



# Emergence of the Sentient Web and the revolutionary impact of Cognitive AI

Dave Raggett <[dsr@w3.org](mailto:dsr@w3.org)>

08 June 2020

ISO/TC 211 50<sup>th</sup> Plenary meeting  
WG4 Geospatial Services

# Where we are now ...

- RDF is a successful framework for representing data and metadata
  - Large suite of standards including SPARQL, OWL, SHACL, Turtle, JSON-LD, ...
    - JSON-LD 1.1 is currently a W3C Proposed Recommendation
    - Data Catalog Vocabulary (DCAT) version 2, W3C Recommendation (Feb 2020)
    - Web of Things W3C Recommendation for abstraction layer for digital twins (April 2020)
  - Plenty of work on ontologies and wide deployment of *schema.org* vocabs
    - W3C/OGC standards for SSN/SOSA, ETSI SAREF suite for IoT
- Growing industry interest in Labelled Property Graphs (LPG)
  - Easier to work with n-ary relationships
  - No need for reification to annotate graph edges
- LPG is weak on interoperability across different vendors
  - ISO work on LPG extensions to SQL and new work item on GQL query language
- Easier RDF initiative seeking to make semantic technologies based upon RDF easier for the average developer (the middle 33%)
  - Desire for simpler solution for graphs and rules, including lists as arrays

# Chunks as an amalgam of RDF and LPG

*Inspired by work in Cognitive Psychology and Neuroscience*

- Chunks as collection of properties whose values name other chunks
  - Values are names, numbers, true, false, quoted string literals, ISO8601 dates, or comma separated lists of values
  - Context chains for handling multiple perspectives
  - Simple mapping to RDF for integration with existing systems
- Simple syntax – simpler than JSON-LD

```
friend f34 {  
  name Joan  
}  
friend {  
  name Jenny  
  likes f34  
}
```

```
dog kindof mammal  
cat kindof mammal
```

is equivalent to

```
kindof {  
  subject dog  
  object mammal  
}  
kindof {  
  subject cat  
  object mammal  
}
```

- Where *friend* is a chunk type, *f34* is a chunk identifier, *name* and *likes* are property names, *Joan* and *Jenny* are also names.
- *likes f34* signifies that Jenny likes Joan via the link to the chunk for Joan.
- Missing chunk identifiers are automatically assigned when inserting a chunk into a graph
- Uses line break or semicolon as punctuation

Chunks correspond to activation across bundles of nerve fibres, see Chris Eliasmith's work on [semantic pointers](#)

