

# **The Virtual Reality of the Mind**

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**Short version: <http://jfsowa.com/talks/vrshort.pdf>**

# Outline

- 1. Embodied and symbolic cognition . . . . . 5**  
*Good old-fashioned AI (GOF AI) is purely symbolic. But the body and its methods of perception and action are essential for human-level cognition.*
- 2. The role of the cerebellum . . . . . 33**  
*The cerebellum is the primary organ for embodied perception and action. It supports the virtual reality at the foundation of complex cognition.*
- 3. Semiotic foundation . . . . . 56**  
*The theory of signs by Charles Sanders Peirce includes symbolic cognition as a derivative and extension of embodied cognition.*
- 4. Natural logic . . . . . 85**  
*People don't always think logically, but they can. Natural logic is the hypothetical version that supports a continuum from informal to formal.*
- 5. The Cognitive Cycle . . . . . 107**  
*Cycles of cycles of observation, learning, reasoning, and purposive action are the basis for cognition and reasoning at every level.*

# Terminology

## **Related, but sometimes controversial terms:**

- **Inner speech.** Conscious, but unspoken language-like thought.
- **Mental imagery.** Consciously imagined sensory patterns.
- **Body image.** Conscious awareness of the body and its posture.
- **Body schema.** A 3-dimensional neural integration of visual and tactile sensations with proprioception and kinesthesia. \*
- **Symbolic cognition.** Hypothesis that cognition is based on the kinds of representations that support spoken and inner speech.
- **Embodied cognition.** Hypothesis that perception, action, and cognition are based on the dynamically changing body schema.

## **Dynamic 3-D mental models are generated by virtual reality (VR).**

- **VR relates the body schema to the real or imagined environment.**
- **In vertebrates, the cerebellum generates the VR from sensory input and/or memories in the cerebral cortex (the outer, largest part of the cerebrum).**
- **Nothing in the cerebellum is conscious, but mental imagery is awareness of a projection of the VR from the cerebellum to the cerebral cortex.**

\* Term coined by Head & Holmes (1911). For recent updates, see [Holmes & Spence \(2008\)](#).

# Theories of Language and Thought

- **Noam Chomsky:** Generative syntax is the essence of language.
- **Roman Jakobson:** Syntax without semantics is meaningless.
- **Michael Halliday:** Language is social semiotic.
- **Jerry Fodor:** Speech is generated from a language of thought.
- **Sydney Lamb:** Knowledge consists of connections in a network.
- **Richard Montague:** Any natural logic must be a formal logic.
- **Ludwig Wittgenstein:** Games (*Sprachspiele*) are the foundation.
- **Yorick Wilks:** Wittgenstein was right, but more detail is needed.
- **Roger Schank:** Background knowledge is essential.
- **Fred Jelinek:** Statistics is key to all language processing.
- **Lotfi Zadeh:** The fuzziness of language is not statistical.
- **Philip Johnson-Laird:** Language is mapped to mental imagery.
- **George Lakoff:** The mapping is done by image-based metaphors.
- **Anna Wierzbicka:** Meaning is based on universal semantic primes.
- **Len Talmy:** Language has the same semantics as cognition.
- **David McNeill:** Speech, gestures, and thought are intimately related.
- **Geoffrey Hinton:** Neural networks are the key to intelligence.
- **Marvin Minsky:** The Society of Mind has many keys.
- **Charles Sanders Peirce:** The mind is the totality of a lifetime of signs.

# 1. Embodied and Symbolic Cognition

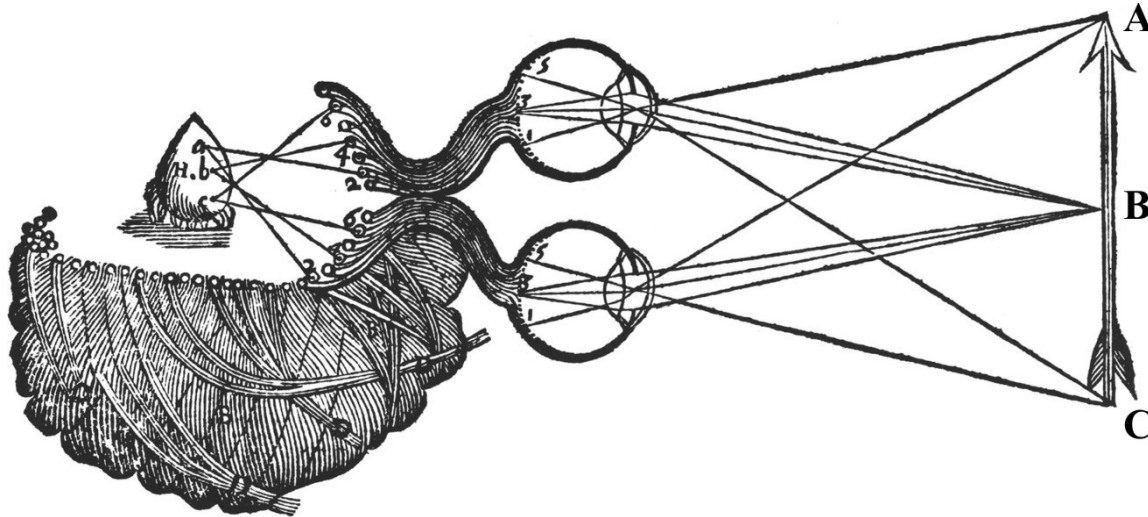
In their 1975 Turing Award lecture, Allen Newell and Herb Simon defined AI as disembodied “symbols and search”:

- “Thought was still wholly intangible and ineffable until modern formal logic interpreted it as the manipulation of formal tokens.”
- “Symbols lie at the root of intelligent action.”
- “A physical symbol system has the necessary and sufficient means for general intelligent action.”

Embodied cognition emphasizes the role of an agent who experiences a situation and acts upon it for some purpose.

- Symbols alone are not sufficient for intelligent perception and action.
- Terry Winograd (1972) used symbolic logic for his project on natural language understanding. But by 1976, he recognized its limitations.
- Haugeland (1985) coined the term GOFAL at a time when many AI researchers began to think that symbolic AI was “old fashioned”.
- Rodney Brooks (1999): “Cognition is in the eye of the beholder.”  
The definitions change with each theory and application.

# Descartes' Error

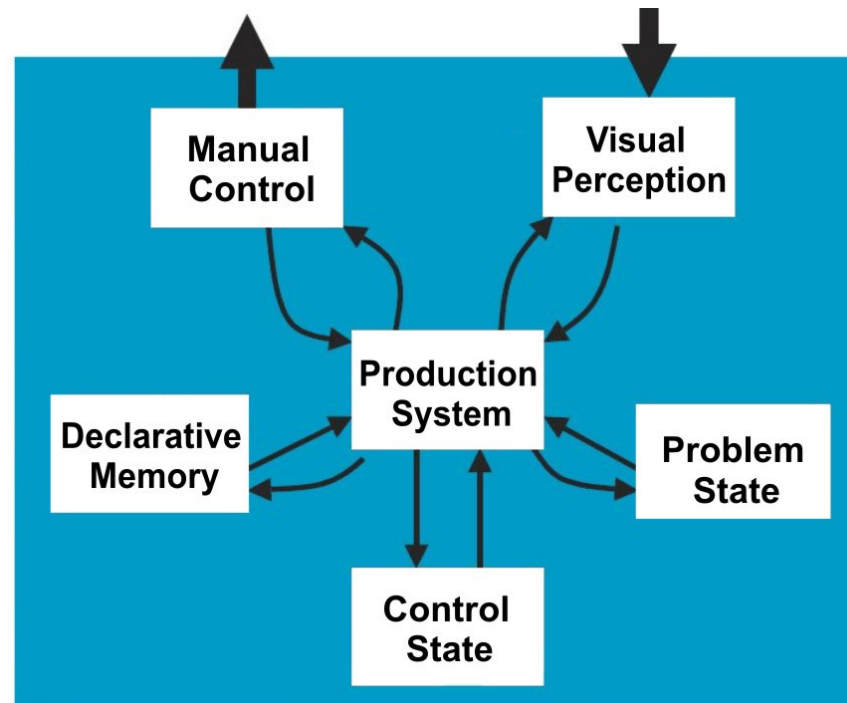


**Descartes (1662): Body and soul are attached at the pineal gland.**

**Damasio (1994): Descartes' error "pervades research and practice":**

- **Philosophy:** "The separation of the most refined operations of mind from the structure and operation of a biological organism."
- **Artificial intelligence:** "The metaphor of mind as software program."
- **Neuroscience:** "The thinking of neuroscientists who insist that the mind can be fully explained solely in terms of brain events, leaving by the wayside the rest of the organism and the surrounding physical and social environment." (pp. 249-251)

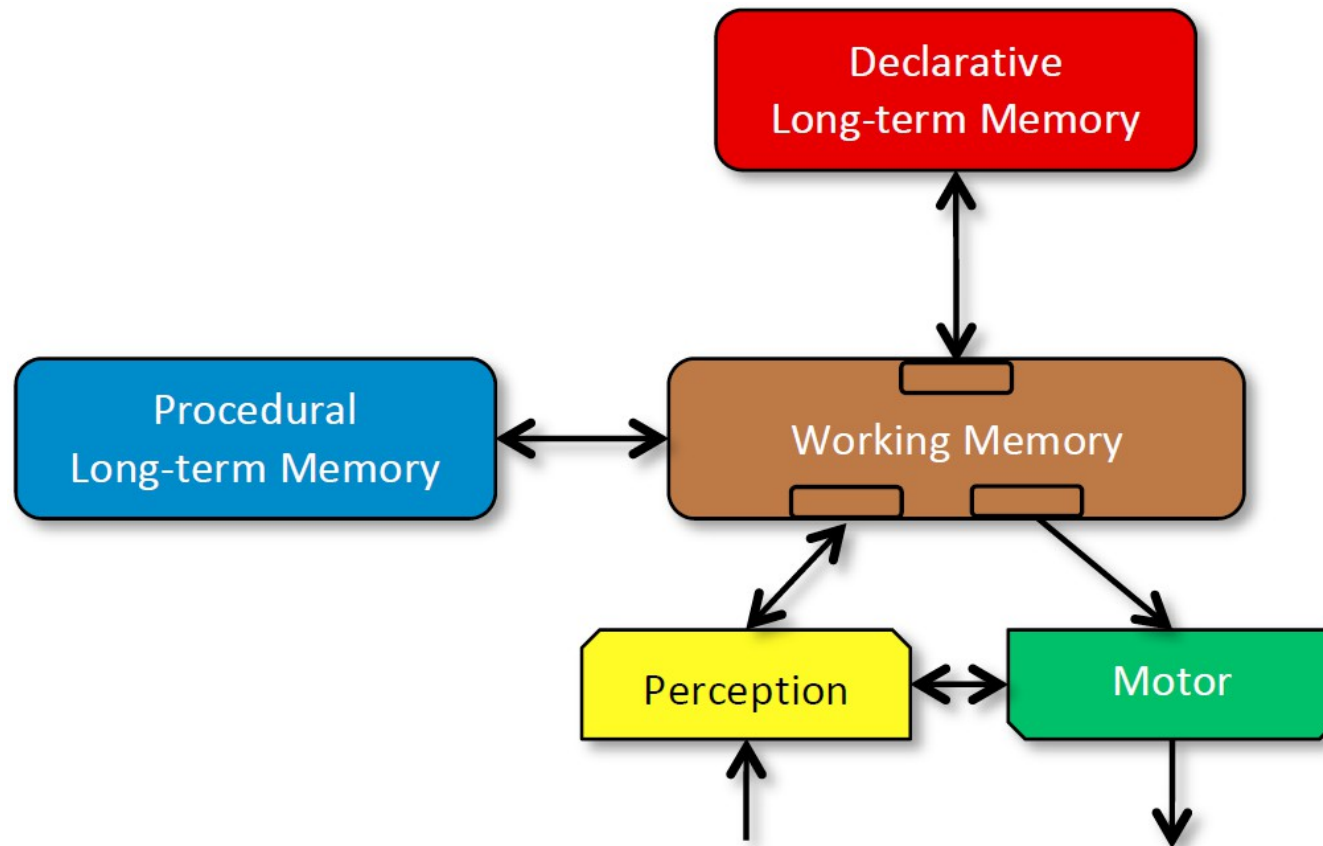
# Adaptive Control Theory — Rational



**ACT-R is a widely used cognitive architecture (Anderson et al. 2004):**

- **Based on a theory of human associative memory (Anderson & Bower 1973) and AI research by Newell, Simon, and others.**
- **Represents knowledge in networks of symbols grouped in *chunks*.**
- **Reasoning is simulated by if-then rules called *productions*.**
- **Separate modules, which process perception and motor control, do not use the symbolic memory system.**

