

# Advanced Course on Human Neuroscience

# Computational modeling

from theory to practice



Marijn van Vliet

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NBE-E4240 2025

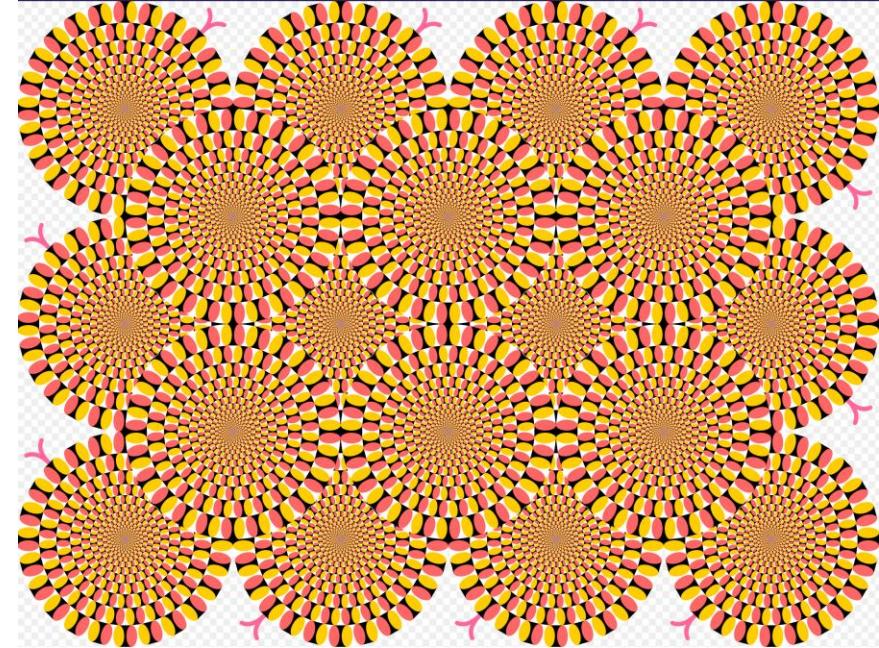
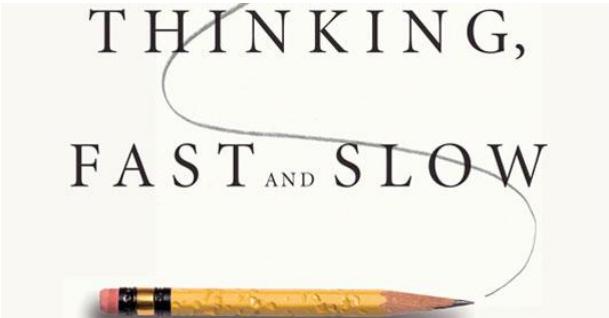
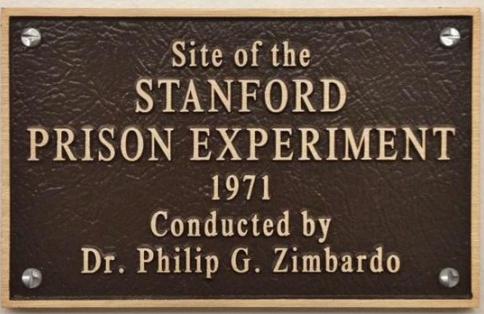
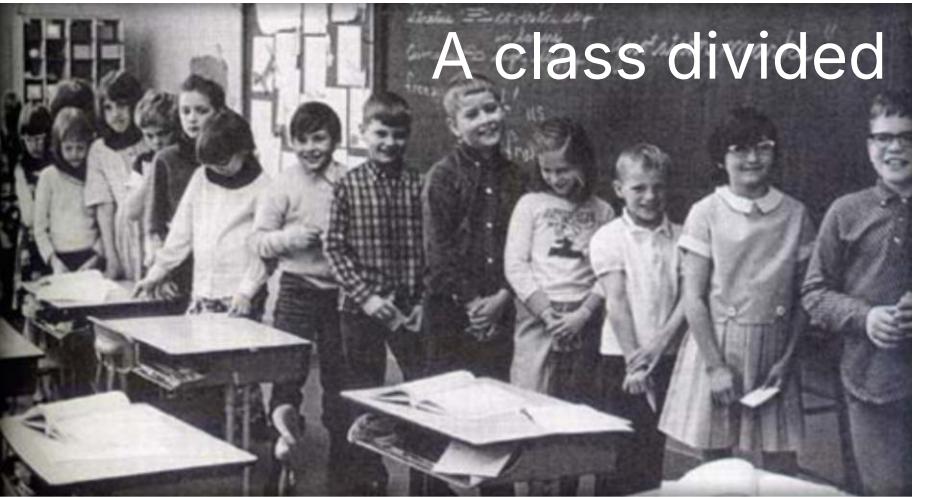
A dense network of colored neurons against a black background.

neurobiology

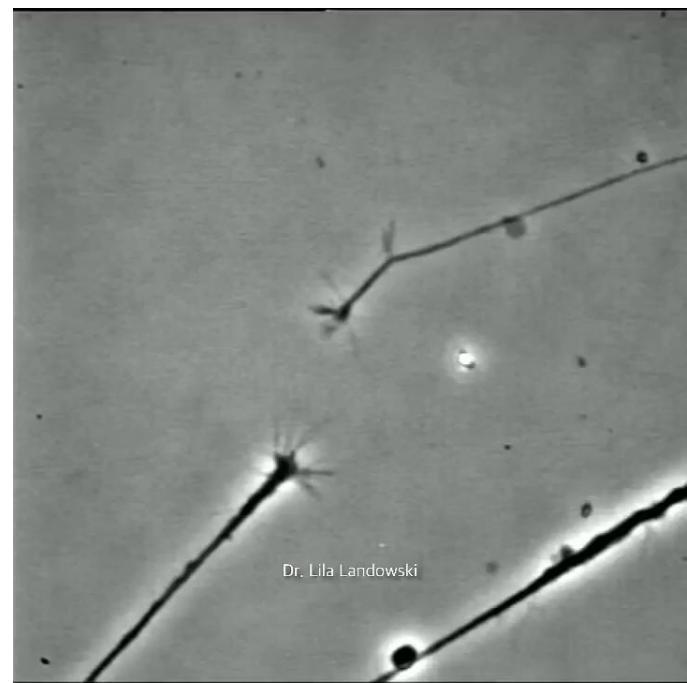
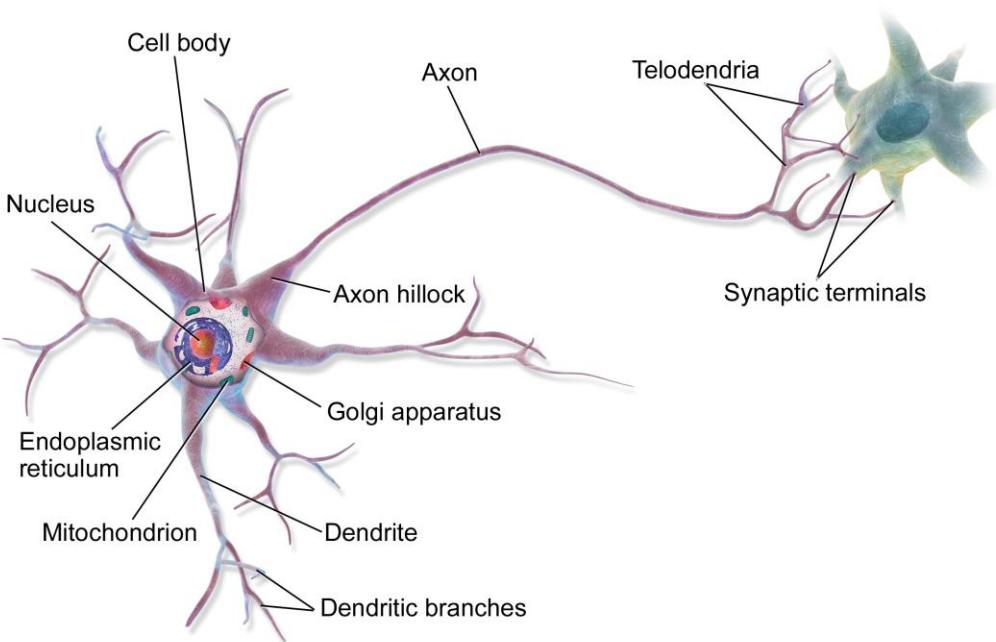
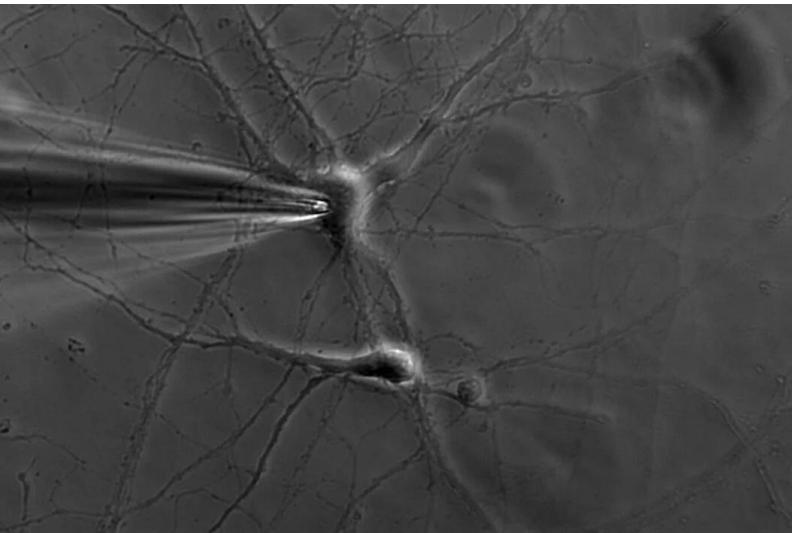
A woman looking at two cupcakes on a table.

psychology

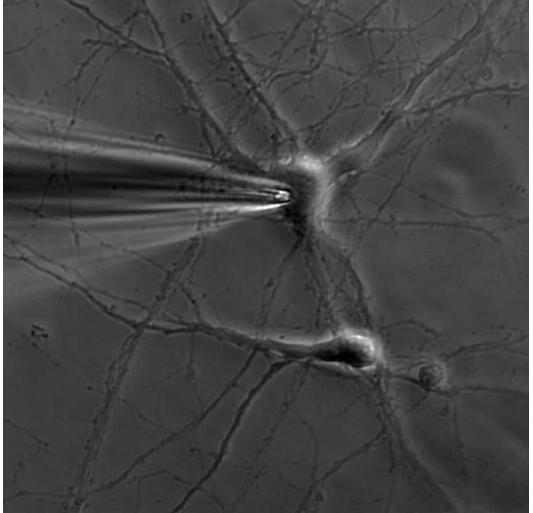
# Psychology



# Neurobiology



neurobiology



A. Aguado

neurons  
synapses  
dendrites



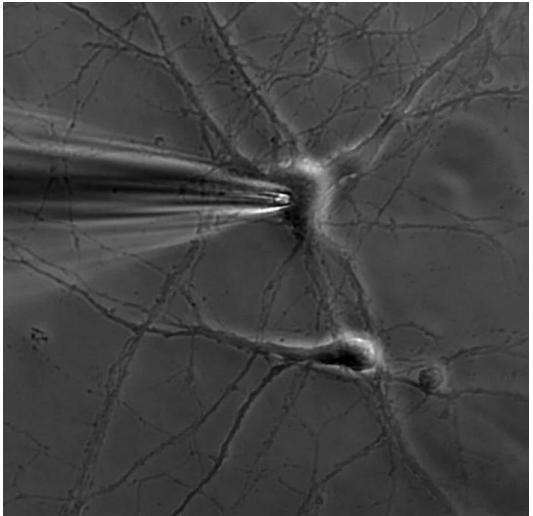
psychology



DALL-E

decision making  
behavior  
perception

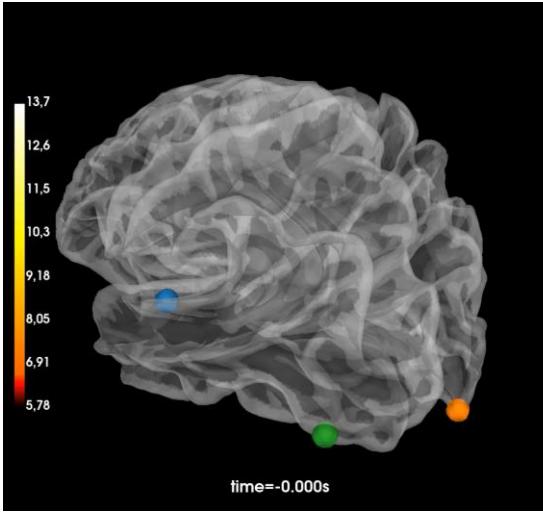
## neurobiology



A. Aguado

neurons  
synapses  
dendrites

## neuroimaging



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evoked responses  
spectral power  
connectivity

## psychology

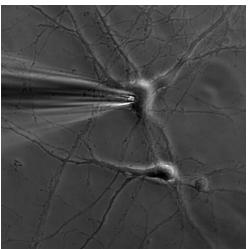


DALL-E

decision making  
behavior  
perception

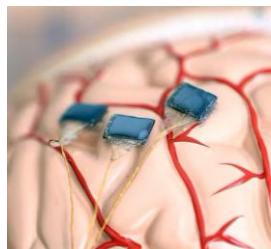
# MICRO → MACRO

neurobiology    electrode arrays



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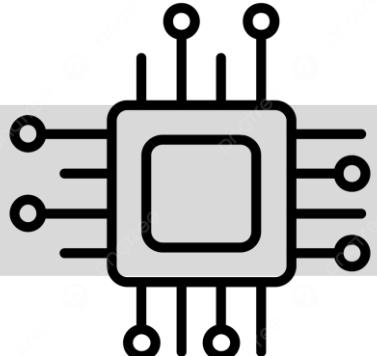
neurons  
synapses  
dendrites



