EPFL

Neuroscience and Machine Learning

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Phys-754 Lecture series on scientific machine learning
September 26, 2024

Part 1

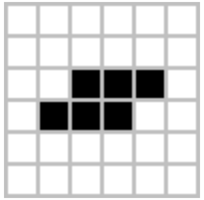
ML tools for neuroscience (studying the brain)

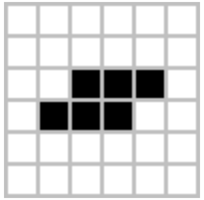
You know, people think mathematics is complicated. Mathematics is the simple bit. It's the stuff we can understand. It's cats that are complicated.

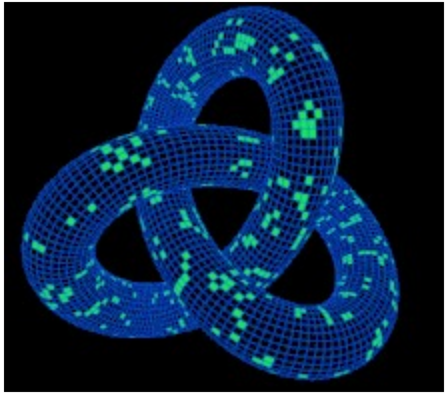
John Horton Conway

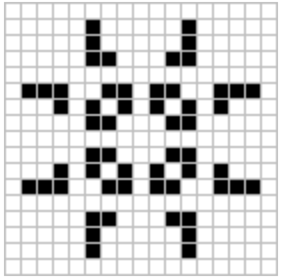
Conway’s game of life

- Any live cell with two or three live neighbors survives.
- Any dead cell with three live neighbors becomes a live cell.
- All other live cells die in the next generation. Similarly, all other dead cells stay dead.





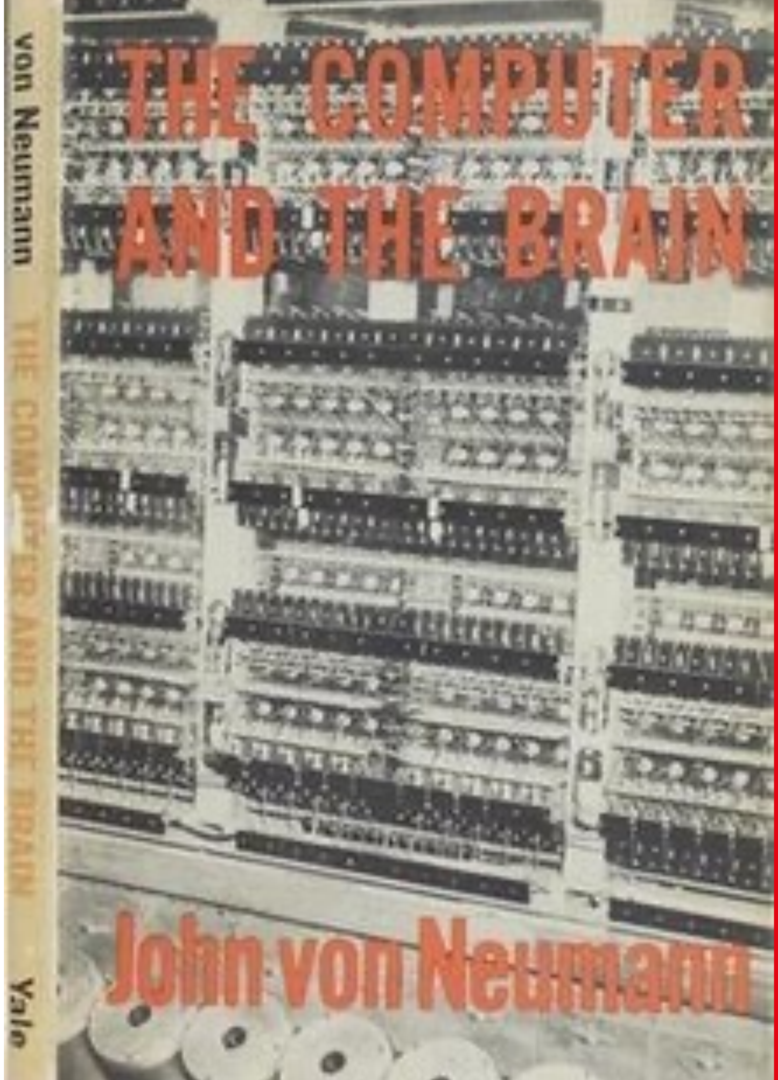




https://en.wikipedia.org/wiki/Human_brain

How does the brain compute?

vs. Turing Machines, von Neumann machines, …



How does the brain compute?

vs. Turing Machines, von Neumann machines, …

https://en.wikipedia.org/wiki/The_Computer_and_the_Brain

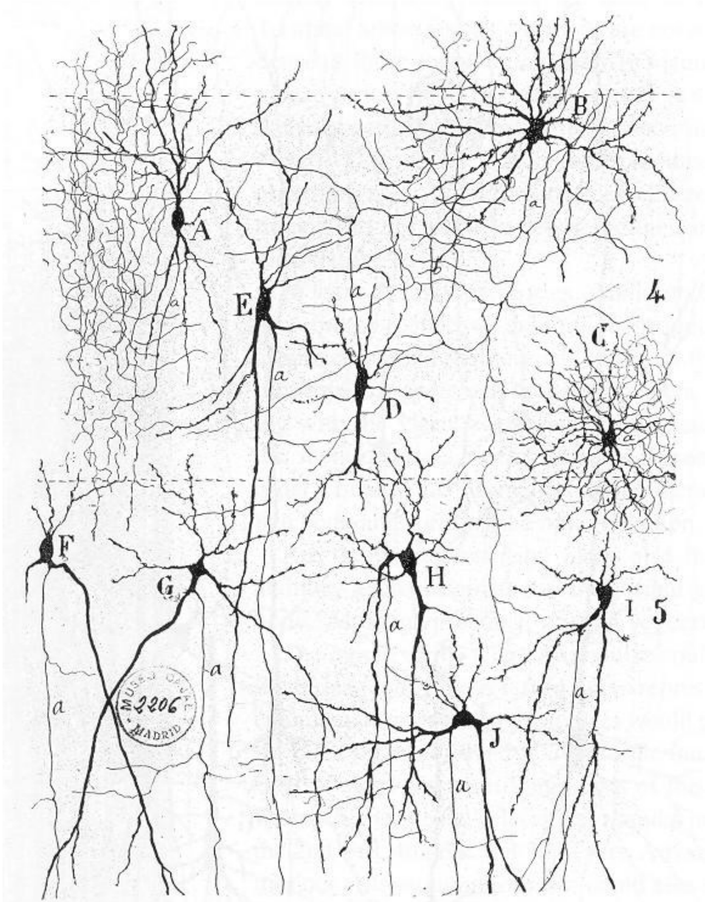
Brains are complex

Human brain:

- 86 billion (10^{10}) neurons
- ~1.5×10^{14} synapses

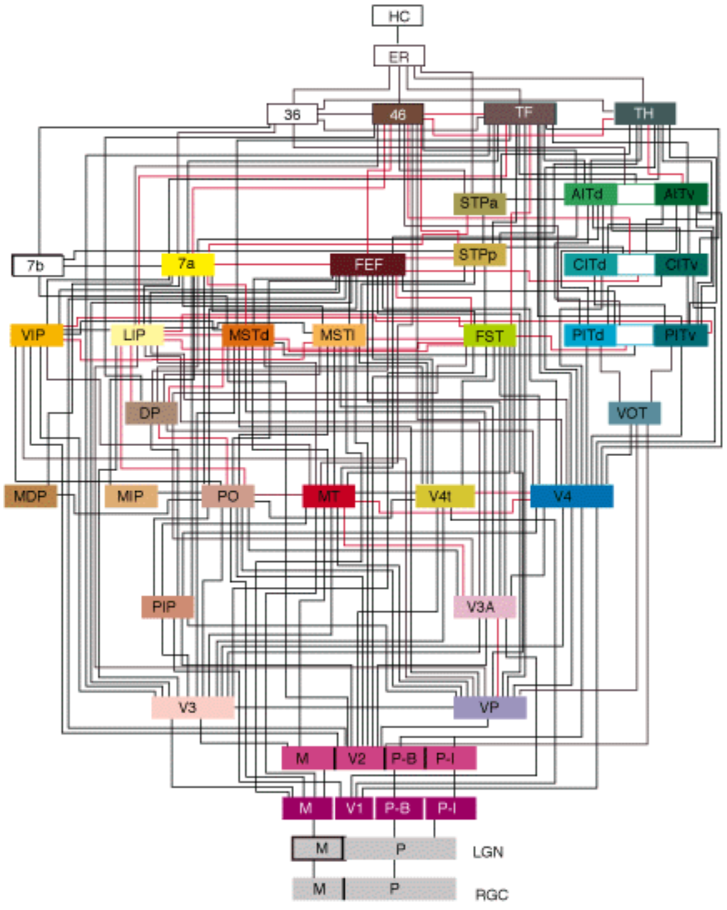
Mouse brain:

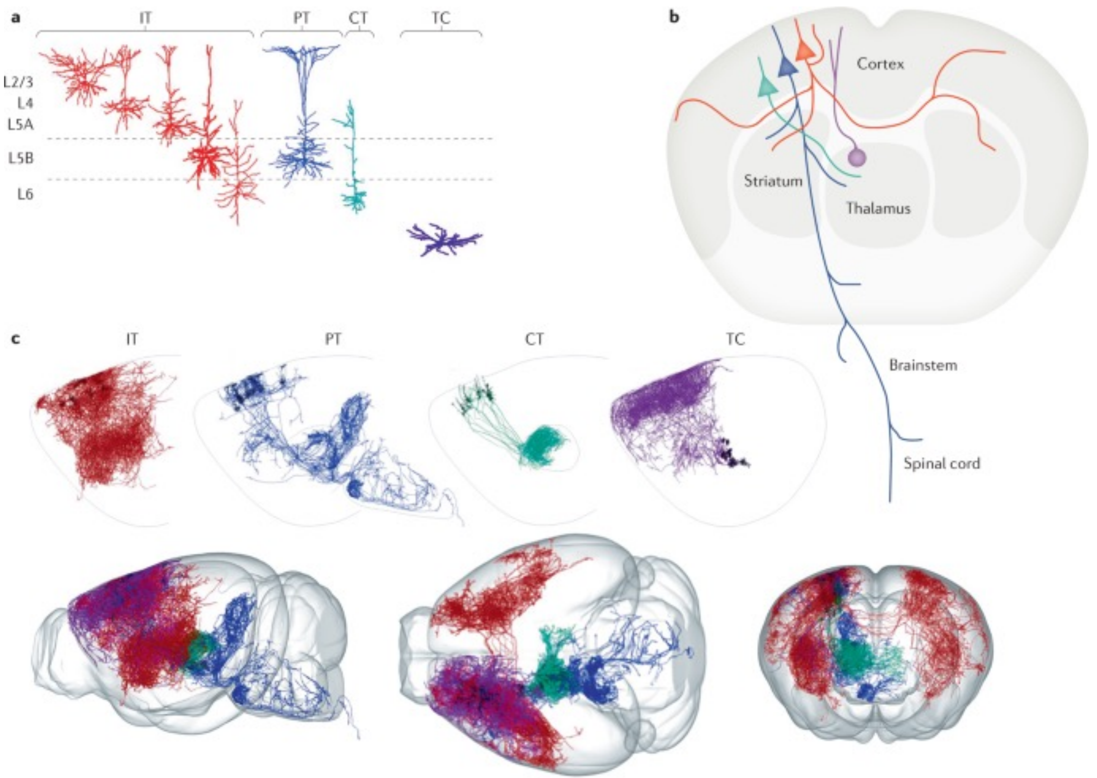
- 71 million neurons
- 10^{12} synapses



Santiago Ramon y Cajal

Neural circuits are staggeringly complex



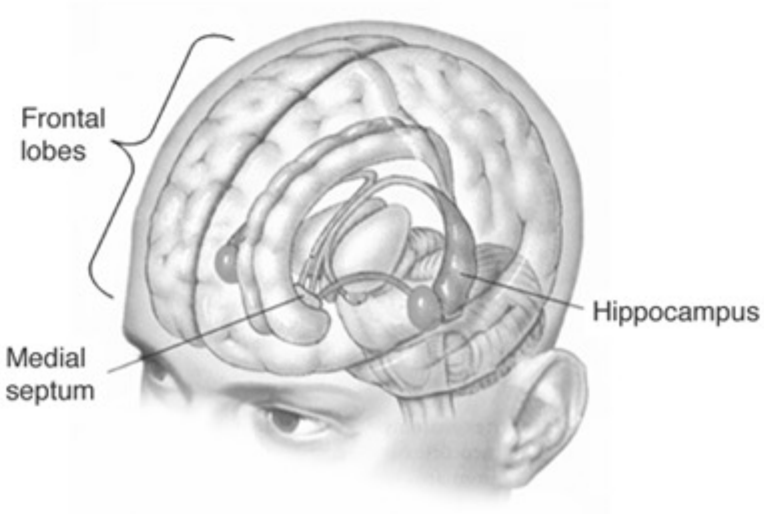


Felleman and Van Essen *Cerebral Cortex* 1991

Shepherd and Yamawaki *Nature review neuroscience* 2021

How do neuroscientists localize brain function?

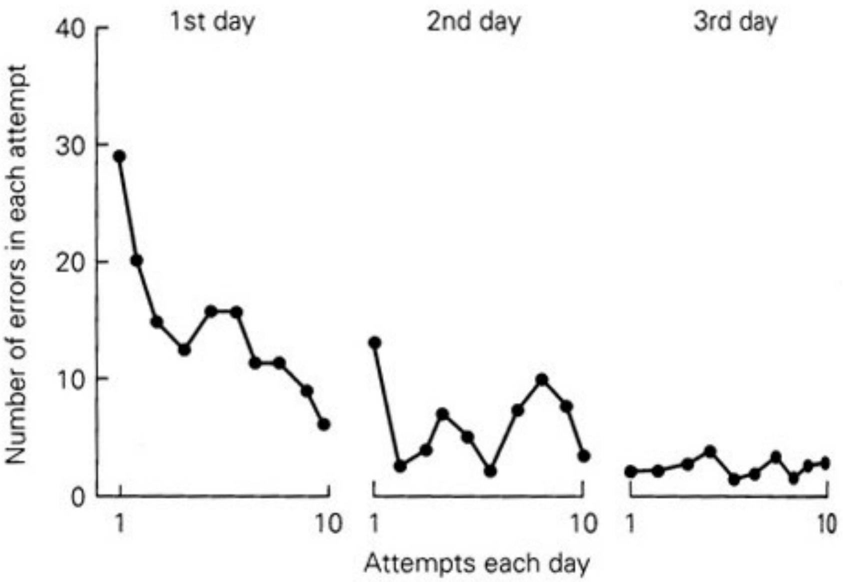
Patient H.M.

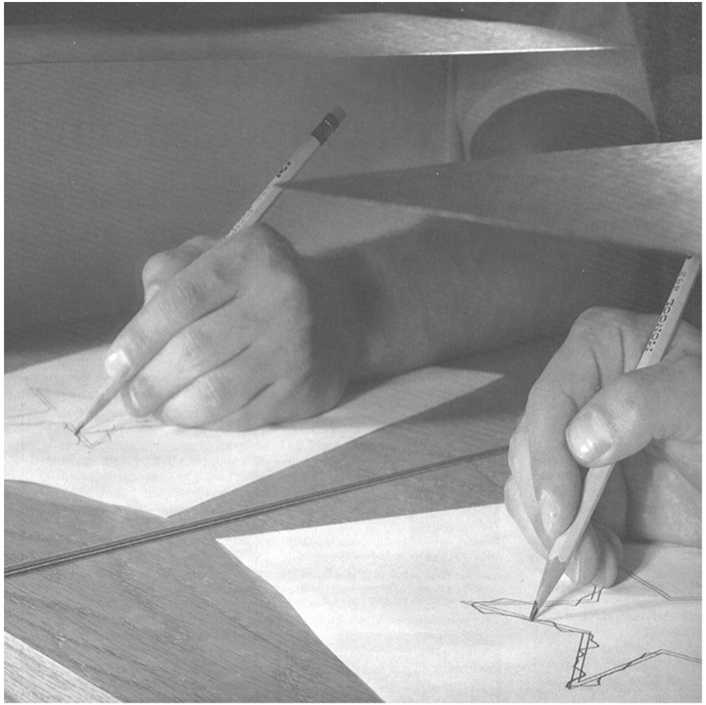


https://en.wikipedia.org/wiki/Henry_Molaison

Milner 1962: mirror drawing could be learned over a period of days by the severely amnesic patient H.M. in the absence of any conscious memory of having practiced the task before

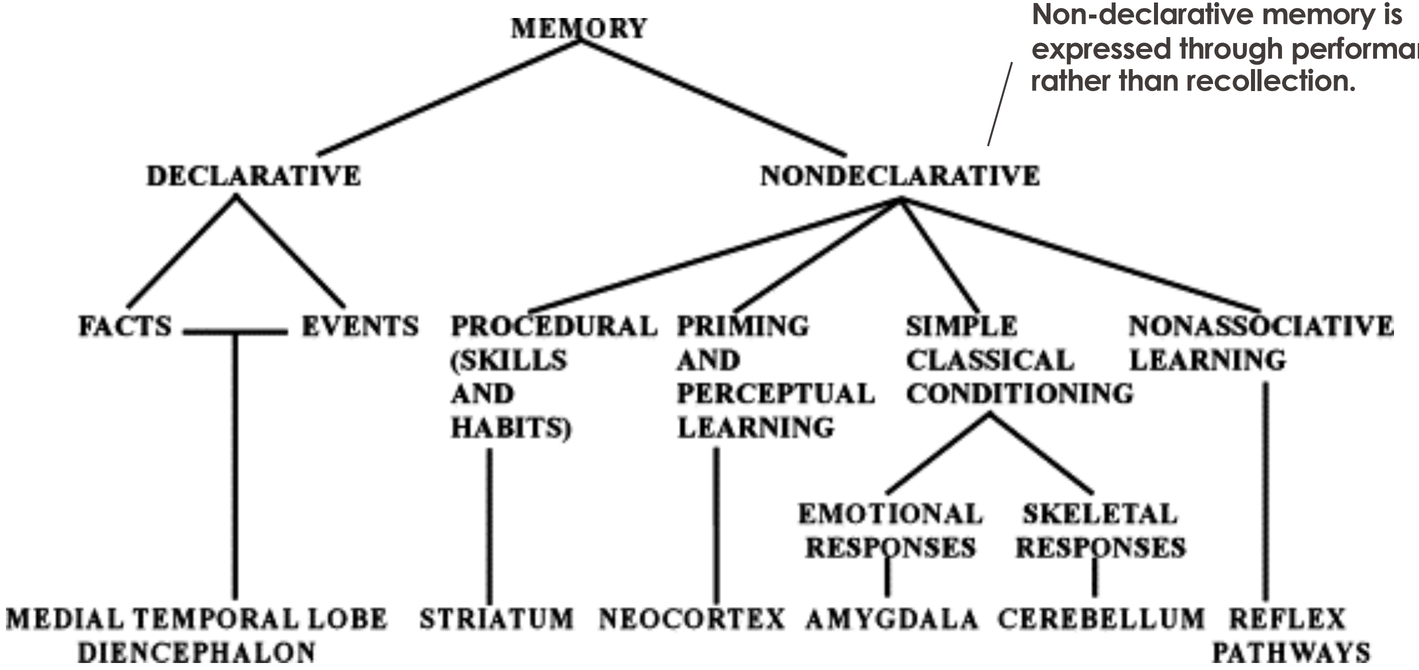
Milner (1962) Physiologie de l'hippocampe.





Kandel et al. Principles of Neural Science 2000 (62-2)

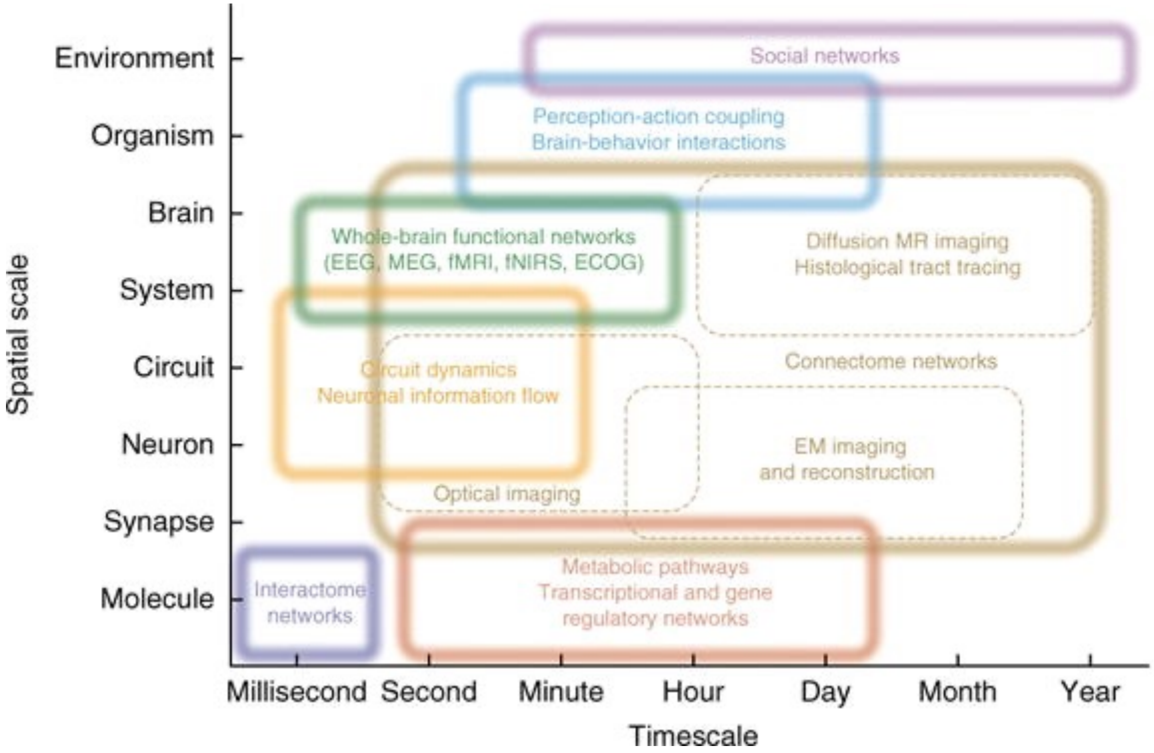
Memory systems of the brain



Non-declarative memory is expressed through performance rather than recollection.