# A Model of the Mind



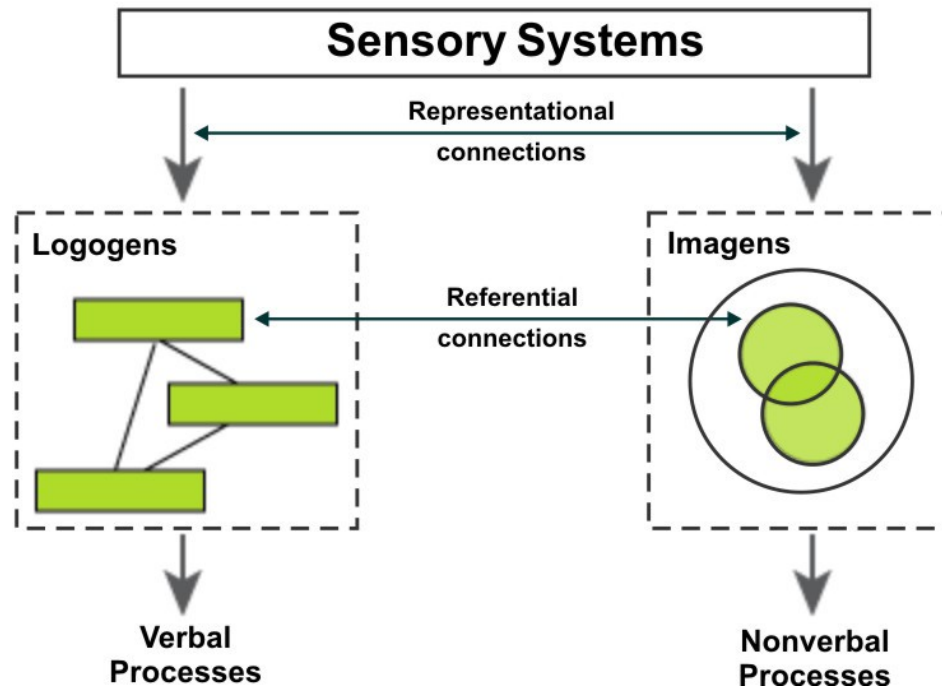
**A synthesis of three symbolic systems: ACT-R, Sigma, and SOAR. \***

- Declarative and procedural LTM store symbols and production rules.
- Working memory includes controls and local data for processing rules.
- Perception and motor control are outside the symbolic system.

\* J. E. Laird, C. Lebiere, P. S. Rosenbloom (2017) [A Standard Model of the Mind](#): Toward a Common Computational Framework across AI, Cognitive Science, Neuroscience, and Robotics.



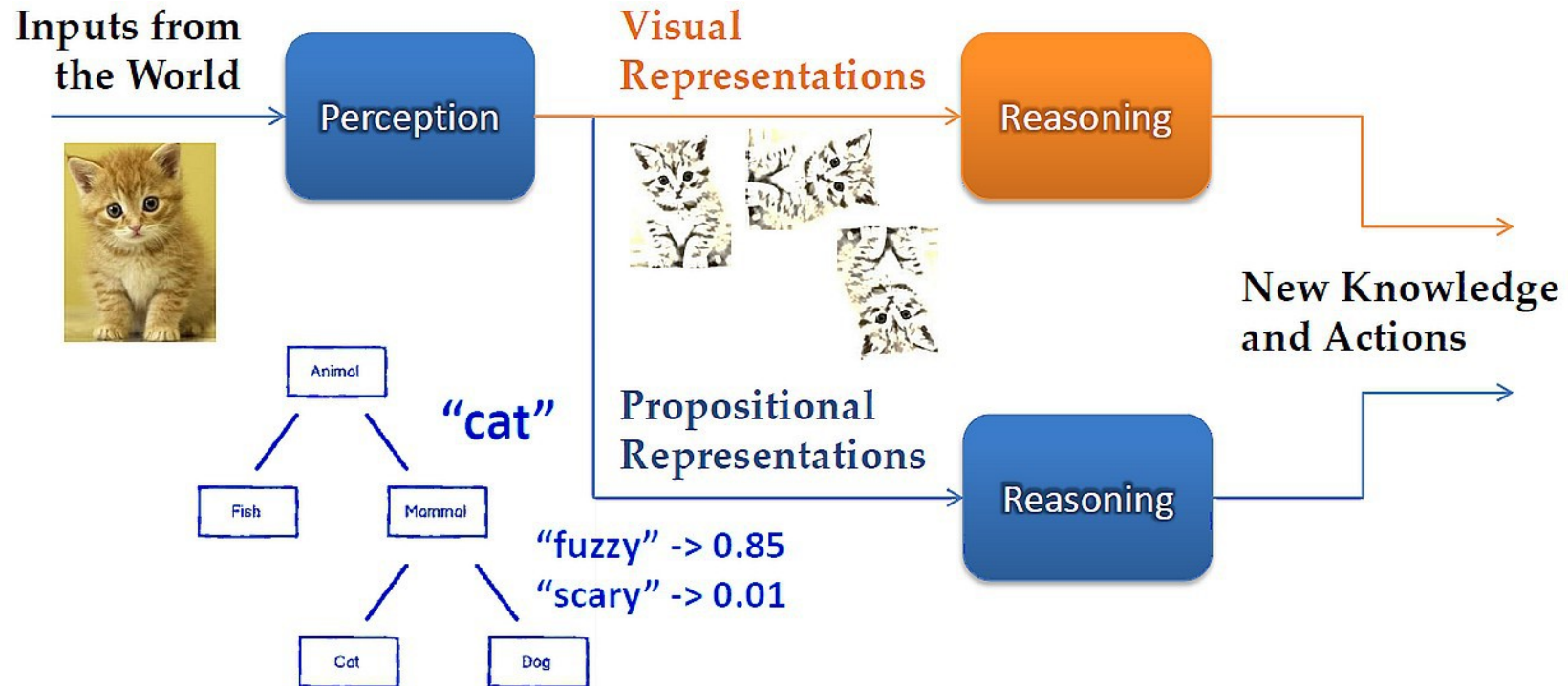
# Dual Coding Theory



**Allan Paivio (1971, 2007) developed Dual Coding Theory (DCT):**

- **Goal: An integrated theory for processing both symbols and imagery.**
- **A network of logogens (symbols) represents verbal knowledge.**
- **Overlapping imagens (percepts) are combined to form images.**
- **The symbolic logogens represent and refer to imagens.**
- **The dotted lines on the enclosures show that the two codes are not isolated. Reasoning methods may use and relate both codes.**

# Reasoning With Both Codes



## Using both methods to answer the same test questions: \*

- Raven's Progressive Matrices as a test of visual reasoning ability.
- Solved by hand-coding images in a propositional form and using production rules to find a solution (Carpenter, Just, & Shell 1990).
- Solved by spatial combinations, rotations, and analogies at the level of a 16 or 17 year-old student (Kunda, McGreggor, & Goel 2009).

\* Diagram adapted from Kunda (2016) [Visual imagination: a view from AI](#).

# A Unified Semiotic System

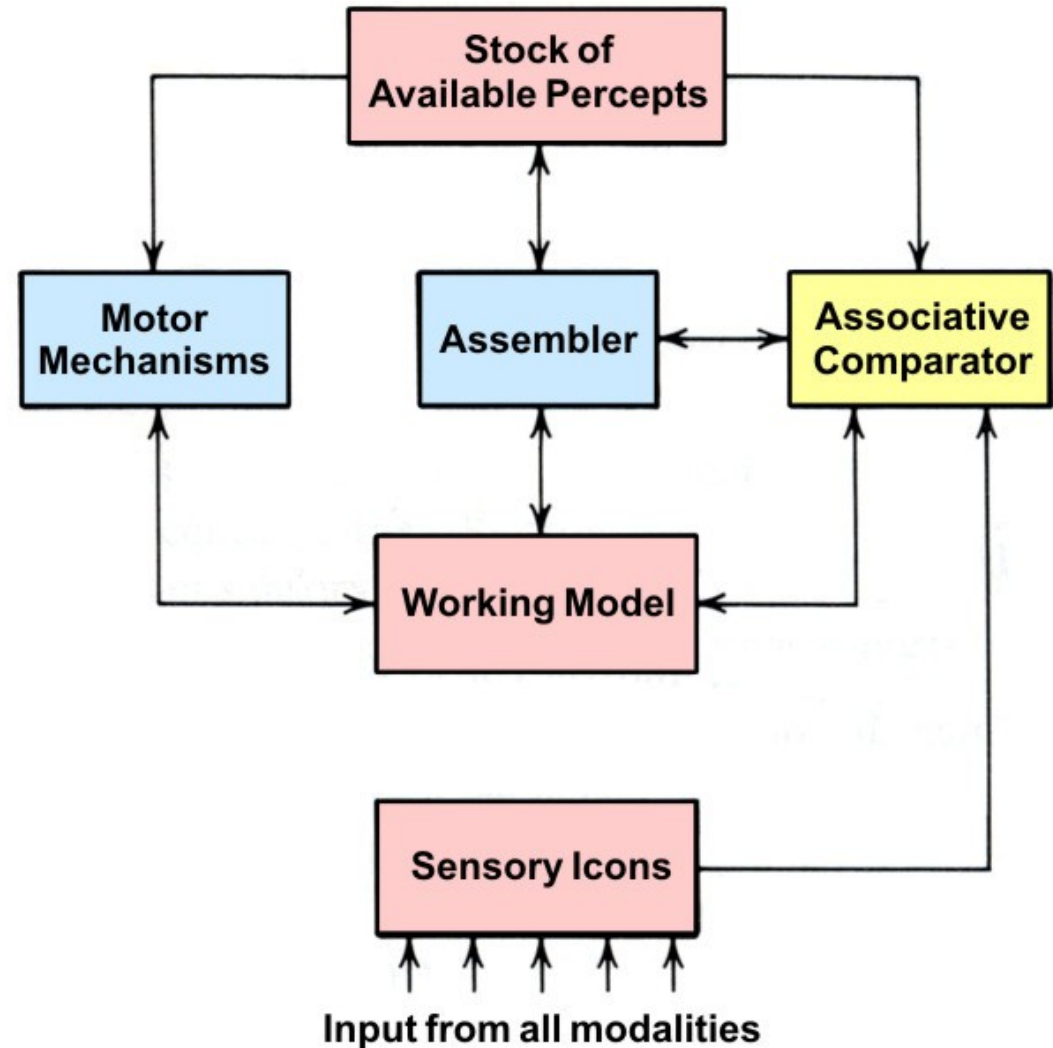
**Charles Sanders Peirce: Every experience, feeling, or thought, conscious or unconscious, is a sign.**

**A mind is the totality of all signs that anyone experiences or imagines.**

**Cognition consists of all semiotic processes that produce or result from those experiences.**

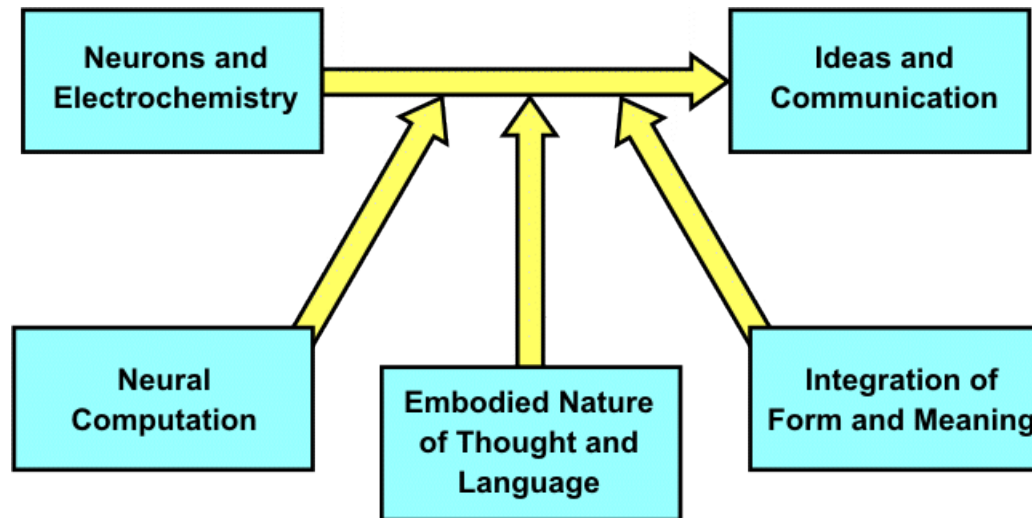
**The patterns for basic signs — icons and indexes — are derived from perception, emotion, and proprioception (internal sensing).**

**Symbols grow from icons and other symbols. Combinations of them produce all the versions of language, logic, mathematics, music, and art.**



\* The diagram is adapted from [Cognitive architectures for conceptual Structures](#) (Sowa 2011).

