Causality, computation and learning in the study of the mind

@kordinglab

The standard reductionist dream in neuroscience

- Take brain and behavior
- Describe it in terms of what brain regions do
- Describe those in terms of what microcircuits do
- Describe those in terms of what neurons do
- Describe those in terms of what molecules do

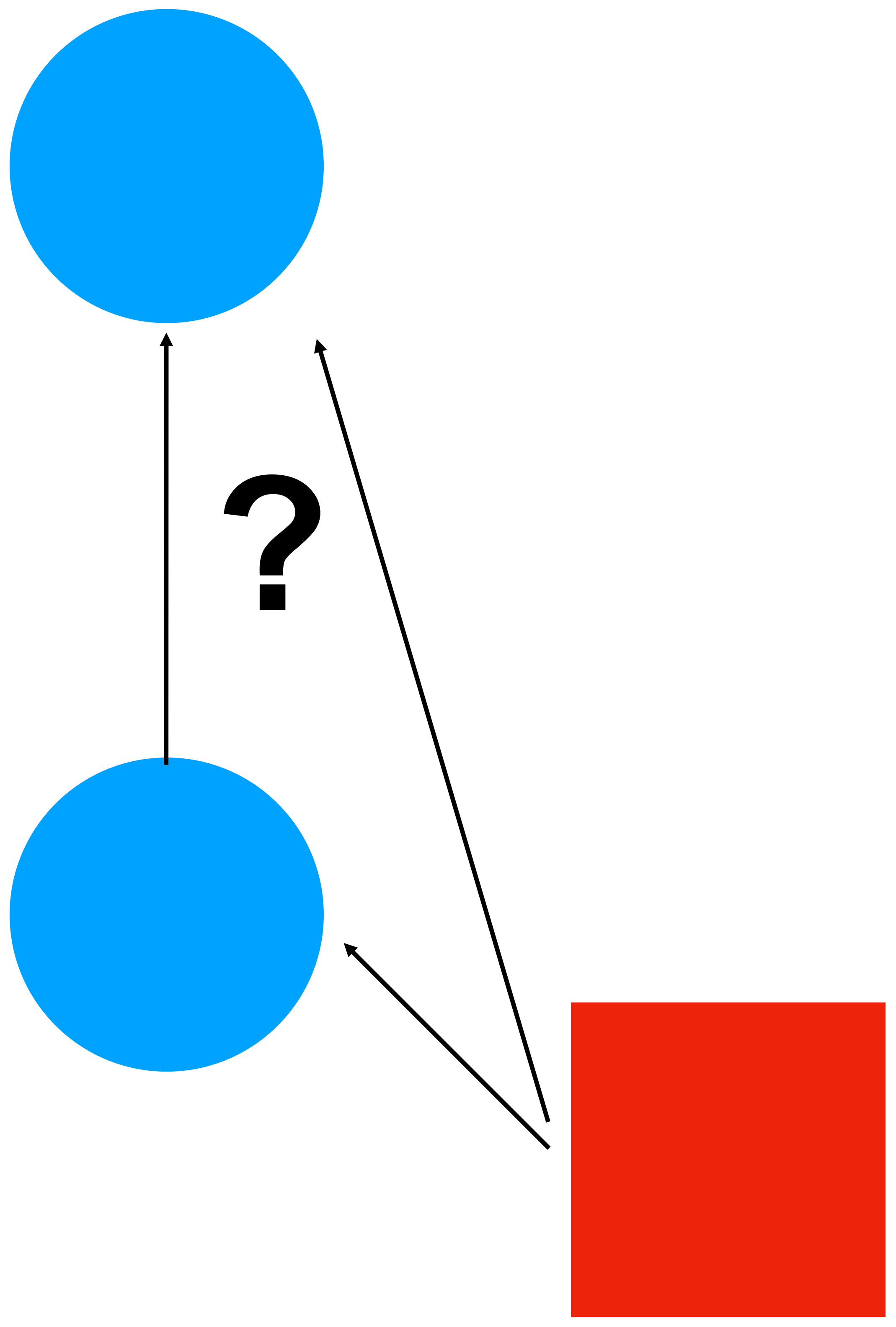
What is in each of these goals?

- A causal question:
  - How do parts of something make something happen at the bigger level
  - For this to be useful these parts must somehow be meaningfully independent
  - But also, information flow
- With the assumption:
  - The relevant causal inference/ discovery is a solvable problem
  - At that level of description there is a notion of simplicity

Why are causal answers so hard?

- Our perturbation methods are low-dimensional
- Our observational approaches are hopelessly confounded
  - Even if they were not we would be underpowered

Why causality is hard: Confounding



A continuum of confounding

- No confounders: e.g. atari, imagenet, go, chess
- Few confounders: starcraft
- Countless confounders: medicine
- 10^11 confounders: brain understanding
- **Let us focus on intuition (Neuromatch Academy)**

Simulate a trivial causal system

$$\vec{x}_{t+1} = \sigma(A\vec{x}_t + \epsilon_t)$$

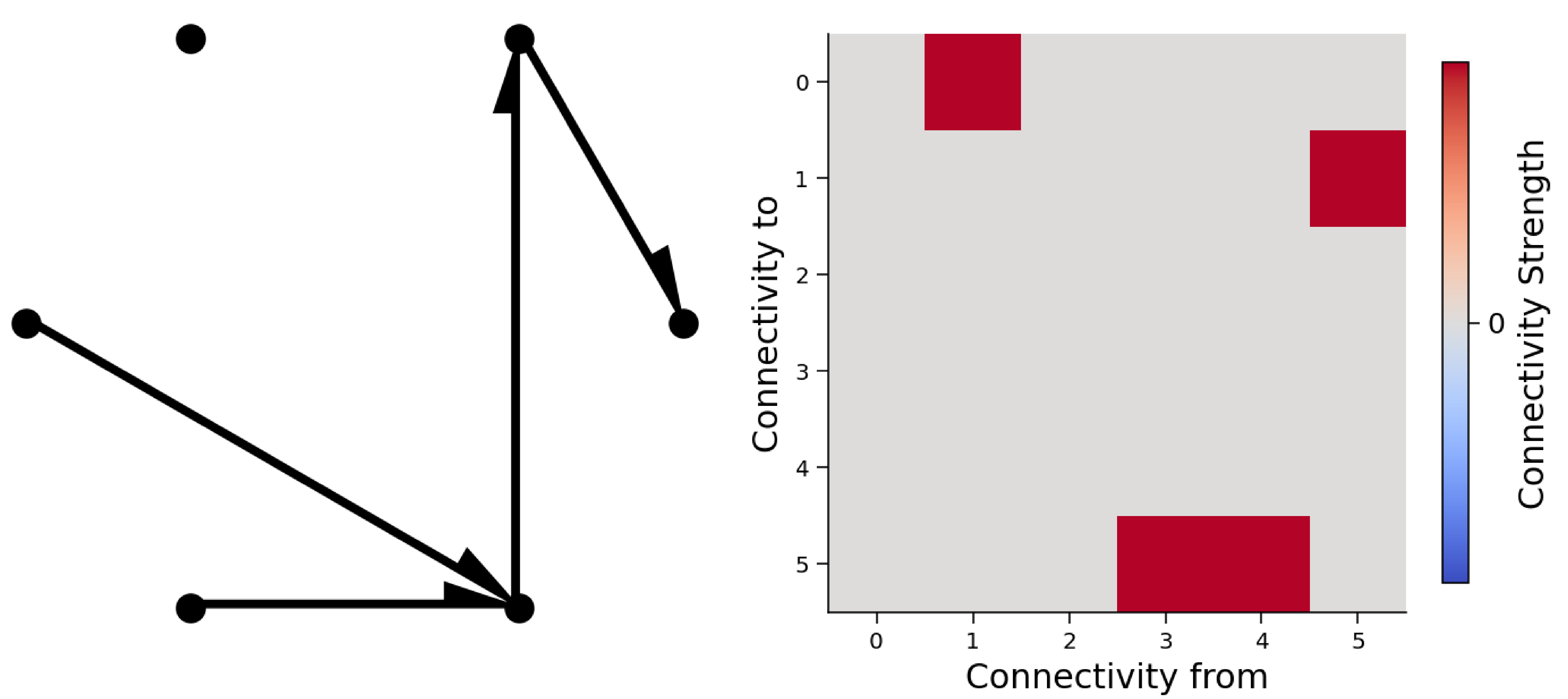
- $\vec{x}_t$ is an n-dimensional vector representing our n-neuron system at timestep t
- σ is a sigmoid nonlinearity
- A is our $n \times n$ *causal ground truth connectivity matrix*
- ϵ_t is random noise: $\epsilon_t \sim N(\vec{0}, I_n)$
- $\vec{x}_0$ is initialized to $\vec{0}$

Is correlation (delay =1) ~ causation?

