welcome to Week 8

Computation and the Brain
Fall 2019

What happened last Wednesday

Reinforcement Learning

Classical conditioning (1960s): The delta rule

Pavlov's conditioning and beyond

Stimulus u, prediction x, weights w

(w, u possibly vectors)

Reward R

$x = u \cdot w$

δ

Rescola-Wagner plasticity: $\mathbf{w \rightarrow w + \varepsilon \cdot (R - x) \cdot w}$

Note that this is gradient descent with error $2(R - x)^2$

But: does not model time and foresight

Animals choose actions
by looking beyond
the present reward…

Reinforcement learning and temporal differences: [Sutton and Barto 1980s]

stimulus u(t), prediction x(t), weights w(t), reward R(t)

x: predicted value of all future rewards…

$x(t) = u(t) \cdot w(t)$

discount

$x(t) = R(t+1) + \gamma \cdot R(t+2) + \gamma^2 \cdot R(t+3) + \gamma^3 \cdot R(t+4) + \ldots$

$\delta = R(t) + \gamma\, x(t) - x(t+1)$ prediction error

Minimize δ^2 via gradient descent

This is the ***Temporal Difference*** algorithm

Reinforcement Learning in the brain

Spot:

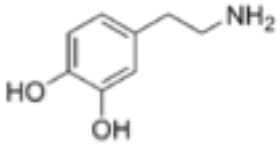
The δ calculator

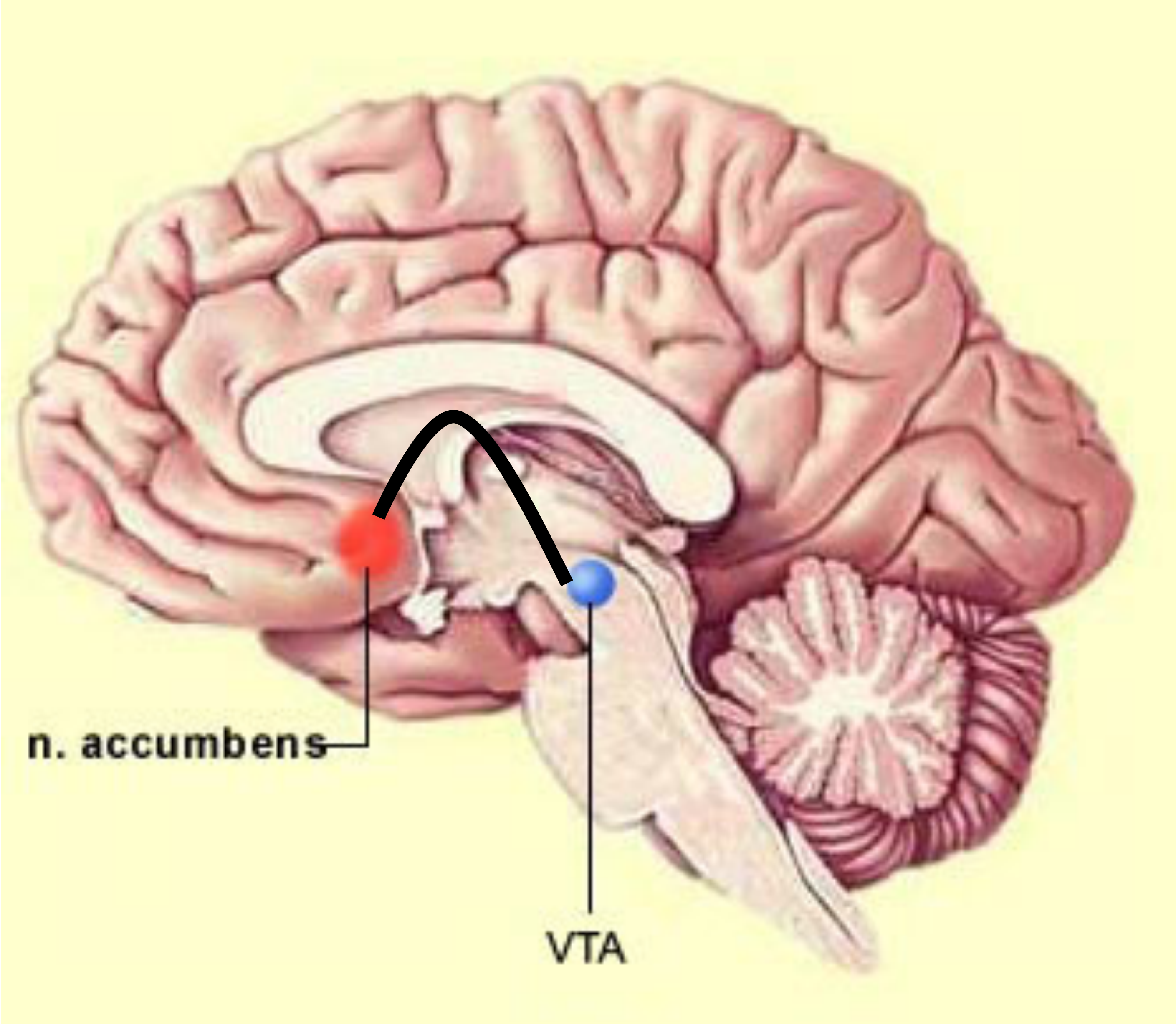
The weights w of the stimuli

The reward delivery system

The reward circuit

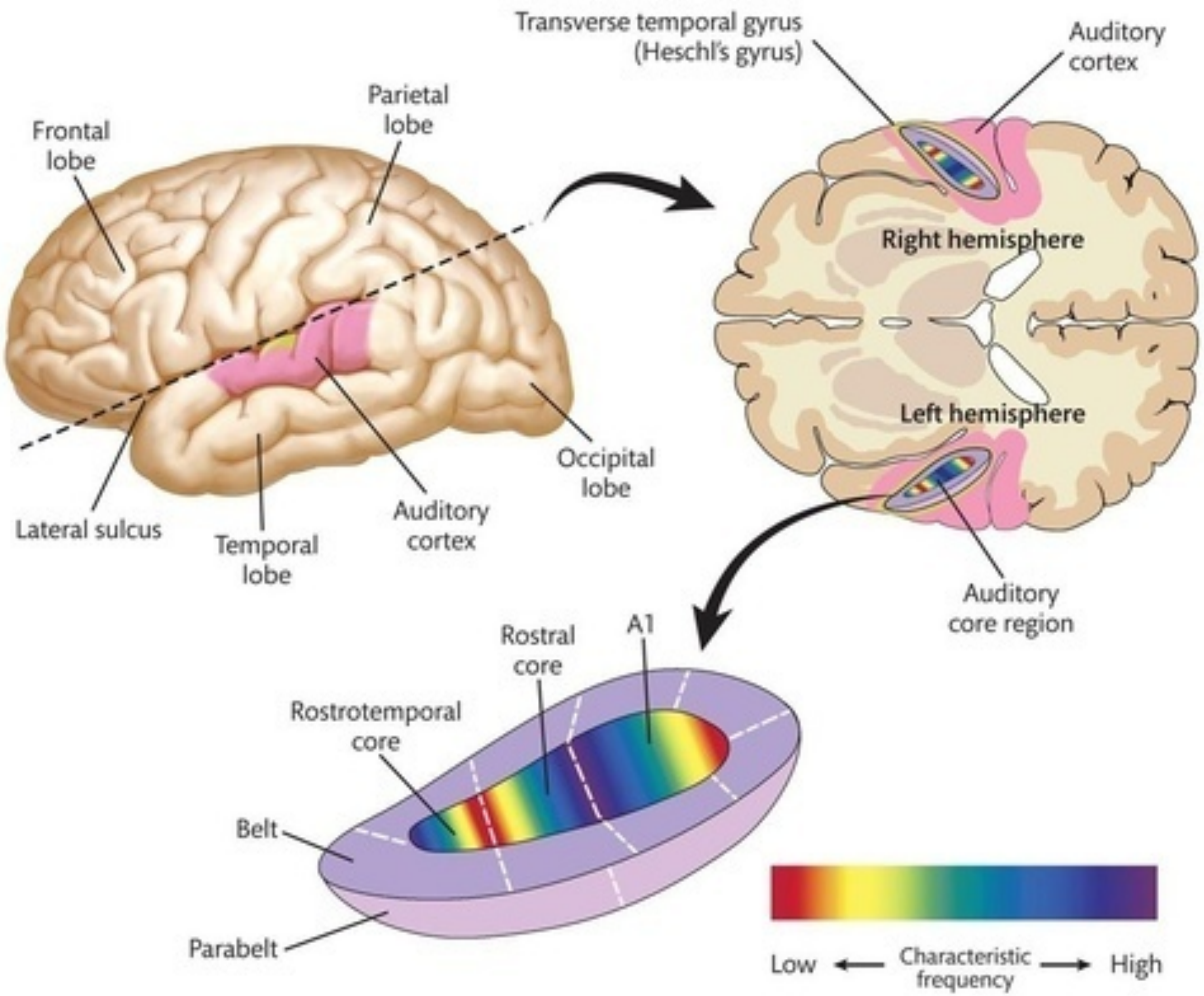
Btw: the reward is

dopamine 



auditory cortex

- Near the ear
- A1, A2, belt, parabelt
- Still cochlea signal goes through thalamus (MGN)
- Specializes in frequencies
- Right: tonal, music
- Left: temporal aspects, rhythm, and ***speech***



Important model in RL: multi-armed bandits

m actions a = 1…m

Each has an unknown reward distribution D_a

You are stuck at the casino for a very long time T

How would you play?

Exploration vs. exploitation

- One machine has the best expectation, M^*
- Best thing to do is play this forever – but you don’t know which…
- So, at time t you choose A(t)
- Every machine i has a (unknown) gap $G_a = M^* - M_a$
- You want to minimize regret: $\text{Regret}(A) = \Sigma_t\, G_{A(t)}$

Exploration vs. exploitation: is linear regret inevitable?

- Lower bound: regret is at least $\log T \cdot (\Sigma_a G_a/KL(a, a^*))$

UCB: Estimate the expectation of every action as

$$\text{current mean} + \sqrt{(\log t/\text{sample size})}$$

- **Theorem**: UCB1 has regret at most $10 \log T \cdot (\Sigma_a G_a)$
- **Theorem:** Thompson's algorithm (parametric representation of the D_i's) achieves lower bound

More advanced model: time-dependent bandits

Suppose now the machines are known Markov chains with a reward at each transition

We know the current states

Discounted rewards

Gittins index of a Markov chain

- Gittins index of M: the smallest reward for which, if you had a choice of any number of rounds with M and then R forever, you would not touch M
- **Gittins Theorem:** The optimum strategy is always play the machine with the highest Gittins index

Markov decision processes (MDPs)

- Gittins allows you to switch Markov chains
- In MDPs the Markov chains all share the same states
- You have a choice of action at each state
- Your choice changes the transition probabilities and the rewards
- Strategy A: You choose, once and for all, what to do at each state, and then follow the resulting Markov chain
- What is the best strategy?