Squire (2004) Neurobiology of Learning and Memory

Methods for measuring brain function



Basset, Nat Neuro 2017

Neural data poses many hard inference problems to extract task relevant variables

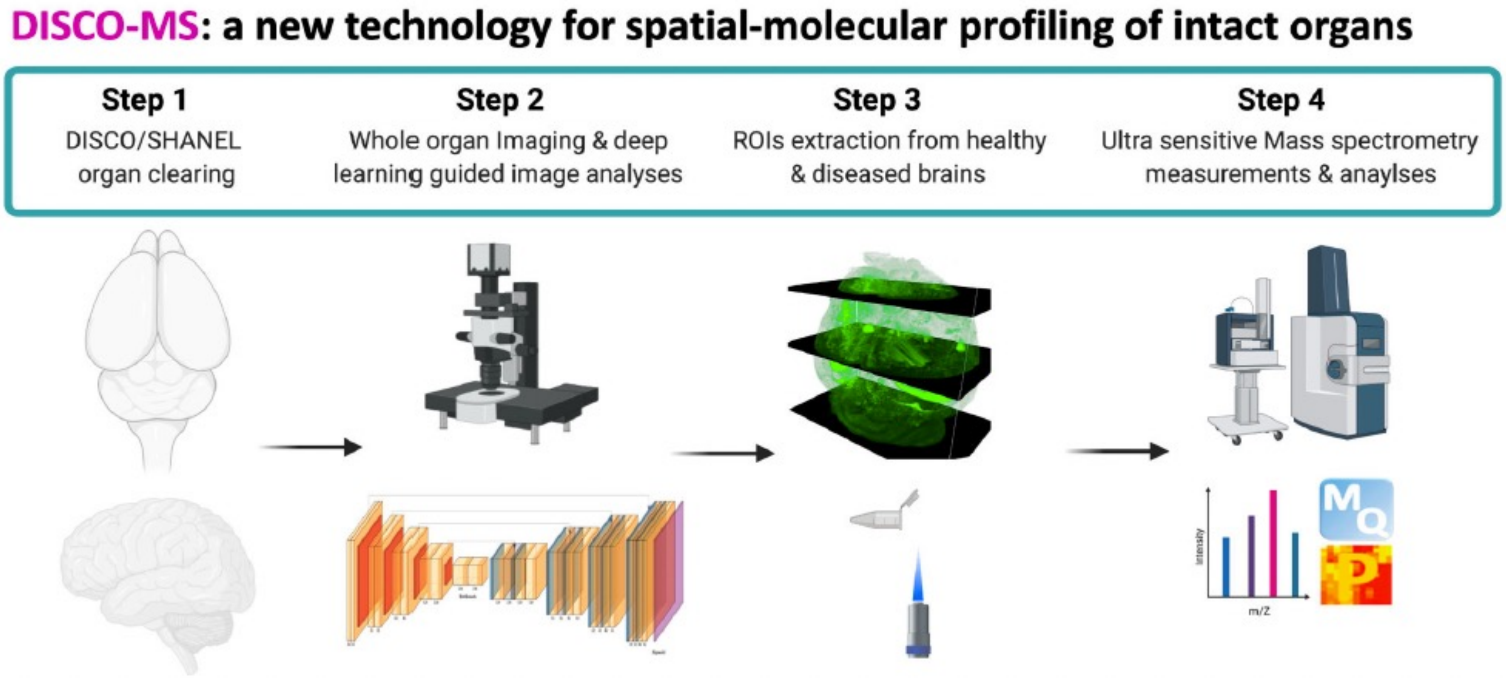
Neural data:

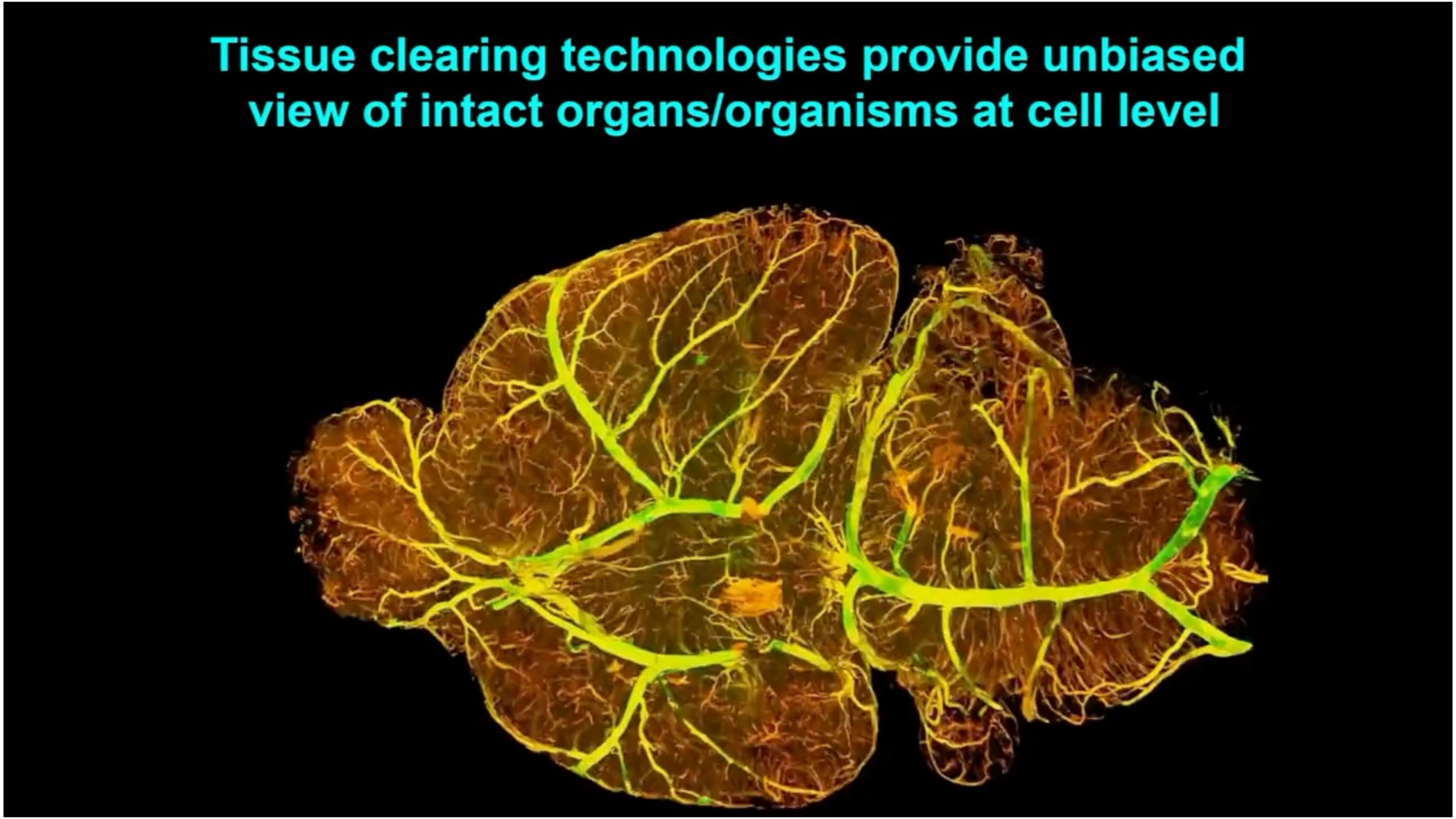
- Cell segmentation, brain area segmentation
- Spike sorting
- Connectomics
- ….

Behavior:

- Pose estimation
- Behavior understanding,
- Action recognition
- …

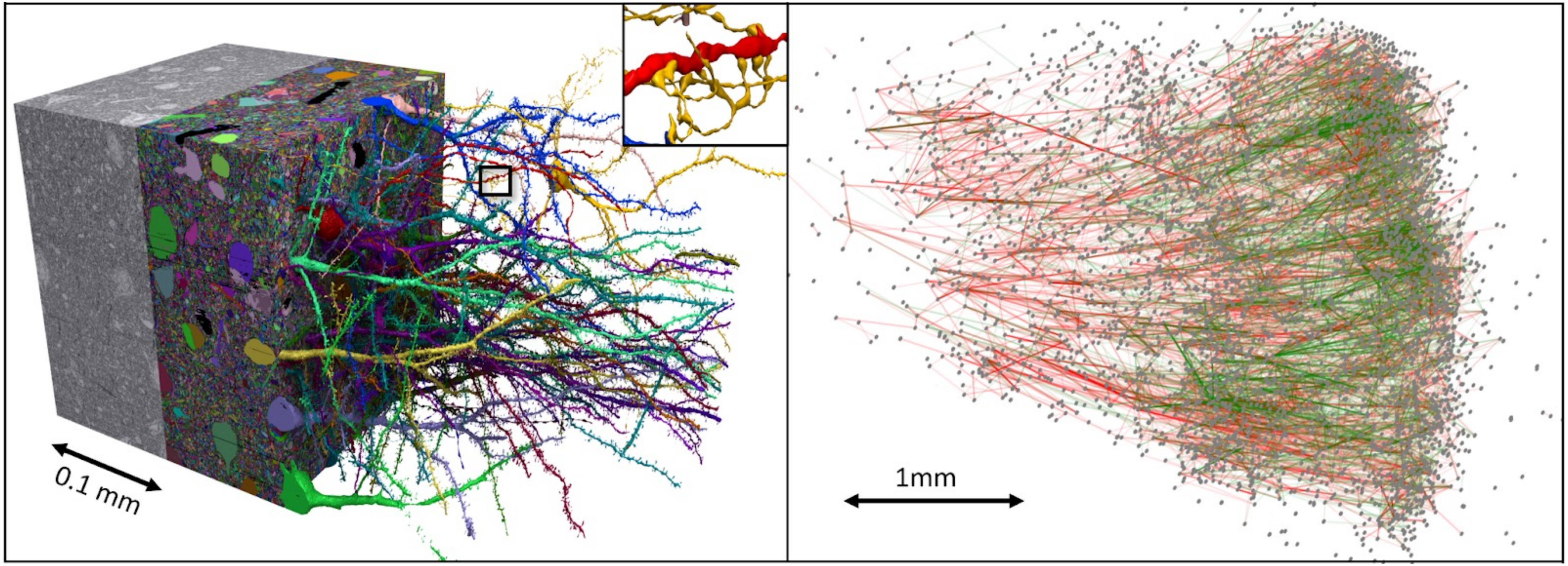
Proteomics of spatially identified tissues in whole organs