# Neural Theory of Language (NTL)



**A cognitive architecture that relates language to neuroscience:**

- The mind is inherently embodied.
- Thought is mostly unconscious.
- Abstract concepts are largely metaphorical.
- Construction grammars relate neural patterns to language patterns.

## References:

The NTL project at UC Berkeley: <https://ntl.icsi.berkeley.edu/ntl/>

George Lakoff & Mark Johnson (1999) *Philosophy in the Flesh: The Embodied Mind*.

Jerome Feldman (2006) *From Molecule to Metaphor: A Neural Theory of Language*.

A review of *Philosophy in the Flesh*: <http://www.jfsowa.com/pubs/lakoff.htm>

# American Sign Language



MANY

DEAF

LEARN

AGENT



ENTER



SPEAK



COLLEGE

*Many deaf students enter hearing colleges.*

**Unlike vocal sounds, many signs have a direct mapping to images and motion. Pointing is used instead of pronouns.**

Diagram adapted from Lou Fant (1983) *The American Sign Language Phrase Book*

# Bilingual Infants

**Study of bilingual infants whose parents speak or sign different languages: \***

- **All six combinations of four languages: English, French, American Sign Language (ASL), and Langue des Signes Québécoise (LSQ).**
- **Monolingual and bilingual babies go through the same stages and at the same ages for both spoken and signed languages.**
- **Hearing babies born to profoundly deaf parents babble with their hands, but not vocally.**
- **Babies bilingual in a spoken and a signed language babble in both modalities – vocally and with their hands.**
- **And they express themselves with equal fluency in their spoken and signed language at every stage of development.**

**The same brain areas that support spoken languages support signed languages, but other areas are also involved. \*\***

\* Laura-Ann Petitto (2005) <http://petitto.net/pubs/published/>

\*\* R. Campbell, M. MacSweeney, & D. Waters (2007) [Sign language and the brain: A review.](#)

# Sign Language and Mental Imagery

**A signed language can take advantage of space and motion:**

- For anything visible, pointing serves the role of pronouns: The index finger is the most natural indexical.
- But references to people and things that left the scene are possible by pointing to where they had been.
- The signer can also introduce new characters and things, place them in fixed locations in the air, and refer to them by pointing.
- The signer can show motion and direction by moving gestures.

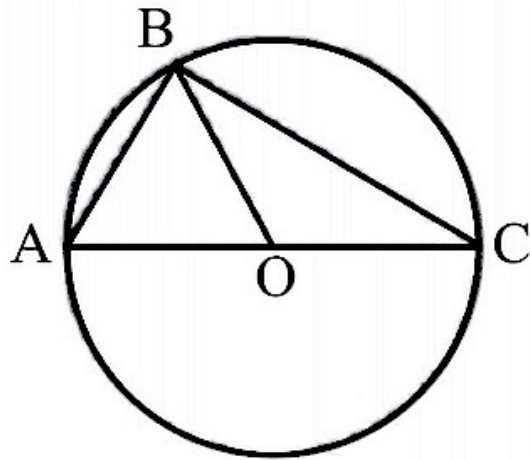
**Hearing adults who learn a signed language become bimodal: \***

- Their brain activation patterns are intermediate between those of deaf signers and hearing non-signers.
- On tests of mental imagery (generating, rotating, remembering, and matching 3-D shapes), they score higher than non-signers.

**Images are fundamental. They are the semantic foundation for every language – signed, spoken, or written.**

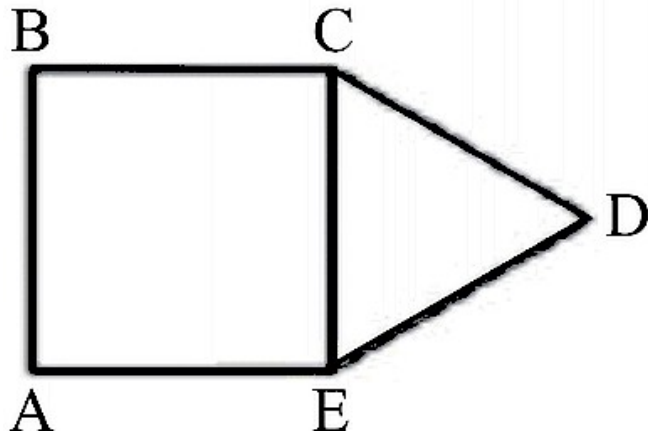
\* Karen Emmorey & Stephen McCulloch (2009) [The bimodal bilingual brain](#).

# Using Imagery to Interpret Language



In the figure to the left, triangle ABC is inscribed in the circle with center O and diameter AC. If  $AB=AO$ , what is the degree measure of angle ABO?

- (A)  $15^\circ$
- (B)  $30^\circ$
- (C)  $45^\circ$
- (D)  $60^\circ$  ✓
- (E)  $90^\circ$



In the figure to the left, CDE is an equilateral triangle and ABCE is a square with an area of 1. What is the perimeter of polygon ABCDE?

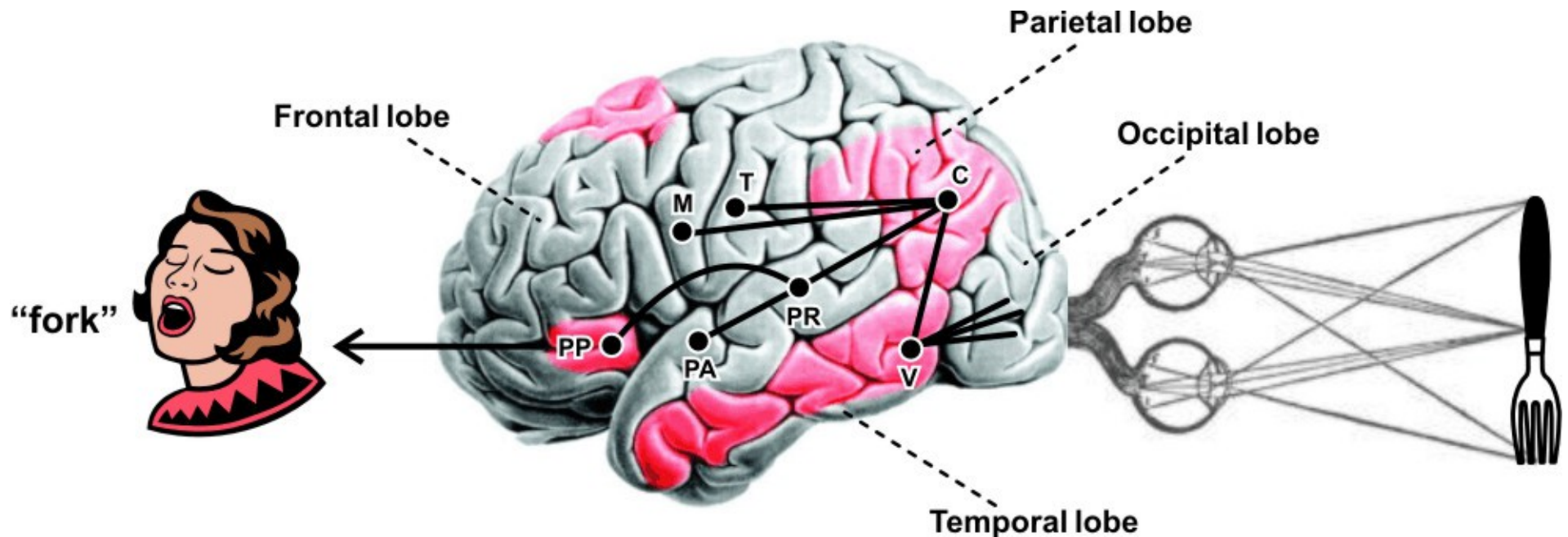
- (A) 4
- (B) 5 ✓
- (C) 6
- (D) 7
- (E) 8

**GeoS solves typical problems on the Geometry SAT exam. \***  
**It uses information from the images to understand the questions.**

\* Developed by the [Allen Institute for AI](#) and the [University of Washington](#).



# Neurocognitive Networks



Sydney Lamb (1999, 2010, 2016) developed **neurocognitive networks**:

- Node C represents a *cortical column* for the concept of a fork.
- V has links to the occipital lobe for visual percepts of forks.
- T has links to afferent nerves for the tactile sensation of a fork.
- M has links to motor nerves for manipulating a fork.
- PR in Wernicke's area represents the word 'fork'.
- PA represents the auditory percept of the word.
- PP in Broca's area links to motor nerves for pronouncing the phonemes.
- Pink areas in the diagram are active in semantics (Binder et al. 2009).

# Meaning in a Network

**How can a network of links define the categories of a language?**

- **The network is not based on a “code” defined by rules or axioms.**
- **It just links patterns of nodes to other patterns of nodes.**
- **Nodes may link to anything: images, sounds, feelings, muscles...**

**Lamb’s principles of categorization: \***

- 1. No small set of defining features (except for special purposes).**
- 2. Fuzzy boundaries.**
- 3. Prototypical members and peripheral members.**
- 4. Subcategories, and sub-subcategories, in hierarchical chains.**
- 5. Categories are in the mind, not in the real world.**
- 6. Categories and their membership vary from one language or cultural system to another.**
- 7. Categories influence thinking, in both appropriate and inappropriate ways.**

\* From slide 85 of <http://www.ruf.rice.edu/~Ingbrain/categories.ppt>

# Long-Distance Connections

Most neurons have short links to nearby neurons.