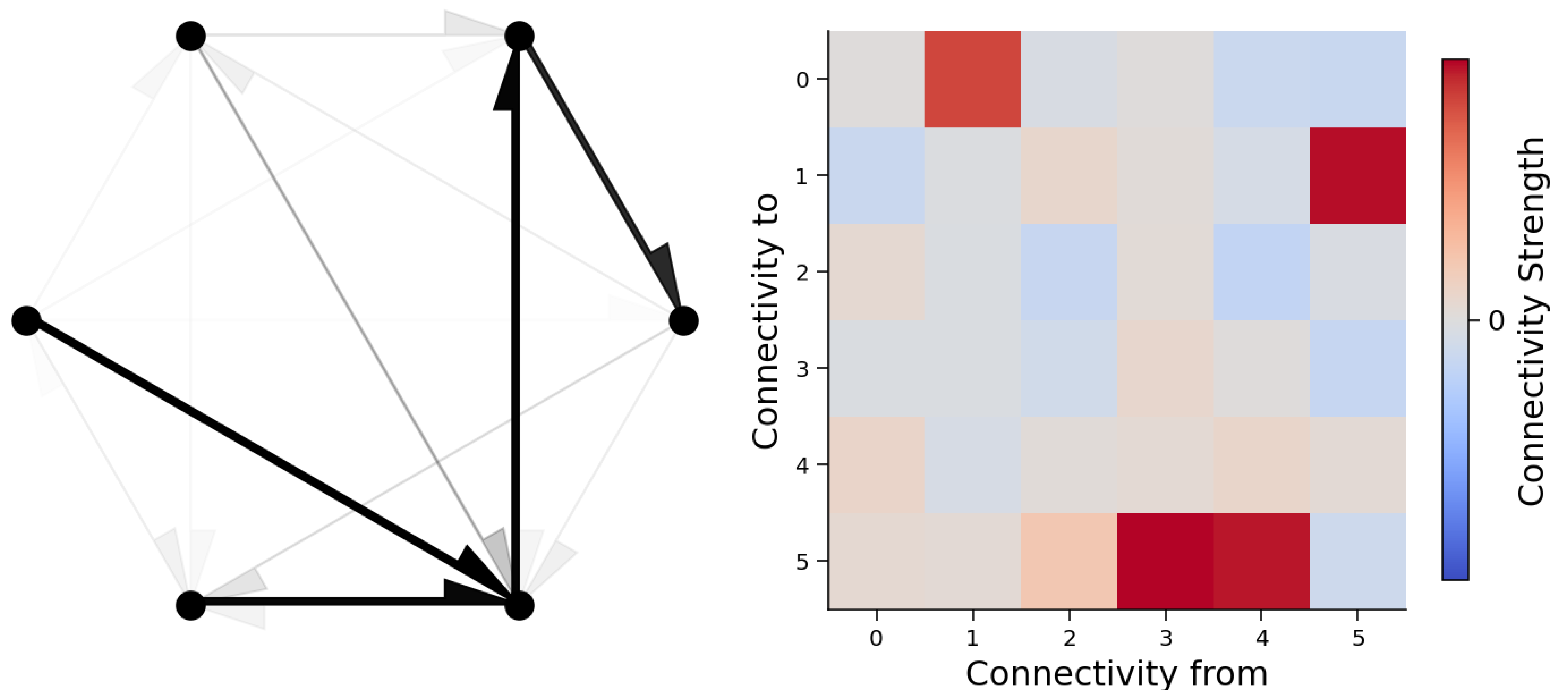
With Tony Liu, Ari Benjamin, Mike X Cohen, Madineh Sarvestani
Yoni Friedman, Ella Batty, Michael Waskom — D15 compneuro.neuromatch.io