Value of a state: Bellman's equation

$$\mathbf{V[state] = max_A\ [R(state,A) + \gamma \cdot E_A\ [V[next\ state]])}$$

Can be solved three different ways as LP

Problem is, Chess has 10^{50} states, Go has 10^{170} and an automated driver may have more…

(Also, rewards are infrequent…)

Deep reinforcement learning

- Policy choice A is a parametrized function of the state
- Action at state s is A(s,θ) – a distribution
- J(θ) = the expected reward of A(s,θ)
- Maximize by stochastic gradient ascent: calculate ∇θ by sampling paths of the Markov chain (roll-outs)
- Various problems arise, solutions developed…
- …AlphaGo, AlphaZero

Today and next three weeks: Language

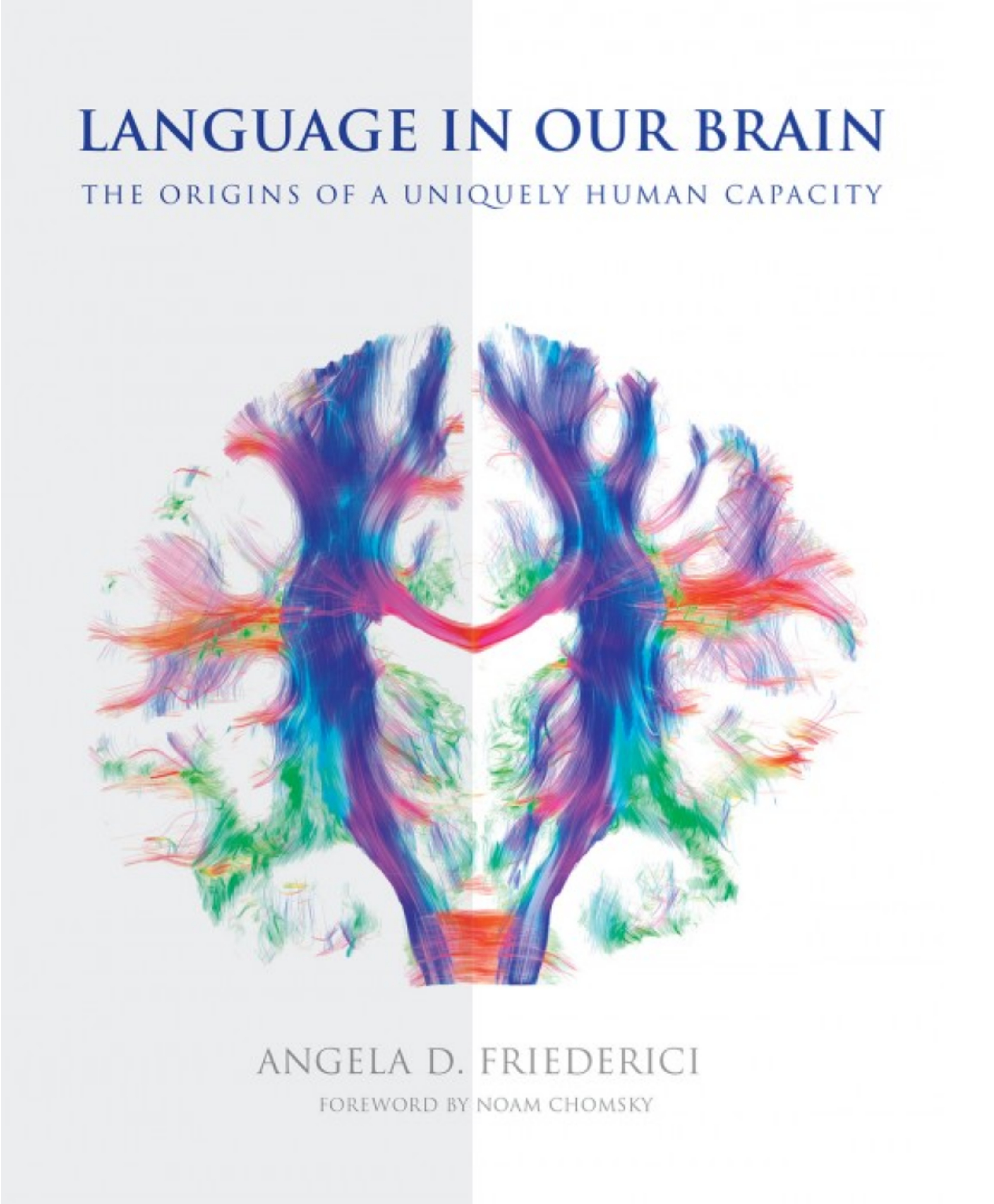
Today:

- Discussion of **[Friederici 2018 book]** Ch 1.1 – 1.5
- ***Discussion of projects***
- Some history and math of language

This and next three weeks: Language

- Next week: Talk on language by Dan Mitropolsky!
- Our work on assemblies and their operations
- Week after that: Talk on NLP by Mike Collins!
- Week after: preliminary project presentations ***(volunteer!!)***
- Plus, reading **[Fr 2019]** Chapters 1, 2 and 3
- ***Week after that: Thanksgiving Eve***

Chapter 1, sections 1 to 5
what have we learned?

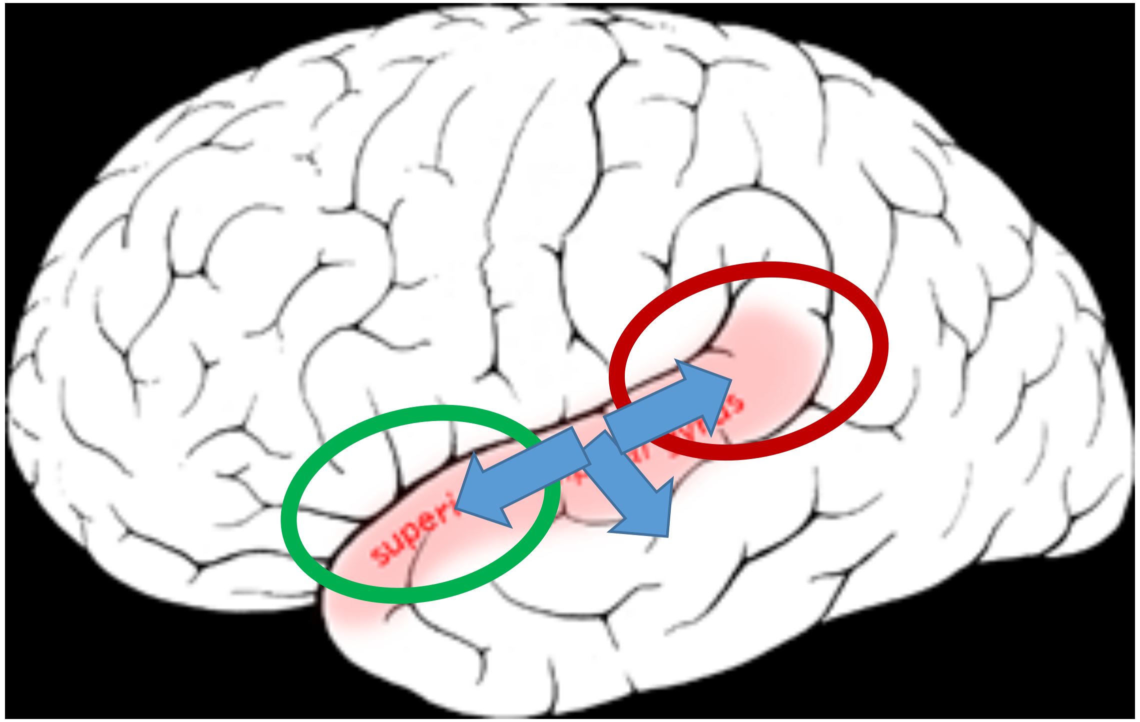


Right off the bat:
“to comprehend an utterance…”

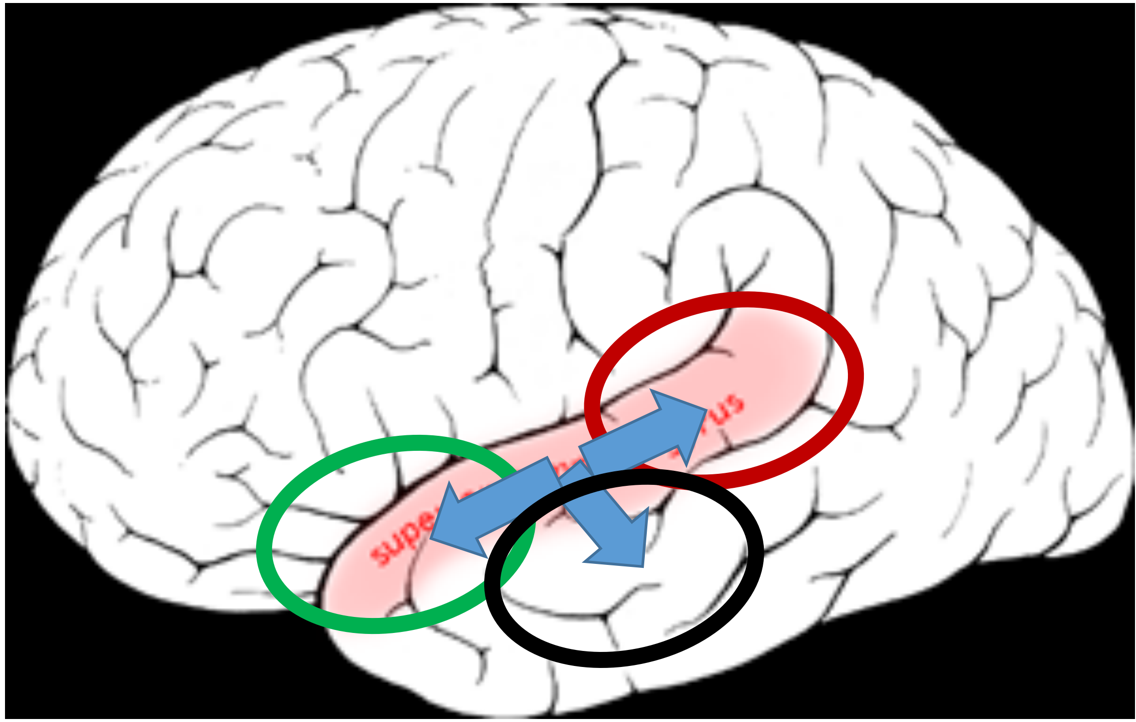
- We are into language ***comprehension***
- (Not generation, for example)
- The basic cognitive model:
- The LH***** builds a syntactic model of what is heard
- It builds a “phase structure” ***(= a tree!)***
- Then integrates syntax and semantics
- (The RH processes prosody: intonation, accentuation)

1.2 Acoustic-phonological processes

Left auditory cortex treats speech sound differently
Propels it to aSTG and pSTG and MTL



1.3 Words and their information
a search for words takes place
-- only real words activate the MTL



1.3. Information about words: the lexicon

- Initial syllable often starts process
- N400 associated with successful lexical-semantic processing
- Many parallel processes seem to be at work
- Word “engrams” or “entries” in the lexicon are hypothesized to have associated attributes accessible by these processes
- Verbs have their argument structure
- The role of MTL and the hippocampus (new words)
- Representation? Memory association? Sparse coding?

