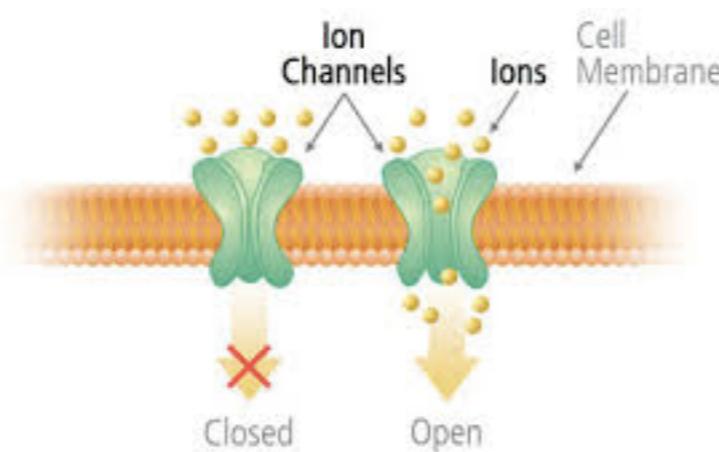
Simulation

Data analysis

AI

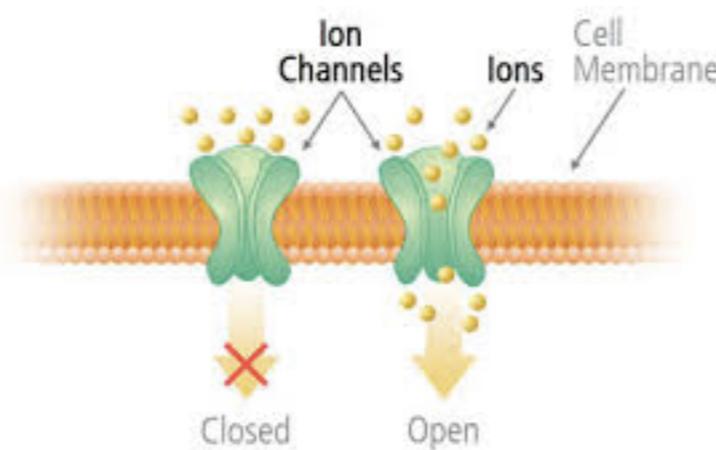
Simulating neural systems

- To better predict and guide experiments



Simulating neural systems

- To better predict and guide experiments

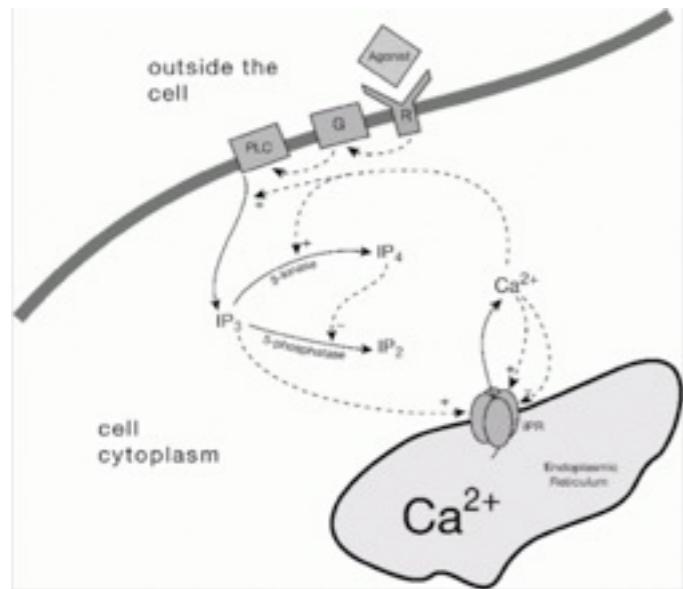


- Framework for thinking clearly:

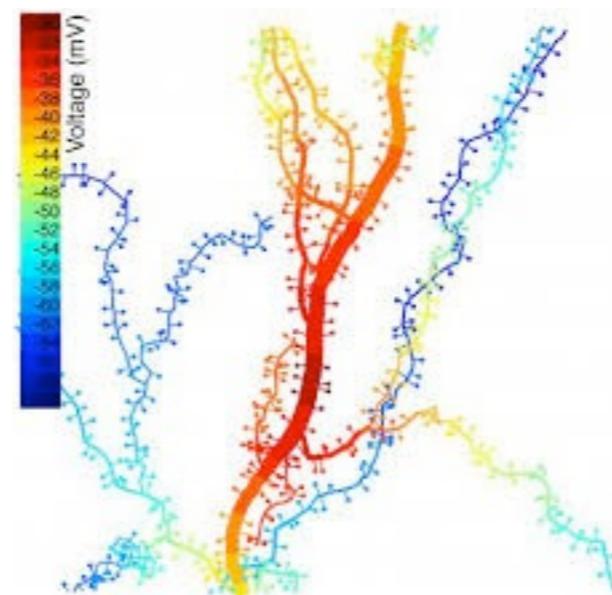
Mathematical formalization → Consistency → True?