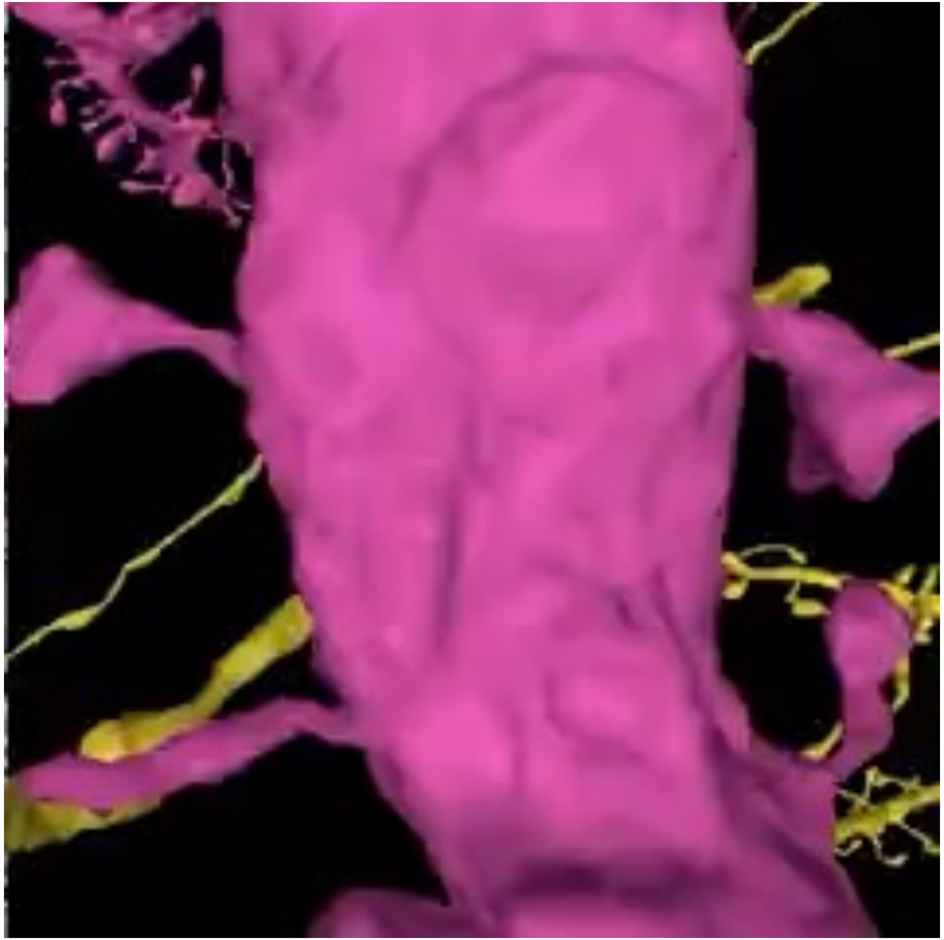


Proteomics of spatially identified tissues in whole organs, Ertürk lab, Helmholtz Institute

A connectomics study of a petascale fragment of human cerebral cortex



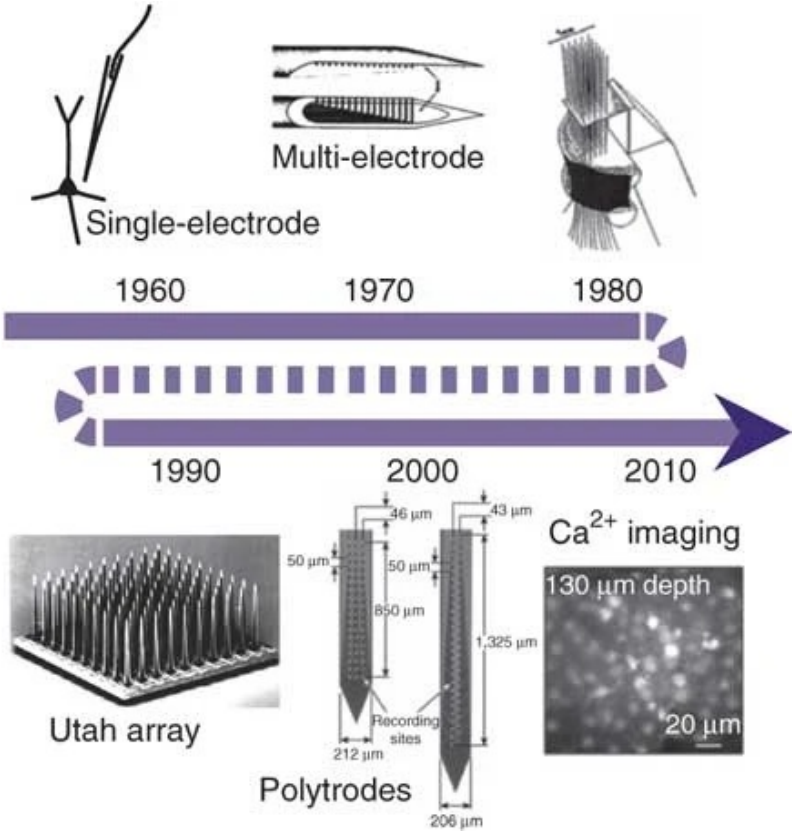
Shapson-Coe et al., Lichtman Lab, Harvard U



Video & image credits: Tolias lab, Xu lab at Cornell, Reid and daCosta labs at AIBS,
Seung lab at Princeton, Paninski lab @ Columbia.

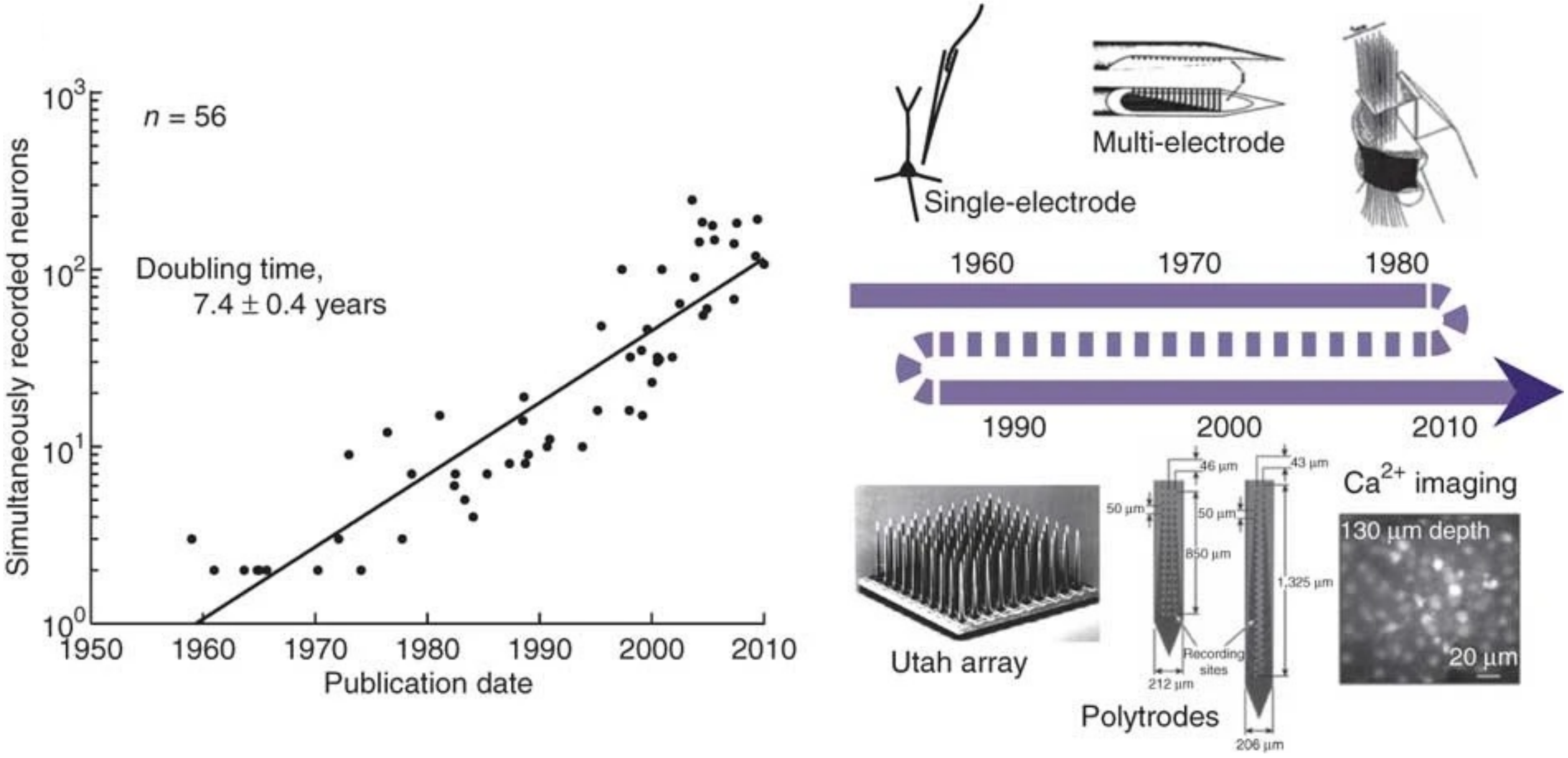
Measuring in vivo brain activity

Single unit recoding: “Moore’s law”



How advances in neural recording affect data analysis, Stevenson & Kording Nature Neuroscience 2011

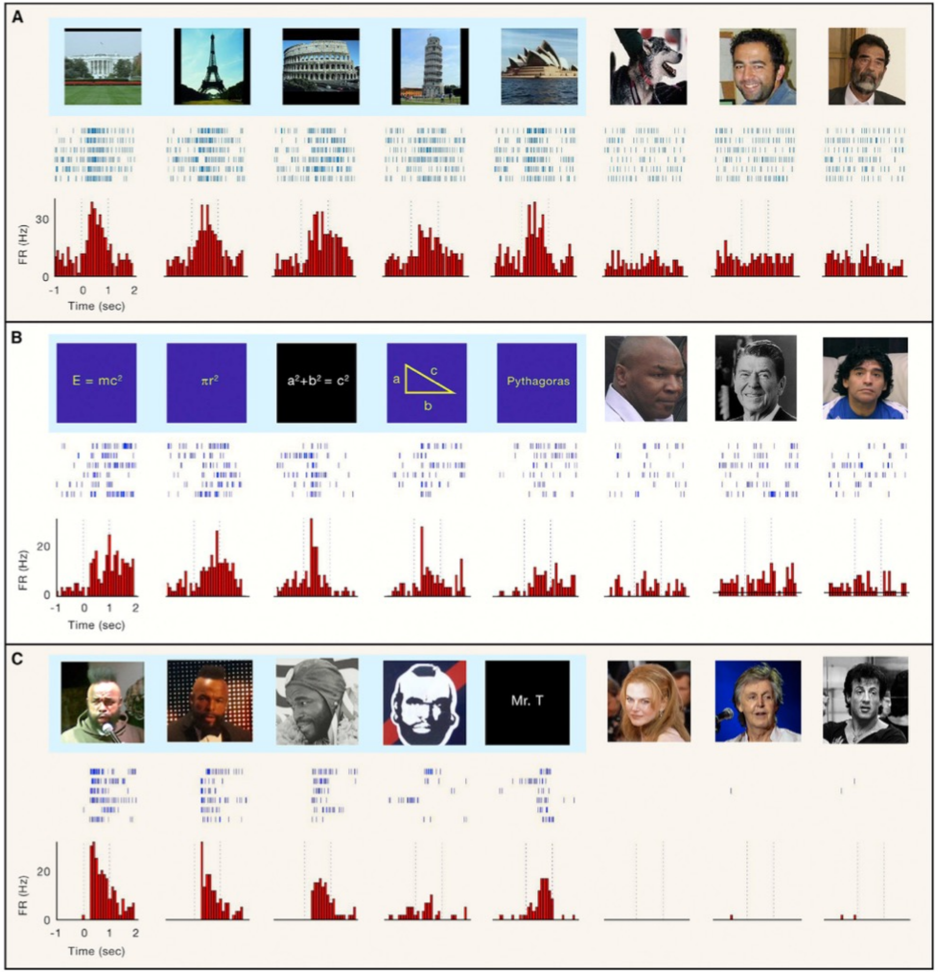
Single unit recoding: “Moore’s law”