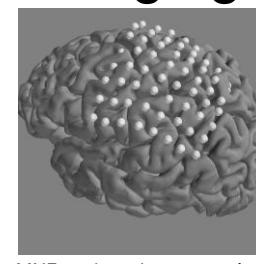
Blackrock Microsystems

spike trains  
tuning curves

computational modeling

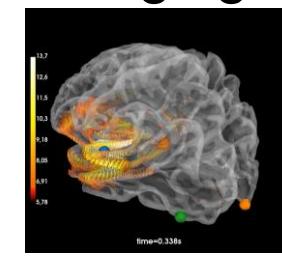


invasive  
imaging



MNE-python documentation

non-invasive  
imaging



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psychology

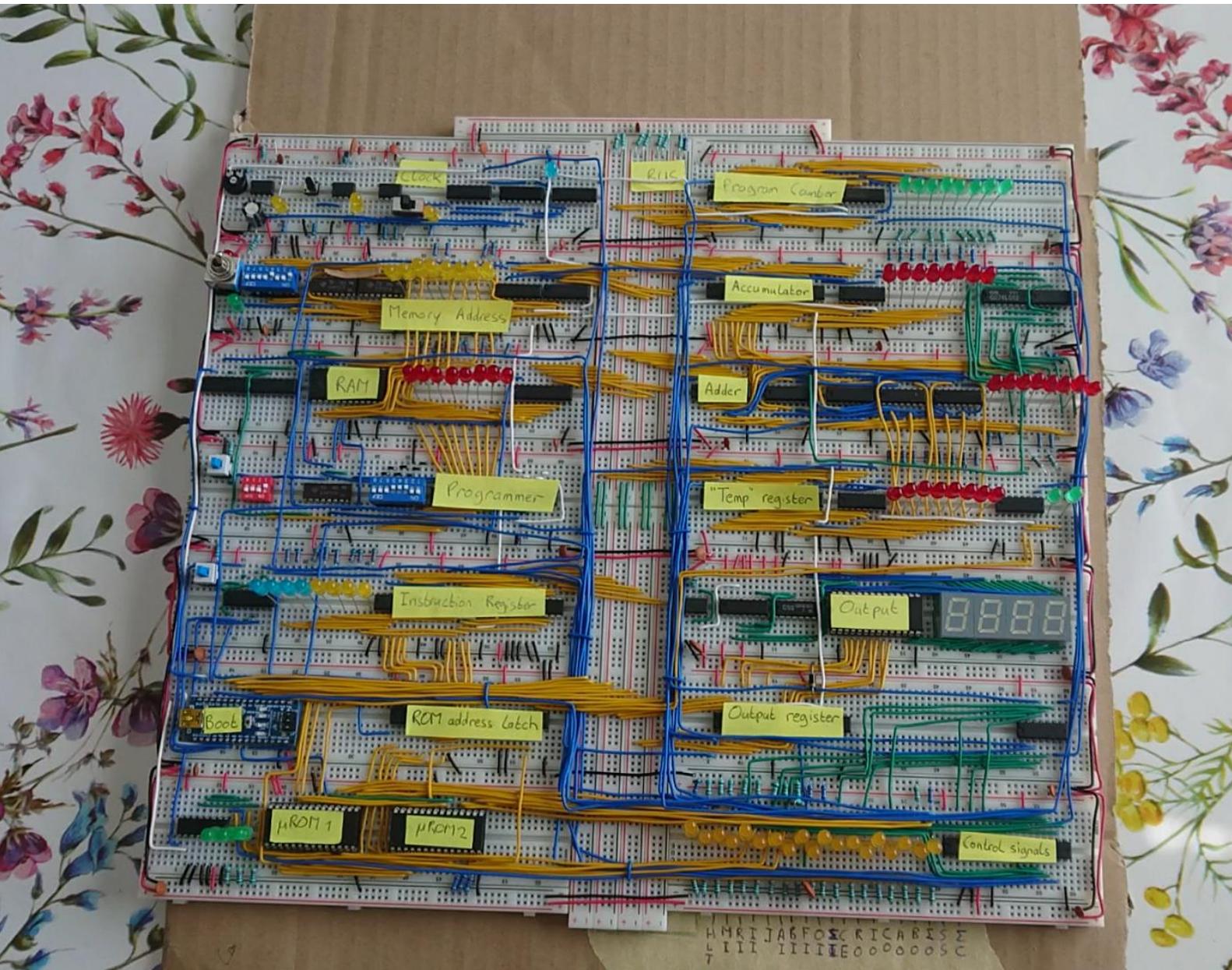


DALL-E

local field potentials    evoked responses  
spectral power    connectivity

decision making  
behavior  
perception

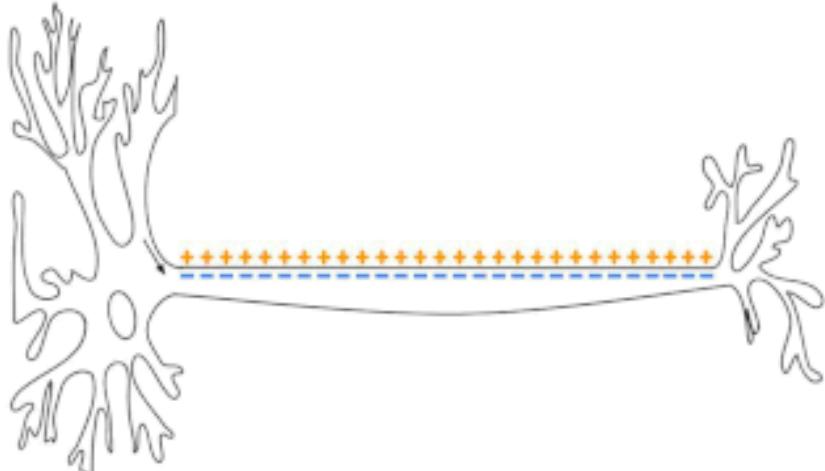
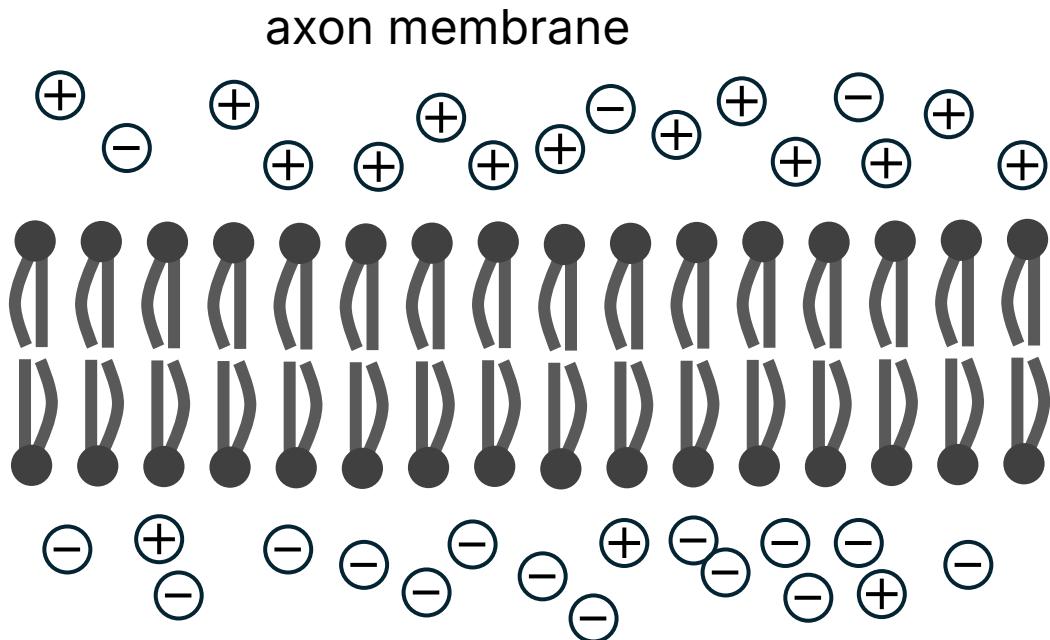
# Engineering approach



“To build the thing is  
to understand the thing”

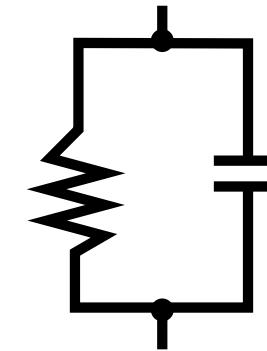


# Lapicque's model of a "spiking" neuron: Leaky Integrate and Fire

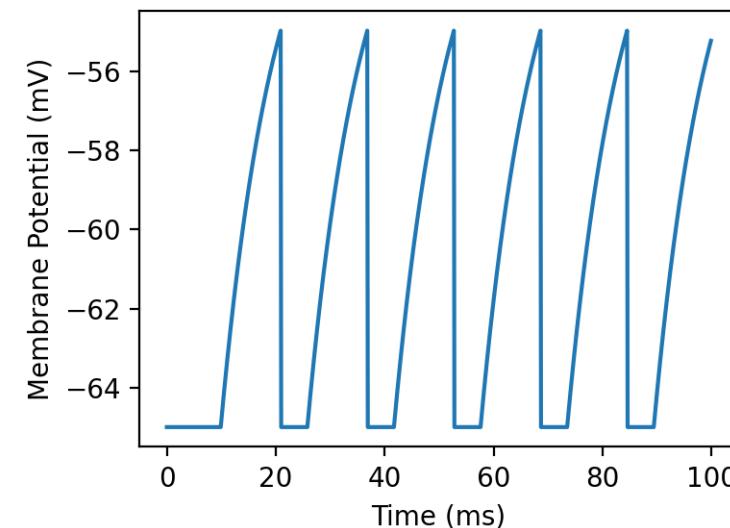


Wikipedia

equivalent circuit

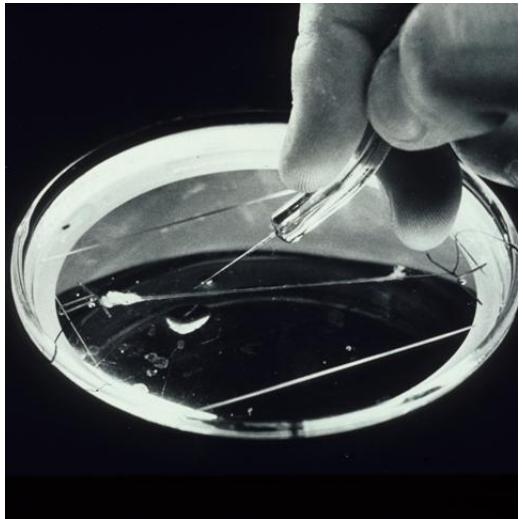


simulation



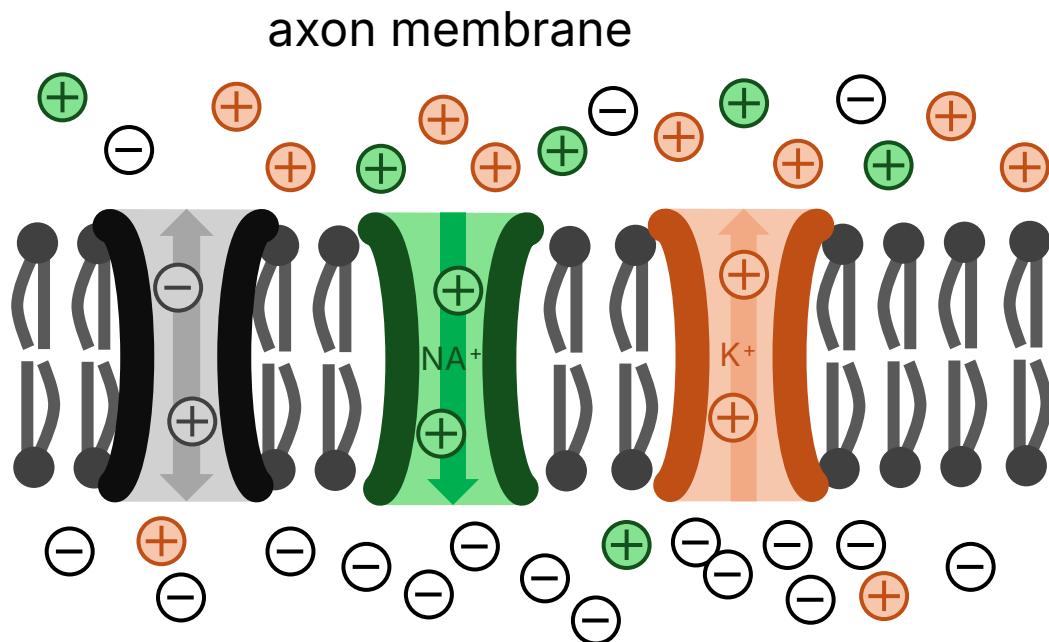
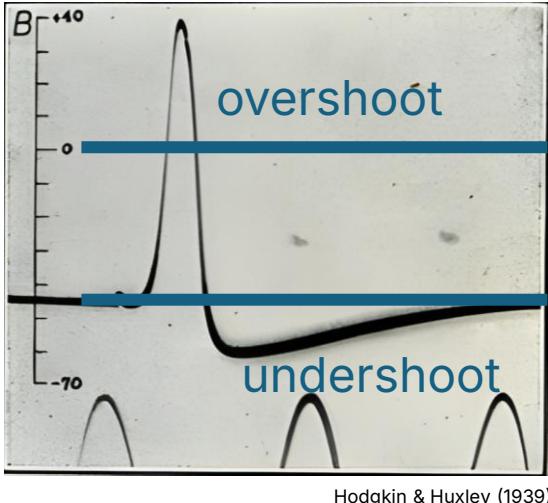
# Hodgkin & Huxley model of a "spiking" neuron

giant axon of a squid

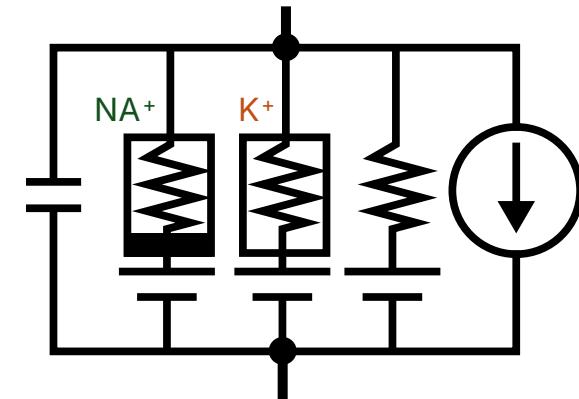


NIH History Office from Bethesda - Giant Axon of Squid, Public Domain

action potential, "spike"

