
welcome
to Lecture 9
Computation and the Brain

What happened last Wednesday

Invited lecture by Melina Tsitsiklis

ECoG experiments with human subjects suggest certain place cells correspond to goals

Then, my recent work
Collaborators:

Santosh Vempa
Georgia Te

Wolfgang Maass

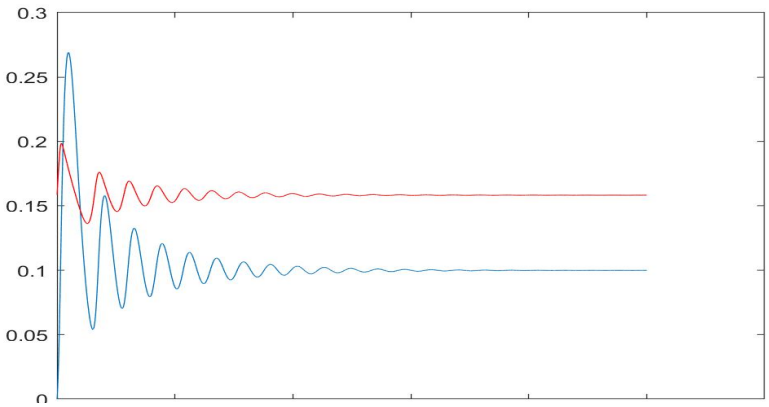
Mike Collins
Columbia U

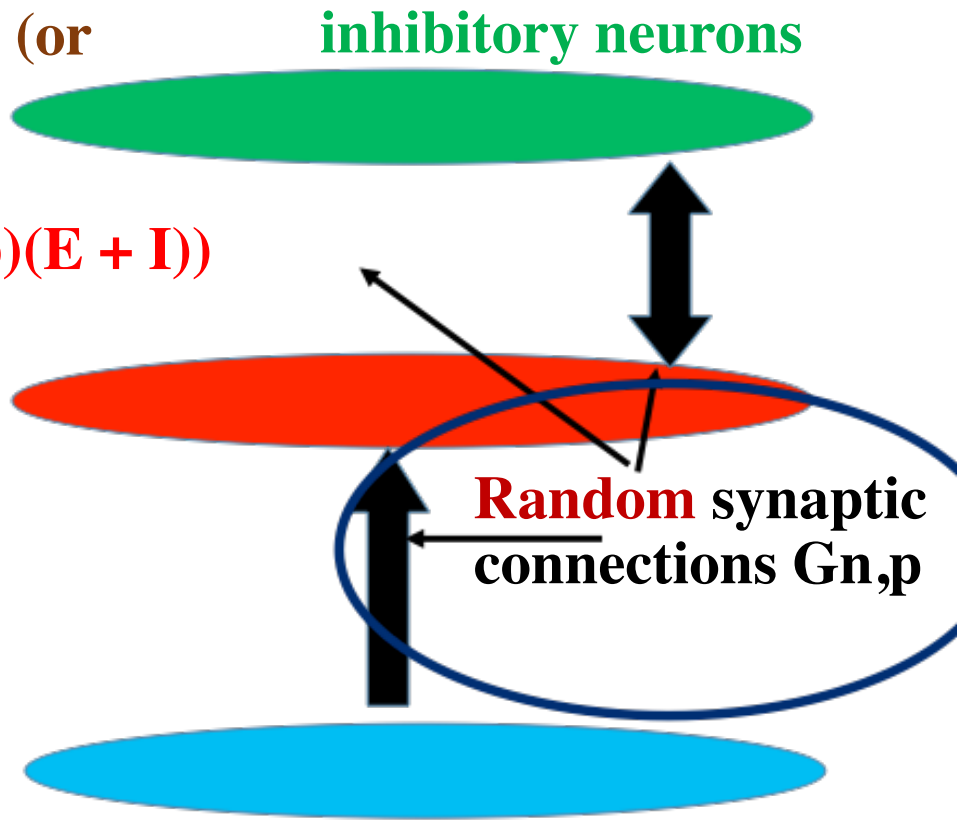
Excitation-Inhibition balance through Gn,p

Gaussian Tail GT(.) (or Φ(.))

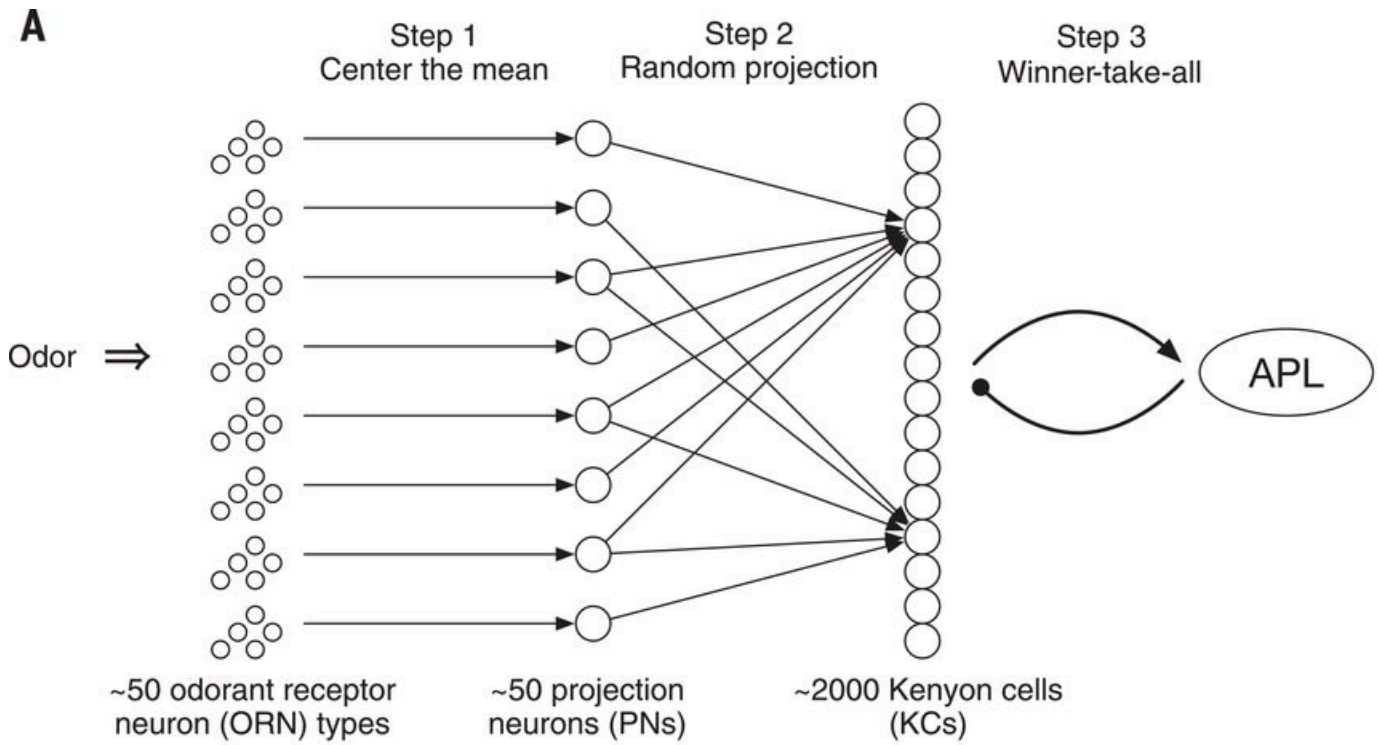
$\tau E \dot{E} = -E + GT(TE, np(E - I), np(1-p)(E + I))$