Great in small system

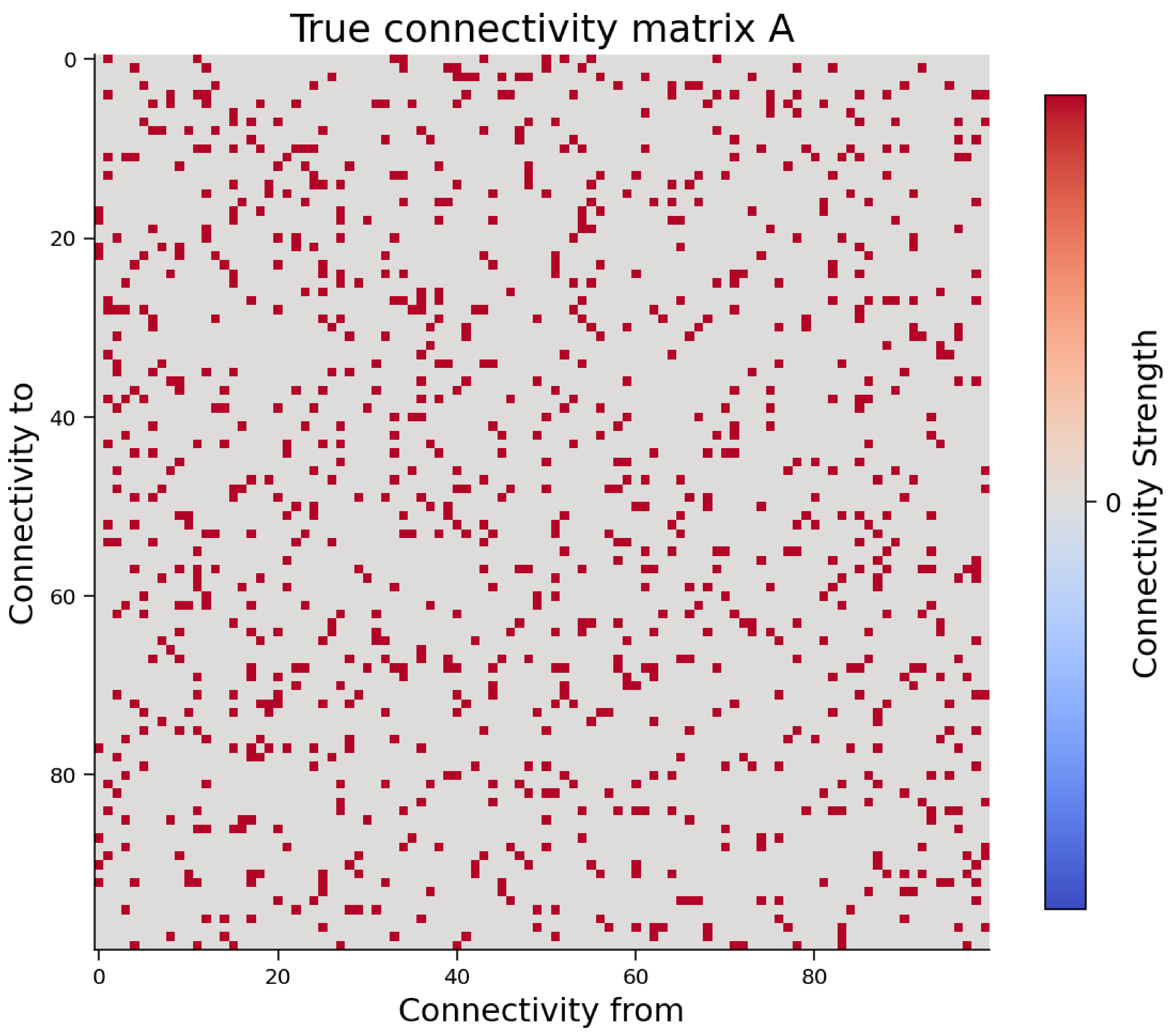
True connectivity matrix A

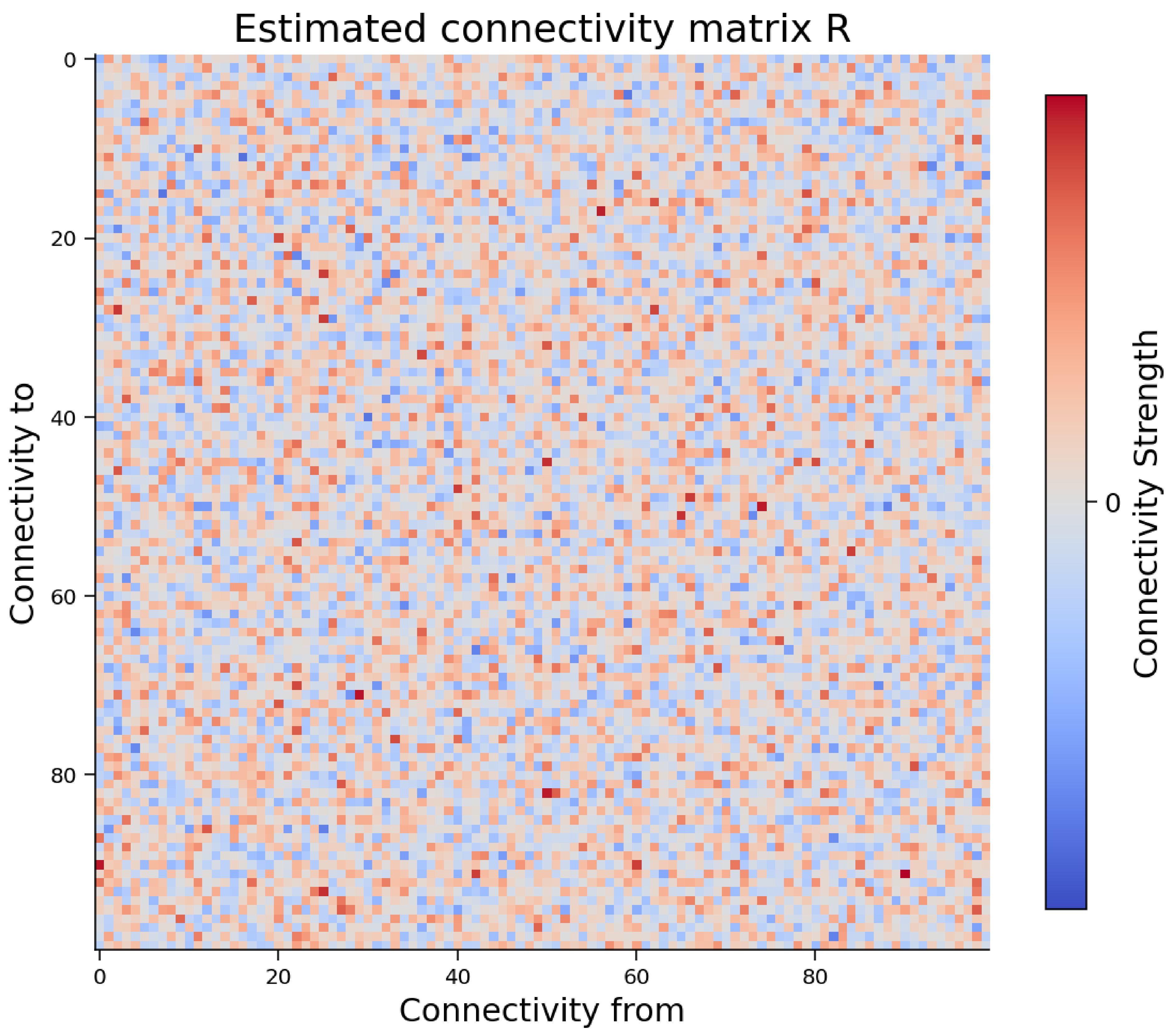


Estimated connectivity matrix R

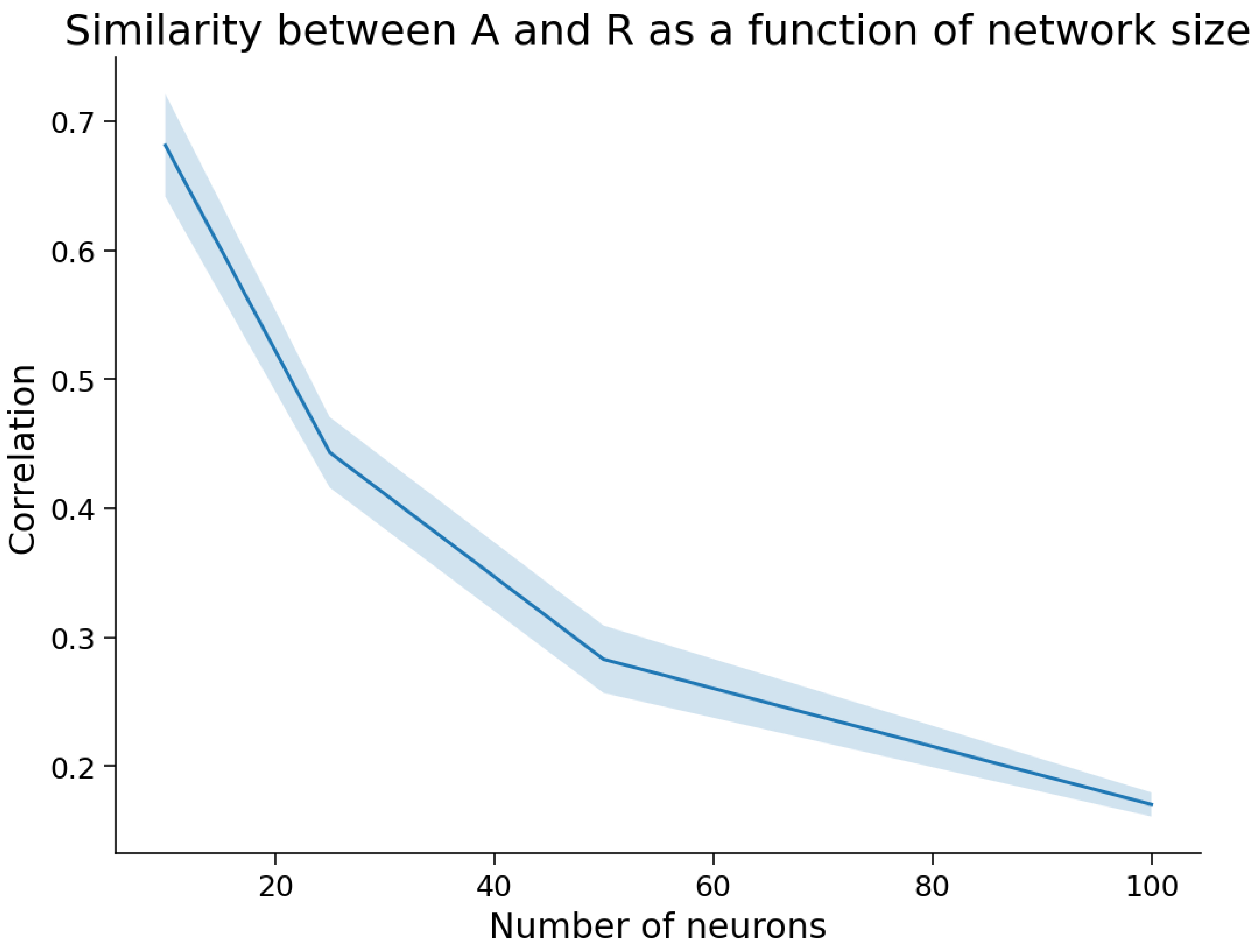


Bad in a big system





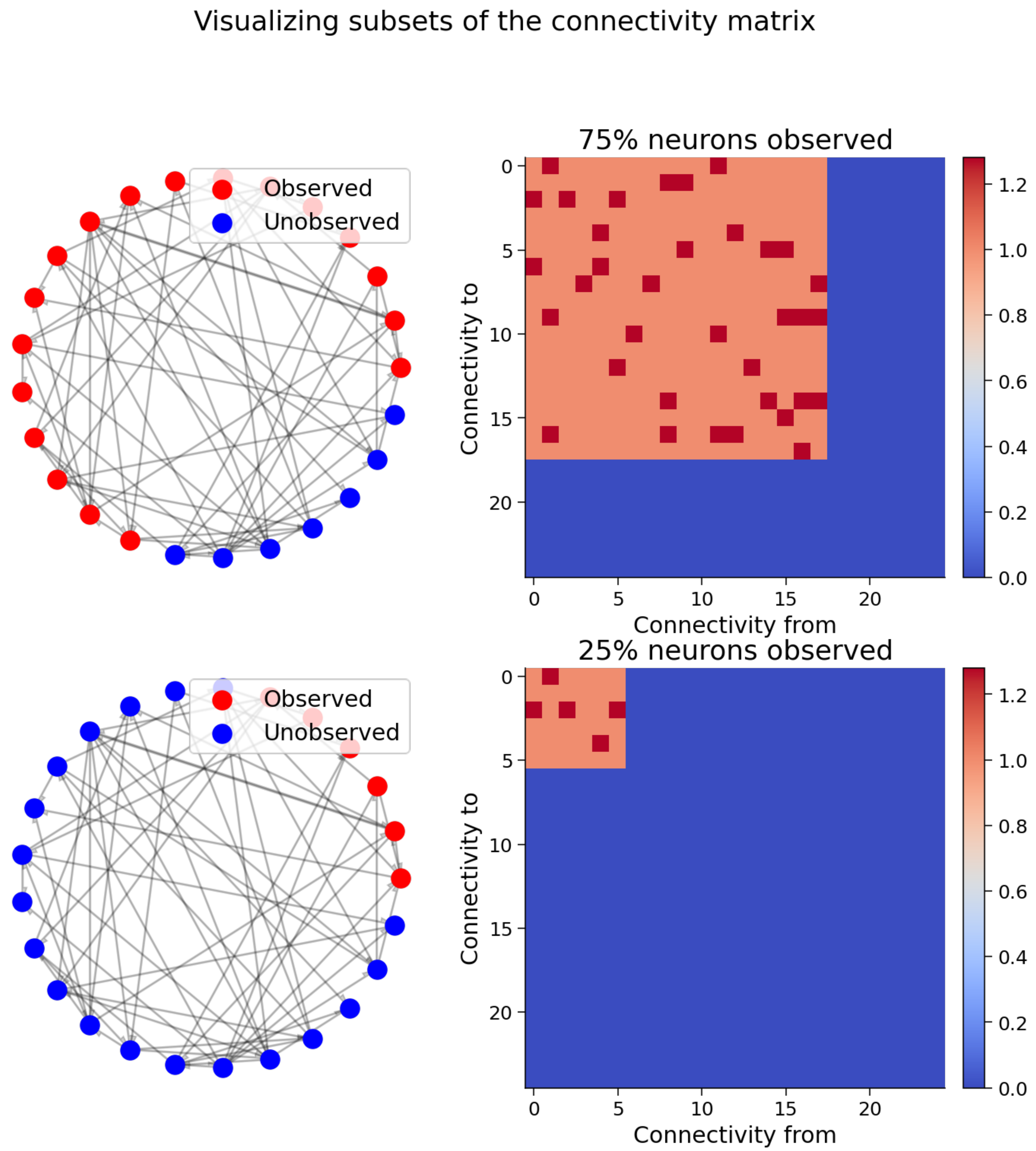
Delayed Correlation vs Causation



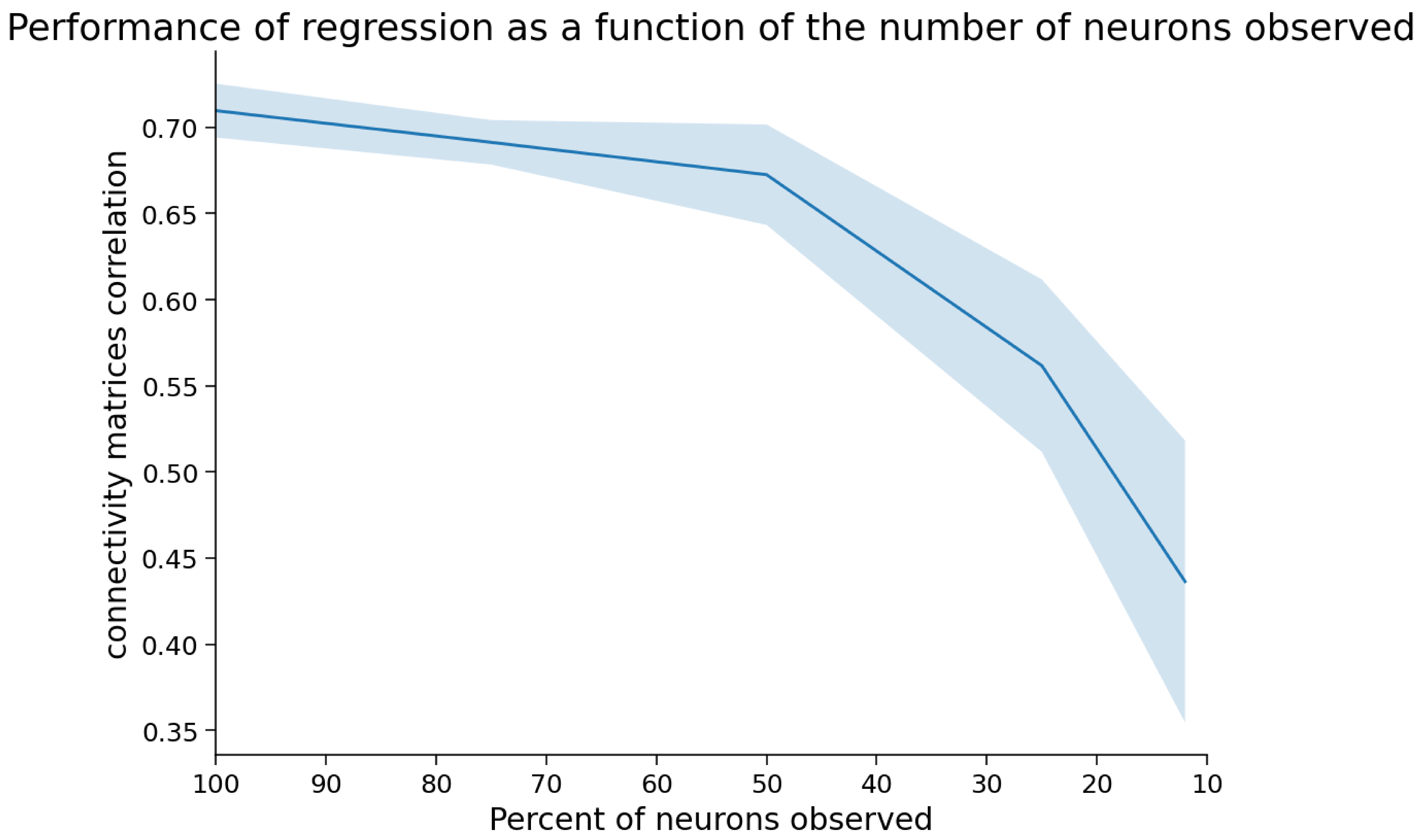
Fixable?

