Computational Neuroscience

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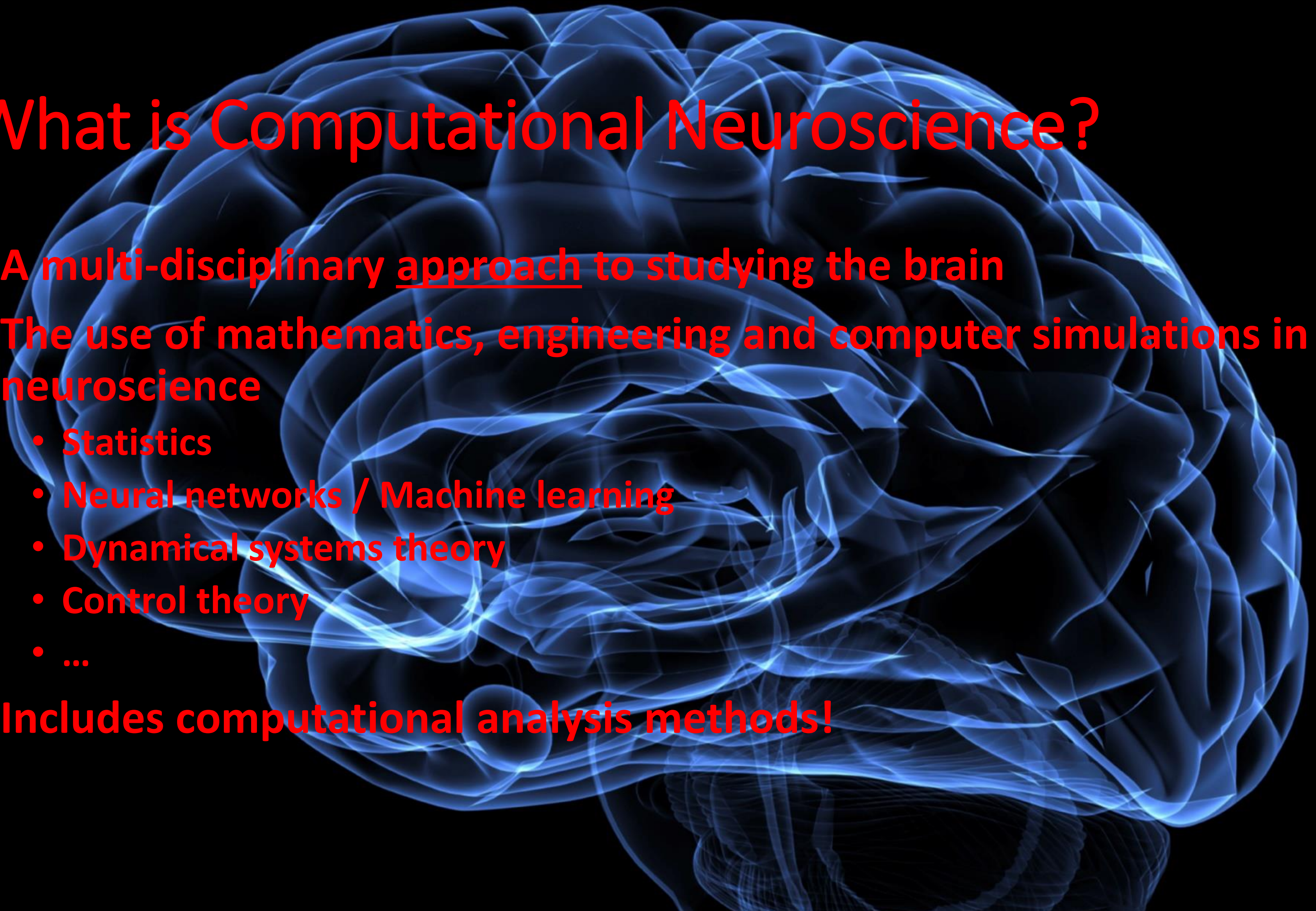
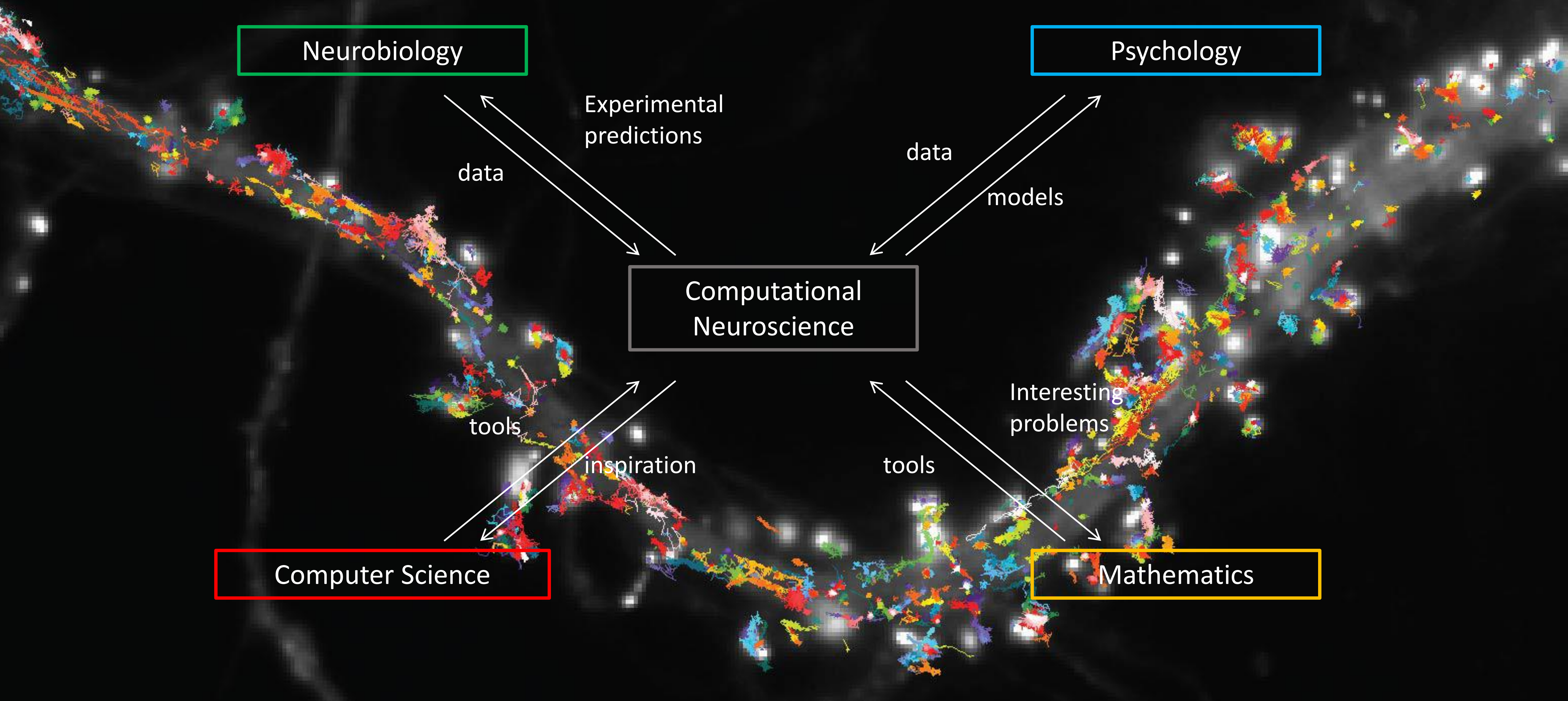