$\tau I \dot{I} = -I + GT(TI, npI, np(1-p)I)$



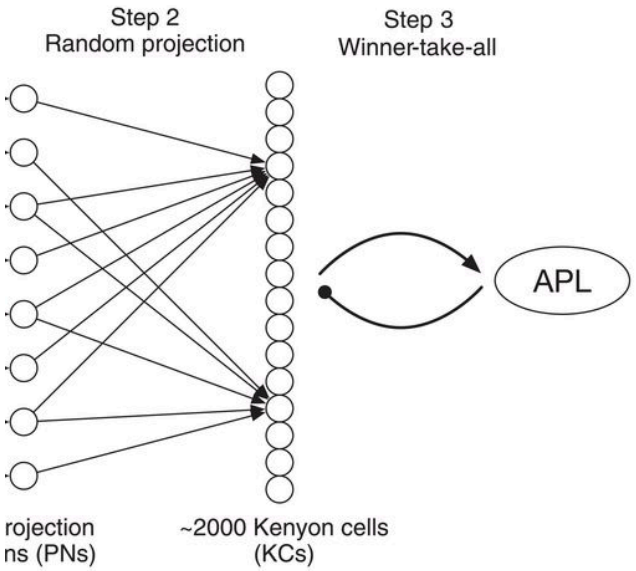


Fly olfaction

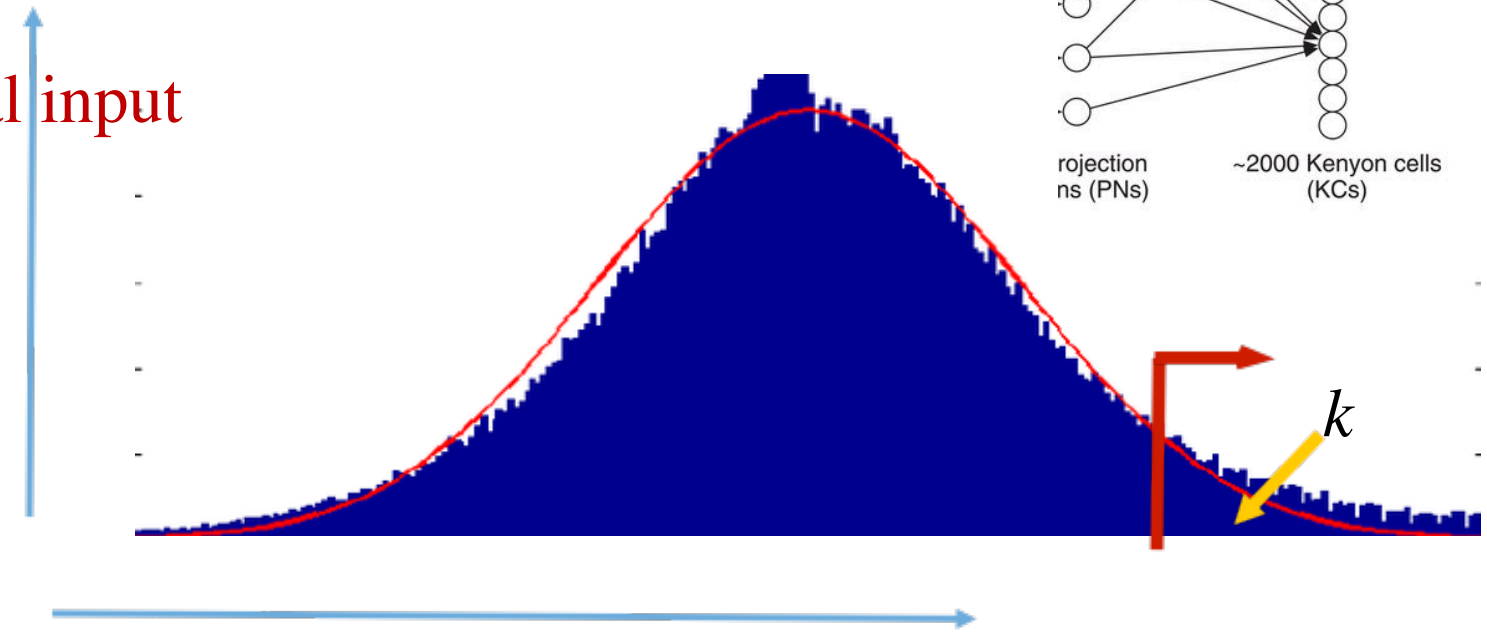


random projection followed by ***cap (RP&C):***
k ≈100 winners (out of ≈2000) take all

RP&C: random projection and cap (k-WTA)



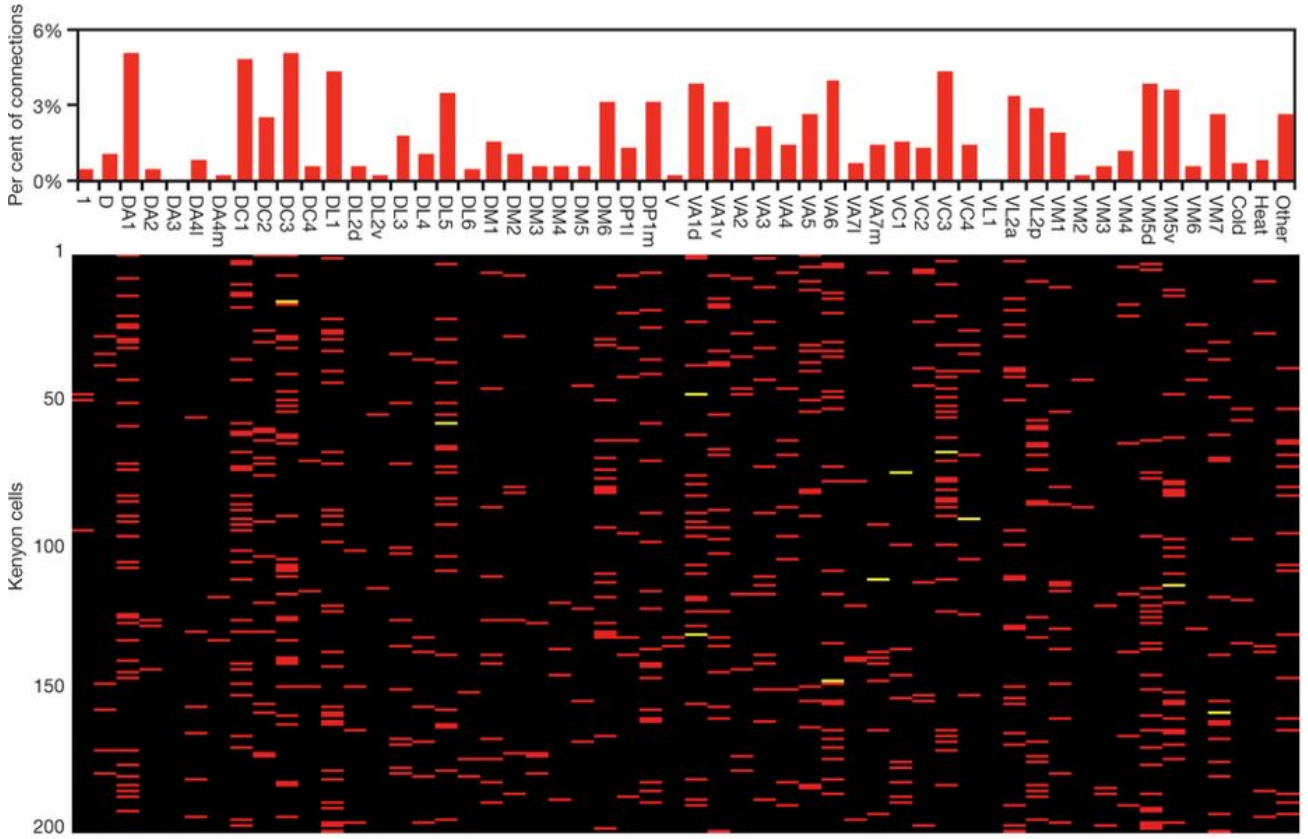
Number of RHS nodes with this total input



Total input at a RHS node

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

Nature apparently strives to create random graphs!

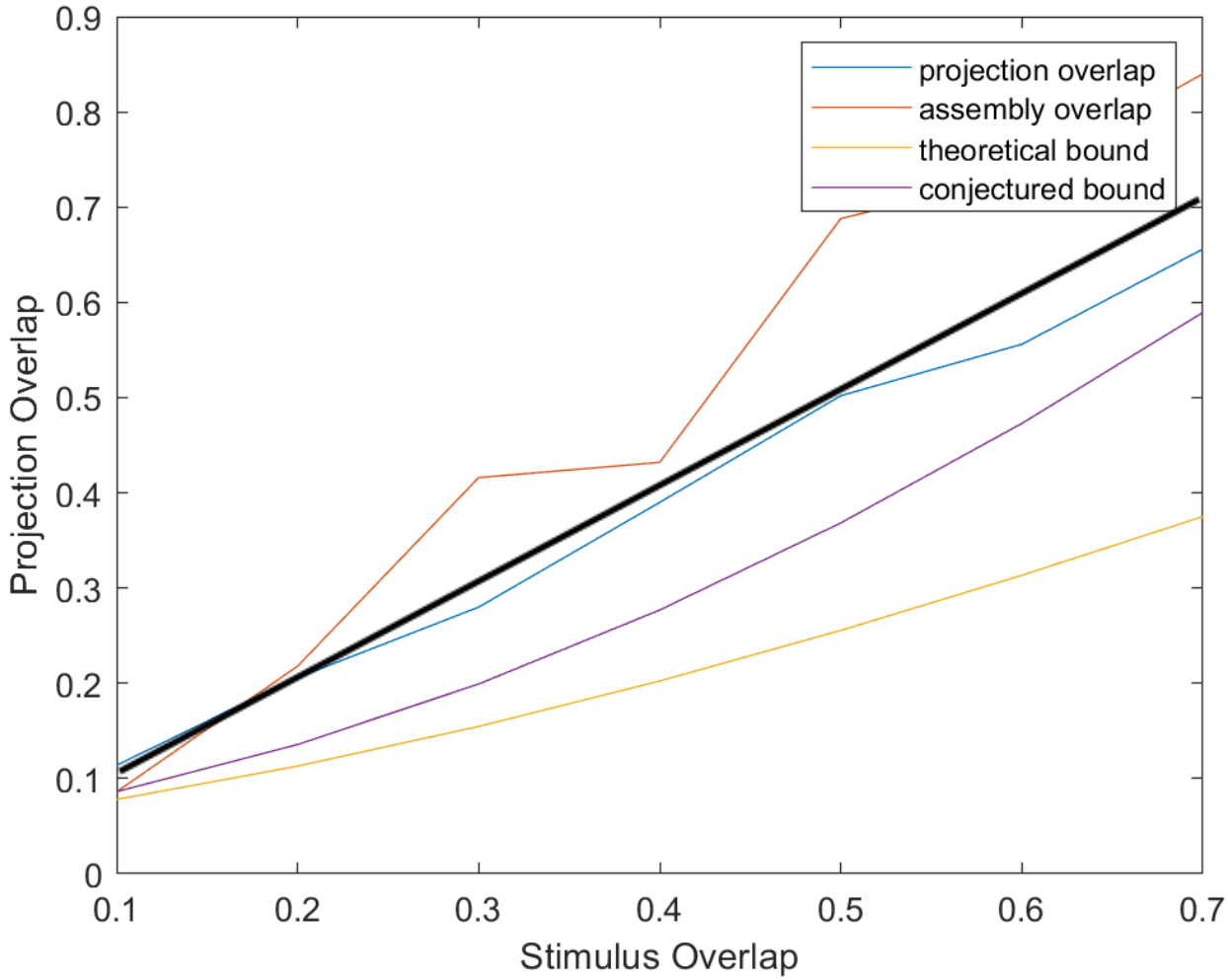


The underlying mathematical reason:

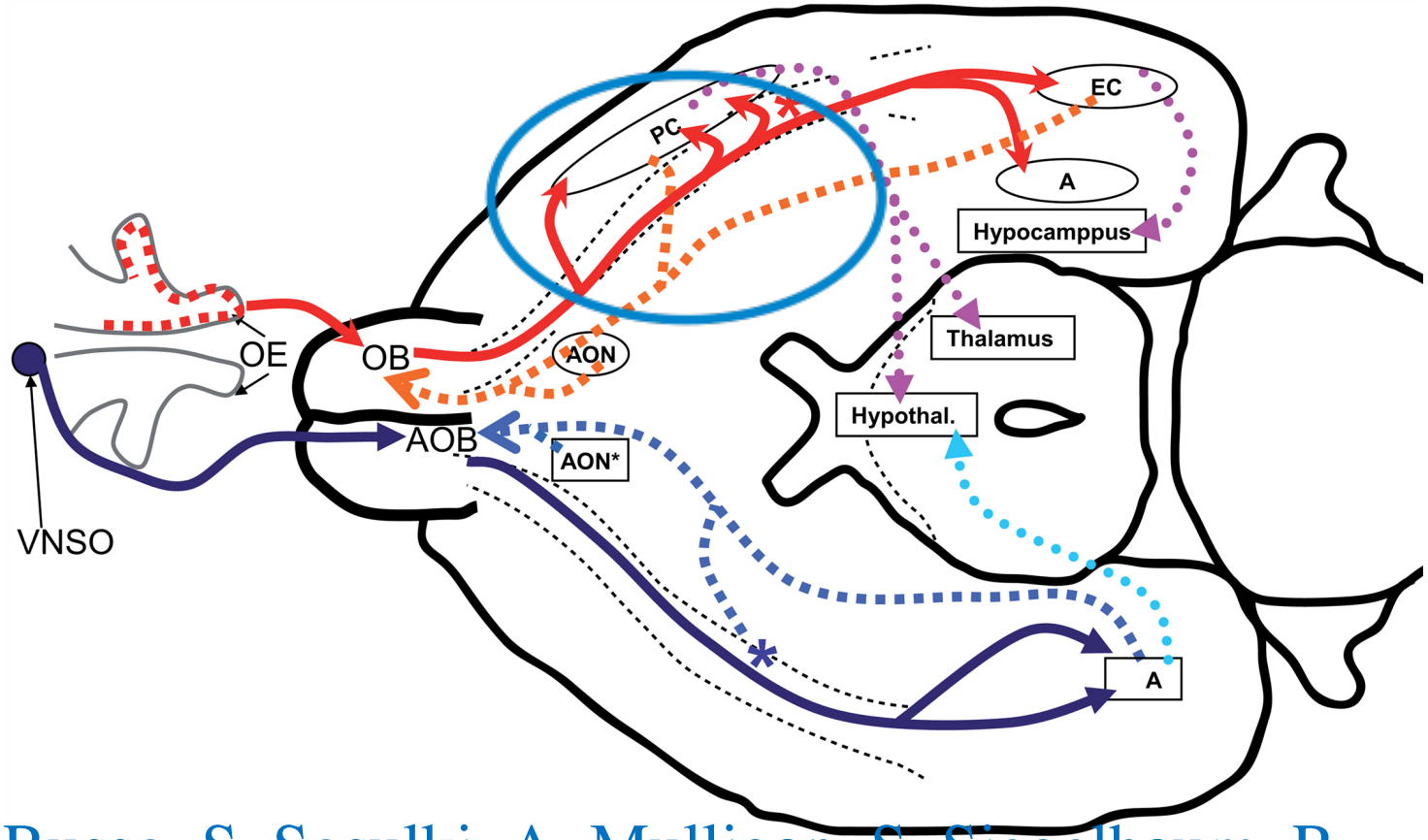
- **Theorem** [P., Vempala, 2018
  The intersection of **cap(A)** ar
  probability, at least

Conjecture:
no denominator

The underlying mathematical reason: compare with simulations



In mammals too!



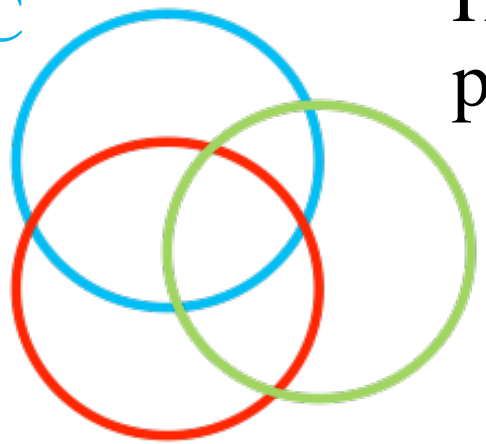
K. Franks, M. Russo, S. Sosulki, A. Mulligan, S. Siegelbaum, R. Axel
"Recurrent Circuitry Dynamically Shapes the Activation of Piriform Cortex." Neuron October 2011

In pictures…

set of spiking neurons

RP&
C

Also,
Hebbian
plasticity



third
RC&P,
and so
on…

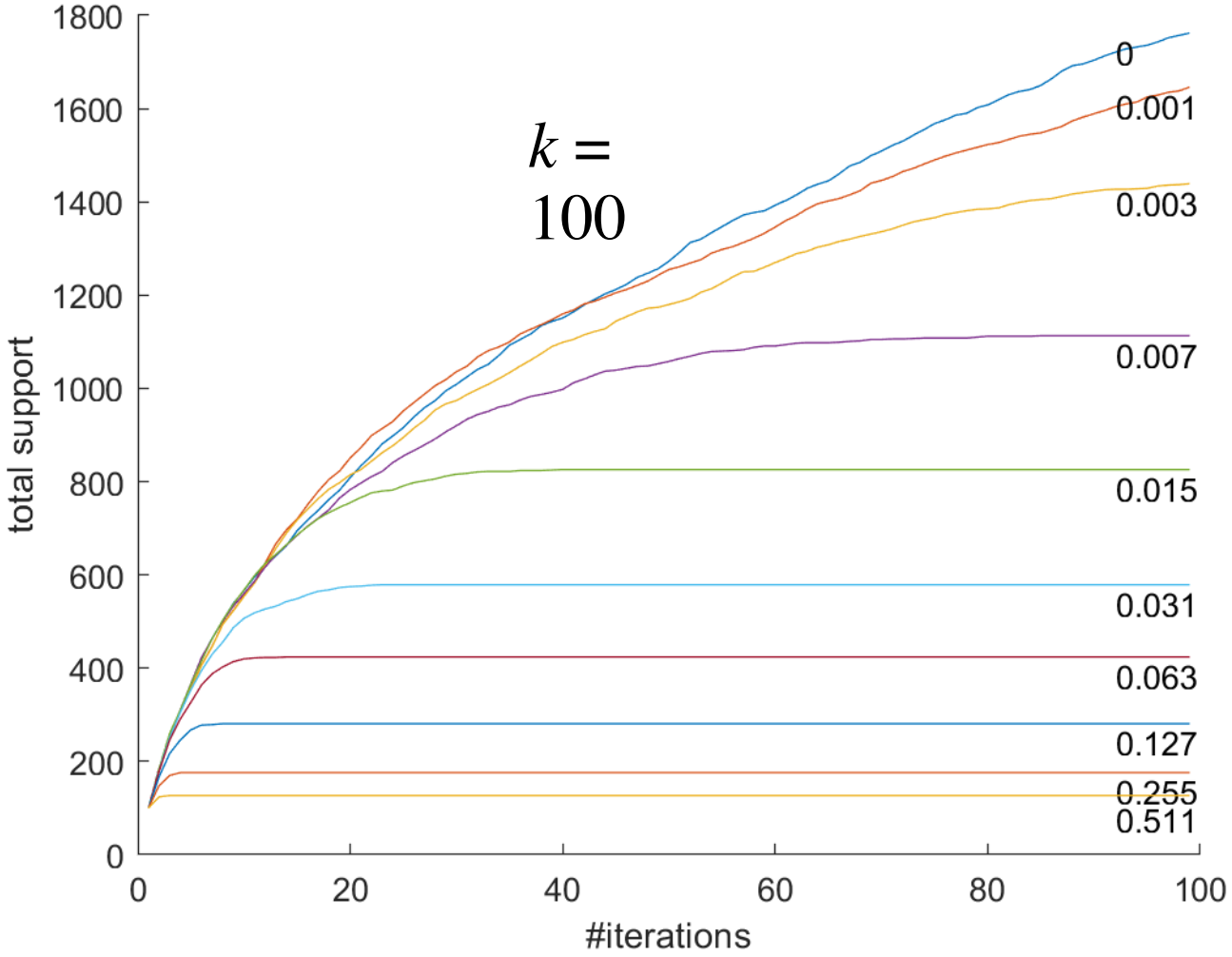
new
RC&P

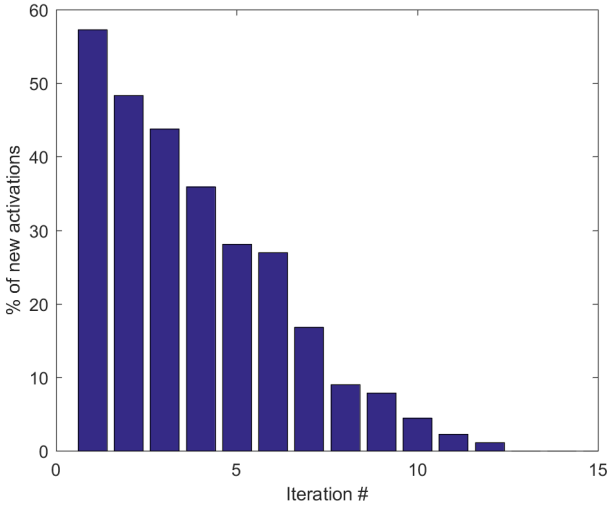
Convergence

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 $0 < \beta < \beta^*$: $k \cdot \exp(0.17 \cdot \ln(n/k)/\beta)$

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


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


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

The Big Picture: Computation in the brain: What is the right level?

- Whole brain?

?

- Spiking neurons and synapses?
- Dendrites?
- Molecules?