Inconsistency → Falsehood

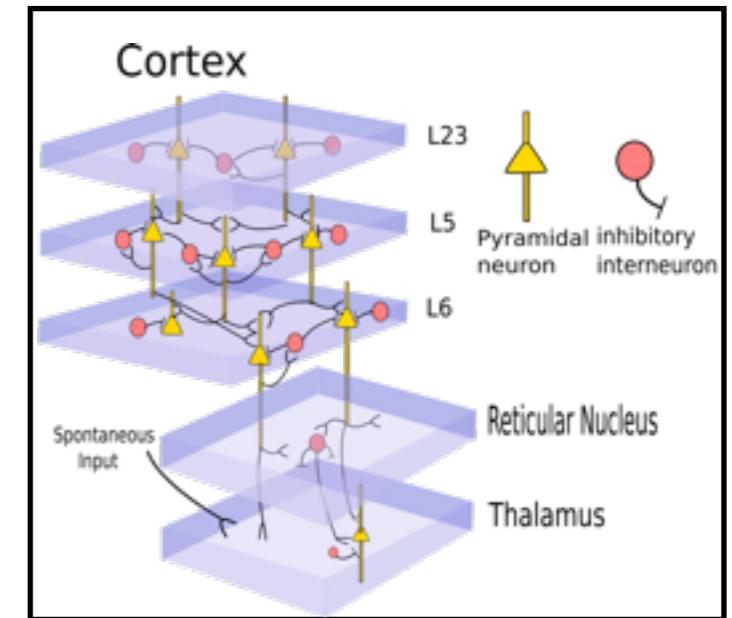
Different scales



Molecular level
(Ca dynamics)



Cellular level
(multi-compartmental)

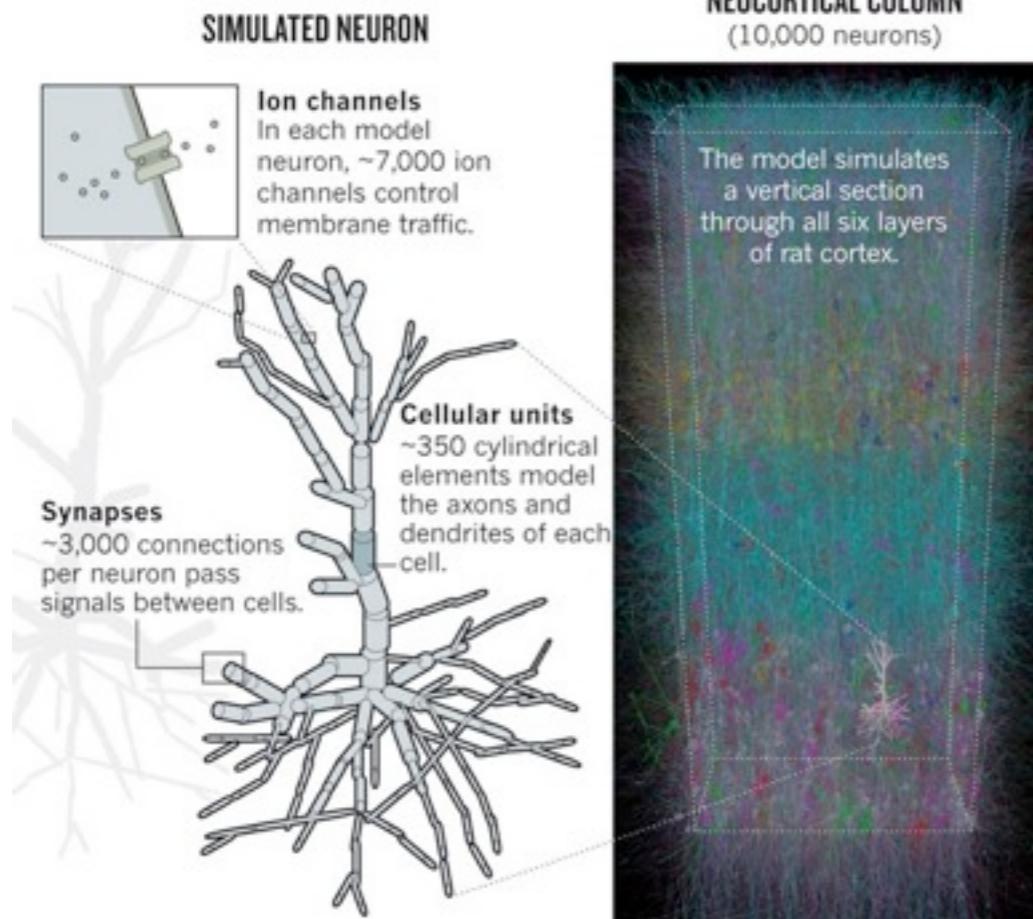


Local circuits
(network dynamics)

