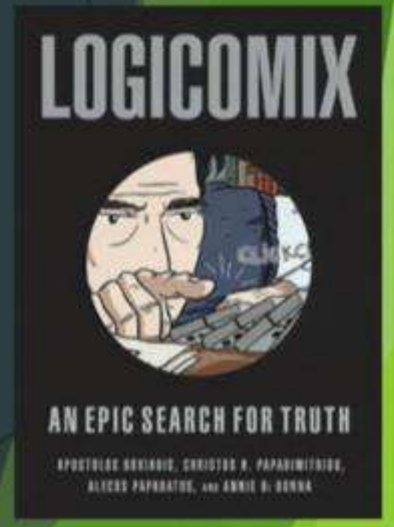
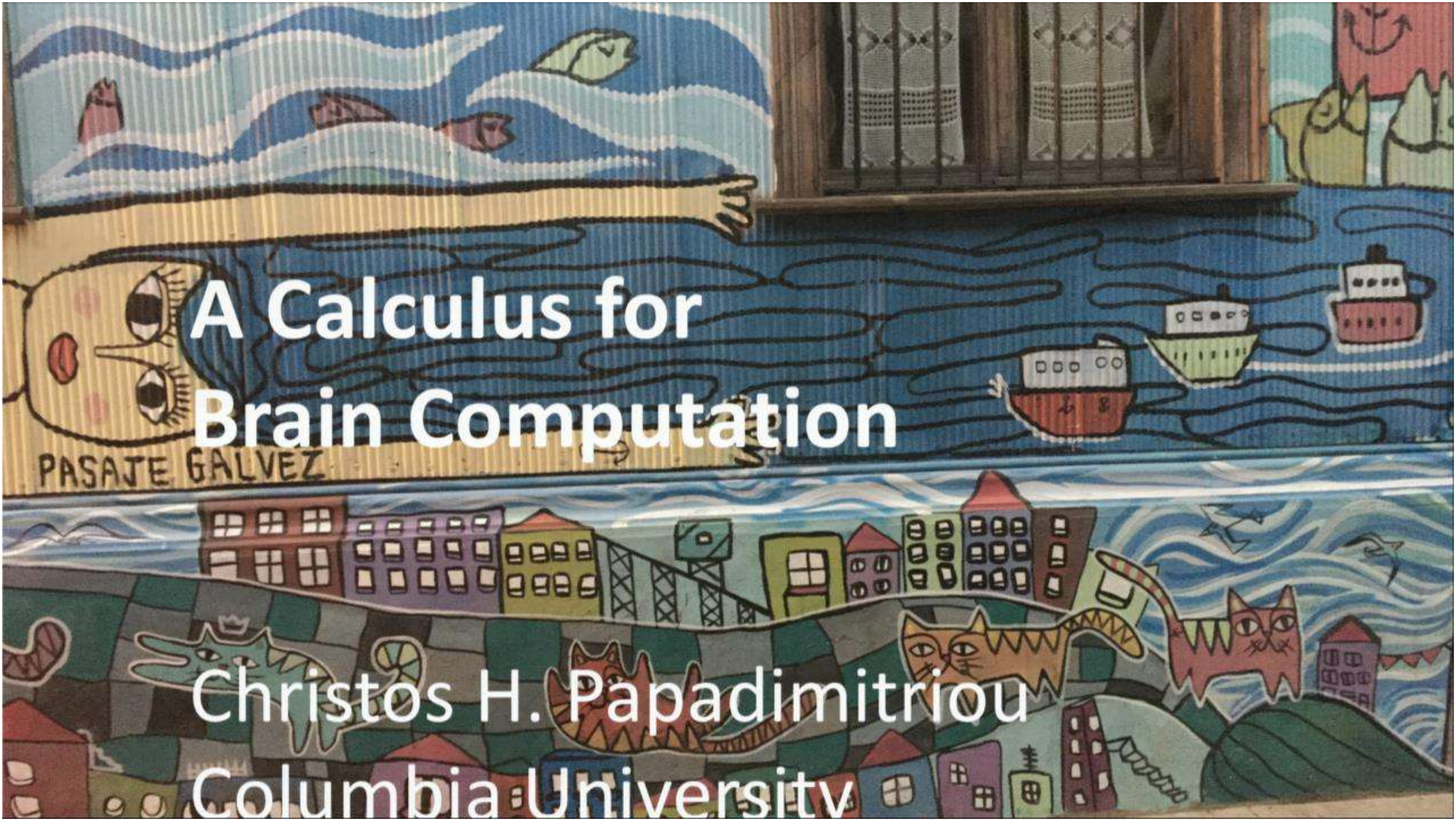
Plenary Speaker: Christos H. Papadimitriou

To: Fred Roberts
From: Tom Leighton and Christos Papadimitriou (chair)
Date: Thu, 6 Mar 1997
Subject: DIMACS Research Evaluation

Our two-member research evaluation team was given seven specific questions (below) relating to the strategic and tactical research goals of DIMACS, and

- He has been awarded the Knuth Prize, IEEE's John von Neumann Medal, the EATCS Award, the IEEE Computer Society Charles Babbage Award, and the Gödel Prize.
- He is a fellow of the ACM and the National Academy of Engineering, and a member of the National Academy of Sciences and the American Academy of Arts and Sciences.
- He has written five textbooks and many articles on algorithms and complexity, and their applications to optimization, databases, control, AI, robotics, economics and game theory, the Internet, evolution, and the brain.
- He co-founded my field, algorithmic game theory, introducing worst-case equilibria and *price of anarchy*.
- He settled the complexity of Euclidian traveling salesman and Nash equilibrium.
- He holds a PhD from Princeton (1976), and eight honorary doctorates.
- He has also written three novels: Turing, Logicomix, and his latest, Independence.





A Calculus for Brain Computation

Christos H. Papadimitriou
Columbia University

Computer Science 1936 – 1995: the Computer

Computer Science 1936 – 1995: the Computer

compilers

operating systems

graphics

databases

intelligent systems

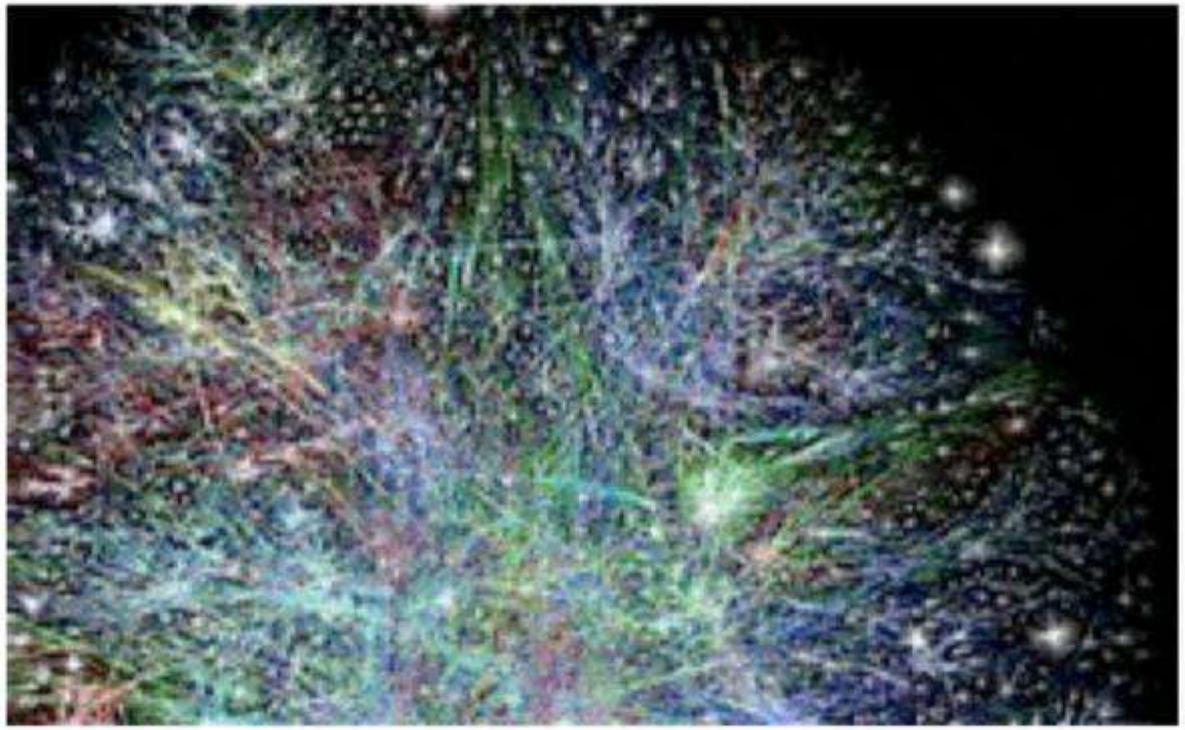
algorithms

chips

networks

P vs NP

Computer Science 1995 – : the Internet



Computer Science 1995 – : the universe

statistical physics

behavior

quantum
physics

dynamics

networks

Computer Science 1995 – : the universe

Computer Science 1995 – : the universe

statistical physics

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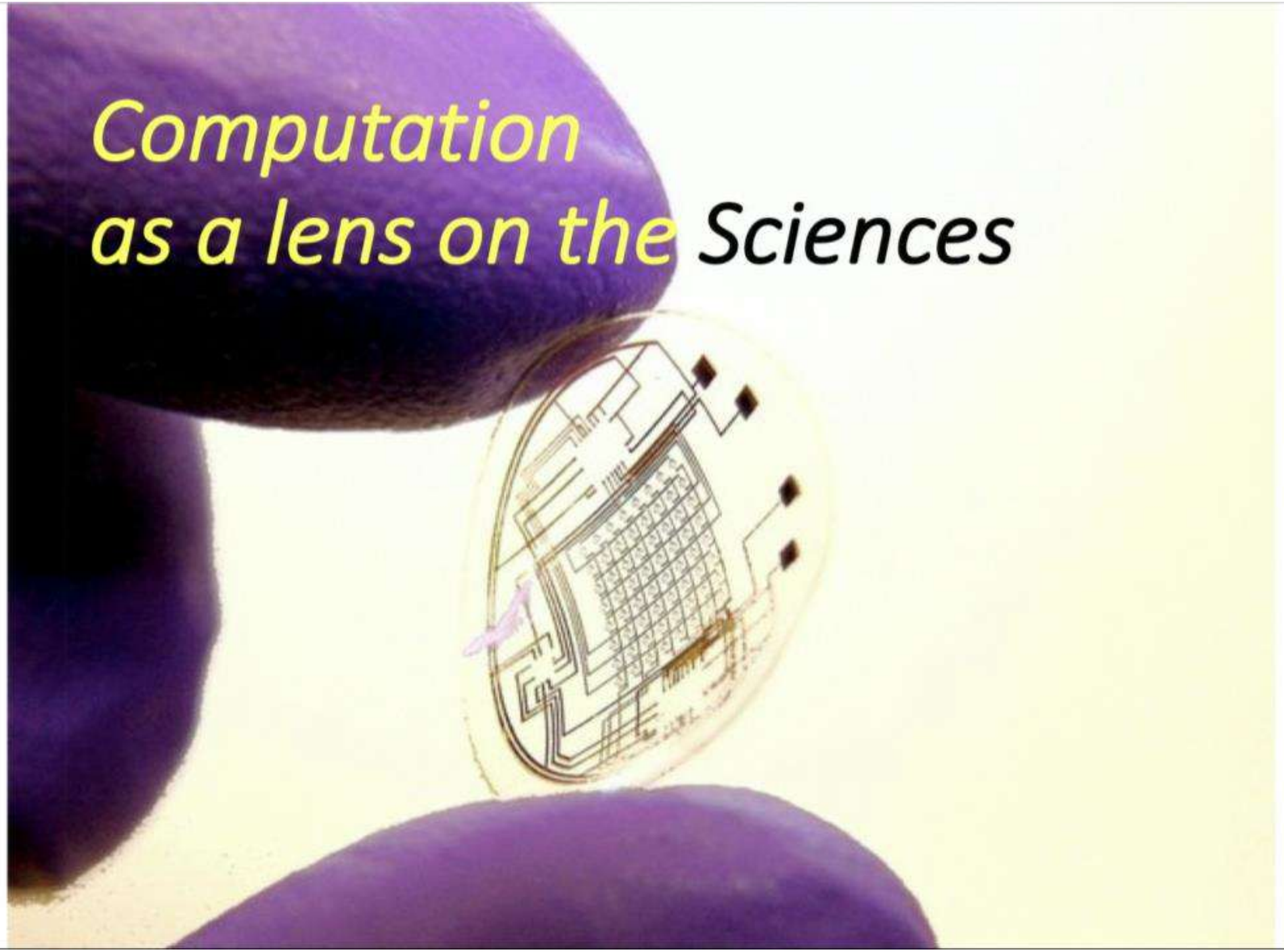
Computation as a lens on the Sciences

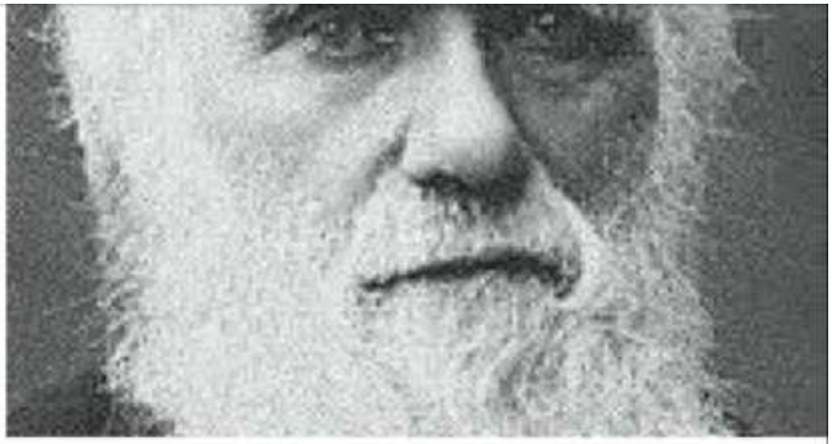


Game Theory and Economics

Game Theory and Economics

Finding a Nash equilibrium is an intractable problem!

Evolution
160 years later

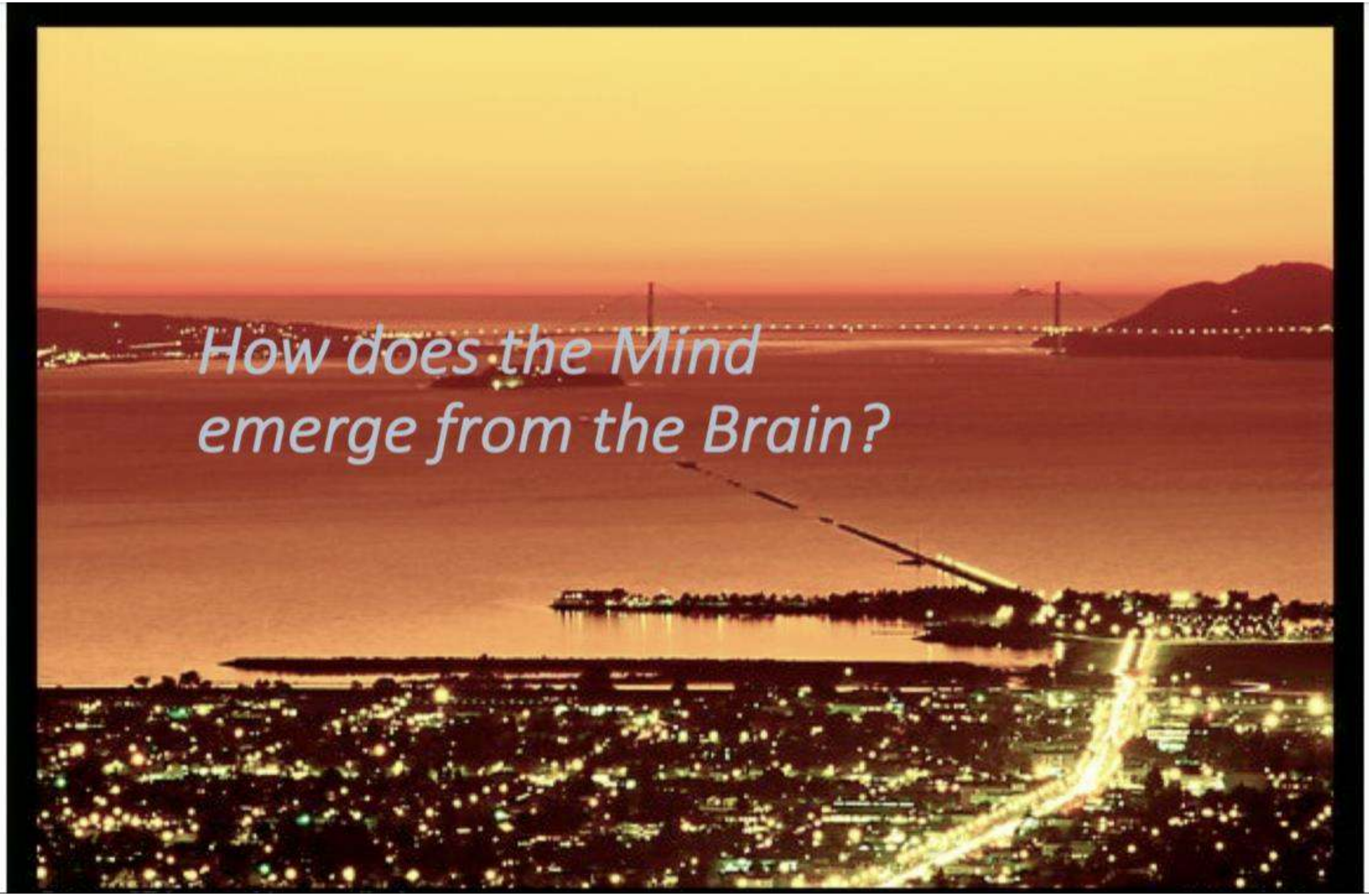


The evolution of a population of genotypes is tantamount to the genes playing a repeated game through ADABOOST (the well known AI algorithm)

Furthermore, every gene in every generation optimizes a trade-off between cumulative fitness and allele entropy

…and next….