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

R. Axel *Neuron*, Sep 2018

The assembly hypothesis

- There is an intermediate level of brain computation
- Implicated in carrying out higher cognitive functions such as reasoning, planning, language, story-telling, math, music…
- 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: it helps us understand an experiment or two – ultimately the brain
- Plausible: no magic involved; the operation must be compiled down to neurons and synapses

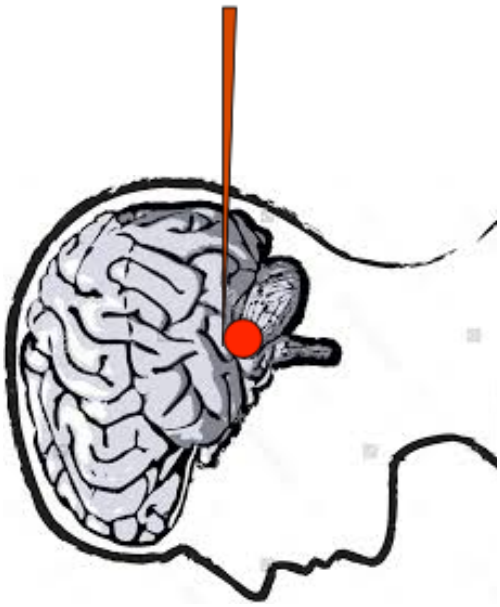
The model

- A finite number of "brain areas" **A**, **B**, **…**
- Each with n (excitatory) neurons ≈ 106-8
- E – I balance: assemblies have k neurons each ≈103-4
- NB: $k \approx \sqrt{n}$ (so assemblies barely intersect)
- All areas have recurrent synapses
- Some areas have synaptic connectivity to others
- Have to be enabled (disinhibited)

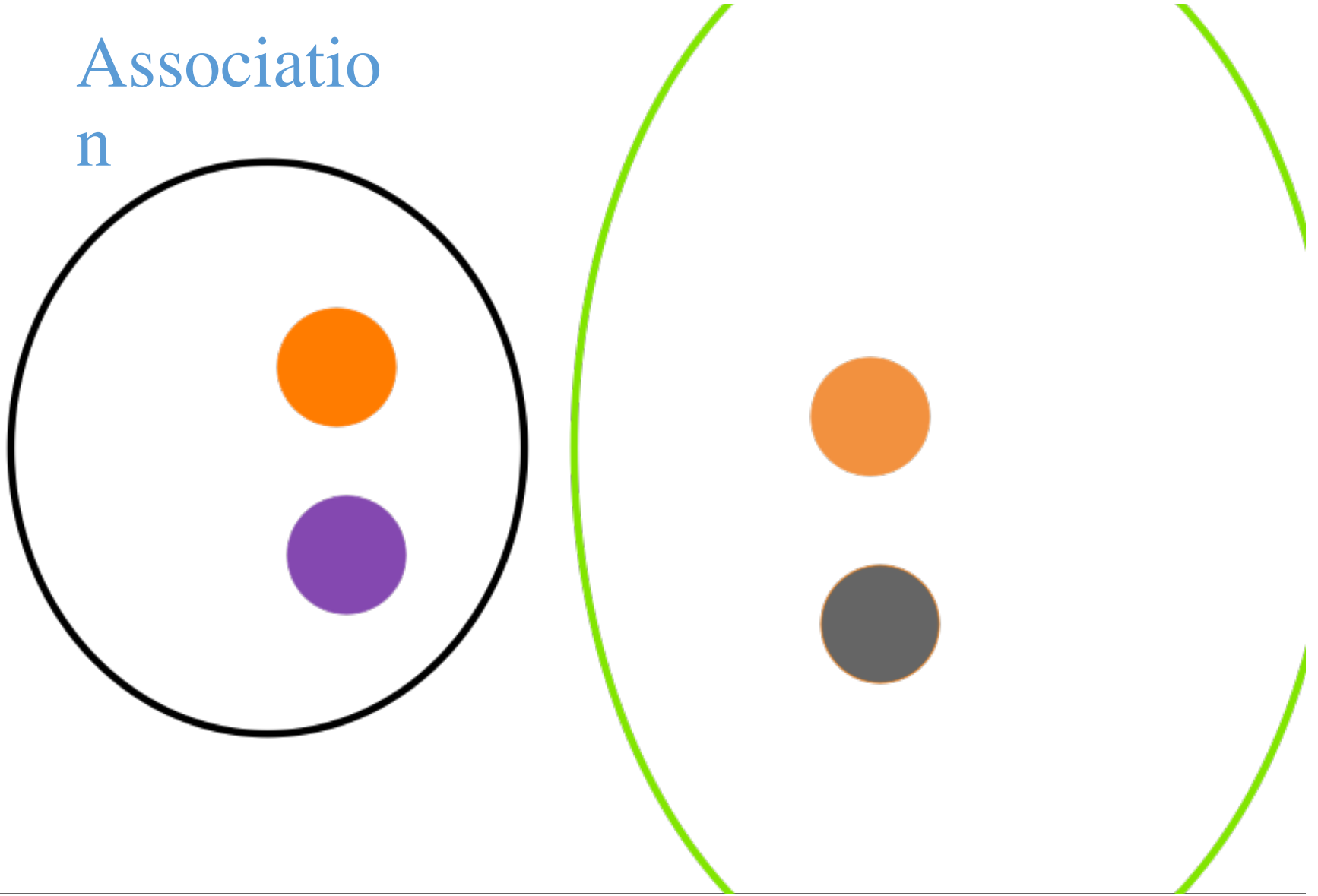
The assembly hypothesis: operations

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

- Q: *Other operations?*
- A: Two assemblies may be associated by sharing cells
- Association encodes “affinity”, similarity, co-occurrence
- Verified experimentally in humans!



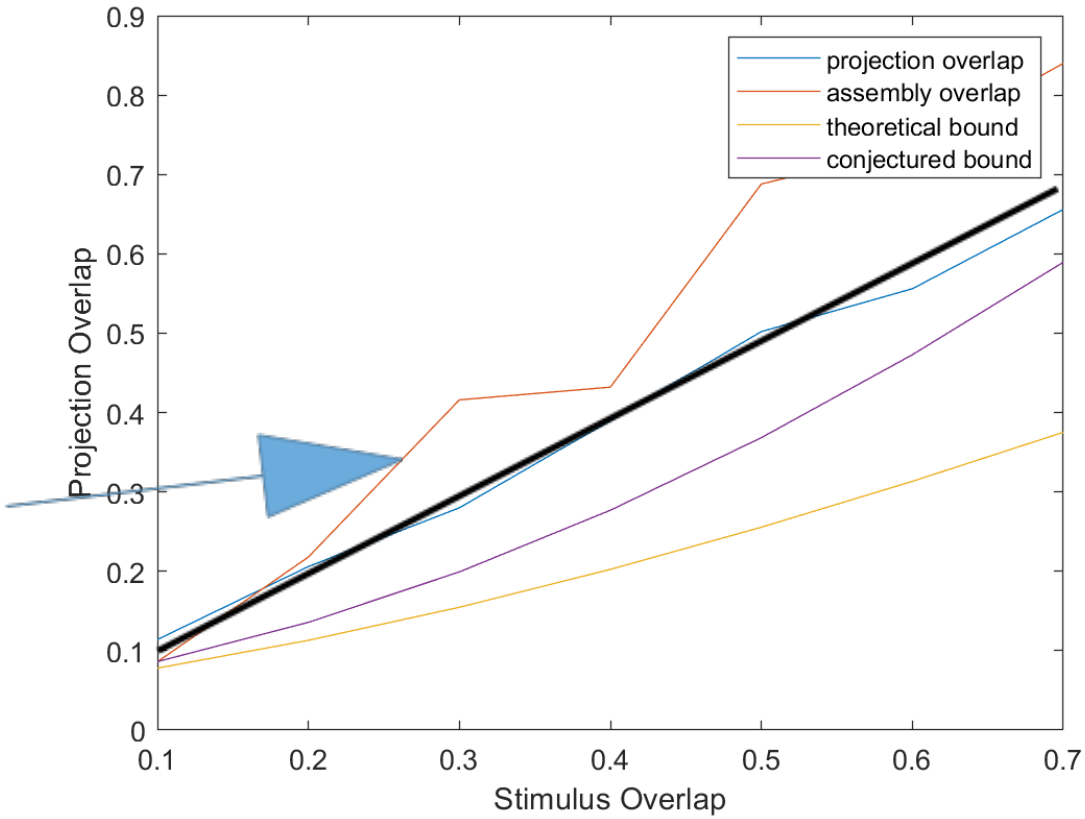
Association



Q: is association preserved under projection?