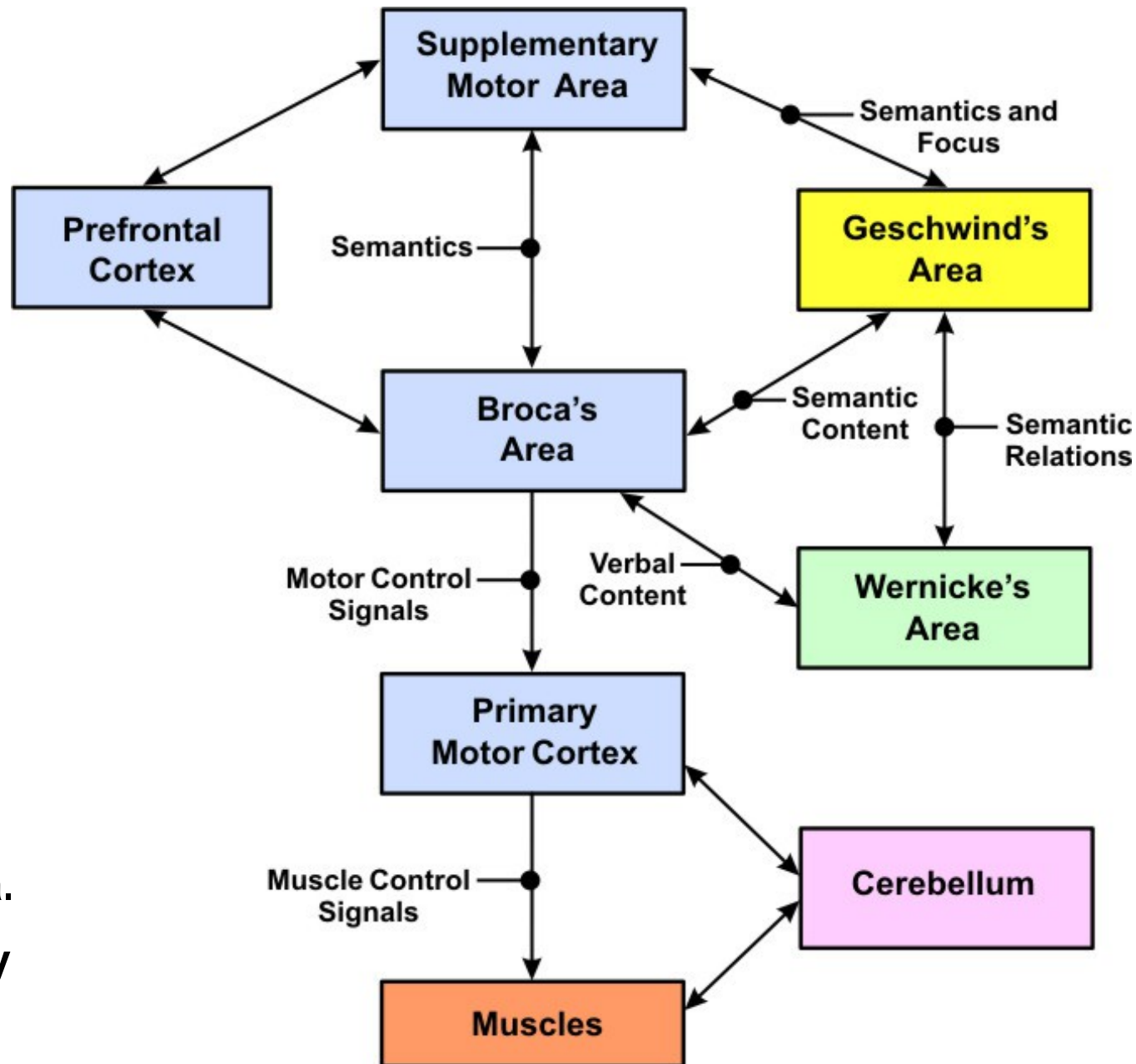
But others make long-distance connections.

The diagram shows long-distance connections among areas of the brain involved in language. \*

The blue boxes represent areas in the frontal lobes; yellow for an area in the parietal lobe; green for an area in the temporal lobe.

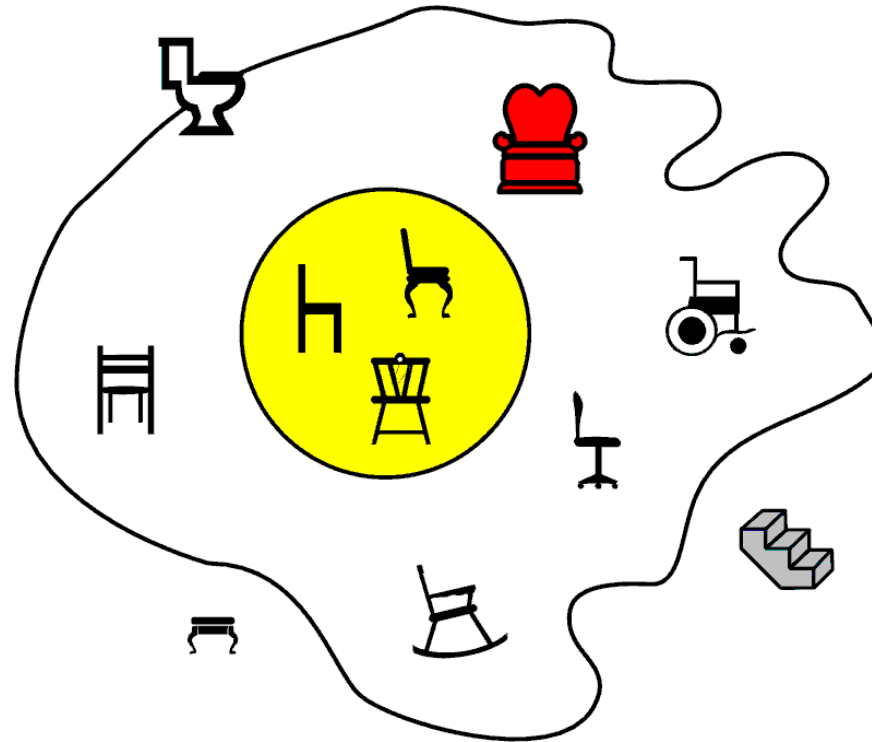
Patterns can be learned and recognized in one area.

But cognition relates many areas across the brain.



\* Diagram adapted from MacNeilage (2008).

# What is a Chair?

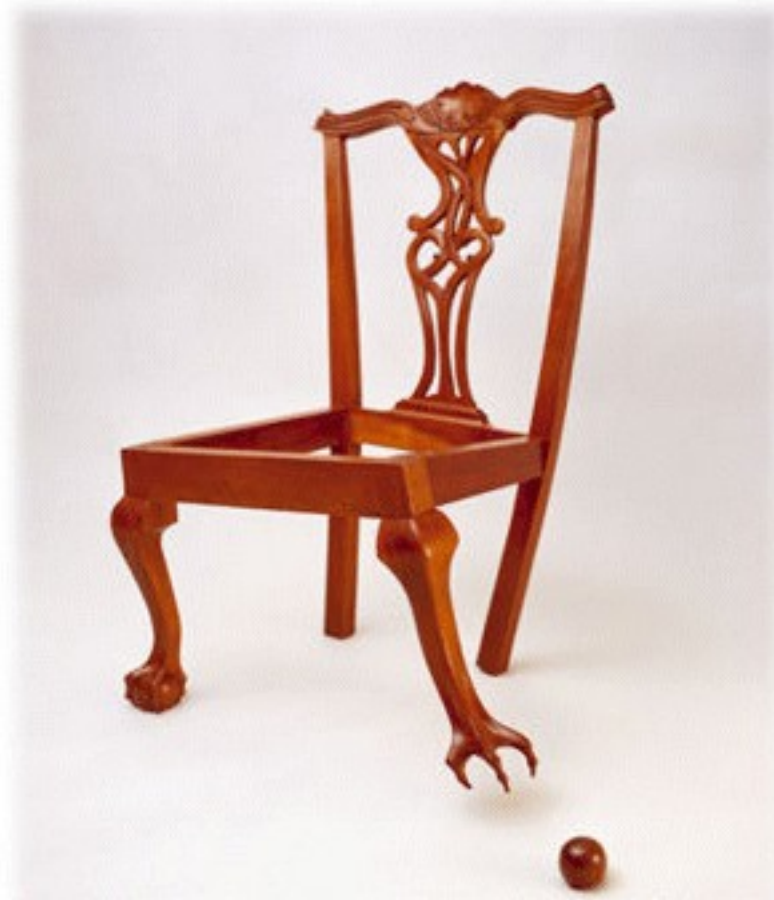


An egg-yolk diagram puts typical examples in the yolk and less common variants in the egg white. (Lehmann & Cohn 1994)

Boundaries resemble the *level cuts* of fuzzy set theory: the fuzzy value 0.9 could be the boundary for the yolk, and 0.7 for the egg white.

But the reasons for the variations are more significant than the numbers.

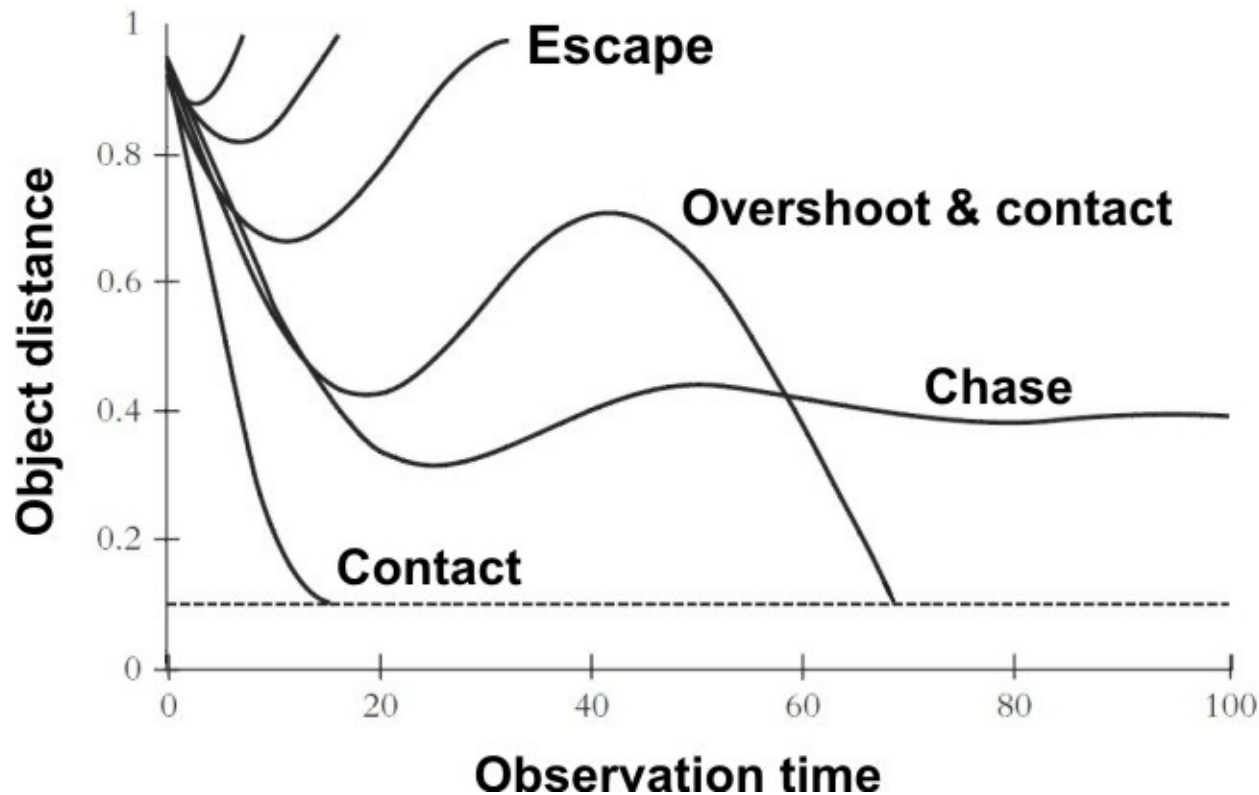
# Is it a Chair? Art? Humor? Fantasy?