How does the Mind emerge from the Brain?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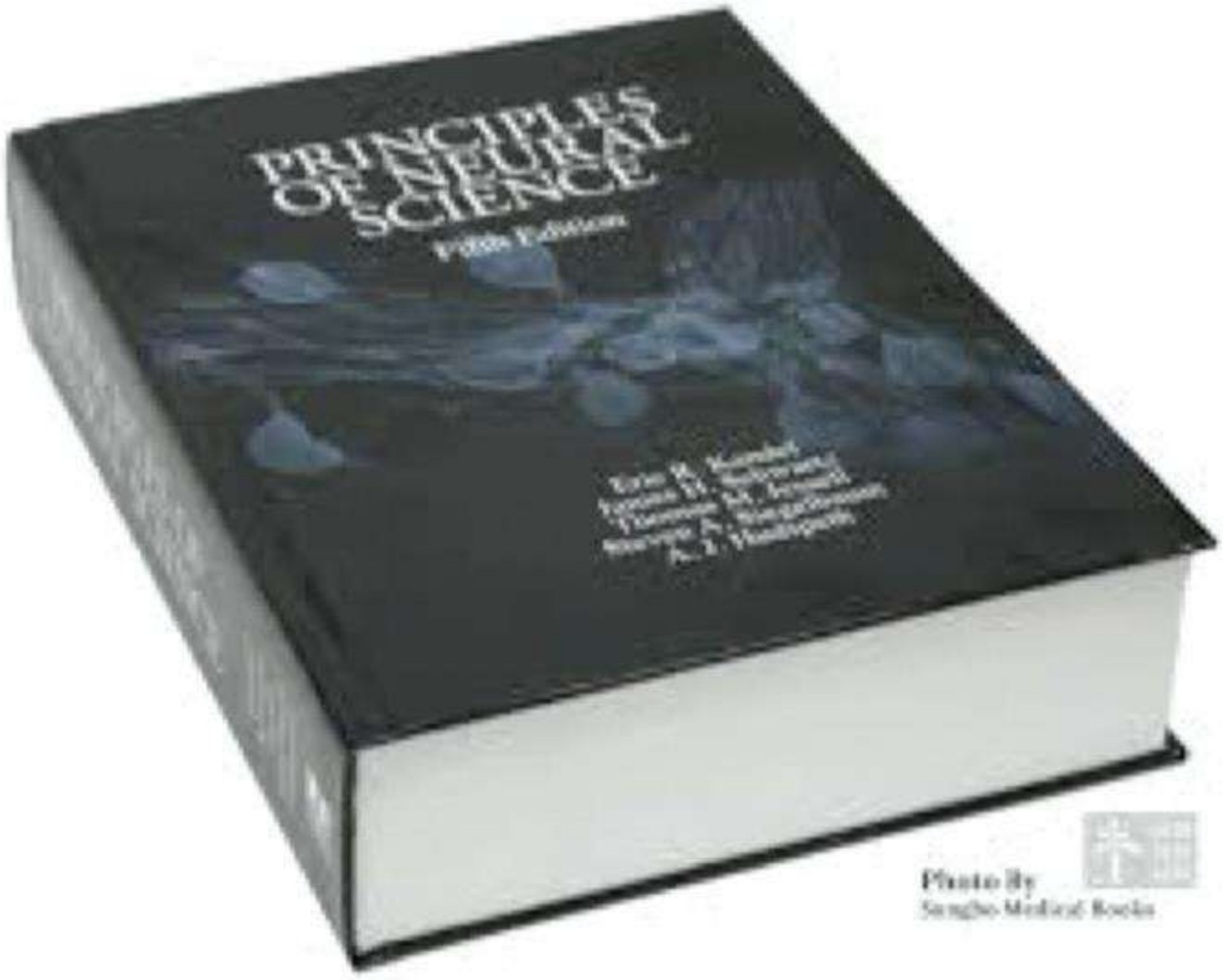
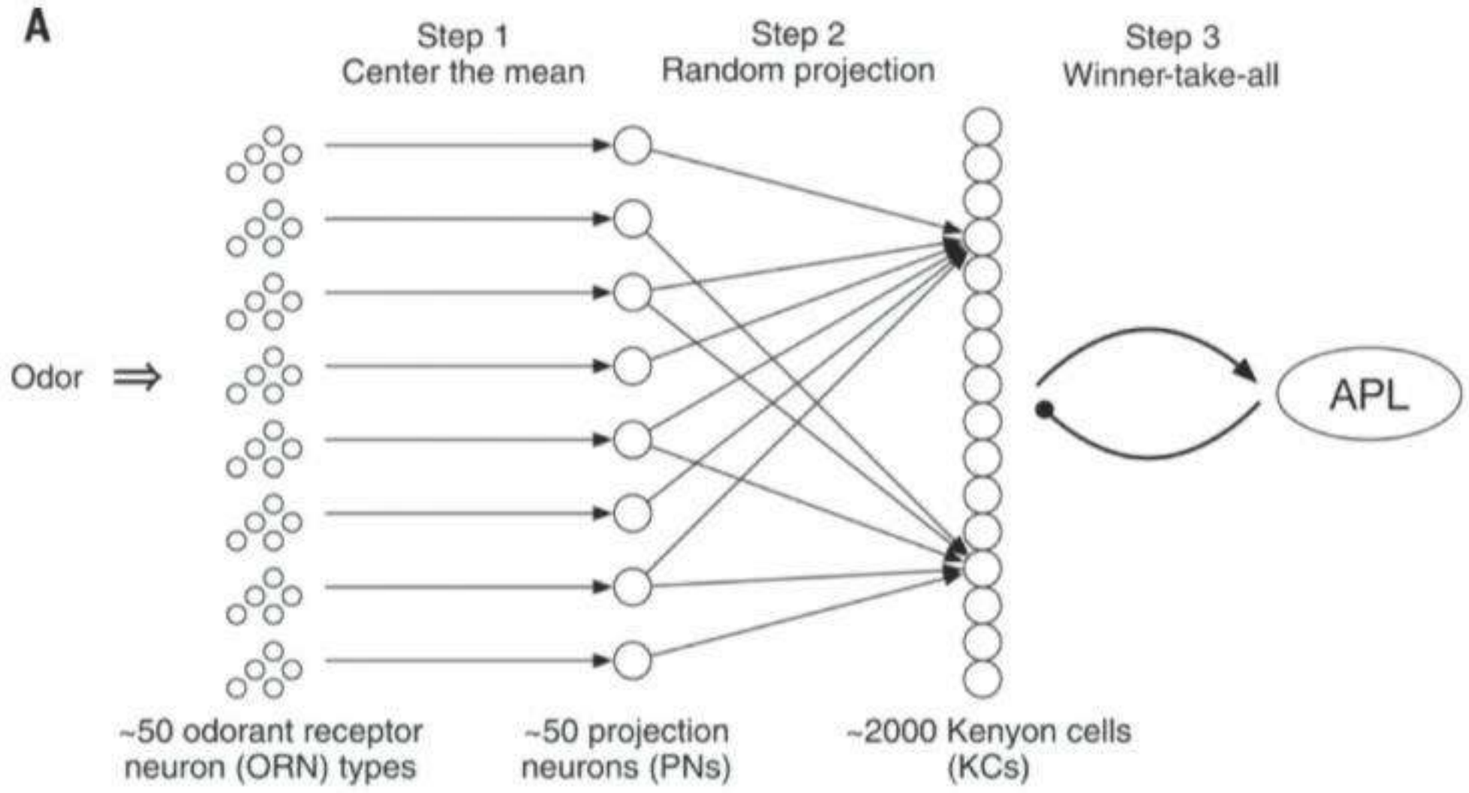


Photo By
Sangbo Medical Books

"…we do not have a logic for the transformation of neural activity into thought … I view discerning [this] logic as the most important future direction of neuroscience…"

Richard Axel: *Neuron* Sep 2018

How fruit flies remember smells



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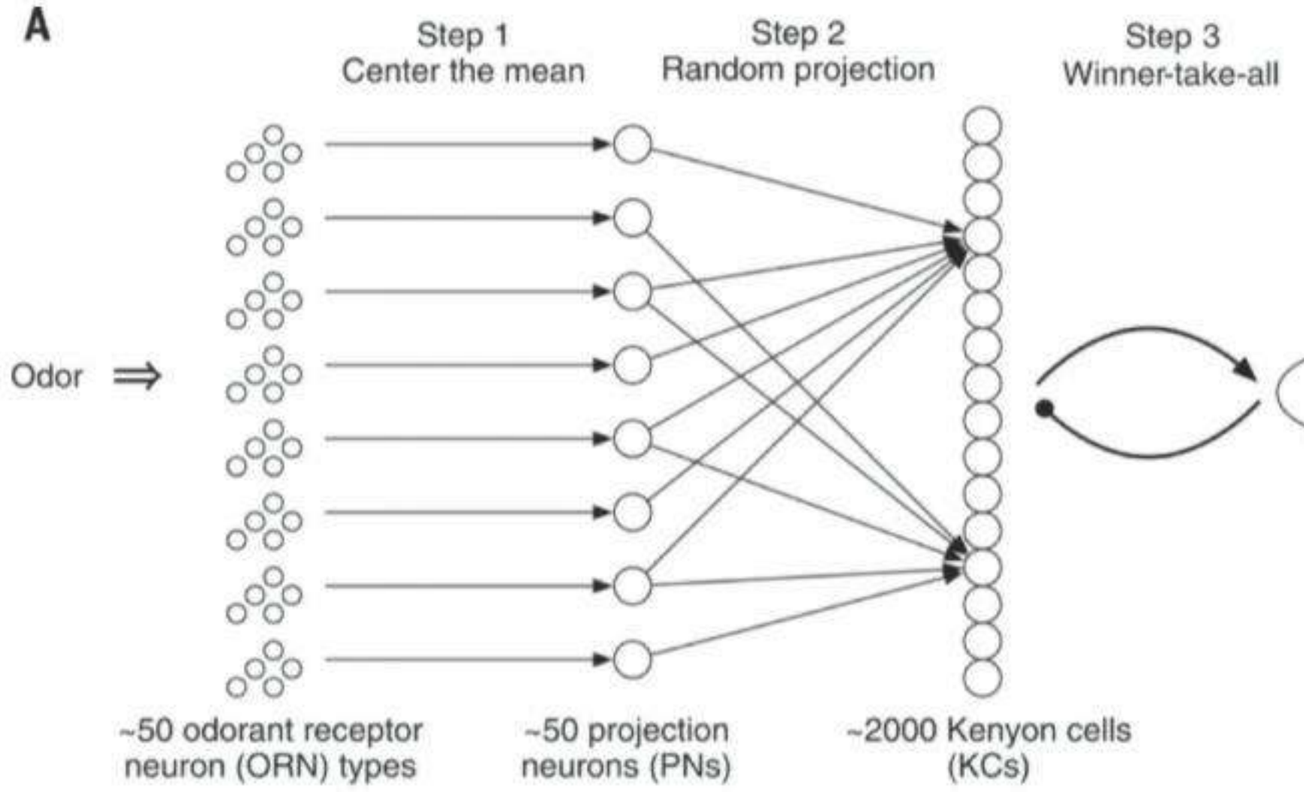
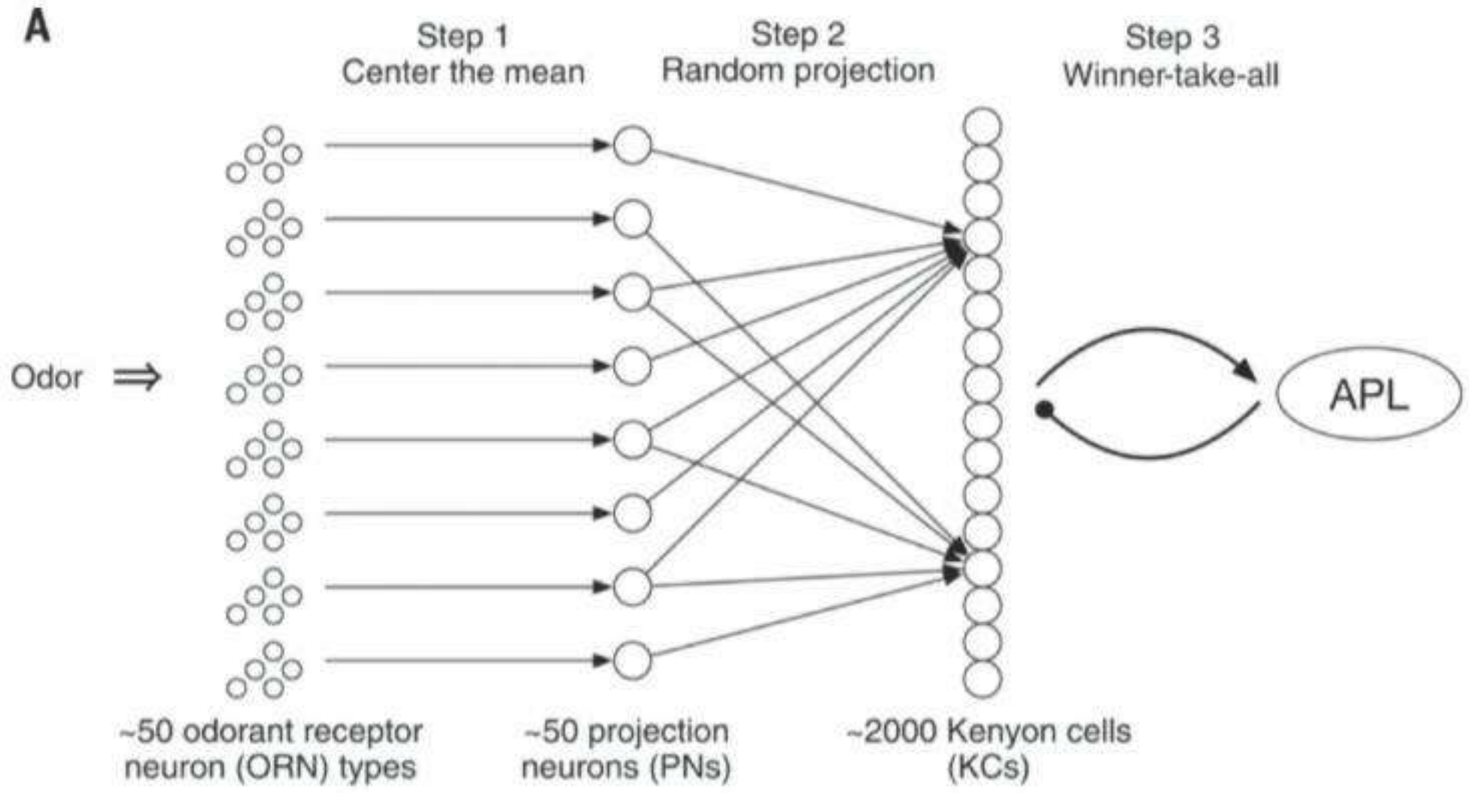


random projection followed by ***cap (RP&C):*** 100 winners (out of 2000) take all

How fruit flies remember smells



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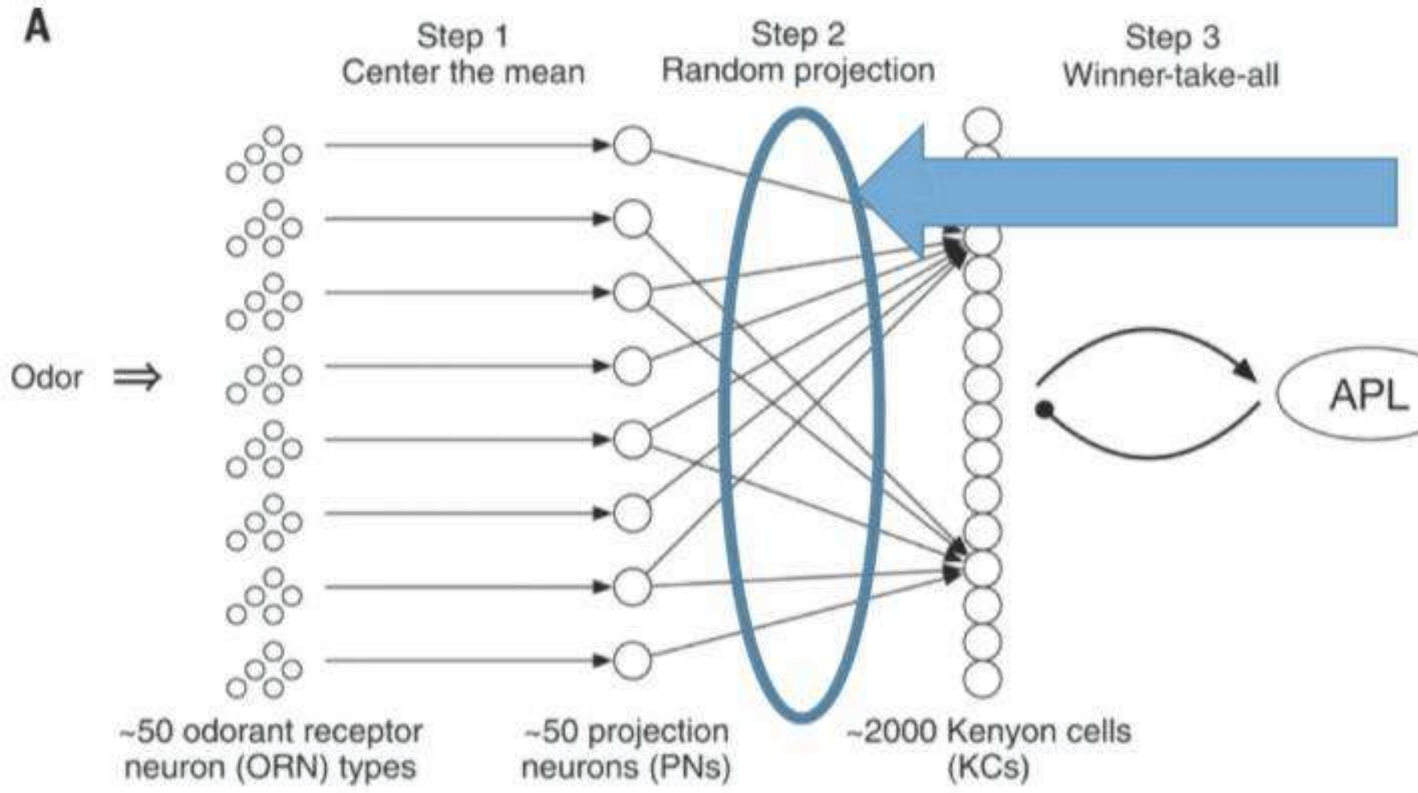
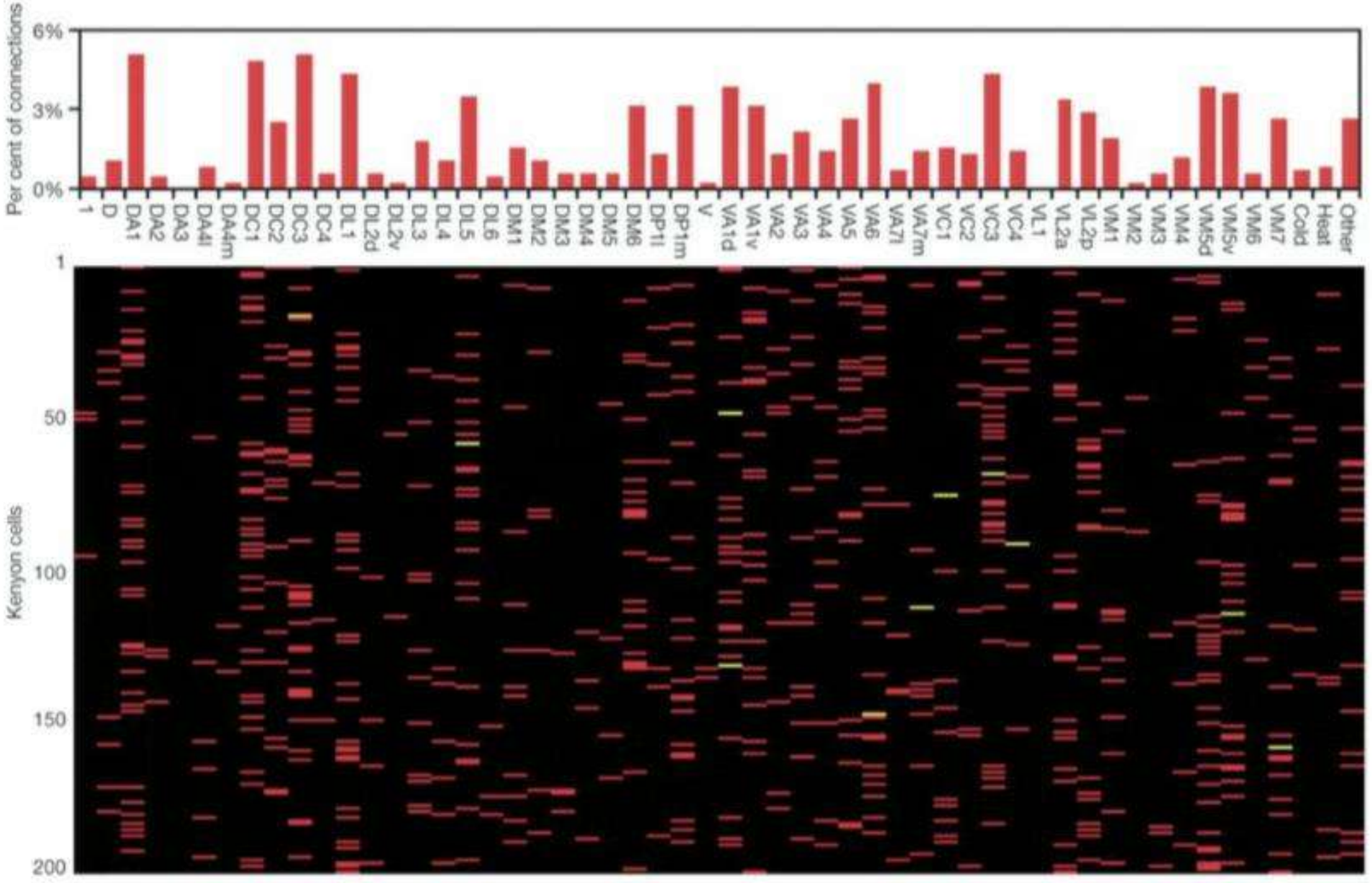


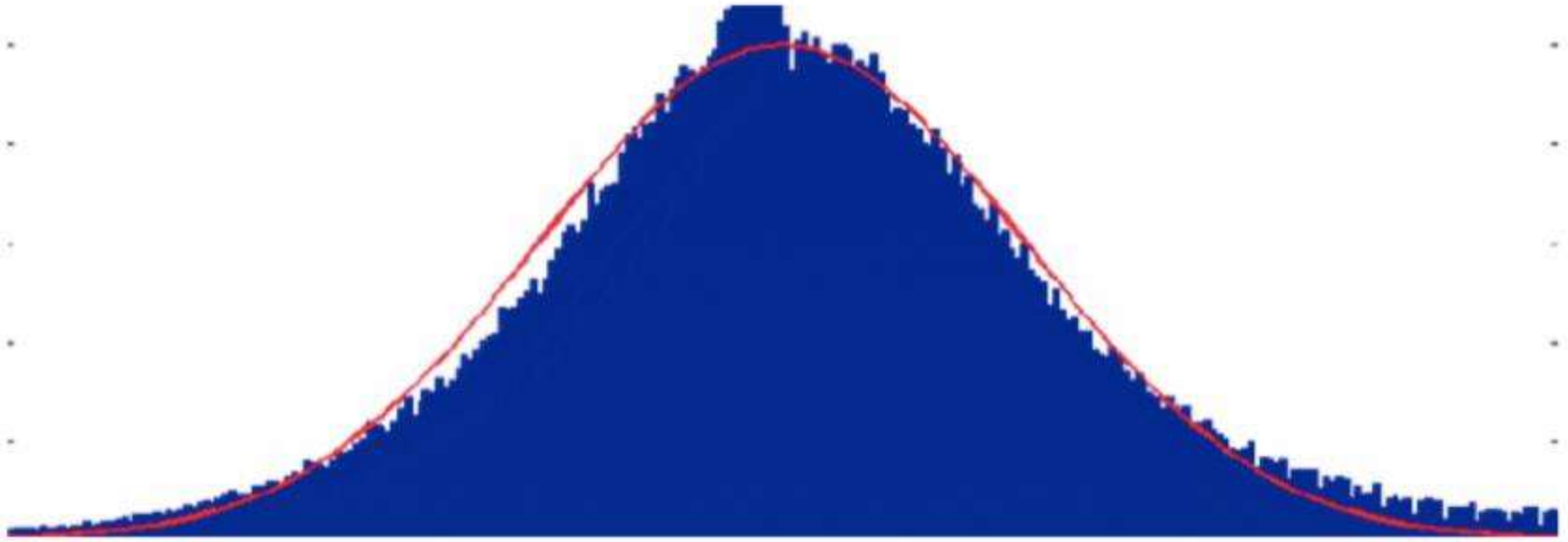
Q: but wait a minute! Is this a random bipartite graph?