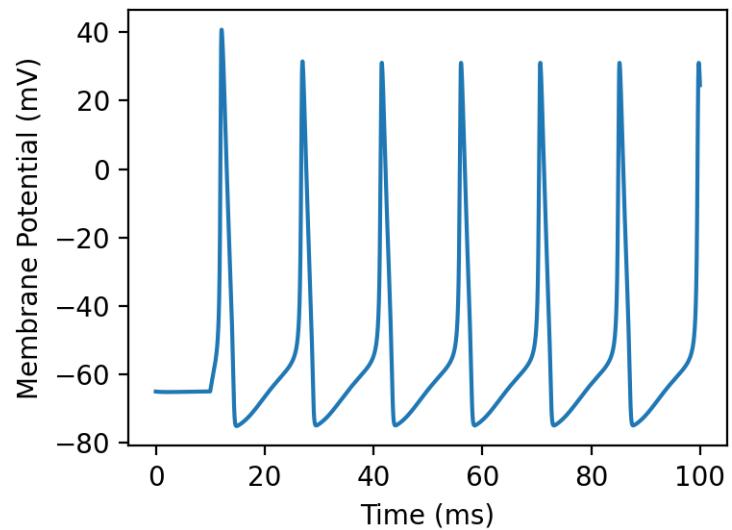


equivalent circuit



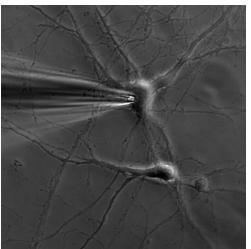
Hodgkin & Huxley

simulation

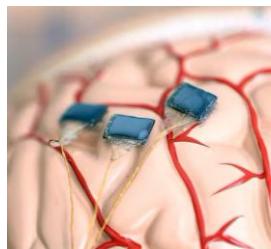


# MICRO → MACRO

neurobiology    electrode arrays



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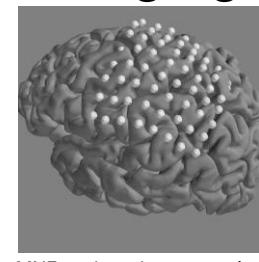
Blackrock Microsystems

neurons  
synapses  
dendrites

spike trains  
tuning curves

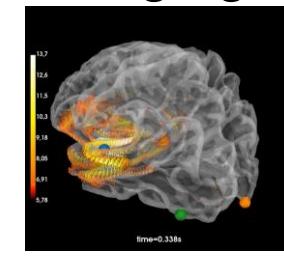
computational modeling

invasive  
imaging



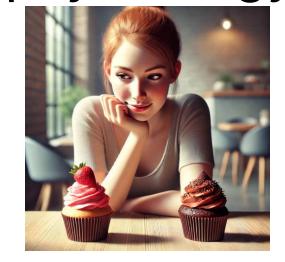
MNE-python documentation

non-invasive  
imaging



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psychology



DALL-E

evoked responses  
spectral power  
connectivity

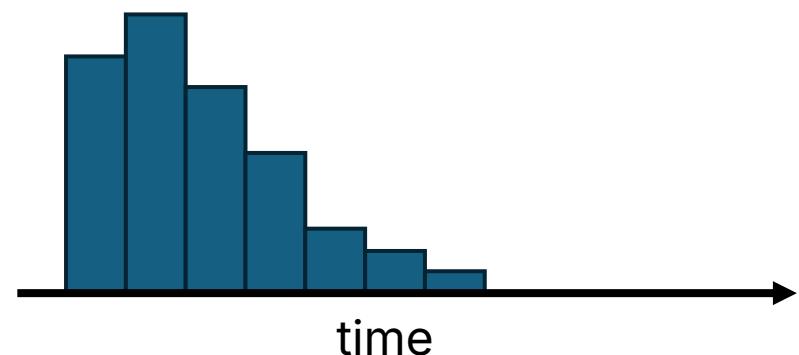
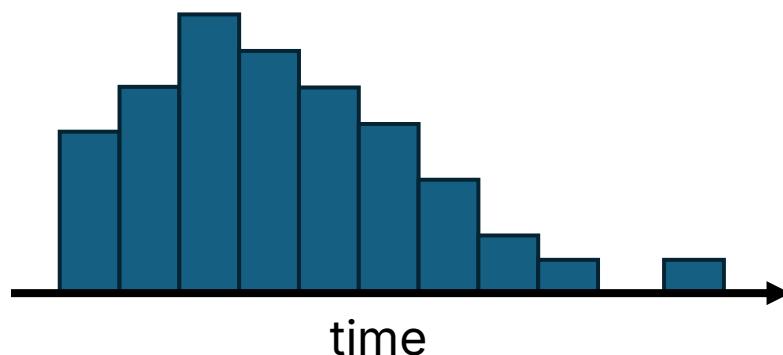
decision making  
behavior  
perception

Hodgkin & Huxley  
1952

# Roger Ratcliff: Drift-diffusion model of decision making

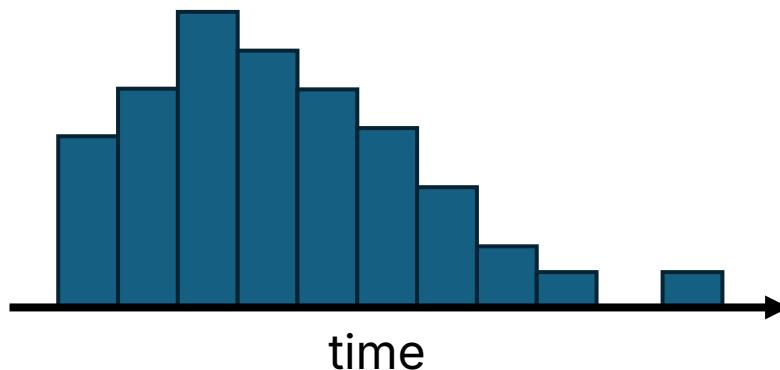
Lexical decision:  
real word?

	participant 1		participant 2	
	response time	choice	response time	choice
SLEP	564 ms	NO	243 ms	NO
BOAT	352 ms	YES	314 ms	YES
MORE	427 ms	YES	215 ms	YES
ADOM	652 ms	NO	293 ms	YES
CARE	258 ms	YES	189 ms	YES
LEEK	348 ms	NO	234 ms	NO
TEER	462 ms	NO	301 ms	YES

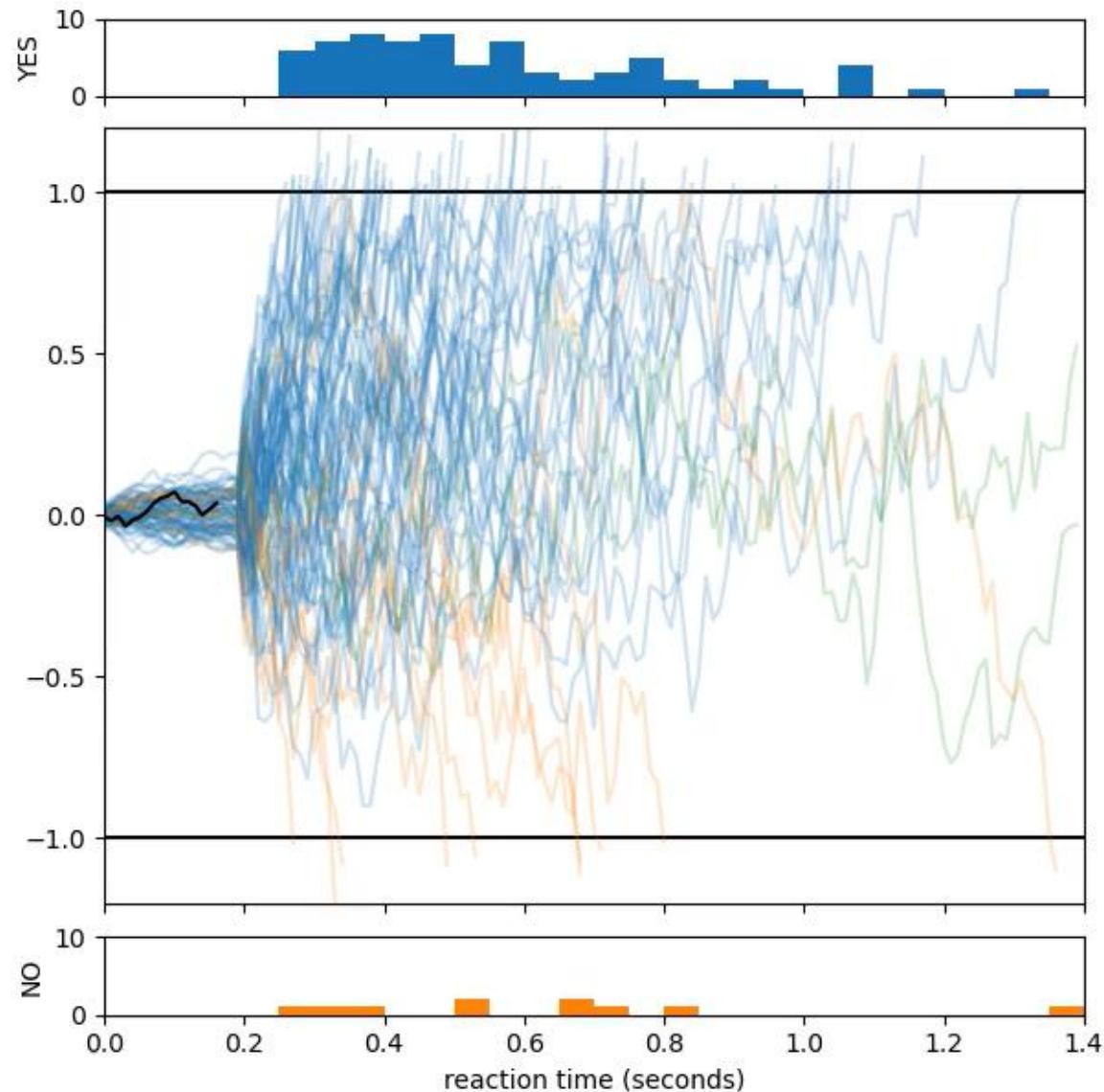


# Roger Ratcliff: Drift-diffusion model of decision making

ground truth RT distribution



simulated RT distribution

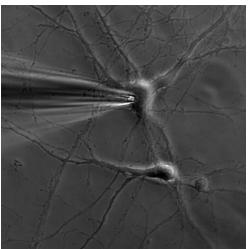


parameters:

noise  
drift rate  
threshold  
non-decision time  
start position

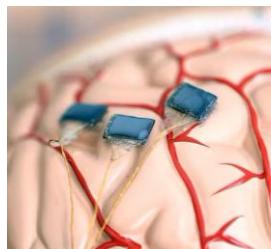
# MICRO → MACRO

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synapses  
dendrites



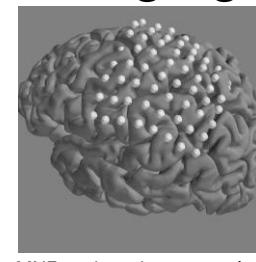
Blackrock Microsystems

spike trains  
tuning curves

## computational modeling

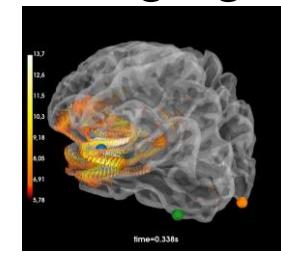
Hodgkin & Huxley  
1952

invasive  
imaging



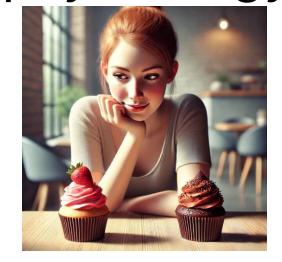
MNE-python documentation

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DALL-E

decision making  
behavior  
perception

local field potentials

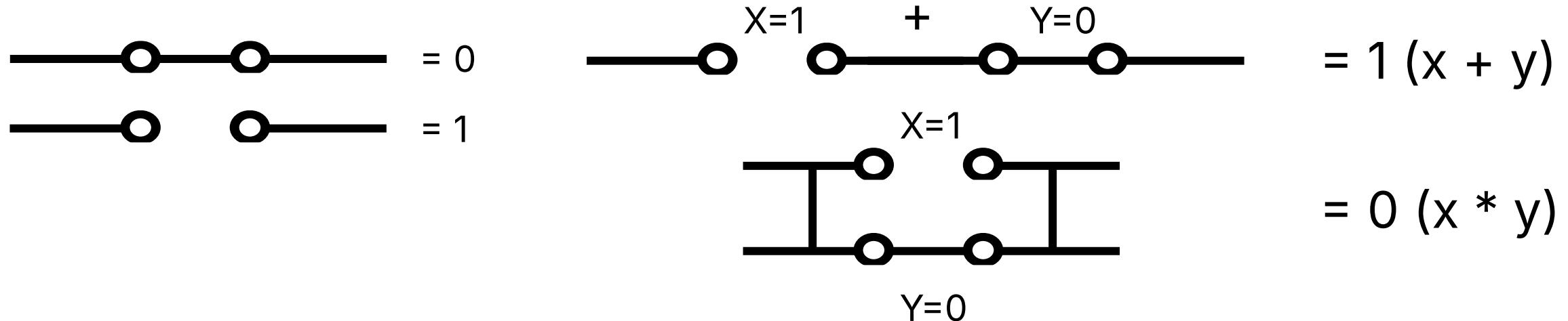
evoked responses  
spectral power  
connectivity

drift-diffusion  
1978

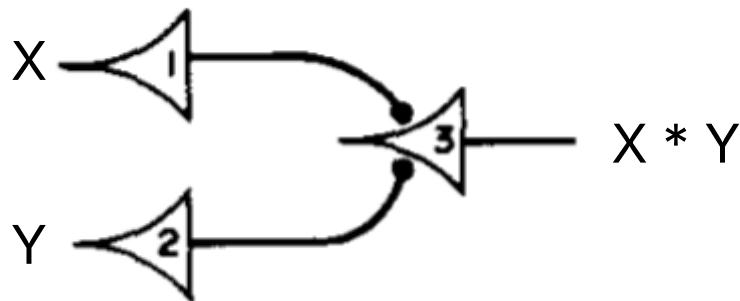
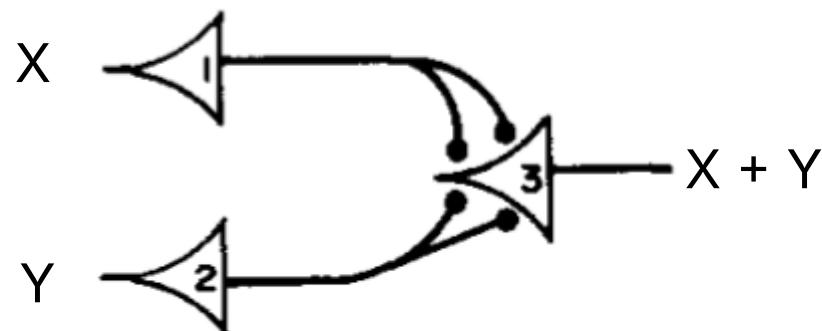
# Building sentience from non-sentient matter: logic & algorithms