# Blending Symbols with Statistics

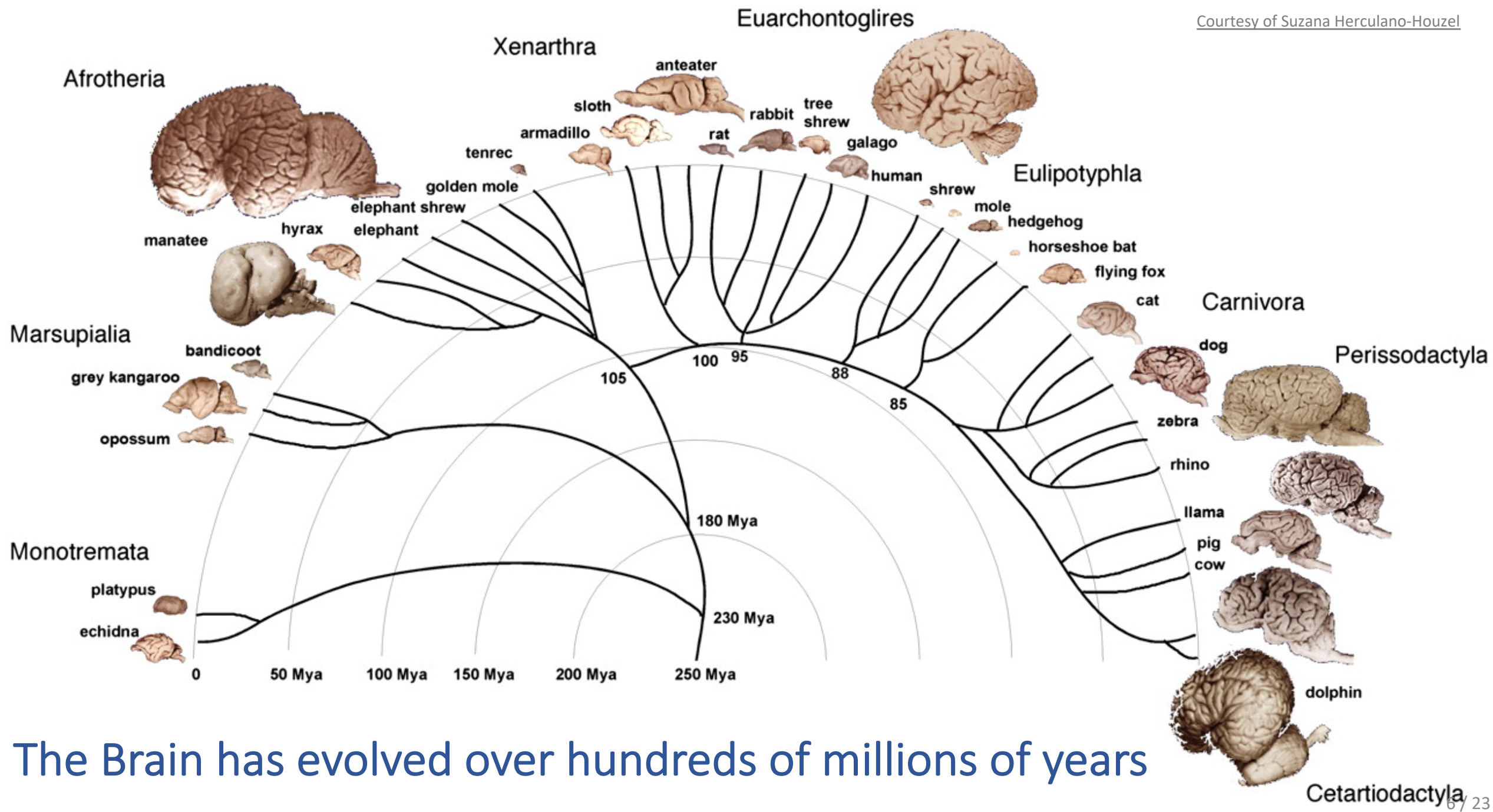


- Traditional approaches to handling data struggle in respect to the uncertainty, incompleteness and inconsistency commonly found in real-world situations
  - This exacerbates the cost for preparing and cleaning data prior to analysis, a major bugbear for data science
- Remembering what's important based upon prior knowledge and past experience
  - Data recall is like web search engines that determine which matches are most likely to be useful as distinct to all the rest
- Machine learning with relatively few examples, just like humans!
  - Unlike *Deep Learning* which starts from scratch, requiring huge numbers of training examples, and lacks salience, making it brittle and easy to fool
- Forms of reasoning that rely on statistical considerations
  - e.g. abduction which seeks explanations of observed behaviours
- Graph manipulation for operational semantics rather than formal semantics and logical proof
- Relational databases are now giving way to graph databases, and will in turn give way to cognitive databases that combine graph data, statistics, rules and graph algorithms
- **Sentient Web**: the combination of the IoT and Cognition to enable ecosystems of smart services
  - Sensing + reasoning federated across the Web

# Cognitive AI



- In short, Artificial Intelligence inspired by advances in the cognitive sciences
- In other words, we would do well to borrow from nature when it comes to building AI systems
- We can mimic nature at a functional level using conventional computer technology without having to implement cognitive agents in terms of artificial neurons
- There are many potential applications of cognitive agents for human-machine collaboration