Human brain project

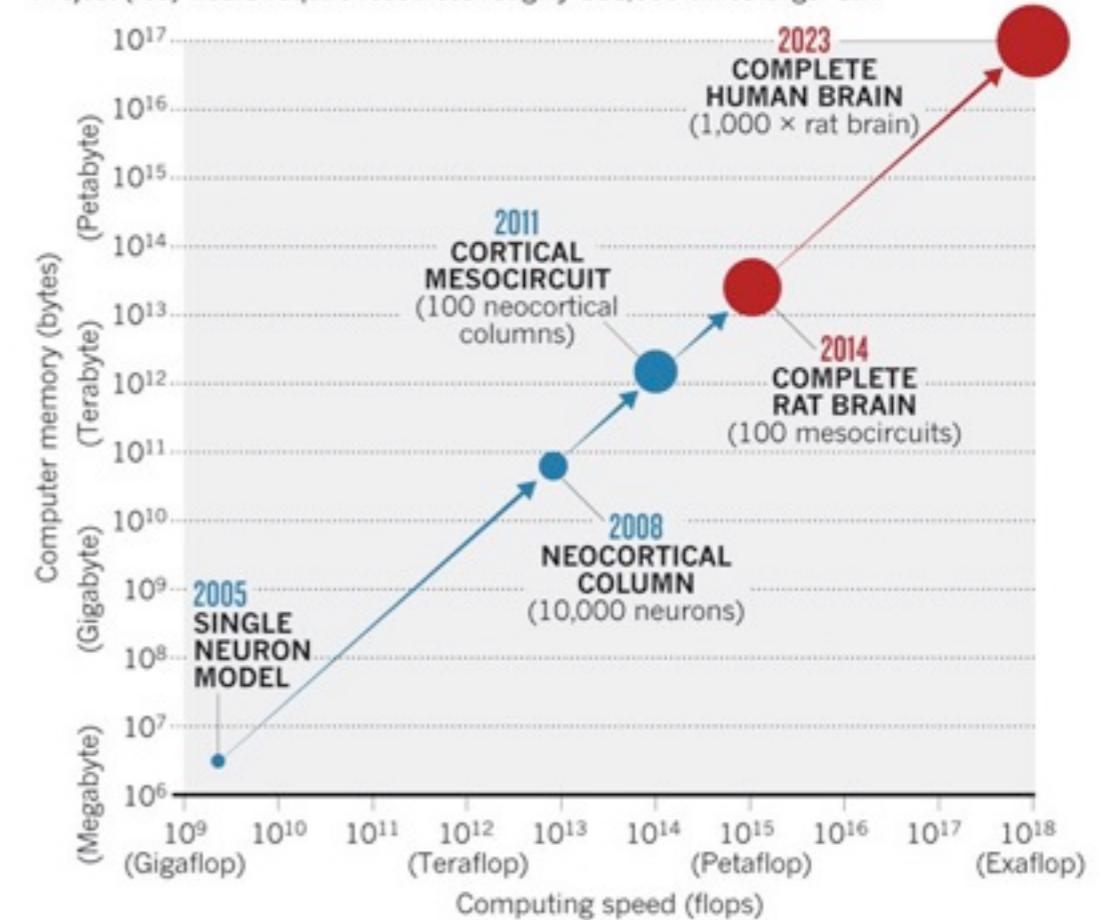
BUILDING A BRAIN

The Blue Brain simulation — a prototype for the Human Brain Project — constructs simulated sections of cortex from the bottom up, starting from detailed models of individual neurons.



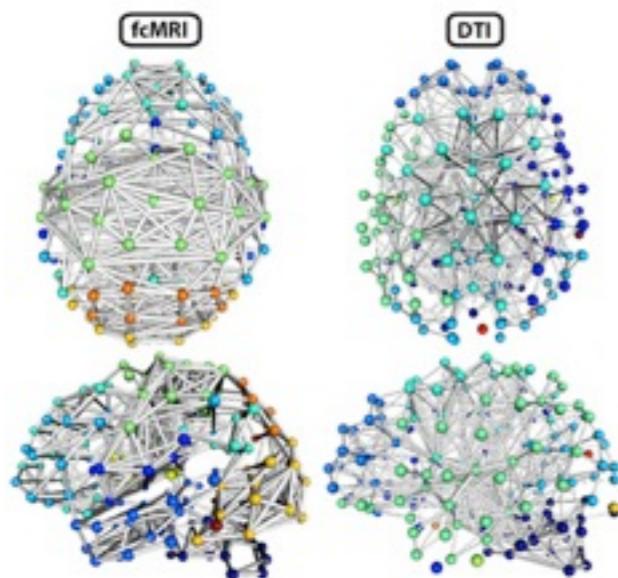
FAR TO GO

The Blue Brain Project has steadily increased the scale of its cortical simulations through the use of cutting-edge supercomputers and ever-increasing memory resources. But the full-scale simulation called for in the proposed Human Brain Project (red) would require resources roughly 100,000 times larger still.