1.4 Initial phrase structure (=Tree) Building

- Syntax-first models
- Word search yields word category "high in the lexical entry since it becomes available fast"
- Early left anterior negativity (ELAN) ***120 – 200ms***
- Seems to signal impossibility of building a tree…
- N400 is about semantic violations

1.4 Initial phrase structure (=Tree) Building

- Left frontal operculum: two-words combinatorics
- Broca’s BA44: the initial building of a small tree.
- ***Merge***

1.5: Syntactic processing

- Syntactic complexity – word order, nesting, movement (??)
- Pseudoword sentences vs sequences: ***Broca!***
- Single Merge ***Broca!***
- ***Also, posterior STG!*** (assigning meaning)
- ***The Poeppel experiment*** (cryptically in [Fr] p. 53 first para, to be explained later today)

- Can machines somehow take in a representation of background knowledge when they try to learn a new task? (reference to the human vs DQN)
- Can machines hope to achieve a similar performance on gaming tasks to humans? Can we compare them with a game that humans can't use any background knowledge for?
- Is there any evidence that the prefrontal cortex performs a form of reinforcement learning similar to Meta-RL?
- How does memory influence reinforcement/reward-based learning in the brain?
- In "learning to learn" the speaker talks about dopamine reaction and the method in which humans optimize for 2-arm bandit problem. Is this process optimized to the theoretical limit? Is the decision to continue with one of the two subconscious?
- In the reading there was a lot of info surrounding current linguistic understanding of grammar.
- Are there any other theories worth trying? Why have we decided this problem is complete and we just need to discover how it's implemented?
- How much more complicated do newer DQN and other reinforcement learning variants vary from basic DQN? I'm guessing they've done a lot with adding extra memory, etc.
- What are the energy based models that have been mentioned multiple times lately? Do they seem like a promising area?
- I'm very curious how brain systems for language map onto deaf people interpreting sign. Are there studies about specific streams of interpretation like the ones in this chapter?
- How does the human brain reason about discount factors? Is it more appropriate to think of our meta-level learning tasks as finite or infinite horizons? Do we use different discount factors for different tasks?
- What's the right language for talking about abstractions? Can most tasks be reduced to questions about relations of objects over time, where there is a goal about future states of relations btw objects, and awareness (or learning) of how acting on objects affects relations?
- I am wondering whether they can generalize the experiment result to the setting with more than 3 arms (rather than 2). Will RL outperform well-developed algorithms like UCB / Thompsons samplings? On the other hand, how about comparing with humans? Does RL still share similarity with the human learning process?
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- Is there any difference in the brain to process a native language vs a foreign langauge? Since we care more about grammar when learning a foreign language, will it affect the way our brain parses it?
  What are the MLE/MAP perspectives to the RL derivations?
- Are more complicated deep RL architectures more prone to overfitting
- What’s the neurobiological explanation behind some potentials having positive vs negative spikes?
- Are there neurogimaging studies done on folks without language (eg. Genie) compared with primate imaging studies that have learned some basic signs? Perhaps early processing may be similar, but processing stops around level of syntax and perhaps with the primates, instead of a jump to semantic processing?
- Are language concepts represented like simple and complex cells? As in, could the language pipeline up through the anterior temporal lobe function as a general processing layer, and we build concepts through ands/ors/unions/intersections of concepts? Eg. is Paris something like city + France + capital etc, and we form new dendritic connections btw concepts when we make new associations?
- The chapter says that “the processes in language are assumed to run in a partly parallel, but cascadic manner .” How does the brain’s neural network handle asynchronous behavior without a clock/flip-flips that make classical computation (and ANNs) work?
- Is there any equivalent in deep-nets to the nesting of different frequency bands that Friederici mentioned, that also reflects phonemic, syllabic, phrasal processing?
- I noticed that the studies mostly focused on English and German, with one study in Japanese - might the tonal characteristics of other languages lead to different insights into the relationship between the two main subprocesses especially at different time-steps?
- The processing pathway of Friederici sounds suspiciously like architecture of human engineered speech processor. How is it possible to know, for example, that phonemes are looked up in a neural word-dictionary when it can’t be observed? I would predict that if these postulated modules are incorrect, attempting to localizes them would result in activation in distant parts of the brain.
- Much of the fundamental theory seems to be built around a small number of language families (Indo-Euro, Japonic, Semitic, Sinitic). For instance author claims “English and German … differ quite dramatically with respect to required syntactic processes”. As someone who knows several languages, including these two, I consider this to be very questionable. What efforts are being made to include pseakers of languages with less representation in neural substrate studies?

- Matt Botvinick made an interesting connection btw dopaminergic learning in the brain and meta-RL. But why focus on meta-learning as opposed to just learning with delayed rewards? Is RL really necessary for meta-learning?
- How does the brain deal with garden path word segmentations and syntactic parses? What does beam search look like in the brain?
- If there was a human similar to patient HM who was not capable of accessing prior experiences when learning new scenarios, would they take as long to learn as DQN does for the Atari game?
- If monkeys were able to learn to pick perfectly without rewards (Botvinick talk) after a given number of experiences, than what is the role of reward in learning?
- Can rL be combined with bio-plausible ANNs (such as spiking NNs) and still be as efficient for training?
- Friederici mentioned that there are no current studies that show the relationship between part of brain for lexical-semantic info and the other part for conceptual-semantic info. What are possible theories for how lexical and conceptual semantics are reconciled in the brain?
- A lot of studies seem to show that there is a difference in the results in different languages. But they tend to focus on first language, and people who only have 1 native language. How does this apply to people with multiple native languages? Could differences in how the brain processes sentences manifest in slight differences iin understanding of the meaning / interpretation of a sentence?
- Is there some kind of muscle memory in the brain to identify what is / isn't a word and is it encoded in the brain? Over time does one lost the ability to differentiate between sounds that they are not used to like Japanese /l/ and /r/? Is it done like how we prune branches of neurons? Can one recover the ability to distinguish different sounds in later periods of life?
- Due to limited short-term memory, can we put an upper bound on complexity of comprehensible sentences? Anything beyond a certain length is either too complex for comprehension?
- The RNN reacts to volatility, and the brain gets a large reaction out of unexpected results. It appears that we get most stimulus from being wrong. In an RNN should positive reward have a different learning rate than error?
- If machines master learning to learn (machines' ability surpasses humans) would we be able to learn everything? This is obviously useful, but what shortcomings could arise?
- Is the cognitive model for auditory language comprehension described in the textbook adequate enough? Can we successfully model it artificially?
- Can we map different layers of NNs to different parts of the brain when it comes to language processing?
- Can we do an example run through of the neural language process, beginning at auditory input all the way to sentence comprehension? Both with respect to where and when different subprocesses take place?

Language:
Some history, and some math

How did language come about?

- Some 3 MYBP the homo group separated from the chimps
- Habilis, floresiensis, neanderthalensis, heidelbergensis, denisovan, erectus, ergaster, sapiens
- Only sapiens seems to have had language
- Evidence: lack of trappings of symbolic behavior such as figurative art
- 80 KYBP: first figurative art in Africa
- Did language come about the same time?

How language came about: the challenges

- 1866: French Academy bans discussion of the origin of language
- “It is an irresistible question because it is about us. But this does not make it a scientific question. If there is no way to find out by science, then there is no way.” Noam Chomsky
- ''If you don't have a related species with a similar trait you have the problem of novelty.'' Richard Lewontin
- Is human fascination with language an exercise in specism?
- ***Pinker: imagine elephants admiring their trunk…***

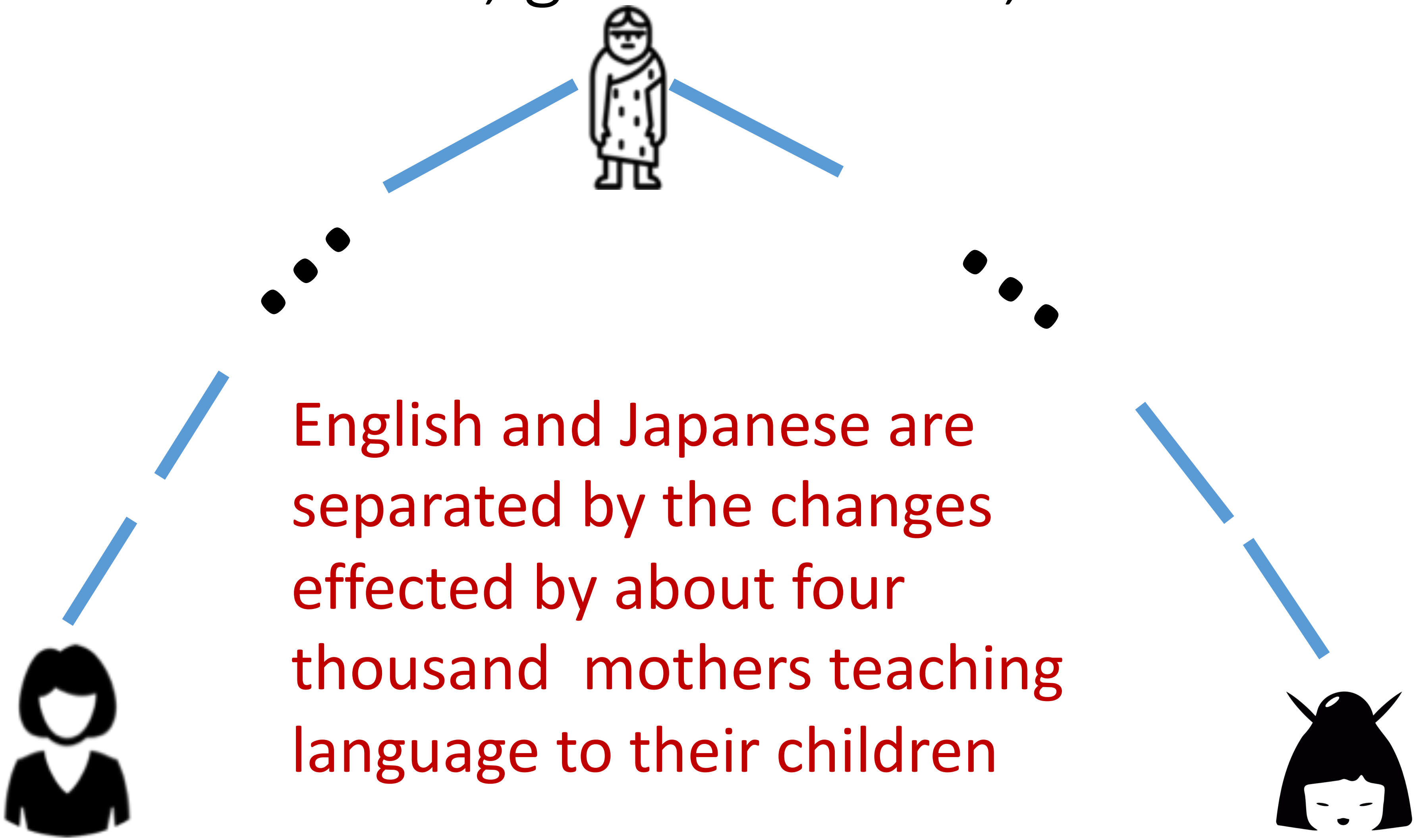
How language came about: Speculation

- Was there a cognitive/neural Big Bang?
- Or gradual progress?
- Perhaps we had language (in some weak sense) far before 80 KYBP
- Maybe around 500 or even 800 KYBP
- Perhaps homo sapiens gestured for a very long time
- C Corballis ***The gestural origin of language*** Wiley 2010
- Q: What is the "weak sense"?
- PA: Hierarchically structured thought? Inner language?

What is needed for language?