- Problem occurs from ignoring confounders
- It may be possible to improve by fitting full models instead of correlation

Alternative, record many neurons, fit jointly



Partial recording makes advantage of multiple regression go away



Why is regression a problem?

$$\widehat{\beta} = (X'X)^{-1}X'Y$$

Omitted Variable Bias Equation

$$y_i = x_i\beta + z_i\delta + u_i$$

$$\widehat{\beta} = (X'X)^{-1}X'(X\beta + Z\delta + U)$$

$$E[\widehat{\beta} \mid X] = \beta + (X'X)^{-1}E[X'Z \mid X]\delta$$

The bias should be arbitrarily big relative to the signal
This problem does not go away with more data

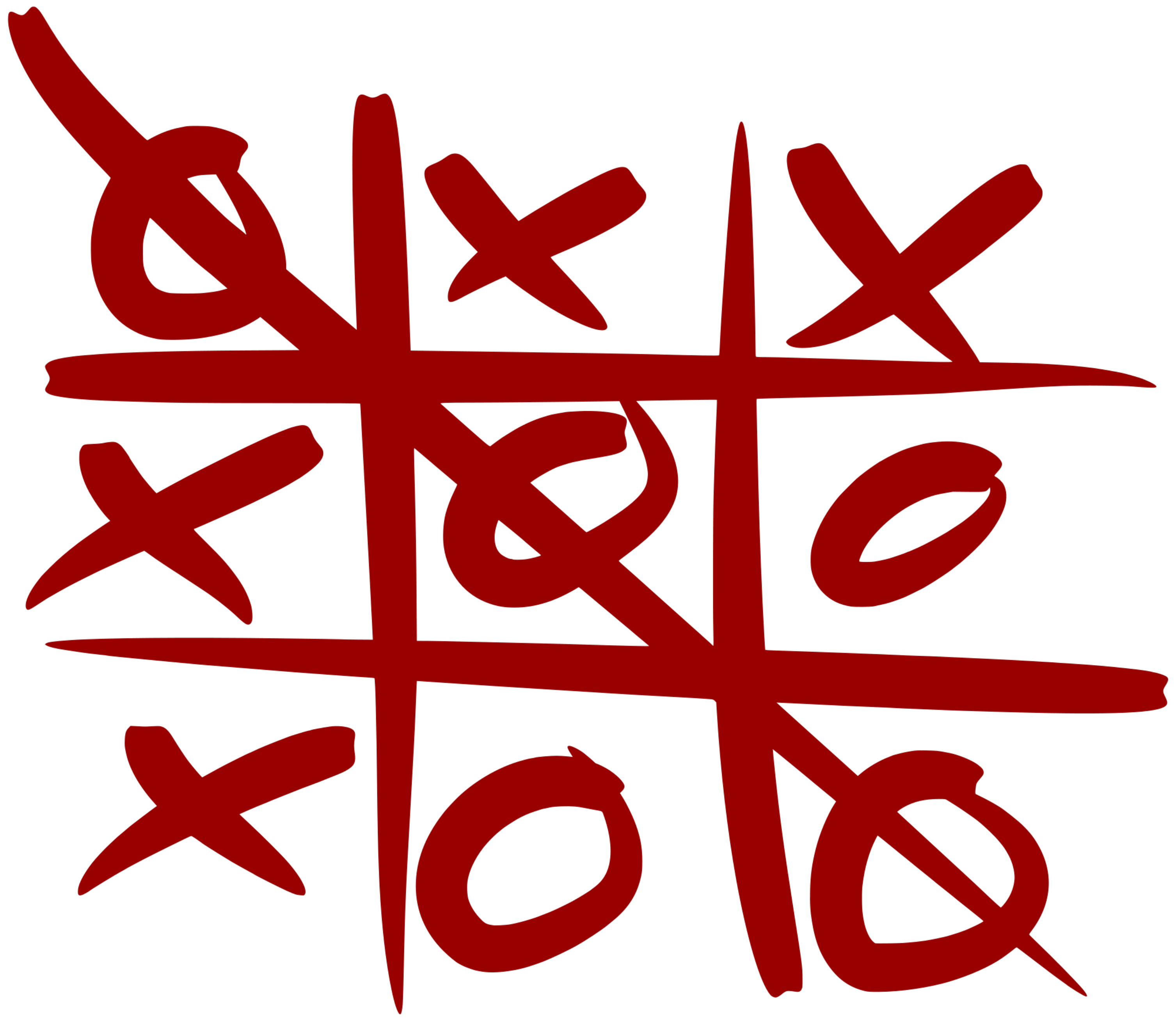
Measuring and interpreting neuronal correlations

Marlene R. Cohen[1] and Adam Kohn[2]

Flavors of understanding and link to complexity

- Know some truths about it
- Predict it
- Fix it
- Simulate it
- Understand how it works

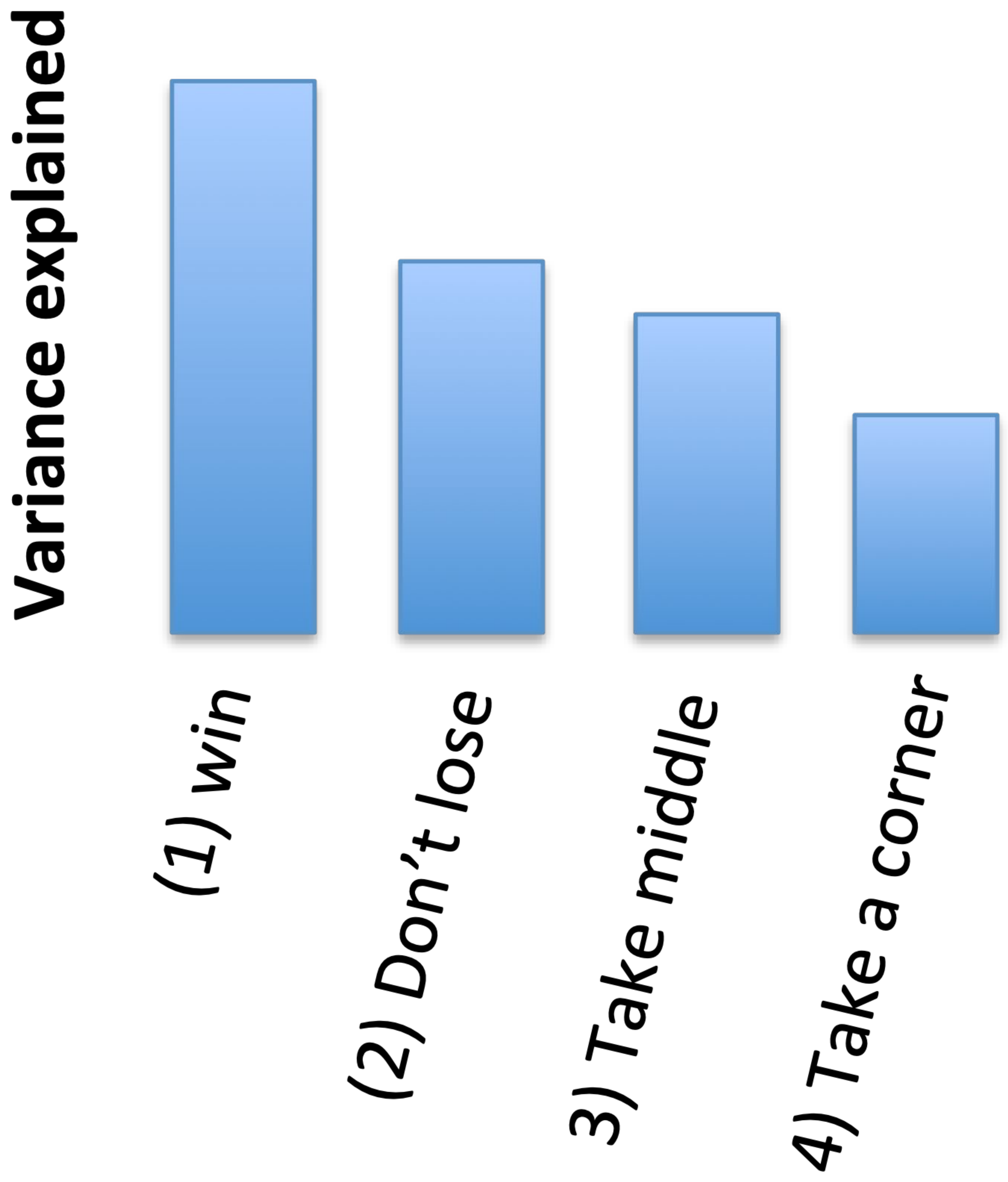
Think about complexity: Tic Tac Toe



255,168 distinct games!