A: ***Random convergence of olfactory input in the Drosophila mushroom body*** by S. Caron, V. Ruta, L. Abbott, R. Axel,2013

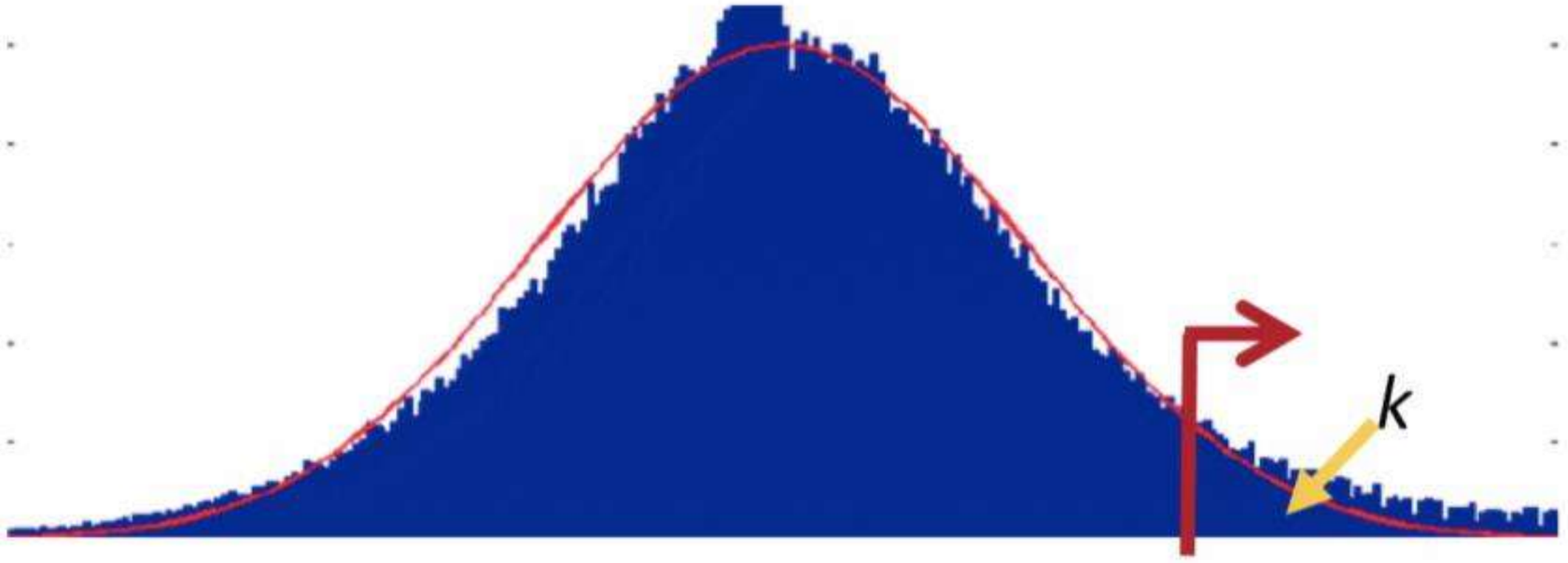
Bottom line: looks like a random bipartite graph, except that the degree distribution of the LHS is not uniform



RP&C

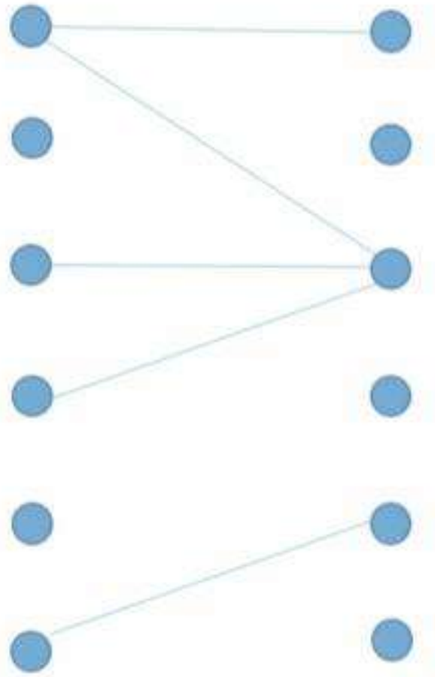


RP&C



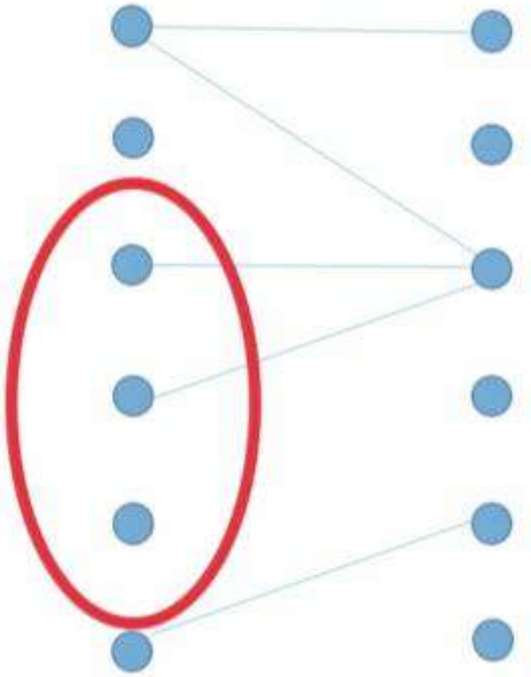
RP&C preserves similarity!

- Random n X n bipartite graph



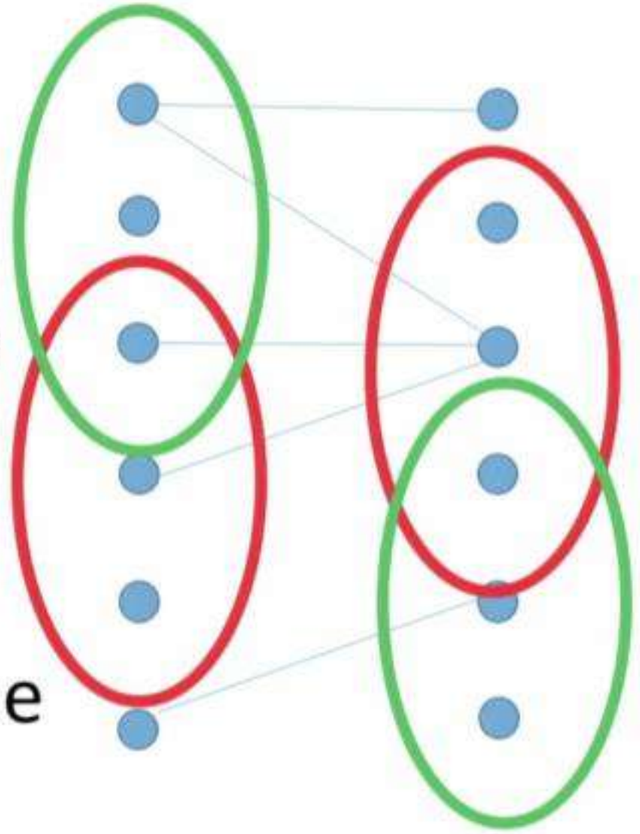
RP&C preserves similarity!

- Random n X n bipartite graph
- A set **A** of k out of n nodes of the LHS fire



RP&C preserves similarity!

- Random n X n bipartite graph
- A set **A** of k out of n nodes of the LHS fire
- A new set **cap(A)** is formed by RP&C
- Repeat now for **B, cap(B)**
- If **A** and **B** overlap in αk nodes, what is the overlap of **cap(A)** and **cap(B)**?

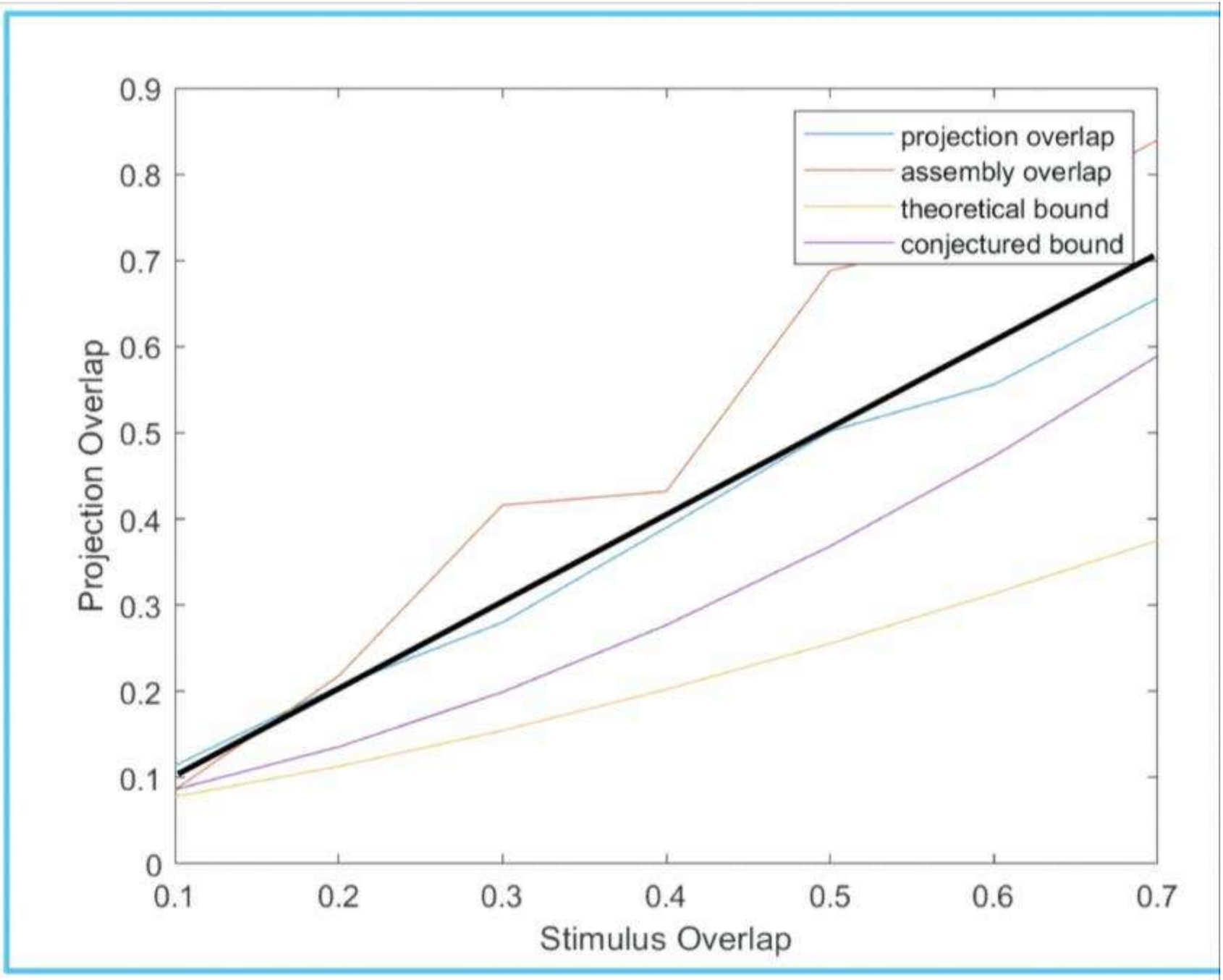


The underlying mathematical reason:

Theorem [P., Vempala, 2018]:
The intersection of **cap(A)** and **cap(B)** will be, with high probability, at least

$$\frac{\left(\frac{k}{n}\right)^{\frac{1-\alpha}{1+\alpha}}}{\left(\ln {}^{n}/_{k}\right)^{\frac{\alpha}{1+\alpha}}}$$

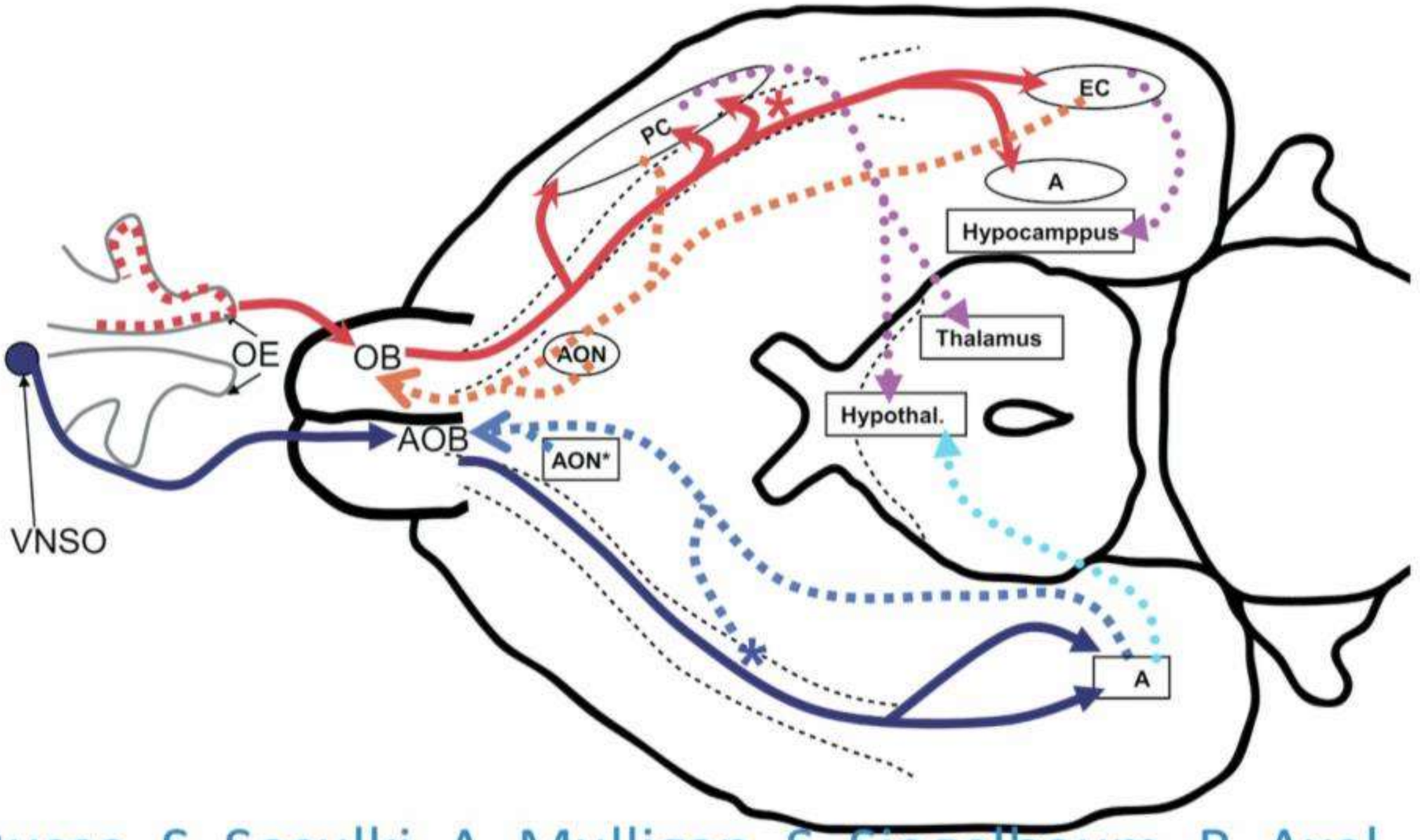
The underlying mathematical reason: compare with simulations



So much for the fruit fly…

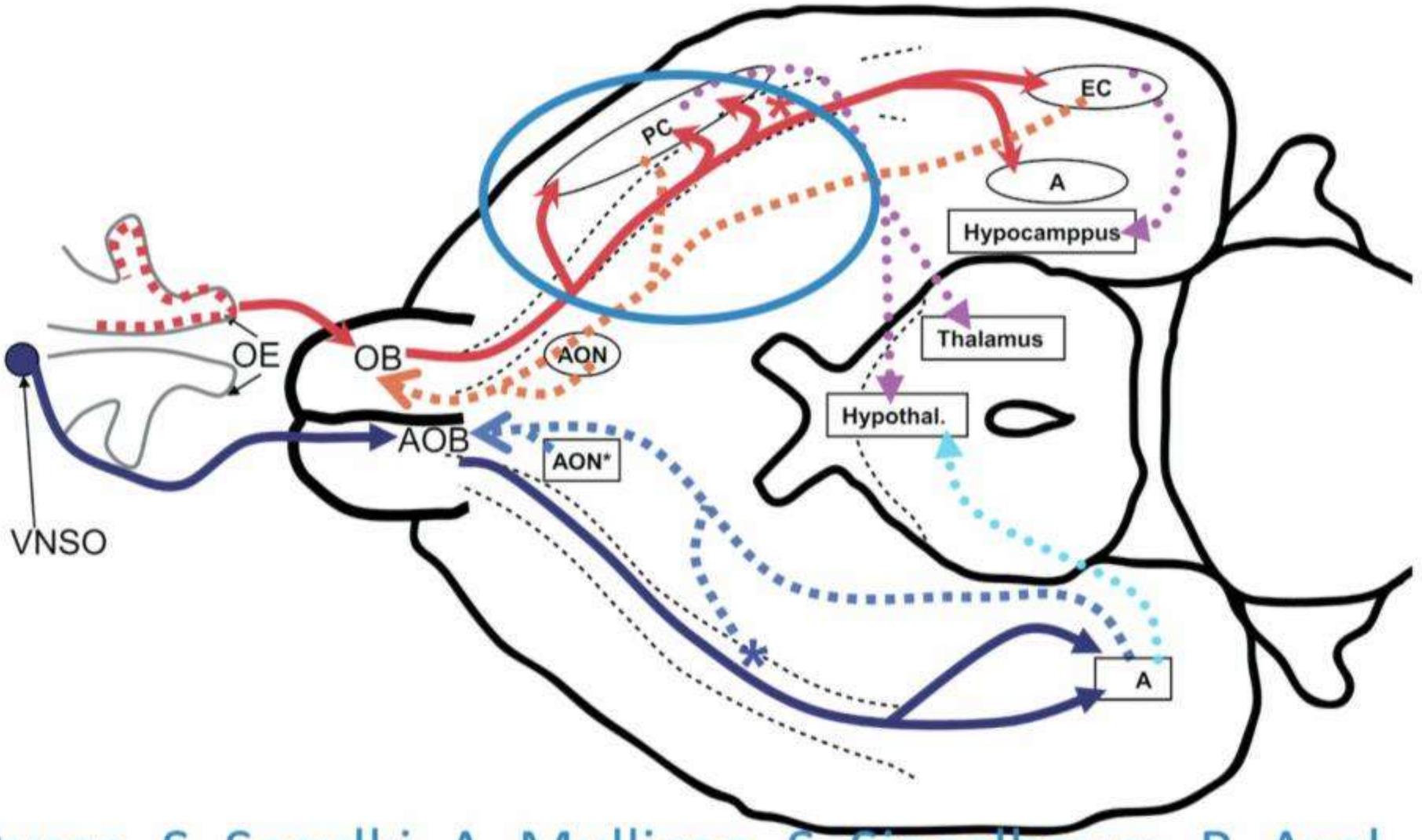
- Q: Does something homologous happen in mammals?

Yes!



K. Franks, M. Russo, S. Sosulki, A. Mulligan, S. Siegelbaum, R. Axel "Recurrent Circuitry Dynamically Shapes the Activation of Piriform Cortex," Neuron October 2011

Yes!