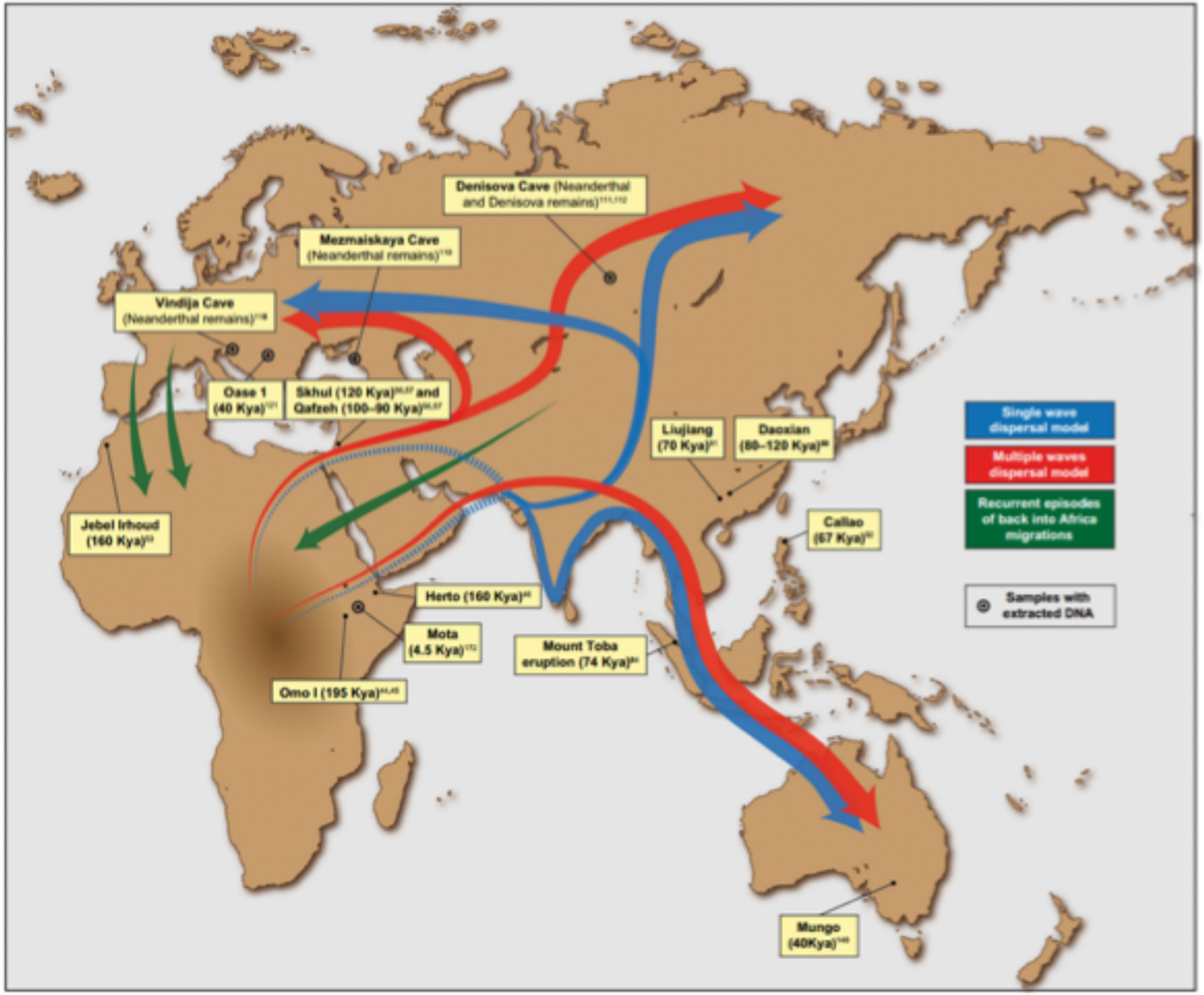
- Is a prohibitively sophisticated muscular system in the mouth/larynx/face/tongue necessary?
- (Or is it all in the Mind?)
- When did we become capable of competent speech?
- Biologists seem to think that many apes are ready…
- MC Corballis thinks that we may have switched to speech long after we could have…
- But why was language of thought an evolutionary advantage?

A tale of two island girls
and their mothers, grandmothers, etc.

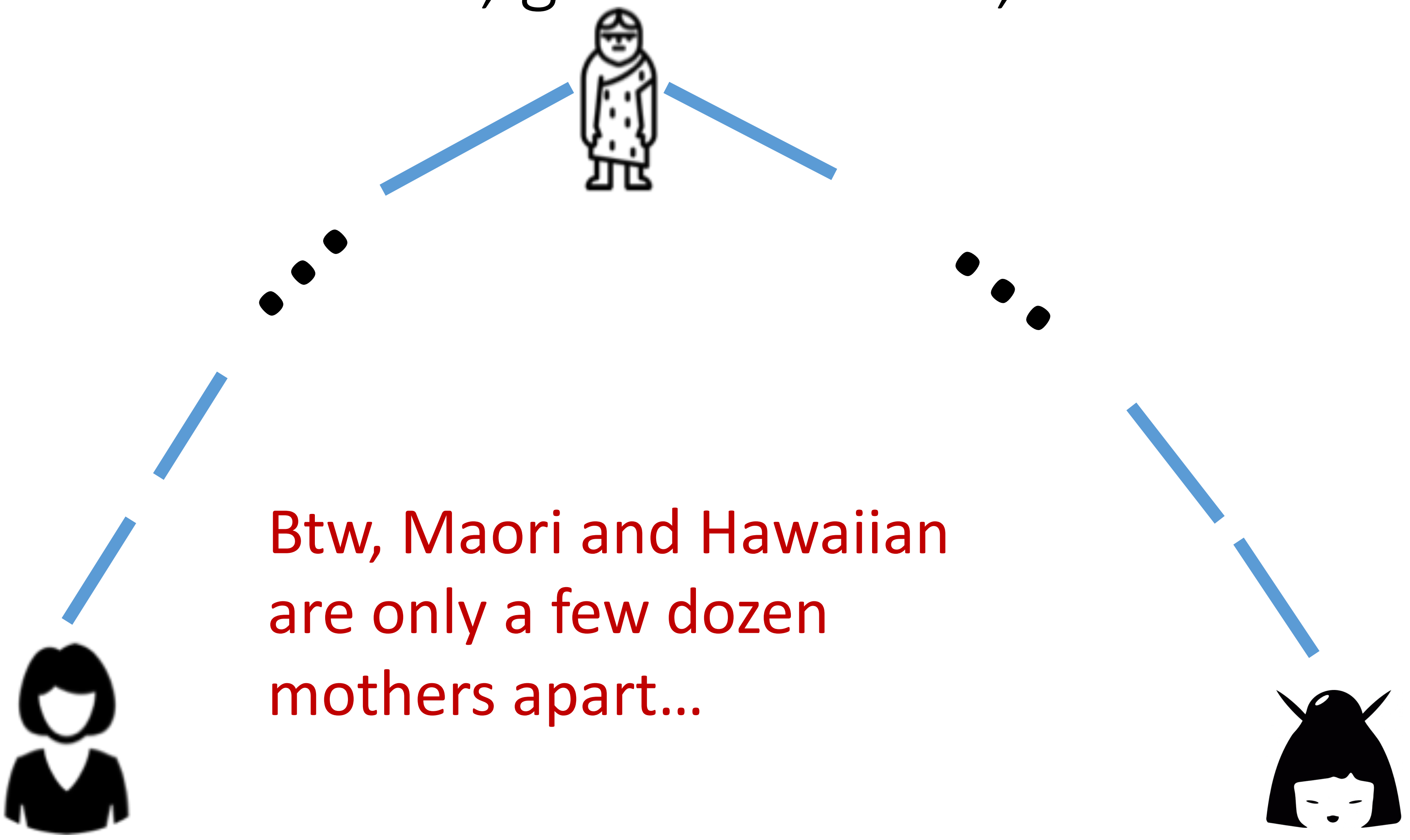


Out of Africa

- 80 - 70 KYBP
- Europe: 40 KYBP
- Americas: 20 KYBP
- Arctic: 10 KYBP
- Polynesia: 2 KYBP
- **Single migration?**
- **Or multiple?**



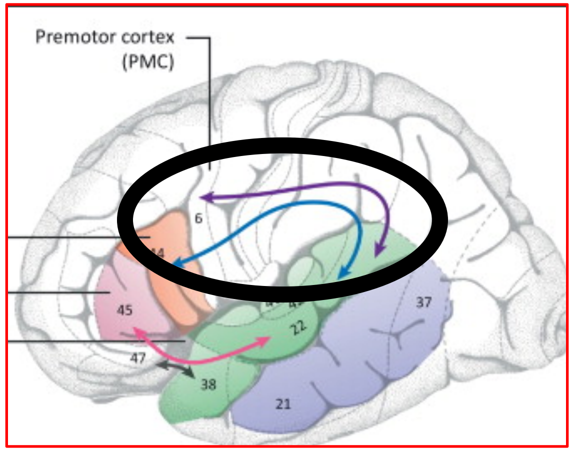
A tale of two island girls and their mothers, grandmothers, etc.

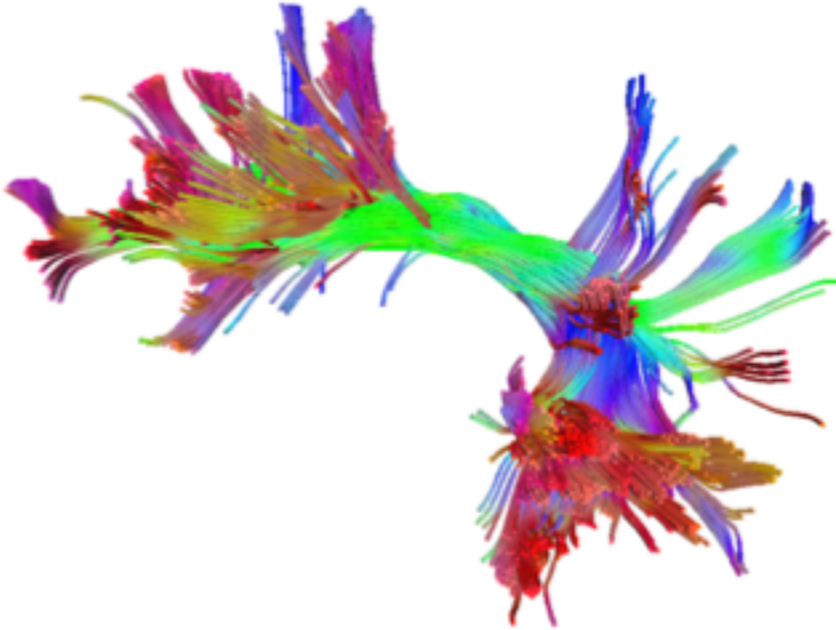


Btw, Maori and Hawaiian are only a few dozen mothers apart…

Was there a neural Bing Bang?

- Our left and right hemispheres are anatomically asymmetric
- Seems to be specific to humans
- Main locus of asymmetry: the ***arcuatum fasciculum***