Recall the fly,
and similarity
preservation:

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



Questions? *Thoughts?* *Feedback?*

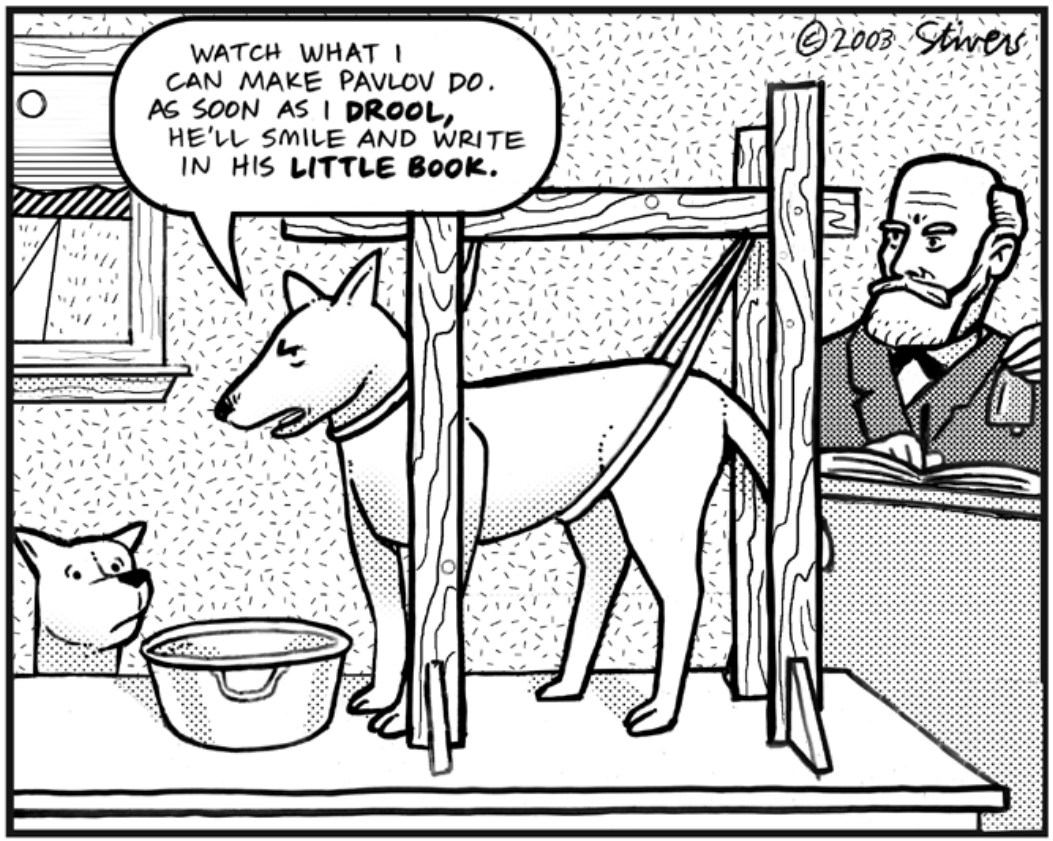
Feedback about the class?

Projects?

Today

- Continue with assemblies
- Motor cortex, motion, and dynamical systems (briefly…)
- Start reinforcement learning

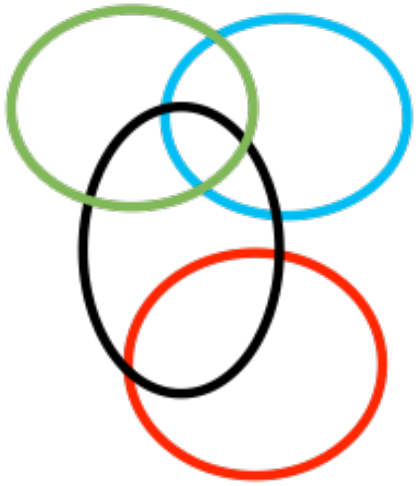
Reinforcement learning…



Next three weeks

- Language
- Evolution and Development
- Anything else?

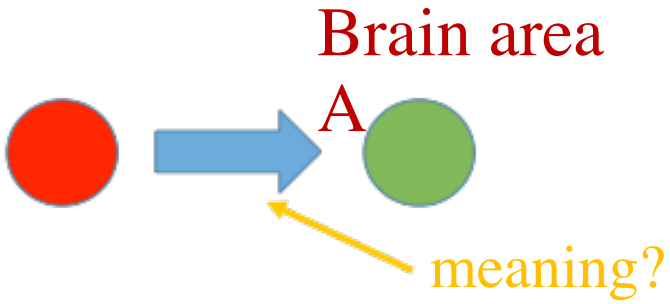
Assembly
association also means
associative memory



Association graph: weighted edges
connect assemblies/concepts that are similar

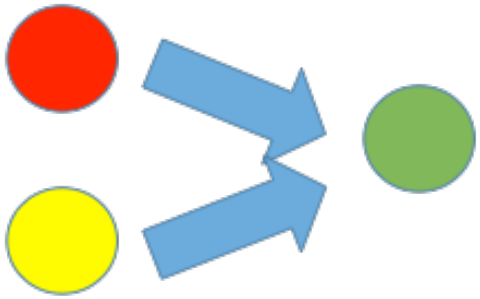
Which graphs are possible?
[ADMPS NIPS 2018]

Beyond project?

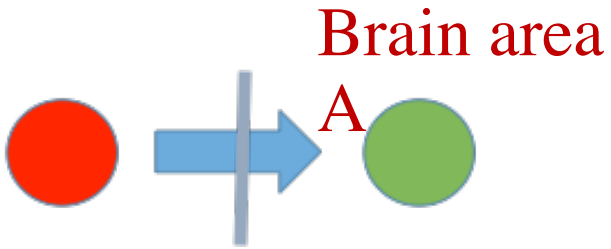


- reciprocal_project(x, A, y)
- (now also y can activate x)

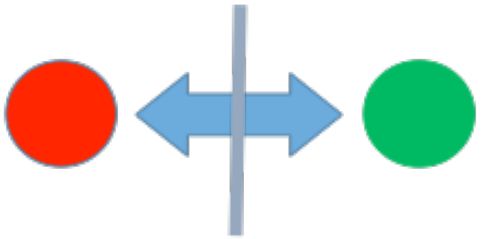
- merge(x, y, A, z)
- assemblies x, y project to create one assembly in area A, call it z
- Creates hierarchies
- Valuable for implementing language



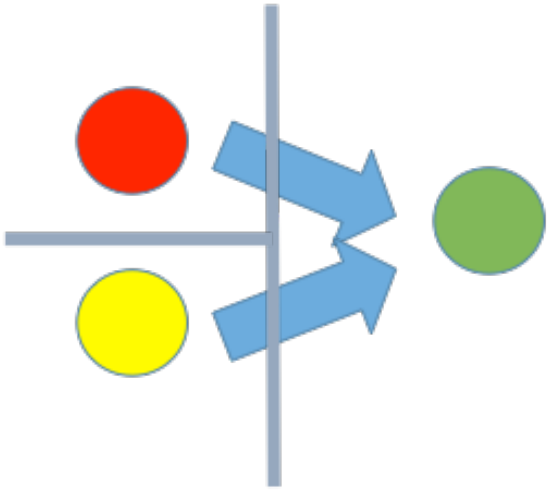
NB: Different areas!



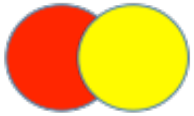
-
- reciprocal_project(x, A, y)



- merge(x, y, A, z)



- associate(x, y): same area



Assembly Operations recap

- project(**y, B, x**)
- associate(**x, y**)
- reciprocal_project(y, B, x)
- merge(x, y, B, z)
- Plus: activate(x), area-read(), assembly-read(), disinhibit(**A**)..

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

A: ***Turing-complete***

Turing complete?

- **Theorem**: The system can simulate with high probability arbitrary $\sqrt{n}$ space Turing machine computations
- What does this mean?
- Recall: "…implicated in carrying out higher cognitive functions such as reasoning, planning, language, story-telling, math, music…"

Turing-complete, some details

- Basically uses project(x, A, y) to simulate circular tape Turing machine
- Four basic brain areas, plus one more area for each state and symbol of the Turing machine
- Stores tape, state, and symbols through project
- "Control commands" like area(x), activate(x), assembly_read(), enable(A,B), etc. Can write:

"if area(assembly_read()) = B then project(x,B,y)"

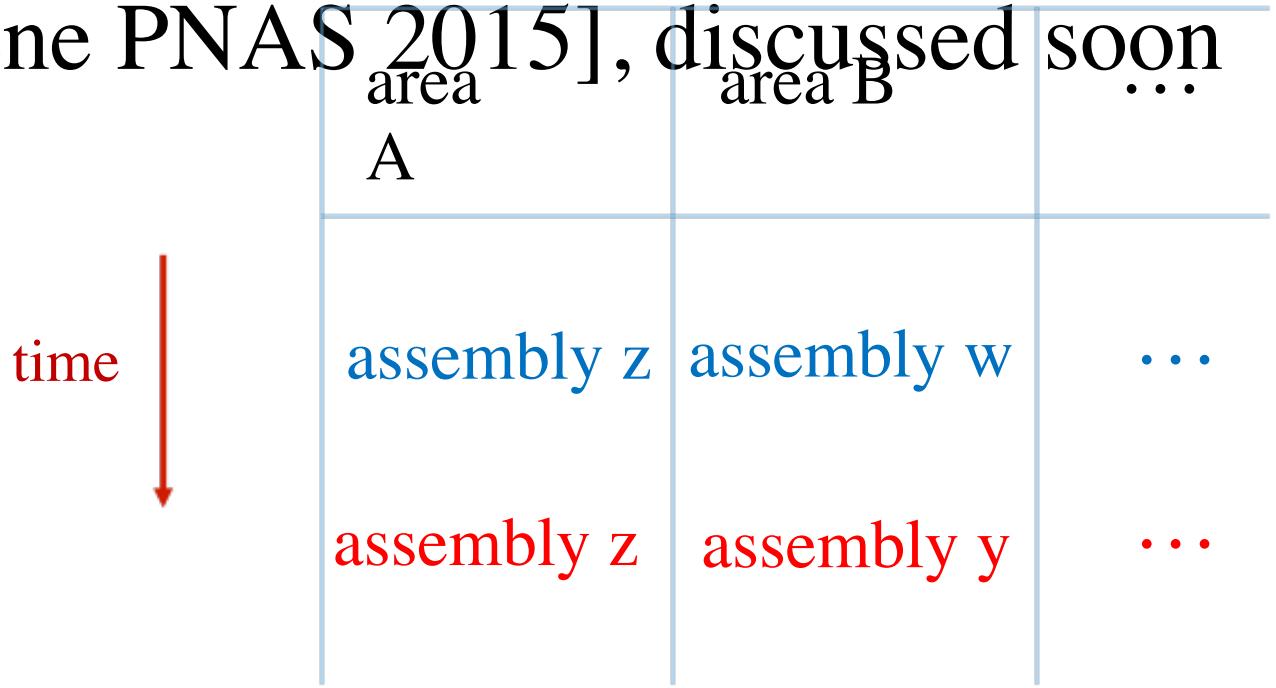
Other modes of Computing with Assemblies: Activation through association

- Activation of overlapping assemblies may trigger pattern completion and associative recall, e.g.