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From the *Discussion* section of Franks *et al.*

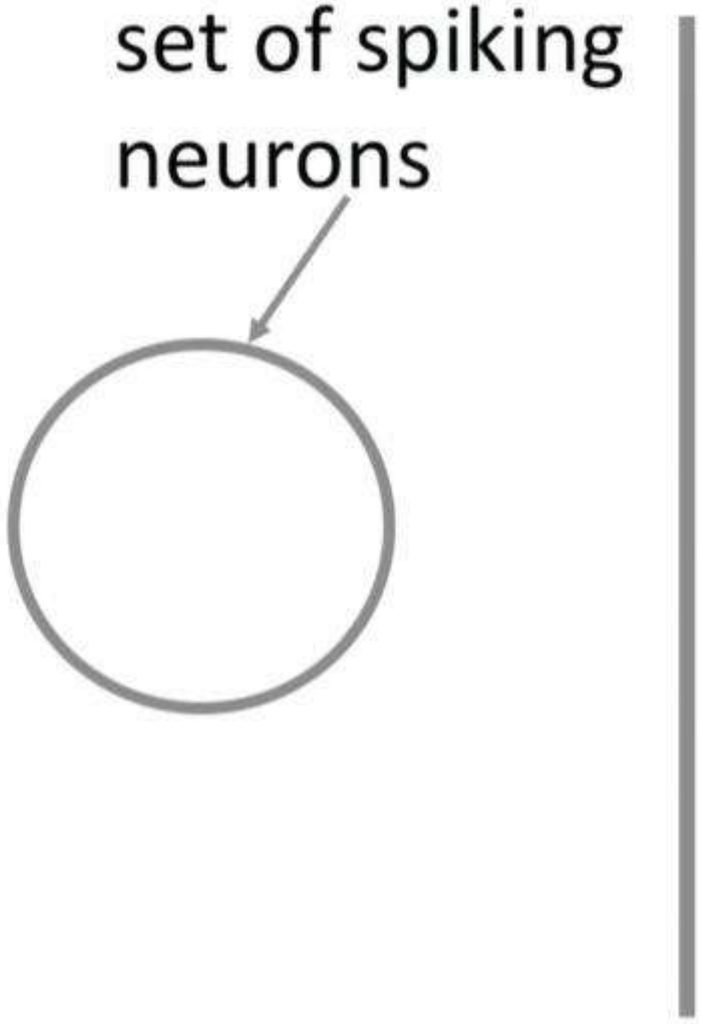
An odorant may [cause] a small subset of [PC] neurons [to fire].

Inhibition triggered by this activity will prevent further firing

This small fraction of … cells would then generate sufficient recurrent excitation to recruit a larger population of neurons.

In the extreme, some cells could receive enough recurrent input to fire … without receiving [initial] input…

In pictures…



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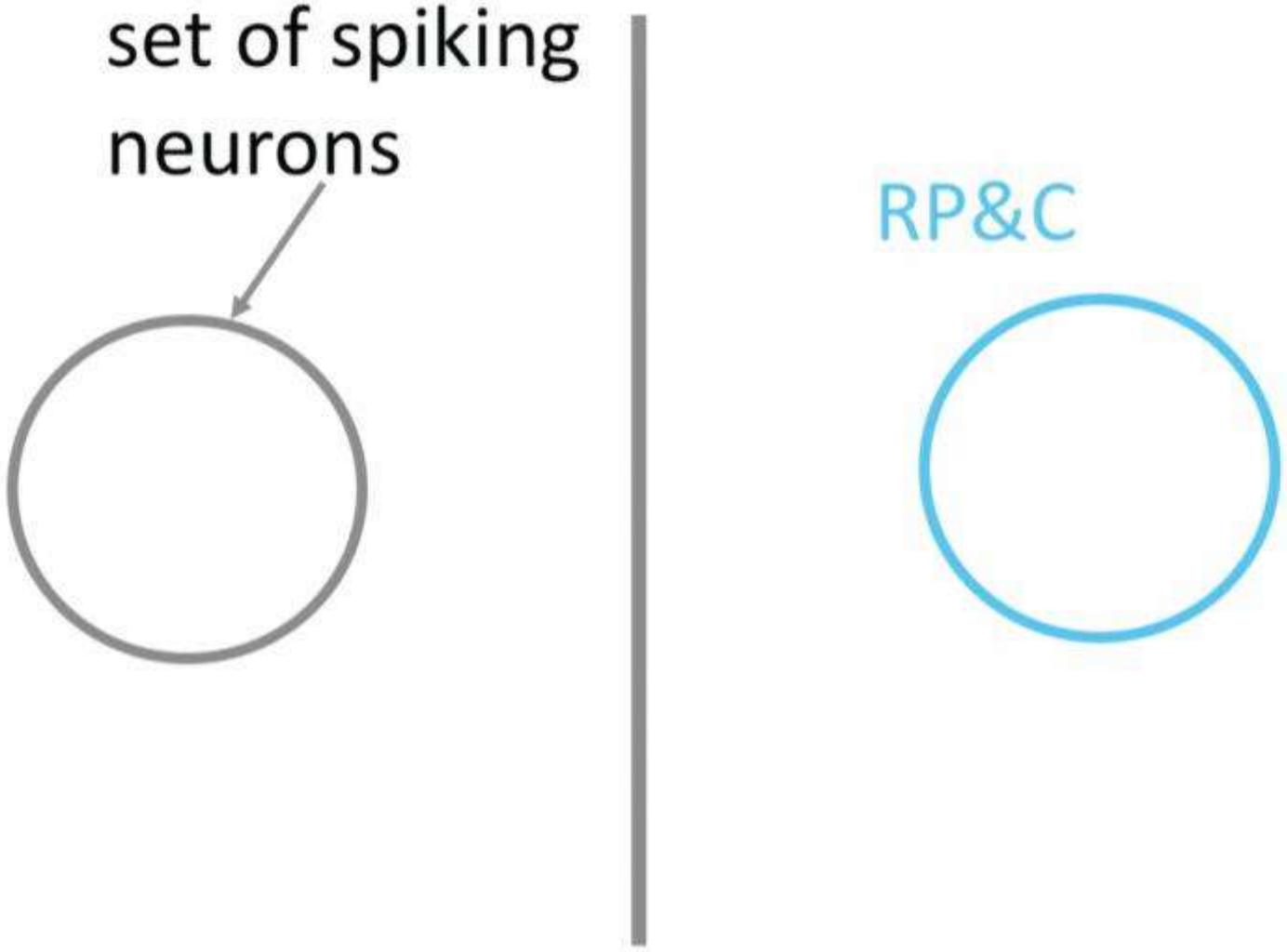

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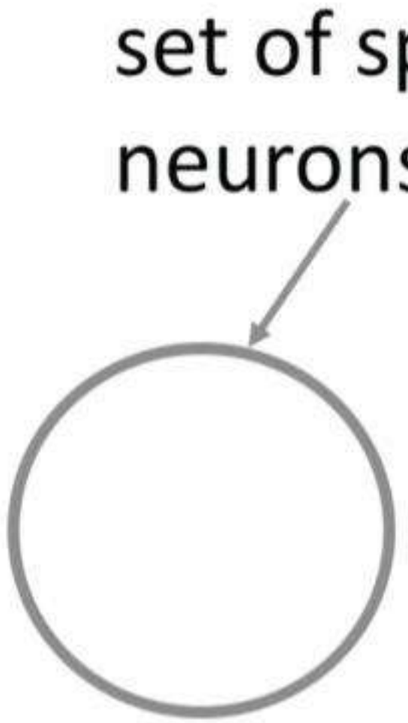

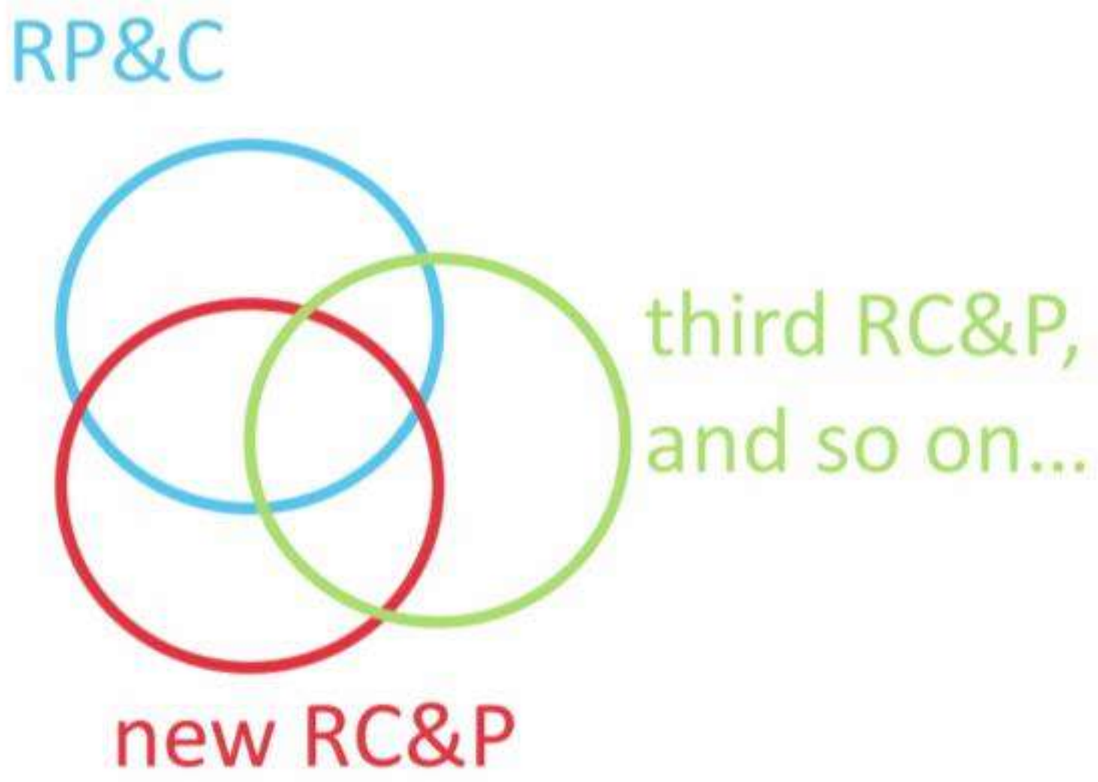

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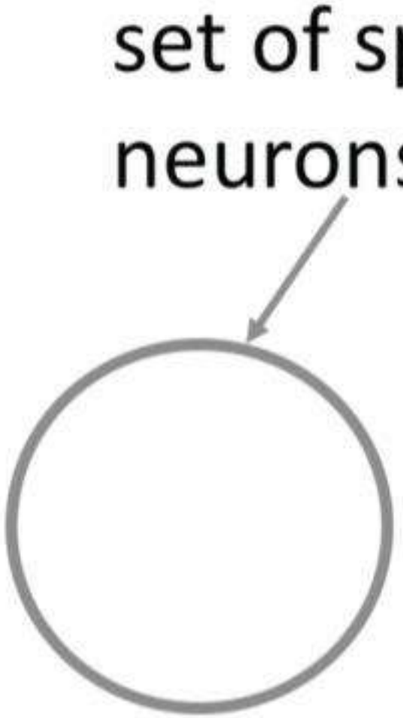
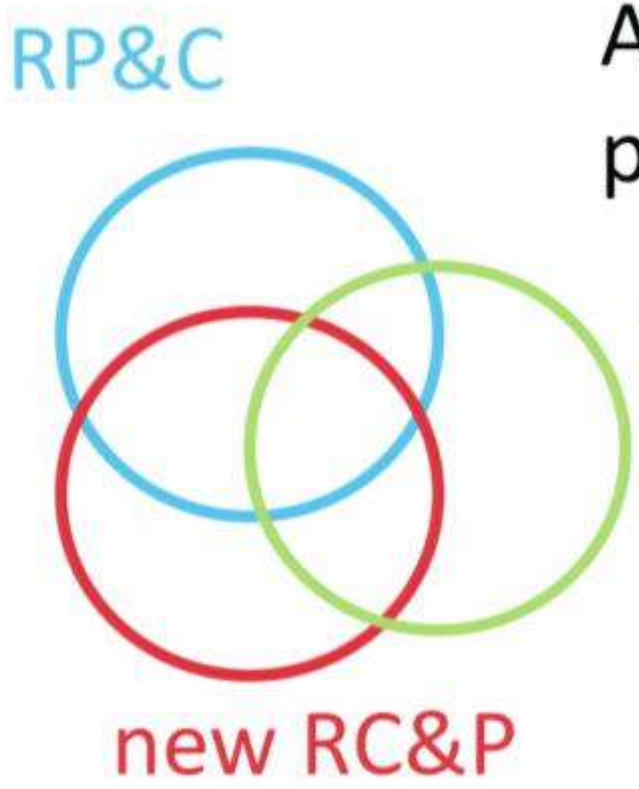




Also, Hebbian plasticity

third RC&P, and so on…

Does this process converge?

And does it preserve similarity?

The model

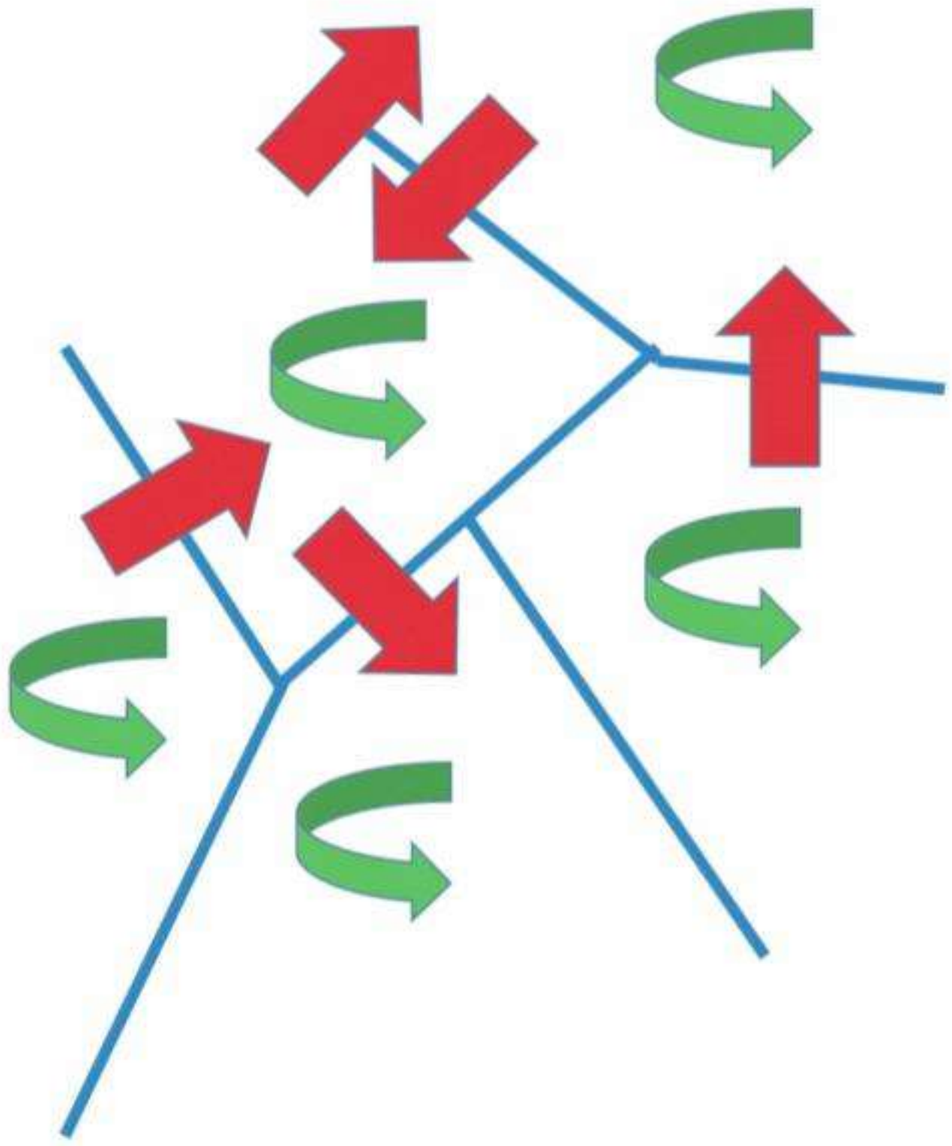
Finite number of brain regions

Each contains n neurons

Inhibition: only k fire

Some pairs of areas are connected by directed $B_{n,p}$ (= bipartite $G_{n,p}$)

All are recurrently connected by directed $G_{n,p}$



The model (cont.)

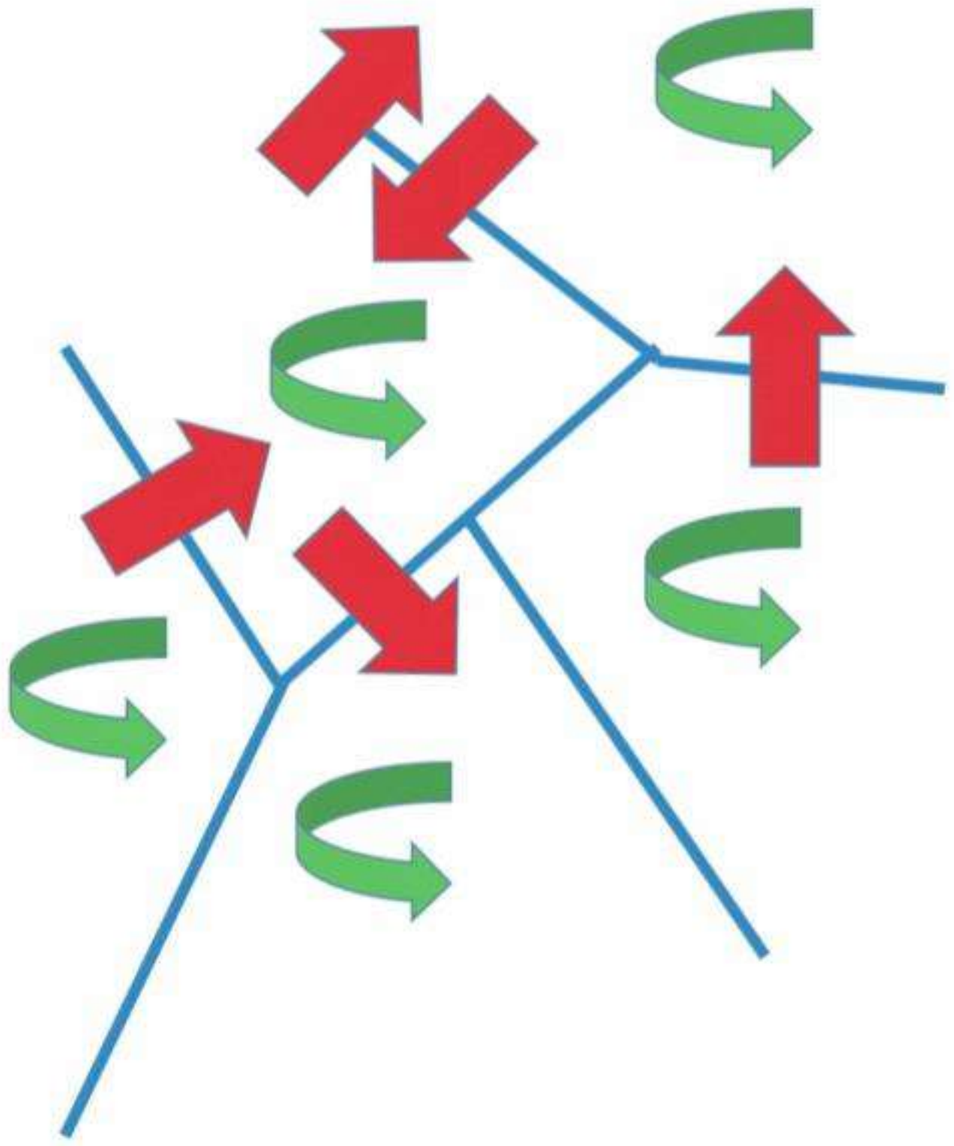
Neurons fire in discrete steps

Selected by RP&C

Connections between areas can be enabled/disabled

Plasticity: If i→j, i fires and in the next step j fires, the weight of i→j is multiplied by (1 + β)