1854 George Boole: *An Investigation of the Laws of Thought*

1937 Claude Shannon: *A Symbolic Analysis of Relay and Switching Circuits*

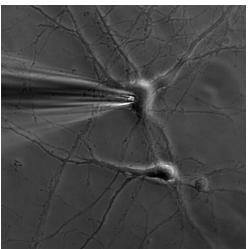


1943 Warren McCulloch: *A Logical Calculus of the Ideas Immanent in Nervous Activity*

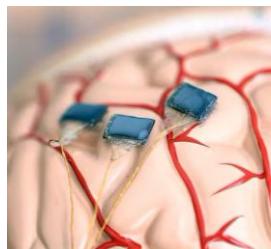


# MICRO → MACRO

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Blackrock Microsystems

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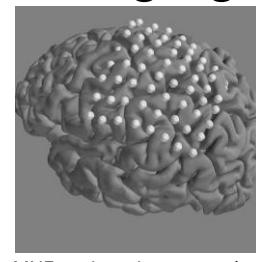
spike trains  
tuning curves

computational modeling

Hodgkin & Huxley  
1952

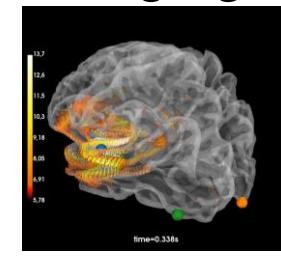
logical neural  
calculus  
1943

invasive  
imaging



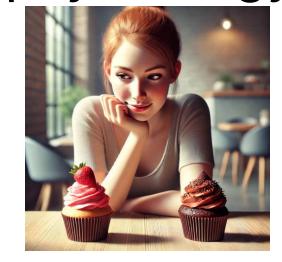
MNE-python documentation

non-invasive  
imaging



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psychology



DALL-E

local field potentials

evoked responses  
spectral power  
connectivity

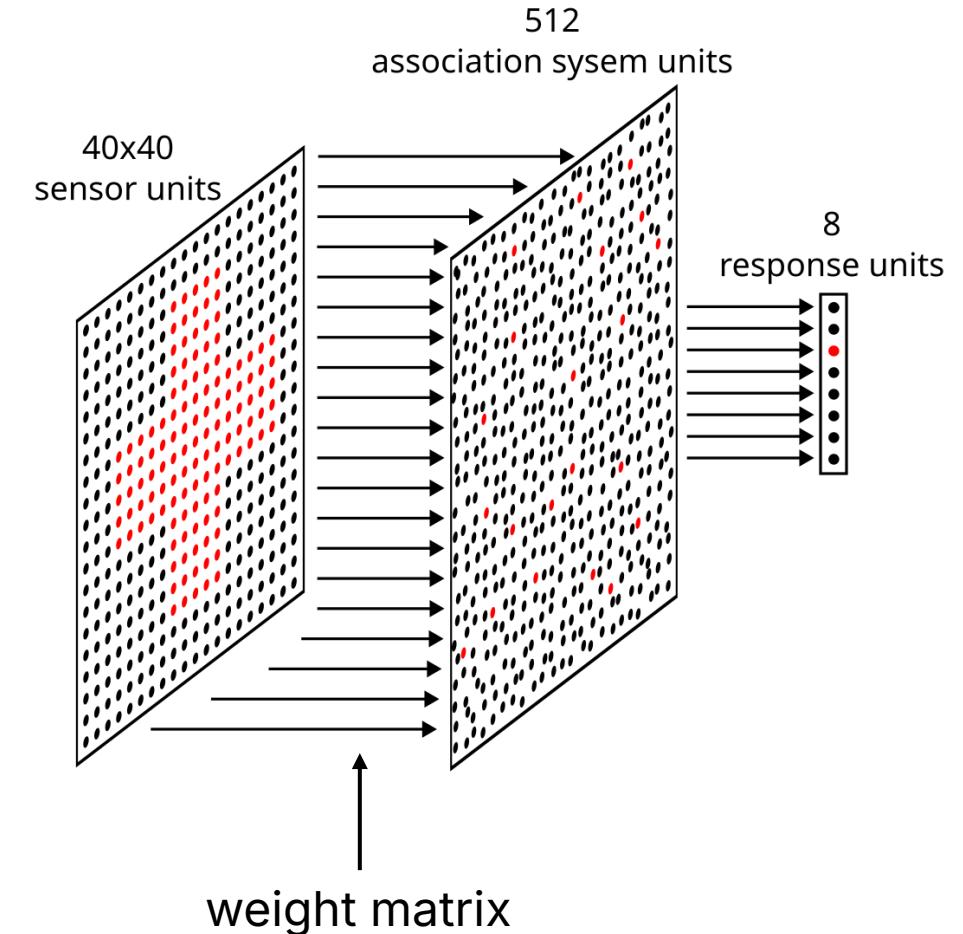
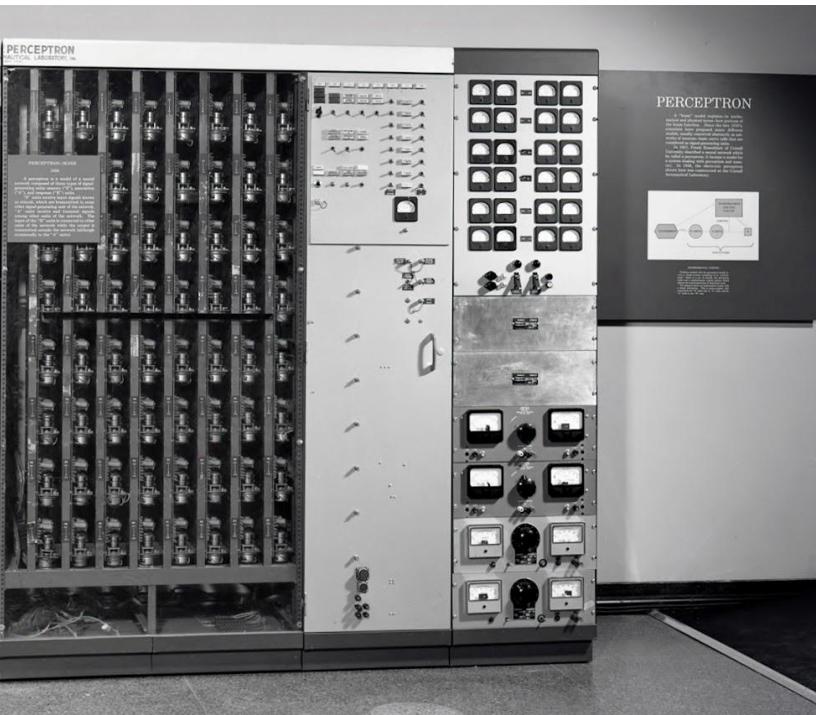
decision making  
behavior  
perception

drift-diffusion  
1978

# Building sentience from non-sentient matter: perceptron

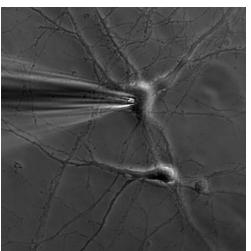


Frank Rosenblatt

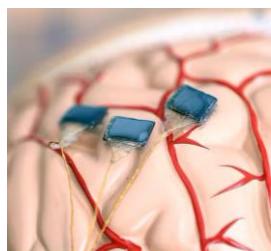


# MICRO → MACRO

neurobiology    electrode arrays



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Blackrock Microsystems

neurons  
synapses  
dendrites

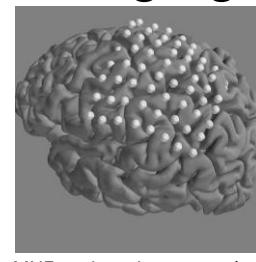
spike trains  
tuning curves

computational modeling

Hodgkin & Huxley  
1952

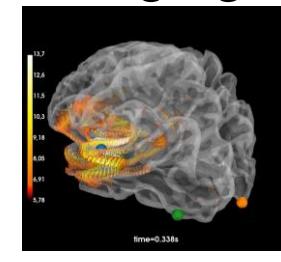
logical neural  
calculus  
1943

invasive  
imaging



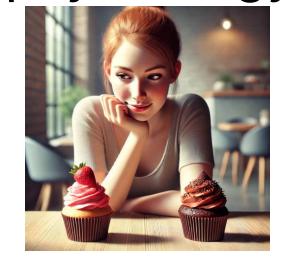
MNE-python documentation

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imaging



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DALL-E

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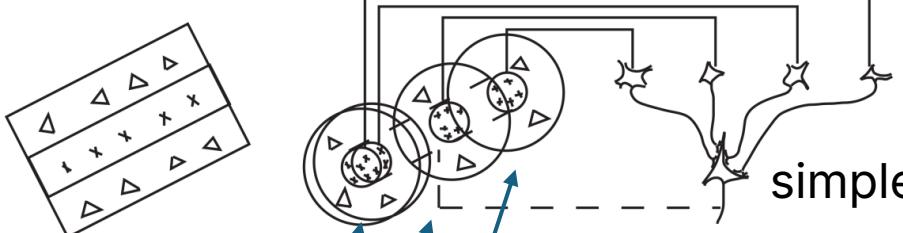
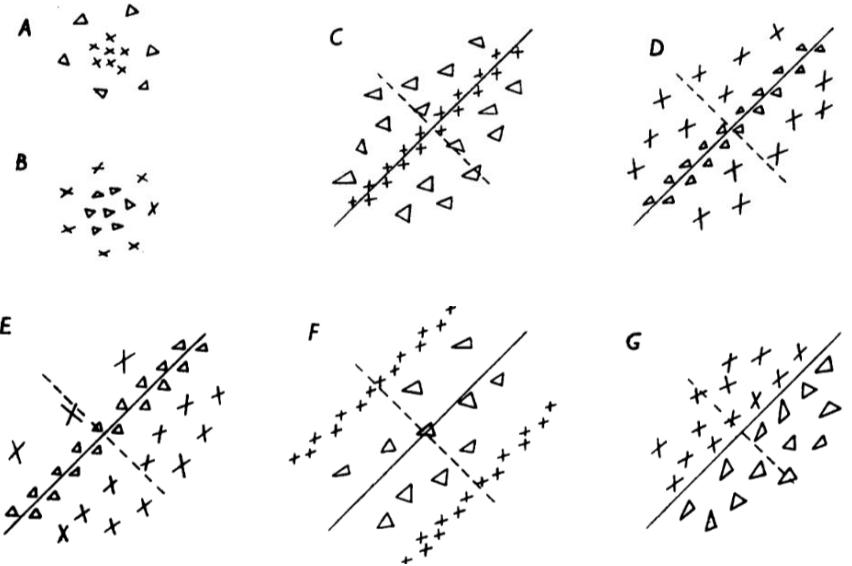
decision making  
behavior  
perception