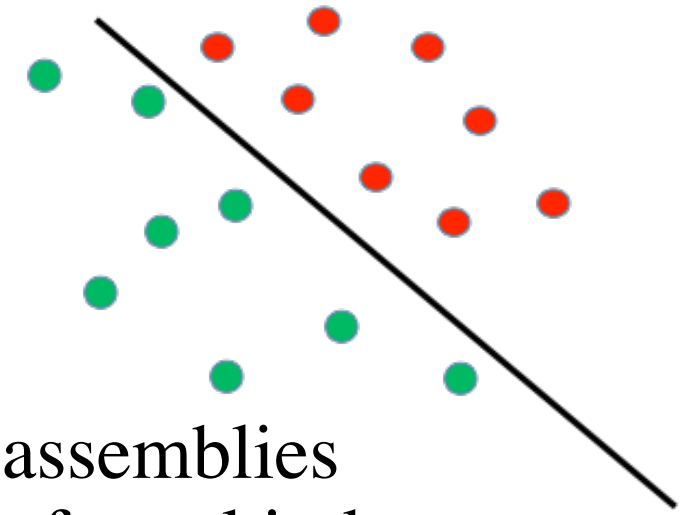
Russian and from Stanford completes to Vlad

- The association graph of a brain area [ADMPS NIPS 2018]
- Powerful probabilistic programming system

Other modes of computing with assemblies: m-ary relations
e.g. *subject – verb – object* [Frankland and Greene PNAS 2015], discussed soon

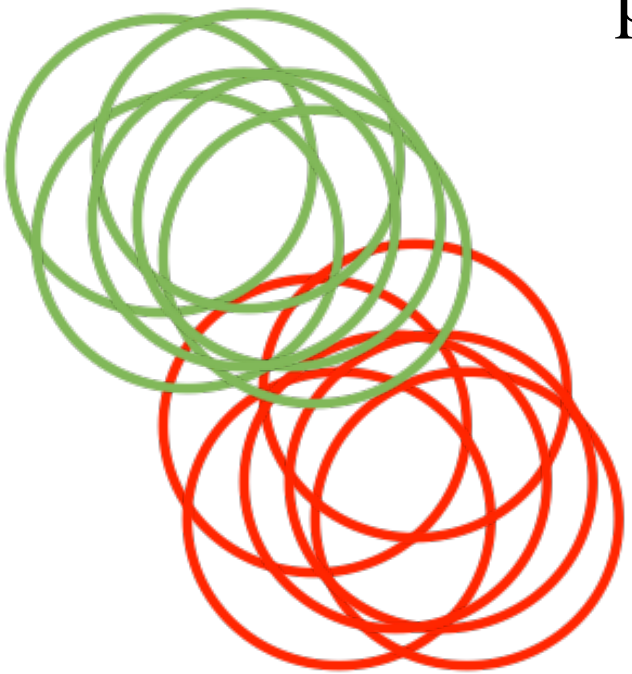


Modes of Computing with Assemblies:
Learning (halfspaces)



assemblies
of two kinds

projected

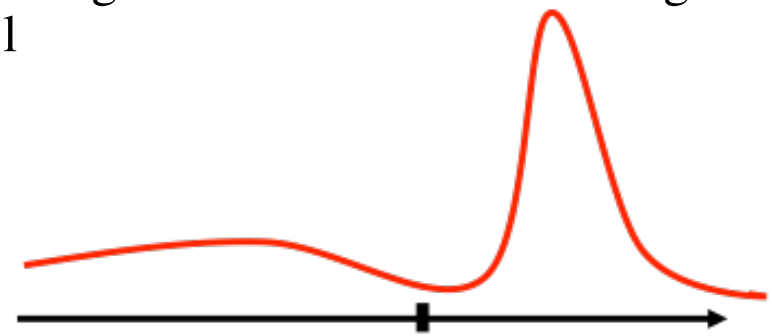


Ultimately: Language

- An envir *us* a few thousand
- A "last-m
- Hypothes s to exploit the Brain
- Invaluab g the Brain
- ***A deluge nents!***

The [Poeppel 2016] experiment

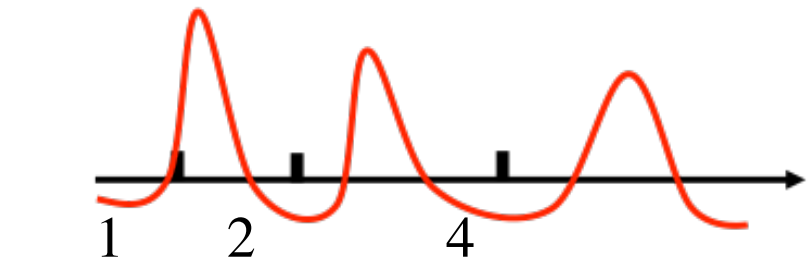
fret ship hil give true melt fans blue guess hits then cats
l



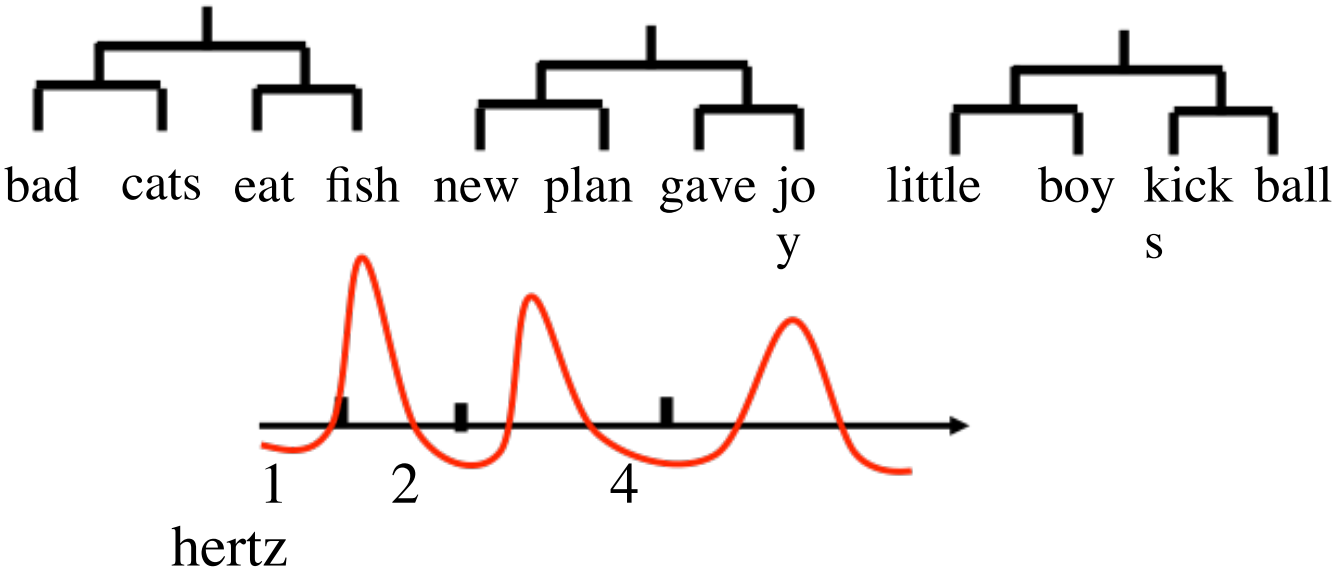
4 hertz

The [Poeppel 2016] experiment, stage II

bad cats eat fish new plan gave joy little boy kicks ball

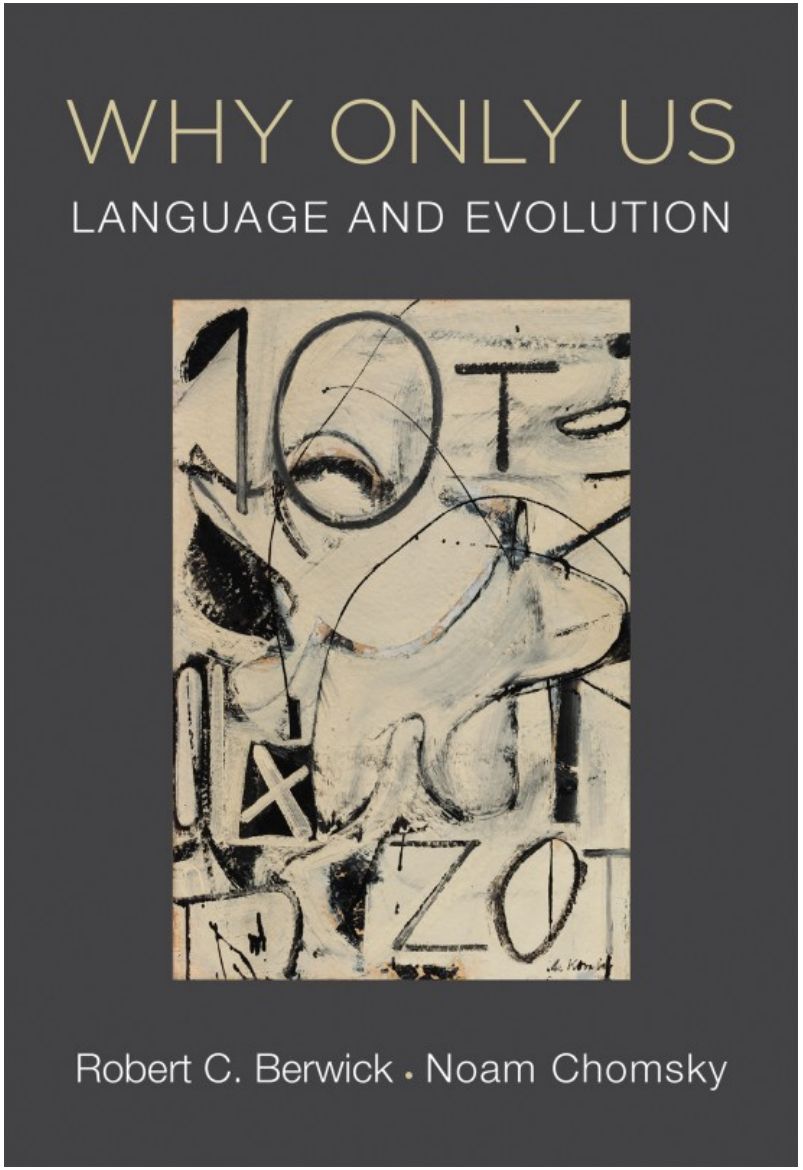


One interpretation



Trees
in our brain?