Also: homeostasis, forgetting



Main parameters, intended values

- $n \sim 10^{7}$
- $k \sim 10^{3 - 4}$
- $p \sim 0.001$
- $\beta \sim 0.10$

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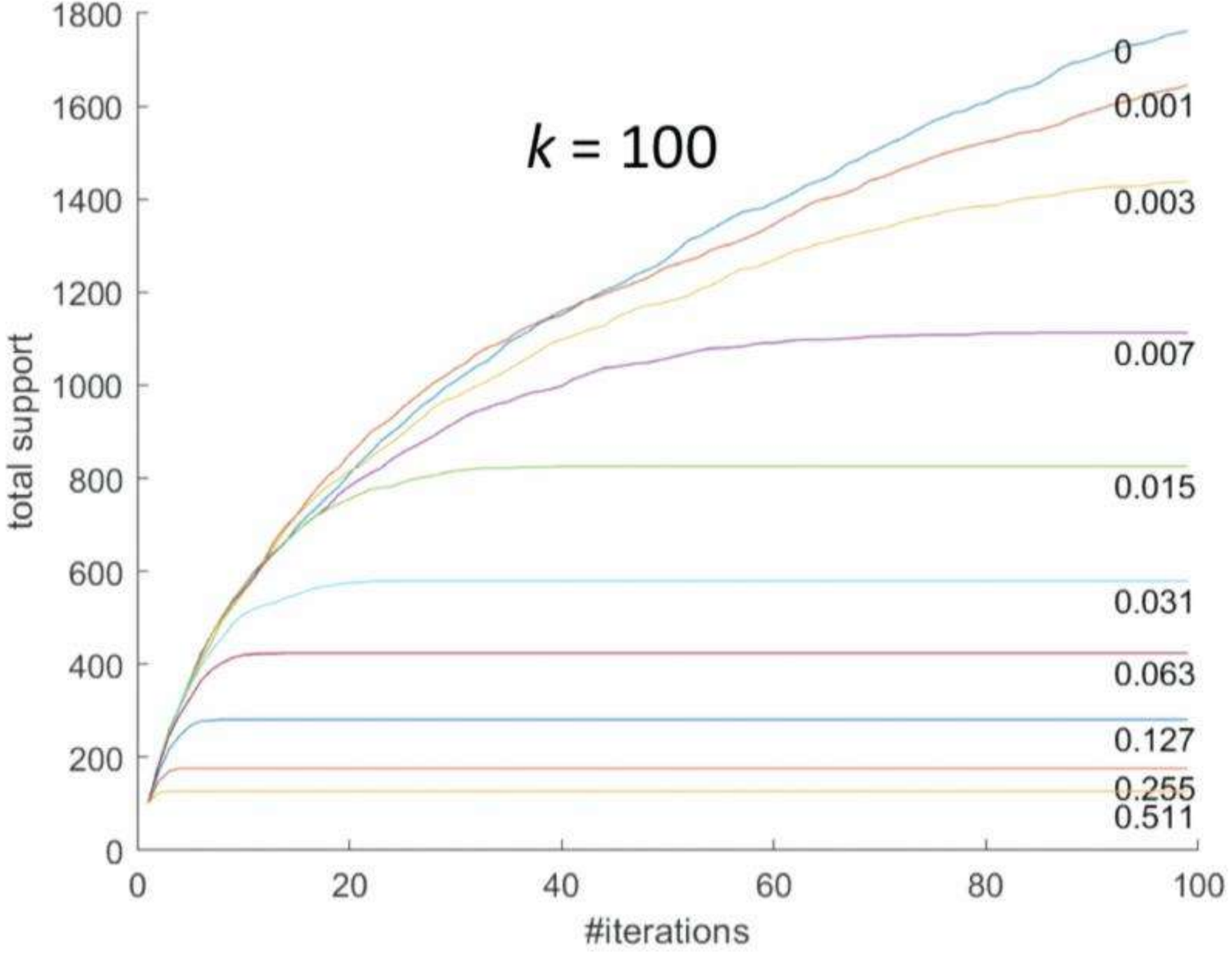
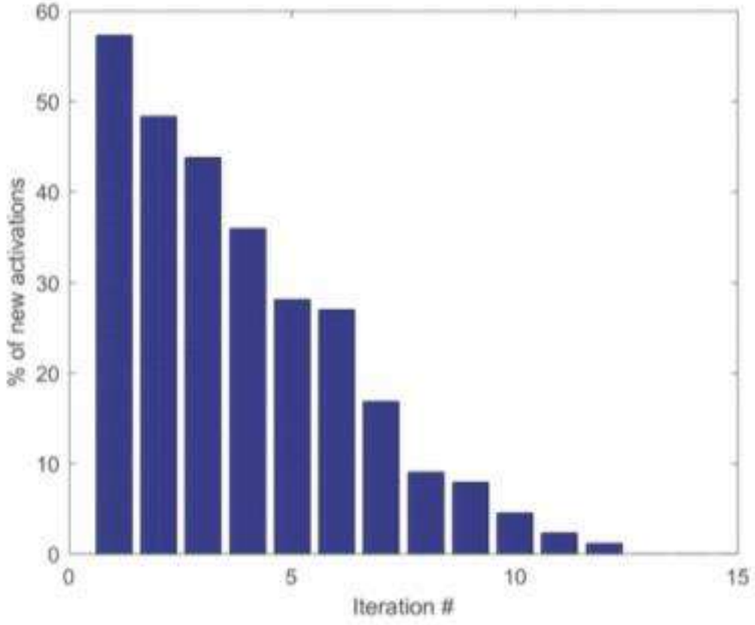
Main ideas: randomness, selection, plasticity

Theorem (P., Vempala 2016-18): The process converges exponentially fast, with high probability, and the *total number of cells involved* is at most:

- If $\beta \geq \beta^*$: $k + o(k)$
- If $0 < \beta < \beta^*$: $k \cdot \exp(0.17 \cdot \ln(n/k)/\beta)$

- $\beta^* = (\sqrt{2} - 1)/(1 + \sqrt{pk/\ln n})$


k = 100
total support
#iterations
0
0.001
0.003
0.007
0.015
0.031
0.063
0.127
0.255
0.511
0
200
400
600
800
1000
1200
1400
1600
1800
0
20
40
60
80
100


% of new activations
Iteration #
0
10
20
30
40
50
60
0
5
10
15

The result of such projection: an *Assembly*

- Set of ≈ *k* neurons in a brain area whose firing (in a pattern) is tantamount to our thinking of a particular memory, concept, name, word, episode, etc.
- [Hebb 1949, Harris 2003, 2005; Buzsaki 2008, 2010, Yuste et al. 2017]
- Simulations of a far more biologically accurate model [Pokorny et al 2018, under submission]

cell

cell**s** (or concept cell**s**)

The Big Picture

Computation in the brain: What is the right level?

The Big Picture

Computation in the brain: What is the right level?

- Molecules?

The Big Picture

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- Spiking neurons and synapses?
- Molecules?

The Big Picture

Computation in the brain: What is the right level?

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- Dendrites?
- Molecules?

The Big Picture

Computation in the brain: What is the right level?

- Whole brain?

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Recall…

"…we do not have a logic for the transformation of neural activity into thought … I view discerning [this] logic as the most important future direction of neuroscience…"

Neuron, Sep 2018

The Big Picture

Computation in the brain: What is the right level?

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The assembly hypothesis

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- Assemblies are its basic representation – its main "data structure"
- What are its fundamental operations?
- NB: an operation must be useful and plausible

Useful and plausible…

- **Useful**: must help explain experiments

- **Plausible**: can be "compiled down" to neurons and synapses

The assembly hypothesis: operations

- Project(x, A, y)
- A = area(y), x = parent(y)
- (Plus, this is how an assembly is first created)

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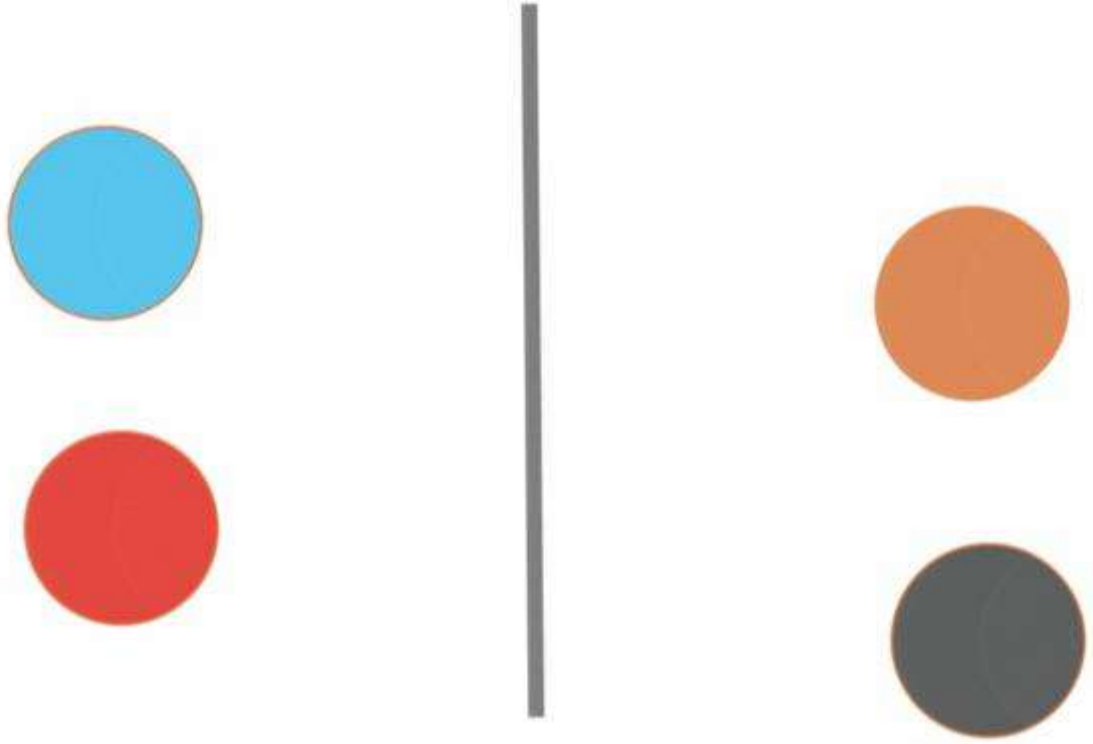
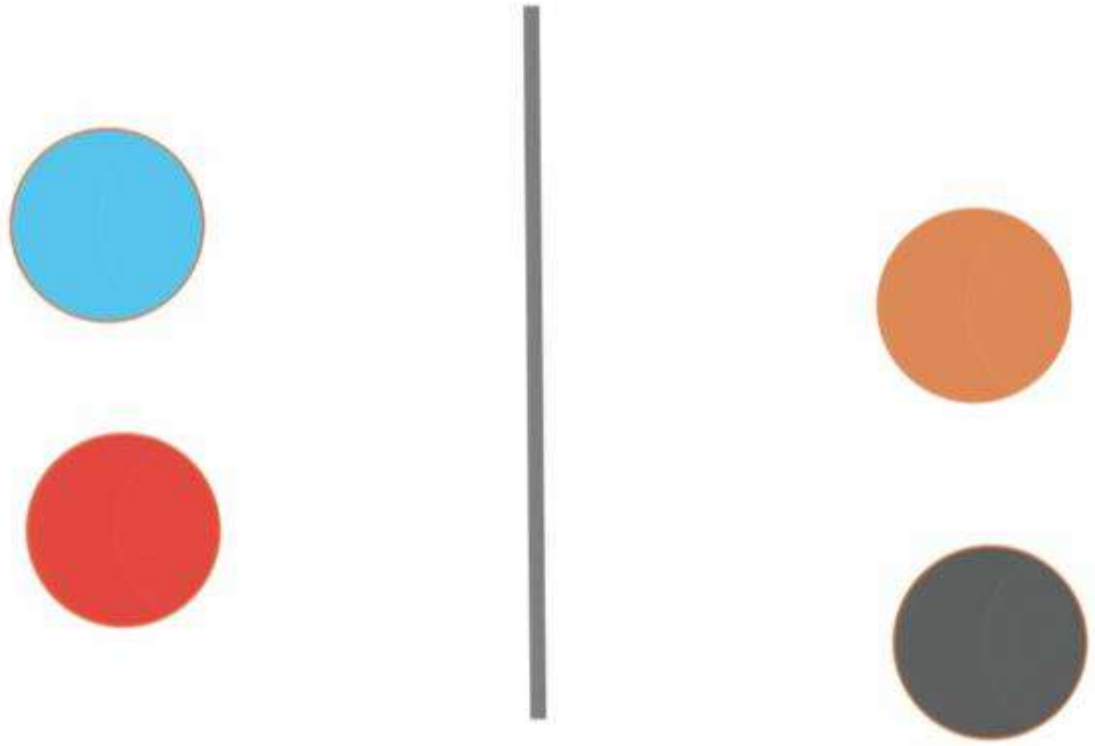
- Project(x, A, y)
- A = area(y), x = parent(y)
- (Plus, this is how an assembly is first created)
- Q: *Other operations?*
- A: Two assemblies may be associated by sharing cells
- Association encodes “affinity”, similarity, co-occurrence…

Association of two assemblies



Association of two assemblies



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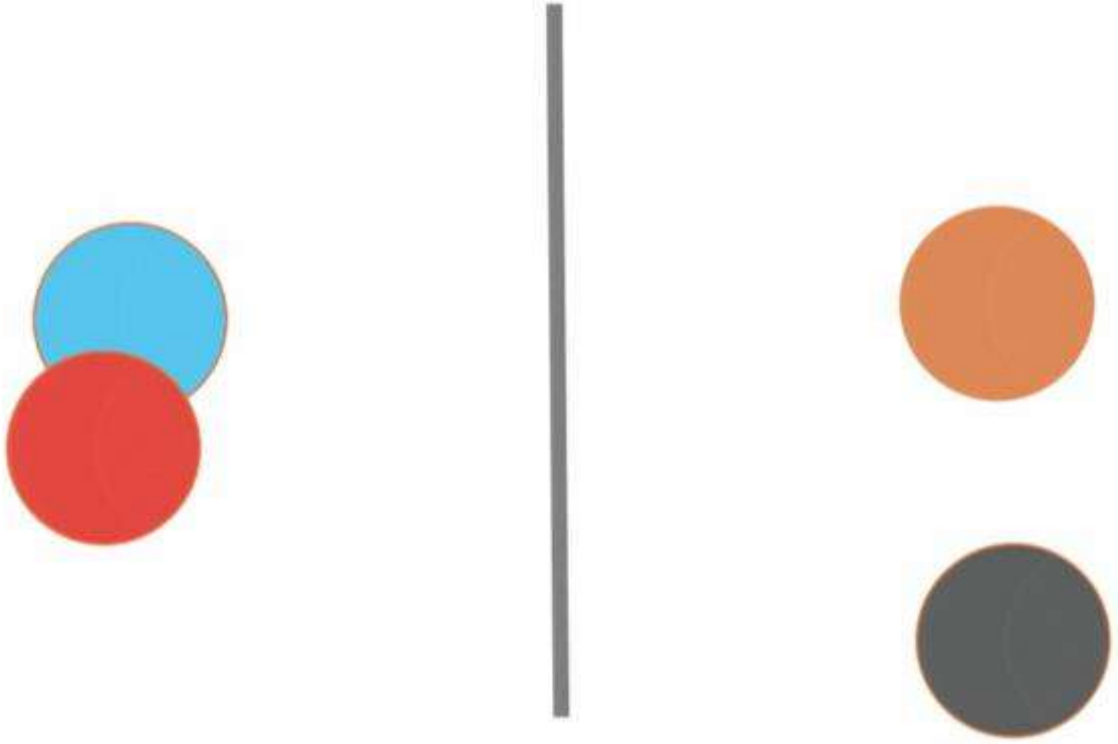
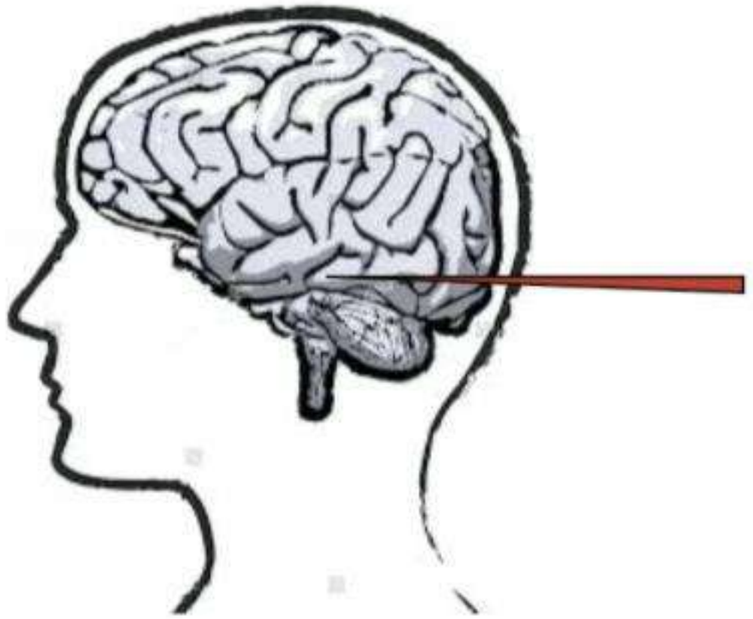
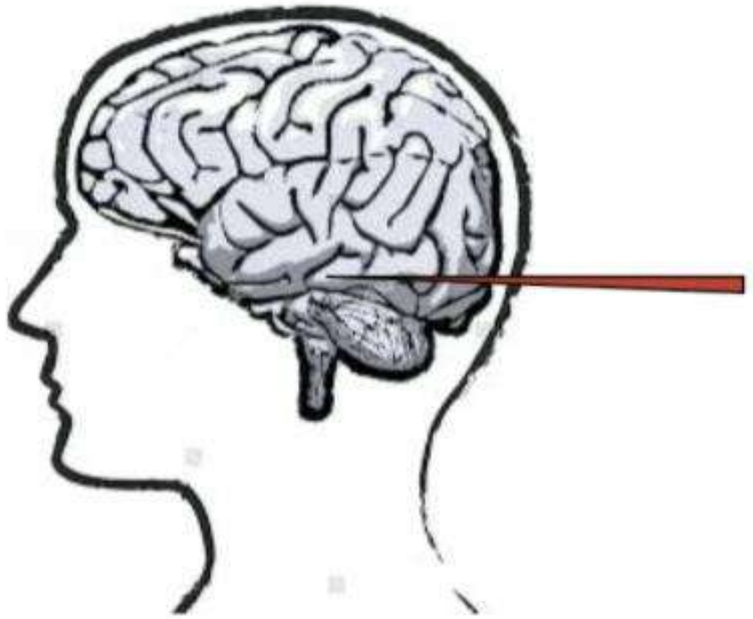
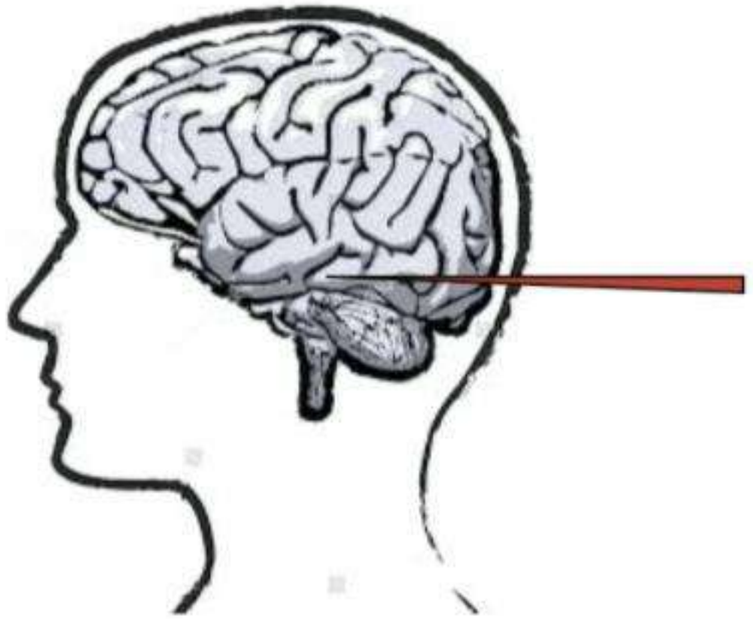
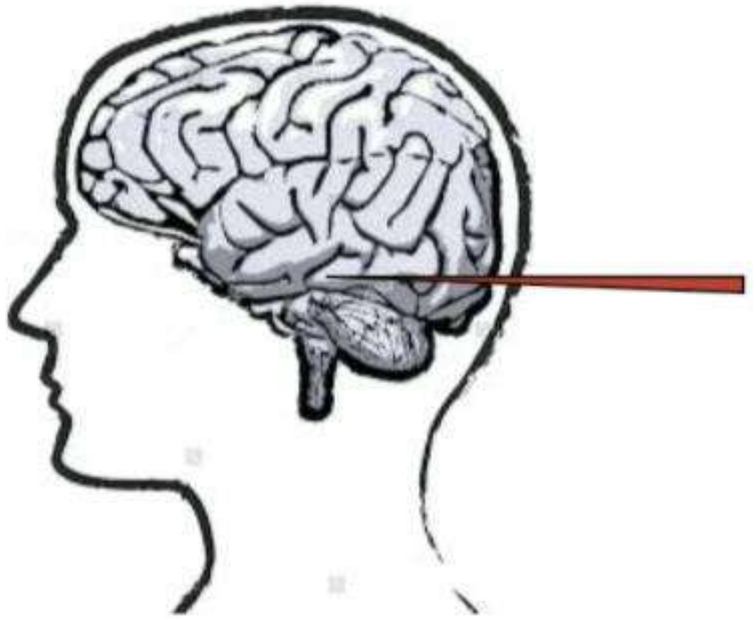


