# Computational Neuroscience Introduction Day

- 9.30am Introduction (C.Machens)
- 10am M1 (C.Machens)
- 10.15am M2 (V. Hakim)
- 10.40 break
- 11.00 Matching Law (S. Deneve)
- 11.20 Rescorla-Wagner Learning (C. Machens)
- 11.40 Reinforcement Learning (J.-P. Nadal)
- 12.00-14.00 Lunch break + paper reading
- 14.00 Student presentations

# Computational Neuroscience: How does the brain work?

Christian Machens
Group for Neural Theory
Ecole normale supérieure Paris

# What's the brain good for?

Tree
no neurons

# What's the brain good for?

Tree
no neurons

C. elegans
302 neurons

brains generate motion
( = behavior)

# What's the brain good for?

Tree
no neurons

C. elegans
302 neurons

Fly
1 000 000

more complex brains generate a greater variety of behaviors

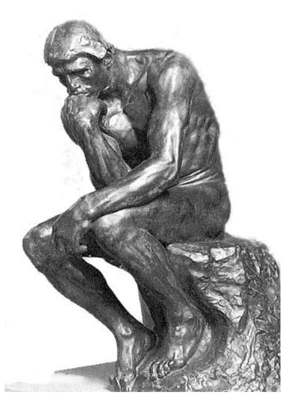
# What's the brain good for?

Tree
no neurons

C. elegans
302 neurons

Fly
1 000 000

Rat
1 000 000 000



Human
100 000 000 000

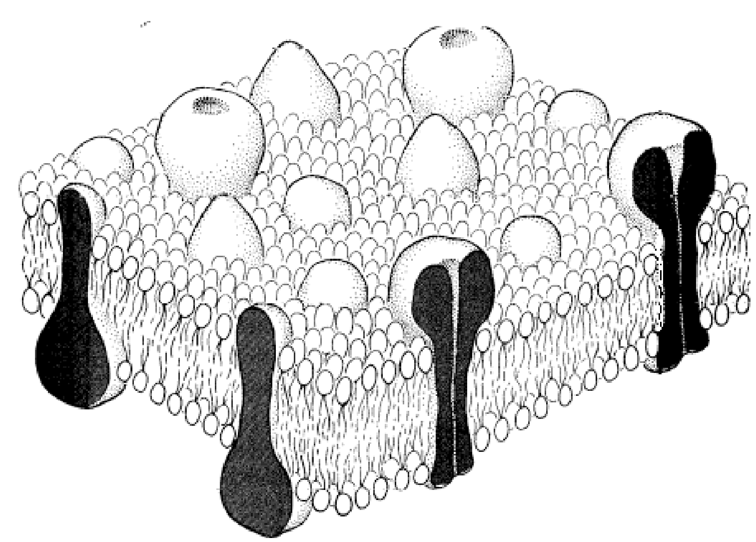
more complex brains generate a greater variety of behaviors

more complex brains can learn more behaviors

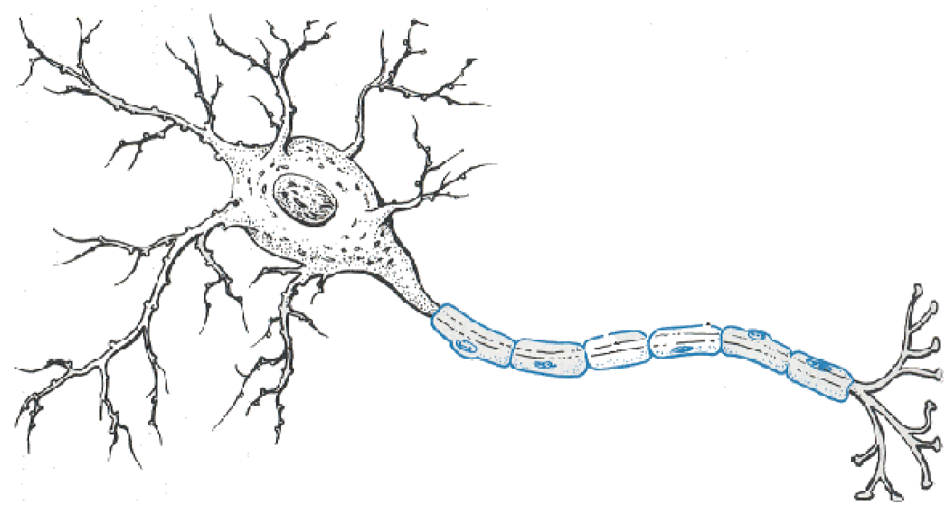
# What's the brain made of?

Molecules

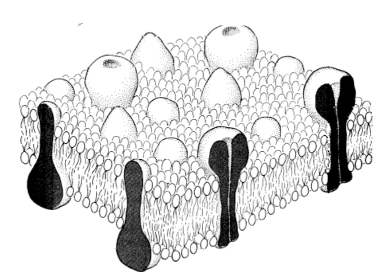
1 nm



# What's the brain made of?

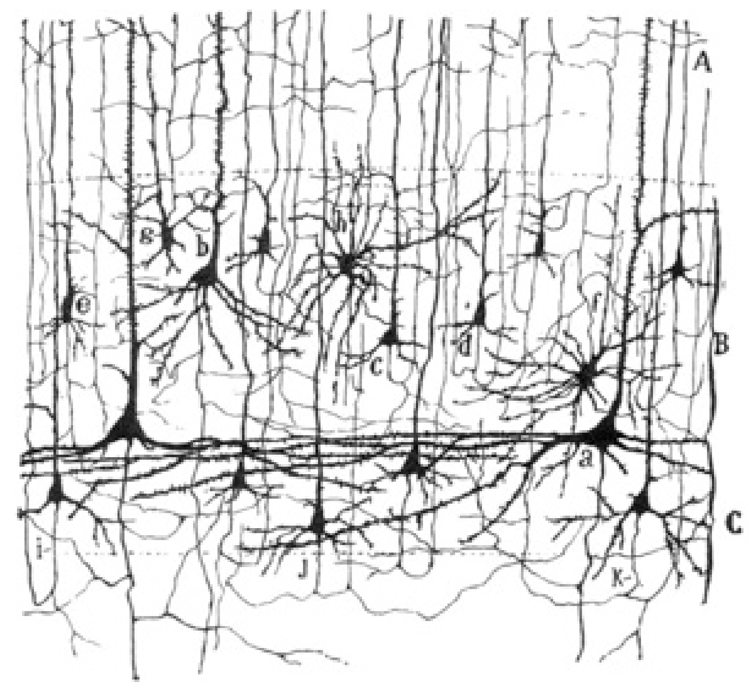


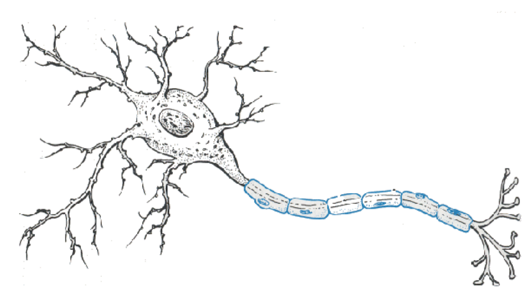
| | |
|---|---|
| Neurons | 100 μm |
| Synapses | 1 μm |
| Molecules | 1 nm |

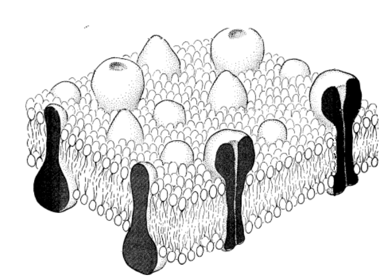


# What's the brain made of?

| | |
|---|---|
| Maps | 1 cm |
| Networks | 1 mm |
| Neurons | 100 μm |
| Synapses | 1 μm |
| Molecules | 1 nm |







# What's the brain made of?

| | |
|---|---|
| CNS | 1 m |
| Systems | 10 cm |
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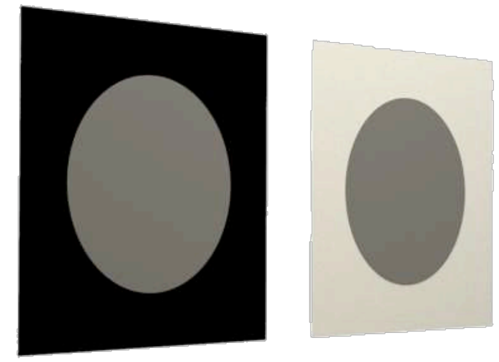

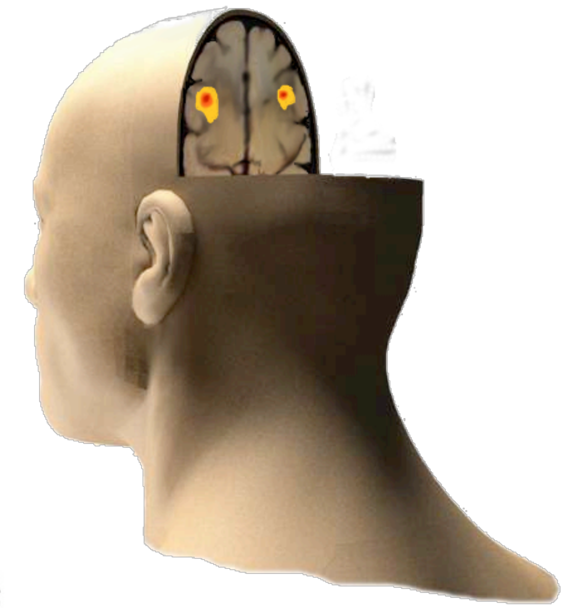

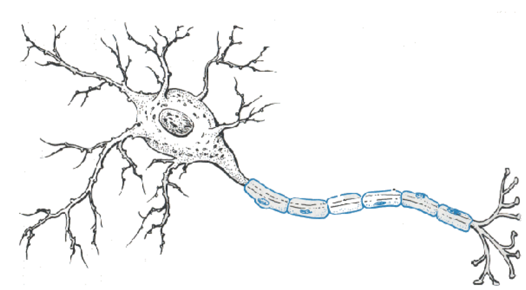

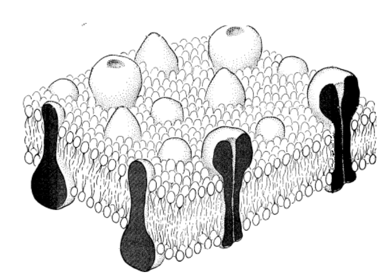

# A physics/engineering approach

Just rebuild the whole thing

# The quest for mechanisms: Constructing systems from parts

| | |
|---|---|
| CNS | 1 m |
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# The quest for mechanisms: Constructing systems from parts