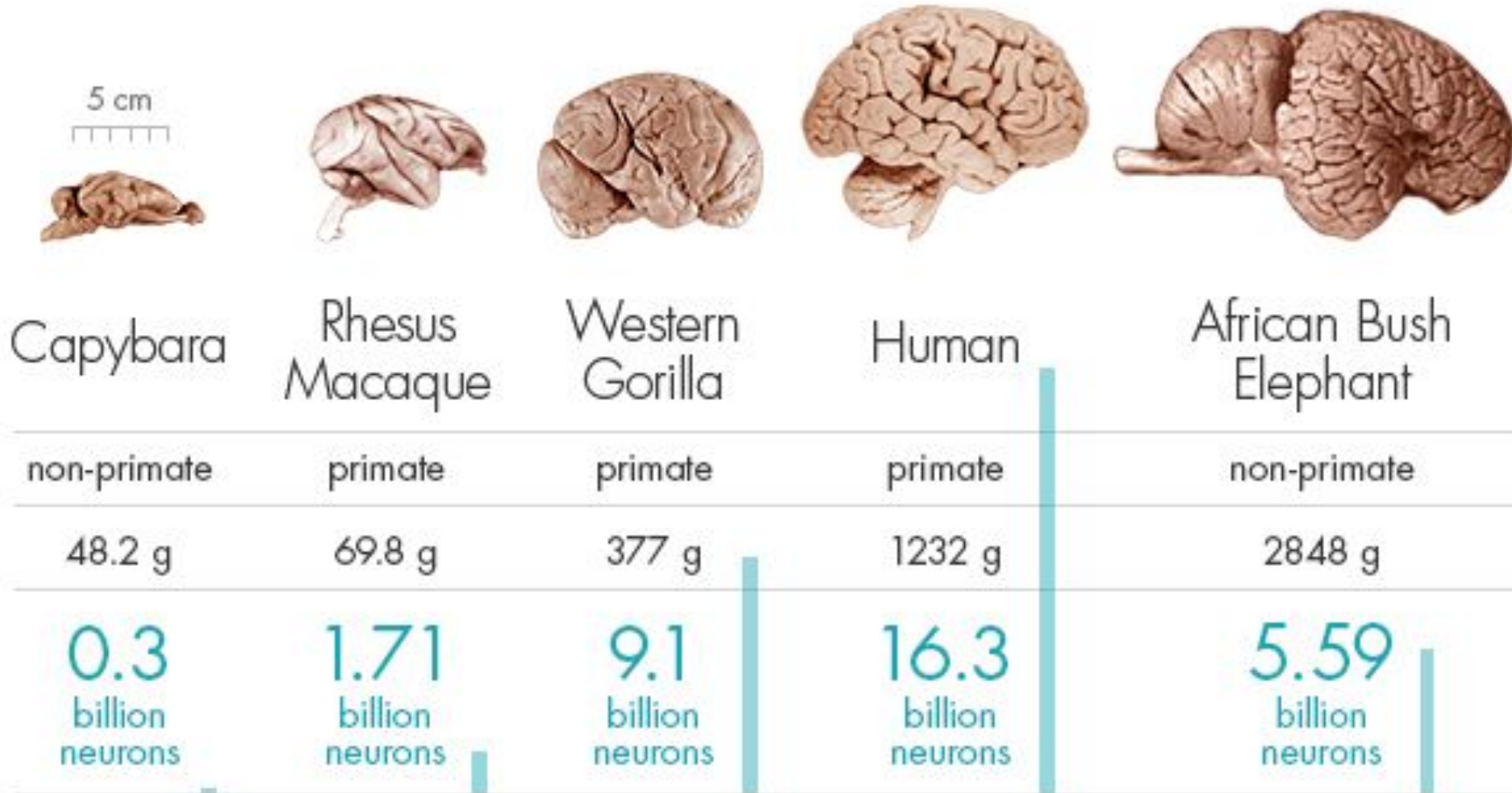


The Brain has evolved over hundreds of millions of years

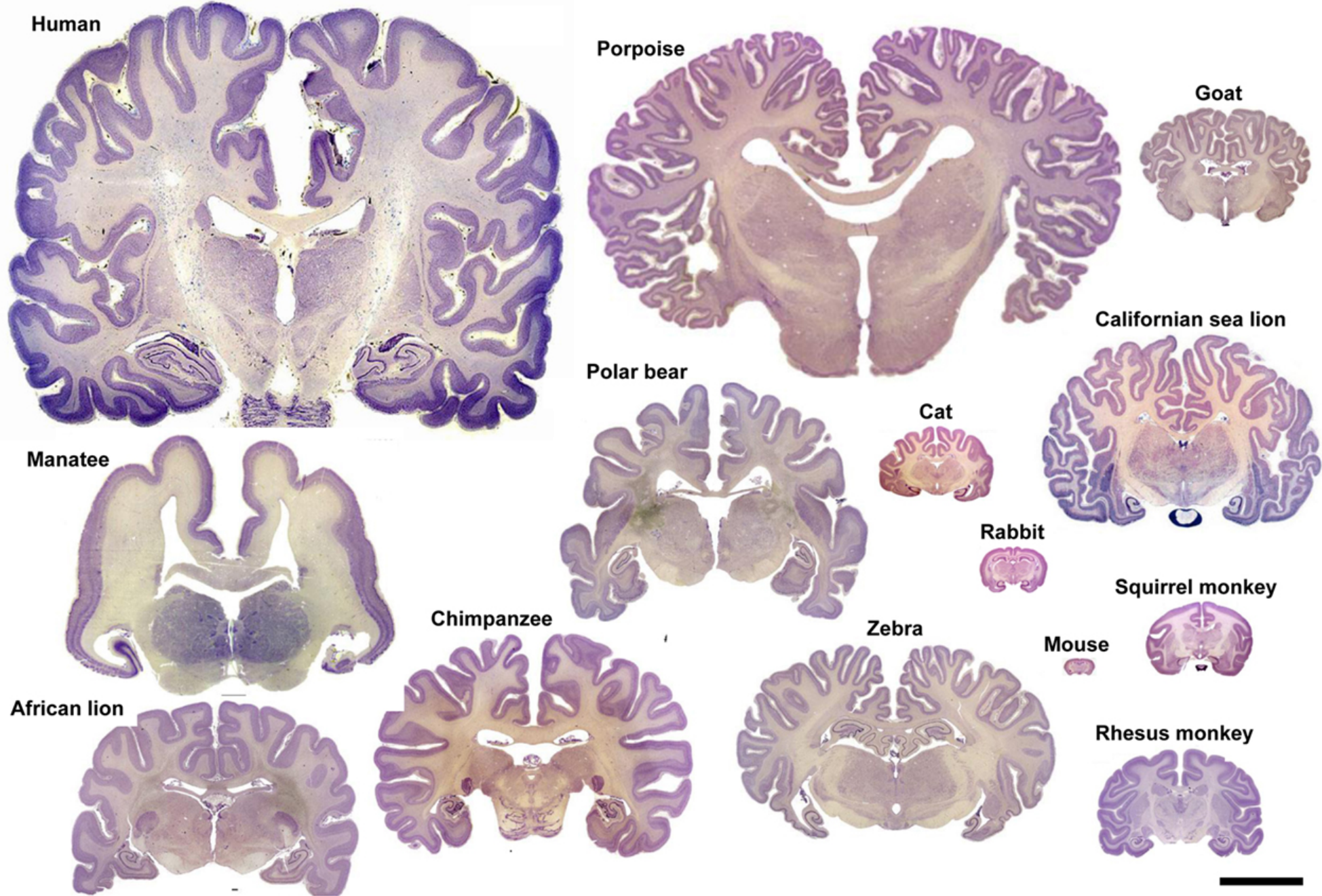
# BRAIN SIZE AND NEURON COUNT

Cerebral cortex mass and neuron count for various mammals.