**In a museum, it's funny. But suppose you saw it at night in an old castle. Meaning is always context dependent.**

**Claw and Ball Chair by Jake Cress. At the Smithsonian Renwick Gallery.**

# Relating Symbols and Images

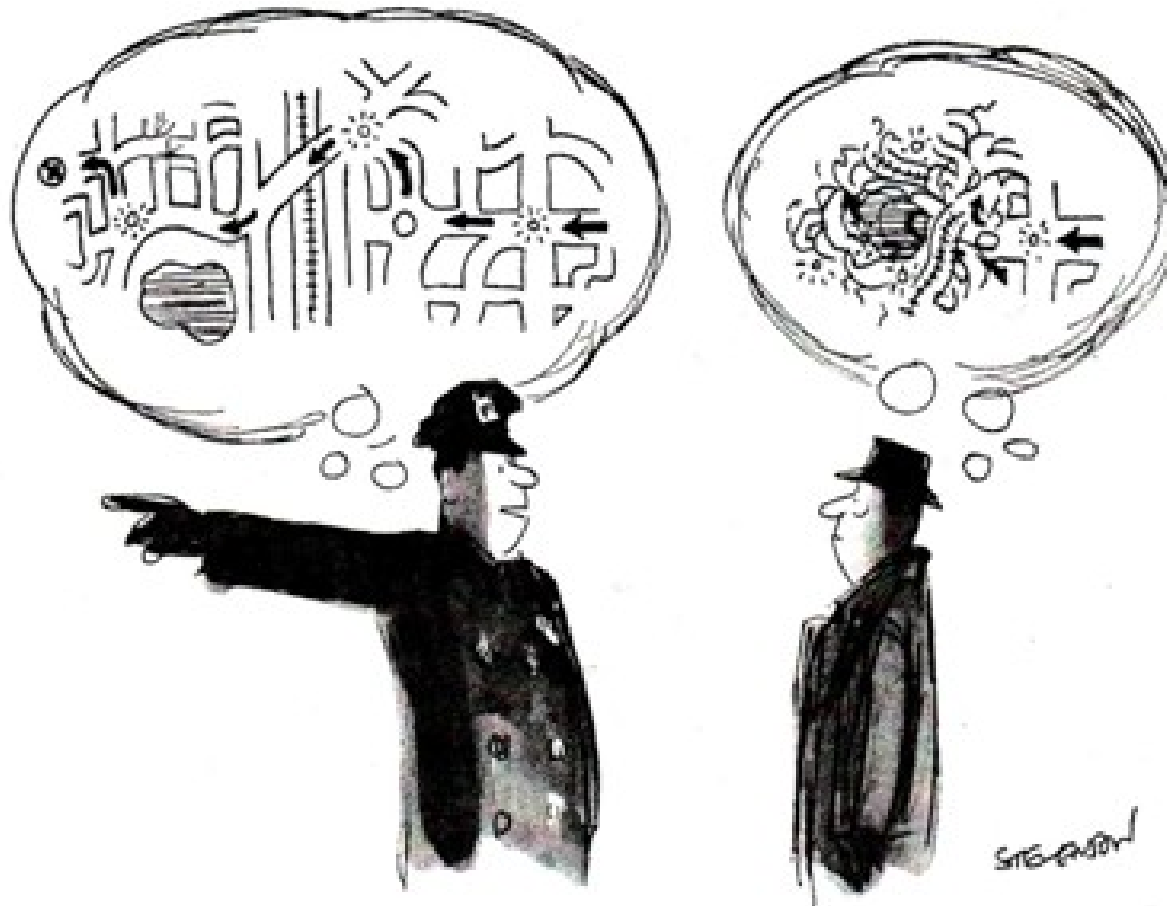


**An infinity of images may be mapped to the same symbol.**

- Any verb may describe a continuum of possible trajectories. \*
- For the details, a picture may be worth a thousand words.
- But each verb expresses the intention of some agent.
- For intentions, a single word may be worth a thousand pictures.

**Nearly all words have an open-ended variety of *microsenses*.**

# Communication



**An image contains much more information than a string of symbols.**

- Expressing a mental image in language loses information.
- Reconstructing an image from language is a rough approximation.
- It's unlikely that a “language of thought” is the medium for storing and reasoning about mental imagery.
- But how is the information processed, remembered, and related?

# Mental Models

## Hypothesis of “artificial causation” by Kenneth Craik (1943):

If the organism carries a ‘small-scale model’ of external reality and of its own possible actions within its head, it is able to try out various alternatives, conclude which is the best of them, react to future situations before they arise, utilize the knowledge of past events in dealing with the present and future, and in every way to react in a much fuller, safer, and more competent manner to the emergencies which face it. (p. 61)

## Proposed as a basis for AI by Marvin Minsky (1963).

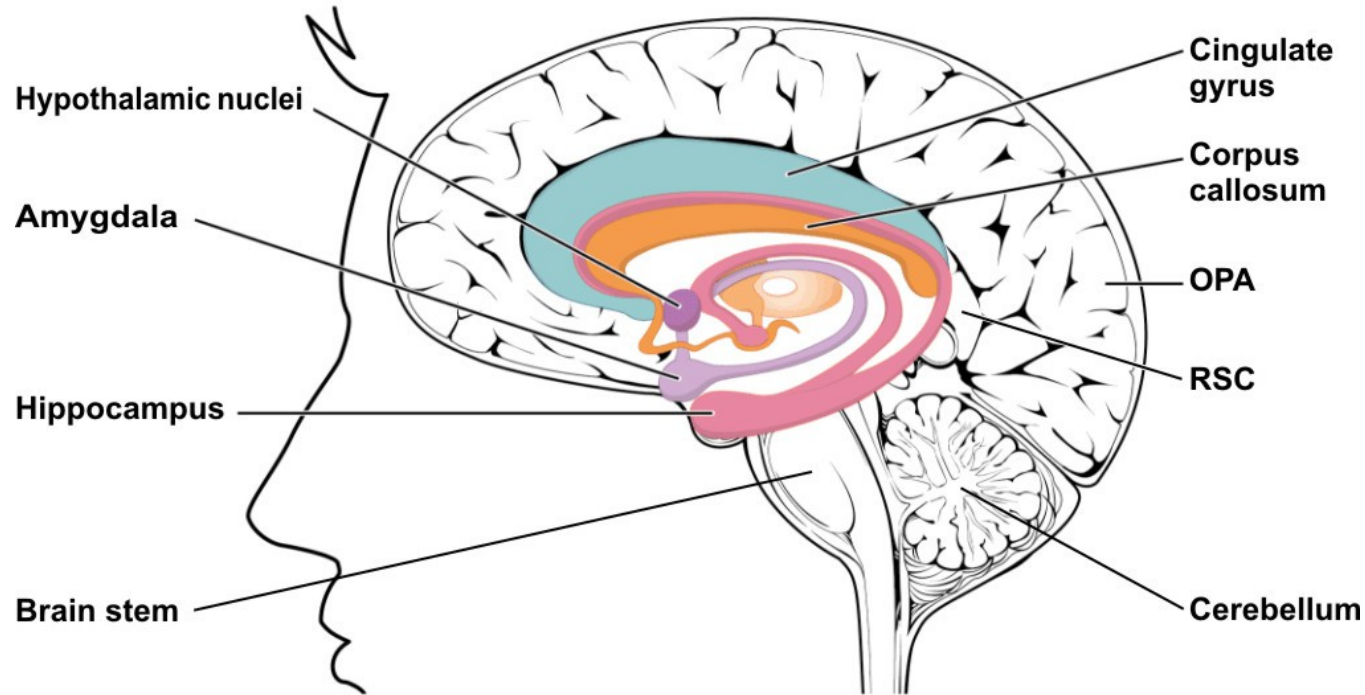
## Widely accepted, but with different interpretations:

- **GOFAI:** The models are constructed from patterns of symbols (chunks, frames, or schemata) and processed by symbolic rules or procedures.
- **Embodied cognition:** The models are analog simulations, represented in patterns that have a direct (topographic) mapping to sensory input.
- **Dual coding:** Both kinds of representations occur in the brain, and both must be integrated for human-level cognition. But how?

**These options have been actively debated for half a century.**



# Mental Imagery



**A panoramic image is constructed from perception and memory:**

- **Brain regions involved: Hippocampus, the occipital place area (OPA), and the retrosplenial complex (RSC or Brodmann's area 29). \***
- **The eyes are constantly flitting from point to point in a scene.**
- **But a stable panoramic view is assembled from multiple retinal images derived from immediate perception and/or memories of past views.**
- **In rats, the RSC is active in learning and running through a maze.**

\* Dilks et al. (2013). Robertson et al. (2016). Diagram adapted from Wikipedia.

# Situated Simulation

## **Neural and psychological research by Lawrence Barsalou: \***

- **Mental models are re-enactments of aspects of previous experience.**
- **Unconscious re-enactments occur during memory and reasoning.**
- **Conscious re-enactments are usually called mental imagery.**

## **Cognition is grounded in perception, action, and proprioception.**

- **Simulations can re-enact social interactions in situations.**
- **Simulated imagery can stimulate the same emotions as perception.**

## **Simulation promotes learning and social understanding:**

- **The neurons (AKA “mirror neurons”) used in performing an action are also activated in seeing another person perform the same action.**
- **Simulations in motor and emotional systems are critical to empathy, social understanding, and successful cooperation.**
- **Since semantics is based on imagery, language enables a speaker to stimulate similar patterns of imagery and feelings in the listener.**

\* See <http://barsaloulab.org/online-articles/navigation-pane-for-articles/>

# Machine Learning (ML)

Most ML methods learn to approximate a function  $f: x \rightarrow y$ , where  $x$  and  $y$  are vectors of features or other observable aspects. \*

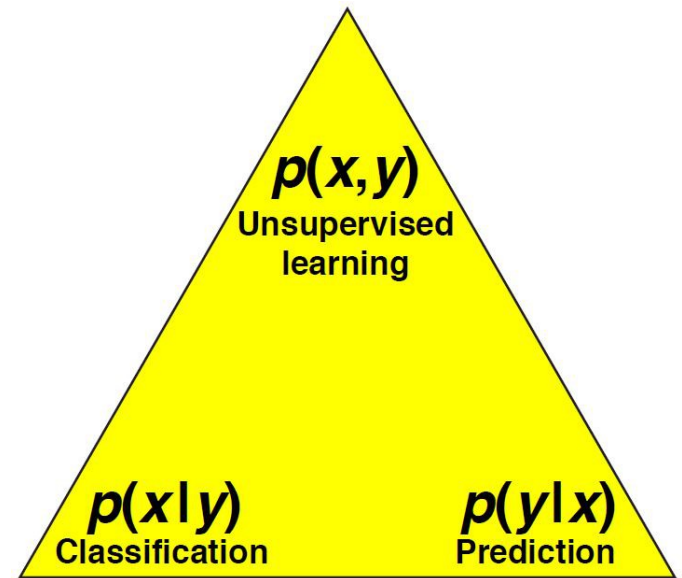
Unsupervised learning begins with a set of pairs of the form  $(x,y)$  and computes an estimated probability  $p(x,y)$  for any  $x$  and  $y$ .

For classification,  $p(x | y)$  is the probability that something described by the feature vector  $y$  belongs to a class  $x$ .

For prediction,  $p(y | x)$  is the probability that a state described by a vector of features  $x$  will be followed by a state described by  $y$ .