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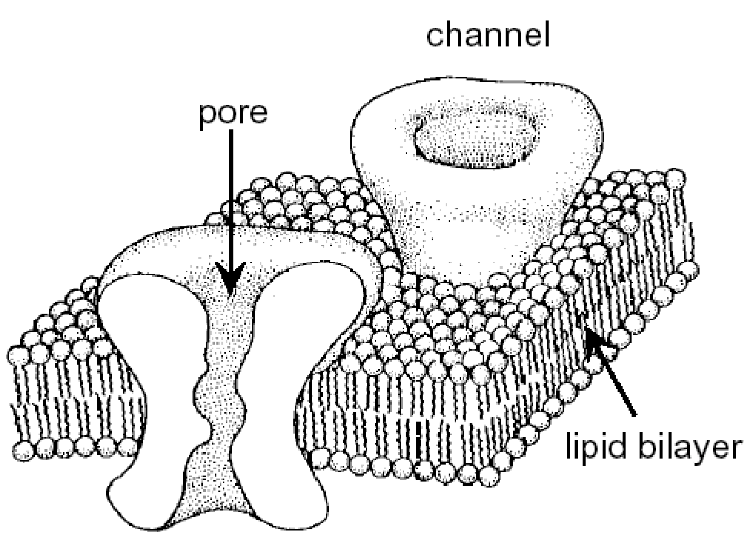
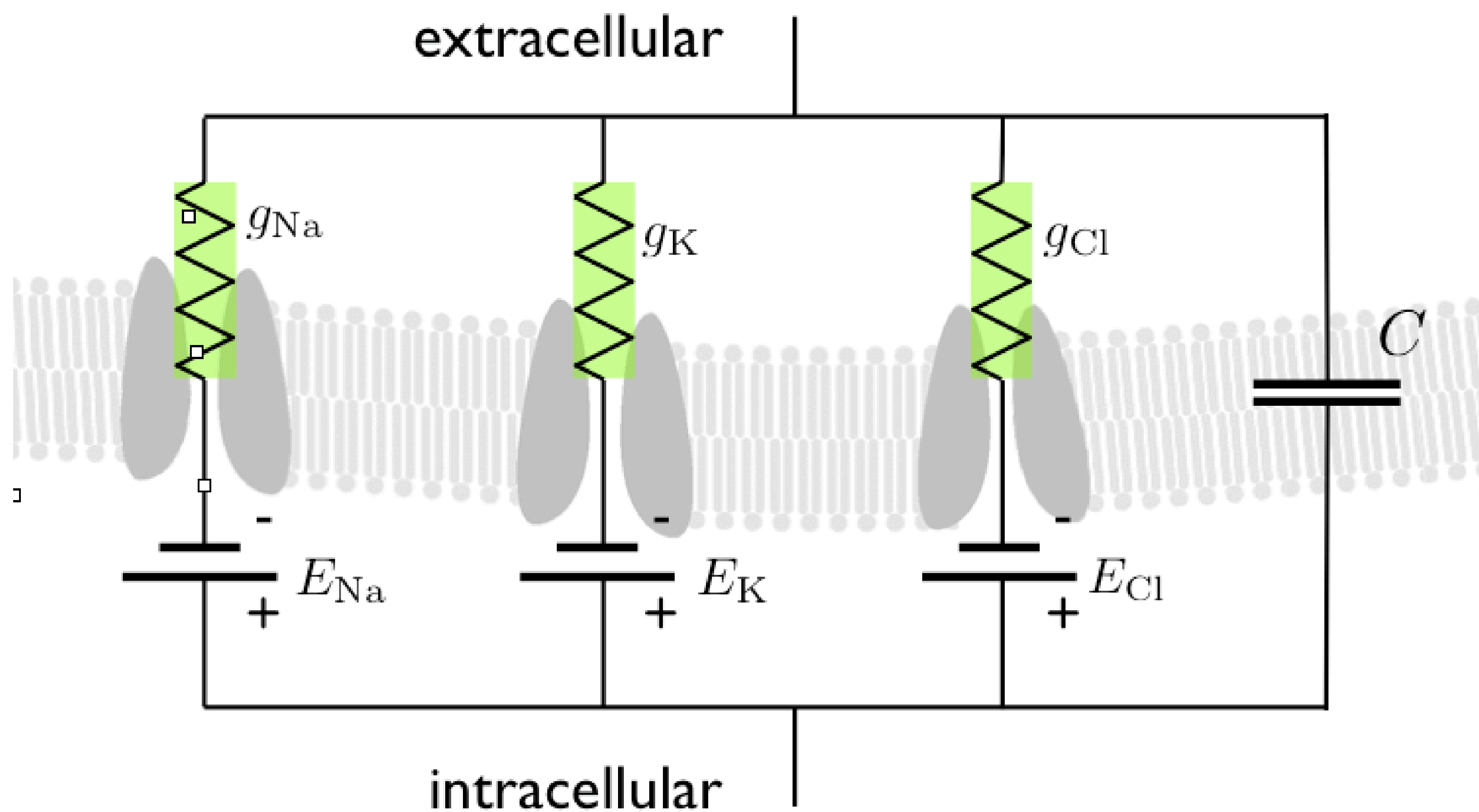
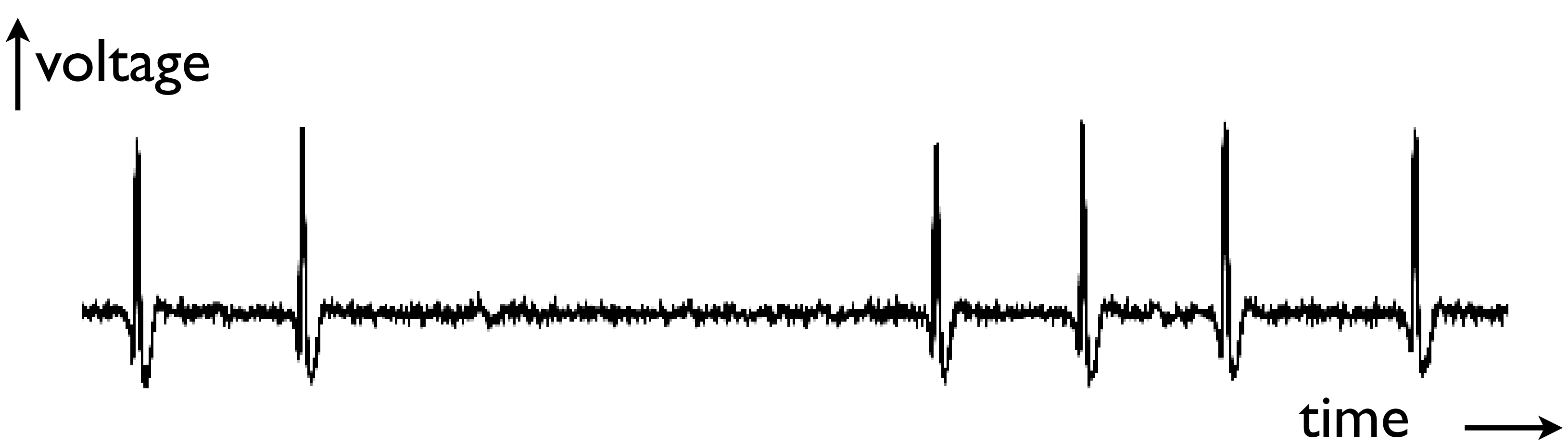
# Biophysics of the membrane voltage:

## The Hodgkin-Huxley Model

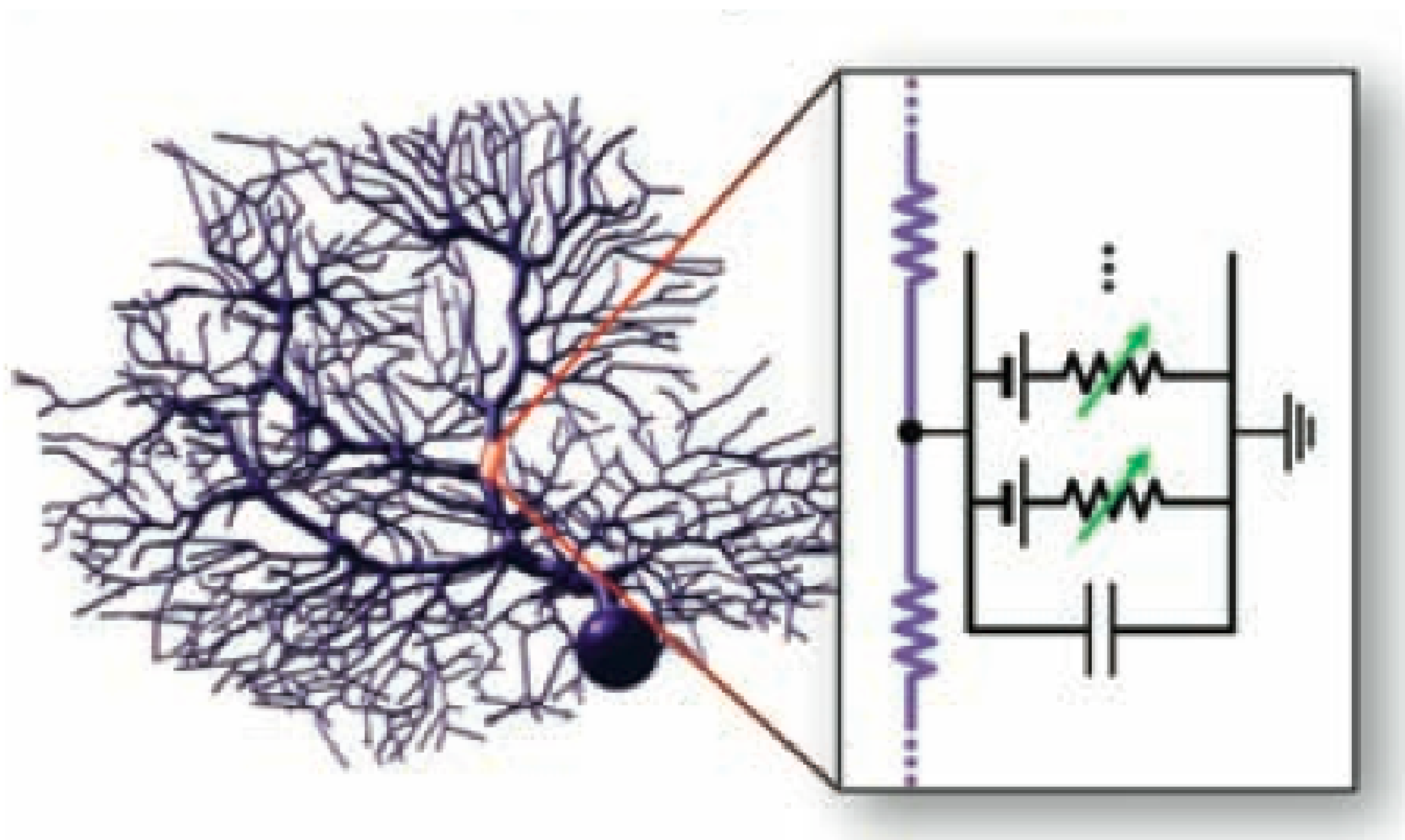


# Reconstructing neurons:

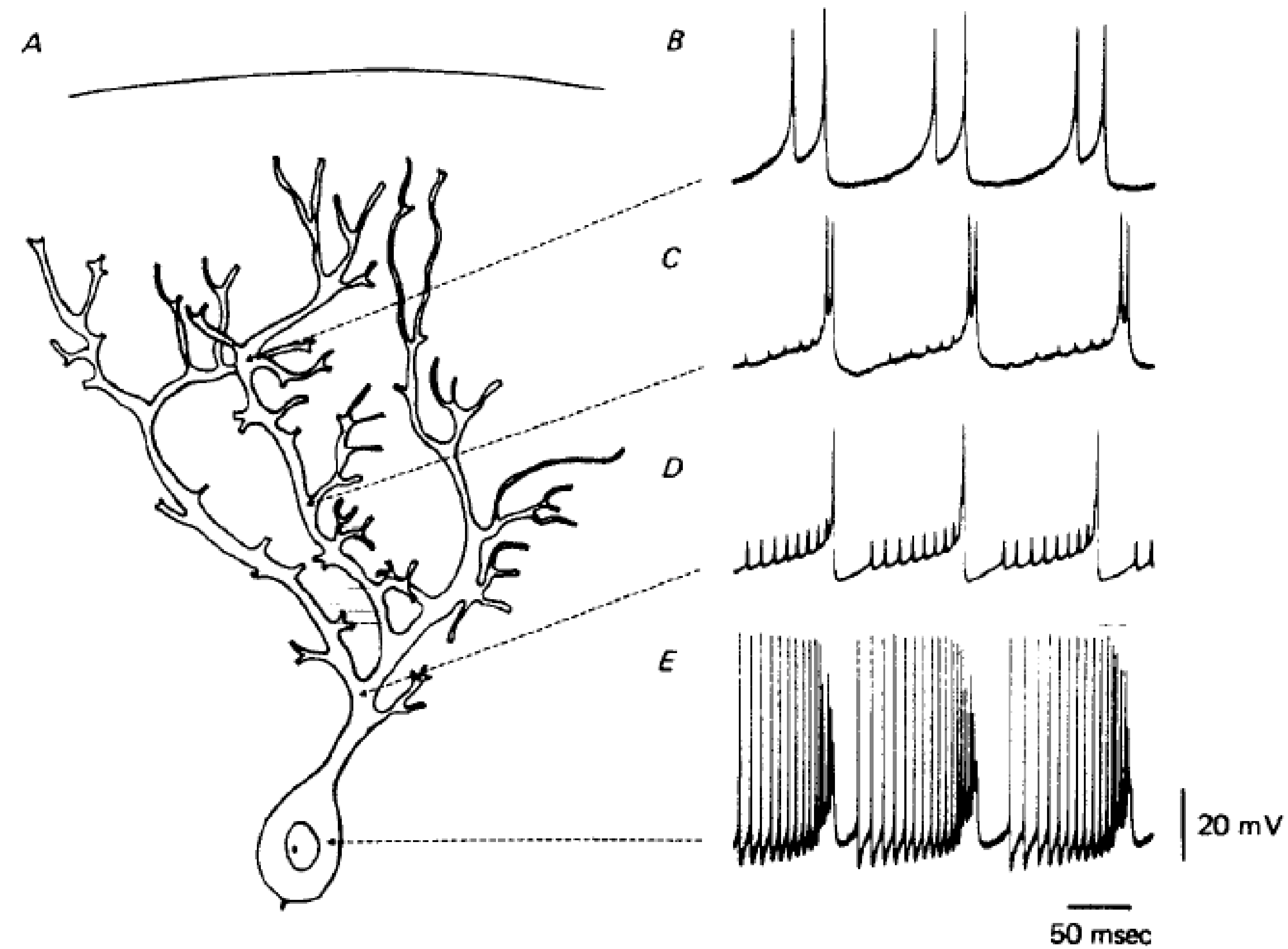
## Ralls' cable theory and compartmental modeling



Detailed compartmental models of single neurons:
Large-scale differential equation models

# Reconstructing neurons

## Simulating the membrane potential




Llinas & Sugimori (1980)

# The quest for mechanisms: Constructing systems from parts

| | |
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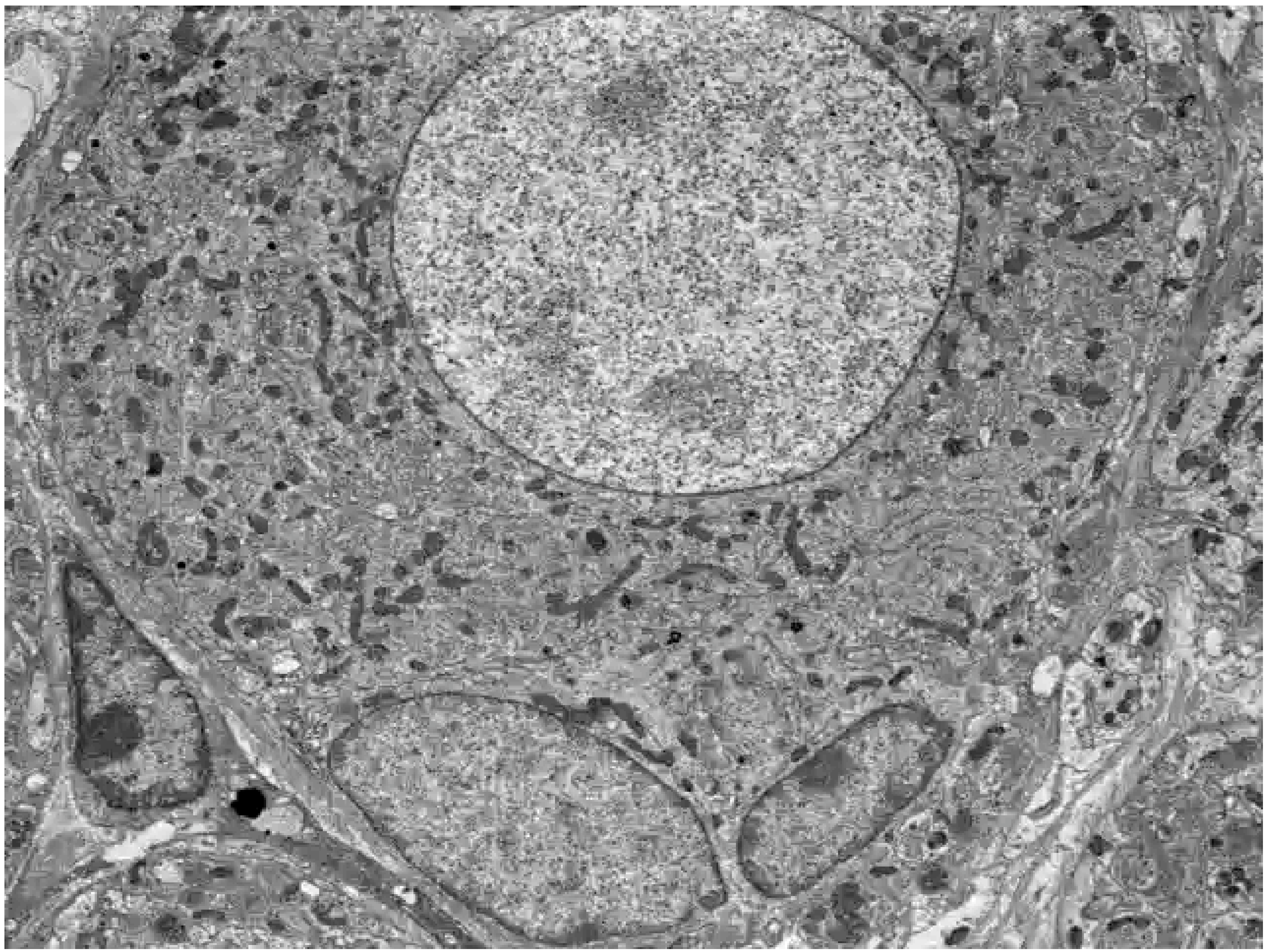
# Reconstructing circuits

## Electron microscopy and brute-force simulations



courtesy of W.Denk

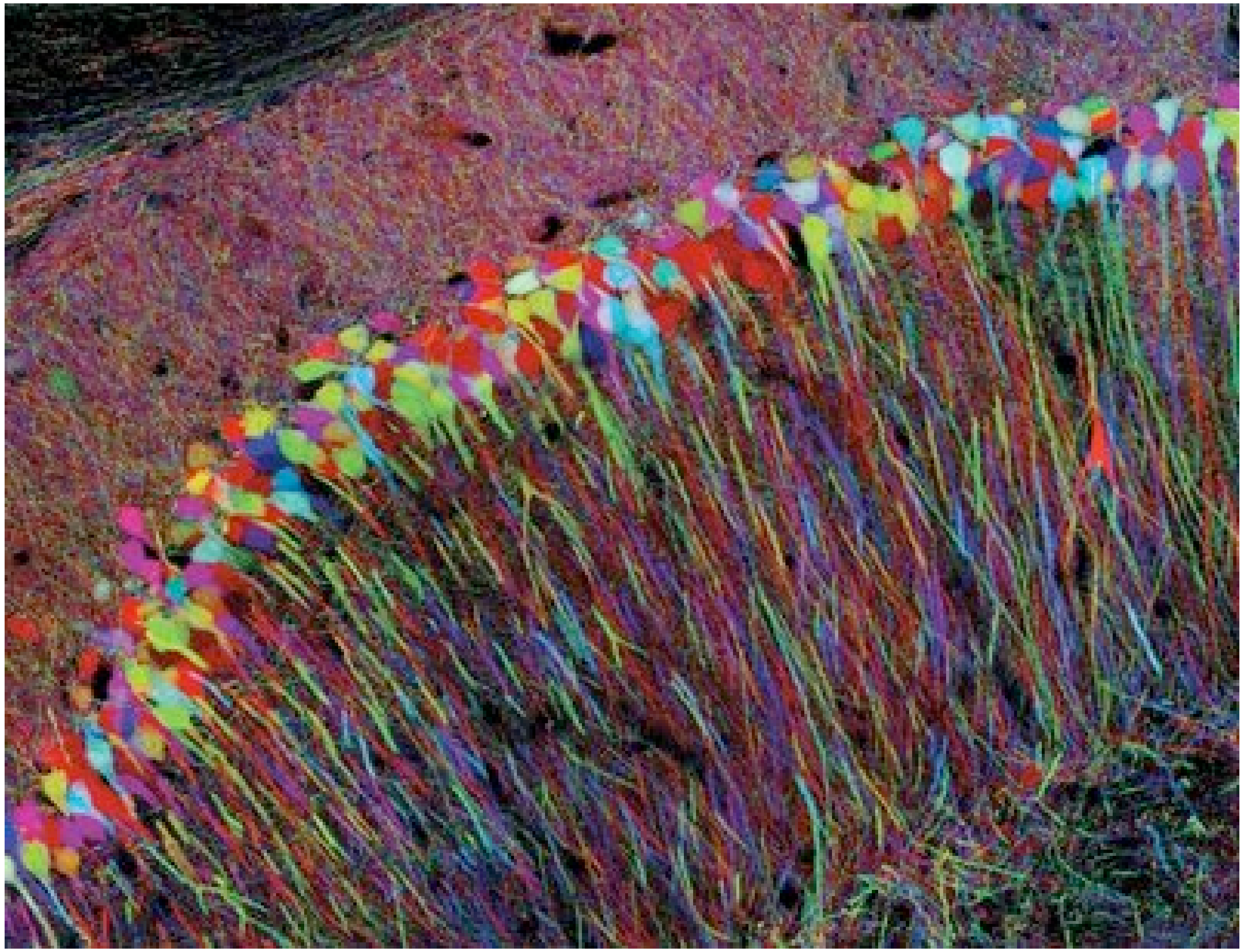
# Reconstructing circuits

## Electron microscopy and brute-force simulations

Scan brain slices and reconstruct the circuit... "connectonomics"