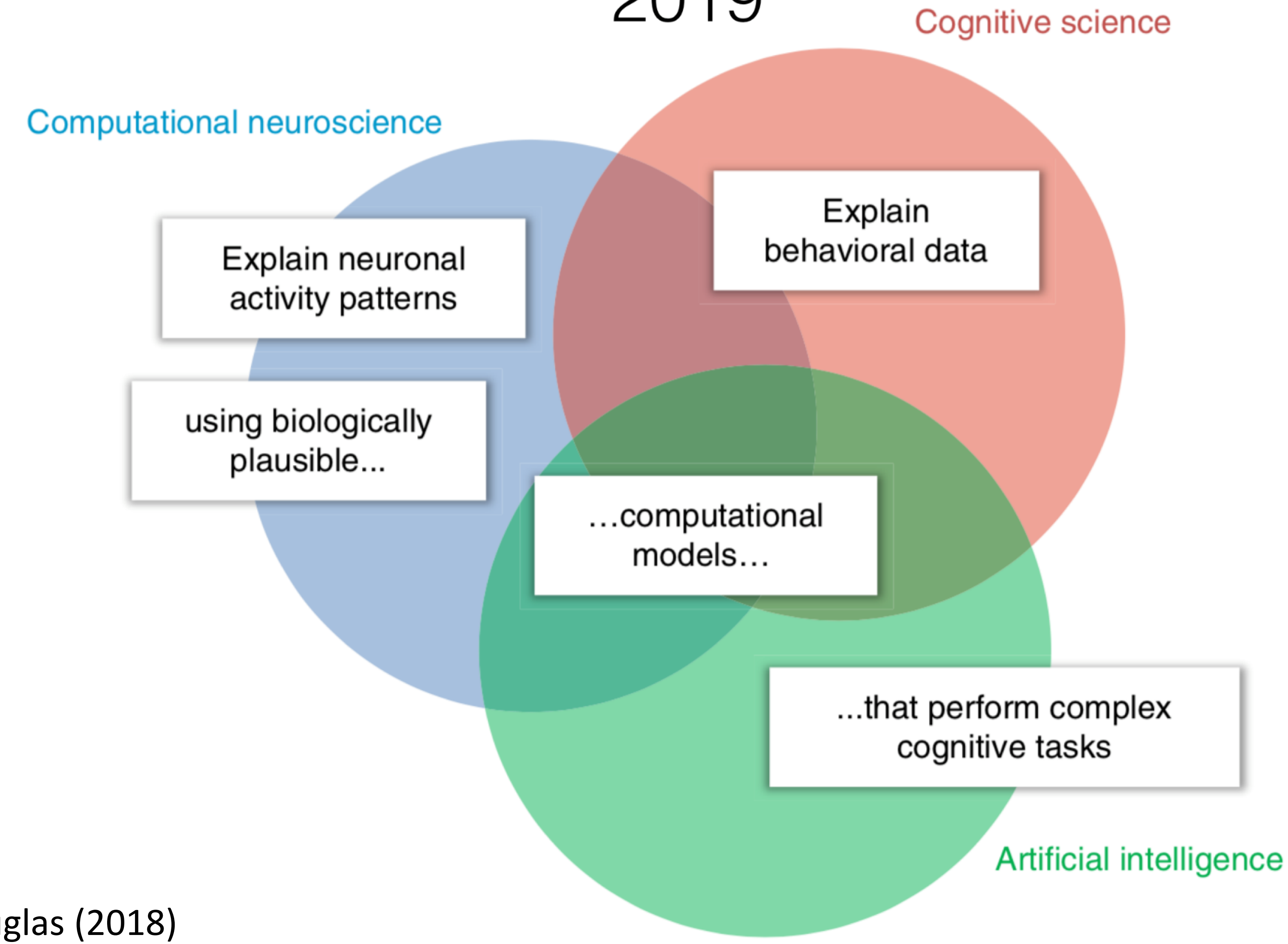
What is Computational Neuroscience?

- **A multi-disciplinary <u>approach</u> to studying the brain**
- **The use of mathematics, engineering and computer simulations in neuroscience**
  - **Statistics**
  - **Neural networks / Machine learning**
  - **Dynamical systems theory**
  - **Control theory**
  - **…**
- **Includes computational analysis methods!**

A multi-disciplinary endeavour

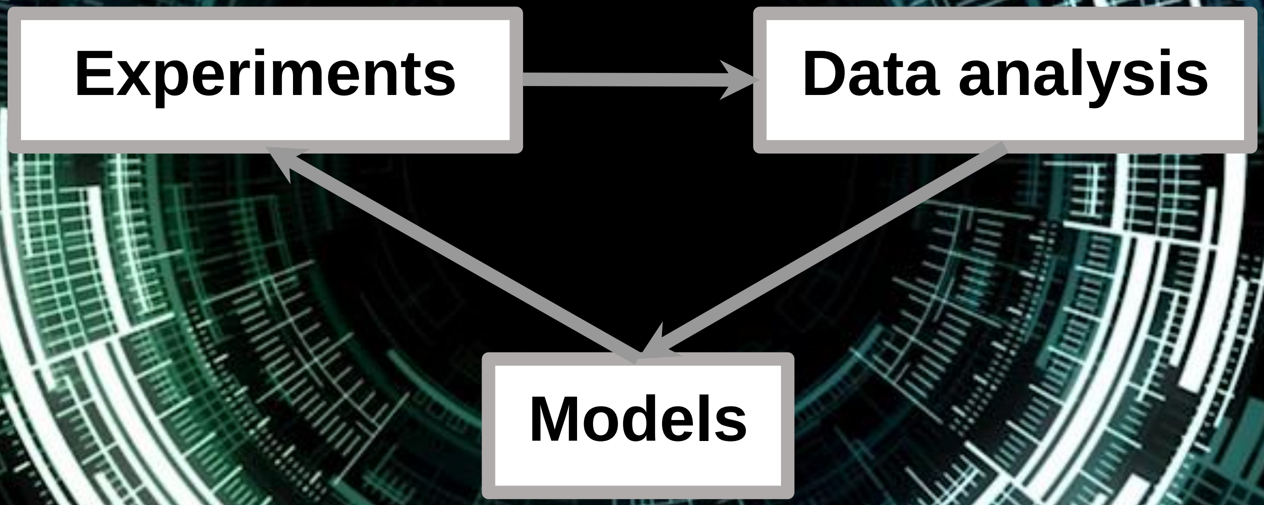


Cognitive Computational Neuroscience 2019



Kriegeskorte & Douglas (2018)

Cycle of scientific discovery



What are models?