- Get serious…



[Frankland & Greene PNAS 2015]

"The ball hit the truck"
vs
"The truck hit the ball"

Different areas of the superior temporal gyrus responded to "truck" in the two sentences
[Recall relations…]

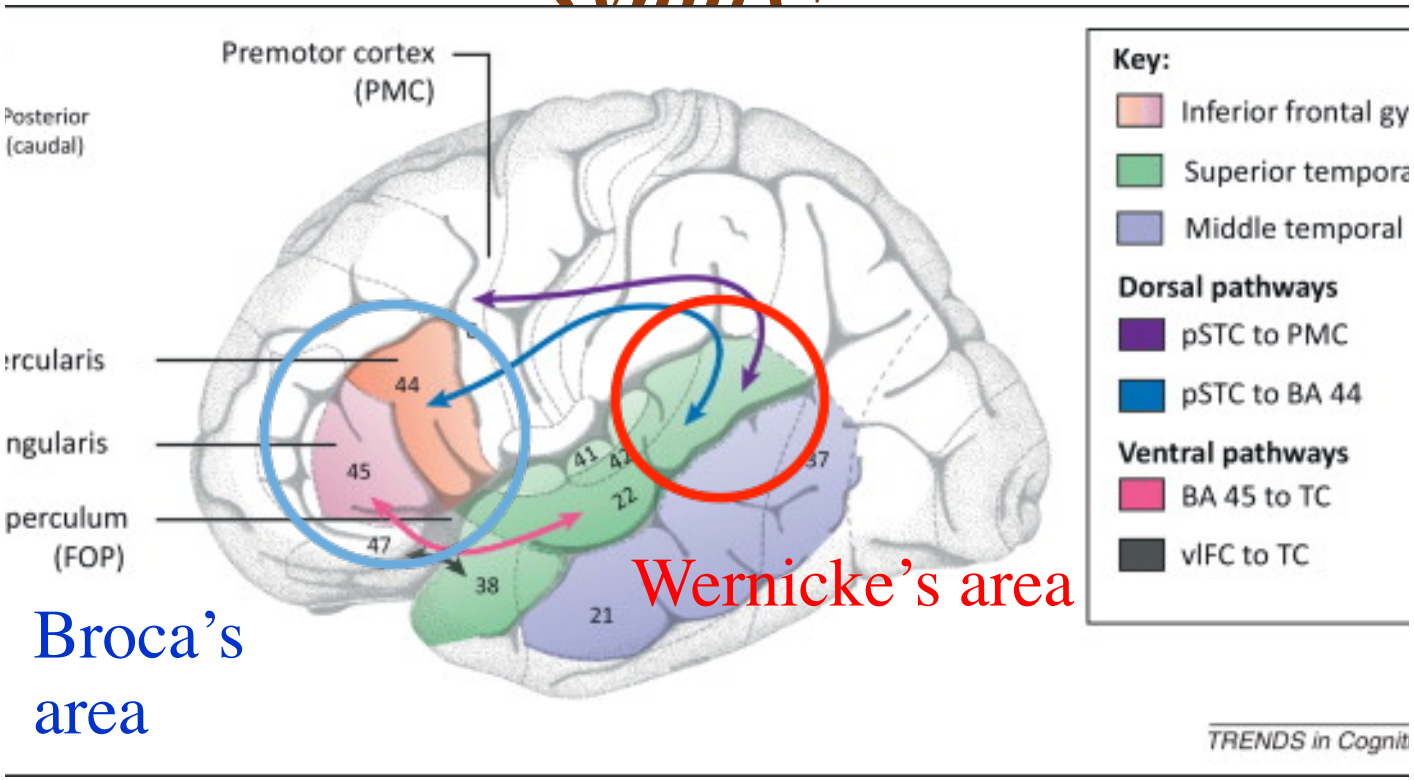
The first area also responded to
"The truck was hit by the ball"

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

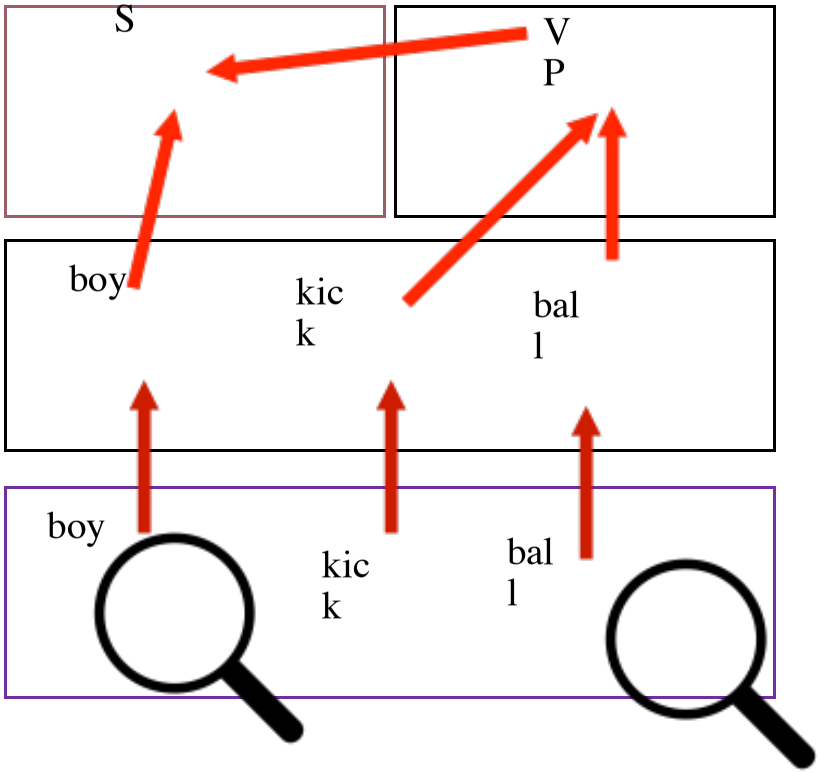
- The completion of phrases, and especially of sentences, lights up parts of Broca's area

cf: Friedericci, "Language in the Brain" MIT Press 2018

[ZF 2010]: Neural pathways for syntax?