How advances in neural recording affect data analysis, Stevenson & Kording Nature Neuroscience 2011

Single units in the human temporal lobe

Neurons can correspond to complex concepts shown in *different ways* in a selective fashion, e.g. “buildings” or “math”



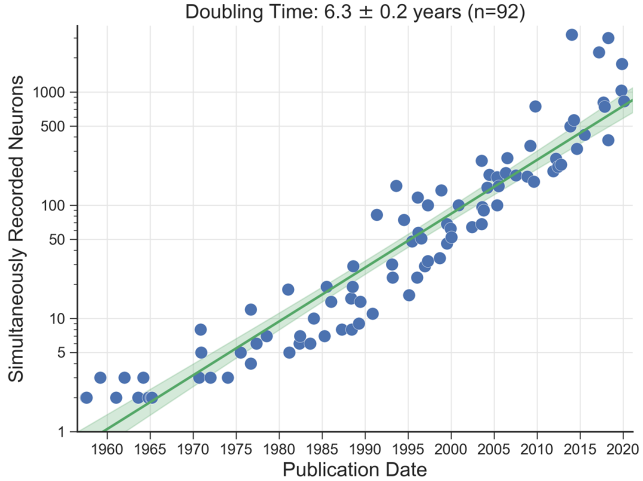
Rasterplots and peristimulus histograms for 3 neurons with stimuli

Quiroga, Cell 2019

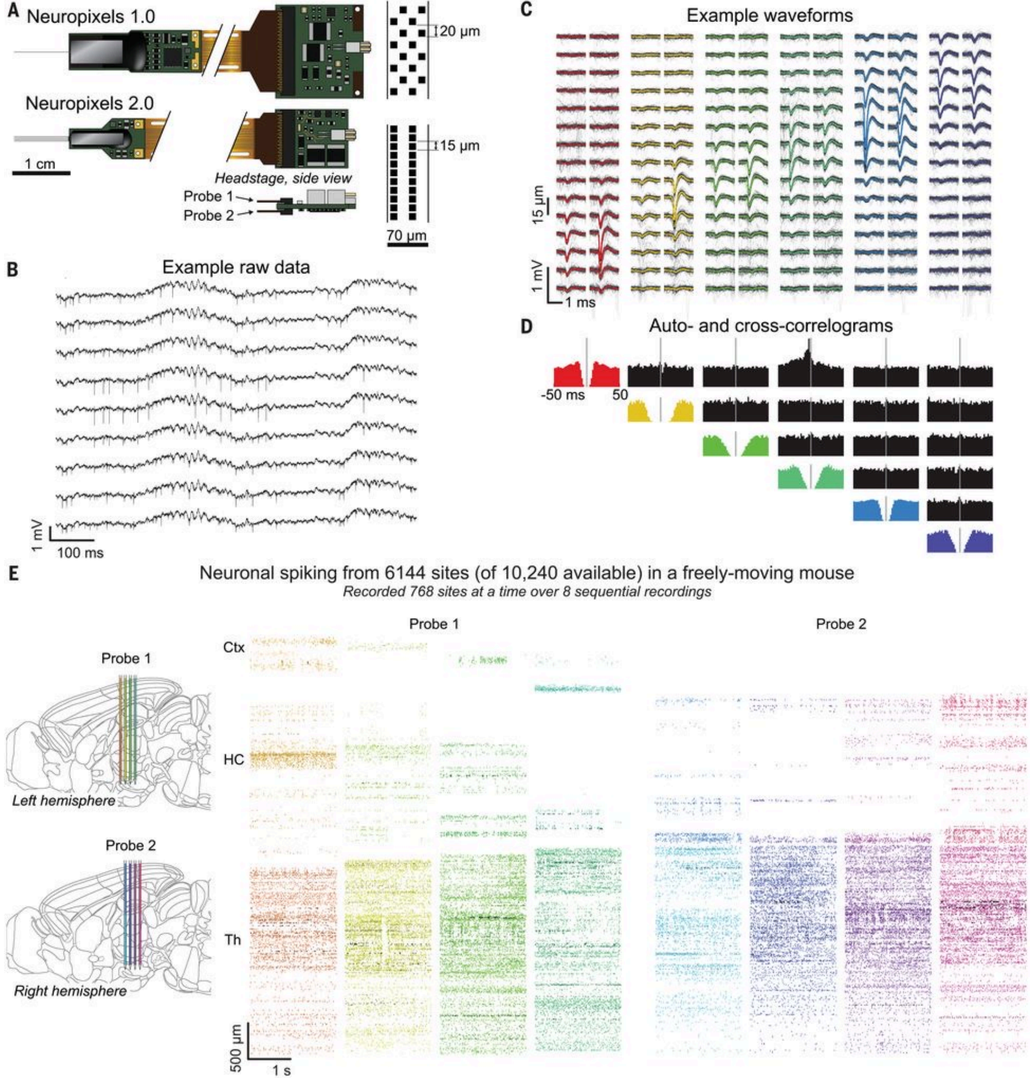
Neuropixel 2.0: high-density probe for stable, long-term recordings

Steinmetz et al. 2020, Science

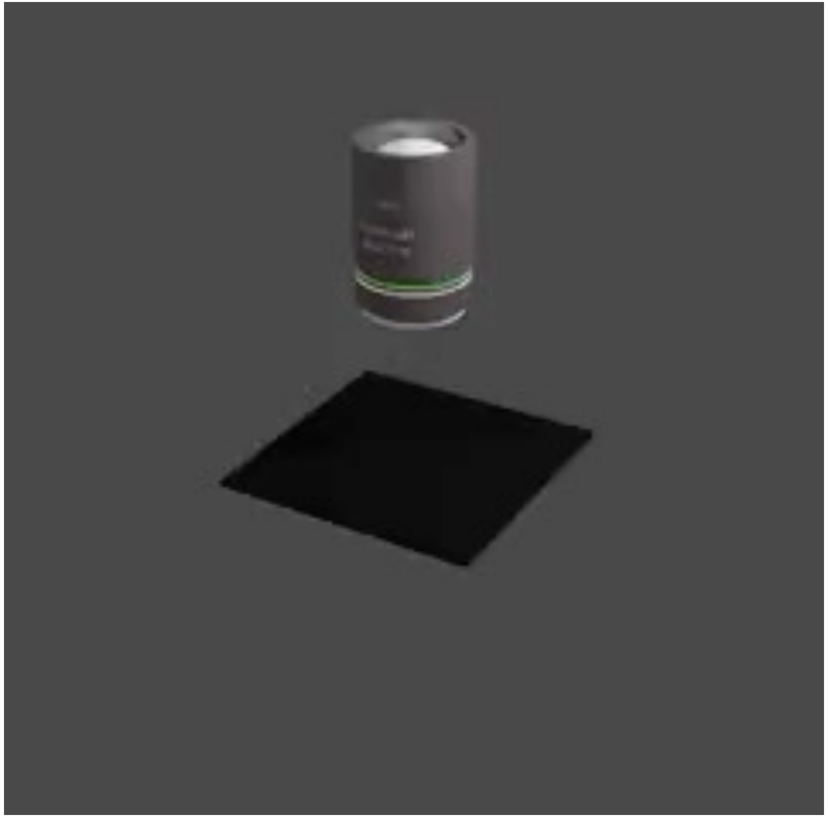
- 10,240 recording sites
  in one implant with ~1.1g