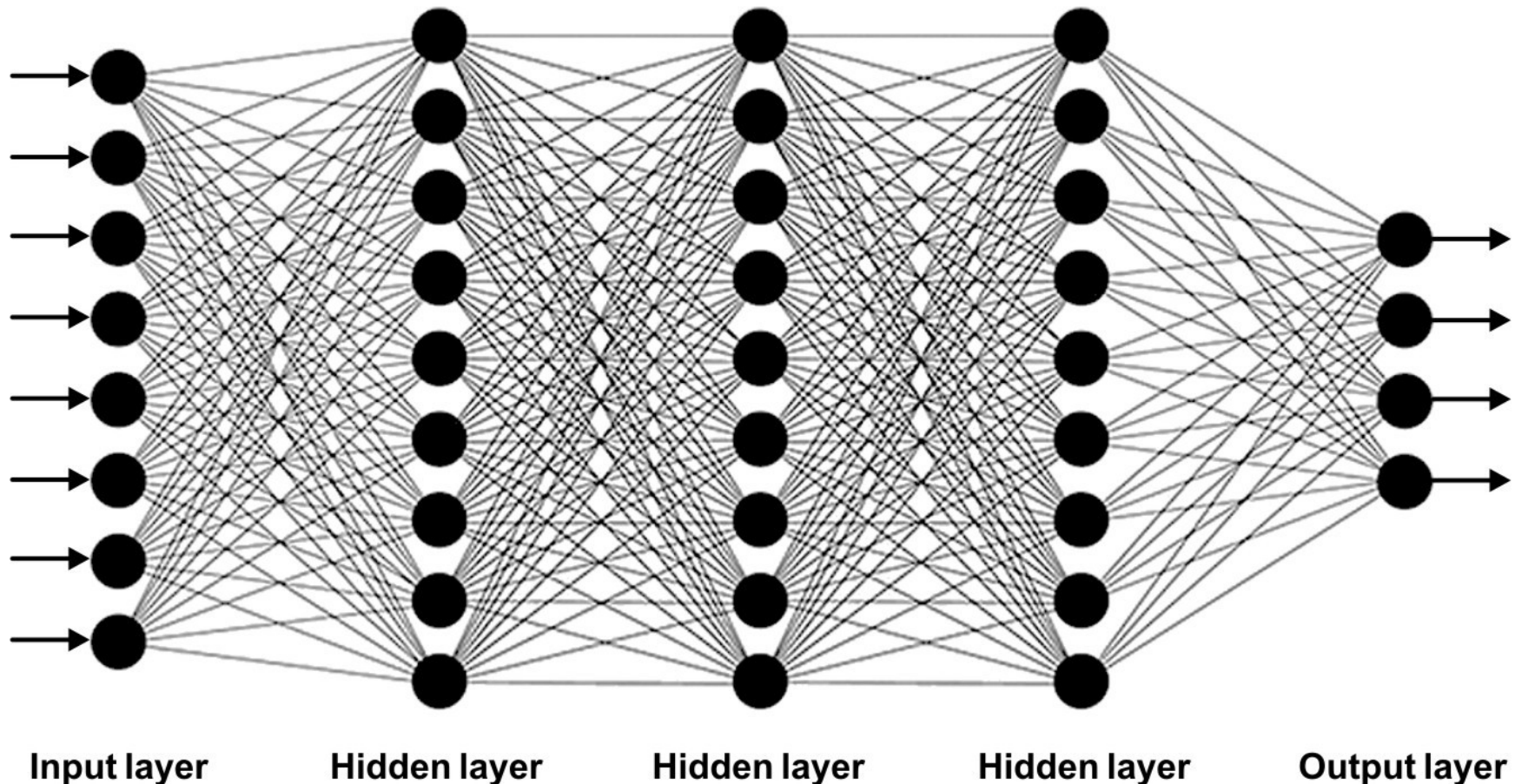
Such functions represent the kind of learning that psychologists analyzed and described by stimulus-response (S-R) theories.

But S-R theories could only explain the early stages of perceptual learning. They could not explain complex language and reasoning.



\* Henry Lin & Max Tegmark (2016) [Why does deep and cheap learning work so well?](#)

# Deep Neural Networks



**DNNs are highly efficient versions of artificial neural networks.**

- **Early ANNs with multiple hidden layers were very slow to learn the weights on the links that define the functions.**
- **The improved algorithms for DNNs enable them to learn complex functions from larger volumes of data in much less time.**

# Machine Learning Applications

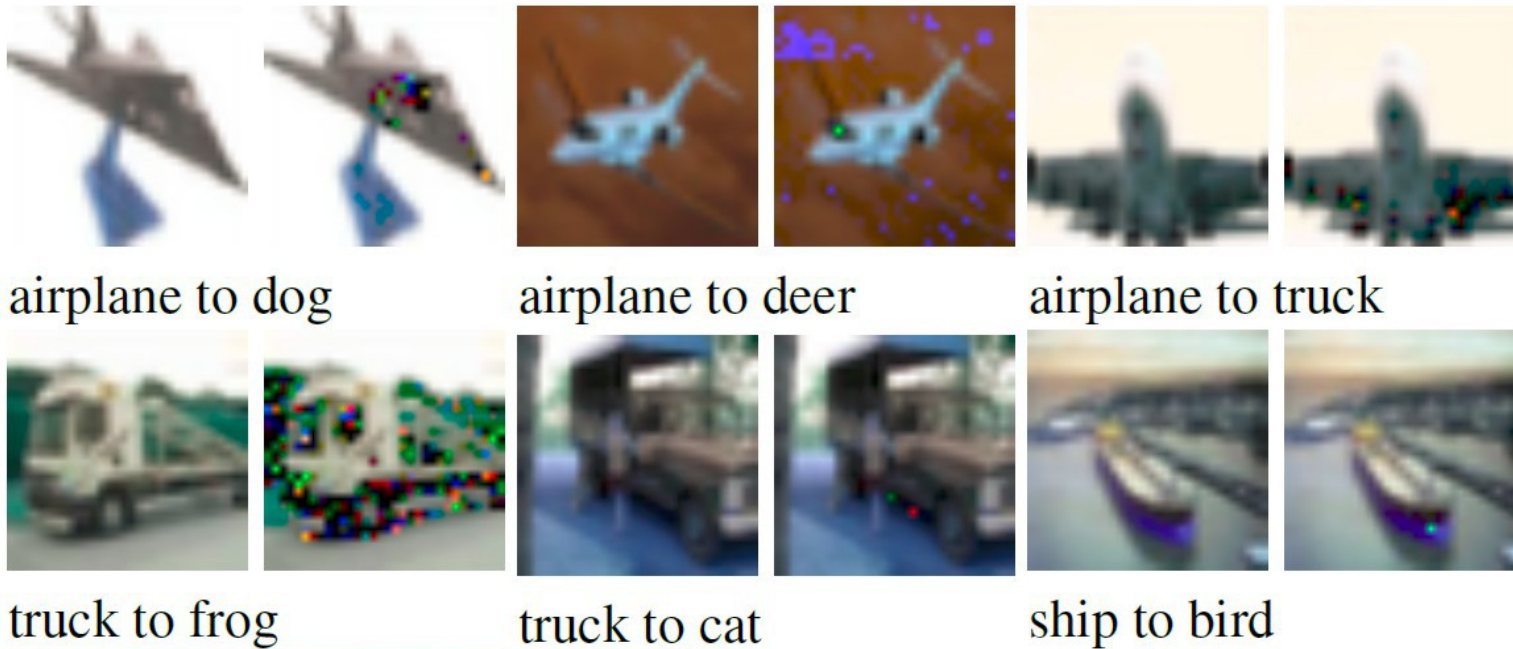
Stimulus $x$	Response $y$	Application
Picture	Are there human faces? (0 or 1)	Photo tagging
Loan application	Will they repay the loan? (0 or 1)	Loan approvals
Ad plus user information	Will user click on ad? (0 or 1)	Targeted online ads
Audio clip	Transcript of audio clip	Speech recognition
English sentence	French sentence	Language translation
Sensors from hard disk, plane engine, etc.	Is it about to fail?	Preventive maintenance
Car camera and other sensors	Position of other cars	Self-driving cars

**Learning a function  $f: x \rightarrow y$  is only one aspect of intelligence.**

- **Observation by Andrew Ng: Current ML methods automate tasks that take less than one second of mental effort by humans. \***
- **Every one of Ng's examples learns to recognize a pattern.**
- **None of them do cognitive reasoning or language understanding.**

\* Andrew Ng (2016) <https://hbr.org/2016/11/what-artificial-intelligence-can-and-cant-do-right-now>

# Slight Perturbations



**Random noise or perturbations may cause a misclassification.**

- Six pairs of images show the originals and slightly modified versions.
- A DNN that correctly classified the first member of each pair made serious mistakes in classifying the modified versions. \*
- Such mistakes in a self-driving car could cause a disaster.

**People and other animals use cognition to correct perception.**

- If they see something unexpected, they blink and take a second look.

\* Huang et al. (2017) [Safety Verification of Deep Neural Networks](#)

# What Makes People Intelligent?

**Minsky's answer: A society of heterogeneous agents. \***

**What magical trick makes us intelligent? The trick is that there is no trick. The power of intelligence stems from our vast diversity, not from any single, perfect principle. Our species has evolved many effective although imperfect methods, and each of us individually develops more on our own. Eventually, very few of our actions and decisions come to depend on any single mechanism. Instead, they emerge from conflicts and negotiations among societies of processes that constantly challenge one another. §30.8**

**The Society of Mind can support an open-ended diversity.**

- **It can accommodate ACT-R, DCT, networks, mental models, etc.**
- **It's convenient for implementing modular AI systems.**
- **But by itself, it doesn't explain how and why those modules are related.**
- **It's a useful framework, but more is required.**

**\* Marvin Minsky (1986) *The Society of Mind*, New York: Simon & Schuster.**

**See also Push Singh & Marvin Minsky (2005) [An architecture for cognitive diversity](#).**

# What is Cognition?

**Barsalou's answer: coordinated non-cognition. \***

- Cognition is “embedded in, distributed across, and inseparable from” the “processes of perceiving, acting, and emoting.”
- Visual and motor simulations are essential to language understanding.
- When people view a static object, they anticipate working with it.
- When people view food, they anticipate its taste when eating it.
- Musicians identify their own performances by recognizing the fingering.
- Affect, feelings, rewards, and value judgments are fundamental to all aspects of reasoning and decision making.
- No single aspect is cognition, but all of them together are cognition.
- Social interactions facilitate learning by stimulating more aspects.

**Barsalou's answer is compatible with the Society of Mind.**

- But Minsky, in 1986, was still thinking in terms of GOFAL.
- The society must integrate the mind and body at every level.

\* Barsalou, Breazeal, & Smith (2007) [Cognition as coordinated non-cognition](#).



# 2. The Role of the Cerebellum

**The cerebellum supports the virtual reality of the mind:**

- The human cerebellum takes only 10% of the volume of the brain, but it has about 70 billion neurons. The cerebrum has only 16 billion. \*
- It plays a major role in perception, movement, cognition, language, planning, emotion, and social interactions. \*\*
- When projected to the cerebral cortex, the VR may be conscious, but the processes in the cerebellum that generate the VR are not conscious.

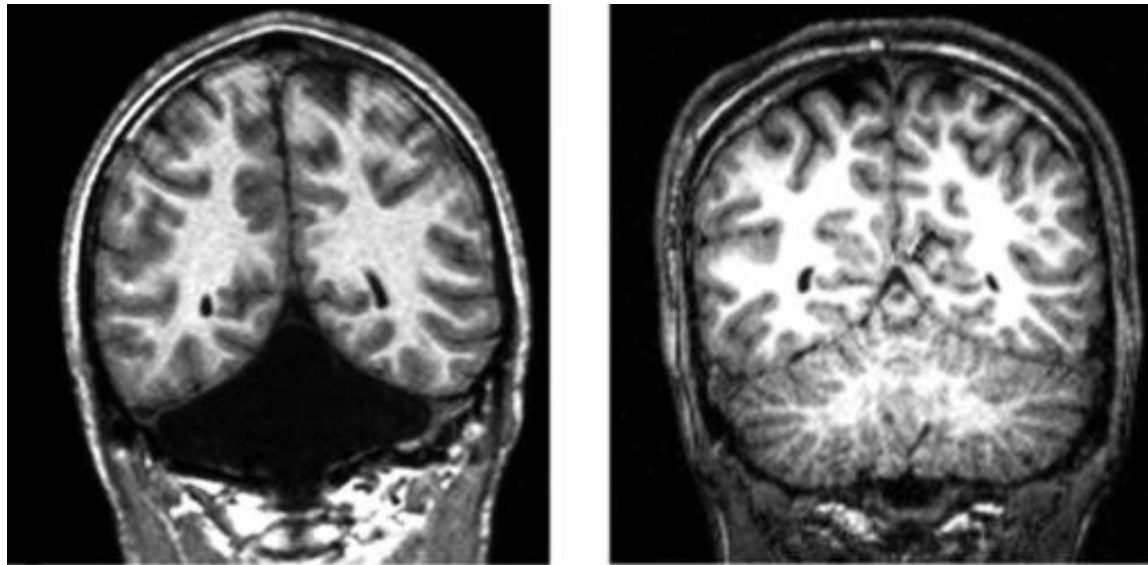
**But many cognitive scientists underestimate its importance:**

- Jeff Hawkins (2004): “If you are born without a cerebellum or it’s damaged, you can lead a pretty normal life.”
- But with only 16 billion neurons, the cerebrum can, at best, simulate the VR slowly, inefficiently, and incompletely.
- If the cerebral cortex is compared to the CPU of a computer, the cerebellum plays the role of a GPU (Graphic Processing Unit).
- The tiny number of people who were born without a cerebellum and survived have severe cognitive deficits.
- For them, life is like playing video games on a computer without a GPU.