Insights not directly accessible
by experiments / data

Models allow for **understanding** and **control** (Rosenblueth & Wiener, 1945)

Interventions, e.g.
experimental, clinical

Requires model validation → experiments!

In other words, a model is a **Hypothesis**!

Studying complex systems requires computational approaches!

Why is modeling important?

- Gain complete understanding of some experimental phenomenon
- Estimate latent states
- Identify hypotheses, assumptions, unknowns
- Make quantitative predictions
- Build a theoretical brain as a model of the real brain (e.g. stroke lesions)
- Inspire new technologies
- Models of neurological diseases to help treatment, rehabilitation, quality of life
- Guidance in designing useful experiments (i.e. animal research)

What can we do?

- Models help answering three potential types of questions about the brain
  - Descriptive = What?
    - Compact summary of large amounts of data
  - Mechanistic = How?
    - Show how neural circuits perform complex function
  - Interpretive = Why?
    - Computations in the brain are usually performed in an optimal or nearly optimal way
    - Understanding optimal algorithms and their implementation to explain why the brain is designed the way it is

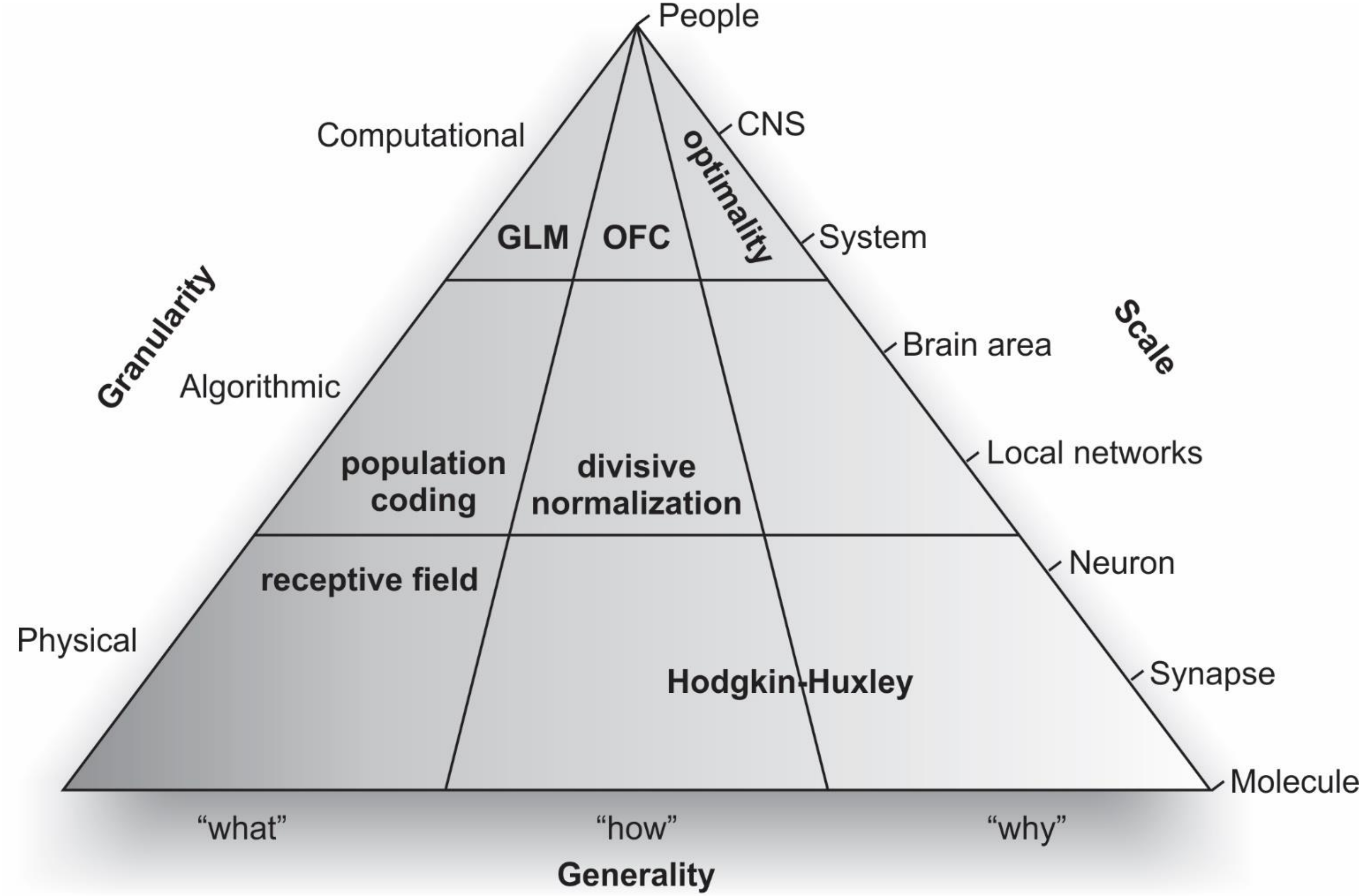
Dayan & Abbott, 2001

Marr’s model hierarchy

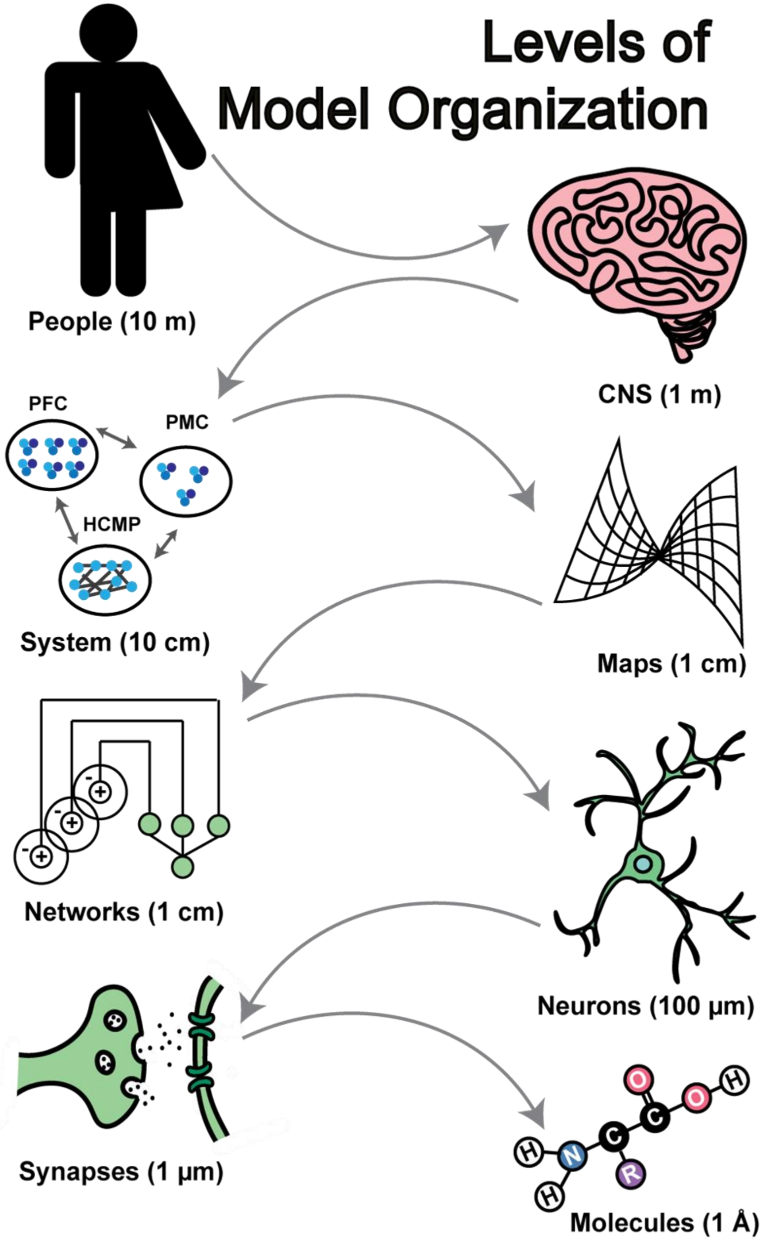
- Computational level - 1
  - Objective?
  - How close to optimal?
  - This is what most computational neuroscience papers do!
- Algorithmic level - 2
  - Data structures?
  - Approximations?
  - Runtime?
  - Some studies get into this (computer science)
- Implementation level -3
  - Hardware? Neurons? Synapses? Molecules?
  - Not addressed enough!

https://onlinelibrary.wiley.com/doi/full/10.1111/tops.12137

Model classifications

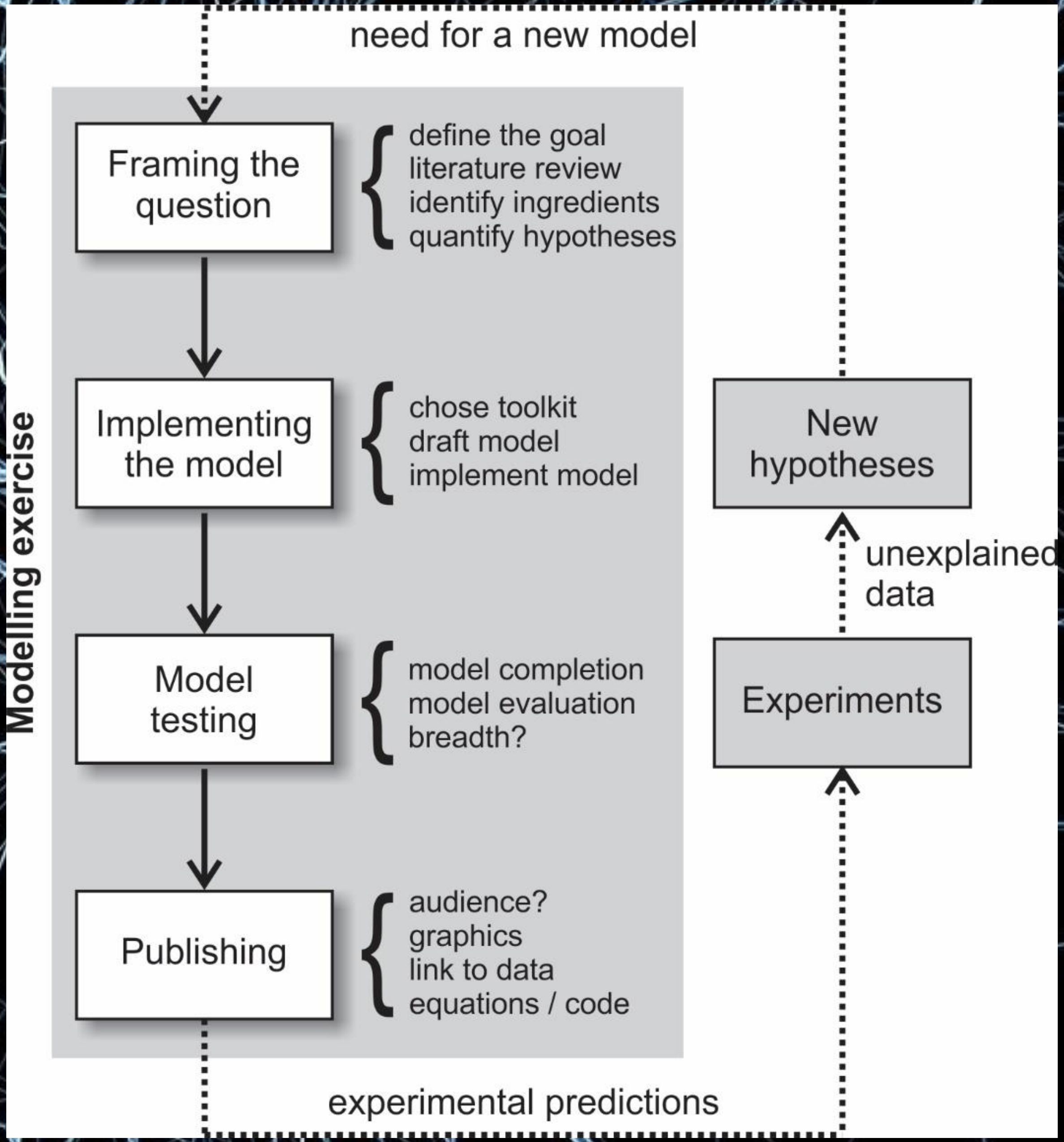


https://osf.io/w56vt/



Modified from Trappenberg (2009), *Fundamentals of Computational Neuroscience*

How to model…?