H. Markram (Lausanne):
"blue-brain project"
B. Sakmann/ W. Denk (Heidelberg)
J. Lichtman (Harvard)
H.S. Seung (MIT)

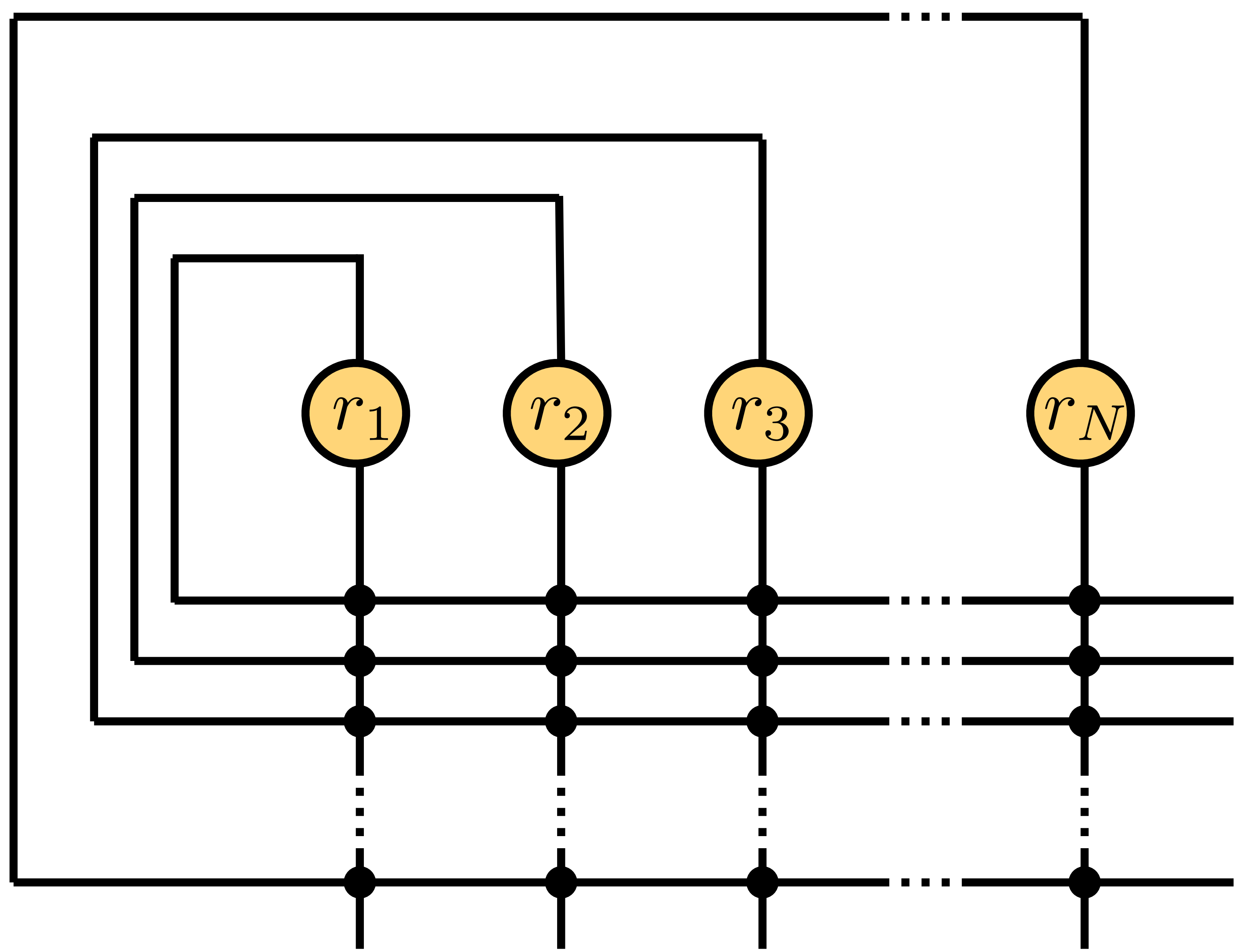
but: the devil is in the details and when it comes to connectivity, details matter!



# Theory of neural networks

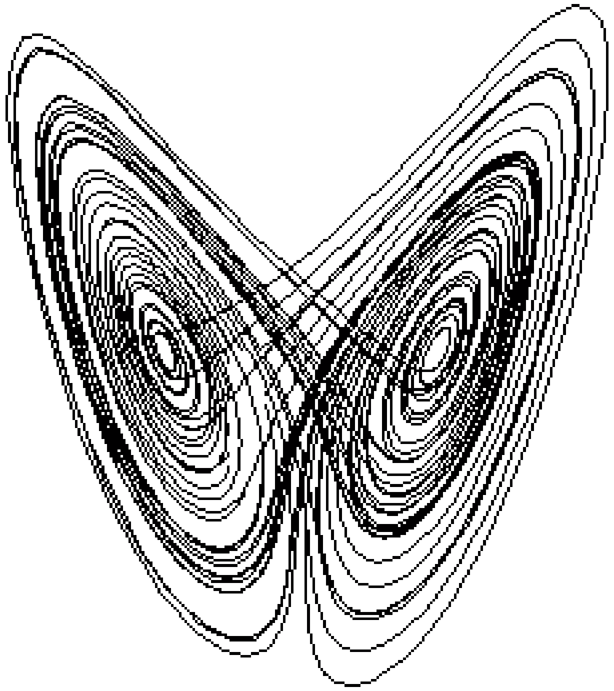
Neurons, synapses ➡ network activity

$$\dot{r}_i = -r_i + f(\sum_{j=1}^{N} w_{ij} r_j + I_i)$$



# Network dynamics largely determined by connectivity

$$\dot{r}_i = -r_i + f(\sum_{j=1}^{N} w_{ij} r_j + I_i)$$



Possible dynamics:

- stable/ unstable fixed points
- limit cycles
- chaotic attractors

Note: different attractors can co-exist in different parts of the state space!

For $N \to \infty$

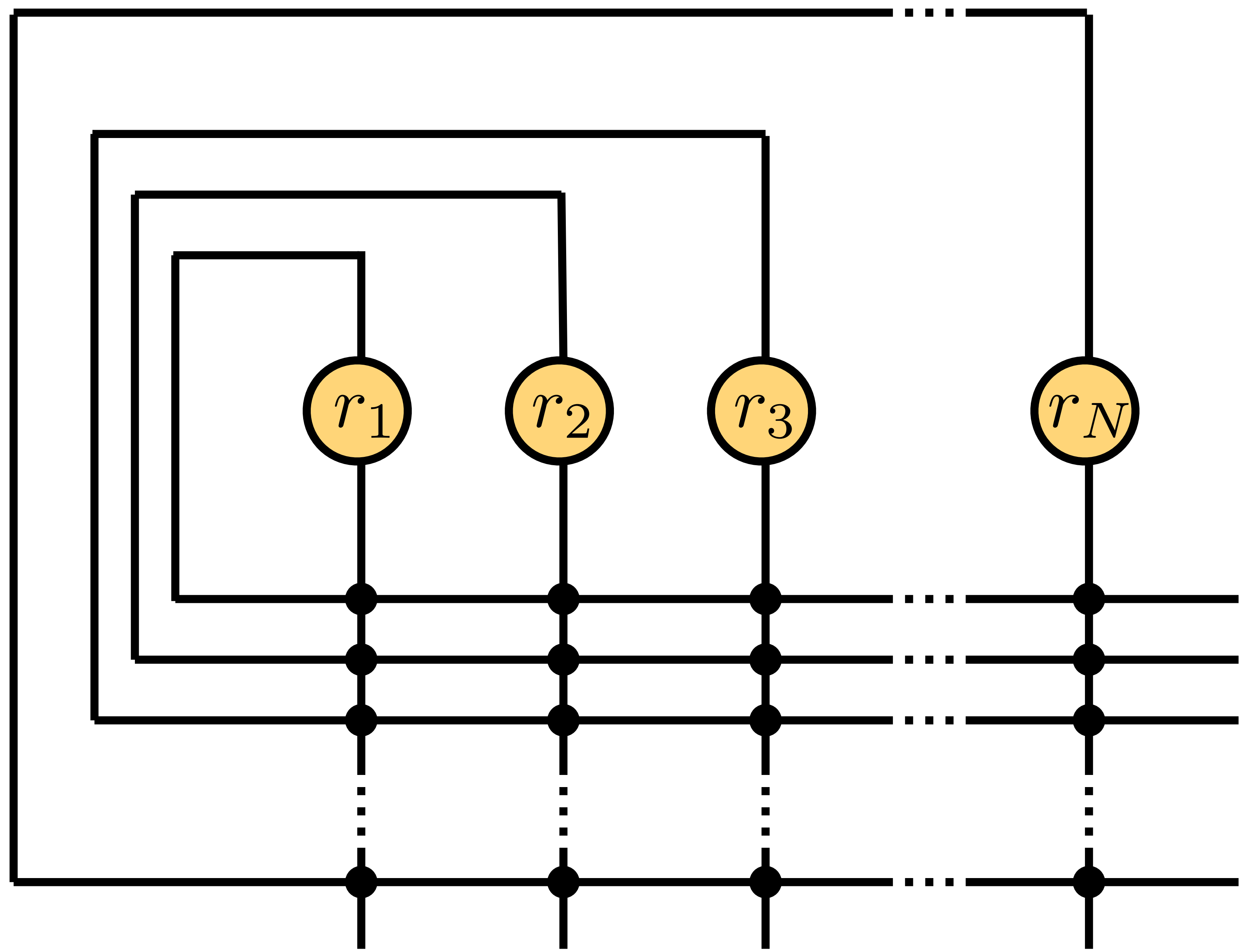
- neural networks can compute anything

# (Statistical) theory of neural networks

Neurons, synapses ➡ network activity

Under what conditions do you get

- only fixed points
- synchronous activity
- asynchronous activity
- Poisson spike trains
- oscillations
- spatial patterns
- ...