perceptron  
1958

drift-diffusion  
1978

# Hubel & Wiesel: cat visual cortex

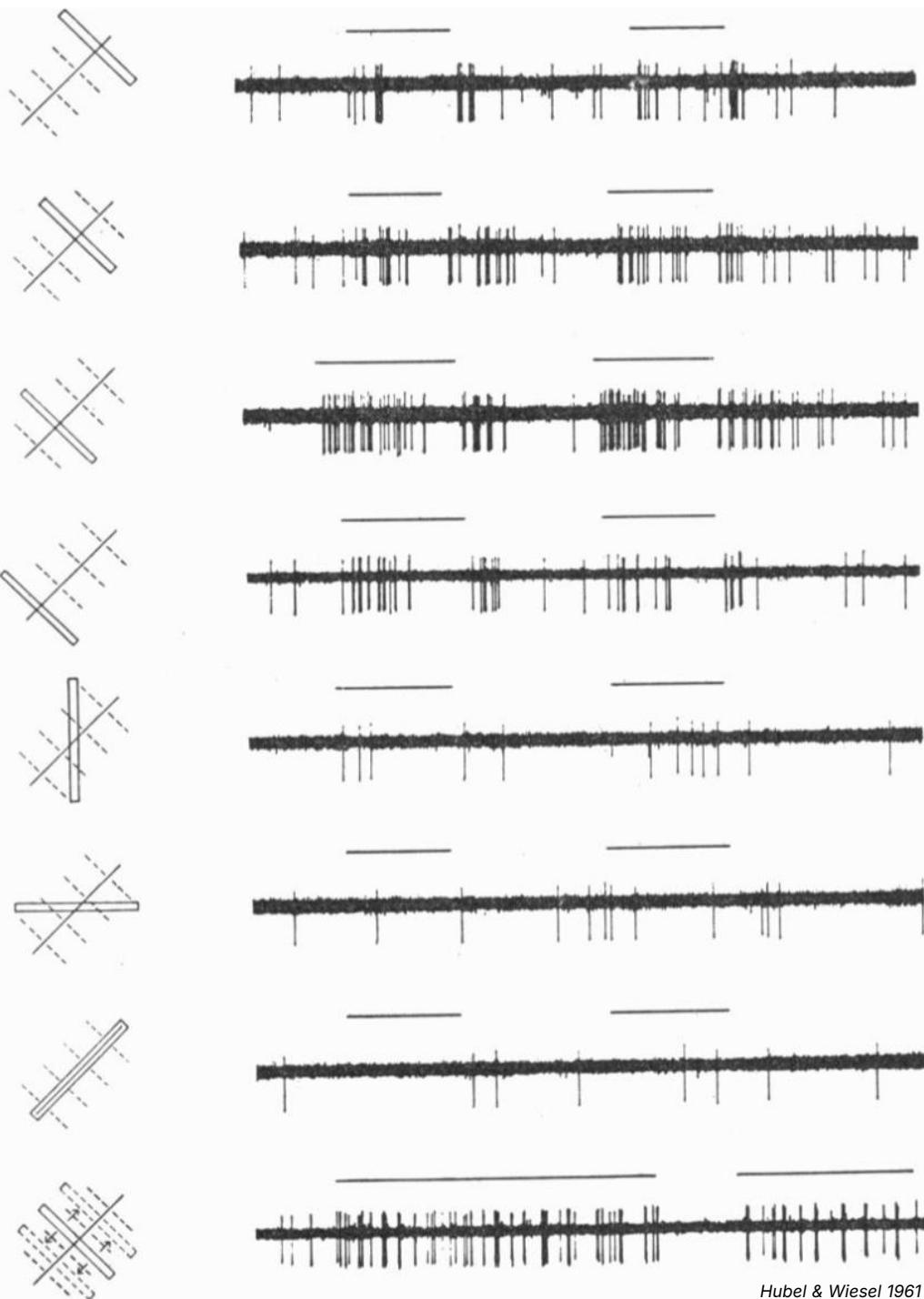
simple cells



geniculate cells in the thalamus

Hubel & Wiesel 1961

complex cells



Hubel & Wiesel 1961

# Poggio, Serre, Riesenhuber: HMAX model of vision

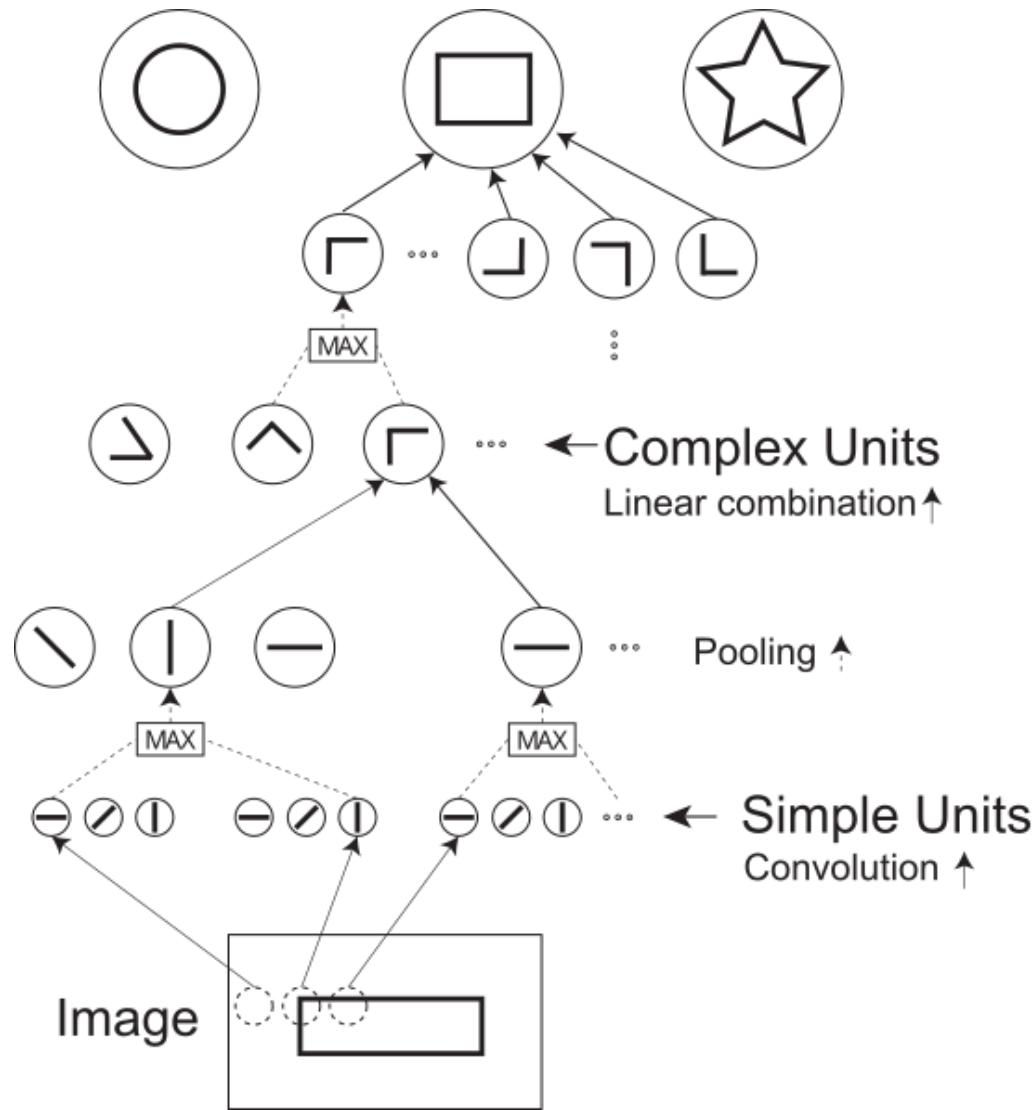
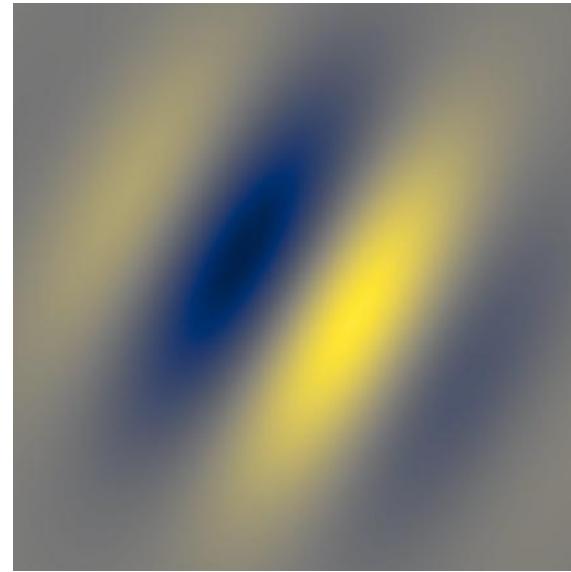


Figure 3. Examples from the MIT face and car datasets.

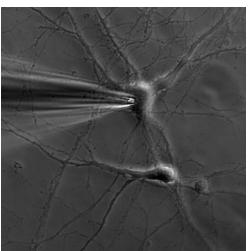


Datasets	Bench.	C2 features	boost	SVM
Leaves (Calt.)	[24]	84.0	<b>97.0</b>	95.9
Cars (Calt.)	[4]	84.8	<b>99.7</b>	<b>99.8</b>
Faces (Calt.)	[4]	96.4	<b>98.2</b>	98.1
Airplanes (Calt.)	[4]	94.0	<b>96.7</b>	94.9
Moto. (Calt.)	[4]	95.0	<b>98.0</b>	97.4
Faces (MIT)	[7]	90.4	<b>95.9</b>	95.3
Cars (MIT)	[11]	75.4	<b>95.1</b>	93.3

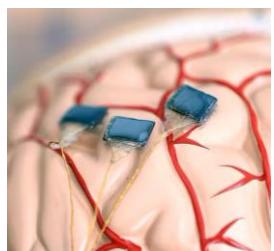
Table 2. C2 features vs. other recognition systems (Bench.).

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neurons  
synapses  
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computational modeling

Hodgkin & Huxley  
1952

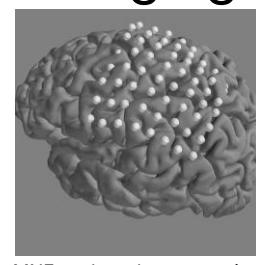
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HMAX  
1999

perceptron  
1958

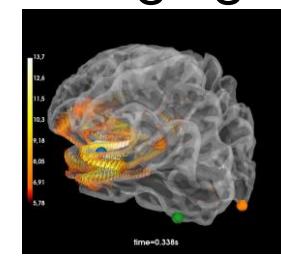
drift-diffusion  
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invasive  
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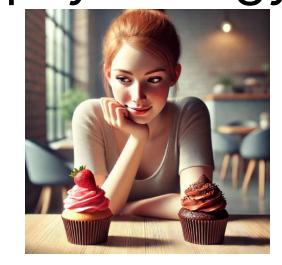
MNE-python documentation

non-invasive  
imaging



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psychology



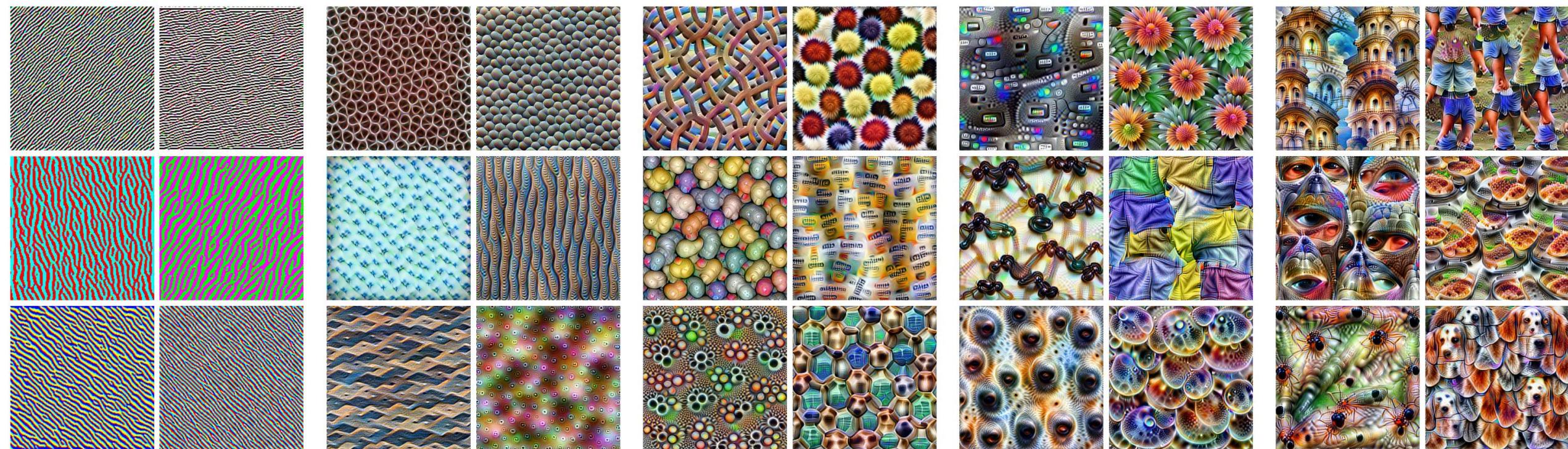
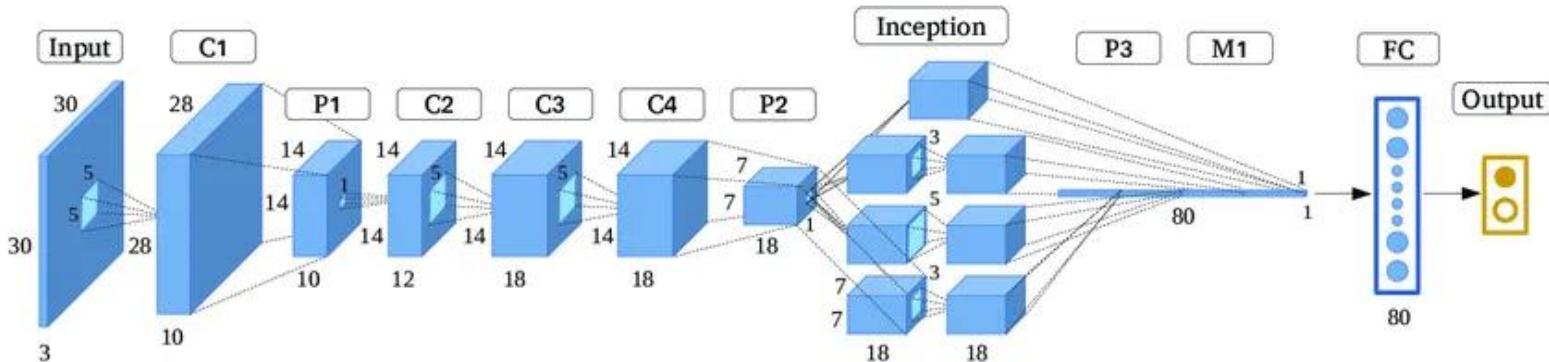
DALL-E

local field potentials  
evoked responses  
spectral power  
connectivity

decision making  
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perception

# Modeling cognitive representations: vision

GoogLeNet



Edges (layer conv2d0)

Textures (layer mixed3a)

Patterns (layer mixed4a)

Parts (layers mixed4b & mixed4c)