\* Suzana Herculano-Houzel (2009, 2012).

\*\* Consensus paper (2014) [The cerebellum's role in movement and cognition.](#)

# Cerebellar Agenesis

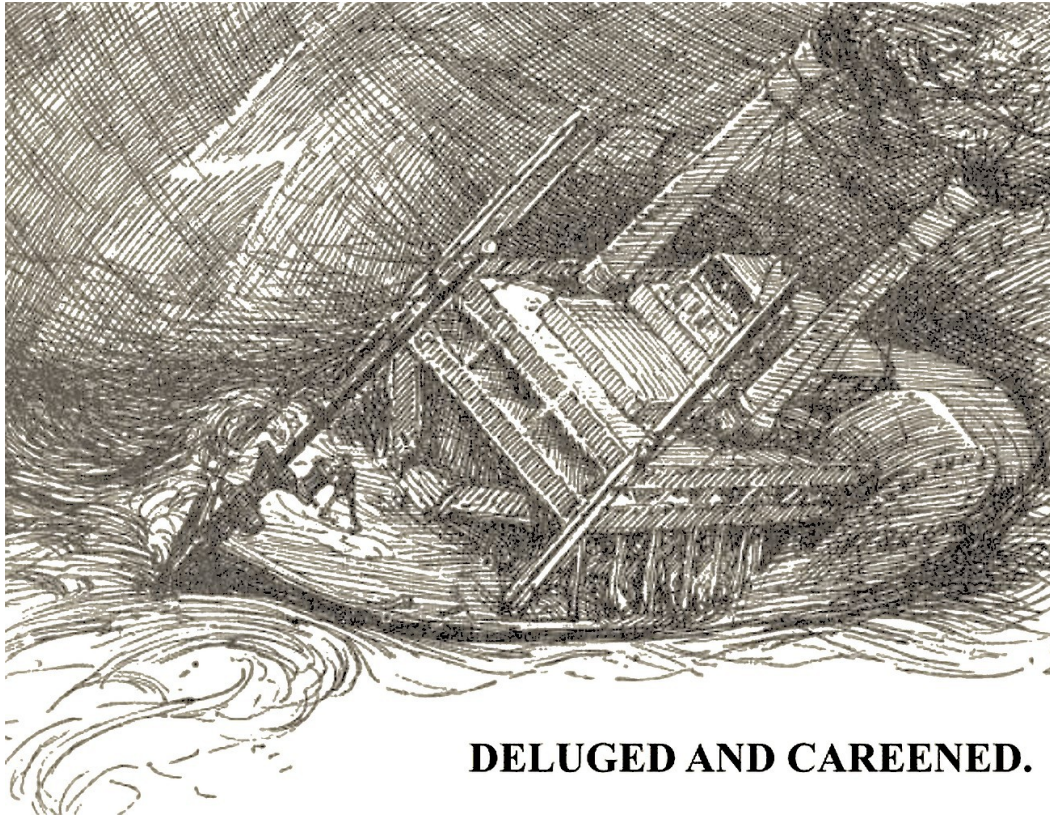


**Jonathan Keleher was born without a cerebellum.**

- On the right is an MRI scan of the brain of a normal male at age 33. \*
- On the left is an MRI scan of JK's brain at the same age. The black space filled with fluid is where the cerebellum should be.
- As a child, JK's developmental stages were long delayed.
- After many years of physical therapy, speech therapy, and special education, JK is now a cheerful, friendly, but awkward adult.
- He is able to hold **an office job**, but he still has cognitive, emotional, social, and learning deficits.

\* See [A Man's Incomplete Brain Reveals Cerebellum's Role In Thought And Emotion](#), NPR.

# Cognition of Physical Phenomena



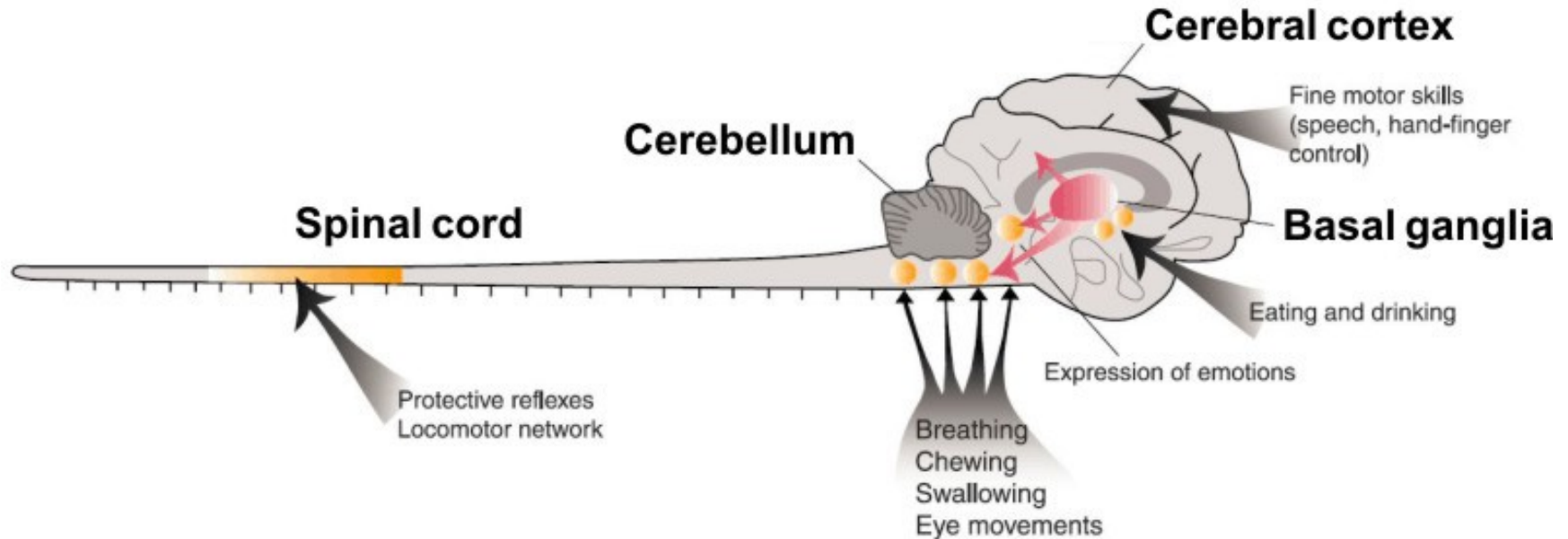
DELUGED AND CAREENED.

From *Life on the Mississippi* by Mark Twain:

“Two things seemed pretty apparent to me. One was, that in order to be a pilot a man had got to learn more than any one man ought to be allowed to know; and the other was, that he must learn it all over again in a different way every twenty-four hours.”

**With a normal cerebellum, Mark Twain eventually became a pilot. But Jon Keleher still cannot ride a bicycle or drive a car.**

# The Vertebrate Brain



**Basic control mechanisms were conserved for 560 million years.**

- Mammals, especially primates, have a greatly enlarged cerebral cortex.
- But the basal ganglia control the motor functions in all vertebrates from the primitive lamprey to the birds and mammals. \*
- Those control functions are not conscious, but their effects, when projected to the cerebral cortex, may become conscious.
- When people are talking while driving, lower processes are in control.
- When complications arise, the cerebral cortex takes conscious control.

\* Diagram from Gillner et al. (2013) [The evolutionary origin of the vertebrate basal ganglia.](#)

# Bird Nest Problem

**Robots can perform many tasks with great precision.**

**But they don't have the flexibility to handle unexpected shapes.**

**They can't build a nest in an irregular tree with irregular twigs, straw, and moss.**

**In terms of brain-body mass ratio, birds are comparable to mammals.**

**And their forebrain is so densely packed with neurons that it's comparable to a primate cerebrum.**

**A human brain has about 60 million neurons per gram. A macaw brain (21 g) or raven (14 g) have about 240 million per gram. \***

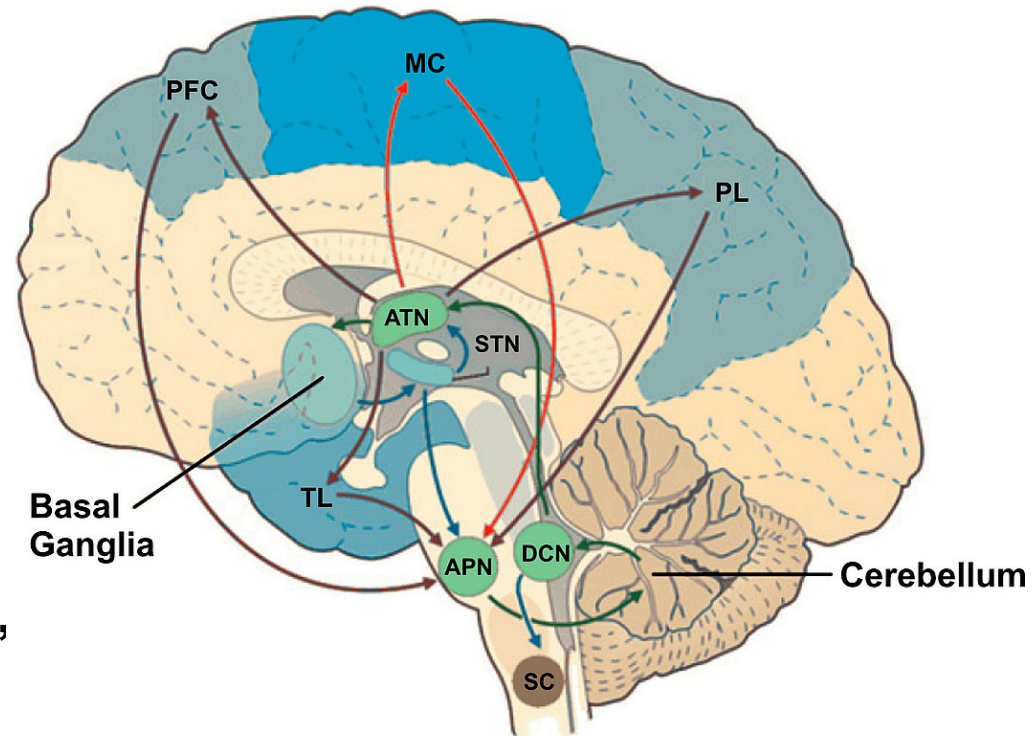


\* See Suzana Herculano-Houzel et al. (2016).

# Cerebellar Connections

The cerebellum has links to and from many areas of the brain.

- The term *virtual reality* describes the unconscious, 3-D simulations by the cerebellum, which may or may not become conscious when projected to the cerebral cortex.
- So-called “mirror neurons” in the the cerebral cortex reflect the connections that support learning, empathy, and cooperation.
- The cerebellum also has links to the basal ganglia, limbic system, and brain stem.
- Abbreviations in the diagram: PFC, prefrontal cortex. MC, motor cortex. PL, parietal lobe. ATN, anterior thalamic nuclei. STN, subthalamic nucleus. TL, temporal lobe. APN, anterior pontine nucleus. DCN, deep cerebellar nuclei. SC, spinal cord. \*



# Cycles in Neural Networks

**Typical DNNs are feed-forward networks (no cycles).**

**Advantages and disadvantages of loops (cycles) in a network:**

- **Cycles allow recursion and more complex computations.**
- **But feedback loops can create unlimited amplification. Without strict controls, they may generate chaos or even an epileptic seizure.**
- **For safety, inhibitory (negative) feedback dampens the oscillations.**
- **Recurrent neural networks (RNNs) support temporal reasoning by restricting cycles to a simulation of time or a time-like sequences.**

**The human brain is organized as a collection of modules:**

- **Within a module, the short, high-speed links are mostly feed forward.**
- **Cycles among modules have longer links, take more time, and are less likely to create chaotic amplification.**

**The cerebellum learns static and dynamic patterns.**

- **It combines and relates sensations from all modalities.**
- **It predicts visual, sensory, and motor movements.**

# Mathematics and the Cerebellum

**The cerebellum is active in mathematical reasoning.**

- Neuroscientists had thought it was dedicated to controlling movement.
- But fMRI scans show that it's active when people are doing math.