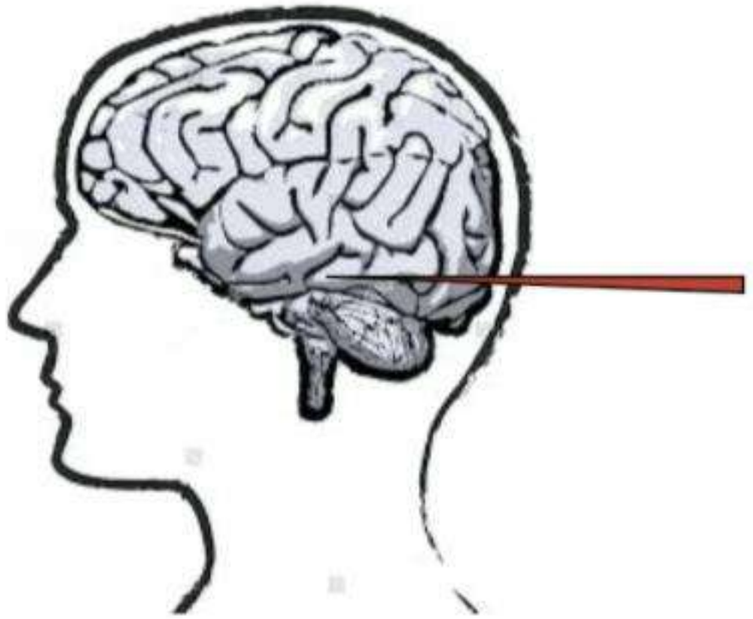
The [Ison et al. 2016] experiment

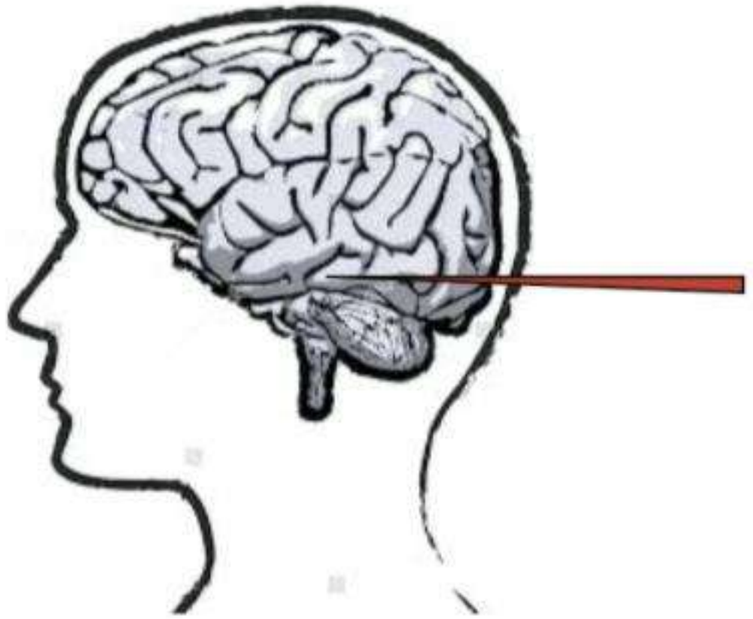


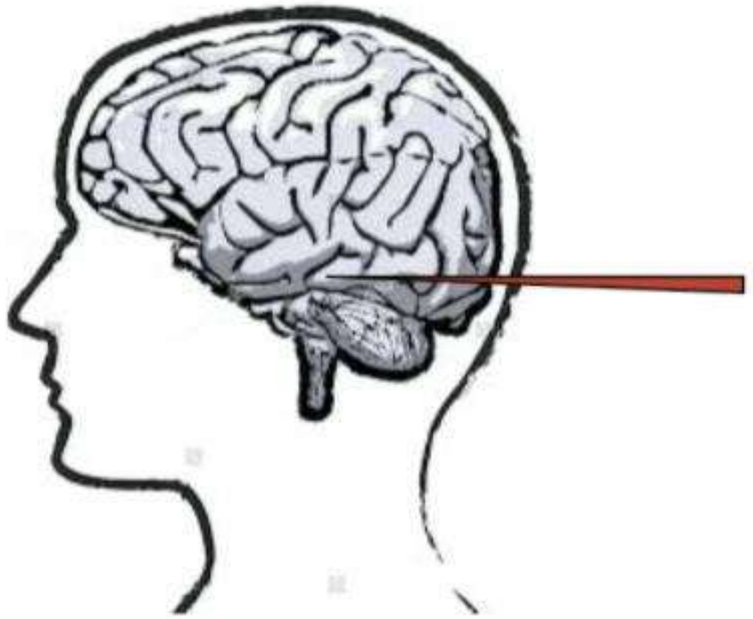


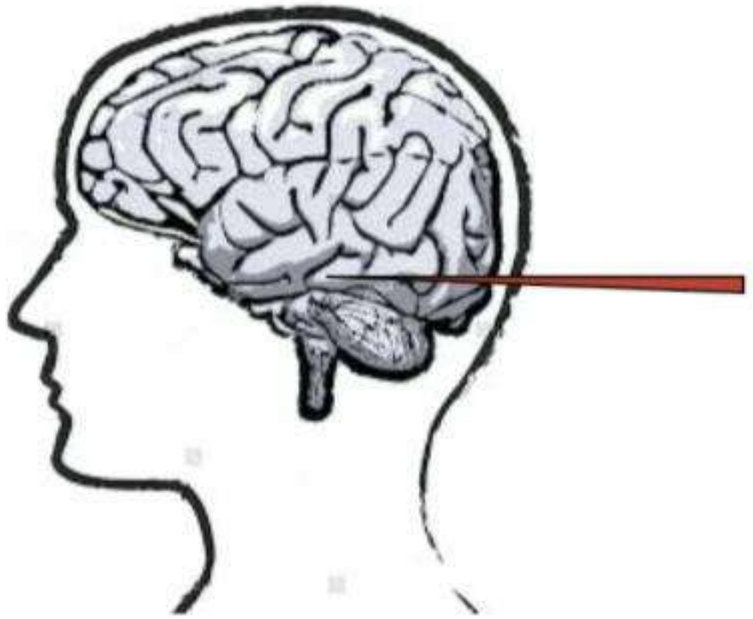


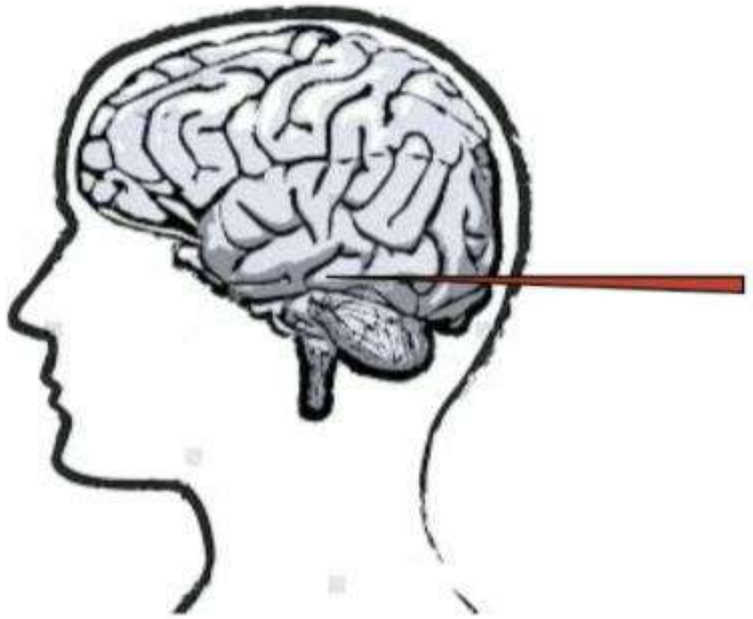








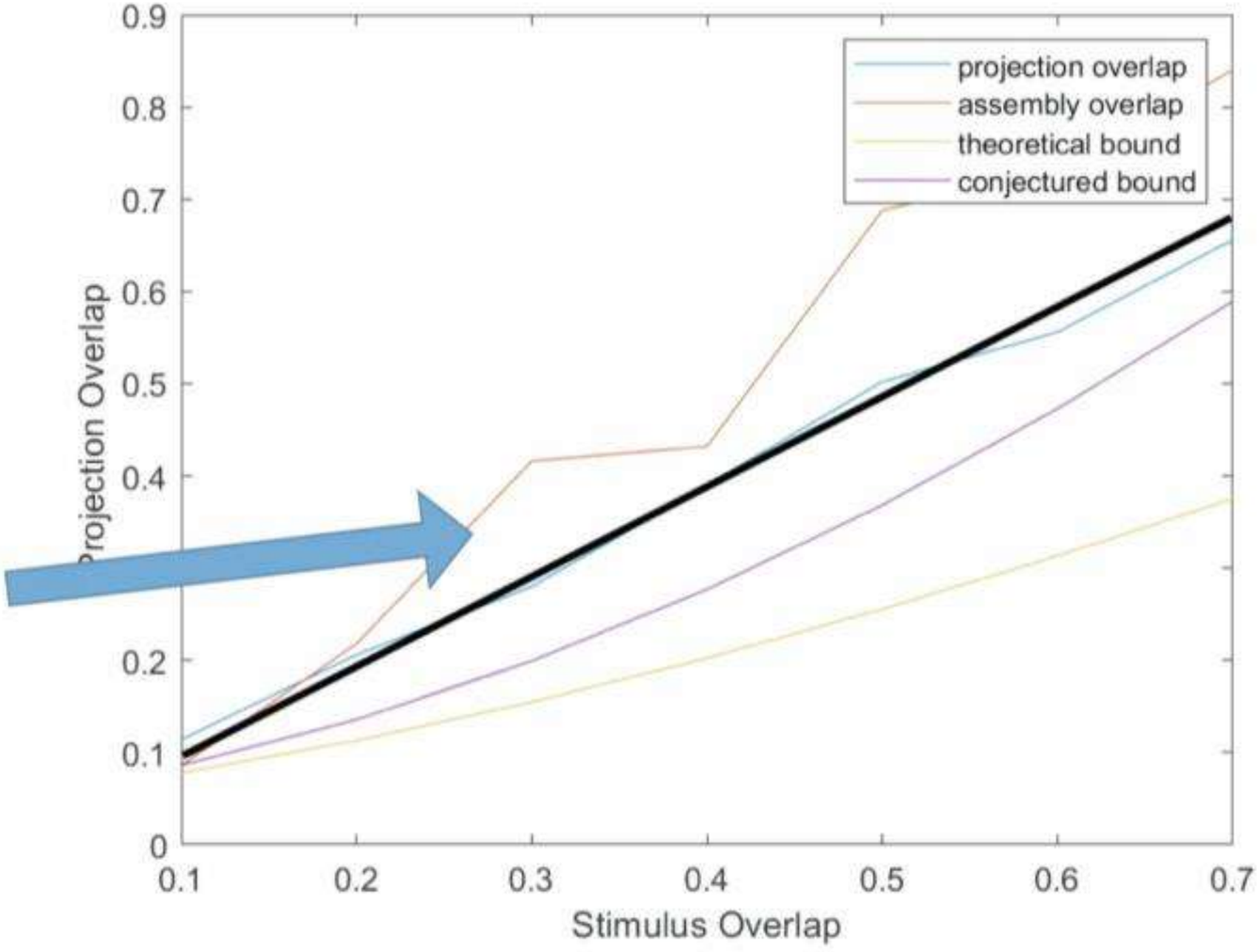




Q: is association preserved under projection?

Recall the fly, and similarity preservation:

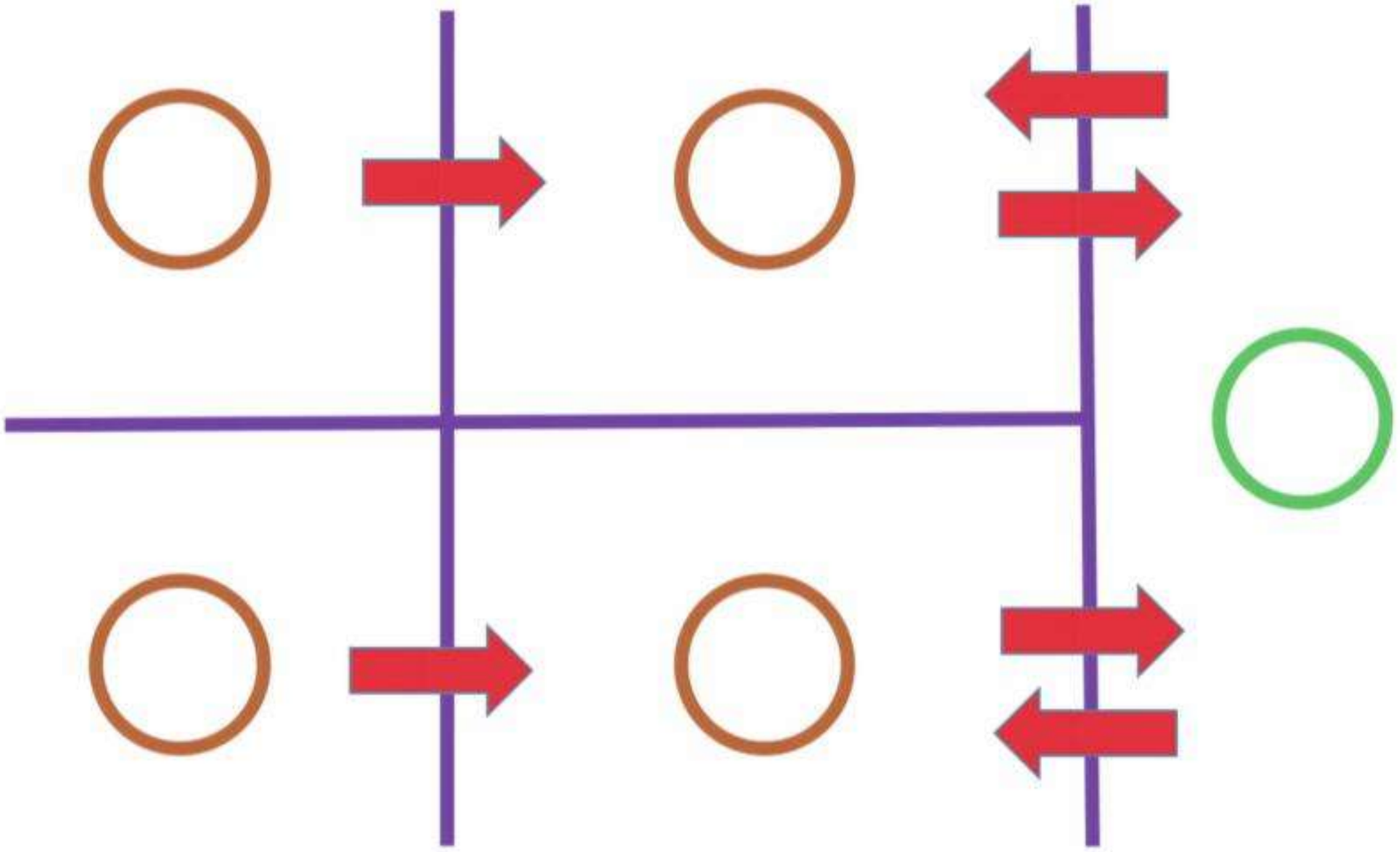
association of assemblies seems to be *very well preserved* under projection



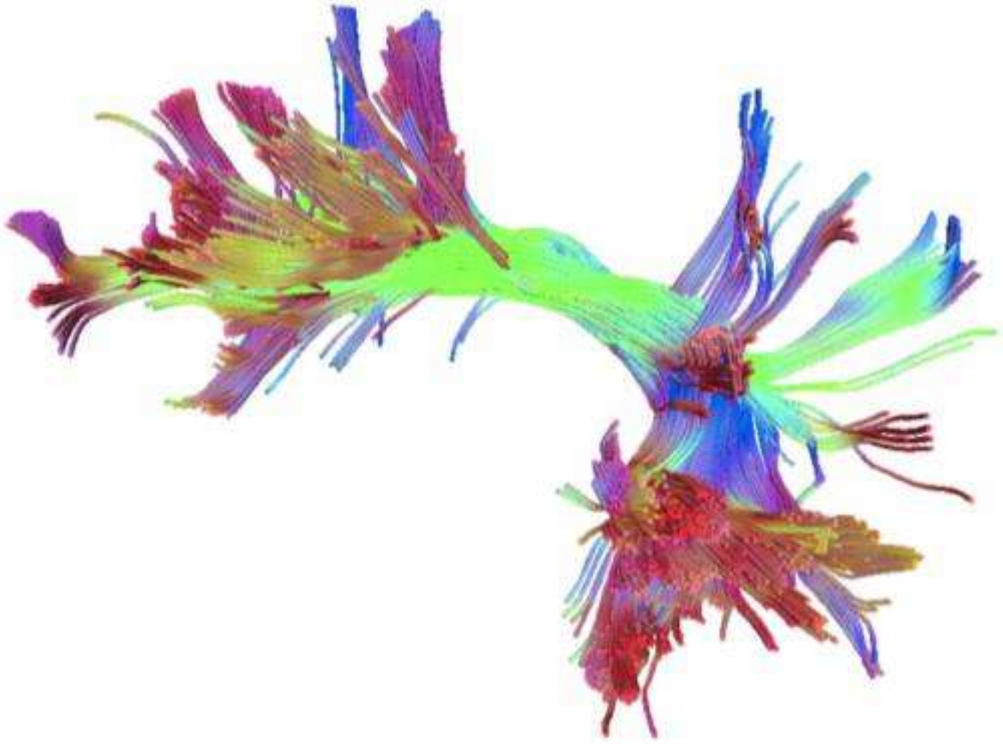
Other operations?

- merge(x, y, A, z)
- (assemblies x, y, from different areas, project to create one assembly in area A, call it z)
- Creates hierarchies
- Valuable for implementing language

Merge: It’s complicated…



Merge: Does it need enhanced hardware? (The mystery of the Arcuate Fasciculus)



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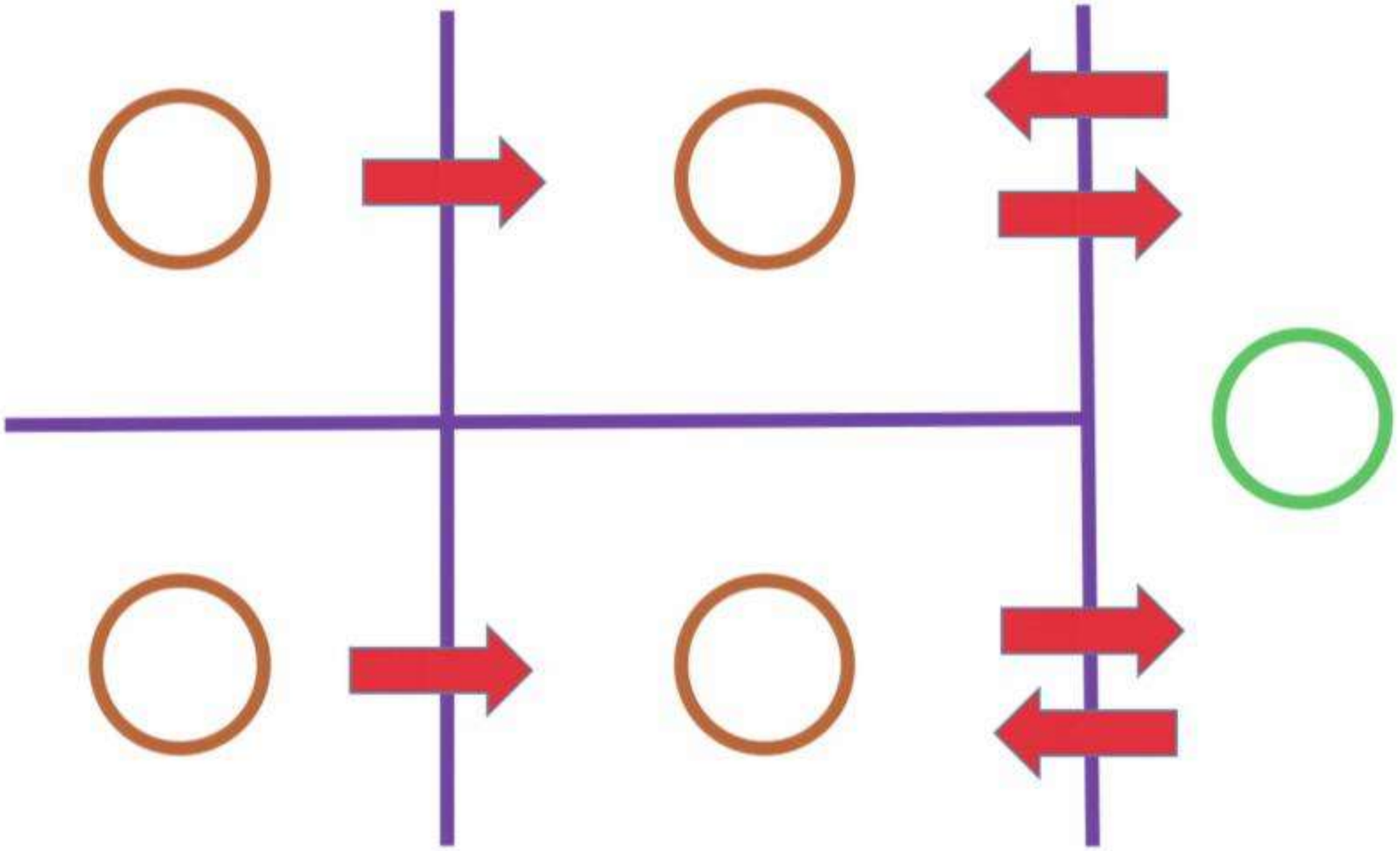