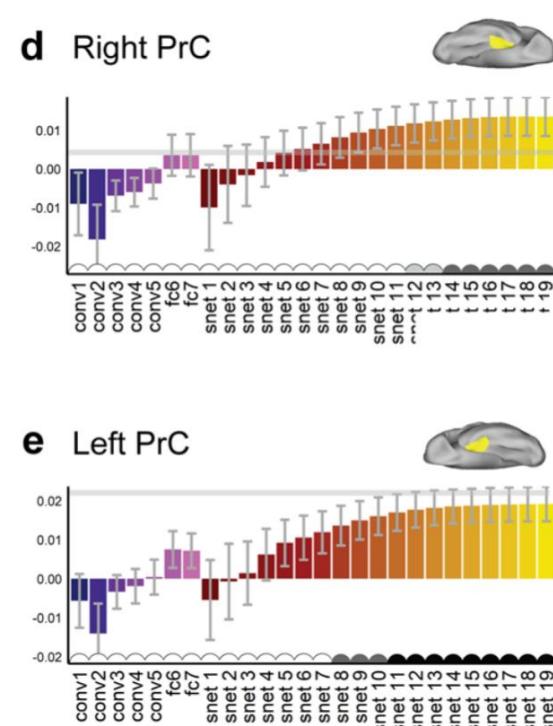
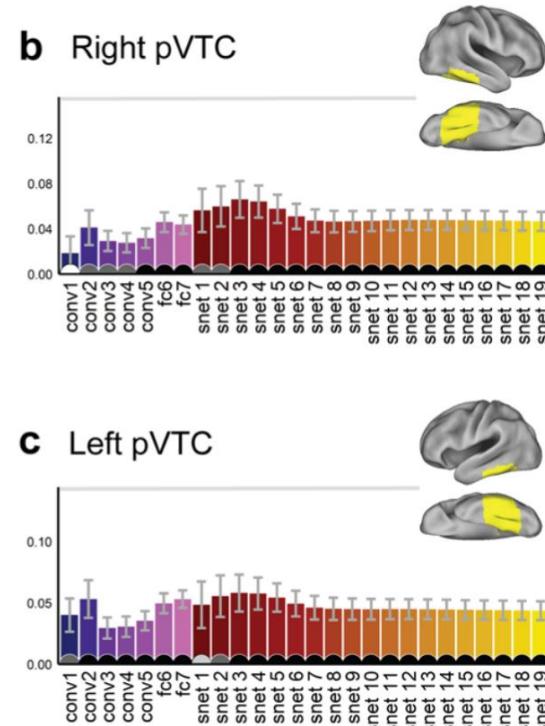
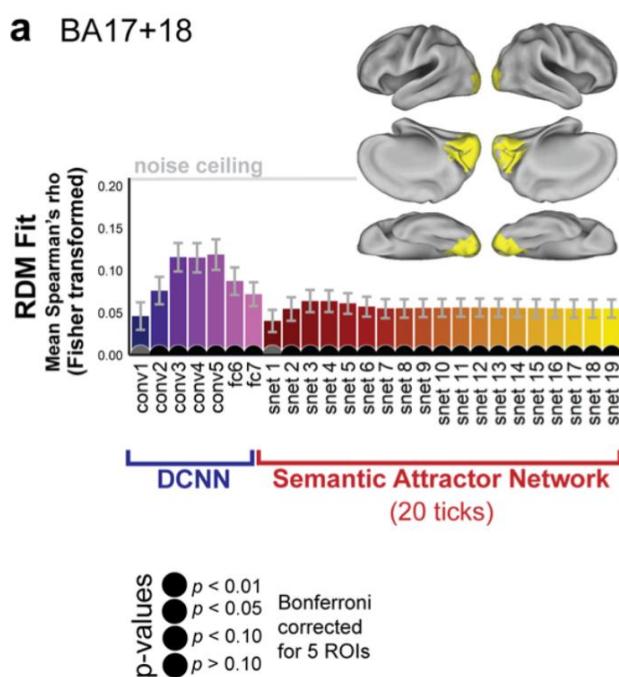
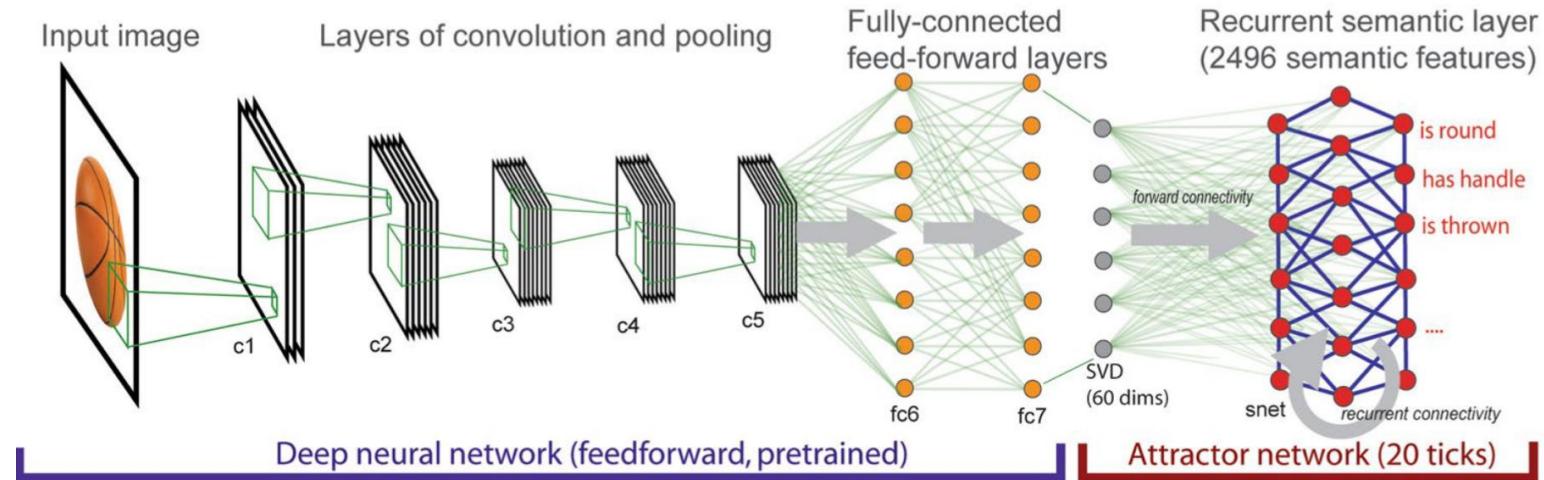
Objects (layers mixed4d & mixed4e)

Chris Olah, Alexander Mordvintsev, Ludwig Schubert

<https://distill.pub/2017/feature-visualization/>

# Comparing CNNs to neuroimaging data

Barry Devereux  
Alex Clarke  
Lorraine Tyler

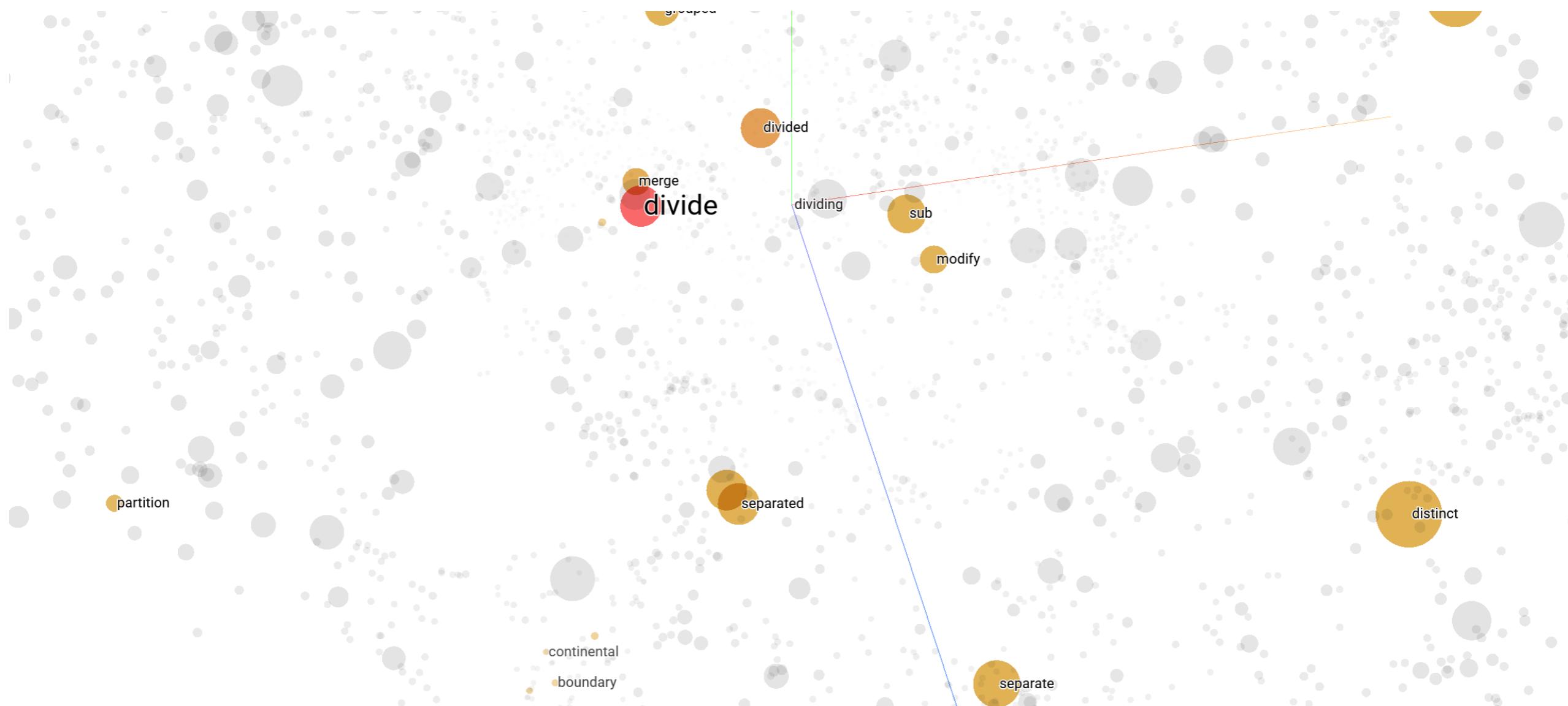


# Modeling cognitive representations: meaning

Tomas Mikolov

<https://projector.tensorflow.org>

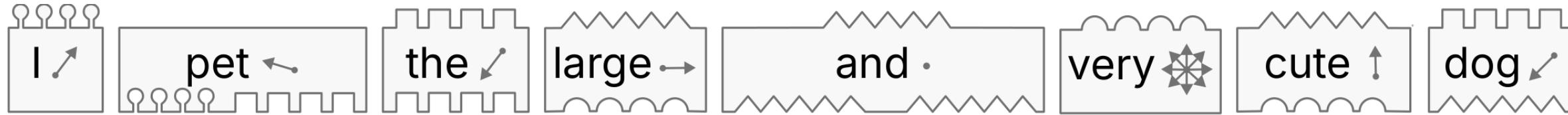
<https://users.aalto.fi/~vanvli1/guessfmri/>



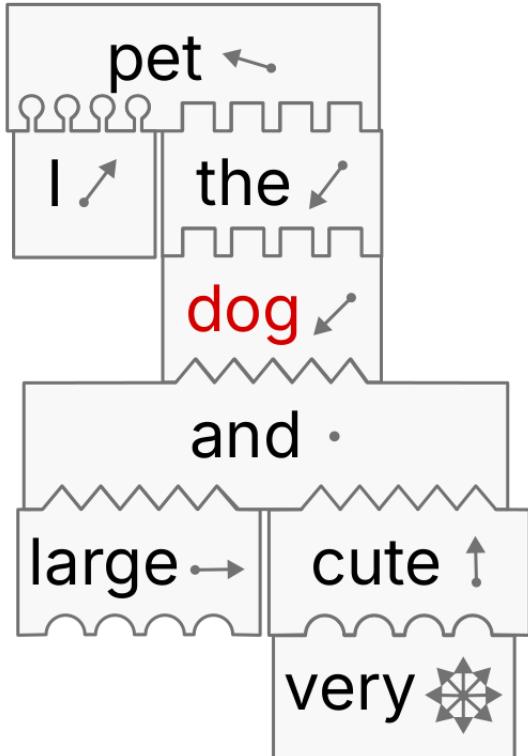
# Large language models (LLMs)

*Attention is all you need:* Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N. Gomez, Łukasz Kaiser, Illia Polosukhin