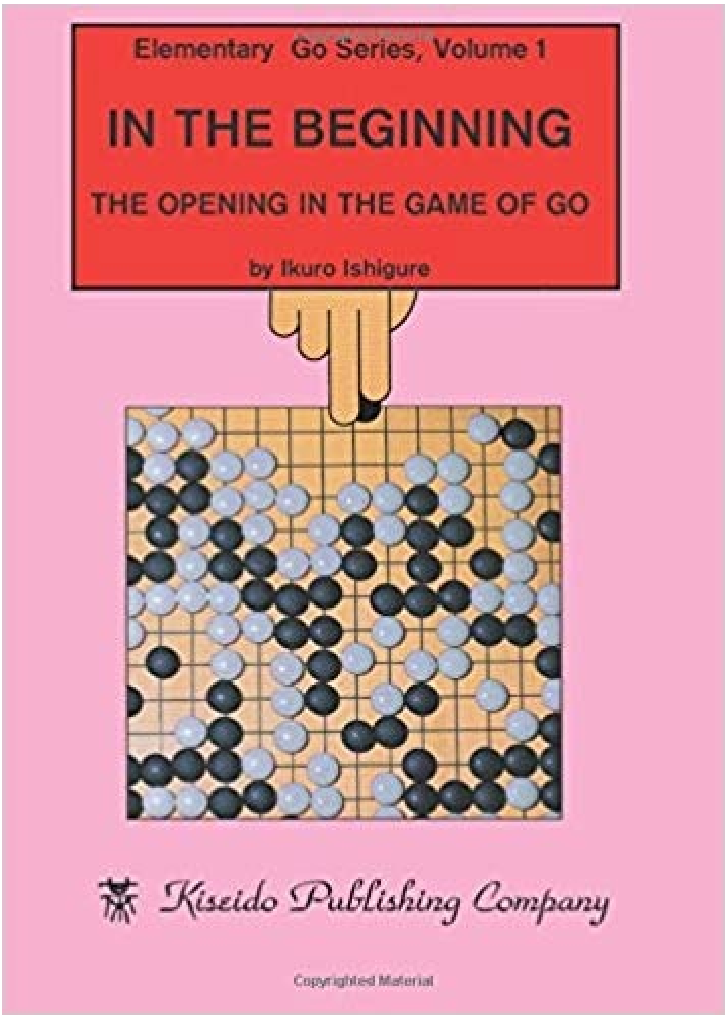
Lillicrap and Kording

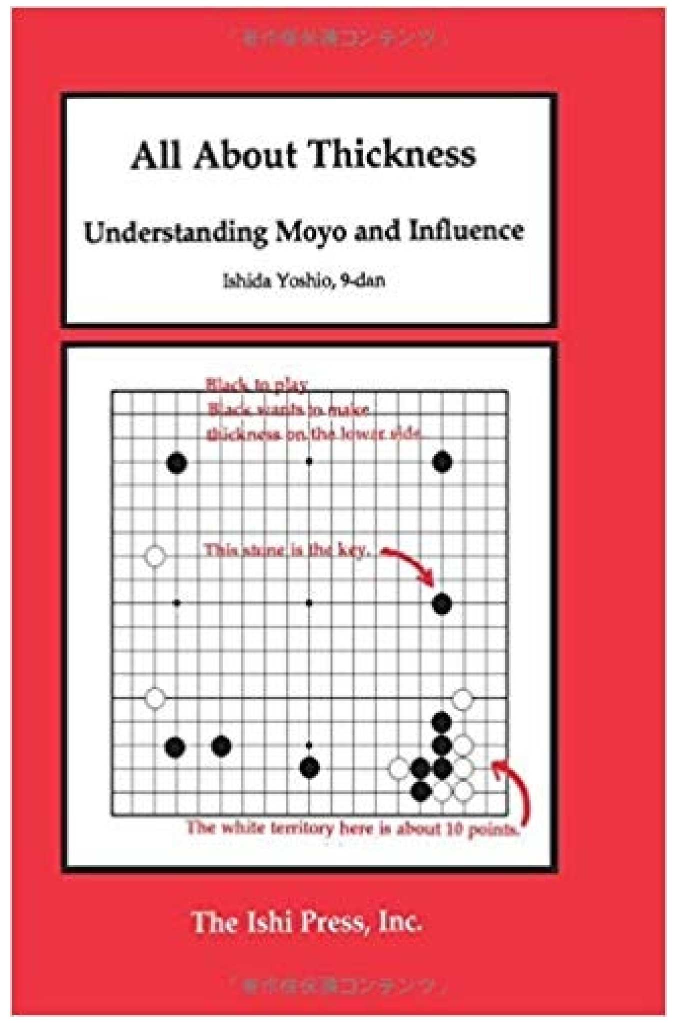
Compressible

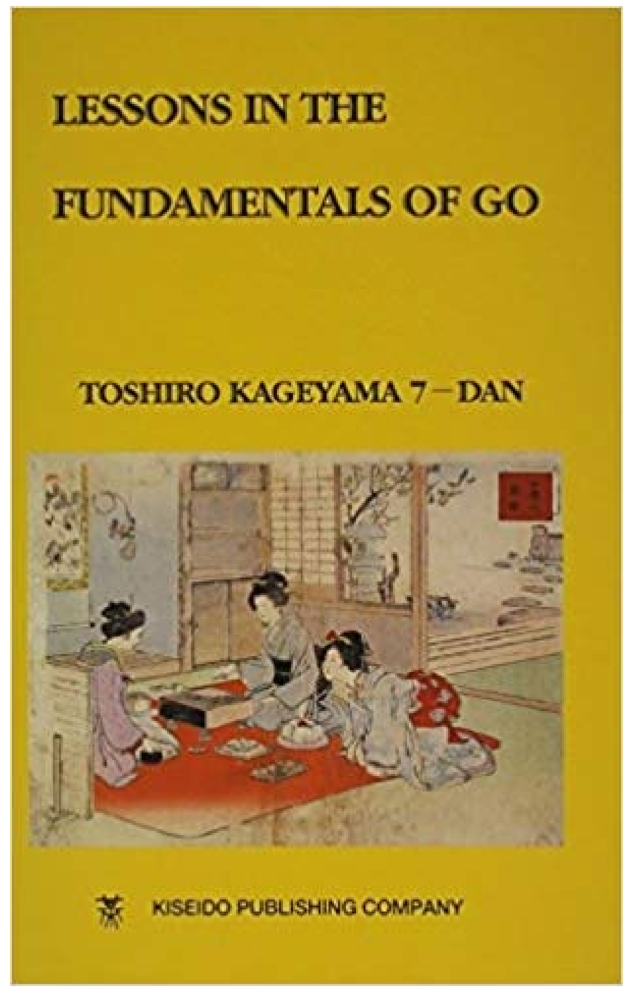


Go

Probably no way to compactly describe it







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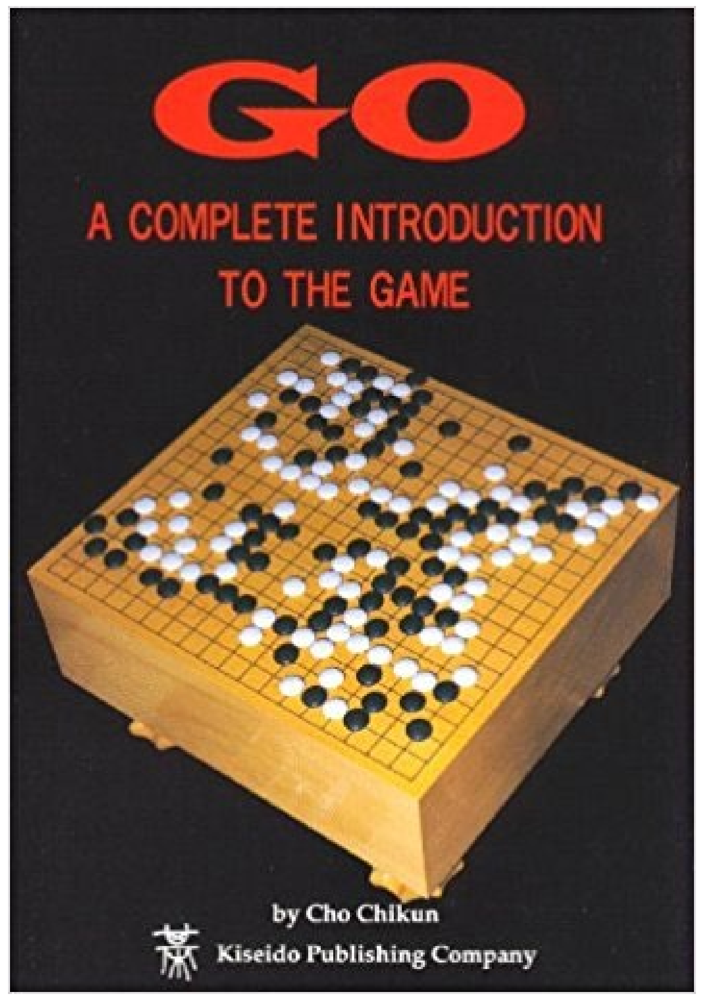
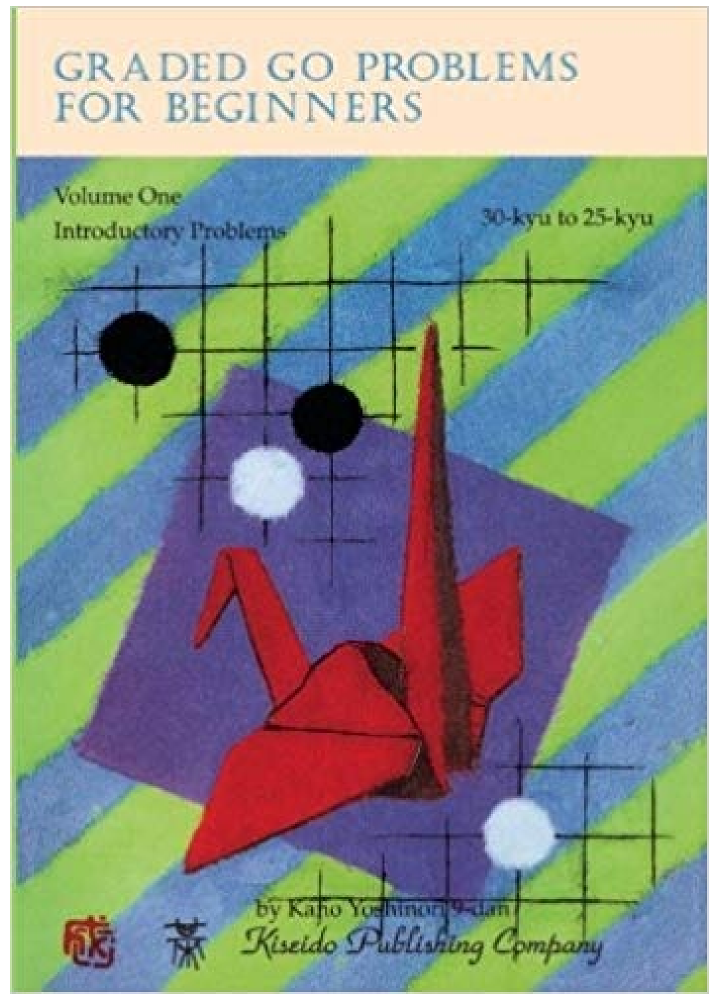