https://stevenson.lab.uconn.edu/scaling/



2 photon microscopy



Video & image credits: Tolias lab, Xu lab at Cornell, Reid and daCosta labs at AIBS,
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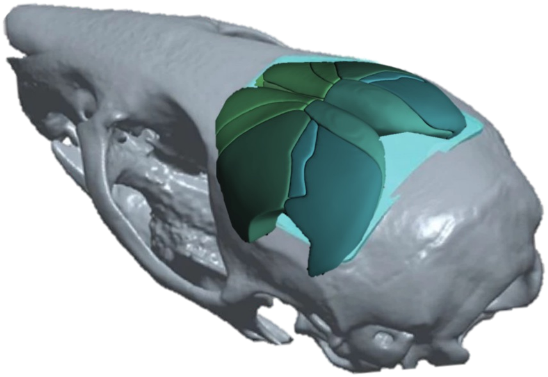
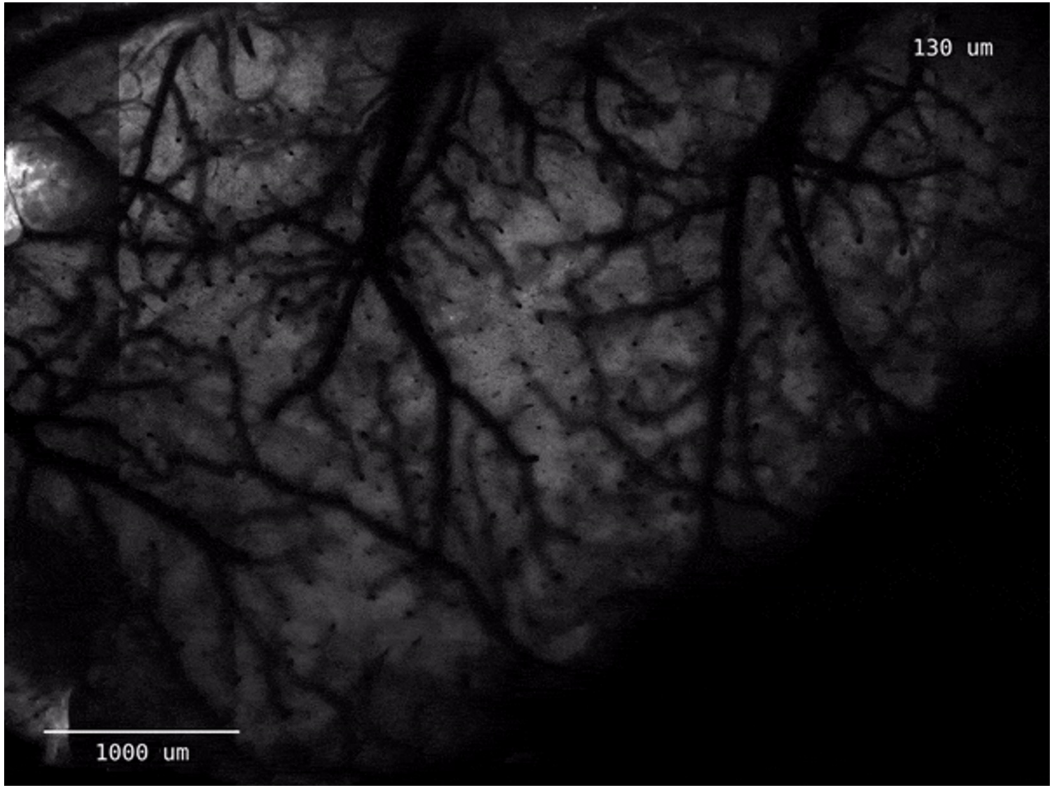
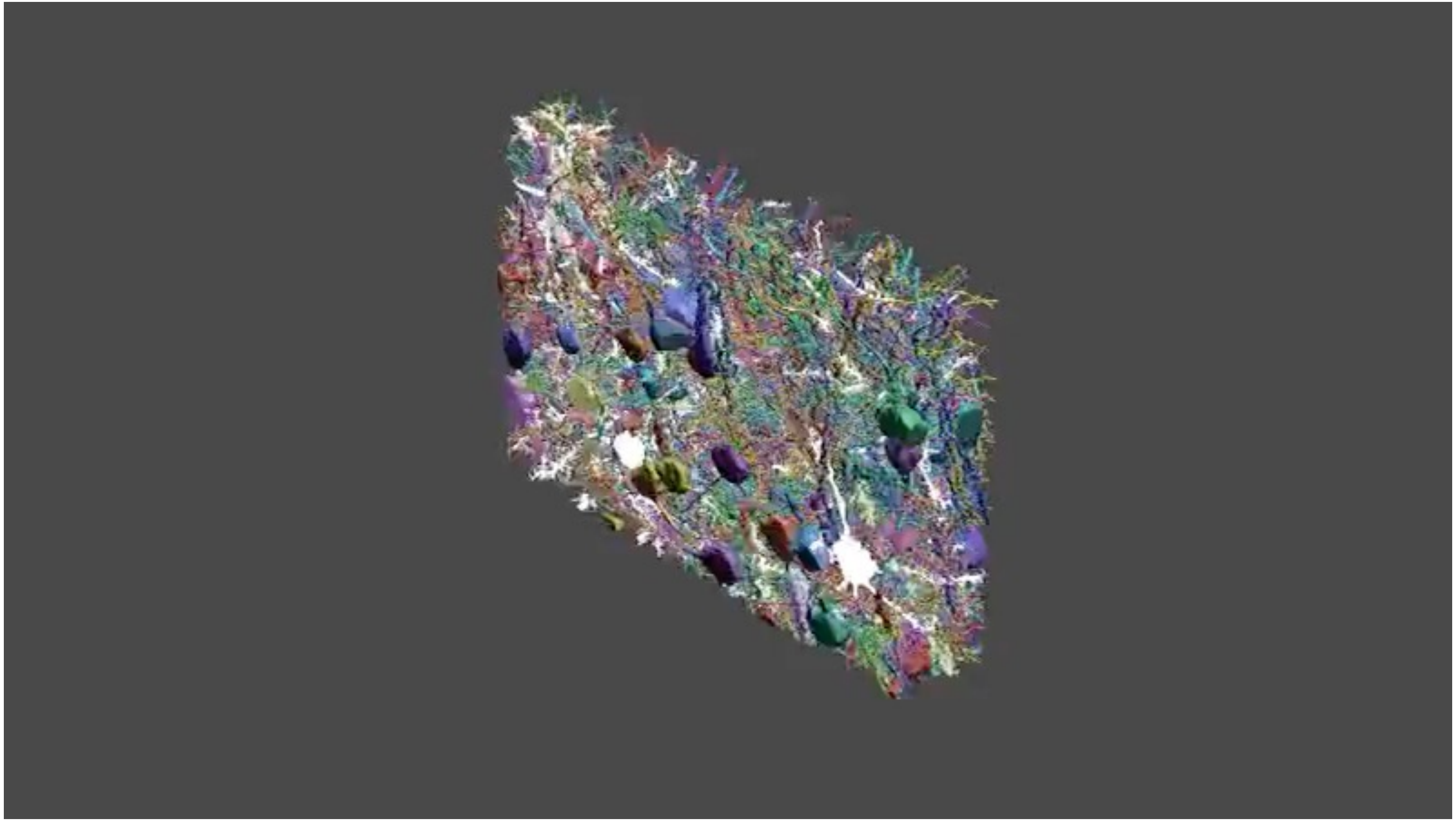


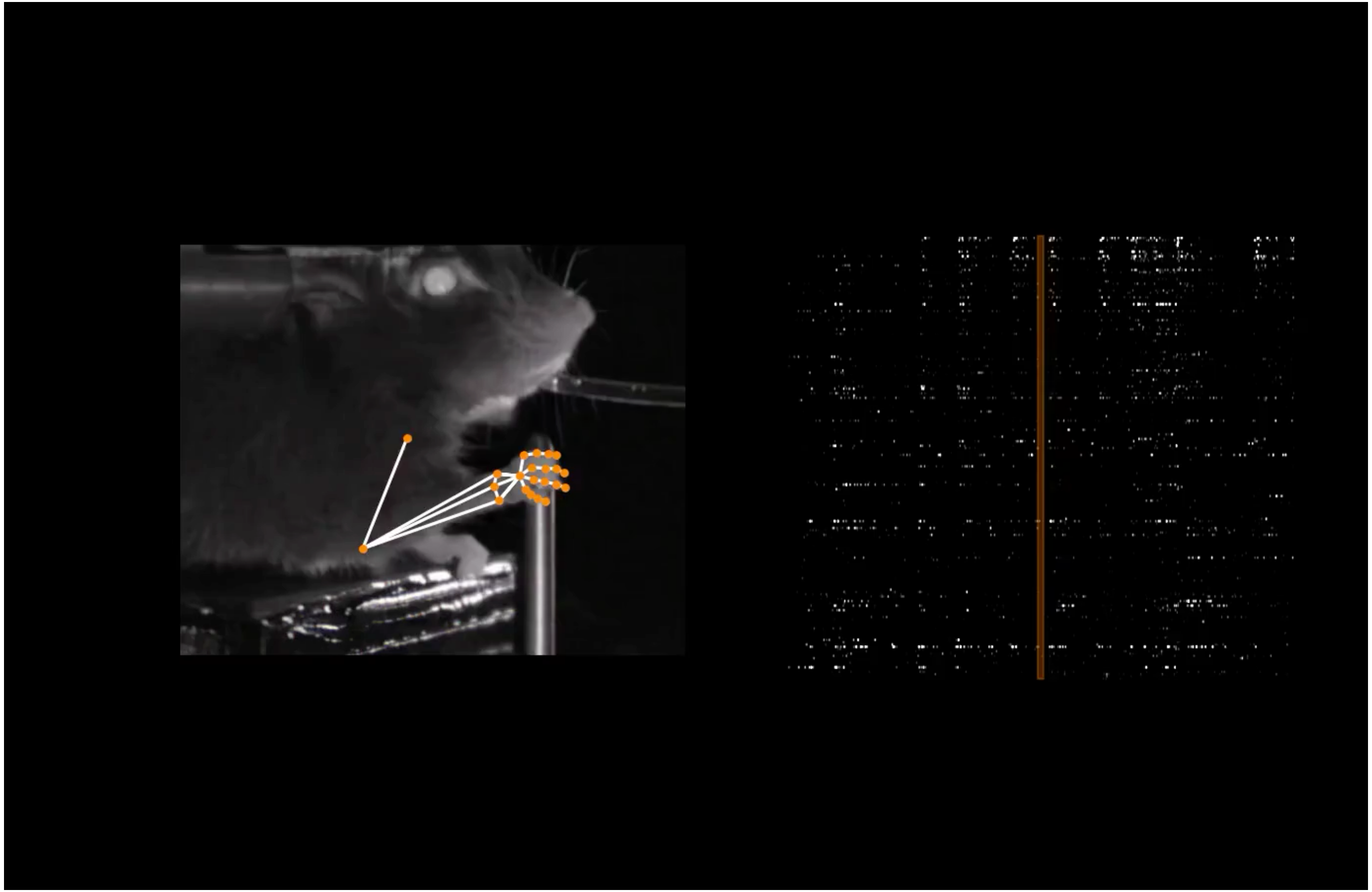


Sofroniew et al. eLife 2016



Video & image credits: Tolias lab, Xu lab at Cornell, Reid and daCosta labs at AIBS,
Seung lab at Princeton, Paninski lab @ Columbia.

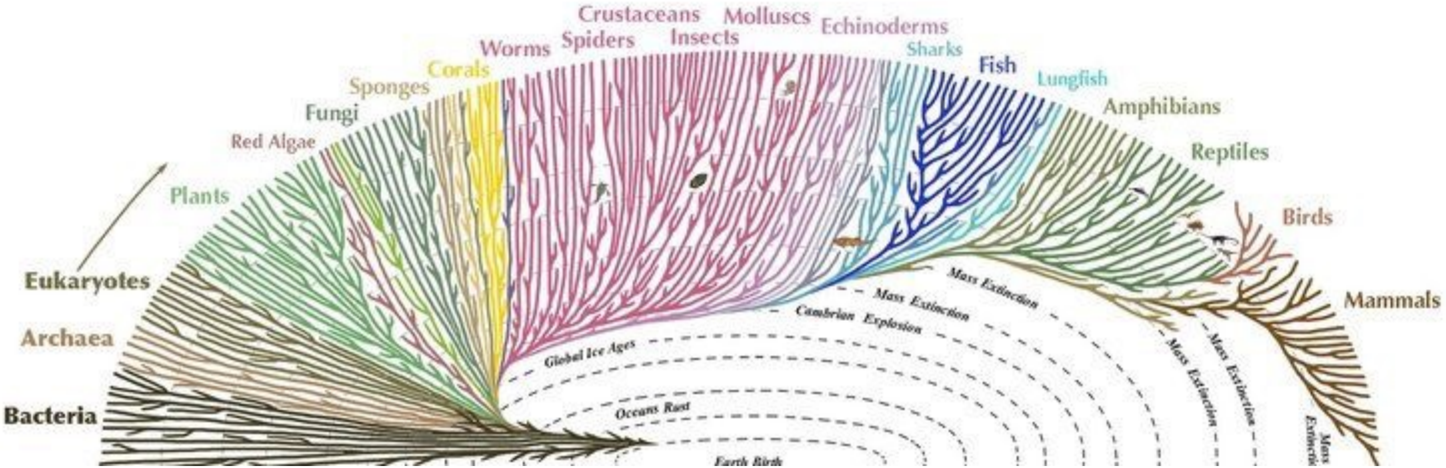
Linking behavior and neural activity



Courtesy: Mackenzie Mathis Lab, EPFL

Challenges for measuring behavior

- Many species
- Fat tail distributions of behaviors



Gunnar Johansson -- Video by James Maas, (Cornell University, 1971)

https://www.youtube.com/watch?v=1F5ICP9SYLU

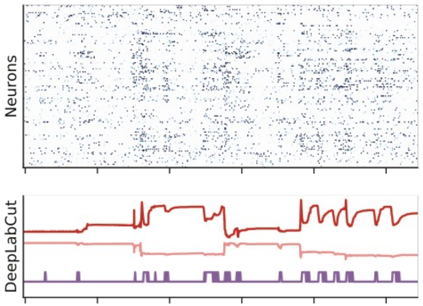
Measuring behavior: Pose estimation

Pixel Representation

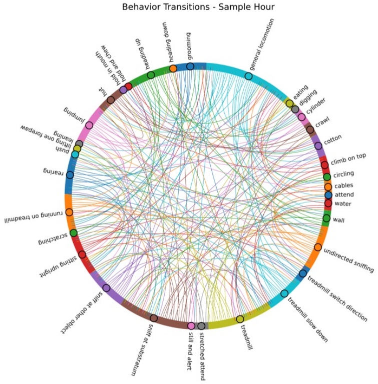
A. Mathis, Schneider, Lauer, M. Mathis, 2020, Neuron