A



B

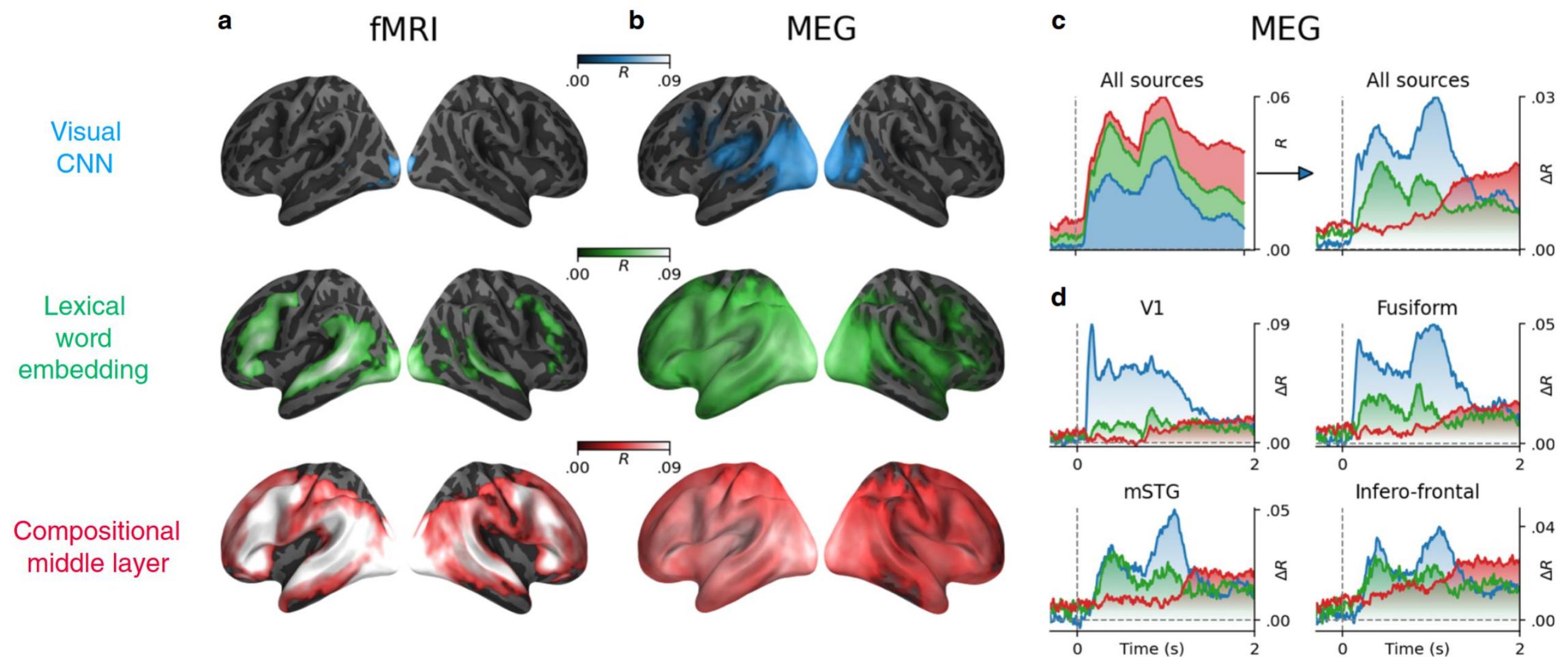


C



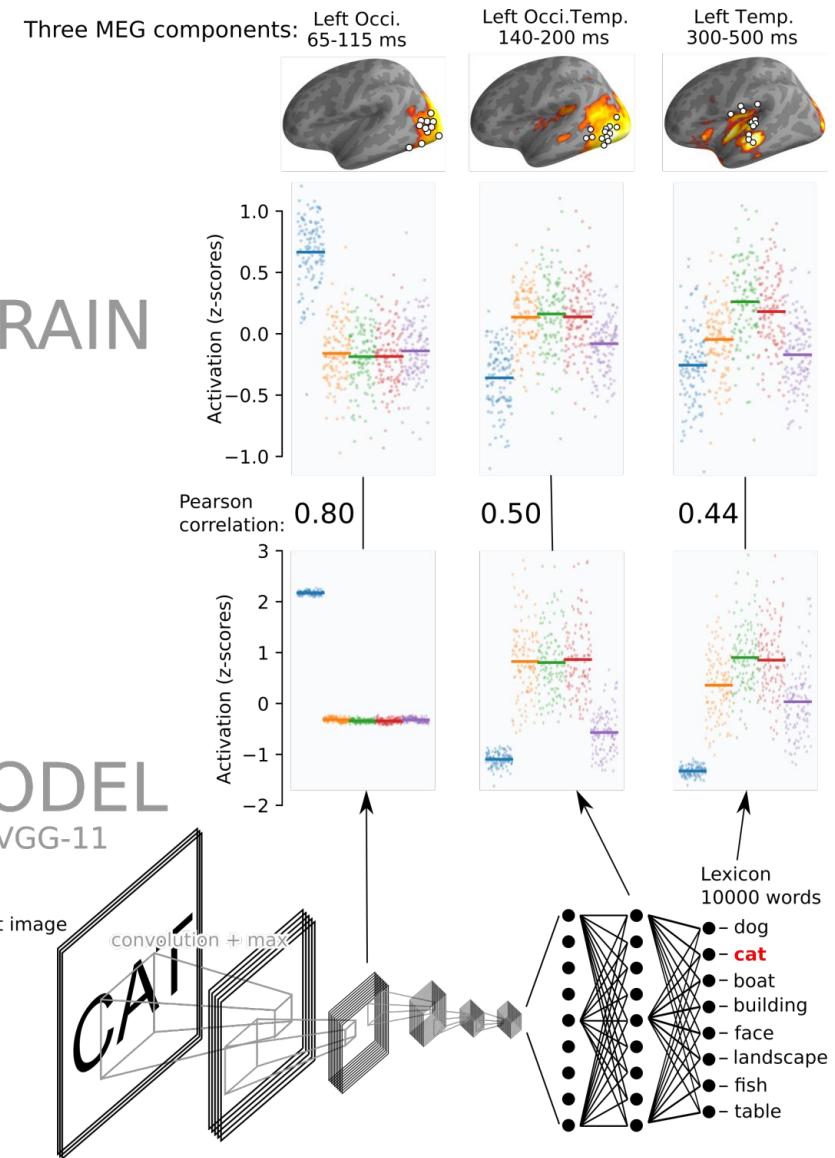
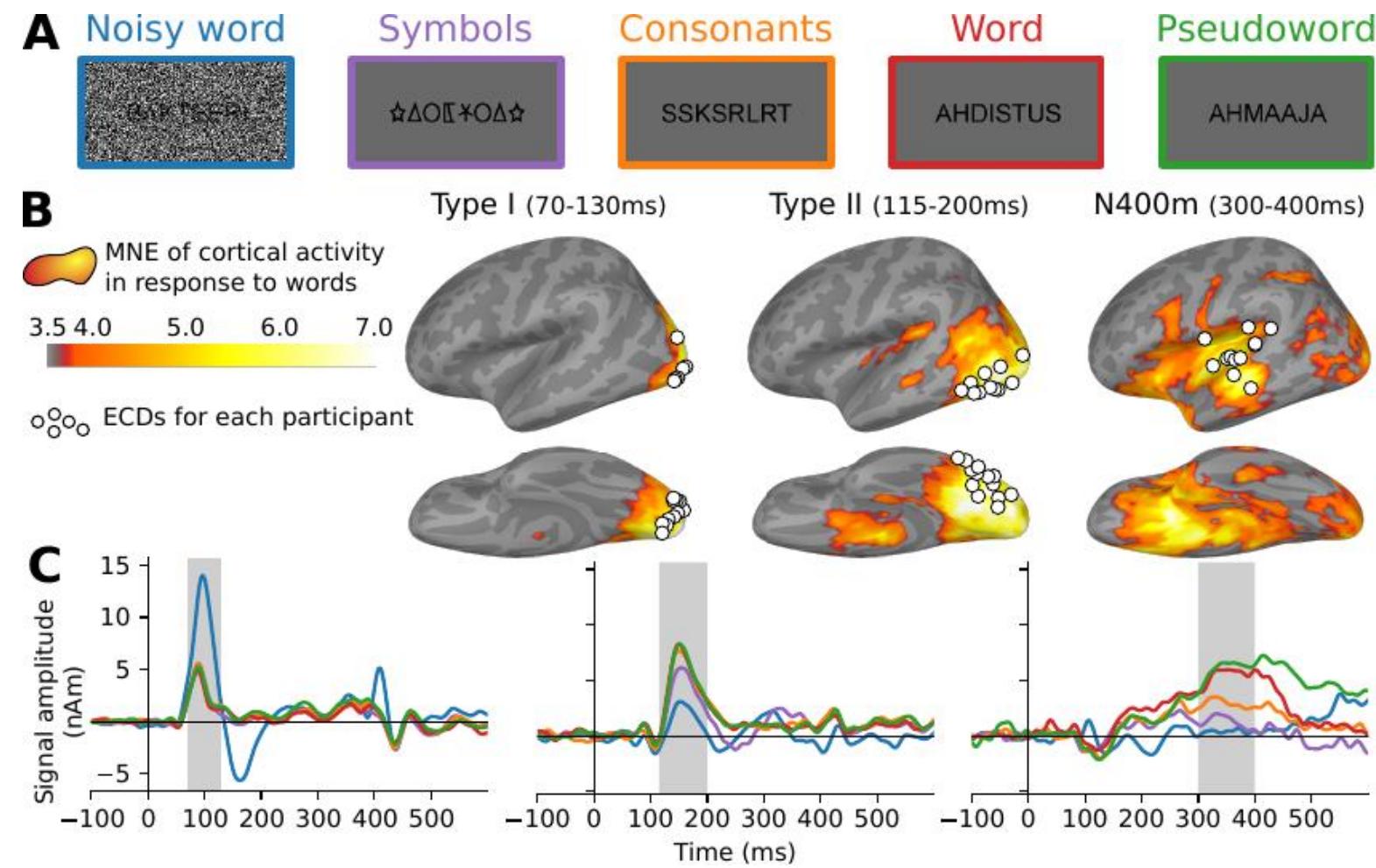
# Comparing LLMs to neuroimaging data

Charlotte Caucheteux & Jean-Rémi King



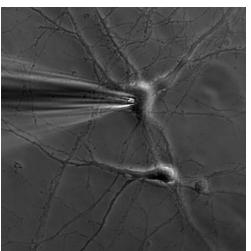
# Modeling EEG/MEG responses

Marijn van Vliet, Oona Rinkinen, Takao Shimizu, Anni-Mari Niskanen, Barry Devereux, Riitta Salmelin

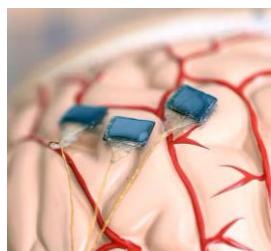


# MICRO → MACRO

neurobiology    electrode arrays



A. Aguado



Blackrock Microsystems

neurons  
synapses  
dendrites

spike trains  
tuning curves

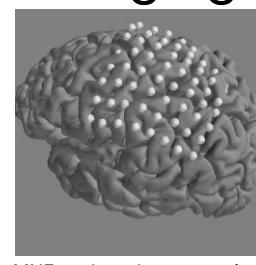
computational modeling

Hodgkin & Huxley  
1952

logical neural  
calculus  
1943

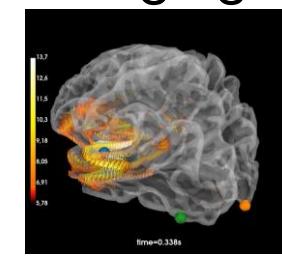
HMAX  
1999

invasive  
imaging



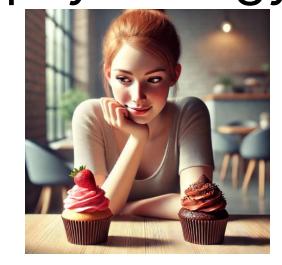
MNE-python documentation

non-invasive  
imaging



Marijn van Vliet

psychology



DALL-E

local field potentials

evoked responses  
spectral power  
connectivity

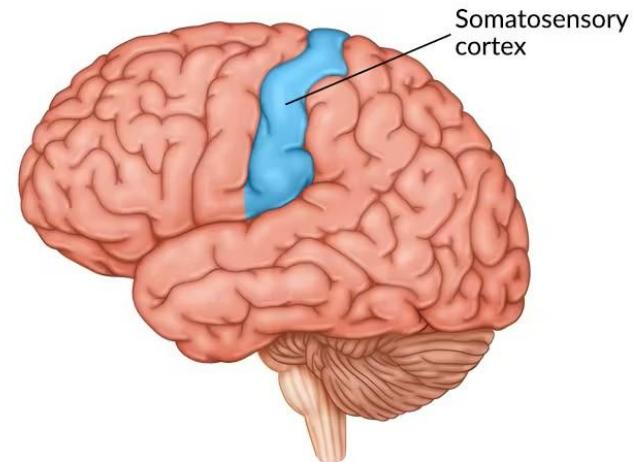
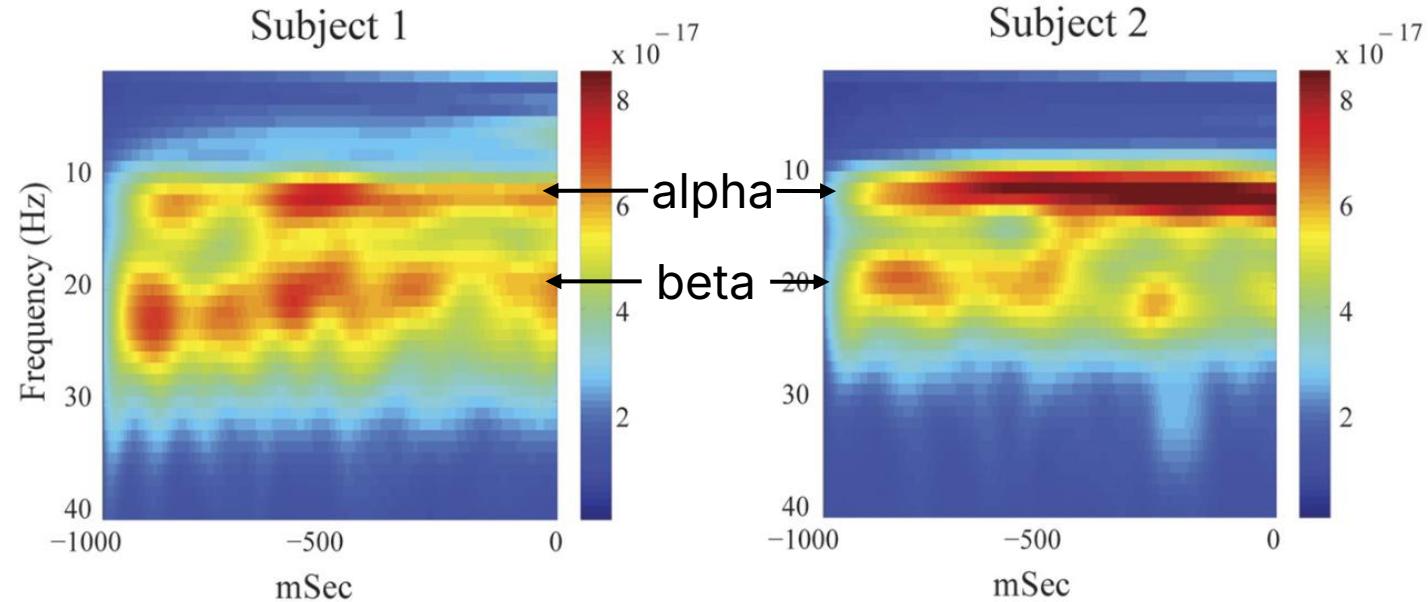
decision making  
behavior  
perception



# Human Neocortical Neurosolver

Tapping on your right hand activates somatosensory cortex:

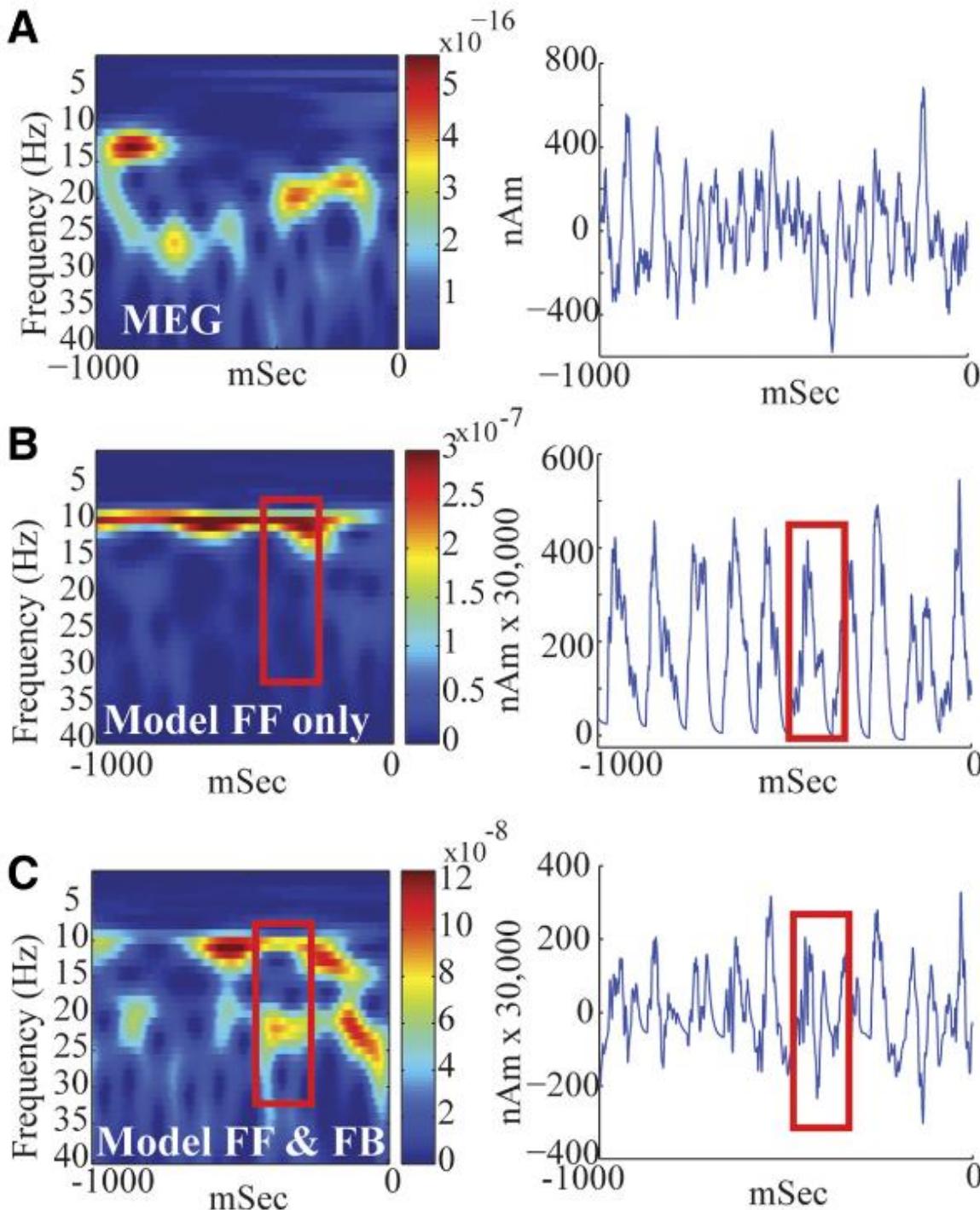
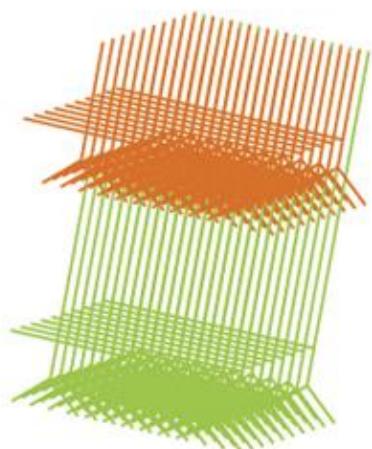
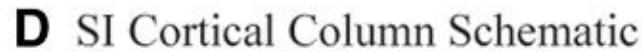
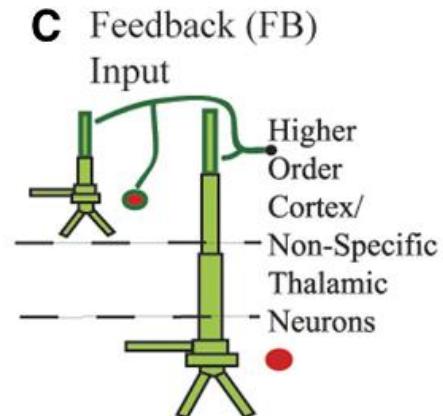
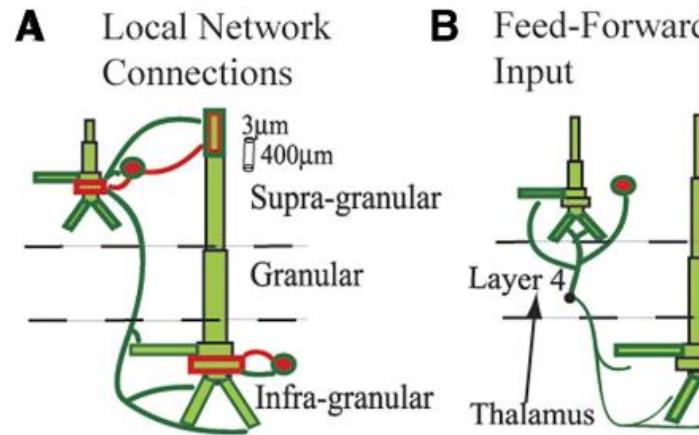
Phenomenon: mu rhythm containing alpha and beta components



Let's simulate a bunch of neurons to reproduce this finding!

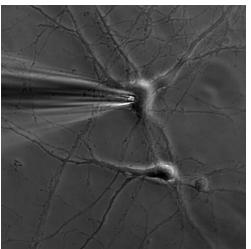
# Human Neocortical Neurosolver

Stephanie Jones, Dominique Pritchett, Michael Sikora, Steven Stufflebeam, Matti Hämäläinen, Christopher Moore

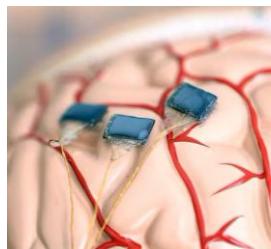


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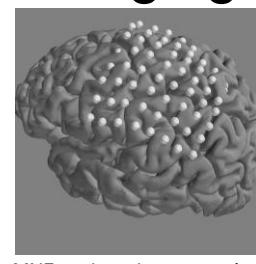
Blackrock Microsystems

neurons  
synapses  
dendrites

spike trains  
tuning curves

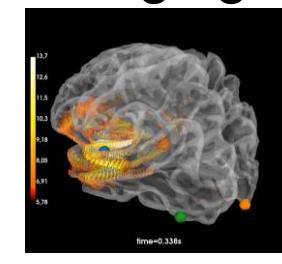
computational modeling

invasive  
imaging



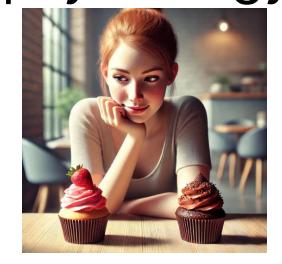
MNE-python documentation

non-invasive  
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Marijn van Vliet

psychology



DALL-E

Hodgkin & Huxley  
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2020

HMAX  
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perceptron  
1958

deep learning  
2017

drift-diffusion  
1978

# Predictive coding

Rajesh Rao, Dana Ballard, Michael Spratling



René Magritte

[...] wir stets solche Objecte als im Gesichtsfelde vorhanden uns vorstellen, wie sie vorhanden sein müssten, um unter den gewöhnlichen normalen Bedingungen des Gebrauchs unserer Augen denselben Eindruck auf den Nervenapparat hervorzubringen.

[...] such objects are always imagined as being present in the field of vision as would have to be there in order to produce the same impression on the nervous mechanism, the eyes being used under ordinary normal conditions.

Hermann von Helmholtz (1867)

I'm entering the living room...

Expectation



Reality



# We must have a new pillow...

## Expectation



## Reality



# When did we get a dog???

## Expectation

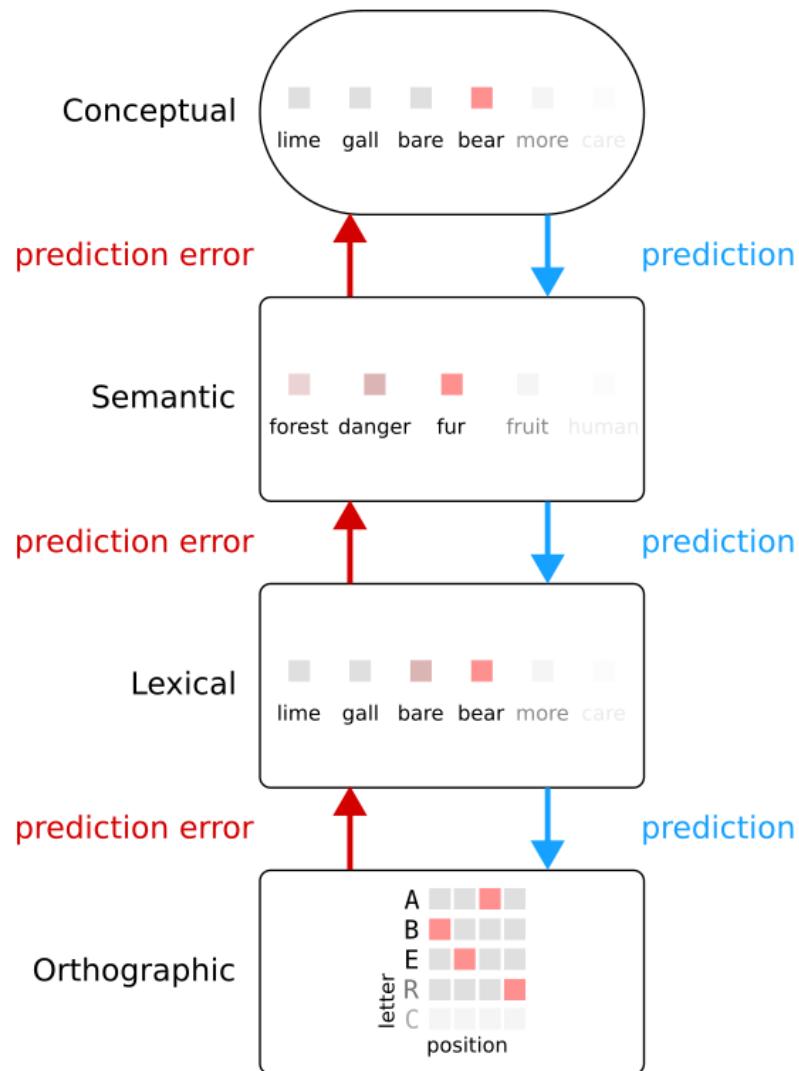


## Reality



# Predictive coding model of visual word recognition

Samer Nour Eddine, Trevor Brothers, Lin Wang, Michael Spratling, Gina R. Kuperberg (2024)

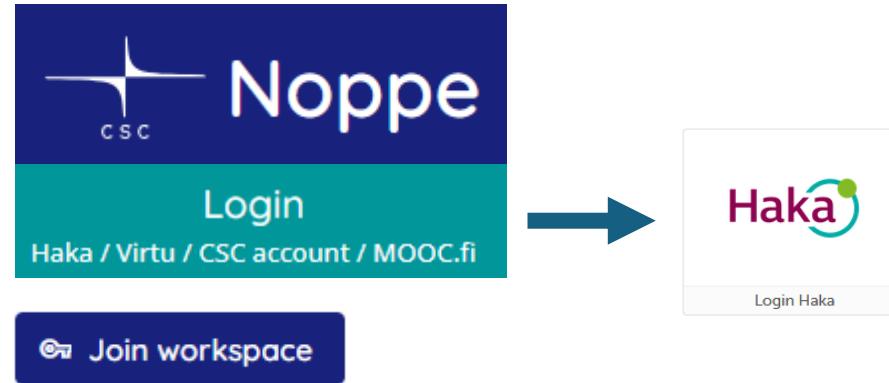


Each layer is doing the following:

1. Based on your current state, predict the state of the layer below ( $\text{prediction} = \text{weights}^{\text{top-down}} * \text{state}$ )
2. Compare the prediction you got from the layer above you to your current state ( $\text{error} = \text{prediction} - \text{state}$ )
3. Send error signal to the layer above ( $\text{error\_signal} = \text{weights}^{\text{bottom-up}} * \text{error}$ )
4. Adjust your state to minimize prediction error  
( $\text{state} = \text{state} + 0.01 * \underbrace{\text{error\_signal}}_{\text{some small value}} \text{ "step-size"}$ )

# Hands-on exercise: predictive coding model of the N400

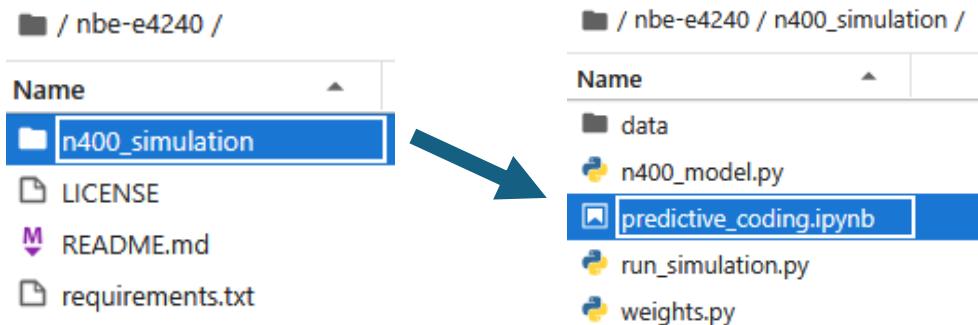
1. Open a browser: **noppe.csc.fi**
2. Login with HAKA account
3. Top right corner: join workspace
4. Enter join code: **nbe-pdyuqajr**



5. Hit the power button



6. Open notebook: n400\_simulation/predictive\_coding.ipynb

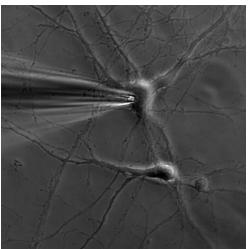


backup: [github.com/wmvanvliet/nbe-e4240](https://github.com/wmvanvliet/nbe-e4240)

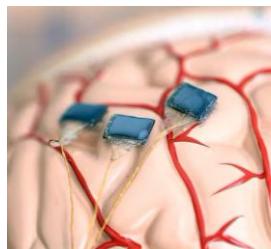


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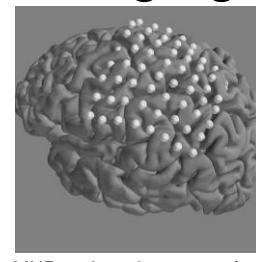
Blackrock Microsystems

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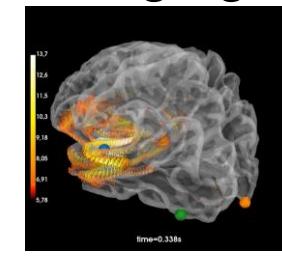
## computational modeling

invasive  
imaging



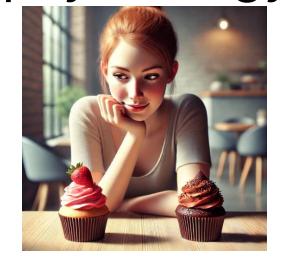
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1978

# Conclusion

Computational modeling: answering questions by building stuff

Is someone actually faster or just performing more sloppy?

How can a bunch of neurons perform a computation?

Is visual word recognition achieved through convolution and pooling?

Why and when does a neuron "spike"?

Are simple and complex cells enough to encode an image?

What if it's not the sensory input itself, but the violation of our expectations that drives neural activity?