Courtesy of Quanta magazine

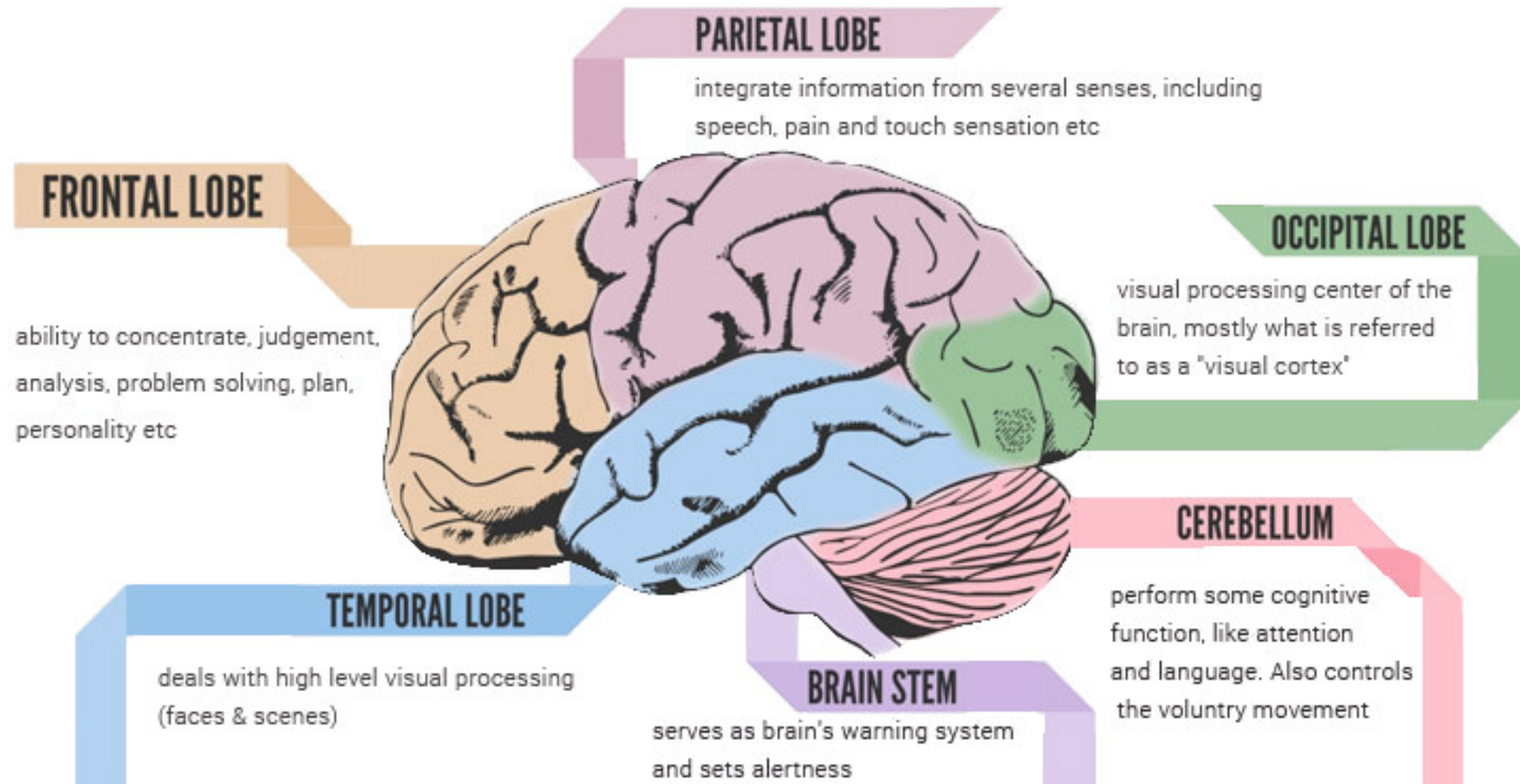


Note: across species, the cortex has under a third of the number of neurons in the cerebellum