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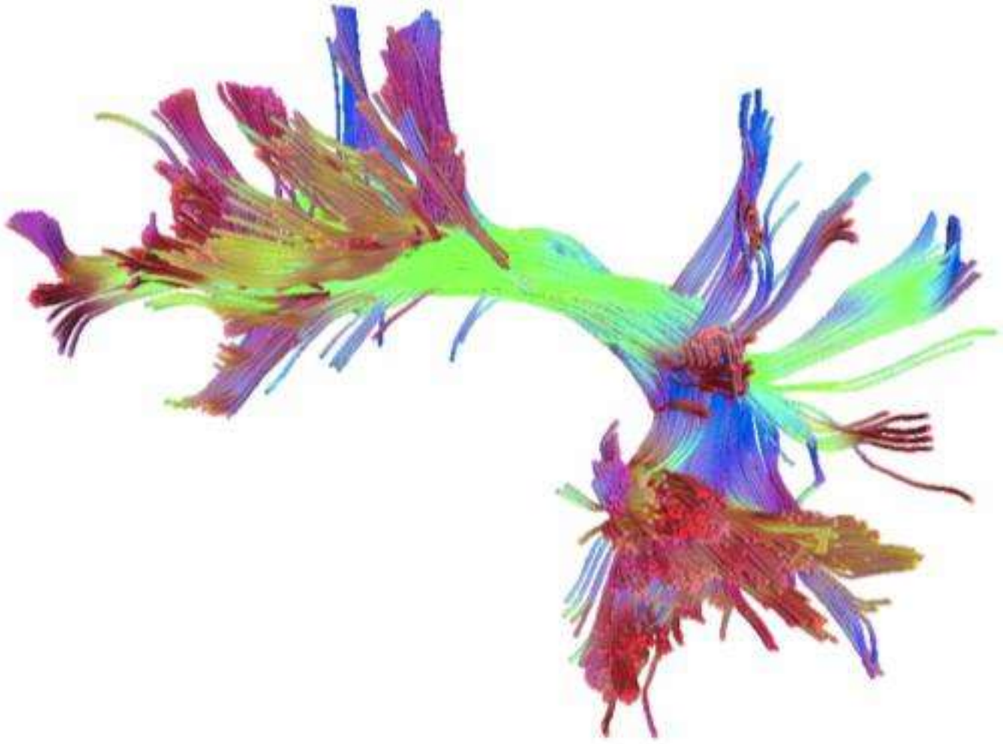

Assembly Operations recap

- project(y, B, x)
- associate(x, y)
- pattern_complete(x, y)
- merge(x, y, B, z)
- Plus: activate(x), read(), disinhibit(A,B)

Assembly Operations recap

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Q: ***How powerful is this system?***

Assembly Operations recap

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- associate(x, y)
- pattern_complete(x, y)
- merge(x, y, B, z)
- Plus: activate(x), read(), disinhibit(A,B)

Q: *How powerful is this system?*

A: *can perform arbitrary √n-space computations*

Ultimately: Language

- An environment created *by us* a few thousand generations ago
- A "last-minute adaptation"
- Hypothesis: it evolved so as to exploit the Brain's strengths
- Invaluable lens for studying the Brain
- ***A deluge of recent experiments!***

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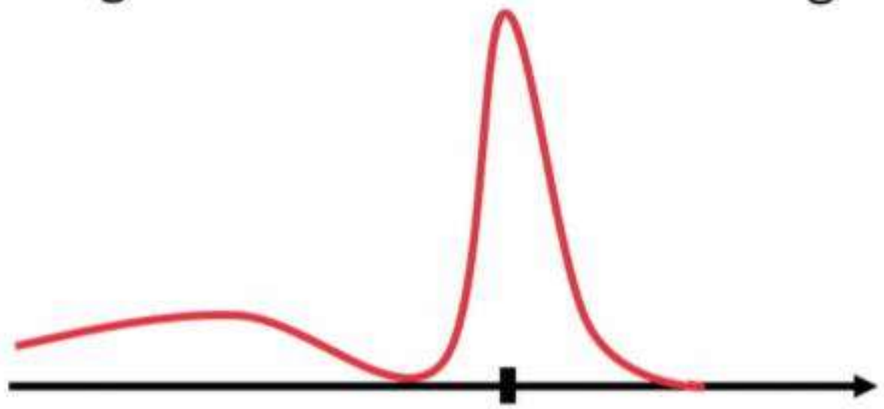

4 hertz

The [Poeppel 2016] experiment, stage II

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bad cats eat fish

The [Poeppel 2016] experiment, stage II

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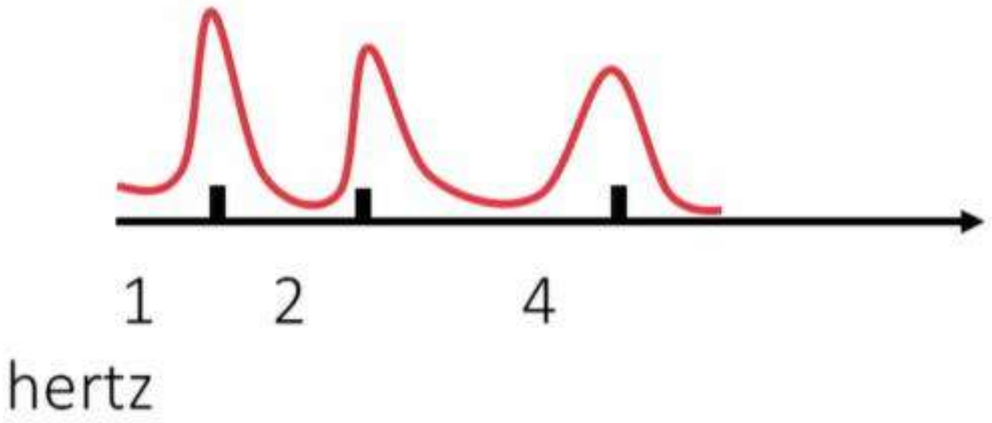
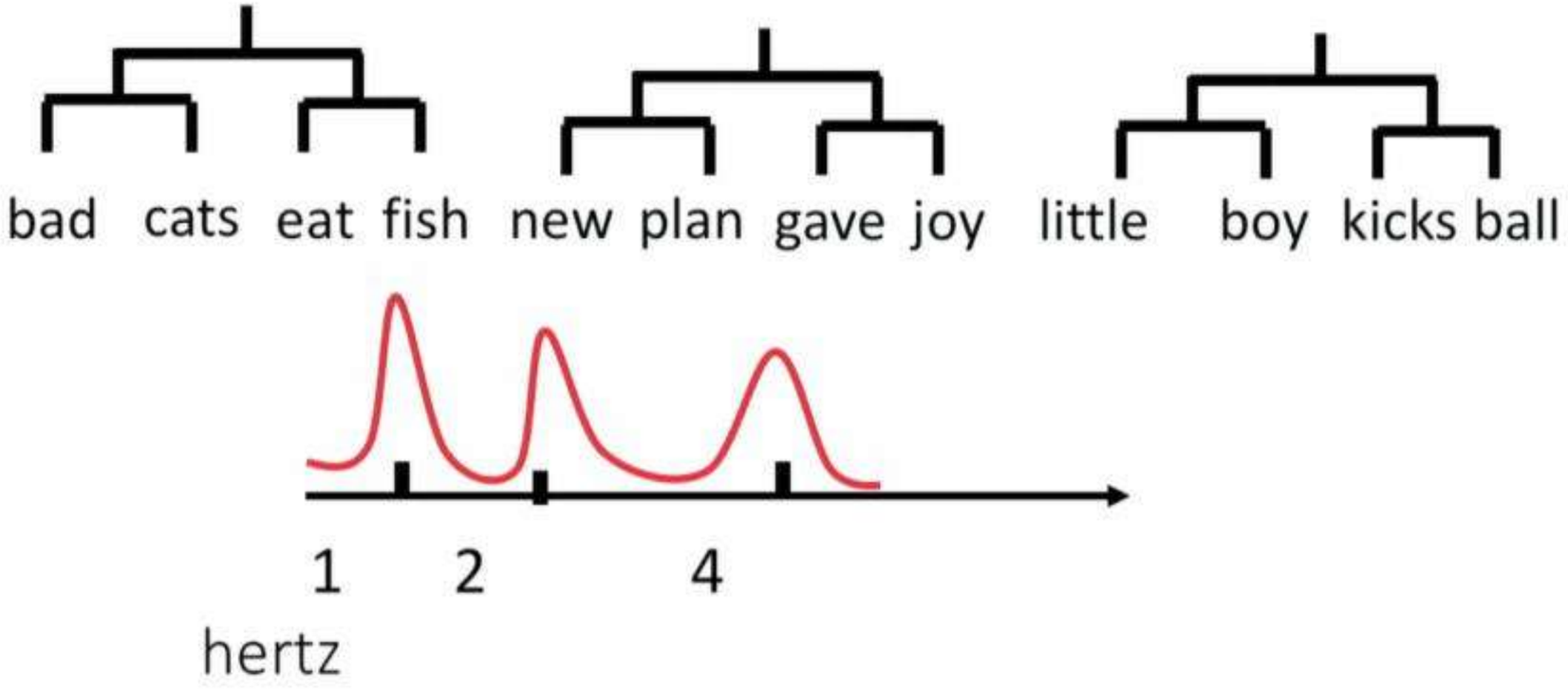


My interpretation



[Frankland & Greene PNAS 2015]

"The ball hit the truck"

vs

"The truck hit the ball''

Different areas of the STG responded to "truck" in the two sentences *[Recall relations…]*

[Frankland & Greene PNAS 2015]

"The ball hit the truck"

vs

"The truck hit the ball''

Different areas of the STG responded to "truck" in the two sentences *[Recall relations…]*

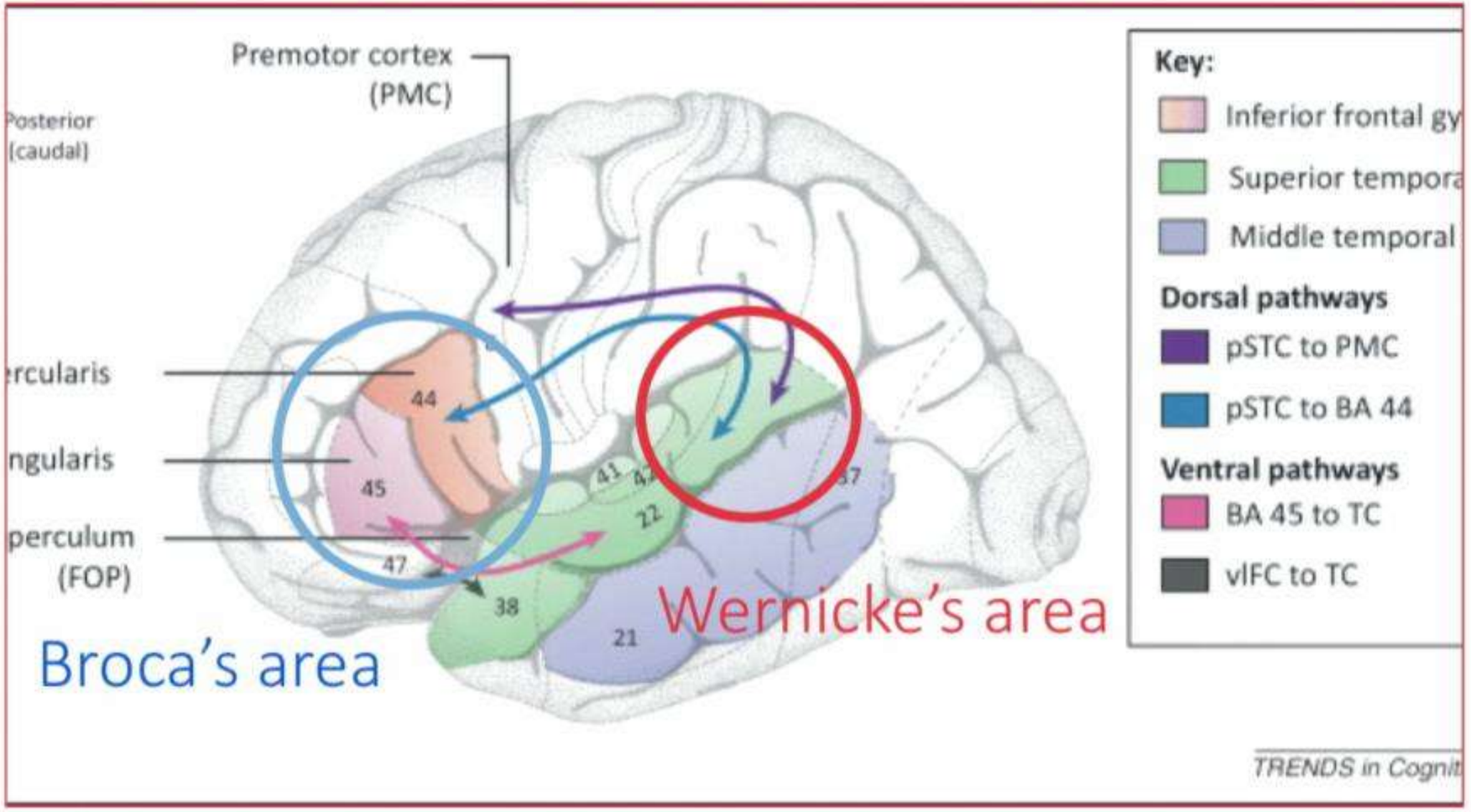
The first area also responded to

"The truck was hit by the ball"

Zaccarella & Friedericci "Merge in the human Brain" *Front. Psych. 2015*

- The completion of phrases, and especially of sentences, lights up parts of Broca's area

[ZF 2010]: Neural pathways for syntax?



a brain architecture for syntax

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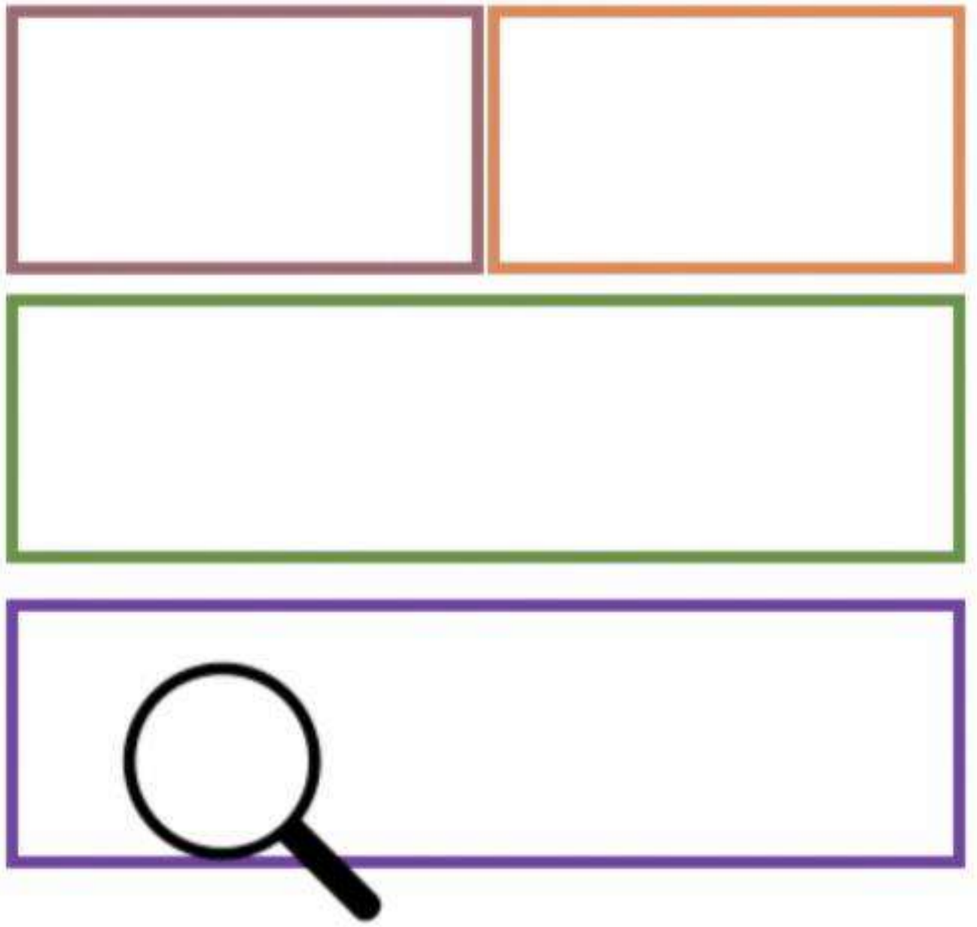

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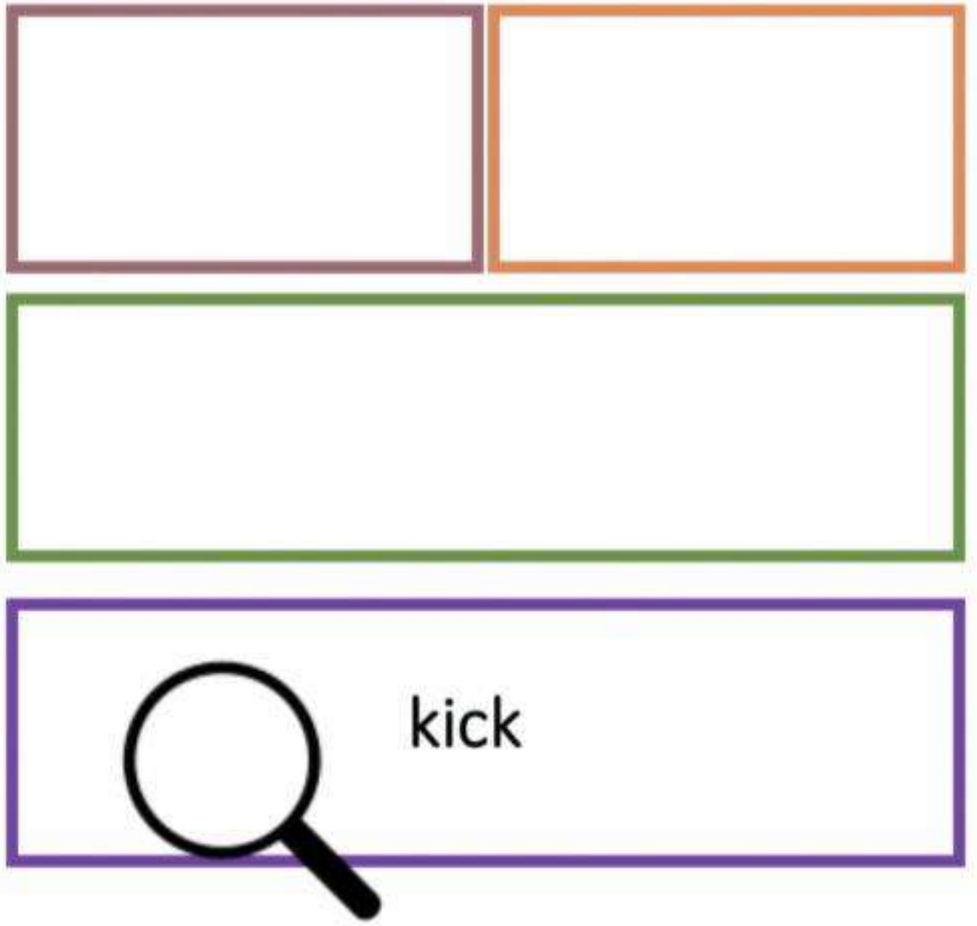

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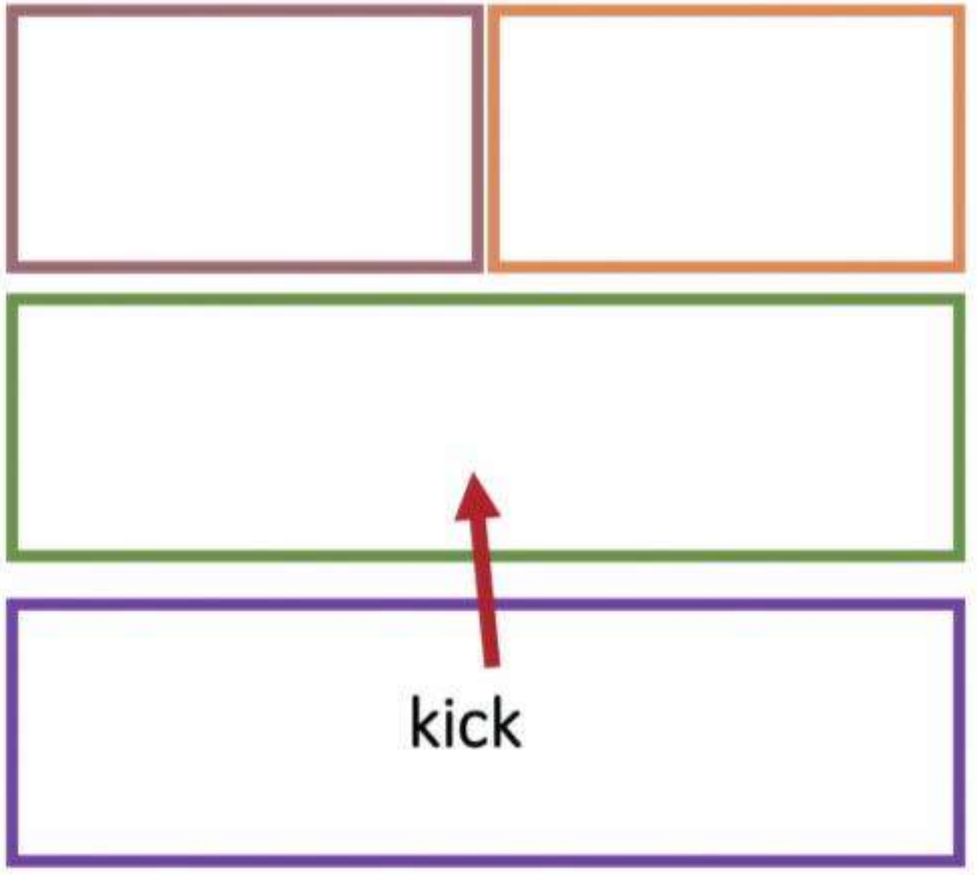