# The quest for mechanisms: Constructing systems from parts

| | |
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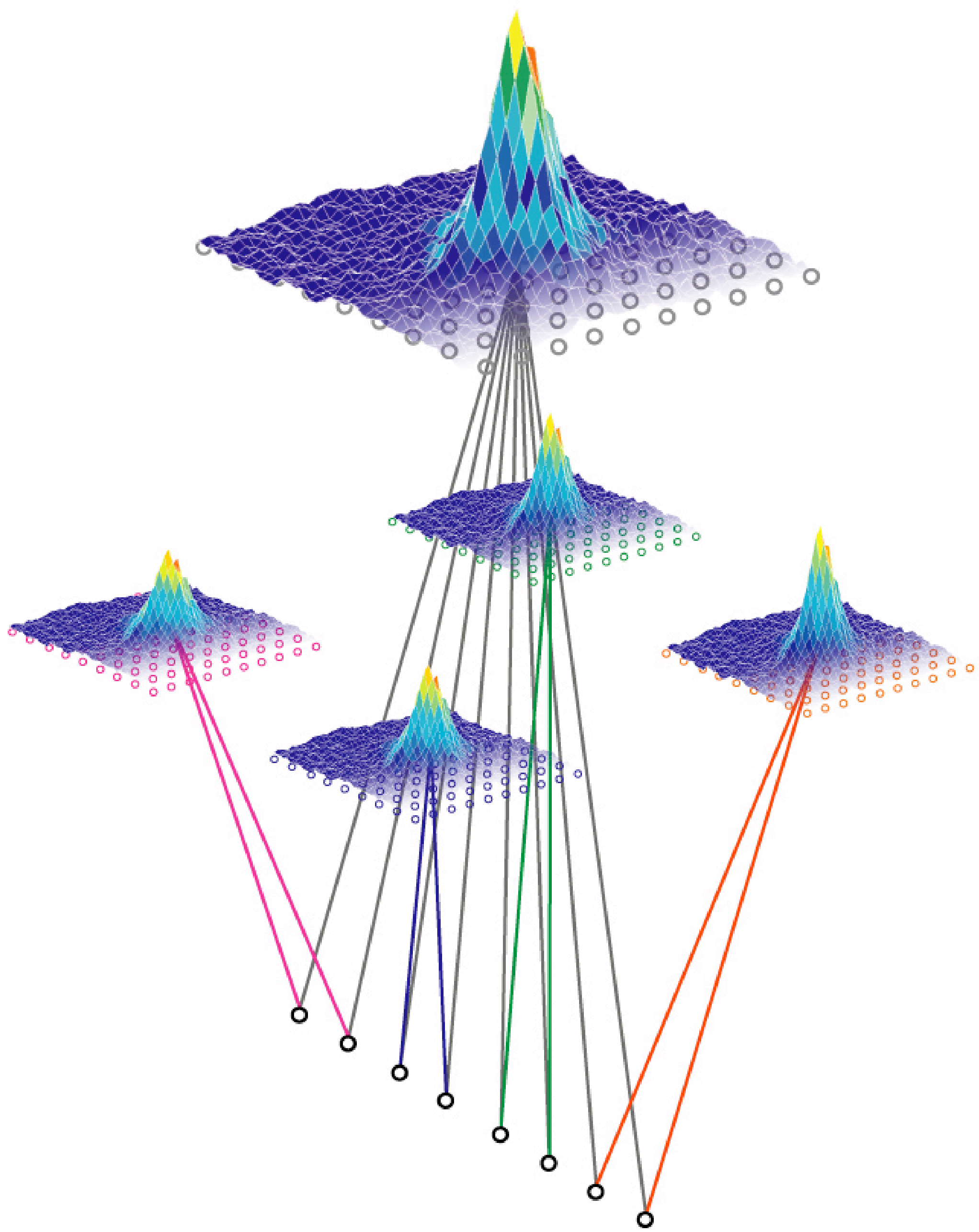
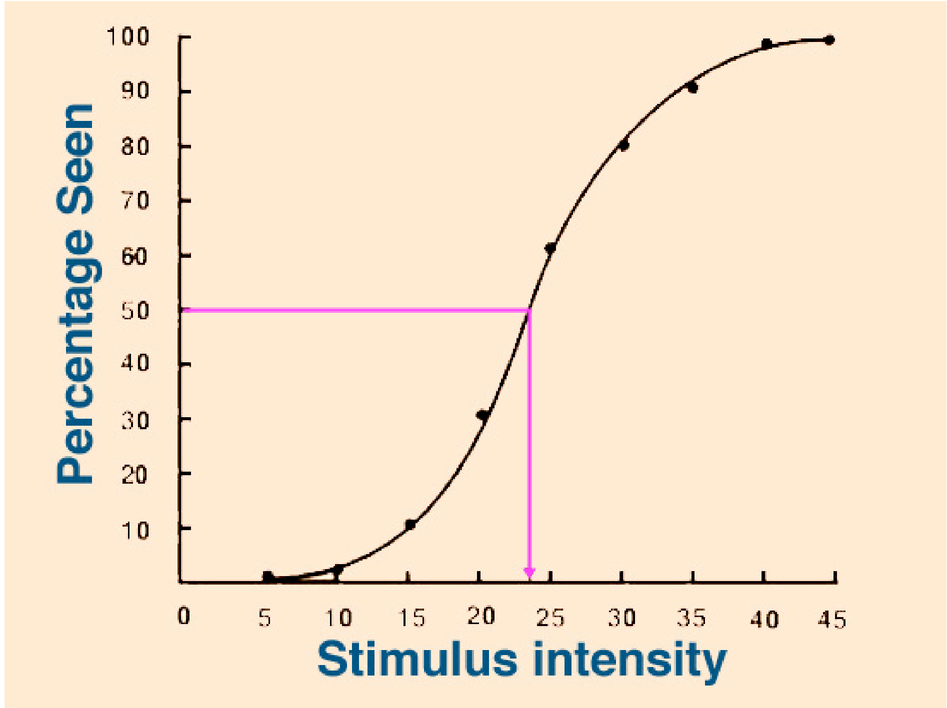
# Connectionist models: From networks to behavior

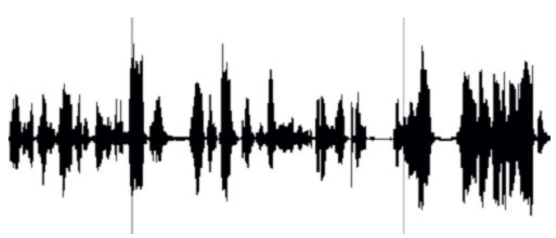




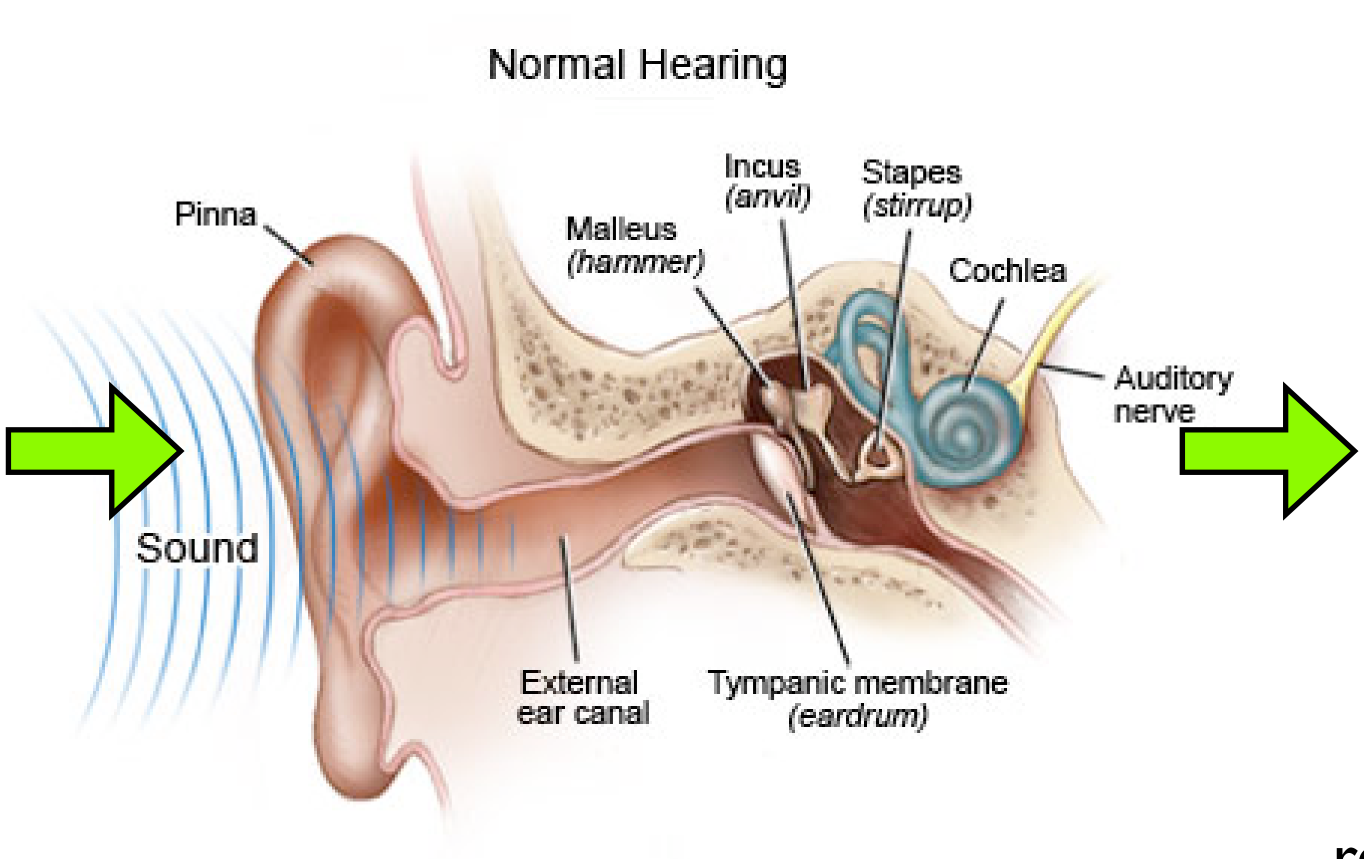
# A computer science approach

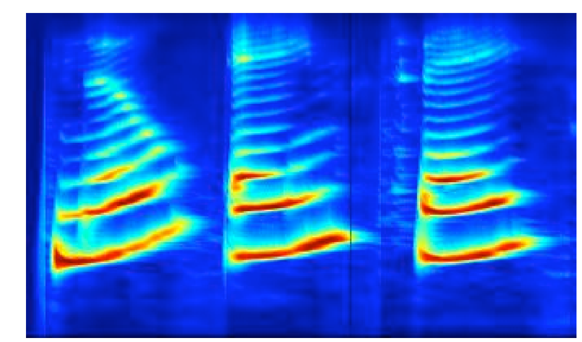
Study the computational problems

# Computation: manipulating information



sound pressure wave



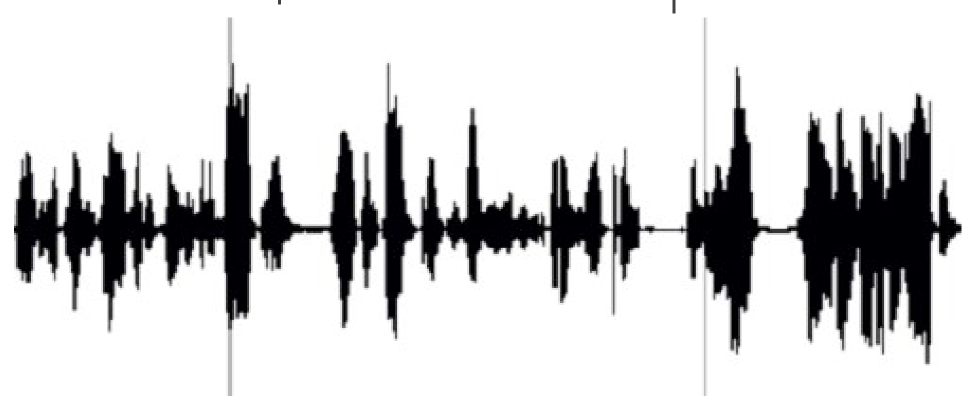
cochleogram
(time-frequency
representation of sound)

# Representation of information, more or less lossy

Example music:

sheet notes

Sound



CD

Language

The other day, I heard this cool jazz CD with this drummer...