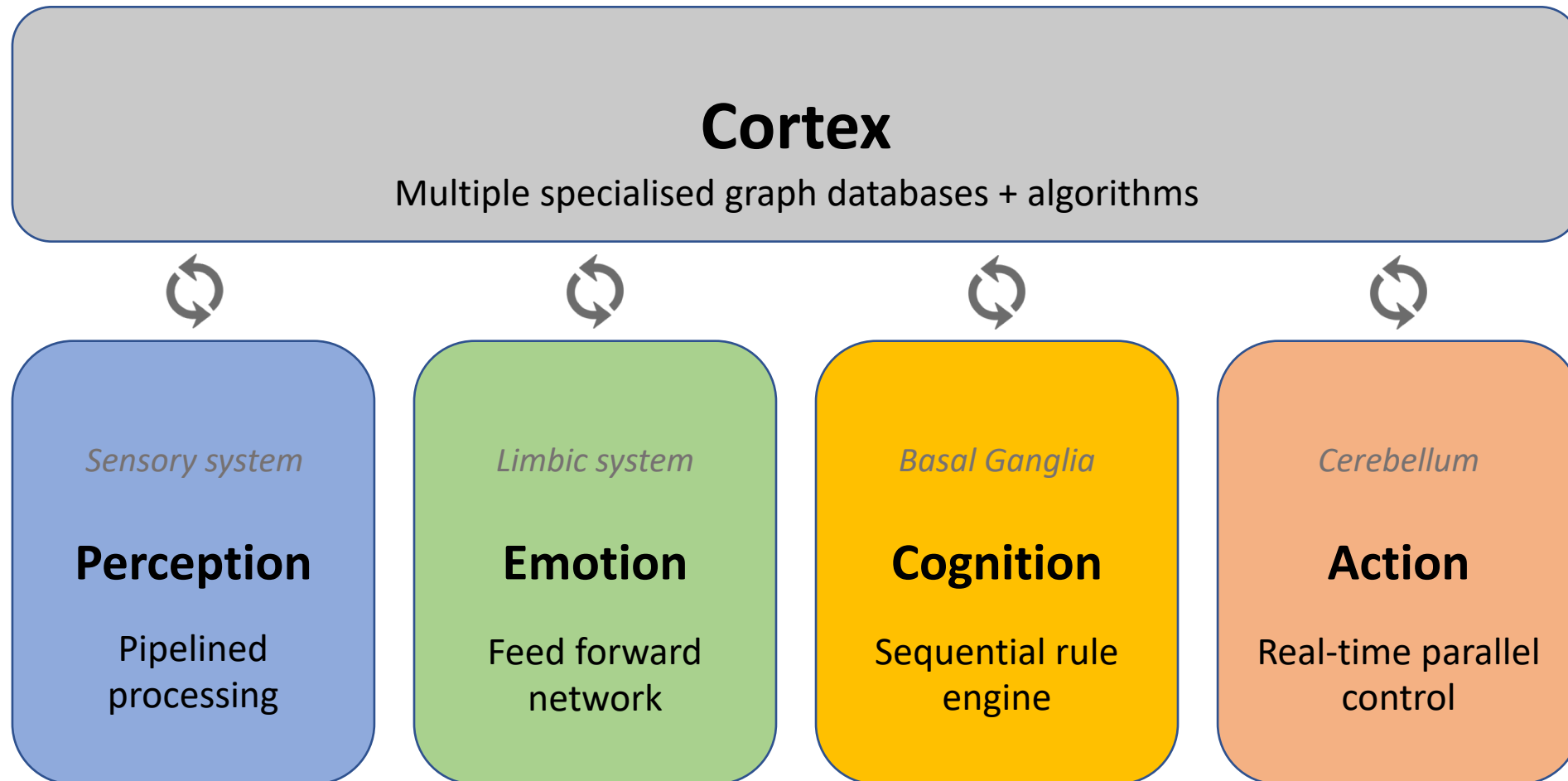


# Brain function – many specialized areas



# Cognitive AI Architecture

with multiple cognitive circuits





# Modelling the Cortex with Cognitive Databases

- The human cortex is functionally equivalent to a set of specialised cognitive databases and associated algorithms
- A cognitive database holds chunks: collections of properties that include references to other chunks
- Chunks are associated with statistical information reflecting prior knowledge and past experience
- Cognitive databases have the potential to store vast amounts of information similar to the human cortex
- **Cognitive databases** can be **local** or **remote**, and **shared** with multiple cognitive agents, subject to **access control** policies
- Memory retrieval fits Web architecture
  - Remote invocation of graph algorithms in request/response pattern rather like HTTP
  - Analogous to Web search engines where results are computed based upon what is likely to be most relevant to the user – impractical and inappropriate to try to return complete set of matches
- Cognitive databases support a variety of algorithms that are executed local to the data
  - Scalable to handling Big Data
- The algorithms depend on the intended function of the database, e.g.
  - Basic storage and recall
  - Specialised algorithms for natural language, spatial and temporal reasoning
  - Algorithms for data analytics

# Sensory Perception

- Our senses
  - Smell, taste, touch, pain, heat, sound, vision, ...
  - **Perception creates short lived representations in the cortex**
  - The cortex can likewise direct sensory processing as needed
- Touch and pain are mapped to a homuncular model of our bodies
- Proprioception – sense of self-movement and body position
  - Limbs, joints, muscle load
  - Vestibular system (inner ear)
- Sound is fleeting
  - Processing word by word
  - Emotional cues

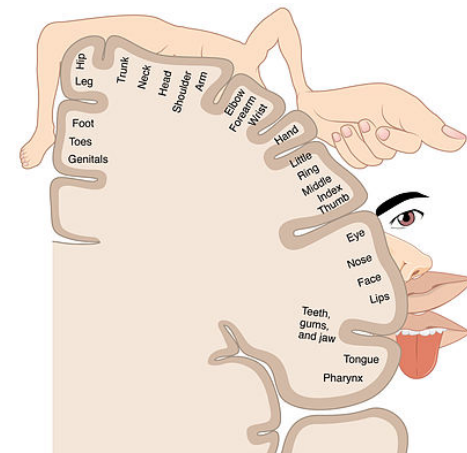
- Vision is much more complex
  - Two eyes for stereo depth perception
  - Each eye: high resolution narrow angle + low resolution wide angle
  - Saccades as eyes swivel to scan areas of interest
  - Good at recognizing many different kinds of things, including their structures & behaviours
  - Context determines what is interesting and relevant
  - Alerts signal relevant things in field of view
  - Focus directs attention to specific things
  - Reinforcement learning from experience