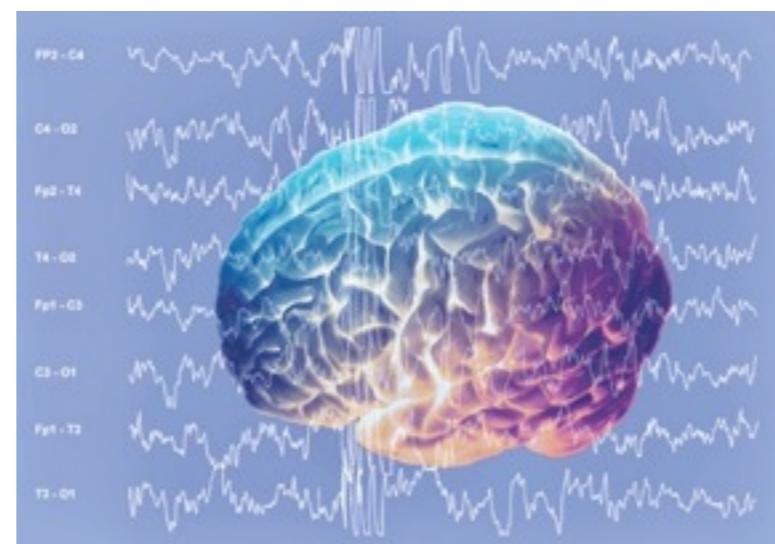


1 billion Euro
65536 cores

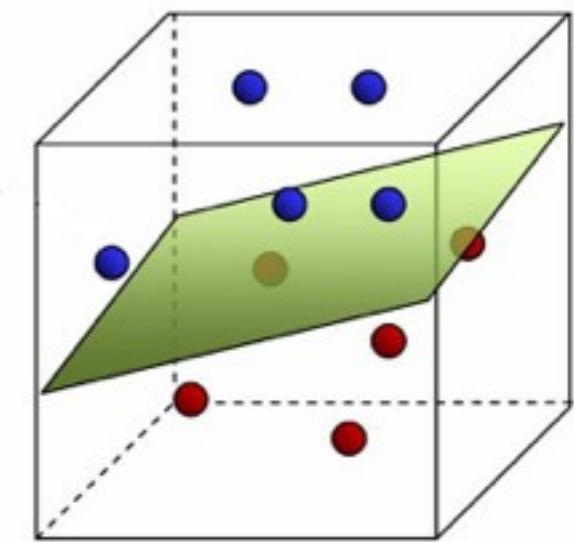
Data analysis



Functional & Structural
connectivity



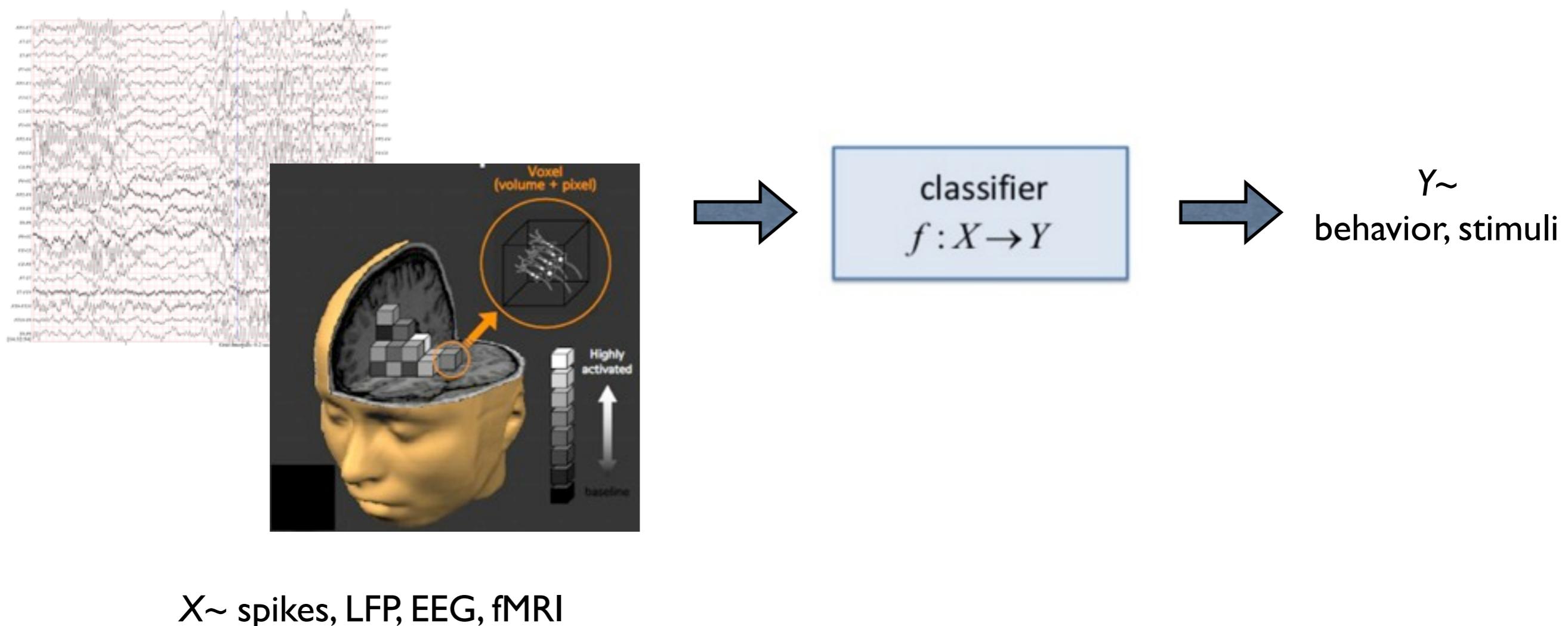
Brain oscillations



Machine learning
(classifiers, regressions)

Machine Learning: algorithms that learn from data

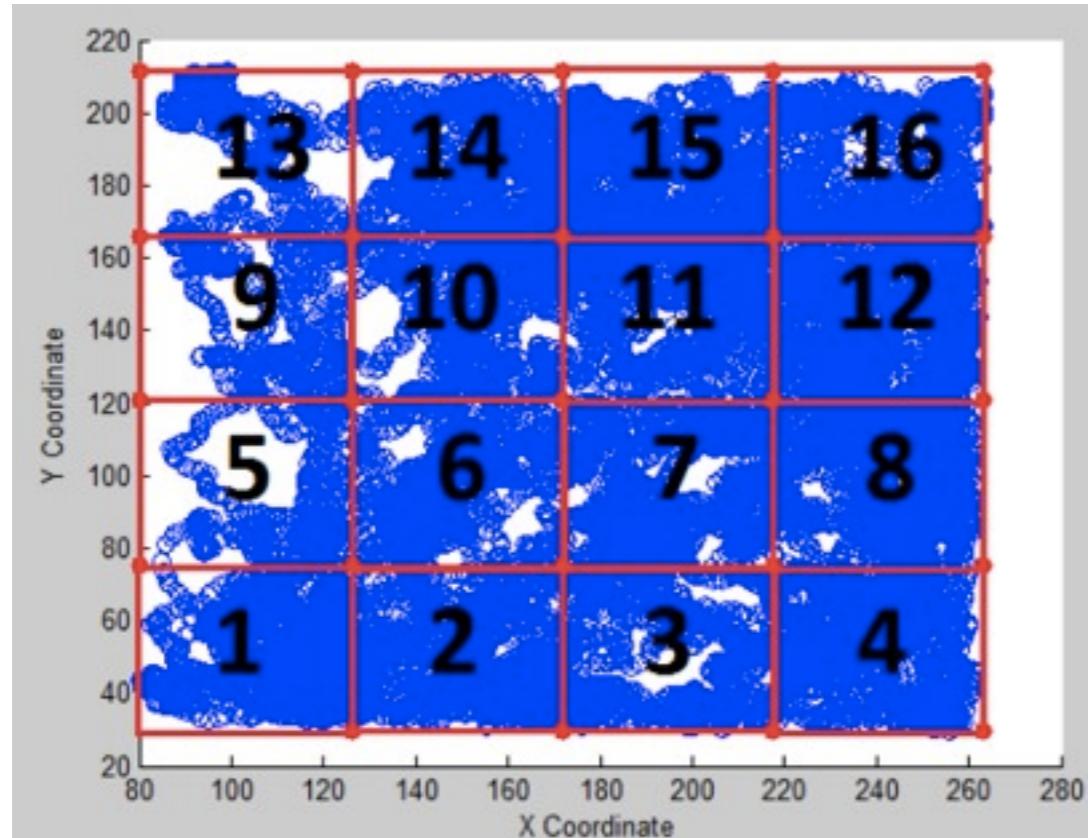
- “Teaches” the algorithm with correct examples to learn the relation between neuronal signals X and behavior Y (or stimulus)
- What? Where? When?