# Why represent information differently?

Example numbers:

| | |
|---|---|
| `XXIII` | Roman System |
| `23` | Decimal System |
| `00010111` | Binary System |

# Representations make information explicit

Example numbers:

| | |
|---|---|
| `XXIII` | mixed decomposition |
| `23` | powers of 10 |
| `00010111` | powers of 2 |

Can you divide this number by 10?

| | |
|---|---|
| `100` | Decimal System |

# Representations make information explicit

Example numbers:

| | |
|---|---|
| `XXIII` | mixed decomposition |
| `23` | powers of 10 |
| `00010111` | powers of 2 |

Can you divide this number by 10?

| | |
|---|---|
| `C` | Roman System |
| `100` | Decimal System |
| `01100100` | Binary System |

# Representations allow for easier algorithms

Example numbers:

| | |
|---|---|
| `XXIII` | in ...? |
| `23` | in multiples of 10 |
| `00010111` | in multiples of 2 |

Can you add these numbers?

```
   29        00011101       XXIX
+ 33      + 00100001   + XXXIII
----      ----------   --------
```

# Representations allow for easier algorithms

Example numbers:

| | |
|---|---|
| `XXIII` | in ...? |
| `23` | in multiples of 10 |
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Can you add these numbers?

```
   29       00011101       XXIX
 + 33     + 00100001   + XXXIII
 ----     ----------   --------
   62
```

# Representations allow for easier algorithms

Example numbers:

| | |
|---|---|
| `XXIII` | in ...? |
| `23` | in multiples of 10 |
| `00010111` | in multiples of 2 |

Can you add these numbers?

```
   29        00011101        XXIX
 + 33      + 00100001    + XXXIII
 ----      ----------    --------
   62        00111110
```

# Representations can ease certain computations

Example numbers:

| | |
|---|---|
| XXIII | in ...? |
| 23 | in multiples of 10 |
| 00010111 | in multiples of 2 |

Can you add these numbers?

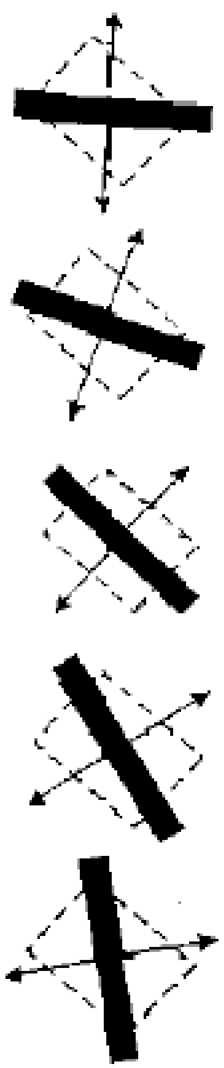
```
   29        00011101        XXIX
+  33      + 00100001    + XXXIII
-----      ----------    --------
   62        00111110
```