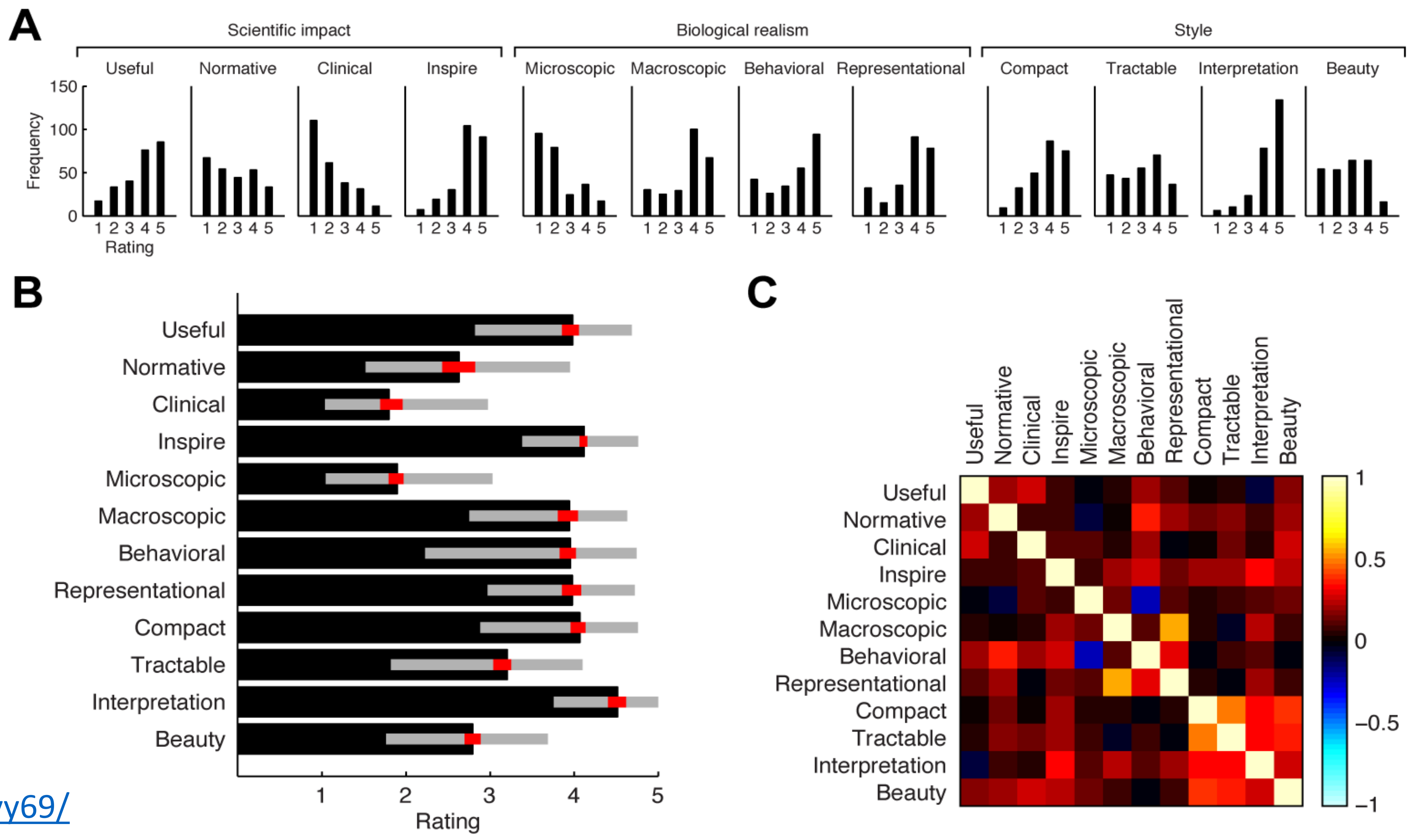


https://osf.io/8gz65/

What’s a good model?

- Explain data
  - p(data|model 1)>>p(data|model 2)
  - Model interfaces with data / data connects to model
- Generalization
  - Out of experiment (new experiment)
  - Out of sample (same experiment, new data)
    - Occam’s razor
    - Reproducibility?
      - Data / experiment / model?
    - Robustness
- New insight
  - Predictions on new domains
  - Interpretability
  - Transfer knowledge by model equivalence between domains
- Usefulness
  - Predictions
  - Inspires new experiments
  - Interventions / policy changes
  - Tech applications
  - Clinical relevance
  - Falsifyable
  - Make assumptions explicit
- Elegance
  - Non-arbitrary structure…
  - Simplicity
  - Computational complexity low
  - Normativity
  - Unification / subsumption
  - Micro-/meso-/macro-realism