Ardi + Tambet

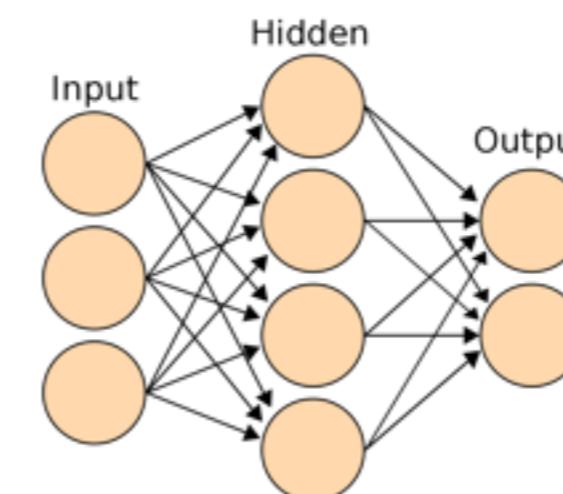
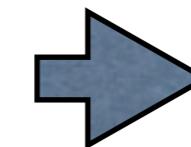
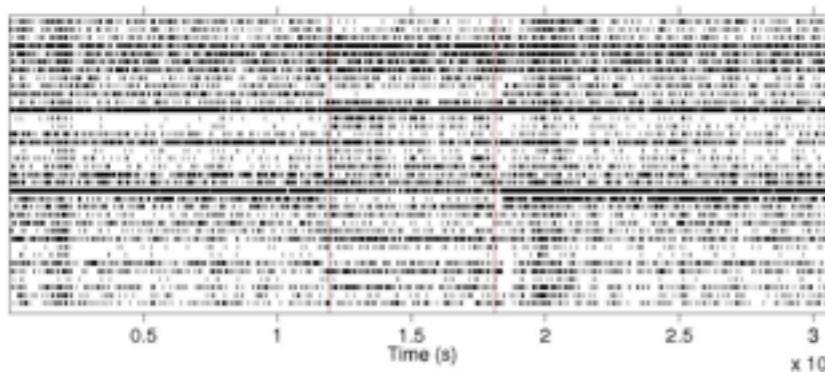
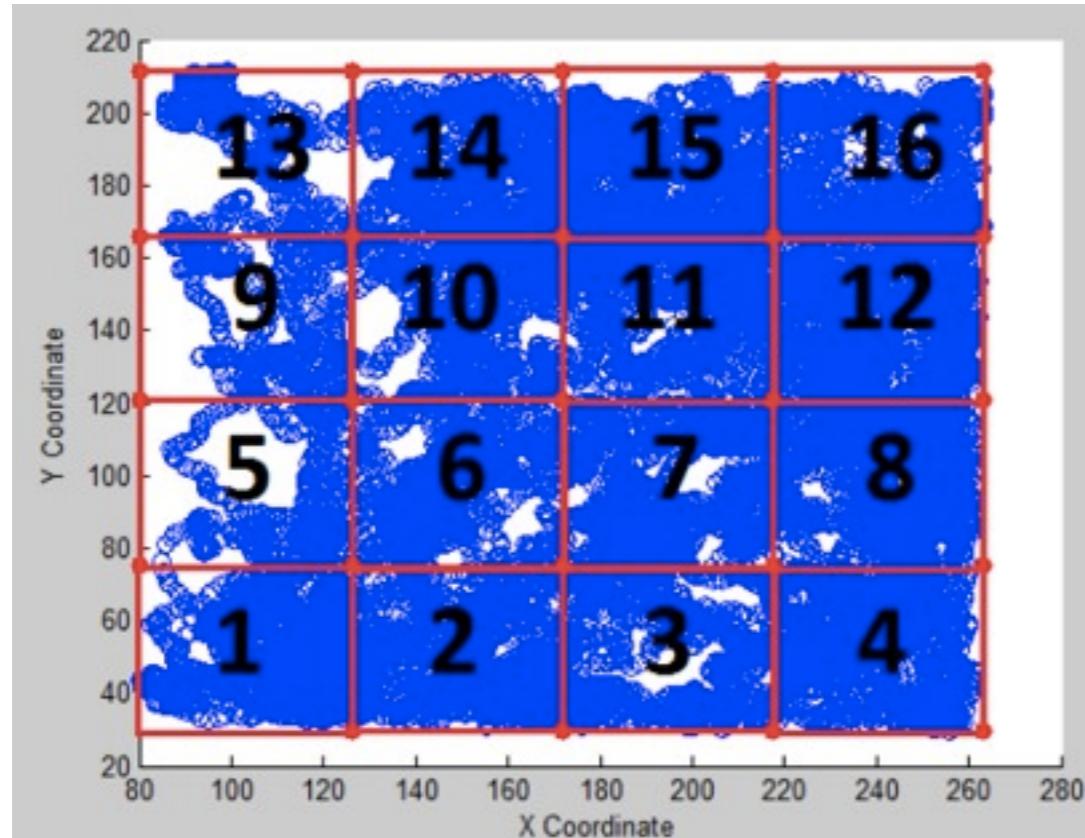
Decoding animal position from brain activity