easy

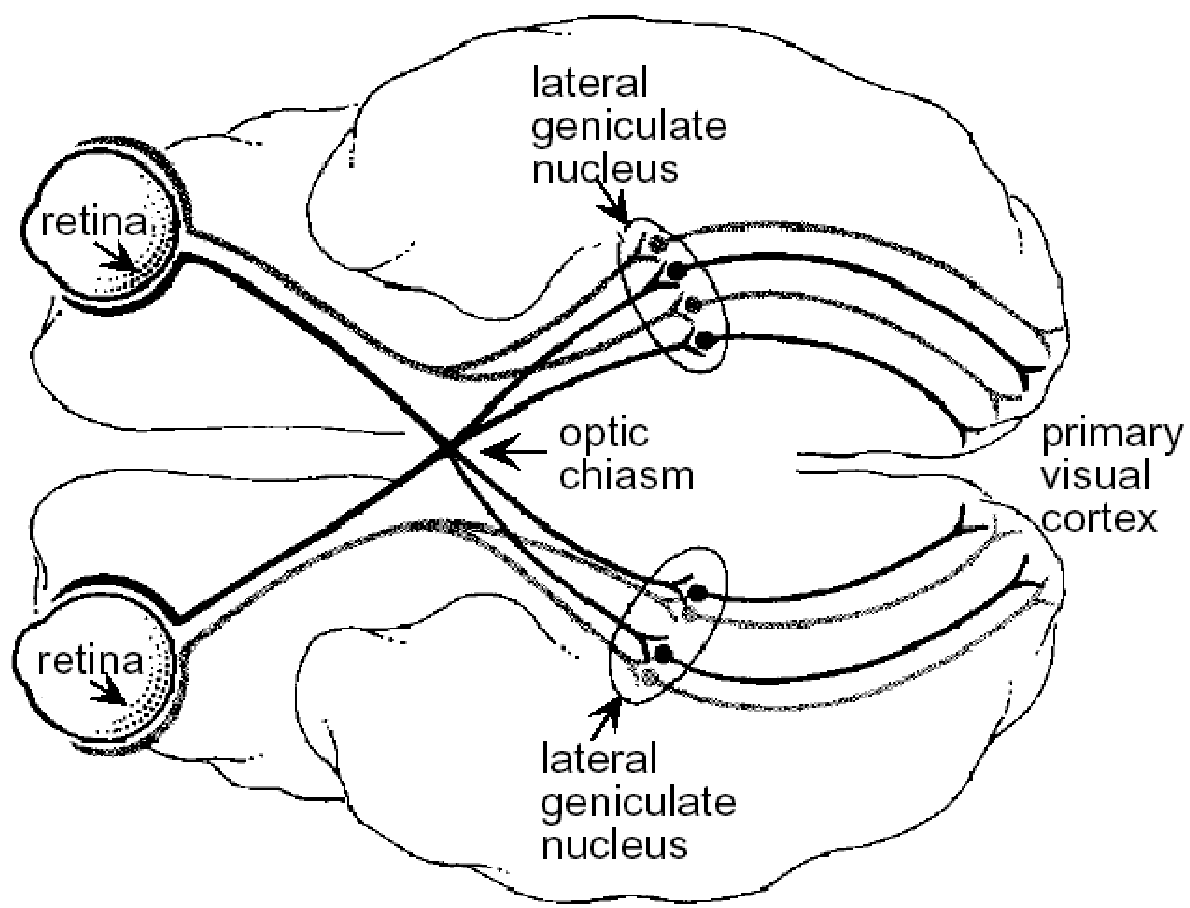
easy

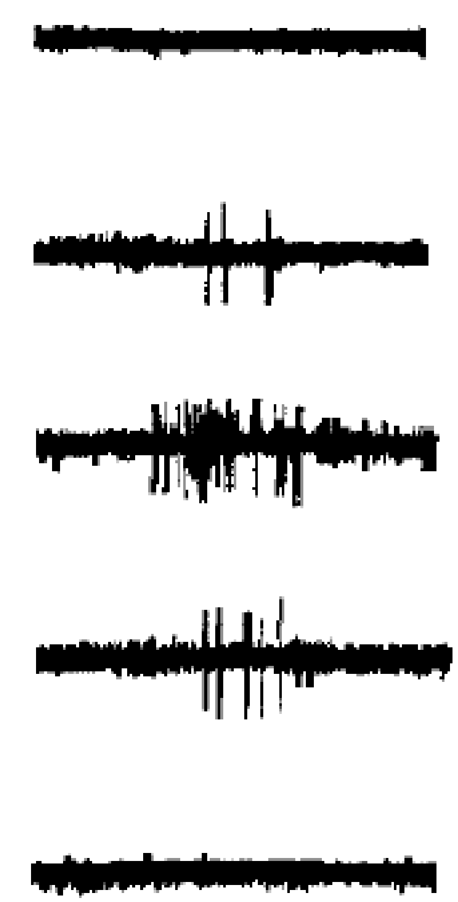
difficult

# Most famous example: “edge detectors” in visual system



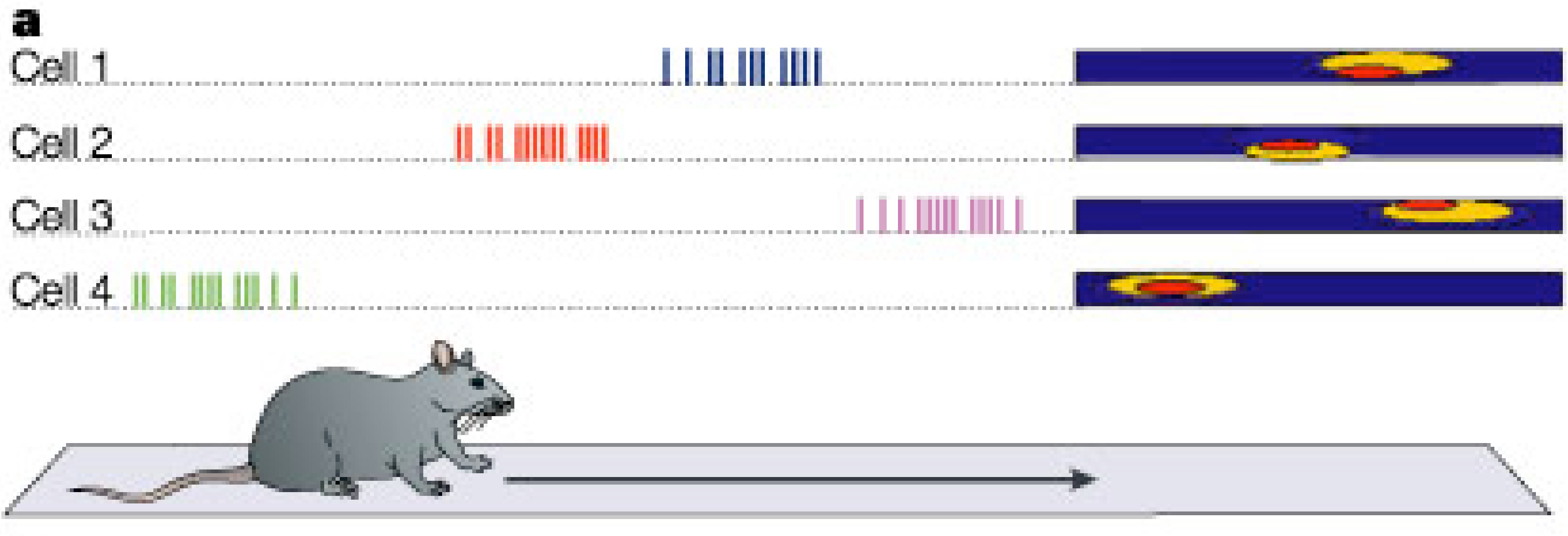
Stimulus:
black bar

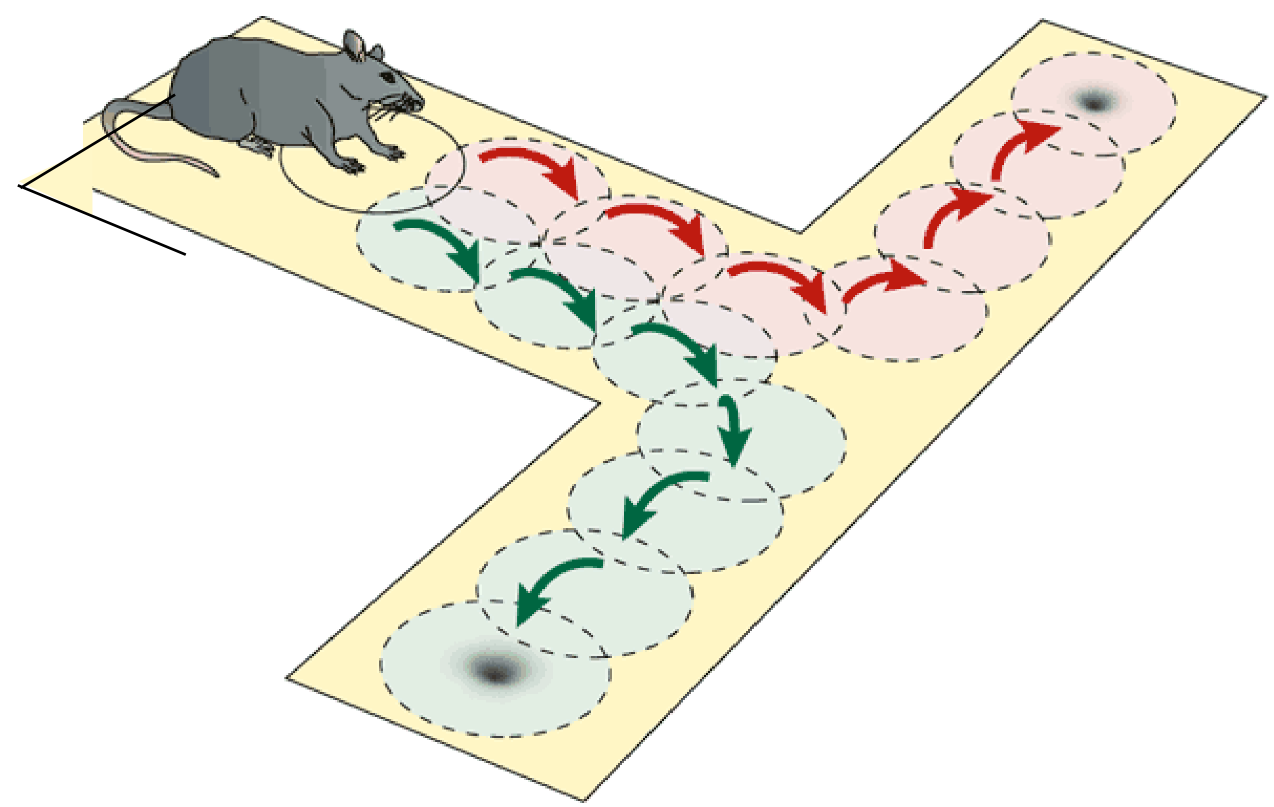


Activity of
a neuron in V1

# Another famous example: Place cells in the hippocampus



# Studying representations in the brain

## Experimental work

- perceptual representations:
  vision, audition, olfaction, etc.
- representation of motor variables
- "higher-order" representations:
  decisions
  short-term memory
  rewards
  dreams
  uncertainty
  ... you name it ...

## Theoretical work

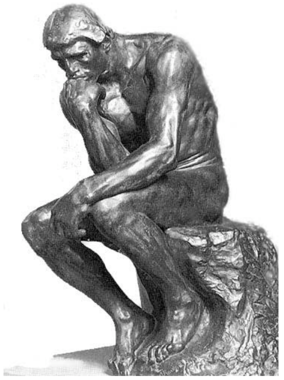
- Quantifying information content
  quest for the neural code,
  information theory, discriminability, ...
- Understanding the computational
  problems: object recognition, sound
  recognition, reward maximization

# What we understand now

very little

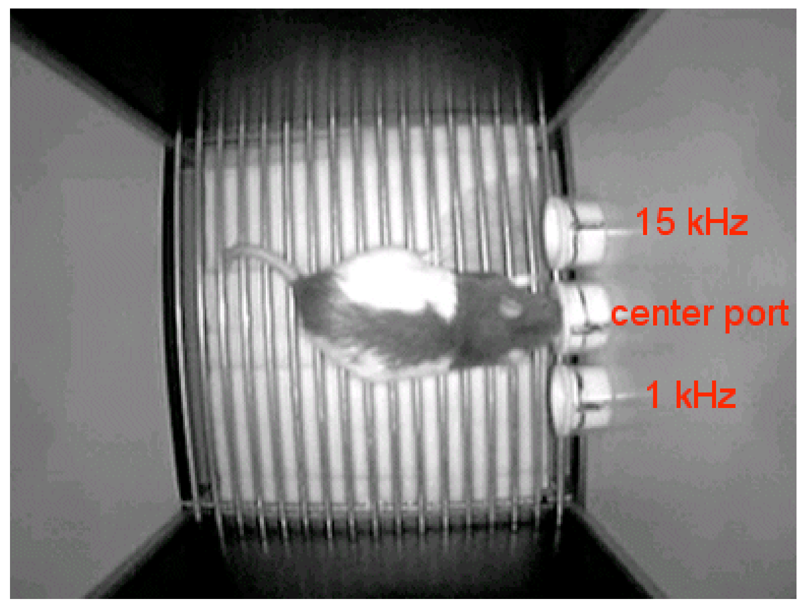
# What we understand now

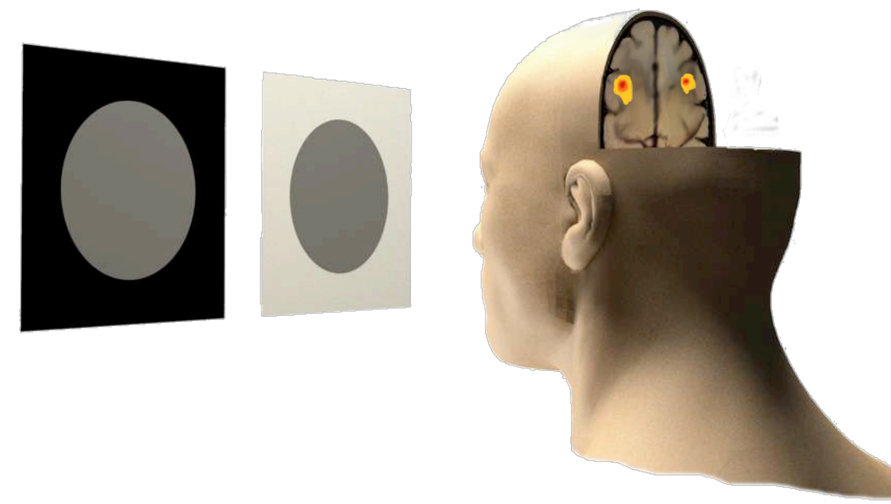
very little



# What we need

- biologists
- psychologists

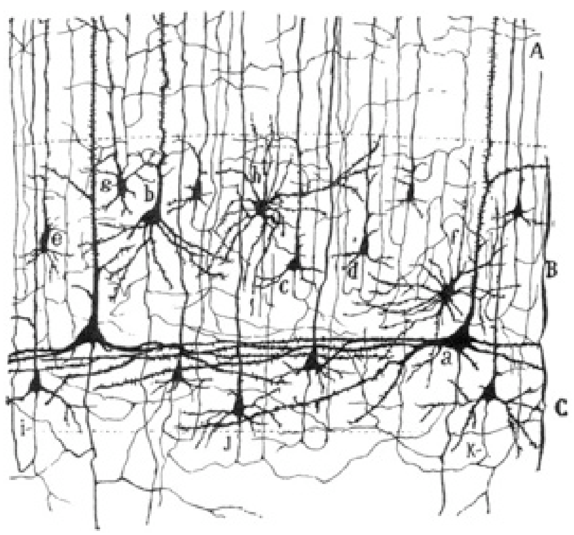


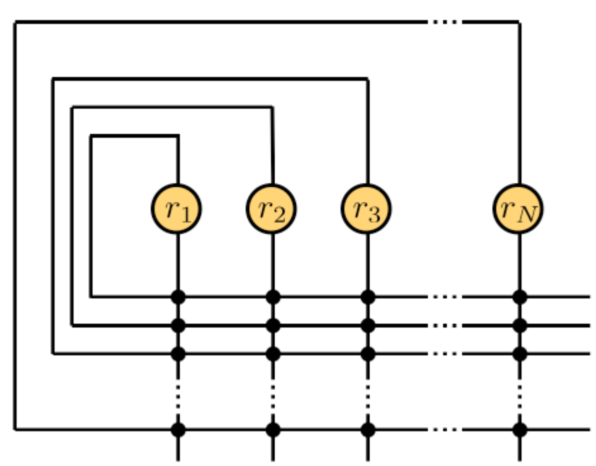



- to probe the brains of animals and humans
- to design and carry out clever experiments
- to investigate and quantify human and animal behavior

# What we need

- physicists, computer scientists, engineers, etc.






$$\dot{r}_1 = -r_1 + f\Big(\sum_{j=1}^{N} w_{1j} r_j + E_1\Big)$$

$$\dot{r}_2 = -r_2 + f\Big(\sum_{j=1}^{N} w_{2j} r_j + E_2\Big)$$

- to formulate mathematical theories of information processing
- to create biophysical models of neural networks

# Teaching in the Cogmaster

## Computational Neuroscience

# Core Classes

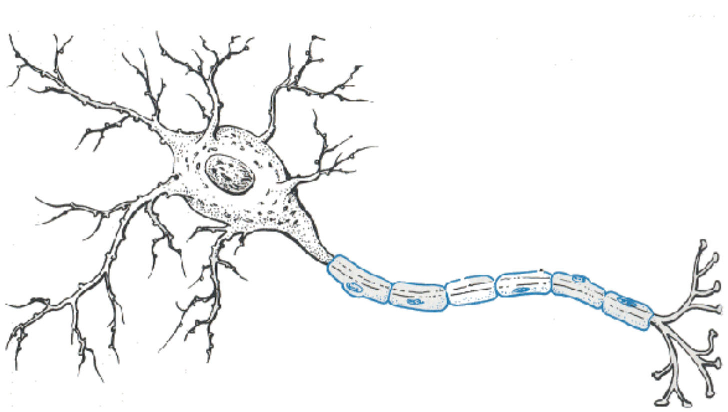
| | |
|---|---|
| M1/S1 | |
| M1/S2 | CO6 Introduction to Comput. Neuroscience<br>AT2 Atelier Comput. Neuroscience |
| M2/S1 | CA6 Theoretical Neuroscience<br>XXX Seminar in Quantitative Neuroscience |
| M2/S2 | YYY Research Seminar |