People care about different things…



https://osf.io/3vy69/

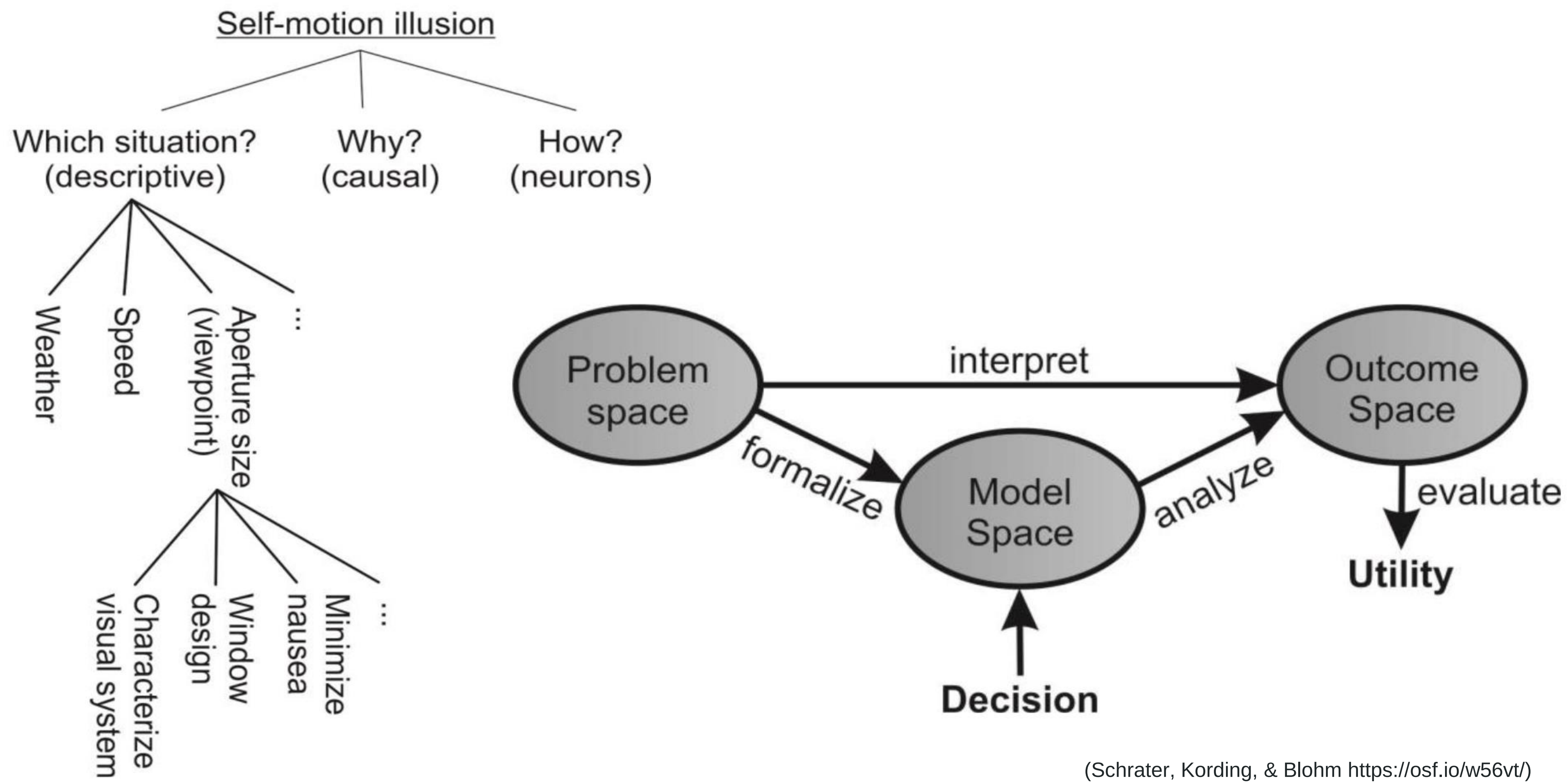
Modeling as a decision process

phenomenon

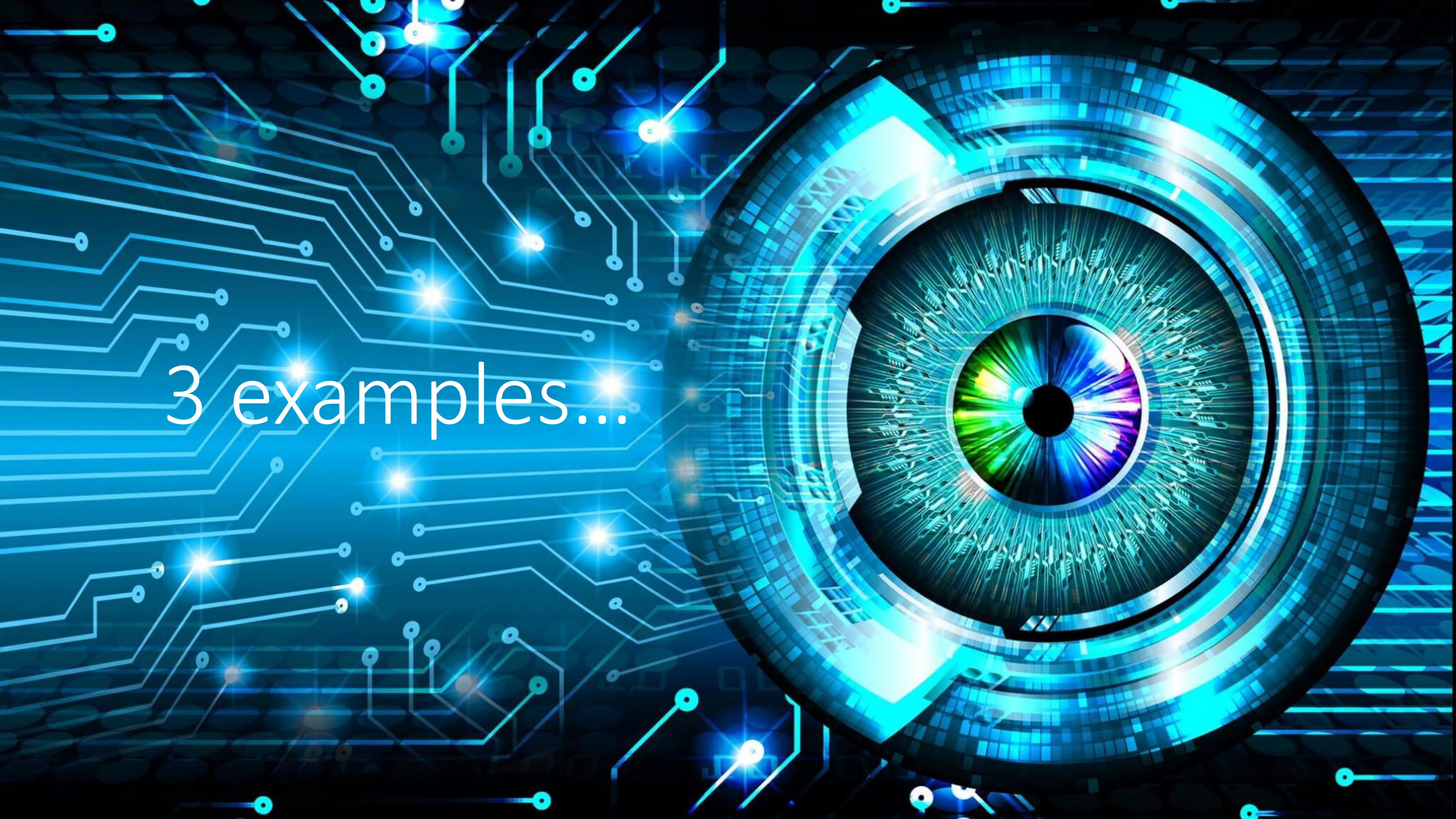
questions

hypotheses

goals



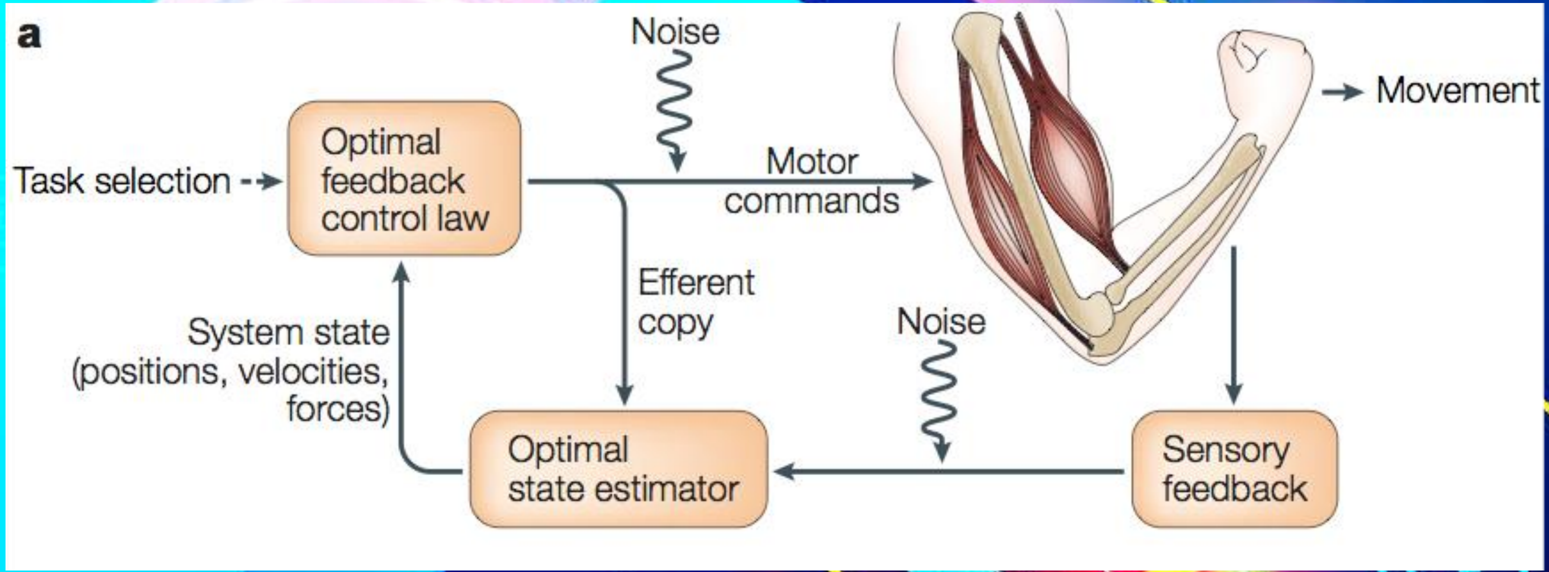
(Schrater, Kording, & Blohm https://osf.io/w56vt/)