Ardi + Tambet

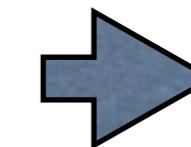
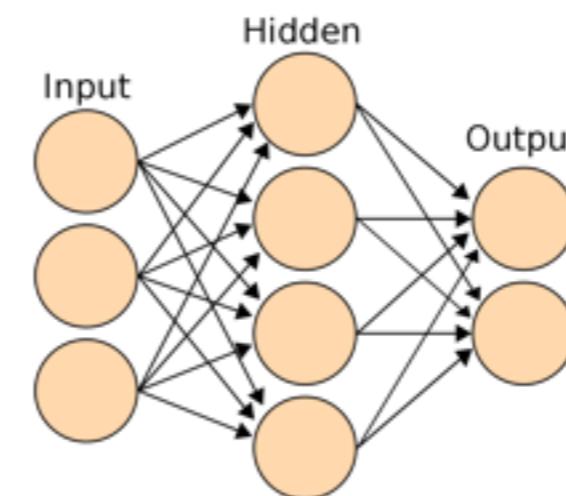
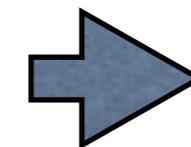
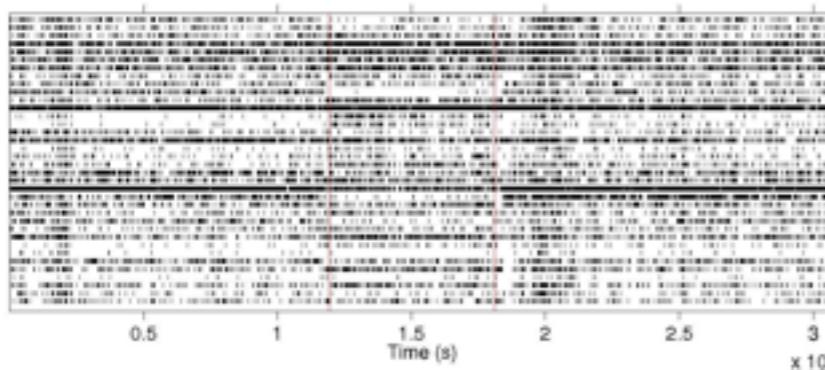
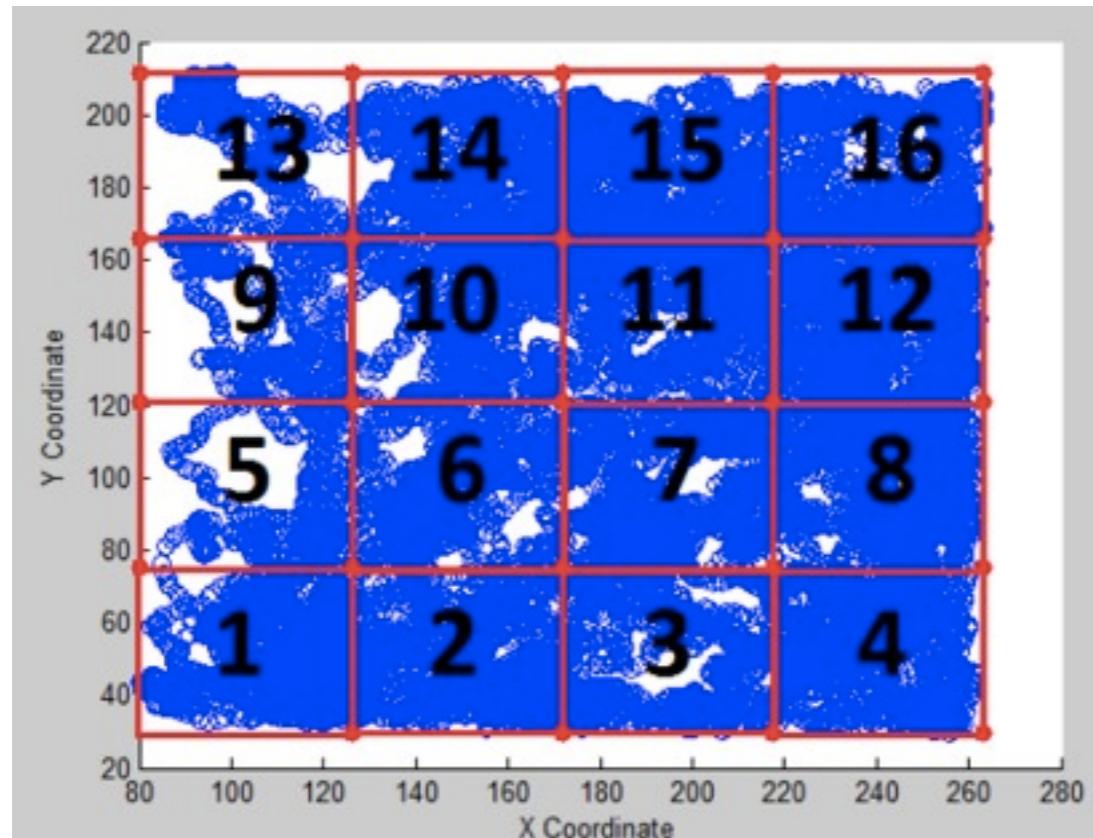
Decoding animal position from brain activity