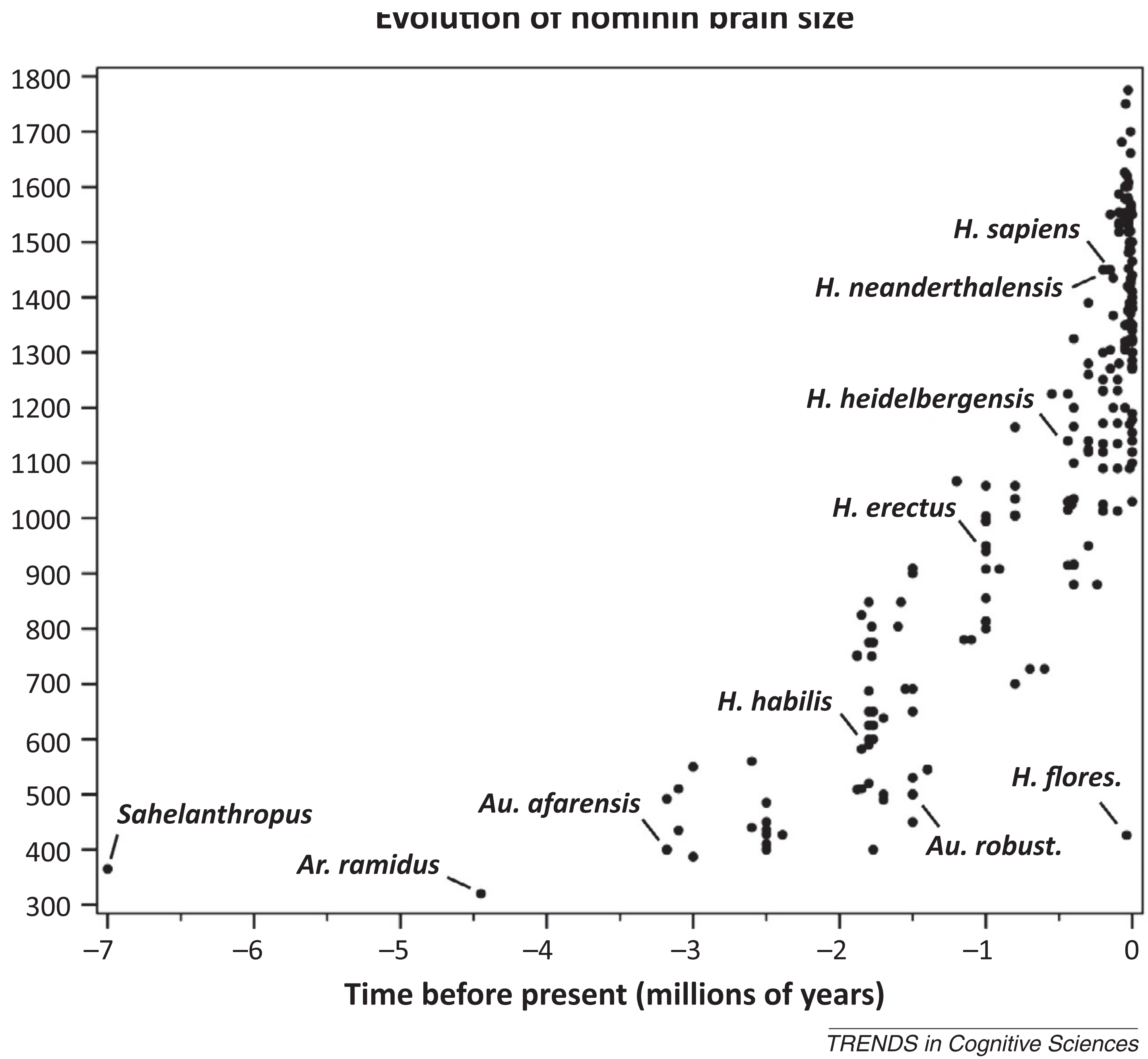


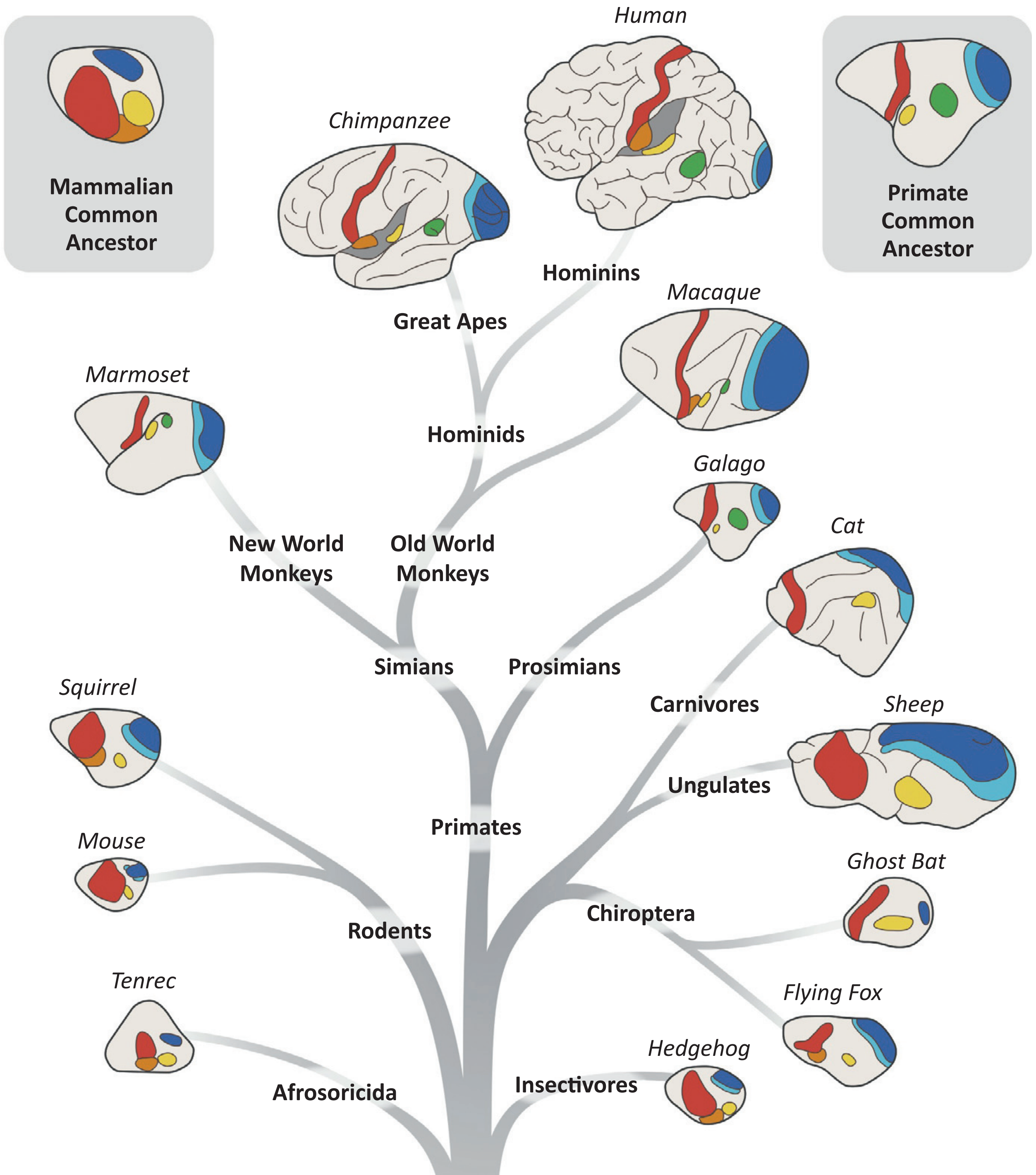
Was there a neural Bing Bang?
(and what is a neural Bing Bang?)

- Our left and write hemispheres are physiological asymmetric
- Main locus of asymmetry: the ***arcuatum fasciculum***
- Left is dominant for 90% of right-handers, the opposite for *female* left-handers
- Degree of lateralization: 60% extreme, 20% mild, 20% almost none
- What happened since the chimp?

Brain size evolution [Buckner and Krienen, 2013]



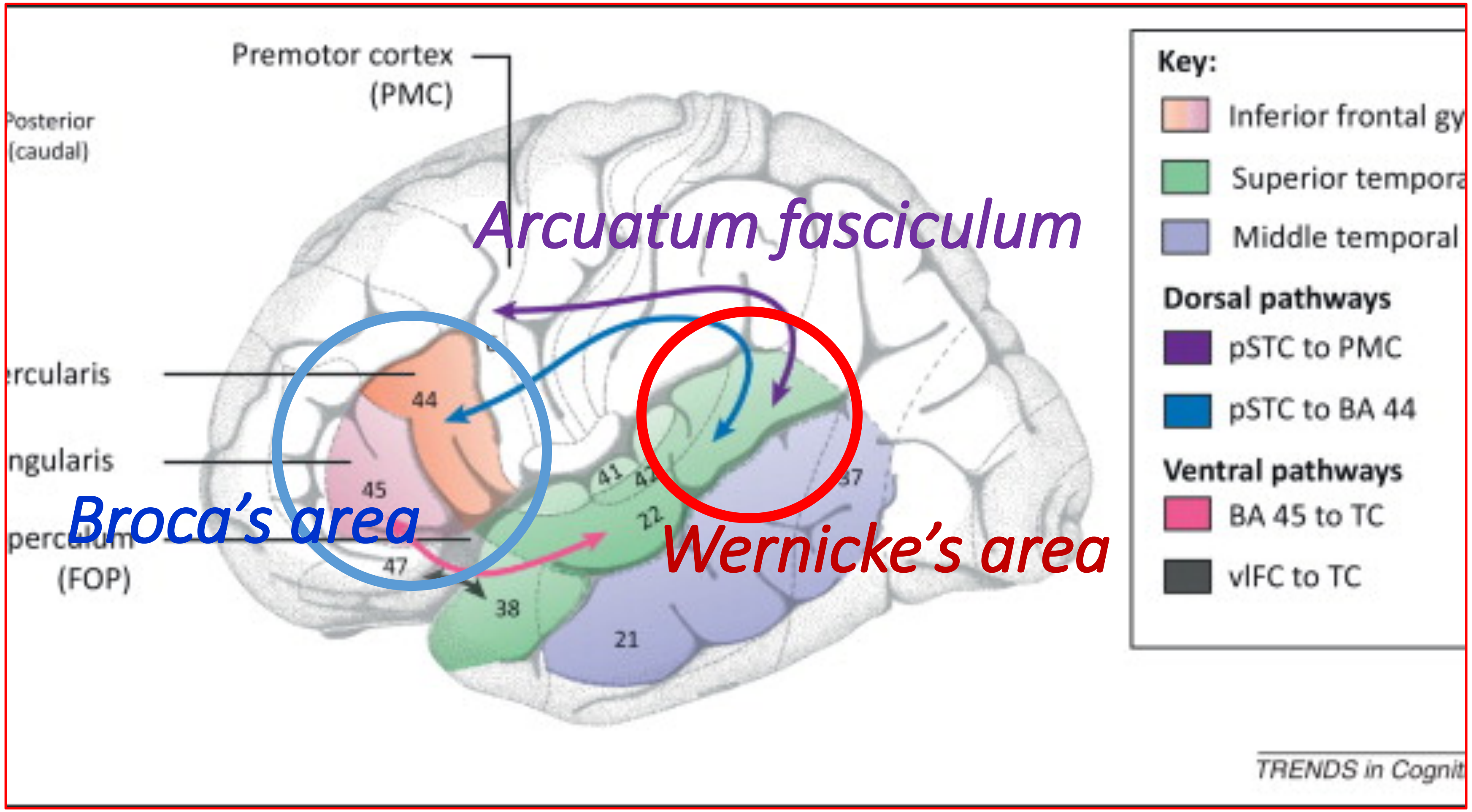
The rise of the association cortex



Language and the Brain: history

- 1830s: language must be in the left hemisphere
- 1870s: Broca (production), Wernicke (comprehension)

The Language hemisphere



Language and the Brain: history

- 1830s: language must be in the left hemisphere
- 1870s: Broca (production), Wernicke (comprehension)
- Revised in 1970s: Broca (syntax, grammar), Wernicke (word meaning and selection)

Broca aphasia

- poor or absent grammar
- difficulty forming complete sentences
- “Cup, me” instead of “I want the cup”
- more difficulty using verbs than nouns correctly
- difficulty repeating what has been said by others
- trouble with writing sentences, reading
- problems with full comprehension
- difficulty following directions
- frustration

Wernicke aphasia

- string words together to make sentences that don’t make sense
- make up words that have no meaning
- unaware of the mistakes in their speech
- deliver words in a normal melodic line, even though the content may not make any sense
- articulate their words normally
- have difficulty repeating sentences
- add words when trying to repeat someone
- interrupt others and speak rapidly