Visual system



Hearing



Cortical homunculus

Implementation as pipelined neural networks

# Emotions, Feelings and Moods

*Towards strong empathic\* AI*



- **Cortico-Limbic system**
- Important from an evolutionary perspective
  - Avoidance of harm, fear of predators, interest in prey, courtship, care of young
- Enhanced for living in social groups
  - Emotional intelligence – awareness of what others are feeling, and signalling your own feelings
- Emotions are associated with a feeling and something they apply to
  - Valence describes whether feeling is positive, neutral or negative
  - Arousal describes whether feeling is calming or exciting
  - Moods are long lasting emotions that lack the cognitive element
- Triggered by
  - Perception (e.g. seeing a predator), reasoning about situations, recall of emotive memories
- Effects
  - Instinctive behaviours and how these are regulated by cognitive control
  - Prioritising what you are thinking about and what feels important
  - Influences on recall, new memories, reinforcement of existing memories and reinforcement learning of behaviours
- Fast and instinctive vs slow and deliberate
  - Rapid instinctive appraisal and response, avoiding the delay incurred with conscious thought, but subject to errors of judgement due to lack of considered thought
  - Functional implementation as a feed-forward classification network

\* **empathic**: /em'paθɪk/ adjective – showing an ability to understand and share the feelings of another

# Cognition and Conscious Thought



- **Cortico basal-ganglia circuit**
  - The centre of conscious thought
- Symbolic (graphs) + sub-symbolic (statistics)
  - Chunk based symbolic representation of concepts and relationships
  - Statistical weights reflecting prior knowledge and past experience
- Rule engine connected to many parts of the cortex
  - Connections via buffers that hold single chunks
  - Rules represent reasoning & procedural knowledge
  - Learned from experience (hierarchical reinforcement learning)
- Sequential application of rules to cognitive buffers
  - Approximately every 50 mS or longer
- Parallel processes for graph algorithms
  - Recall of memories
  - Selection of rules
- Autobiographical and episodic memories
- Reasoning at multiple levels of abstraction

**Chunks:** a collection of properties that include references to other chunks

**Modules:** specialised graph databases and algorithms, accessed via buffers that hold a single chunk

**Rules:** conditions ranging over module chunk buffers, and actions that either update the buffers or invoke graph algorithms

# Action



Courtesy of Freepik

- **Cortico cerebellar circuit**
- Handles actions devolved to it by conscious thought
- Real-time control with parallel processing
- Contains more than three times the number of neurons in the cortex\*
- Cerebellum acts as flight controller managing activation of myriad sets of muscles in coordination with perceptual input from the cortex
- Offloads processing from cortico basal-ganglia circuit thereby enabling higher level thought whilst actions are underway
- Performance degrades when conscious thought diverts visual attention, starving cerebellum of visual feedback
- Learning through experience, starting with conscious thought
- Implemented as suite of real-time continuous state machines
- Examples: talking, walking and playing the piano

\* The human cerebellum contains 70 billion nerves vs 20 billion for the cerebral cortex, see [Suzana Herculano-Houzel](#), 2010

# Application to Autonomous Vehicles

- **Cognitive AI demo that runs in a web page**
- Mapping data for a small town was exported from Open Street Maps as XML (3.1MB) and transformed into chunks (637 KB or 128 KB compressed)
  - Points with latitude & longitude
  - Paths as sequence of points
  - Roads as collections of paths
- Graph algorithm for spatial indexing – constructs corresponding Quad Tree index with chunks
- Graph algorithm for route planning (“A star”)
- Visual model raises alerts that signal
  - When approaching junction
  - When entering & leaving junction
  - When arriving to the destination
- Cognitive rules as chunks for ease of learning
  - Start and stop turn indicator lights
  - Initiate braking or accelerating
  - Initiate lane tracking and turning
- Functional model of cortico-cerebellar circuit provides real-time control of brakes, acceleration and steering, as initiated by cognitive rules

## # retrieve turn

```
alert {@module goal; kind turn; turn ?id }
=>
    turn {@module goal; @do recall; @id ?id}
```

## # prepare for turn

```
turn {@module goal; @id ?id; signal ?direction}
=>
    action {@module car; @do brake; turn ?id},
    action {@module car; @do signal; signal ?direction},
    alert {@module goal; @do clear}
```

## # start turn

```
alert {@module goal; kind stop}
=>
    action {@module car; @do steer; mode turn},
    action {@module car; @do cruise; speed 20},
    alert {@module goal; @do clear}
```