Ardi + Tambet

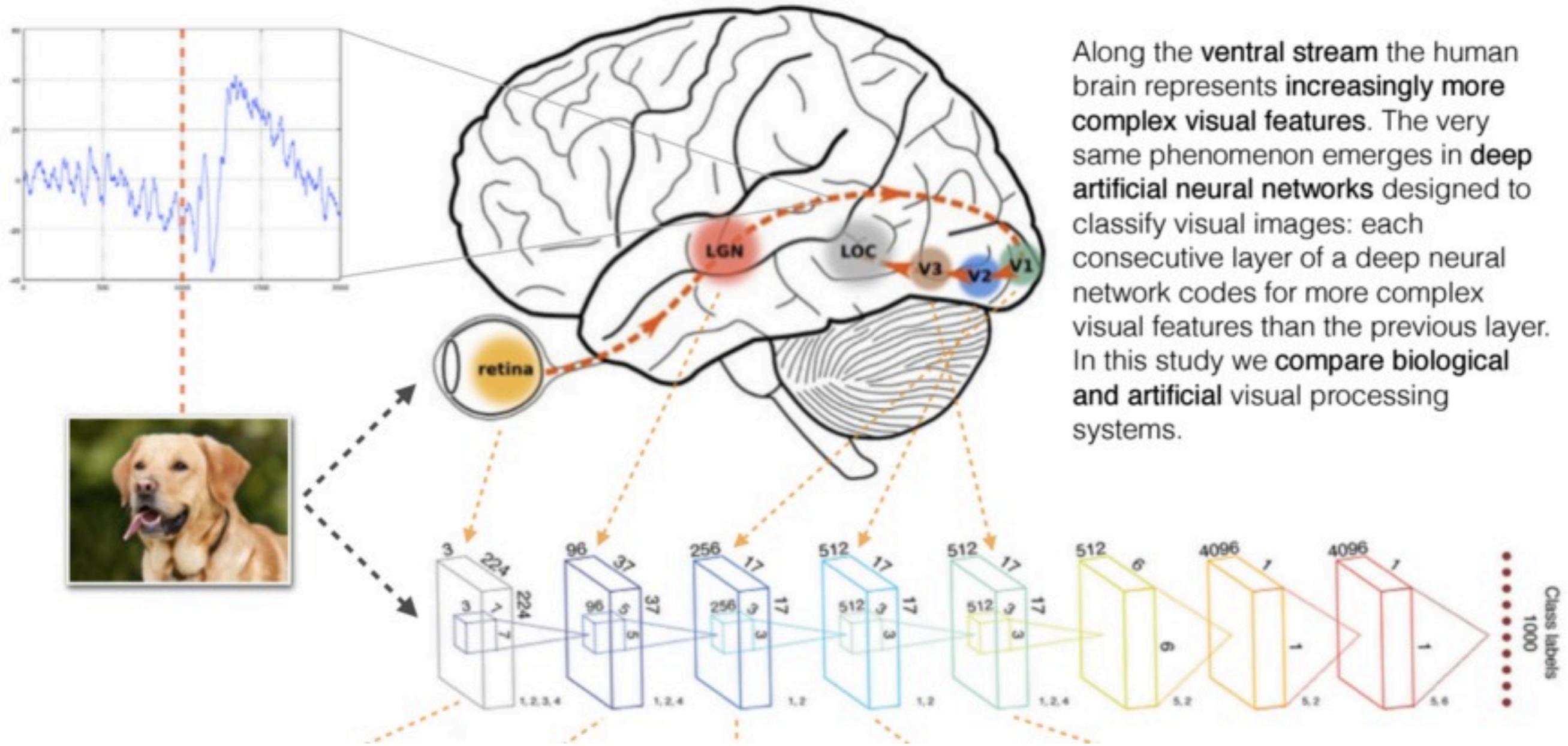
Decoding animal position from brain activity