Conduction aphasia

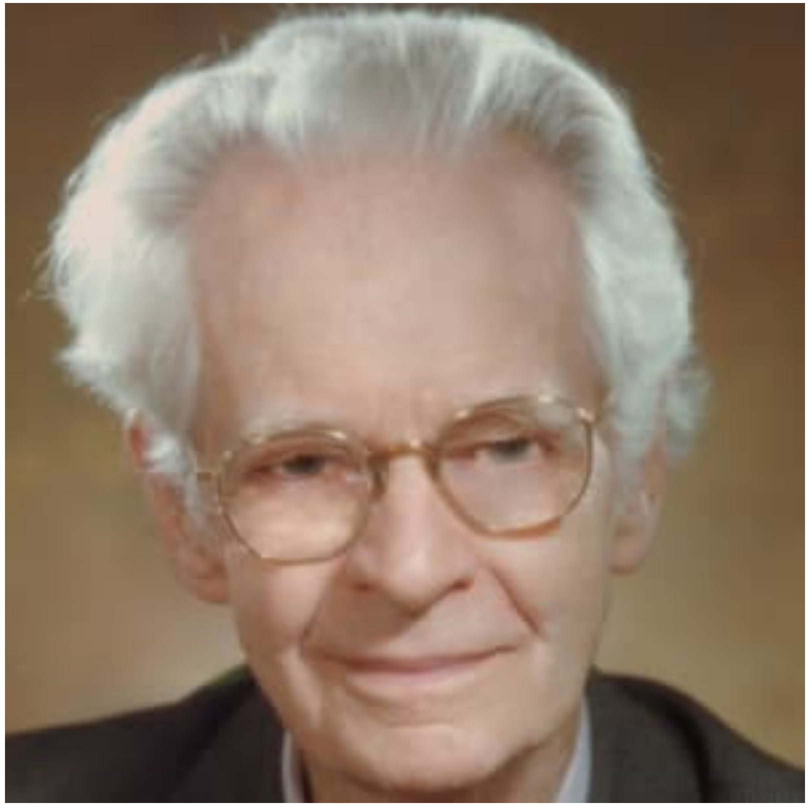
- Repeat after me:

  “I do not suffer from conduction aphasia”

- Lesions in arcuate fasciculus OR Broca OR Wernicke…
- But this is the only symptom of AF lesion

What does this mean?

Meanwhile in Cambridge, Mass, ca 1960 : The Skinner – Chomsky debate



The Skinner - Chomsky debate

- Or the behaviorist – structuralist debate
- Skinner believed, and showed by experiments, that behavior is the result of received reinforcements
- Influenced by J. Locke’s tabula rasa
- His 1958 book “Verbal behavior” went a bridge too far
- Chomsky’s devastating critique is far better known and accepted than the book

Chomsky’s theory

- Language is innate
- Enormous gap between stimulus and competence
- Grammar is innate and universal
- Children only have to tune it with “details” (parameters)
- What makes us different: Recursion and infinity
- The minimalist program (1990s): all you need is merge

Grammar

S → A V P (agent, verb, patient)

A → Alice | Bob | Chris | David

V → loves | hates | collects | enjoys

P → children | jewels | animals | toys

The sentence generation algorithm:

Start with S

Keep replacing a symbol in the current string with rhs of rule that has the symbol on lhs, until no such possibility

Recursion and infinity

S→ A V P

S → S and S

A → Alice | Bob | Chris | David

V → loves | hates | collects | enjoys

P → children | jewels | animals | toys

Recursion and infinity

S→ A V P

S → A said that S

S → S and S

A → Alice | Bob | Chris | David

V → loves | hates | collects | enjoys

P → children | jewels | animals | toys

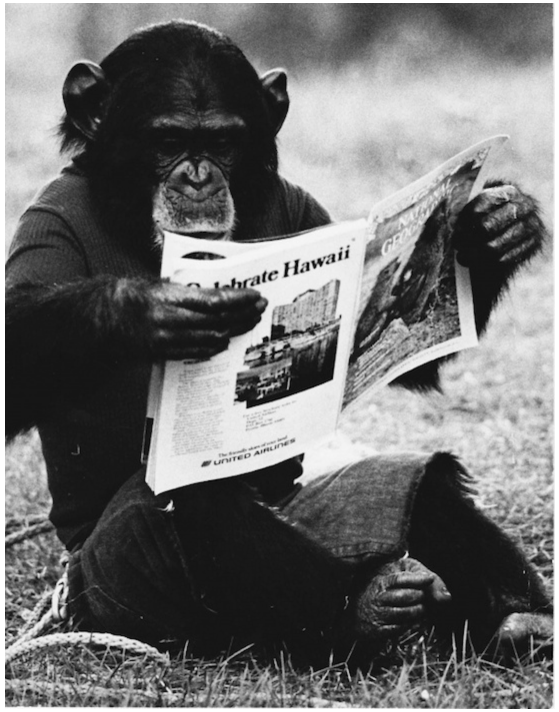
A propos recursion and infinity: the Pirahã controversy

- No number words, eg for “one”
- “few” and “more”
- No color words
- Daniel Everett 2010:

“No recursion!”

Besides universality:
how about exclusivity?

Nim Chimpsky



Koko the Gorilla

Song birds

The Chomsky hierarchy

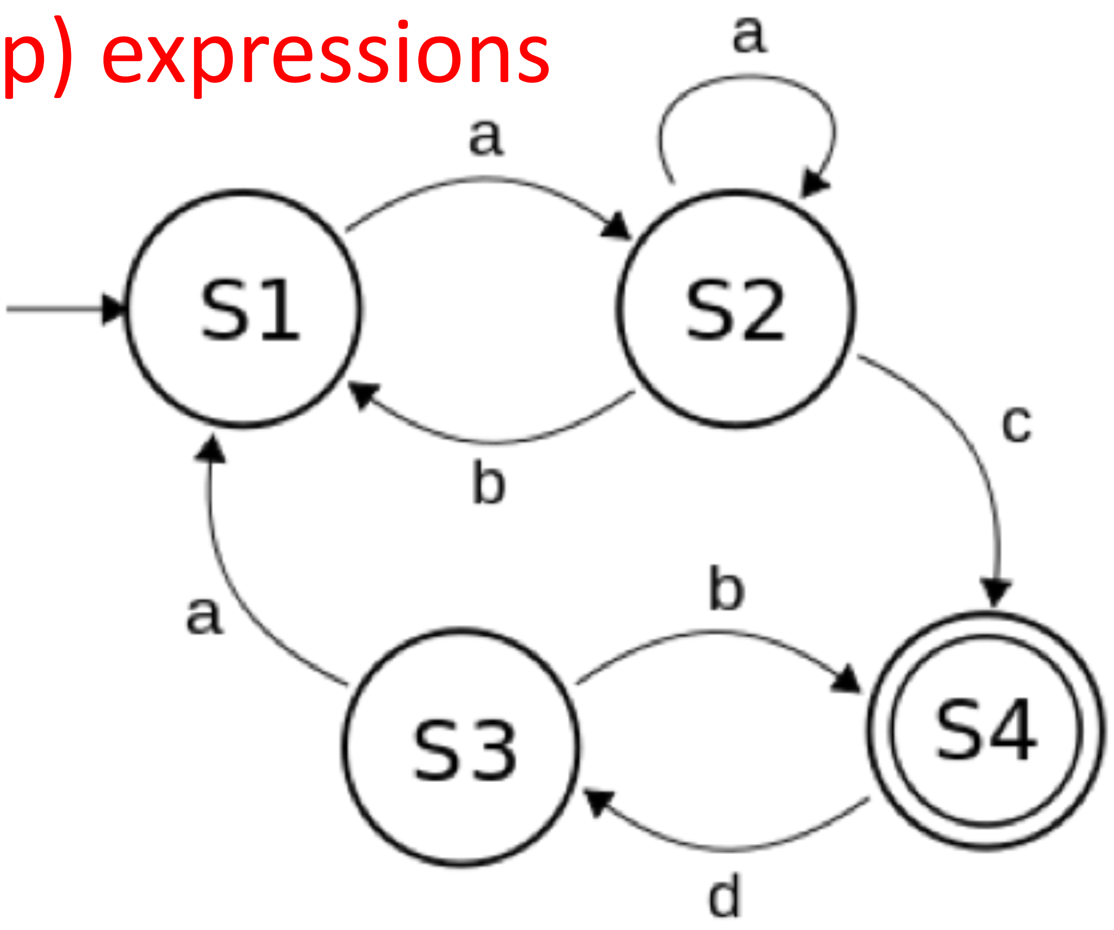
Four increasingly general kinds of (recursive, infinitary) grammars (restrictions on rules rules)

(Assume only caps occur in lhs)

1. Regular or right-linear: A → a b B
2. Context–free: S → a B b S
3. Context-sensitive: SB → SabB (rhs no shorter than lhs)
4. General: SDD → aBa

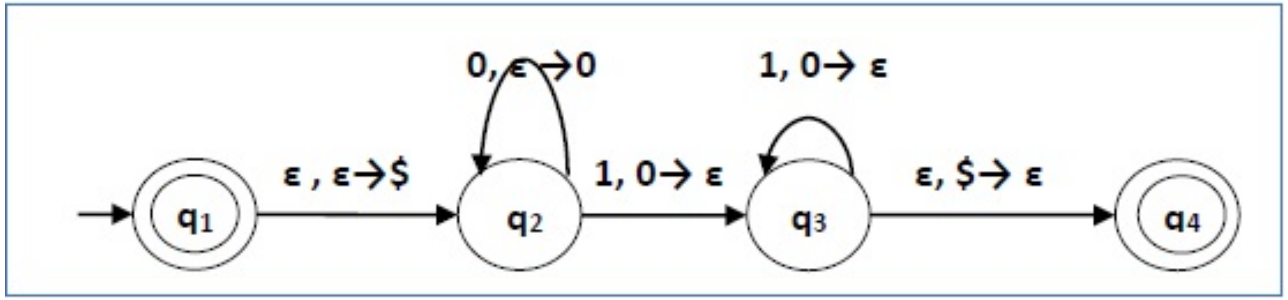
Grammar type hierarchy induces a machine/recognizer hierarchy

- Right linear grammars A → abB correspond to finite state machines or regular (grep) expressions
- One-way reading, finite states
- E.g., (a+b)aa(bb+ab)*
- **But not $\{a^n b^n : n \geq 0\}$**



The Chomsky hierarchy II

- Context-free (or phrase-structure) grammars $A \rightarrow bBA$ correspond to nondeterministic pushdown automata
- Finite states, one-way reading, but can also look at/modify the top of a stack
- E.g. $\{a^n b^n : n \geq 0\}$, palindromes, Python,…
- **But not $\{ww$: w a word $\}$, or $\{a^n b^n c^n : n \geq 0\}$**