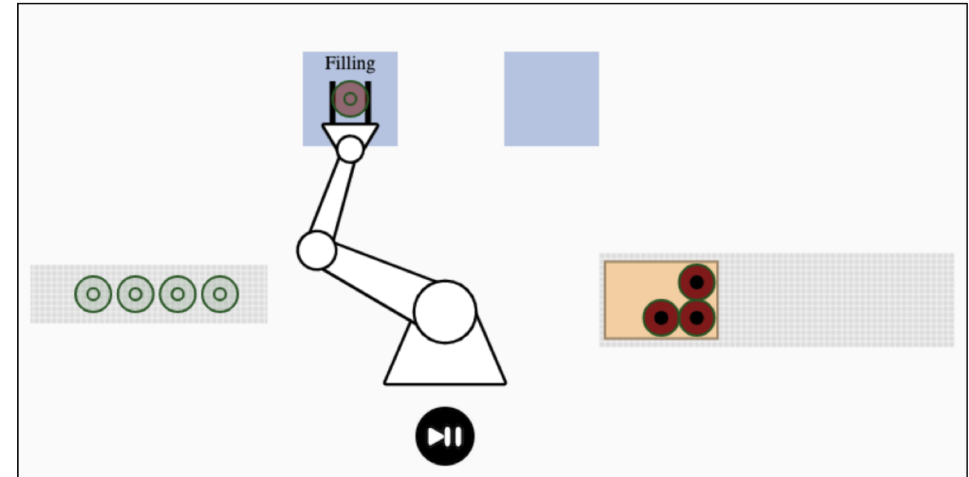
# Application to Smart factories

- **Cognitive AI demo that runs in a web page**
- Live simulation of bottling plant with robot, conveyor belts, filling and capping stations
- Real-time control by a cognitive agent

```
# add bottle when belt1 has space and wait afresh  
space {thing belt1} =>  
action {@do addBottle; thing belt1},  
space {@do wait; thing belt1; space 30}
```

```
# add box when belt2 has space and wait afresh  
space {thing belt2} =>  
action {@do addBox; thing belt2},  
action {@do stop; thing belt2},  
space {@do wait; thing belt2; space 95}
```

```
# stop belt when it is full and move arm  
full {thing belt1} =>  
action {@do stop; thing belt1},  
action {@do move; x -120; y -75; angle -180; gap 40; step 1}
```



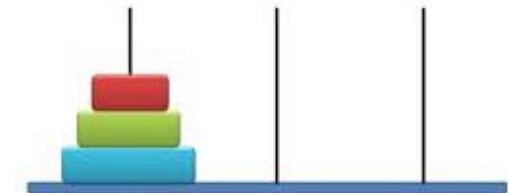
Log:

```
executed rule _:17 stop  
set goal to: after _:54 {step 1}  
executed rule _:27 move  
set goal to: after _:55 {step 2}  
executed rule _:30 grasp  
set goal to: after _:56 {step 3}  
starting belt1  
wait on filled  
executed rule _:34 start
```

# Natural Language Processing

- NLU as combination of pipelined processing + deliberative reasoning
  - Lexicon of words, their parts of speech, word senses and linguistic tags, e.g. person, number, case, gender
  - Spreading activation model for disambiguation based upon the context and statistical likelihood
  - Word by word generation of word dependency graph
  - Explicit reasoning to map word graph to semantics
  - Similar approach in reverse for NLG
- Work now underway on demos for NL understanding and generation
  - Start simple then iterative enrichment
  - Suggestions for scenarios and example dialogues welcomed!

Towers of Hanoi



# move the red disc to the right peg

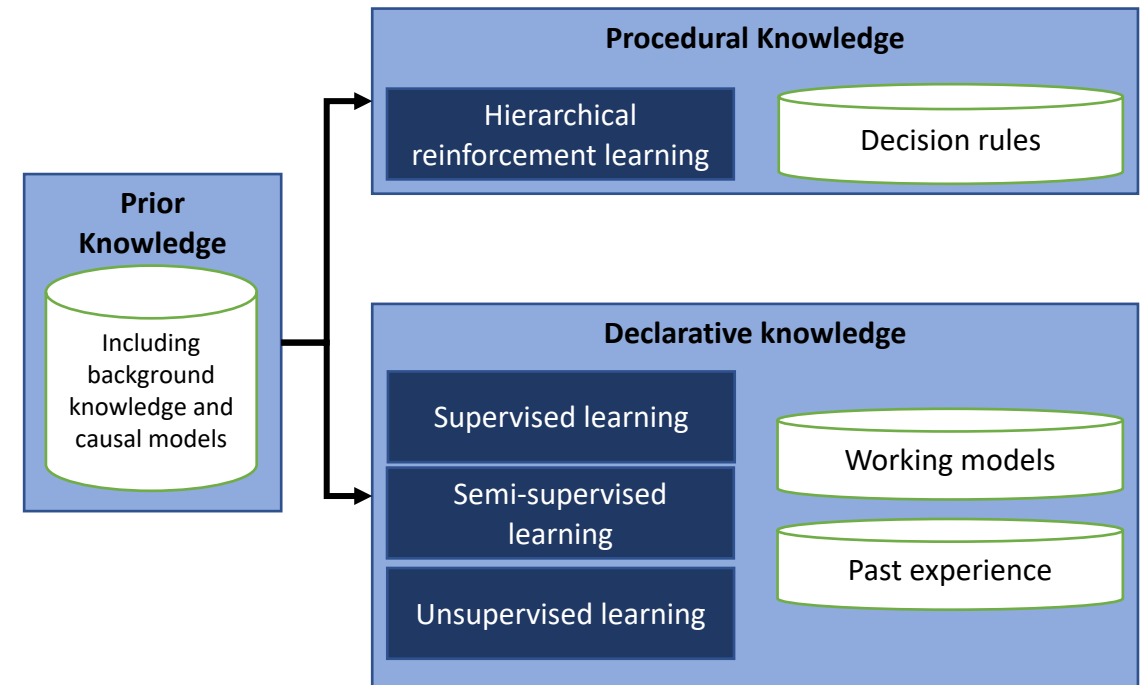
verb v1 {word move; subject p1; to p2}  
phrase p1 {word disc; det the; adj red}  
phrase p2 {word peg; det the; adj right}