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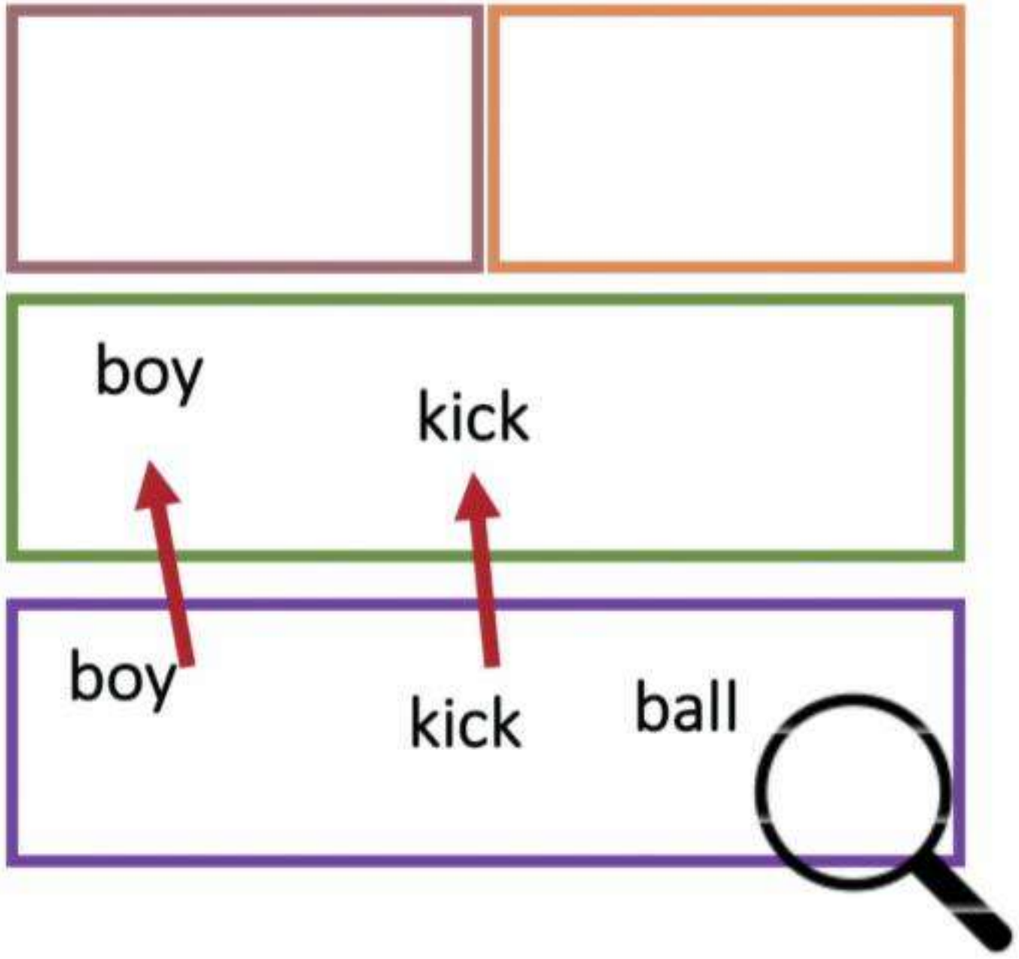

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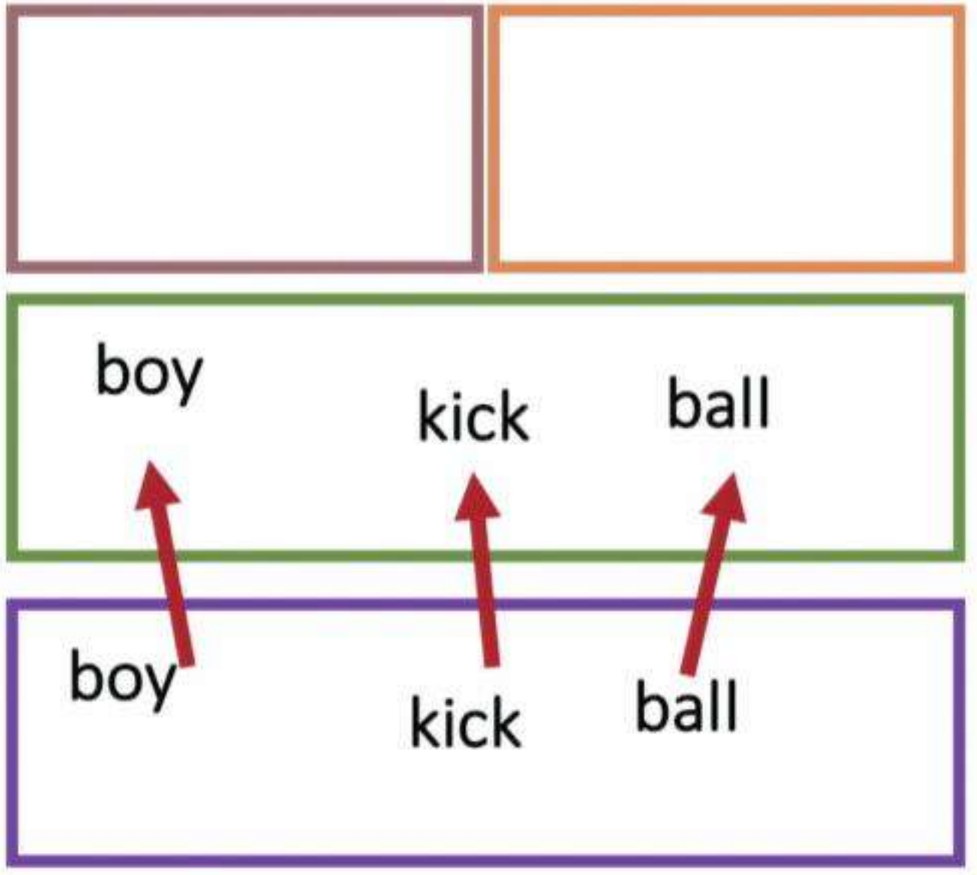

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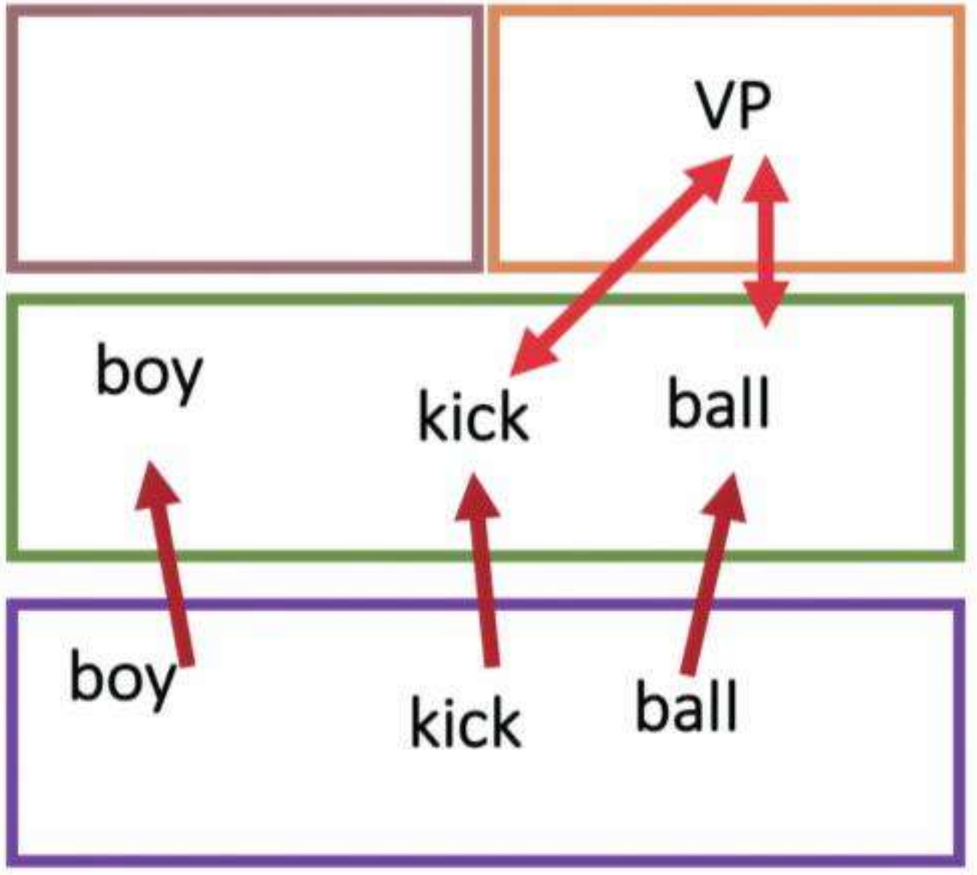

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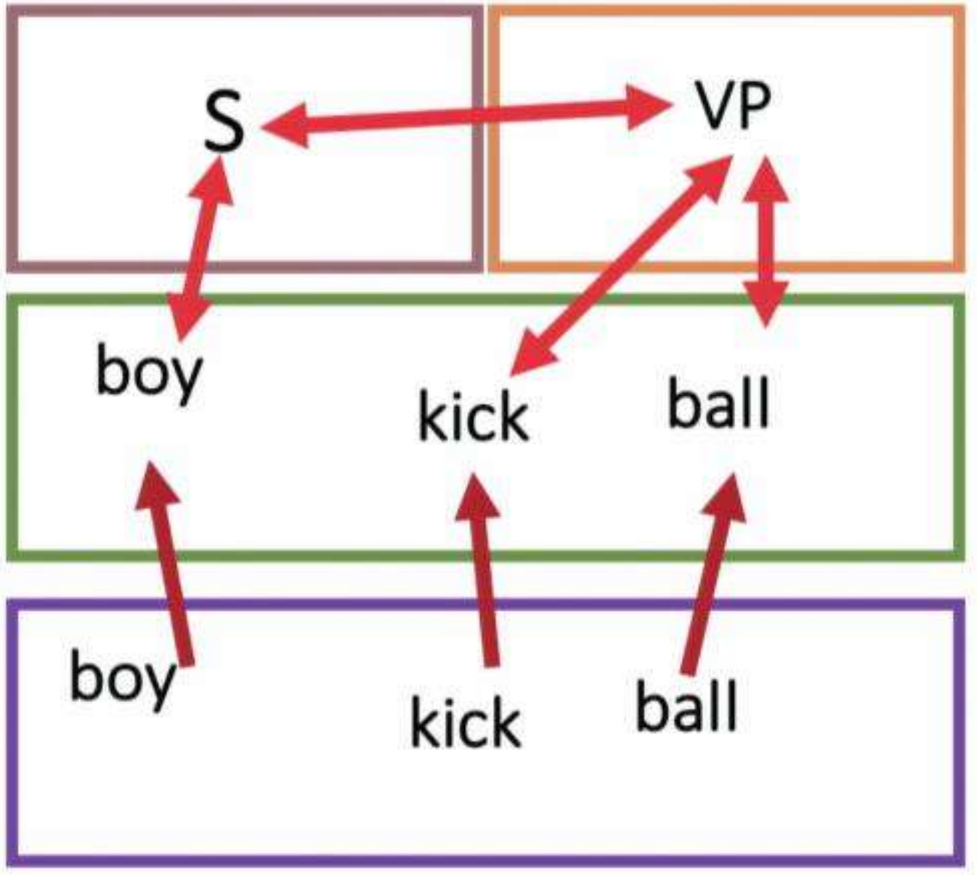
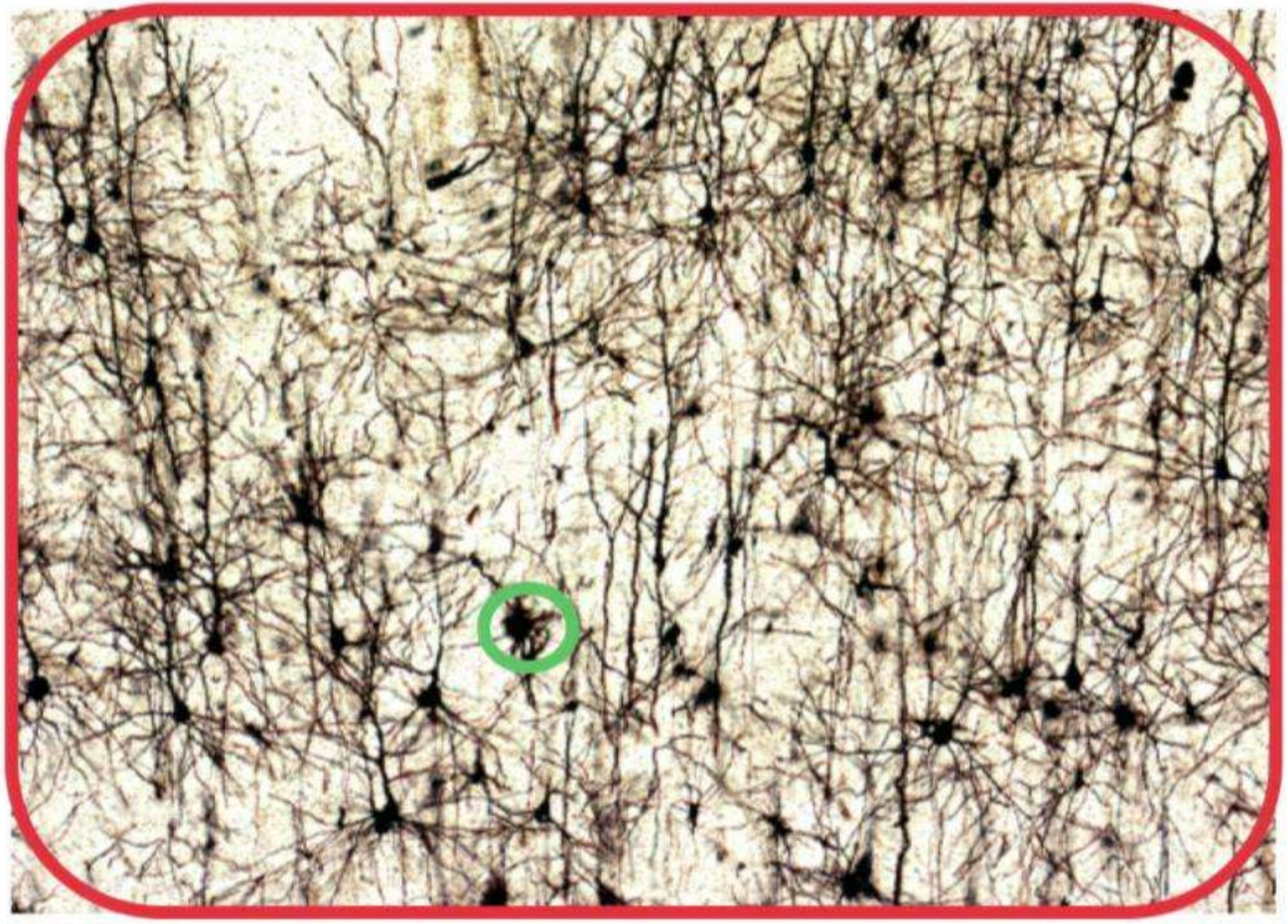
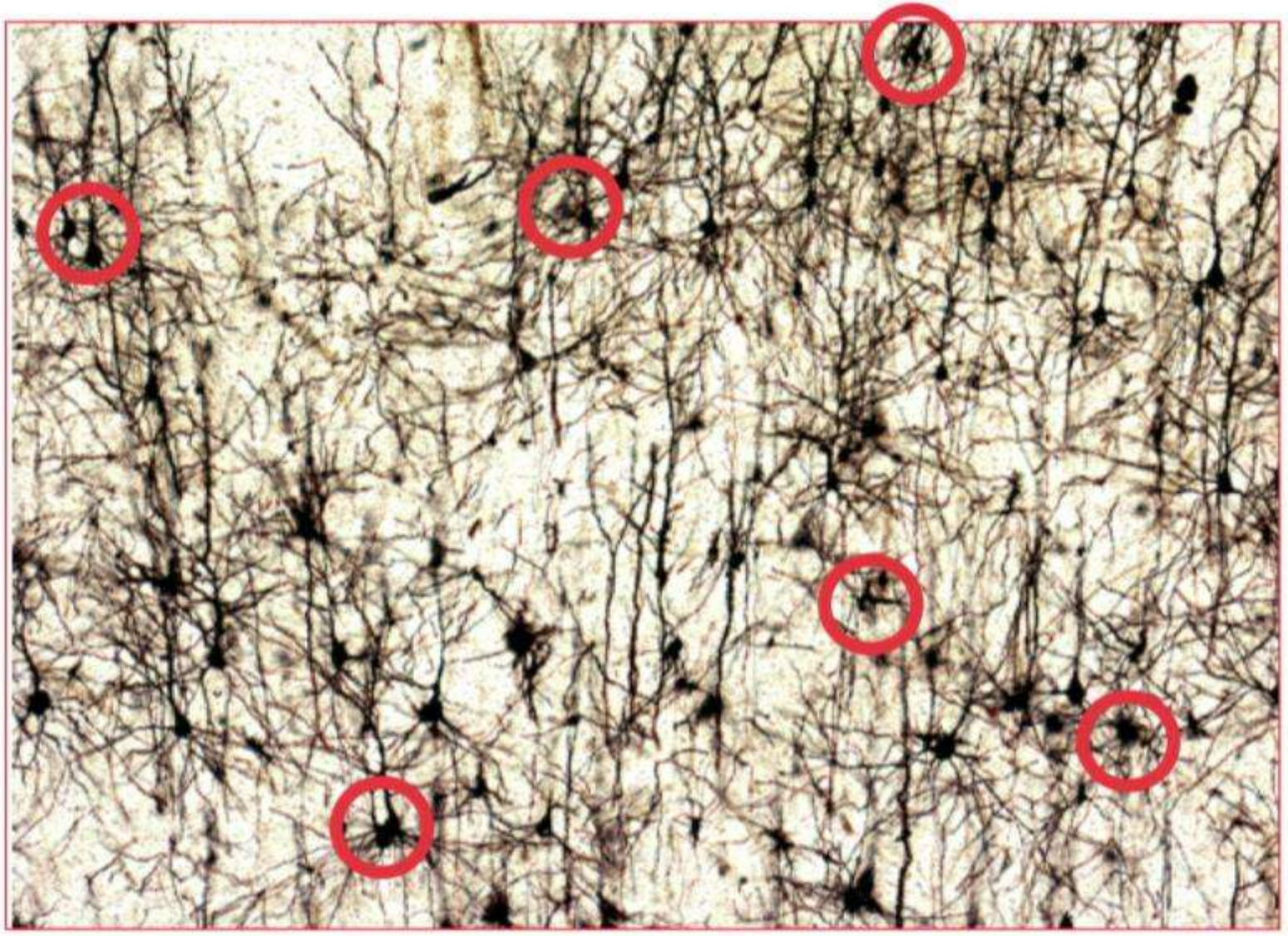


In conclusion:
What C Golgi and S Ramon y Cajal saw



The assembly hypothesis



Soooooooo…

- The study of the Brain is fascinating and bottomless
- Assemblies and their operations may be one productive path to thinking about computation in the brain
- Are they the seat of Axels's logic?
- How do assemblies learn and predict?
- How can one test/verify/falsify the Assembly Hypothesis through experiments?

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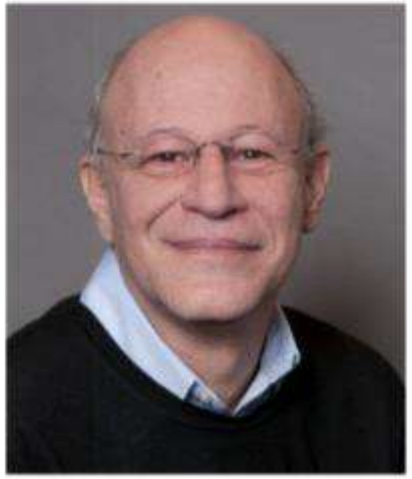
Dan Mitropolsky
Columbia

Larry Abbott
Columbia



Mike Collins
Columbia

Wolfgang Maass
TUGraz


Thanks!
PASAJE GALVEZ