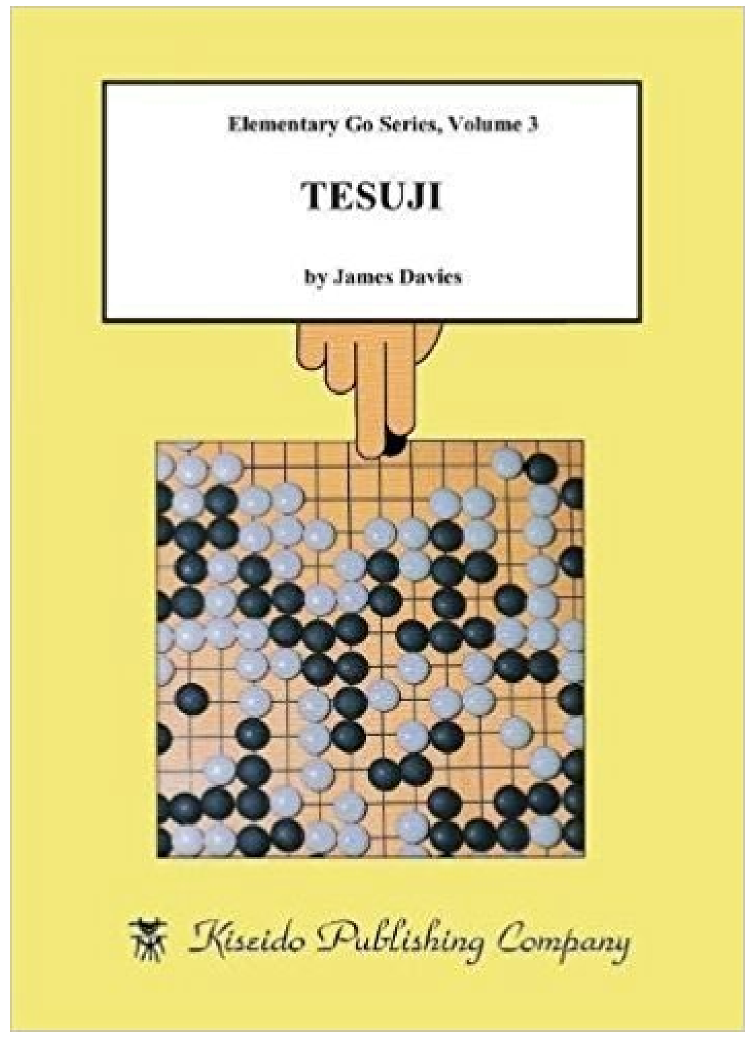
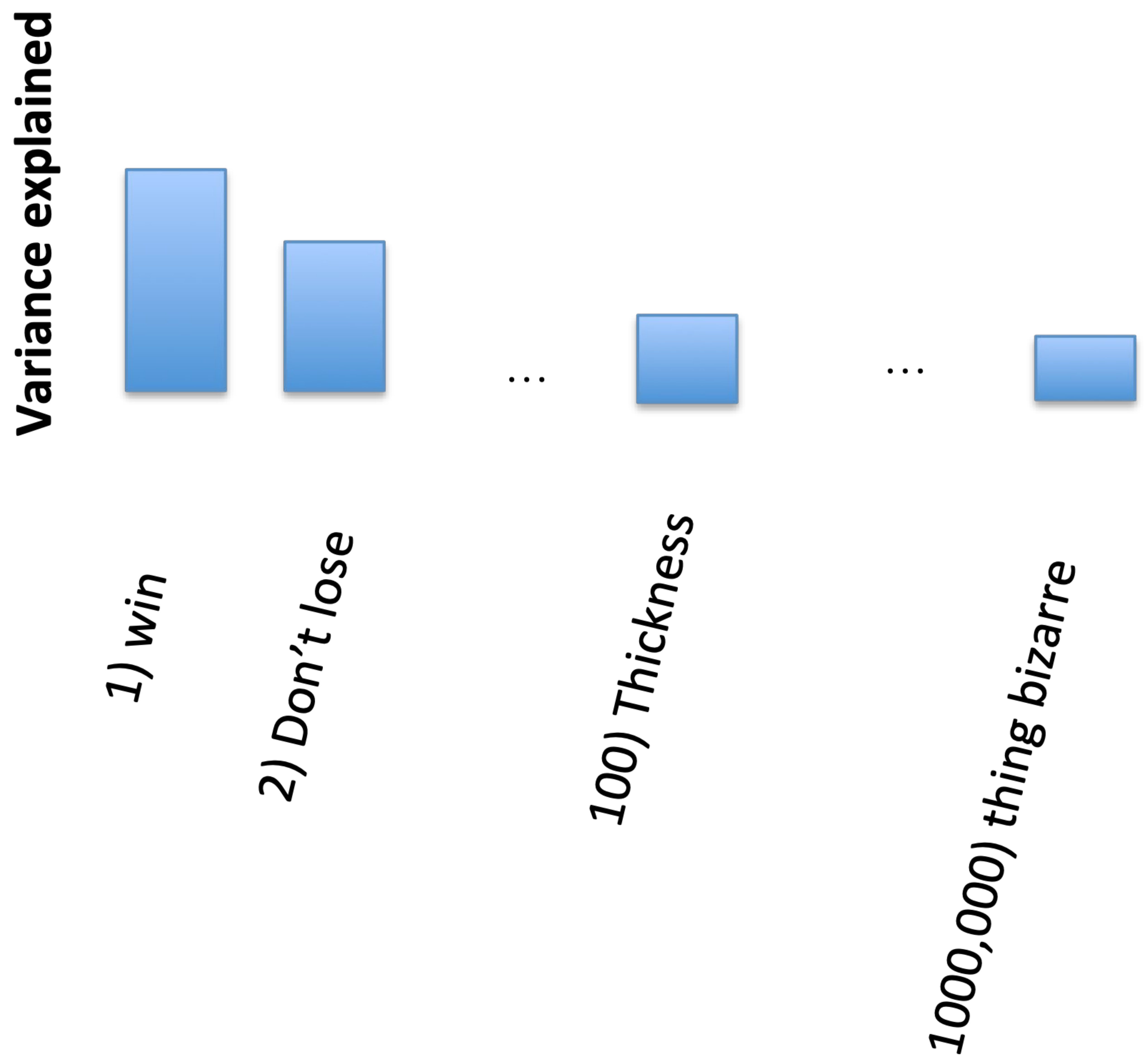








They are all real. Replicable from Go grand master to Go grandmaster.

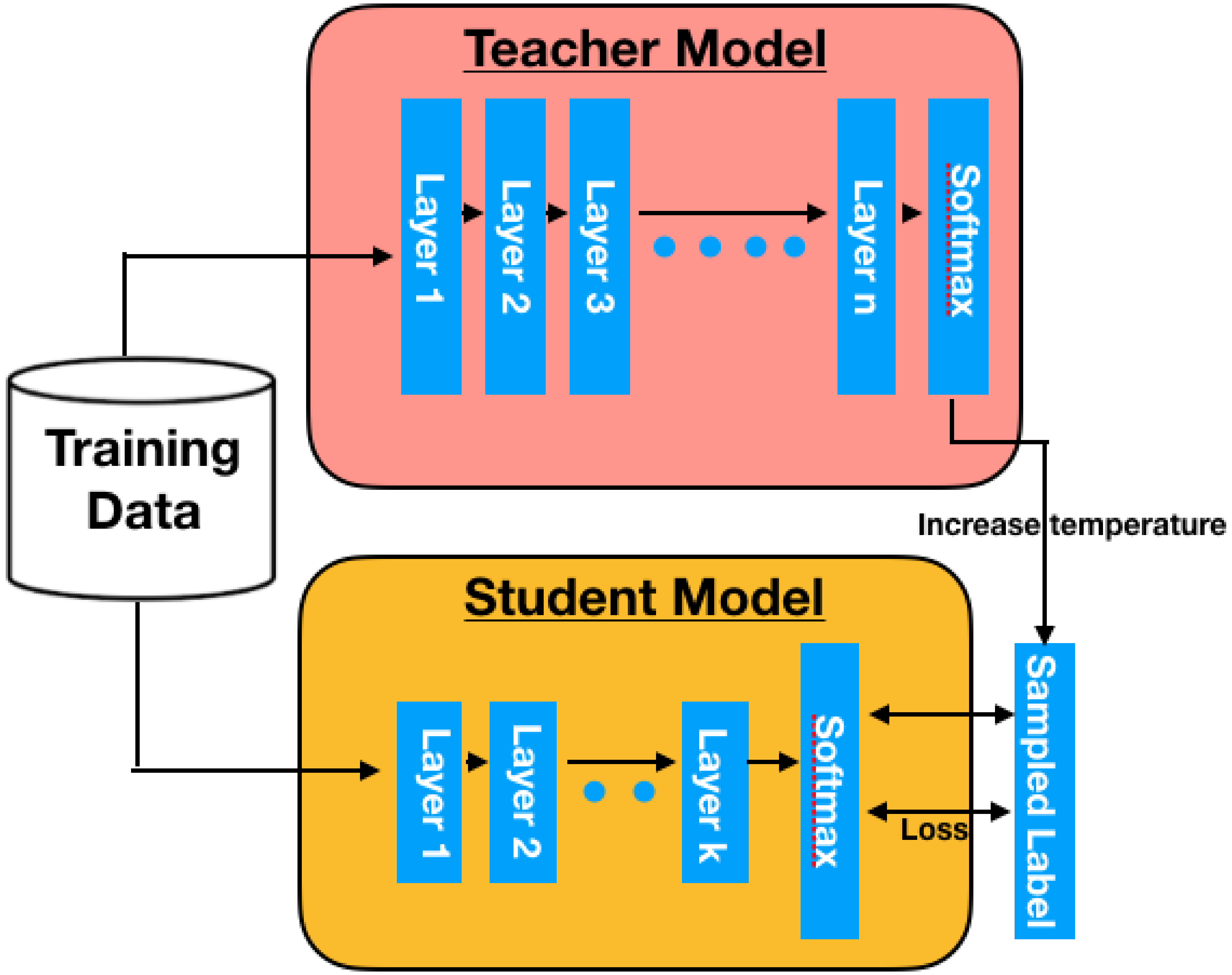
Understand a neural network

- **Pytorch code**
- Vs the **Weight dump**

How much information about the world does an intelligence have?