PDA for L= $\{0^n 1^n \mid n \geq 0\}$

Recall…

ABABABAB..: regular

vs

…AAAAABBBBB…: context free

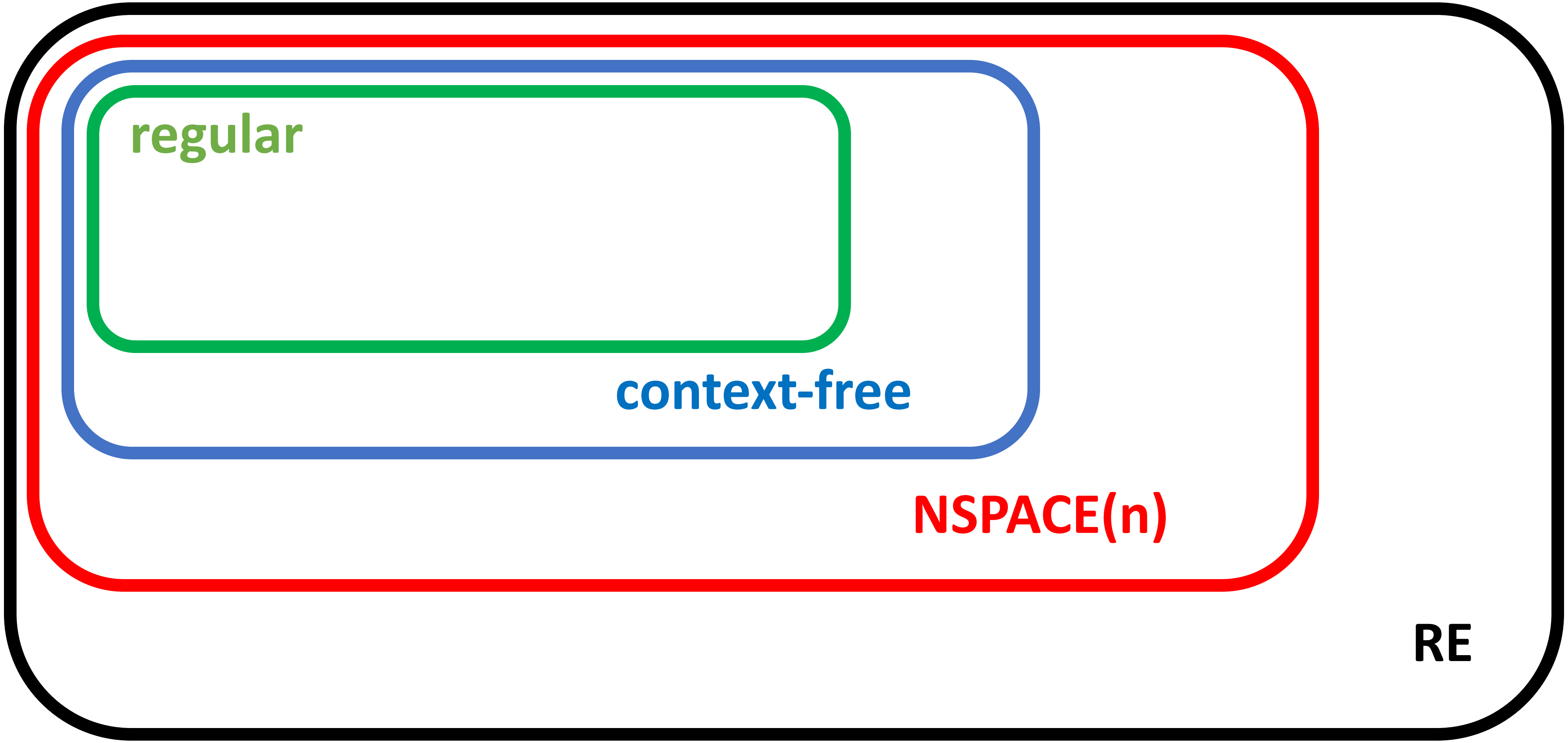
The Chomsky hierarchy III

- Context-sensitive (or non-shrinking) grammars AB → bBab correspond to nondeterministic Turing machines that run in linear space (LBA's)
- E.g. {ww: w a word }, $\{a^n b^n c^n : n \geq 0\}$,…
- **But not {M: M is (the description of) a Turing machine destined to halt}**

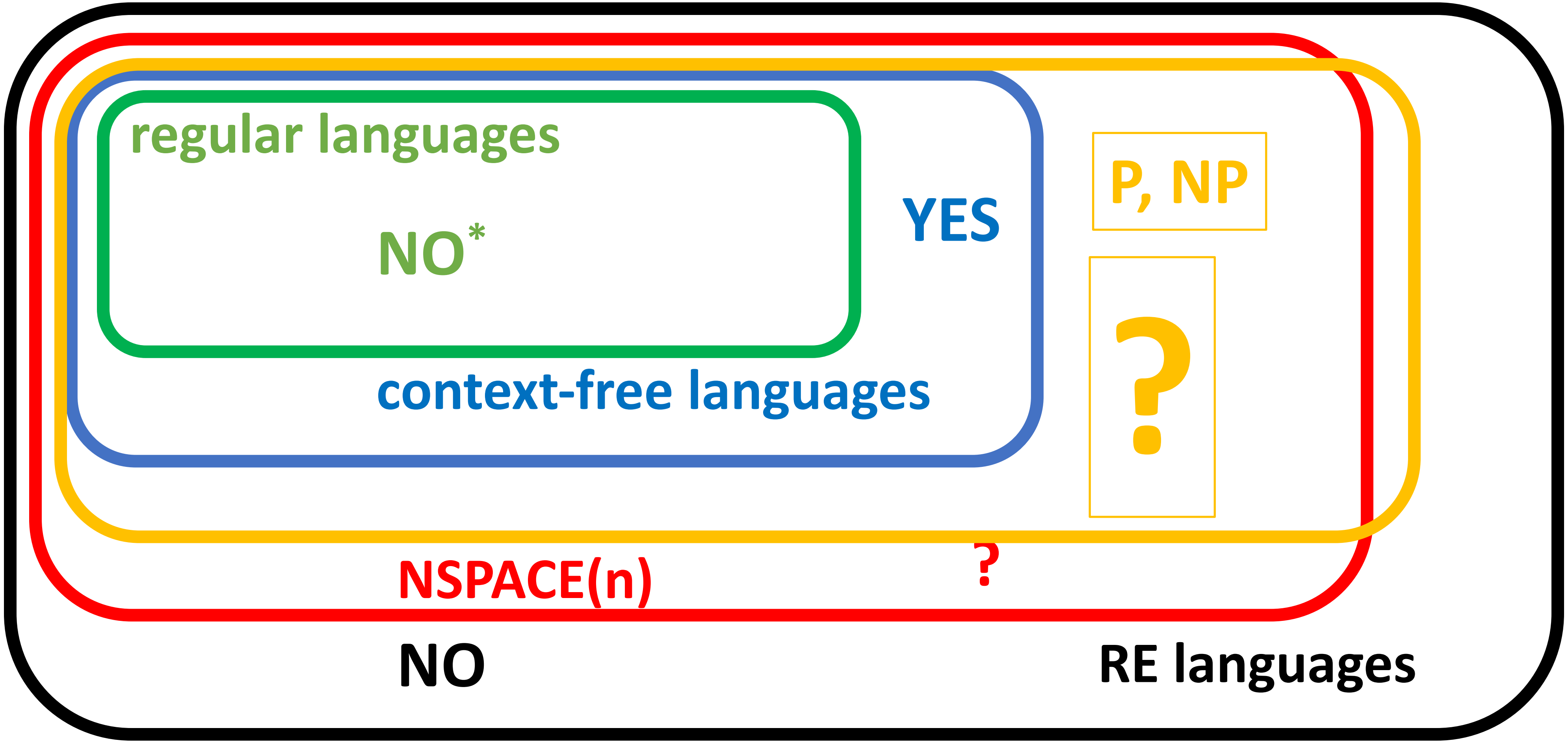
The Chomsky hierarchy IV

- Unrestricted grammars correspond to Turing machines that accept by halting
- All recursively enumerable (RE) languages: decision problems "solved" by Turing machines that reject by never halting…

The Chomsky hierarchy



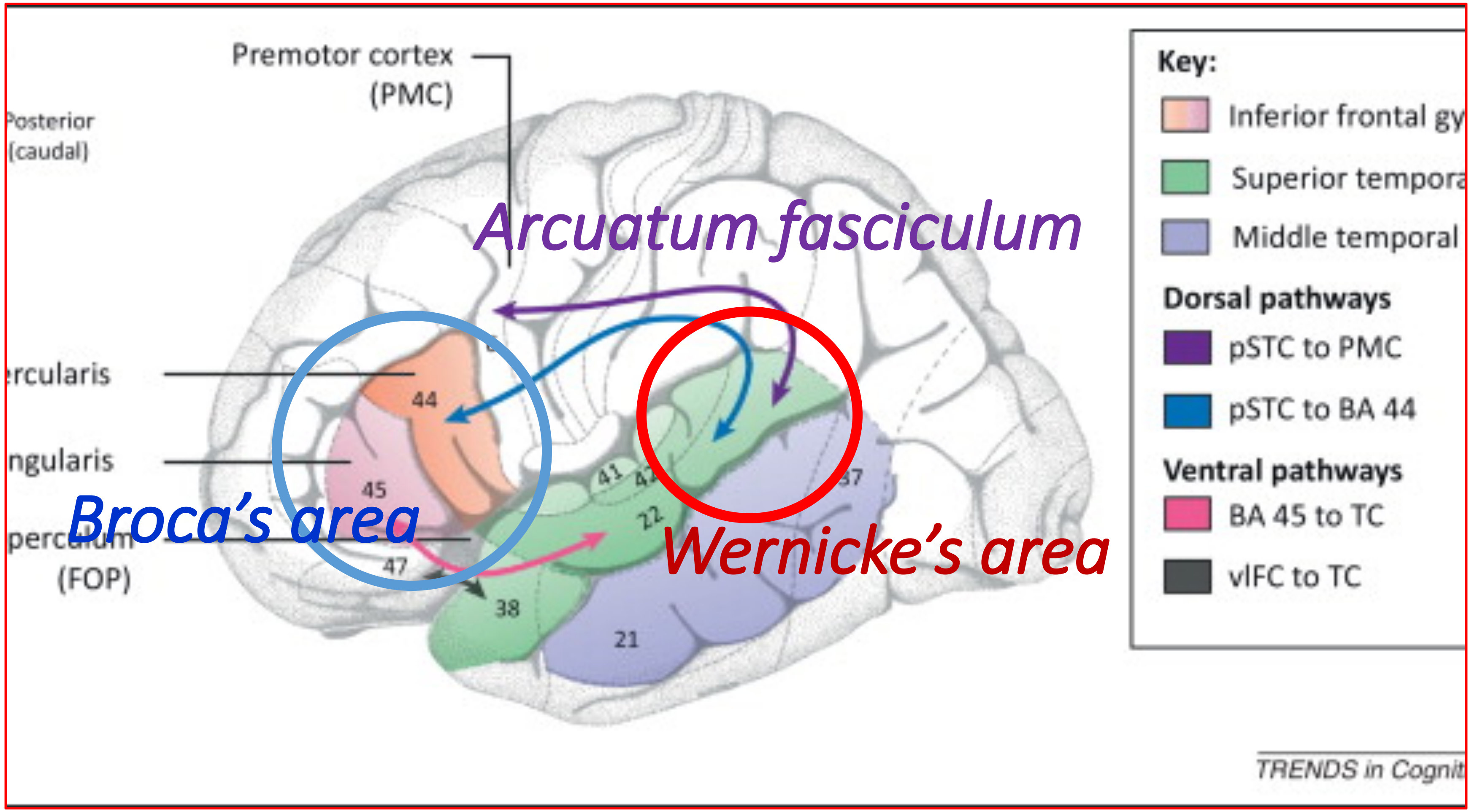
The Chomsky hierarchy:
Nondeterminism makes a difference?