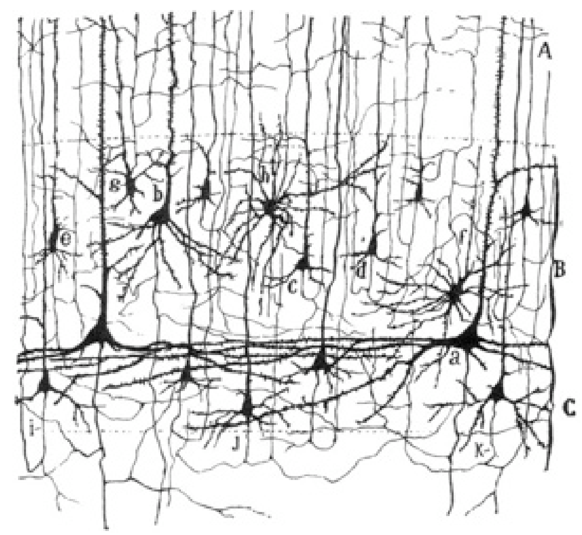
L3/M1

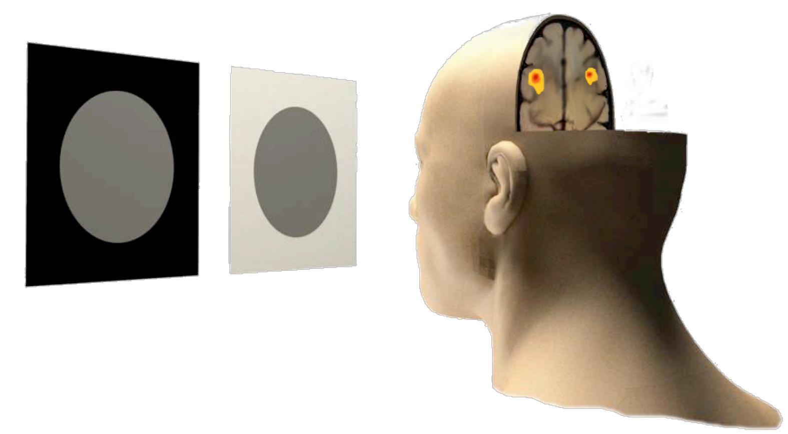
# CO6 Introduction aux neurosciences computationnels

Christian Machens

**S2, Wed, 17-19**







## Neurons

- Membrane voltage
- Action potentials
- Computations

## Networks

- Attractors
- Associative memory
- Decision-making
- Sensory processing

## Behavior

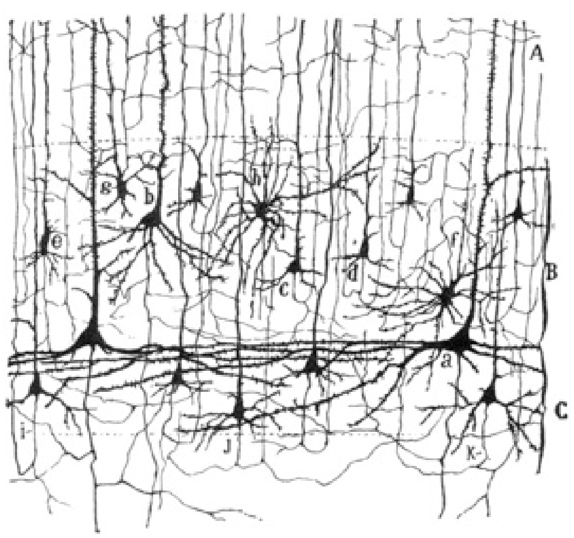
- Psychophysics
- Reinforcement Learning
- Neuroeconomics

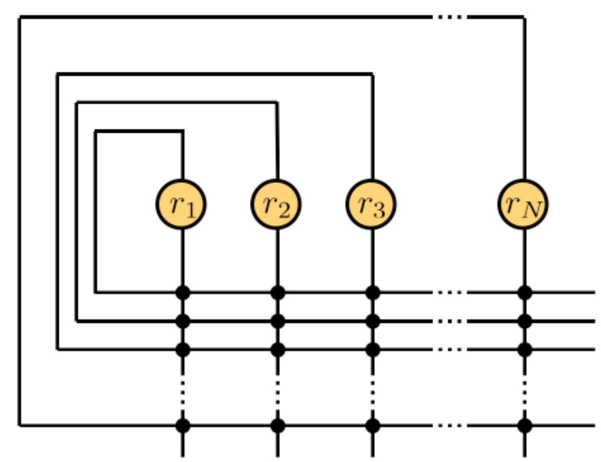
L3/M1

# CO6 Introduction aux neurosciences computationnels

Christian Machens

**S2, Wed, 17-19**



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$$\dot{r}_2 = -r_2 + f\Big(\sum_{j=1}^{N} w_{2j} r_j + E_2\Big)$$

## What you need

- Basic math skills,
  High-School Level
  (ask if you are uncertain!)

## What you get

- Foundations of Comp Neurosci
- 4 ECTS

## Validation

- 100% exam

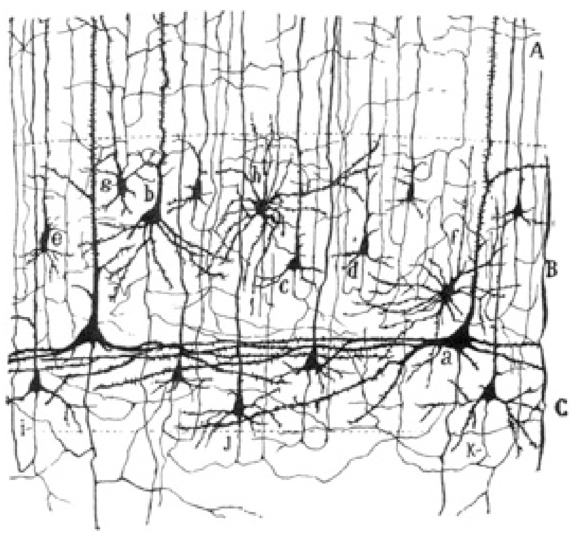
L3/M1

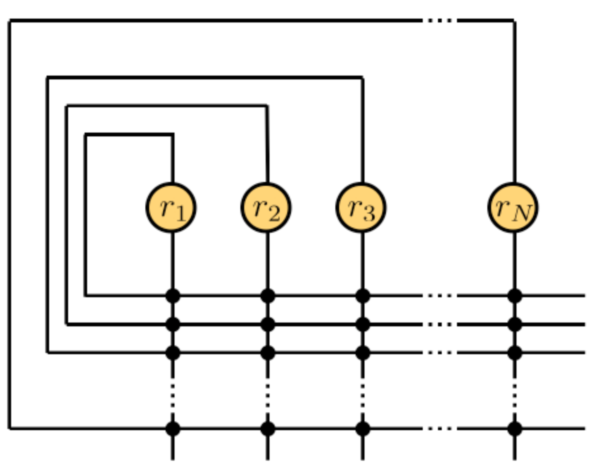
# AT2

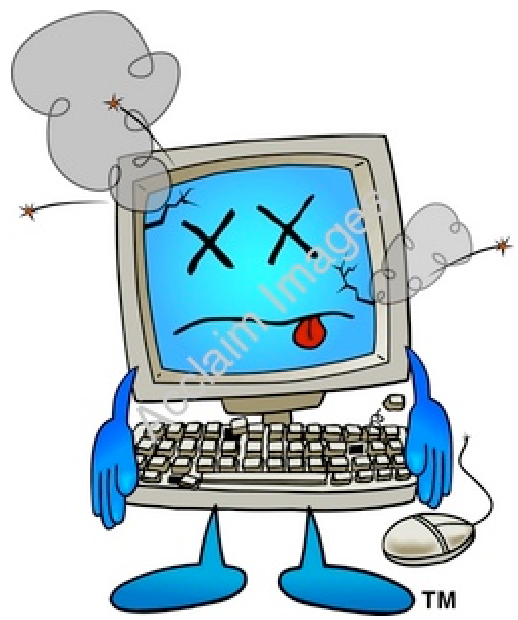
# Atelier théorique neuromodélisation

Christian Machens

**S2, Tue, 10-12**






## What you need

- Basic math skills

  High School Level

## What you get

- Putting models into the computer!
- 4 ECTS

## Validation

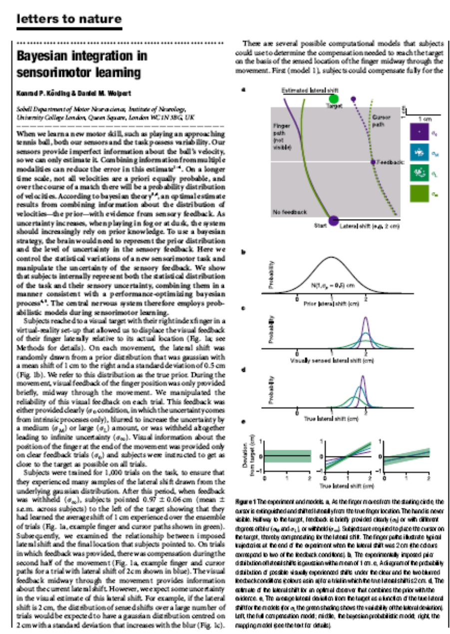
- 100% course exercises

M1/M2

# XXX Seminar / Journal Club Quantitative Neuroscience

Rava da Silveira, Vincent Hakim, Christian Machens

**S3, Tue, 15.30-17**
**Start: Sep 30th**



letters to nature

Bayesian integration in sensorimotor learning

## What you need

- Basic knowledge of computational neuroscience (ask if you are uncertain!)

## What you get

- Learn about recent research
- Learn how to give a talk
- 3 ECTS

## Validation

- 50% talk
- 50 % course participation

**Talks in French or English**

M1/M2

# CA6 Theoretical Neuroscience

Rava da Silveira, Vincent Hakim, Nicolas Brunel, Jean-Pierre Nadal

# If you are looking for more classes with a computational twist, contact us!

- CO8 Rational Decision Theory

- Computational Neuroscience
  (Single Cell Modeling) Romain Brette

- Statistical Learning Theory (Gerard Dreyfus)

<u>etc. etc.</u>

# Computational Neuroscience Research in the Cogmaster and Beyond

ENS: Group for Neural Theory
(Sophie Deneve, Christian Machens, ... )
ENS: Laboratoire de Physique Statistique
(Jean-Pierre Nadal, Vincent Hakim ... )
Paris V: Laboratoire de Neurophysique et Physiologie
(Nicolas Brunel, ... )

you can find more labs under:

http://cogmaster.net
http://neurocomp.risc.cnrs.fr

for internship / stages / Master's thesis: contact the faculty! (email etc.)