- Distillation
- Complexity calculations
- Back of the envelope calculations

Distillation



from mc.ai

Factor 10-100 on MNIST, imagenet

e.g. Ba and Caruana, Zhu et al 2018

Can we compress NNs?

- MNIST -> soft decision trees
    - BAD
- imagenet

Back of the envelope human

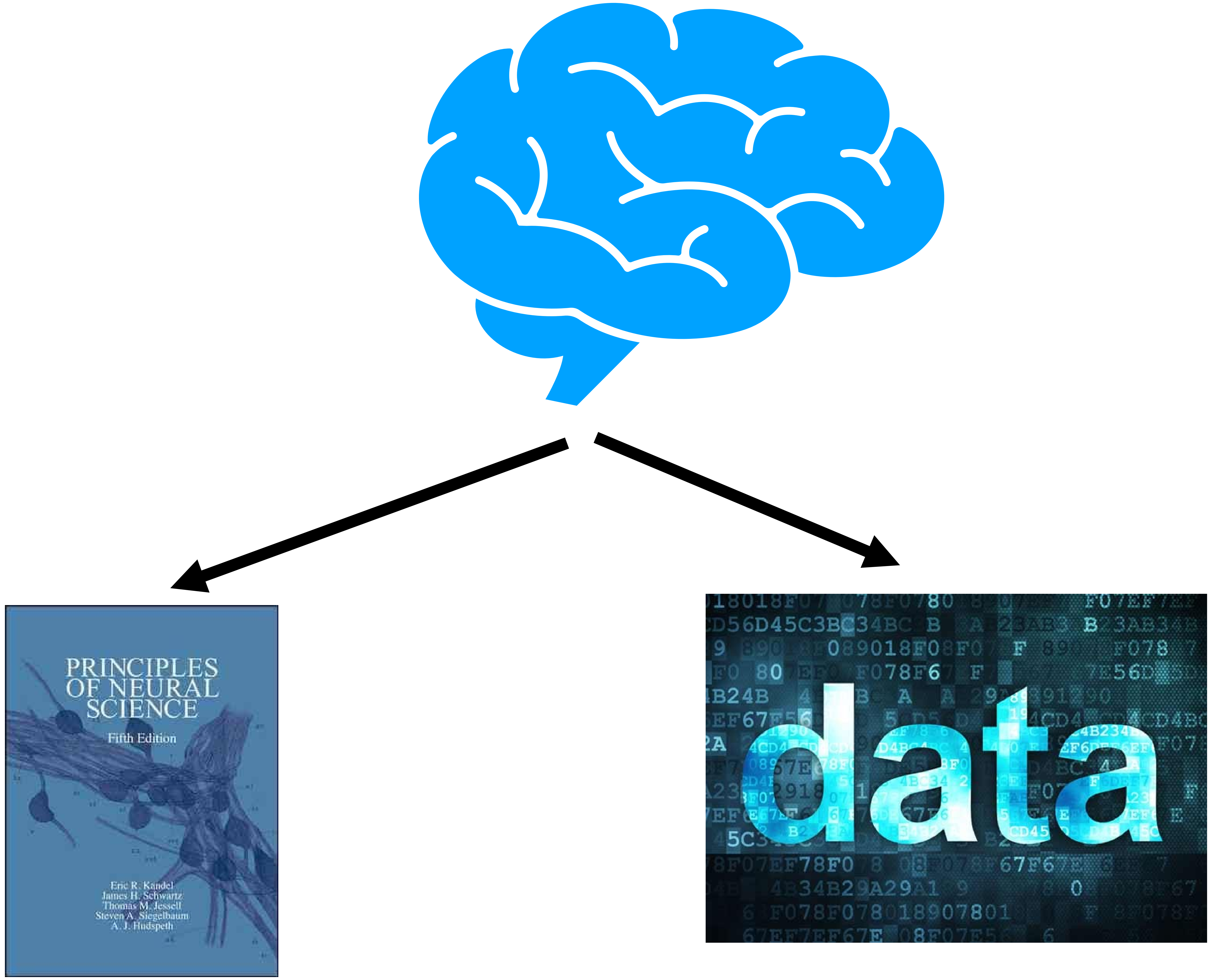
- 10 bits/s
- pi*10^7 seconds/a
- 30 years

- 10^10 bits
- 10^6 bits/book -> 10^4 books

H(DNA)<<H(World)

- DNA: 2*3*10^9 nucleotides
  - mostly non-nervous system
  - of nervous system possibly much non-computational
  - very non-compressed
- Nurture >> Nature

Ok. So what if the brain is not compressible?

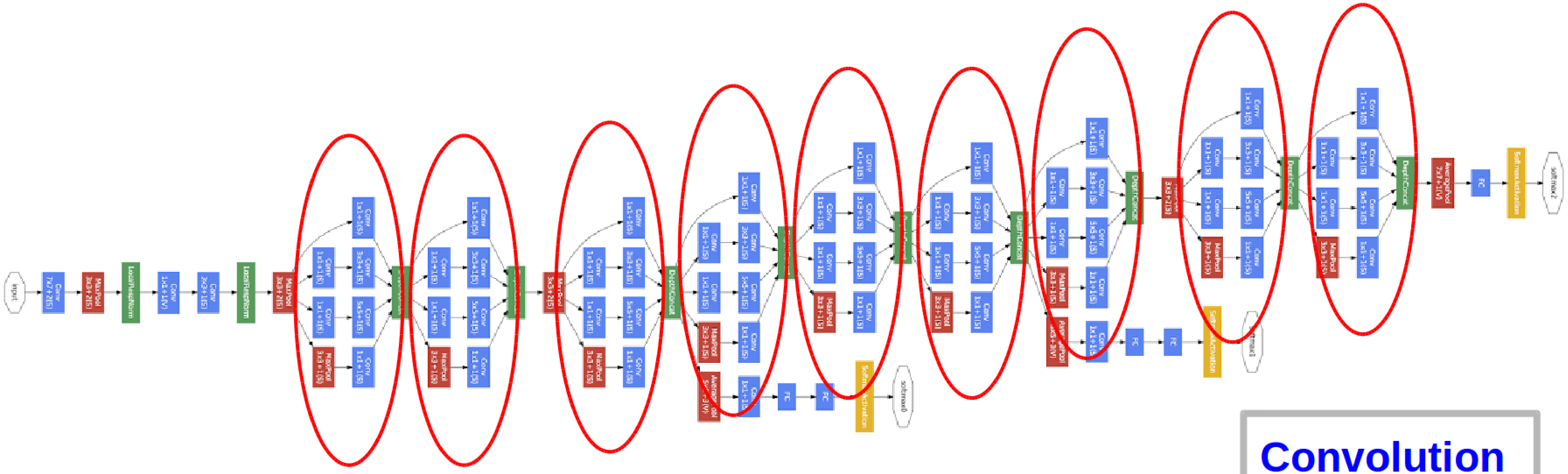


Argument in a nutshell

- Pytorch code to make an ANN is easy for us to understand
- Resulting network is (probably) impossible to understand
- So lets do the analogue of the first in neuroscience

- **Don’t study the mind. Study the process that makes the mind.**

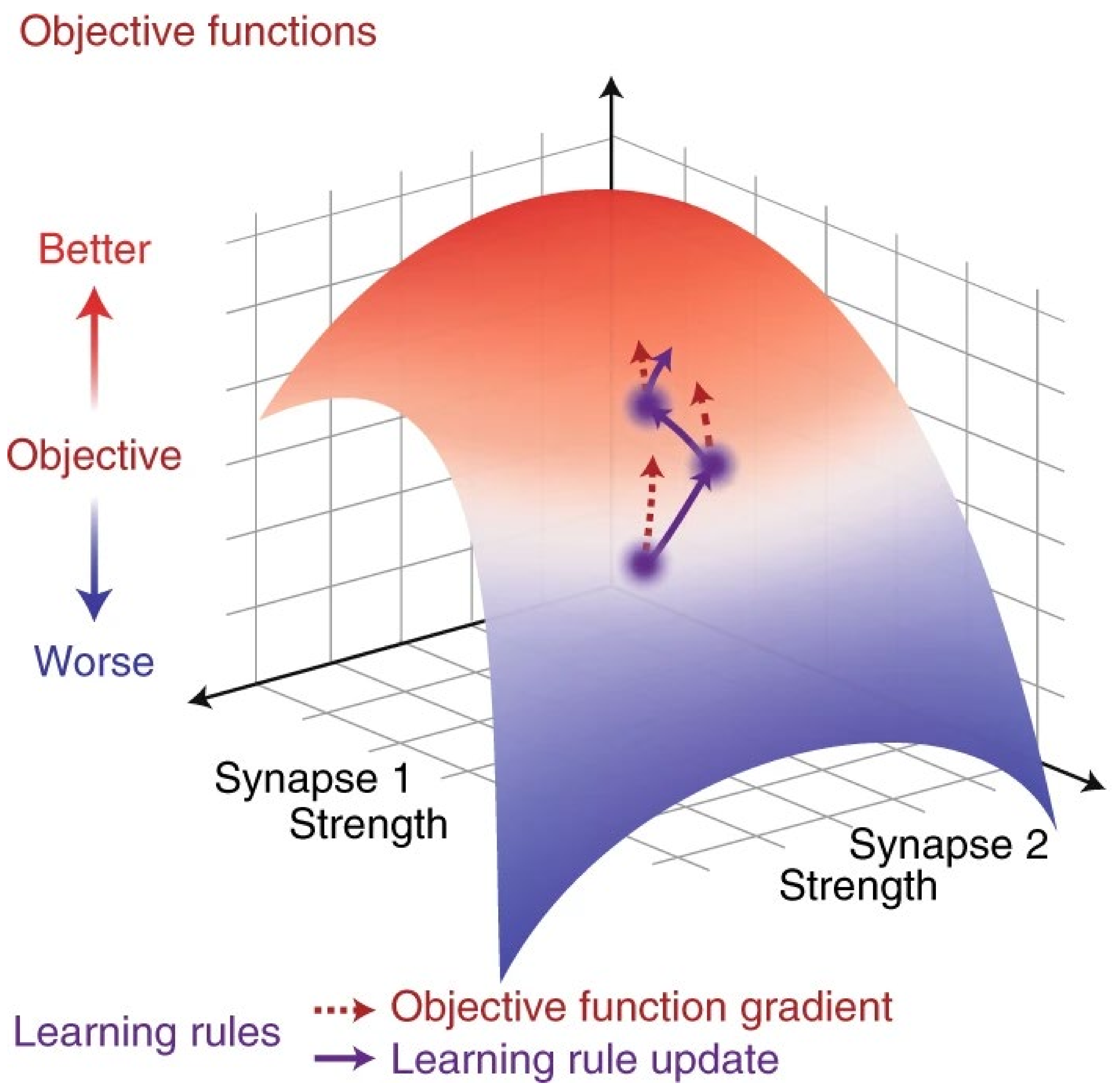
Architecture (Googlenet)