The Chomsky hierarchy

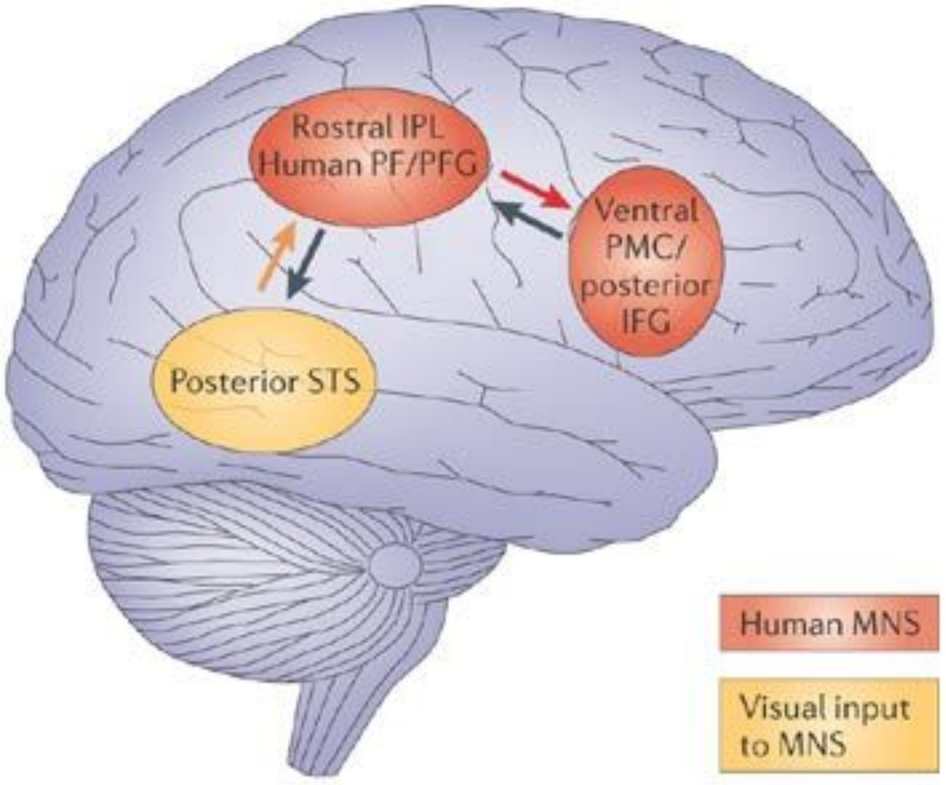
- Tremendous influence on CS
- Much of the research agenda in the 1960s TCS
- Helped us understand how to write compilers
- Trained us for the real problems to come – most importantly, P vs NP…

Meanwhile, in the language hemisphere: a deluge of brilliant experiments



Incidentally:
the mirror neural system

- Helps us understand the actions and intentions of others (and imitate)
- In humans and primates
- (and a little in songbirds…)
- Seems closely related to language (look where it sits…)
- Cf: Corballis (and signing precursors) Lakoff (language hijacks motion)



…this text pulsates at four Hertz, the rhythm of four beats per second, and I believe that you may find this rhythm a bit familiar, because it coincides with the rhythm of speech, and I don't mean my speech but speech in general, by all speakers, in all languages…

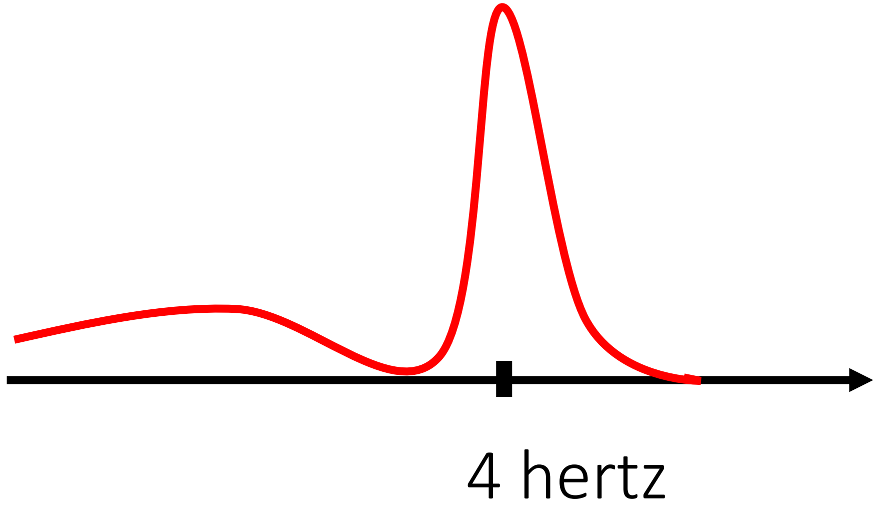
θ

…in contrast, this text pulsates a dozen times faster at fifty Hertz, the rhythm of spiking neurons in the Brain…

γ

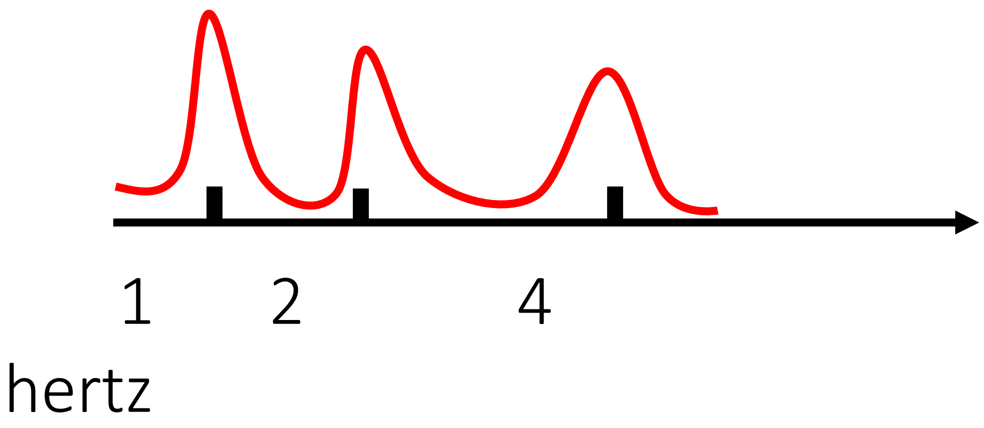
The [Poeppel 2016] experiment

fret ship hill give true melt fans blue guess hits then cats

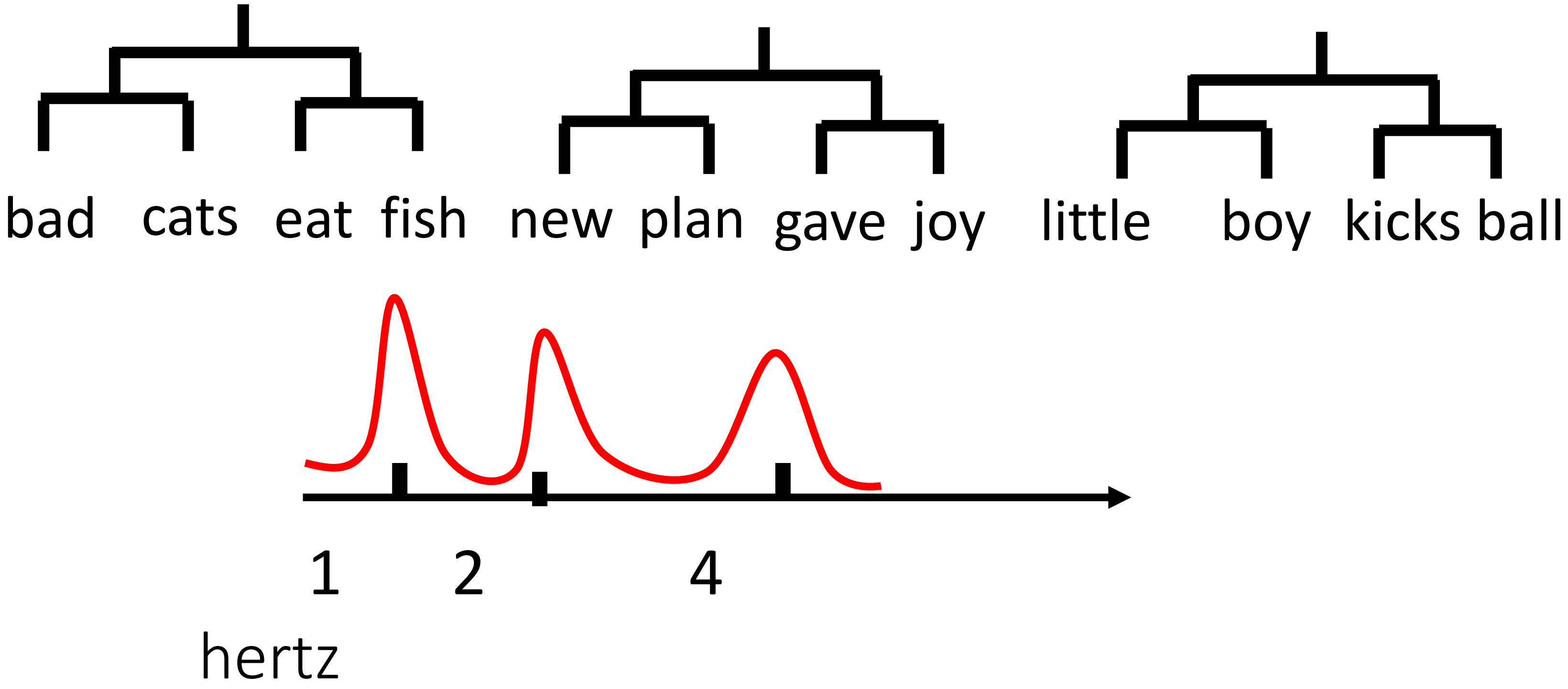


The [Poeppel 2016] experiment, stage II

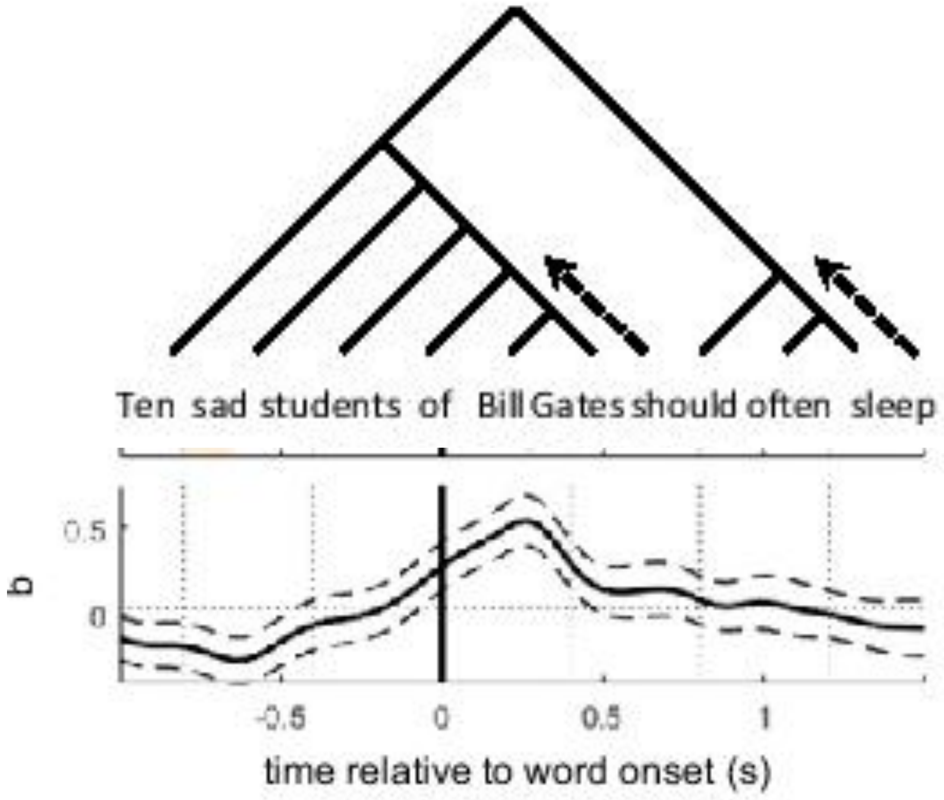
bad cats eat fish new plan gave joy little boy kicks ball



My interpretation



[Nelson...Dehaene, PNAS 2017]



[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”

But…

- By what mechanism can each tree-building step be carried out by a dozen or so spikes?

- 12 ~ gamma / theta

We shall come back – and spend a lecture – on this

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