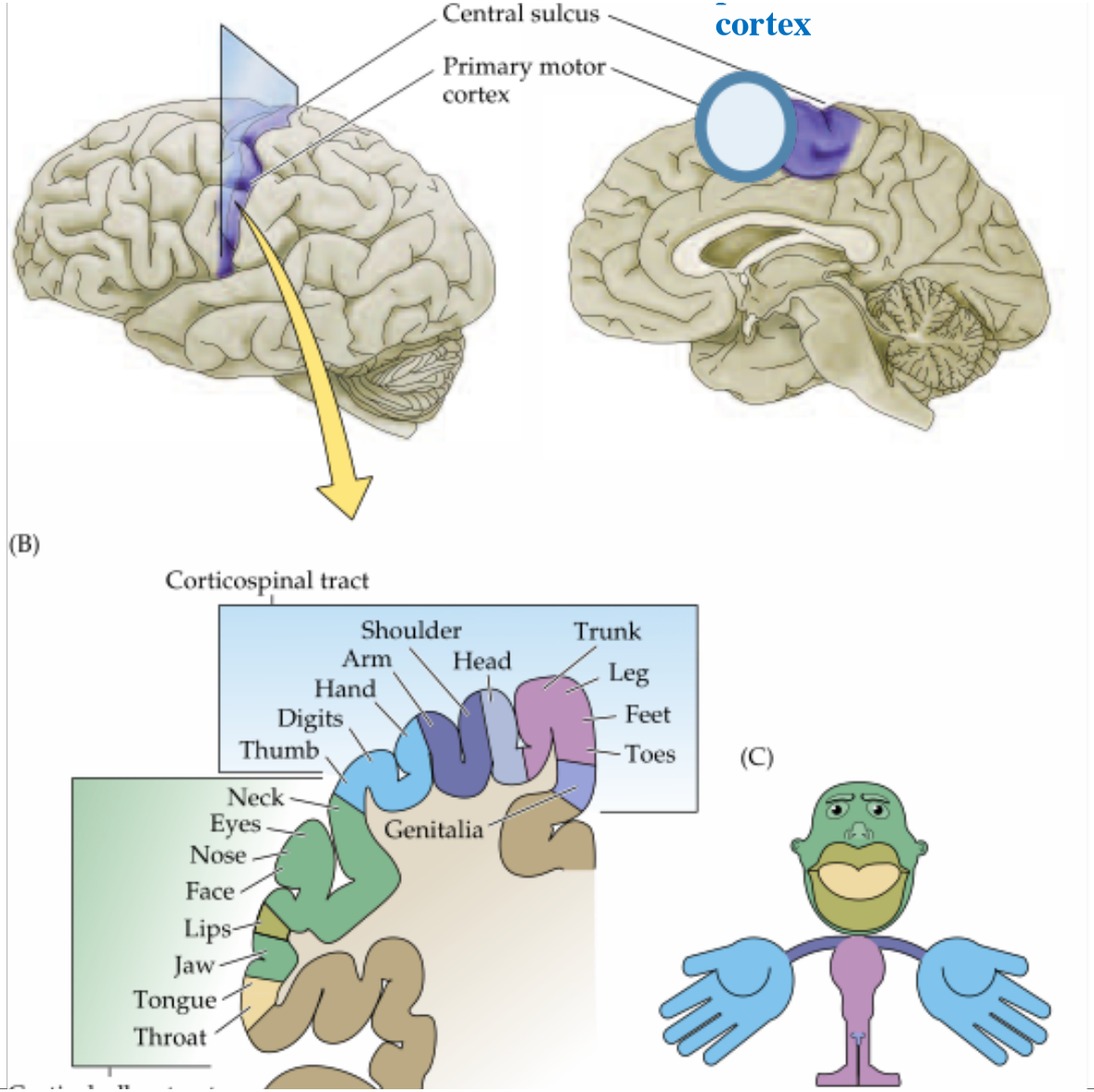


Wild speculation: a candidate brain architecture for syntax

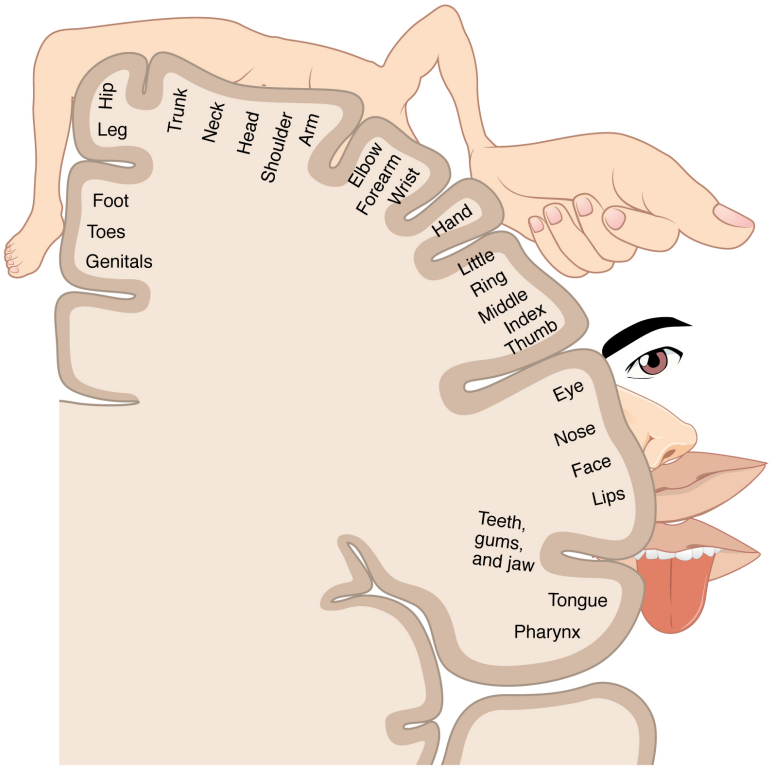


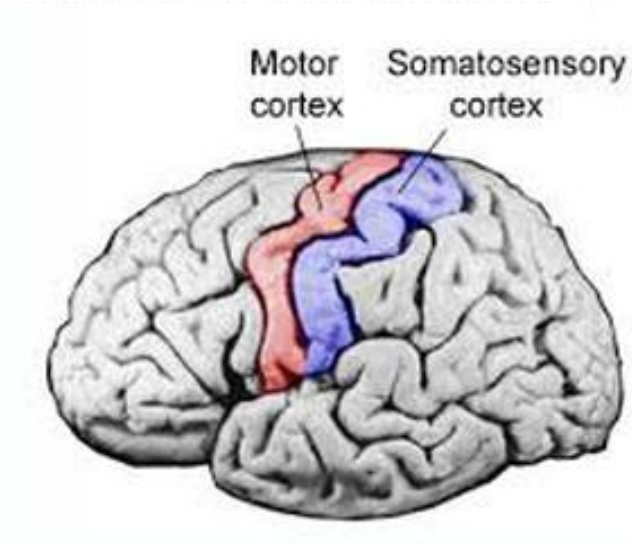
We shall return to Language. Next:

The Motor Cortex



Compare with: the somatosensory humunculus





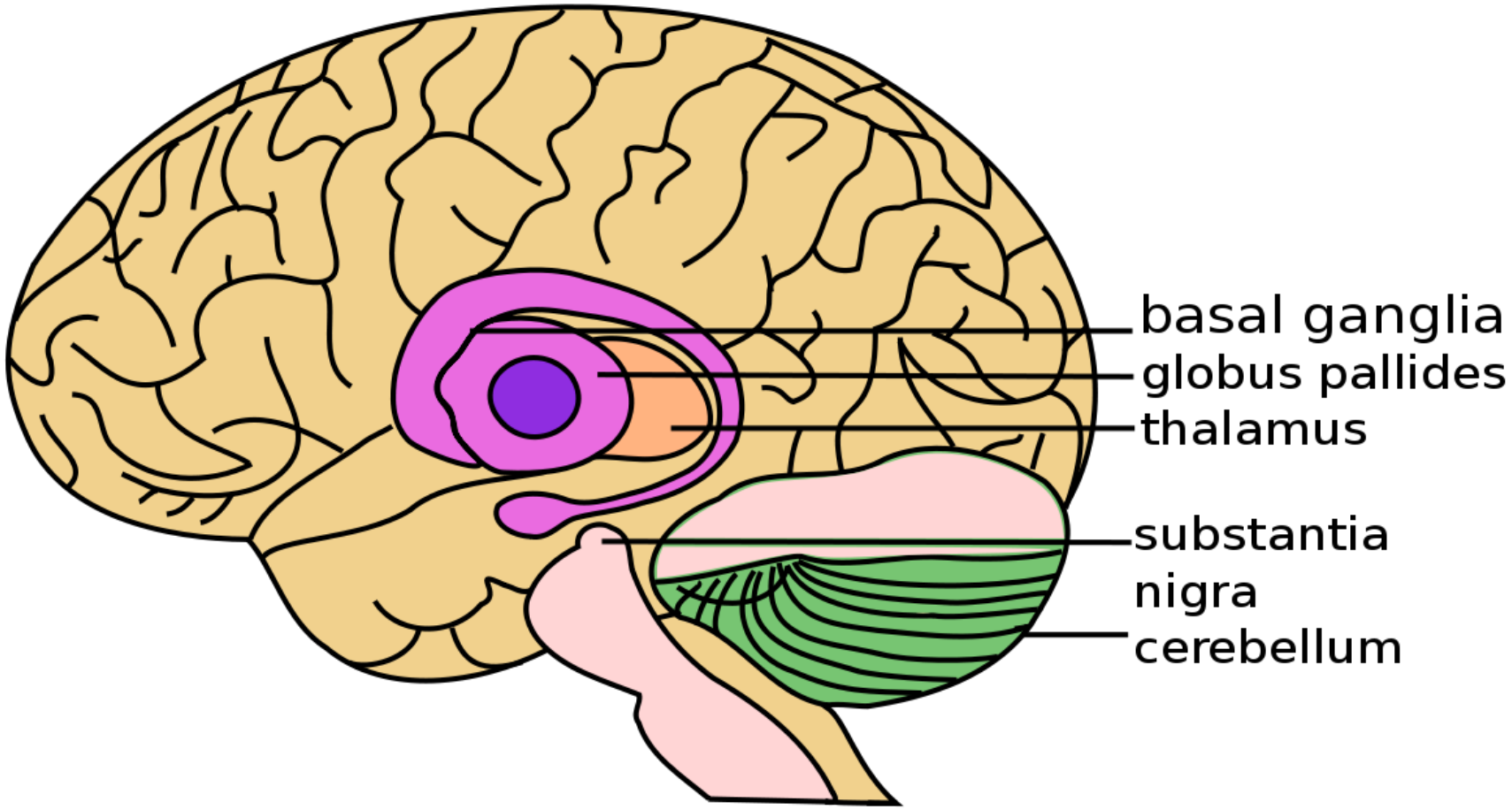
Back to the motor system:

- Motor maps date back to the 1960s and were found to be basically right. ***But*** the complete picture is much more complicated and under construction…
- Motor talent is reflected in motor cortex areas. E.g., violinists, cellists, and classical guitarists appear to have exaggerated left digit areas, presumably developed in parallel with their motor talent. This means the map is plastic

Back to the motor system (cont):

- Premotor cortex receives input from many brain areas, provides input to the motor cortex, and is implicated in conditional motion
- Motor and premotor cortex are just the remote control center of a complex and very extensive system, involving also the brain stem, spinal cord, nerves in muscles, **basal ganglia,** and much more

Basal Ganglia and Related Structures of the Brain



What do we know (about the motor cortex) (and when did we know it)

- 1890s: Motor cortex discovered: electrical stimulation causes limb motion
- 1900s: The first "motor maps"
- 1960s-2000s: Sophisticated recording and electrical stimulation technology allows extensive experimentation
- Theories of motor cortex reflect emerging theories of the visual cortex (simple and complex cells, coding of movements etc.)

The paper [Churchland et al. 2012]

- Classical view: a neuron in the motor encodes the motion being enacted
- But this coding appears to be complicated (polyphasic)
- That is, its firing rate is a function of many motion parameters simultaneously, such as direction, speed, state of muscles, positions of bones, etc.

$$rit = fi(par1, par2, \ldots, par30)$$

The paper [Churchland et al. 2012]:
and in this corner…

- Opposing view: a neuron in the MC is a row (eqn) of a dynamical system, whereby the MC generates and controls movement: $\dot{\mathbf{r}}t = \mathbf{f}(\mathbf{r}t, \mathbf{u}t)$
- So, neural responses reflect underlying dynamics, and encode stimuli only incidentally
- Hypothesis: ”movement generation across the animal kingdom involves rhythmic, oscillatory activity”
- **BUT** does the neural state rotate during all motion (even non-rhythmic movement like reaching)?

- Two animals
- Three motions
- Two of the motions are rhythmic, the third is not
- The all have significant cyclic projections of neural activity
- ***jPCA***