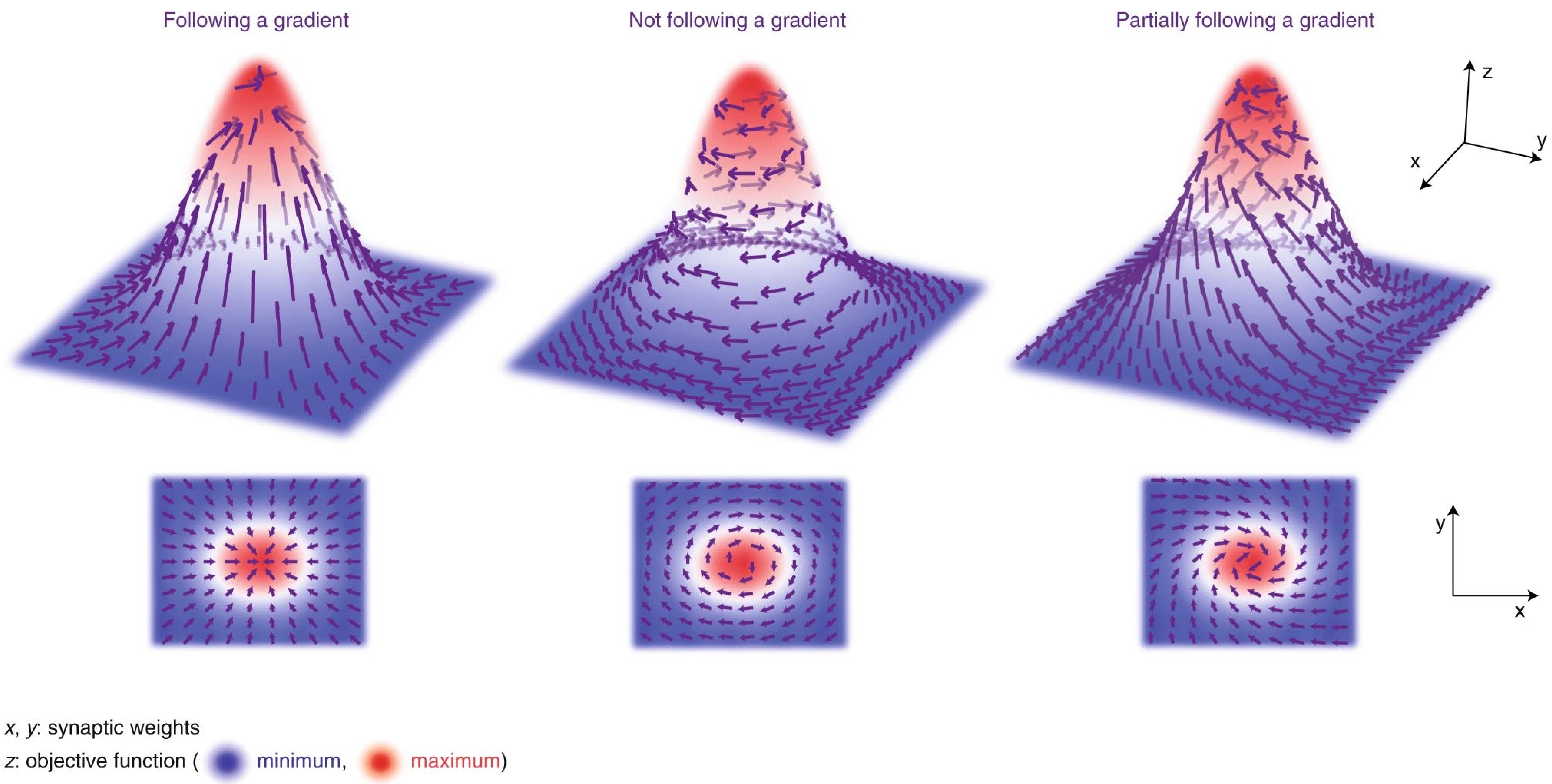
Convolution
Pooling
Softmax
Concat/Normalize

Richards et al review paper

Objective function (softmax)



Should brain follow a gradient?

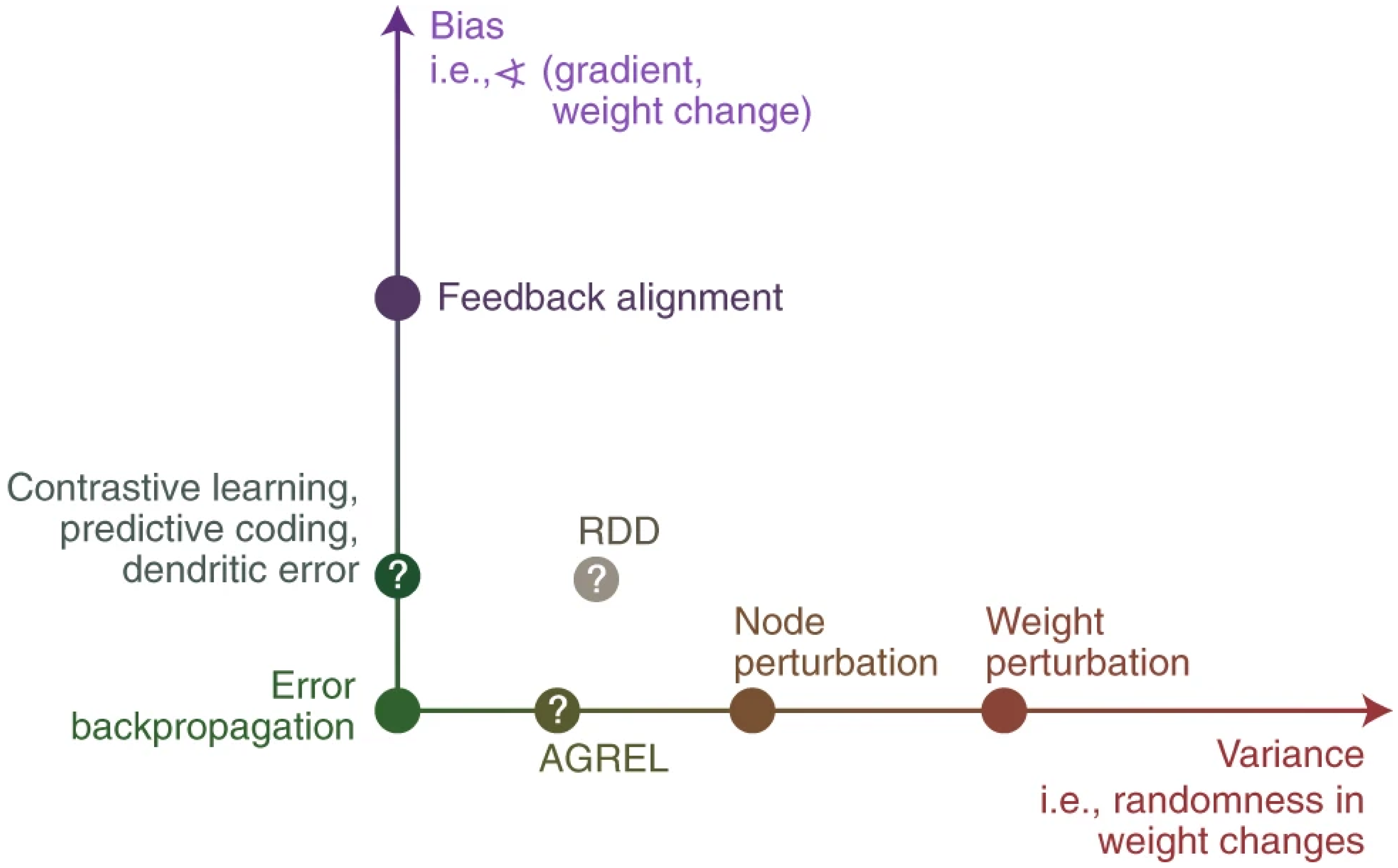


Optimizer (SGD)

$$Q(w) = \frac{1}{n}\sum_{i=1}^{n} Q_i(w)$$

$$w := w - \eta \nabla Q(w) = w - \eta \sum_{i=1}^{n} \nabla Q_i(w)/n$$

Efficiency is a real criterion



Data and embodiment

- Embodiment matters
  - Part of mechanism
  - Makes causality possible
  - Recasts problem of intelligence
  - Intelligence may be defined in relation to embodied cognition
- Curricula matter to make anything work
- A lot of aspects of data matter

Zador et al review paper

Learning is for the future

- Classical ML: Future distribution is like past distribution (i.i.d.)
- Multi-task: Future distribution is drawn from fixed distribution (i.i.d.)
- Etc
- But in reality: we want to be optimal in potential future world that relates to past worlds

For that reason we need

- Continual progressive learning
- Causal representations: causal structures are stable
- Curiosity: we want to learn what matters for future
- Constraints: we need to use our species’ past knowledge of evolutions

Three causal paths

- Bottom up: molecules -> spikes -> populations ->behavior
- Evolution: Ecological Niche -> Specification of Brains
  - There is something unique about the human niche
- Learning: Niche+Specification -> Actual Brains

Take home message

- Pytorch code to make an ANN is easy for us to understand
- Resulting network is (probably) impossible to understand
- So lets do the analogue of the first in neuroscience