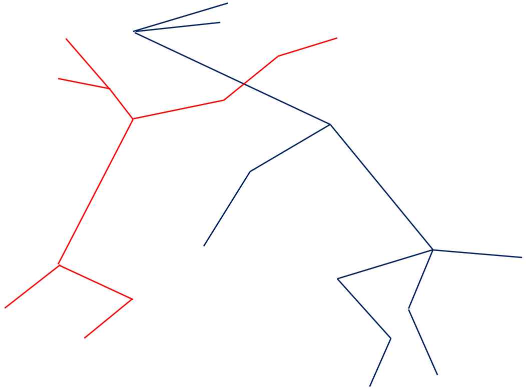
From pose to kinematics, actions, neural coding......

kinematics

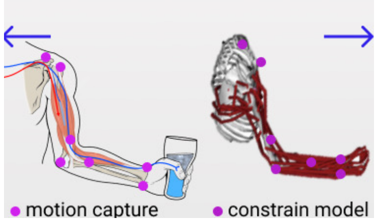


actions





biomechanics / modeling



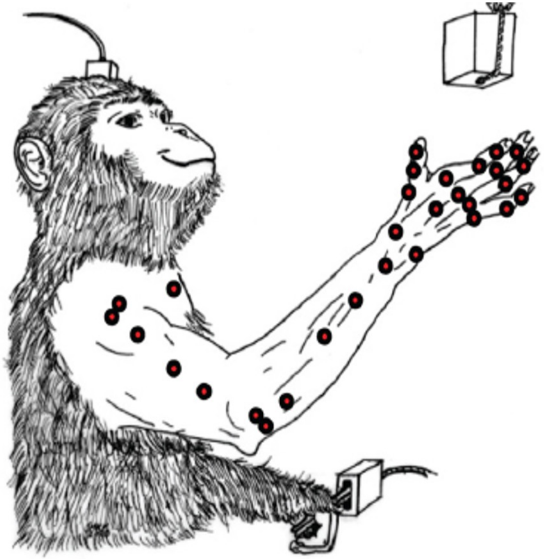
Primer

A Primer on Motion Capture with Deep Learning: Principles, Pitfalls, and Perspectives

Alexander Mathis,[1,2,3,*] Steffen Schneider,[3,4] Jessy Lauer,[1,2,3] and Mackenzie Weygandt Mathis[1,2,3,*]
[1]Center for Neuroprosthetics, Center for Intelligent Systems, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland
[2]Brain Mind Institute, School of Life Sciences, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland
[3]The Rowland Institute at Harvard, Harvard University, Cambridge, MA, USA
[4]University of Tübingen and International Max Planck Research School for Intelligent Systems, Tübingen, Germany
*Correspondence: alexander.mathis@epfl.ch (A.M.), mackenzie.mathis@epfl.ch (M.W.M.)
https://doi.org/10.1016/j.neuron.2020.09.017

Marker-based pose estimation

Bernstein, 1920



Vargas-Irwin et al. 2010

Reviewed in A. Mathis, Schneider, Lauer, M. Mathis, 2020, Neuron

Deep learning revolution for human pose estimation

deep neural networks

image → Predictor → pose

train

A lot of labeled images (>10^6 joints!)

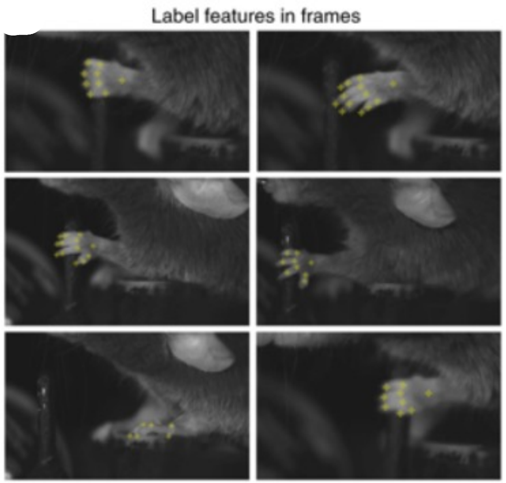
MoDeep – *starting 2014*
DeepPose
Conv. PoseMachines
…
DeeperCut
OpenPose
…
HRNet
…
TokenPose
…
BUCTD
ViTPose
…

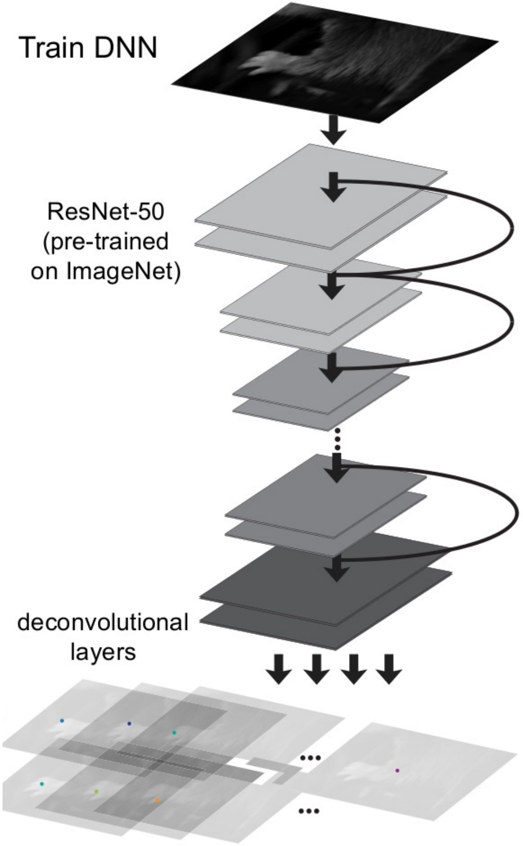
> 60,000 papers on human pose estimation with Deep Learning

Appealing properties:

- Work "in the wild"
- Robust (backgrounds, individuals, etc.)
- Relatively fast
- No body model
- No (manual) parameter tuning

DeepLabCut: a toolbox for markerless pose estimation via **transfer learning**





141 labeled frames

A. Mathis …. M.W. Mathis* and Bethge*
Nature Neurosci, 2018

3D cheetah pose estimation in the wild to study tail biomechanics

3D cheetah pose estimation in the wild to study tail biomechanics

- Joska et al. ICRA 2021
  Nath et al. Nature Protocols 2019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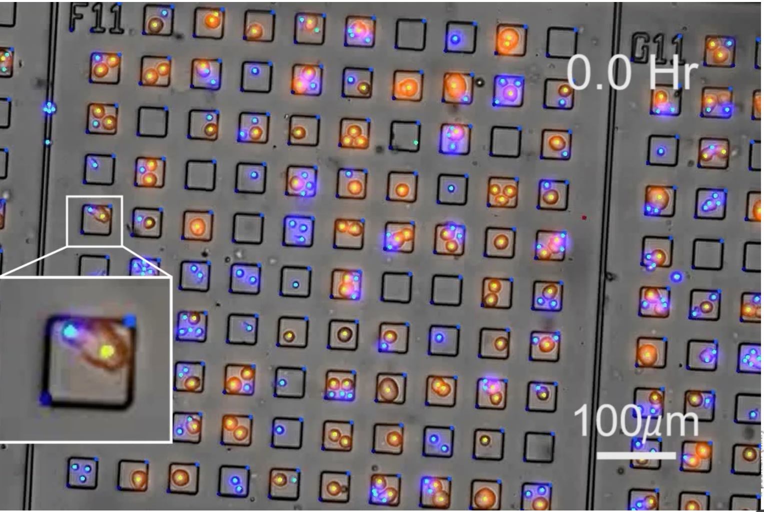
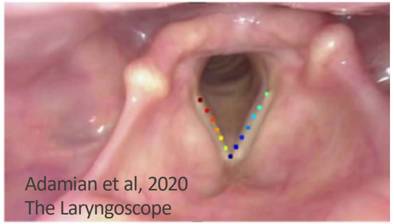
DeepLabCut: a toolbox for efficient markerless pose estimation

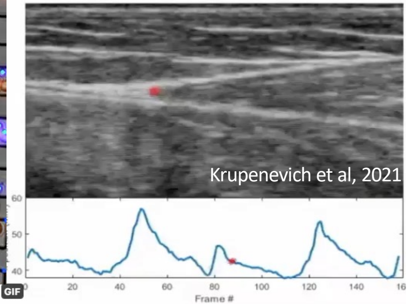
Cells	Tissues	Organisms



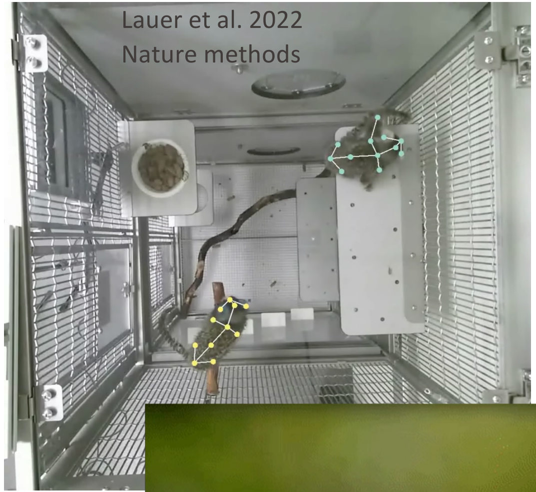
Cachot et al. 2021
Science Advances



Adamian et al, 2020
The Laryngoscope



Krupenevich et al, 2021



Lauer et al. 2022
Nature methods

- www.deeplabcut.org
- Active user community (i.e., help!)
- Collaborative ☺
- **>110 code contributors on GitHub**
- **> 700,000** downloads
- **> 3,000** citations
- Used in over **1,000 i**nstitutes around the world

Chan Zuckerberg Initiative

Nature Neuro 2018, Nature Protocols 2019, Neuron 2020, WACV 2021, ICRA, 2021, CVPR-W 2021, Nature Methods 2022, CVPR-W 2023, ICCV 2023 , Nature Comms 2024