# after application of ruleset

move m1 {disc disc3; to peg3}

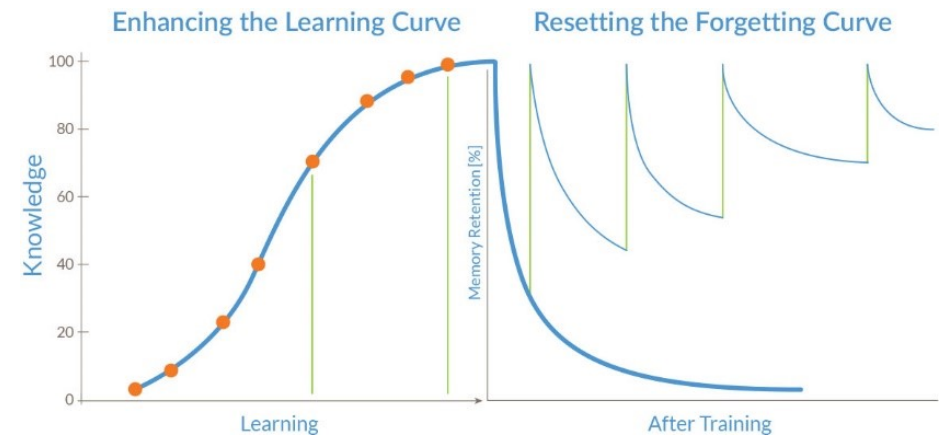
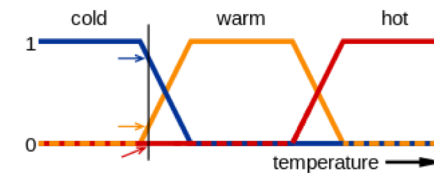
# Machine Learning

- Manual development of knowledge won't scale cost effectively
- We therefore need to rely on machine learning for declarative and procedural knowledge
  - Many algorithms to take advantage of
- Prior knowledge enables learning from small datasets
- Semi-supervised learning as human guided exploration with attention to salience
- Active learning – continuous, surprise driven
  - Mimicking humans as prediction machines – we attend to novelty to improve our predictions
- Use with natural language for teaching skills to cognitive agents



# Richer Ways to Reason

- Many forms of reasoning have to deal with uncertainties, e.g.
  - Induction: building models to explain regularities
  - Abduction: determining the most likely explanation of some observations
  - Causal reasoning about plans
  - Fuzzy reasoning involving blends of different states
- Mimicking human memory
  - In any large knowledgebase we only want to recall what is relevant to the current situation based upon past experience
  - Spreading activation – concepts are easier to recall on account of their relationship with other concepts\*
  - Ebbinghaus forgetting curve – our ability to recall information drops off over time unless boosted by repetition
  - Closely space repetitions have less effect



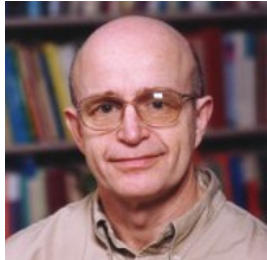
\* Nature figured out the “Page Rank” algorithm many millions of years ago!

# W3C Cognitive AI Community Group

See: <https://www.w3.org/community/cogai/>, <https://github.com/w3c/cogai>

- Participation is open to all, free of charge
- Focus on demonstrating the potential of Cognitive AI
  - A roadmap for developing **AI that is strong, empathic and trustworthy**
- Collaboration on defining use cases, requirements and datasets for use in demonstrators
  - <https://github.com/w3c/cogai/tree/master/demos>
- Work on open source implementations and scaling experiments
- Work on identifying and analysing application areas, e.g.
  - Helping non-programmers to work with data (worth \$21B by 2022 according to Forester)
  - Cognitive agents in support of customer services (worth \$5.6B by 2023)
  - Smart chatbots for personal healthcare
  - Assistants for detecting and responding to cyberattacks
  - Teaching assistants for self-paced online learning
  - Autonomous vehicles
  - Smart manufacturing
- Outreach to explain the huge opportunities for Cognitive AI

# Acknowledgements



- Chunk rules are a form of production rules as introduced by [Alan Newell](#) in 1973 and later featured in his [SOAR](#) project
- [John Anderson's](#) work on human associative memory in 1973, later combined with production rules for ACT in 1976, maturing as ACT-R in 1993. [ACT-R](#) is a theory for simulating and understanding human cognition that has been widely applied to cognitive science experiments
- [Marvin Minsky](#) for his work on frames, metacognition, self-awareness and the importance of emotions for cognitive control
- European Commission for funding from the Horizon 2020 research and innovation programme under grant agreement No. 780732, [Boost 4.0](#) big data for factories



# Cognitive AI

*giving computing a human touch*