3 examples…

Normative models of behaviour

Scott, 2004



$$\mathbf{x}^{(k+1)} = A\mathbf{x}^{(k)} + C\mathbf{u}^{(k)} + \boldsymbol{\varepsilon}_u^{(k)}$$

$$\mathbf{y}^{(k)} = B\mathbf{x}^{(k)} + \boldsymbol{\varepsilon}_y^{(k)}$$

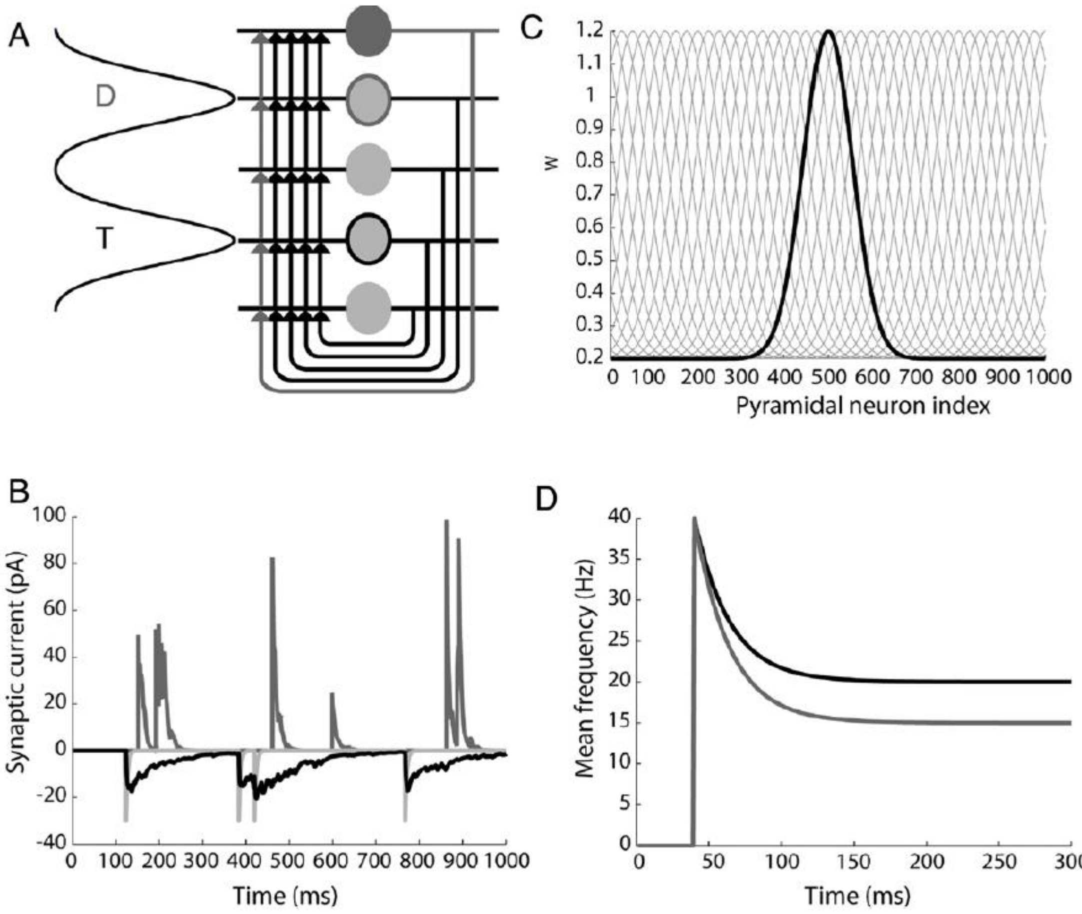
$$J = \sum_{k=0}^{p-1} \mathbf{u}^{(k)T} L^{(k)} \mathbf{u}^{(k)} + \mathbf{y}^{(k+1)T} T^{(k+1)} \mathbf{y}^{(k+1)}$$

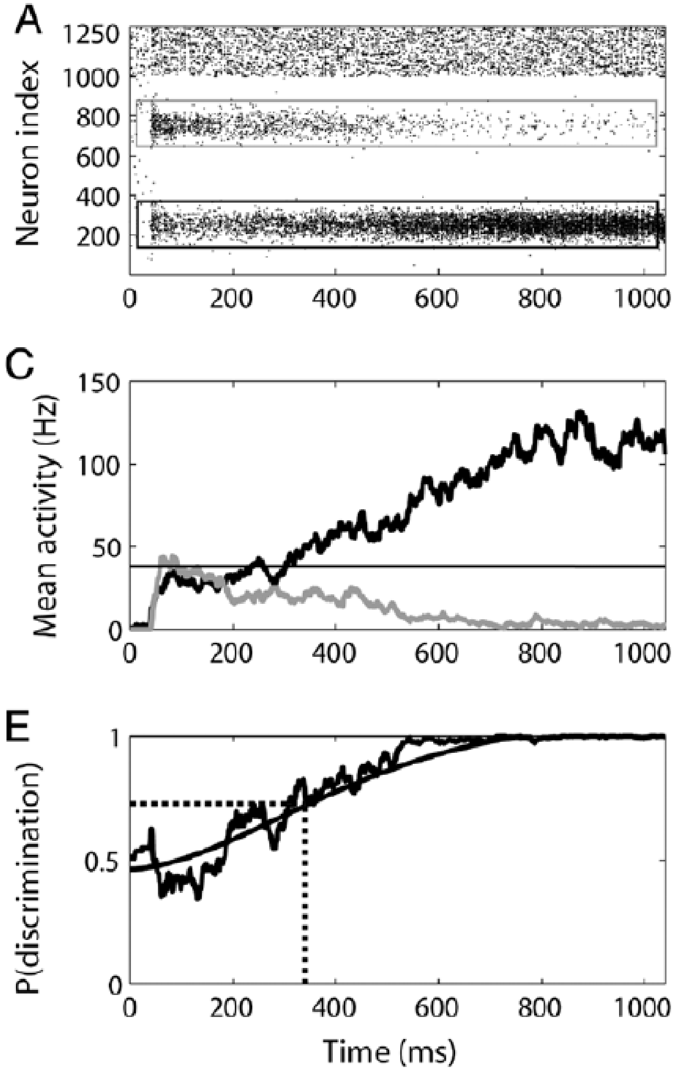
$$\mathbf{u}^{(k)} = G^{(k)} \hat{\mathbf{x}}^{(k)}$$

$$\hat{\mathbf{x}}^{(k+1)} = \hat{A}\hat{\mathbf{x}}^{(k)} + \hat{A}K^{(k)}\left(\mathbf{y}^{(k)} - \hat{\mathbf{y}}^{(k)}\right) + \hat{C}\mathbf{u}^{(k)}$$