Ilya

Comparing biological and artificial vision



Playing Atari with Deep Reinforcement Learning



Playing Atari with Deep Reinforcement Learning





Pong



Breakout



Seaquest



Beam Rider



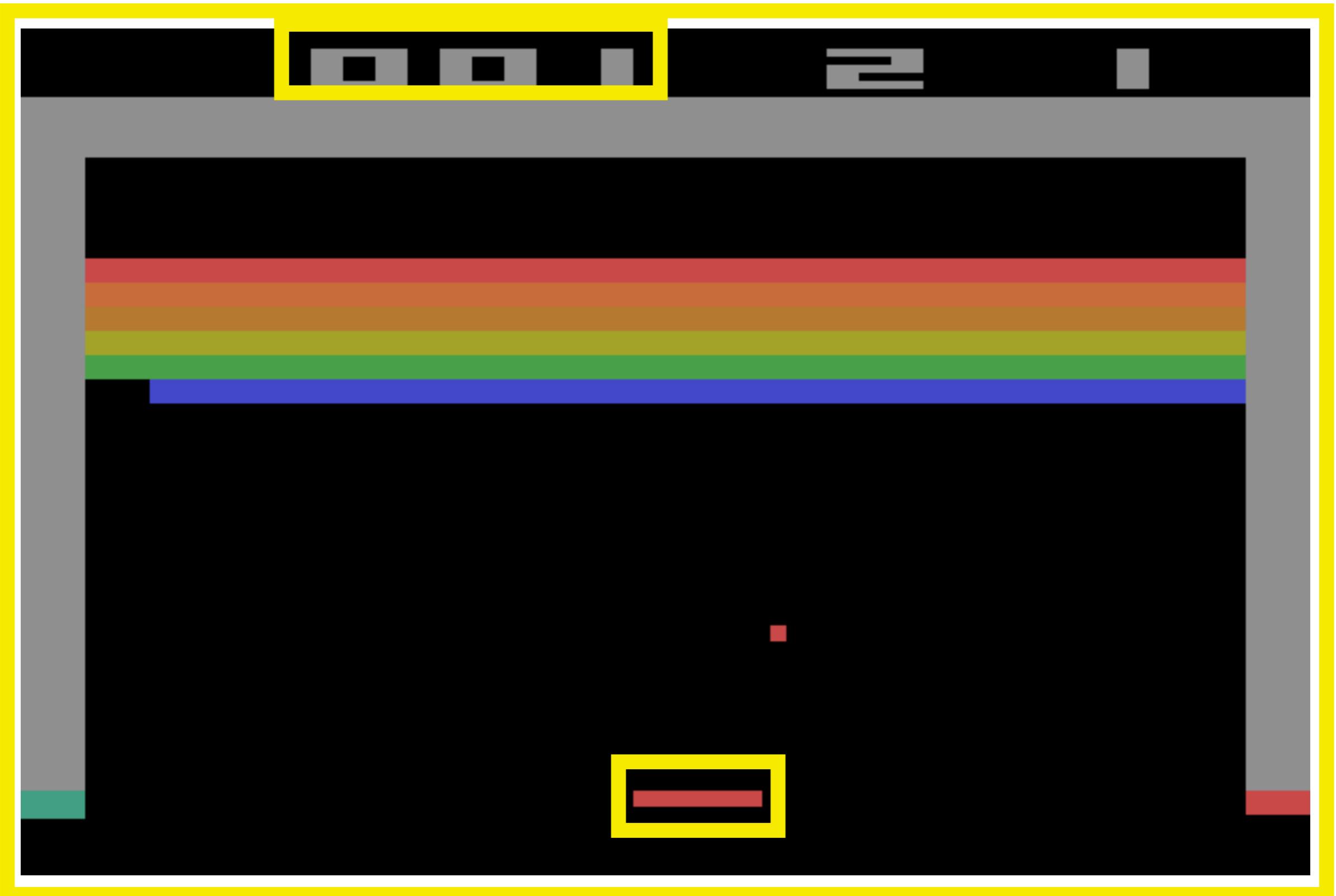
Space Invaders



Enduro

IA that in few hours learns to play better than humans!

Reward



Input

Action



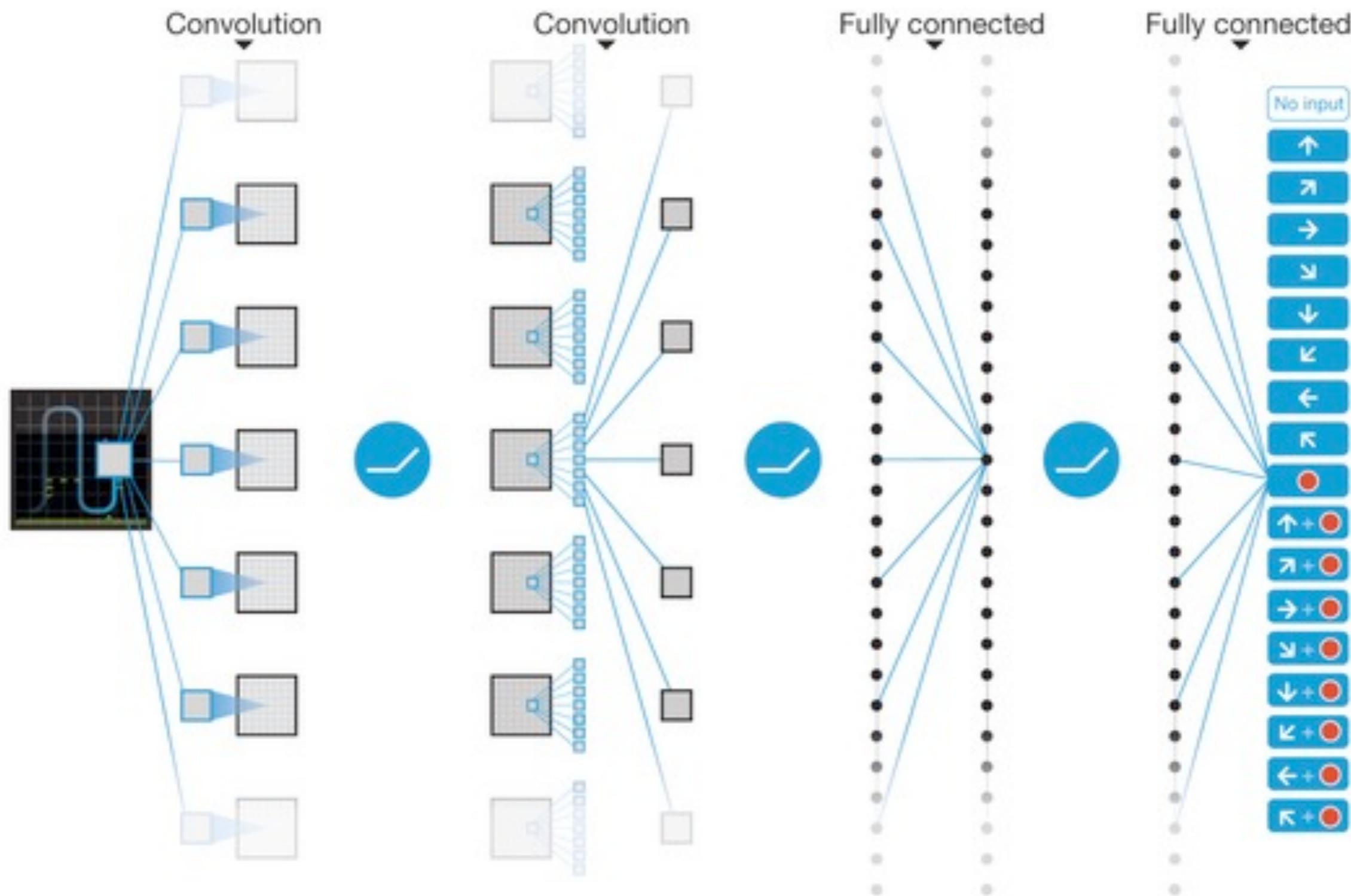


It does not know the game rules, nor what is a ball, nor that blocks can be broken,...



It does not know the game rules, nor what is a ball, nor that blocks can be broken,...

Its only obsession in life is to increase the reward!



Multiagent Cooperation and Competition with Deep Reinforcement Learning

Video: competitive mode of playing

Multiagent Cooperation and Competition with Deep Reinforcement Learning

Video: cooperative mode of playing

Open questions

- How are memories encoded and retrieved?
- What does the activity of the brain at rest represents?
- How do brains simulate the future plans and events?
- What makes human intelligence different?
- Why do brains sleep and dream?
- What is consciousness?

To know more

From computer to brain: Foundations of computational neuroscience, William W. Lytton, Springer, 2002

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