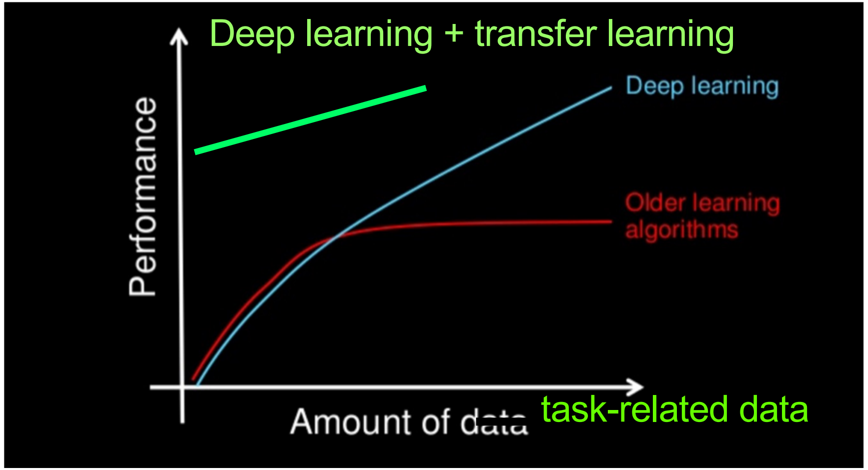
Transfer learning enables pose estimation with less data

Pre-trained! (i.e. on ImageNet)

image → Predictor → pose

train

Only a few examples (10-200) for most applications



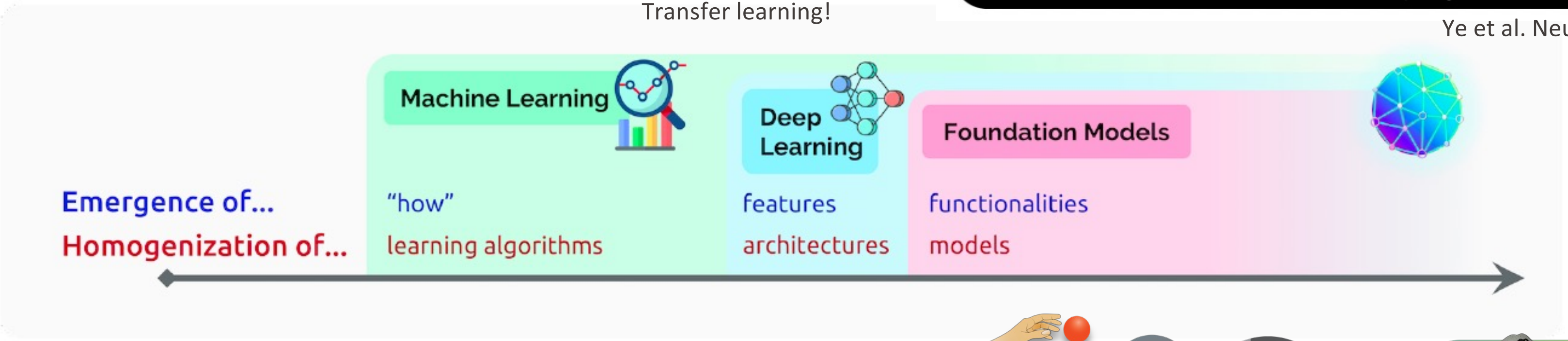
Andrew Ng

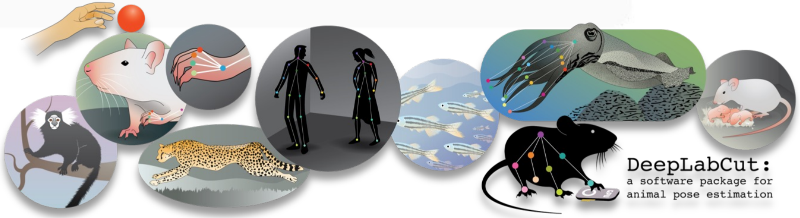
DeepLabCut

Transfer learning!

WildCLIP - Gabeff, Russwurm, Tuia, Mathis
CVPR CV4Animals (oral) 2023 & IJCV 2024

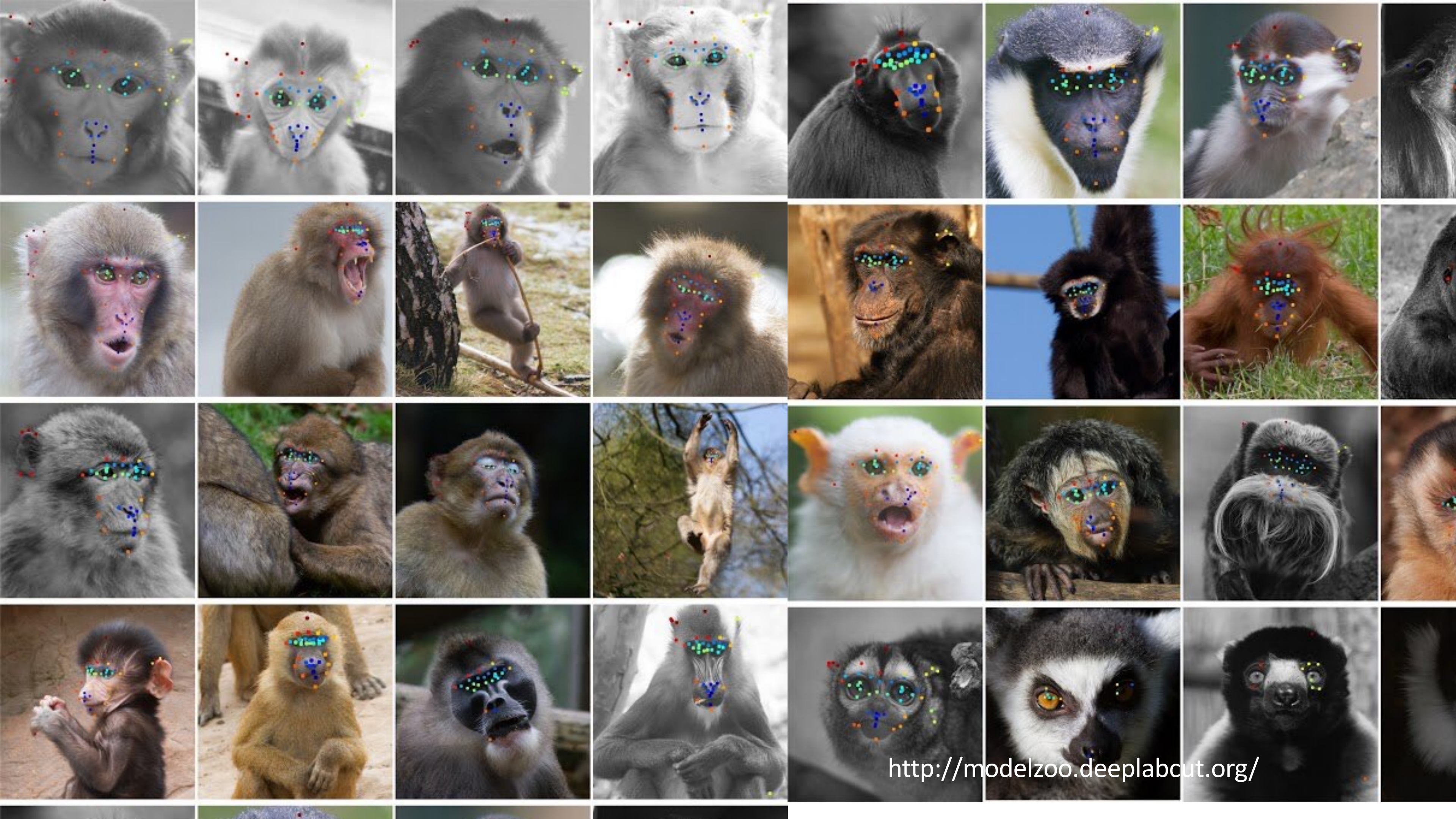
Ye et al. NeurIPS 23





Ye et al. Nat Coms 2024

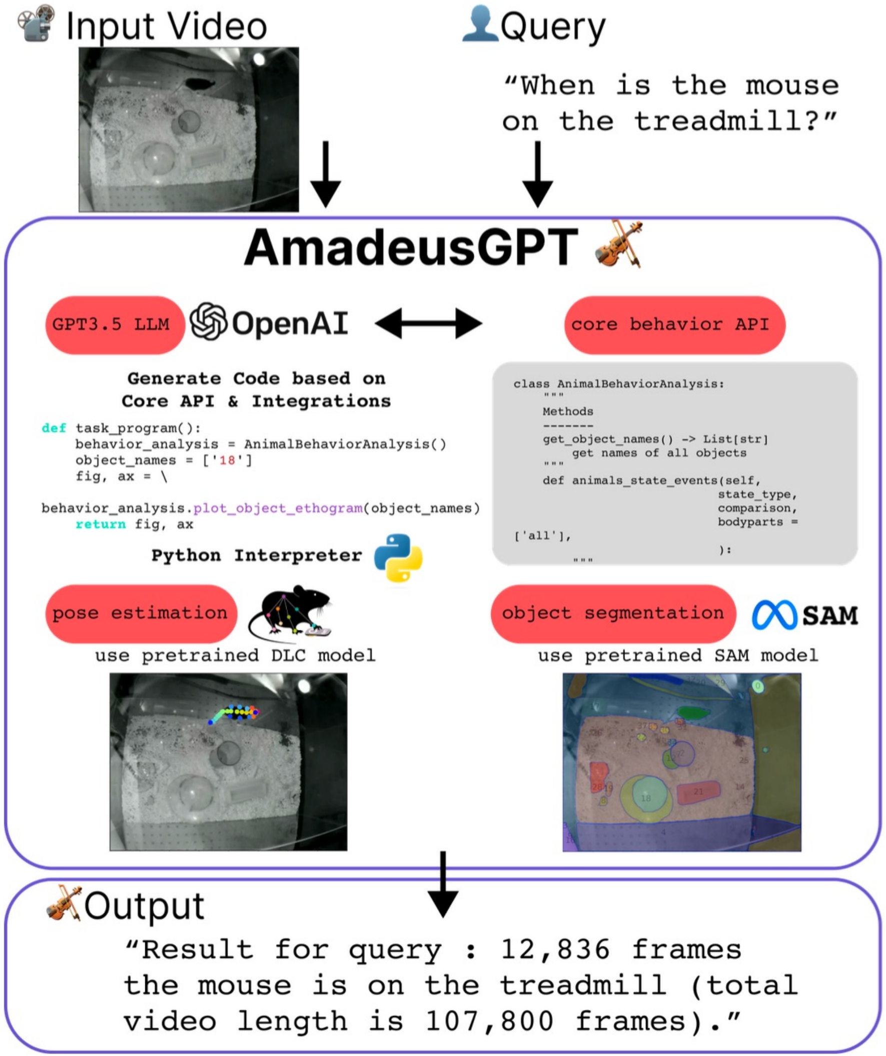
From: On the Opportunities and Risks of Foundation Models by Bommasani et al, arxiv 2021


http://modelzoo.deeplabcut.org/

AmadeusGPT:

a natural language interface
for interactive animal behavioral analysis

Towards more userfriendly and
more intuitive (codefree) interfaces
building on foundation models



S. Ye, Lauer, Zhou, A Mathis, MW Mathis NeurIPS 2023

Intermediate conclusions

Modern tools capture rich datasets of the brain

Machine learning is a work horse for many tasks in neuroscience

- pose estimation, animal identification, behavior understanding …
- cell segmentation, spike sorting …

Many underlying algorithms (e.g., CNNs) are loosely inspired by how the brain works