Torodov & Jordan, 2002

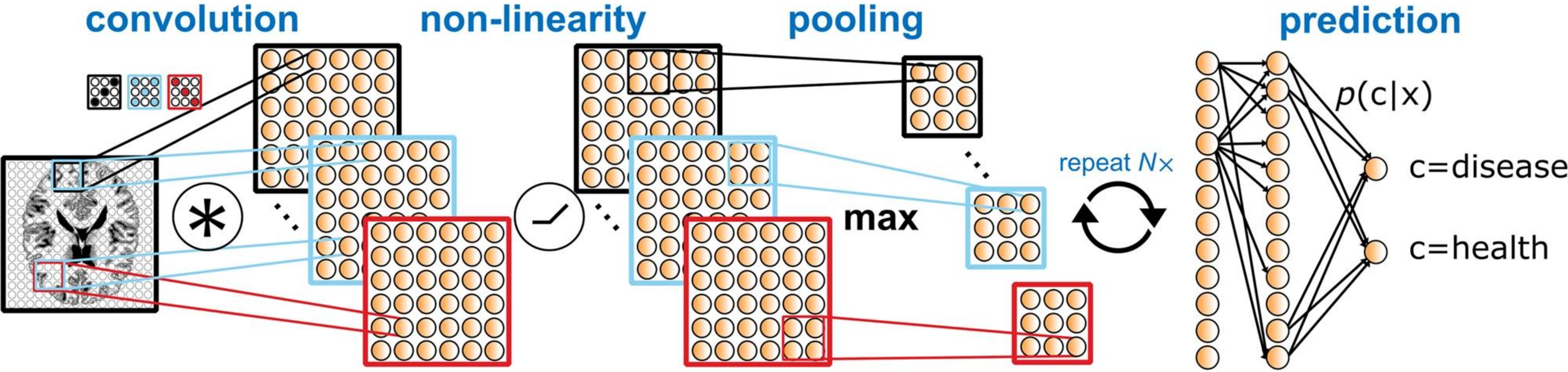
Spiking network models



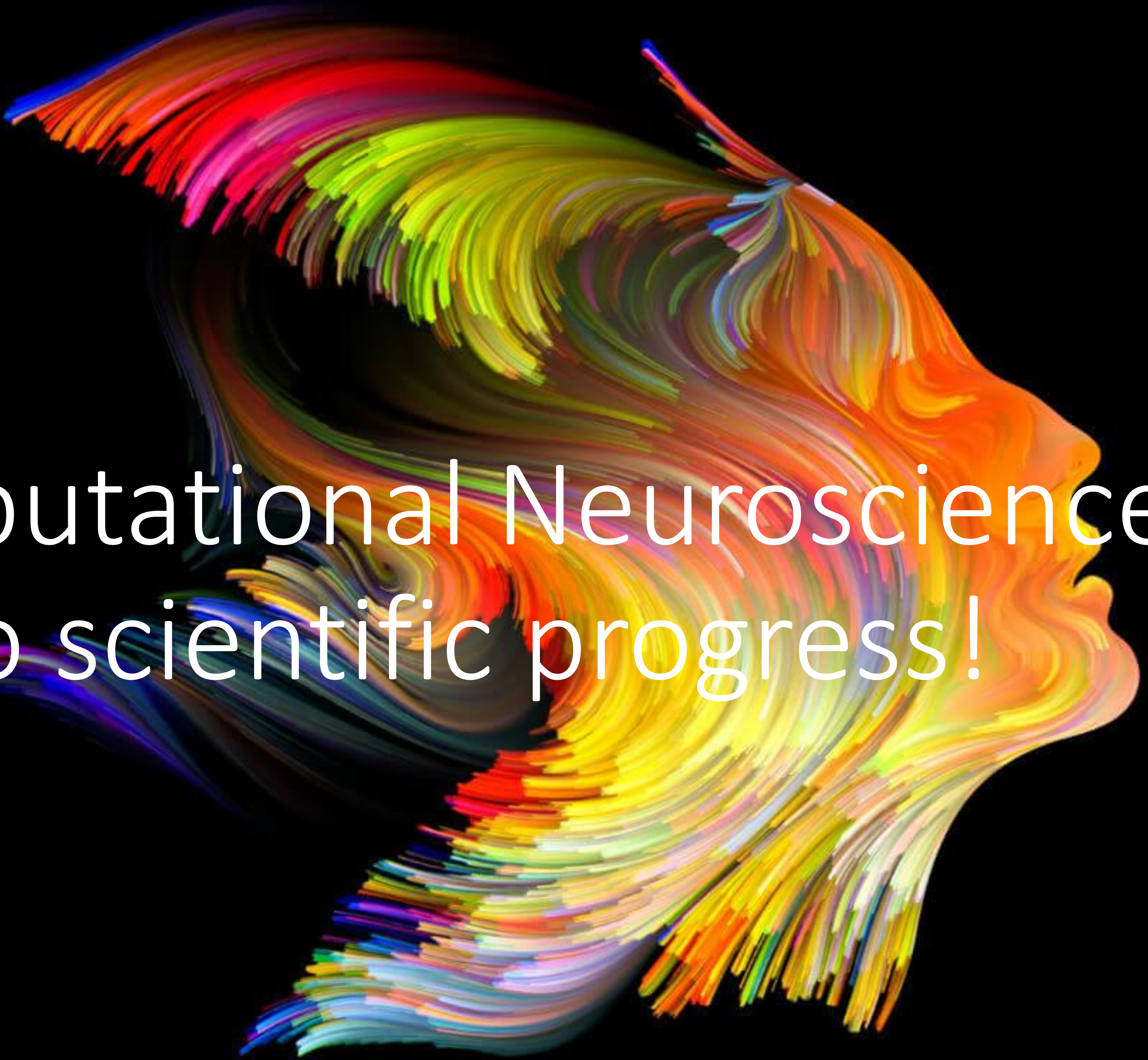


Standage & Pare 2011

Clinical models



Durstewitz, et al., 2019



Computational Neuroscience is key to scientific progress!

Want to know more?

neuromatch
academy

https://compneuro.neuromatch.io

Intro to modeling
W1D1
W1D2