**It's even active for the most abstract branches of mathematics:**

- Early studies showed that the cerebellum is active in arithmetic. \*
- But it's active in expert reasoning in every branch of mathematics.

**Comparison of mathematicians and non-mathematicians: \*\***

- **Subjects:** Experts in algebra, analysis, geometry, or topology.
- **Controls:** Same academic standing, but mathematically naive.
- During an fMRI scan, they classified sentences as meaningful or meaningless. If meaningful, they also responded true or false.
- For sentences about math, the cerebellum was active for mathematicians, but not for the non-mathematicians.
- This confirms introspective reports by mathematicians. (See next slide).

\* S. Feng et al. (2008) [The cerebellum connectivity in mathematics cognition.](#)

\*\* M. Almaric & S. Dehaene (2016) [Brain networks for advanced mathematics.](#)



# Mathematics and Imagery

## Paul Halmos, mathematician:

**“Mathematics — this may surprise or shock some — is never deductive in its creation. The mathematician at work makes vague guesses, visualizes broad generalizations, and jumps to unwarranted conclusions. He arranges and rearranges his ideas, and becomes convinced of their truth long before he can write down a logical proof... the deductive stage, writing the results down, and writing its rigorous proof are relatively trivial once the real insight arrives; it is more the draftsman’s work not the architect’s.” \***

## Albert Einstein, physicist:

**“The words or the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be *voluntarily* reproduced and combined... The above-mentioned elements are, in my case, of visual and some of muscular type. Conventional words or other signs have to be sought for laboriously only in a secondary stage, when the mentioned associative play is sufficiently established and can be reproduced at will.” \*\***

\* Halmos (1968). \*\* Quoted by Hadamard (1945). See also Lakoff & Núñez (2000).

# Autism and the Cerebellum

## **Patients with with autistic spectrum disorder (ASD) \***

- **Often have decreased cell counts in the cerebellum.**
- **May also have impairments in connections of the cerebellum to areas of the cerebral cortex for movement, language, and social interactions.**

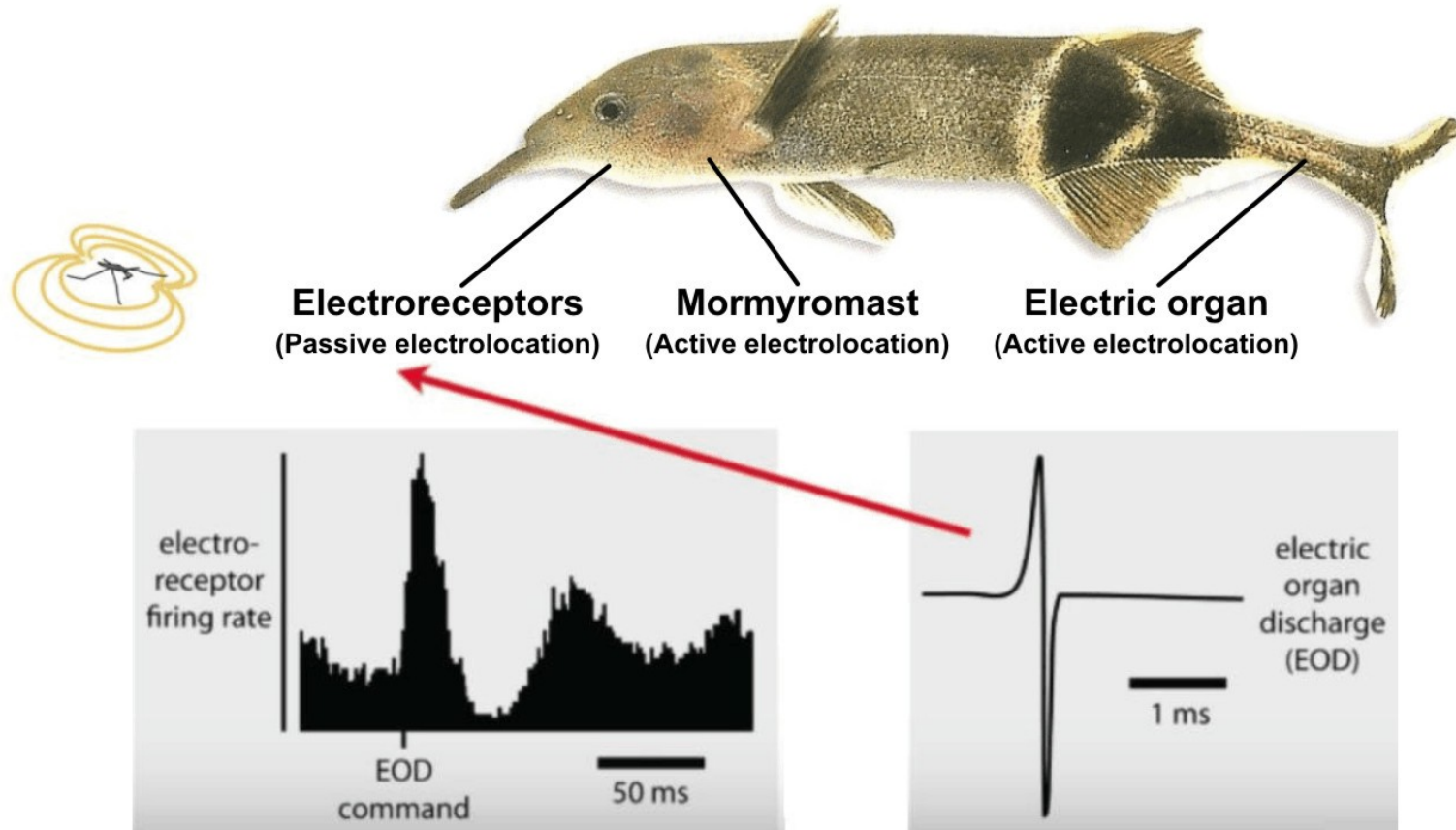
## **Jon Keleher was not autistic, but he had some ASD symptoms:**

- **Late learning to speak and subsequent impairment in language use.**
- **Flat emotions and shallow social relationships.**
- **Difficulty in learning by watching others indicates the importance of simulations in the cerebellum for understanding social relations.**
- **ASD and cerebellar agenesis have very different etiology, but deficits in the cerebellum and the cerebellar loops may lead to similar symptoms.**

**This evidence shows the importance of the cerebellar links for relating imagery to cognition, emotion, and language.**

\* D'Mello & Stoodley (2015) [Cerebro-cerebellar circuits in autism spectrum disorder](#).  
A. Crippa et al. (2016) [Cortico-cerebellar connectivity in ASD](#).

# Elephantnose Fish (*Gnathonemus petersii*)



**A fish with a larger brain-body mass ratio than humans.**

**Its “gigantocerebellum” does an amazing amount of computation:**

**Generate an electrical pulse, subtract its own electrical field from the response to detect the field of an insect, and compute the location of the prey relative to its own body while both of them are moving.**

\* Diagram adapted from Wikipedia and a [lecture by Larry Abbot](#).

# Two Kinds of Bats

**Fruit bats eat stationary food in daylight hours.**

**Insect-eating bats catch flying food in the dark.**

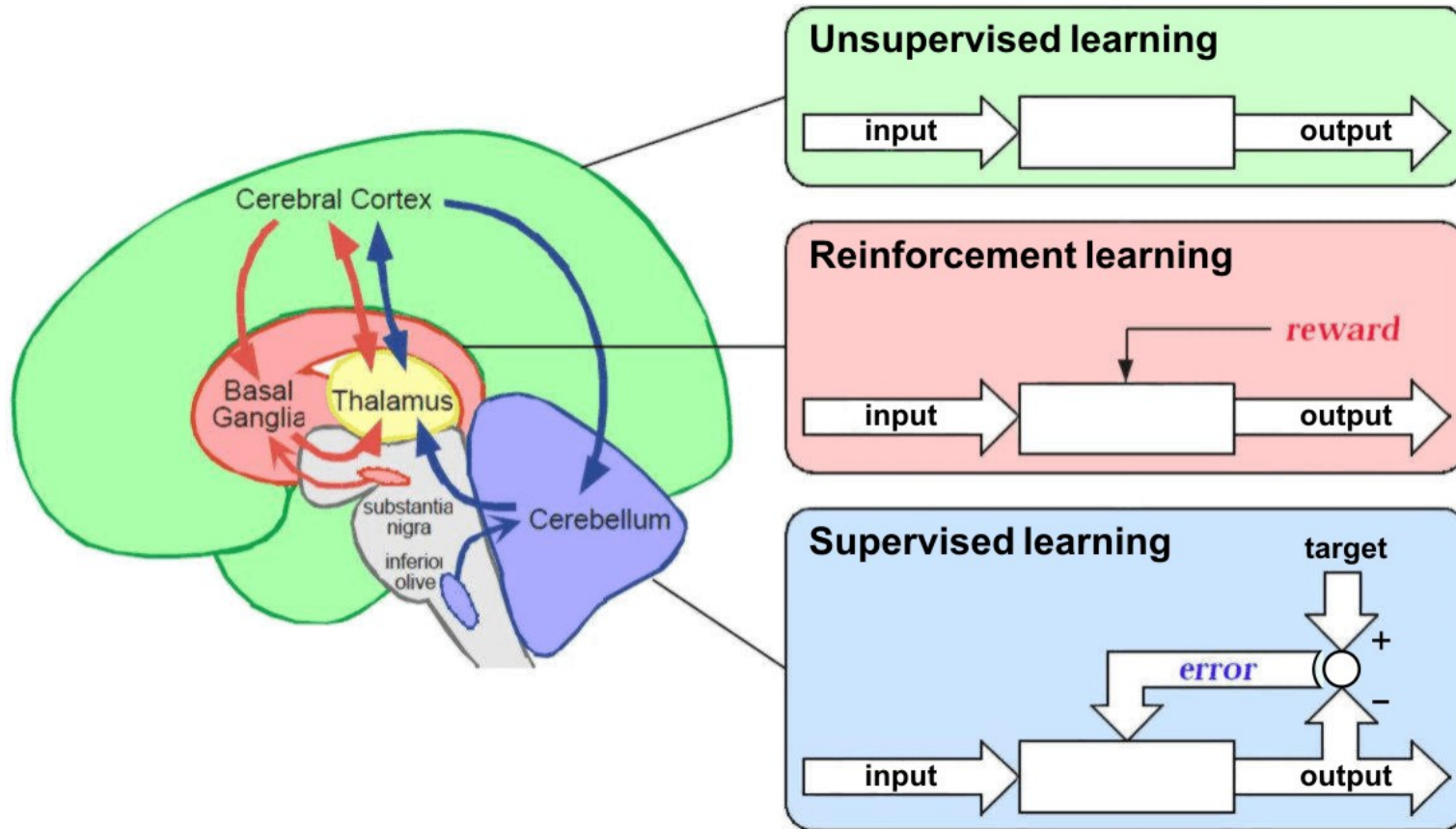
**Comparison with the cerebellum of birds and dolphins:**

- **The lobes of the cerebellum of both kinds of bats have similarities to the lobes of birds, because they fly in 3-dimensional space.**
- **The lobes of the cerebellum of dolphins also have similarities to the lobes of birds, because dolphins swim in 3-D space.**
- **The auditory lobes of the cerebellum for dolphins and the insect-eating bats have similarities because they both use echolocation.**
- **The greater sensory complexity for insect-eating bats is correlated with a relatively larger cerebellum.**

**Implications:**

- **The primary role of the cerebellum is to process sensory input.**
- **The generation of motor control signals is less demanding.**

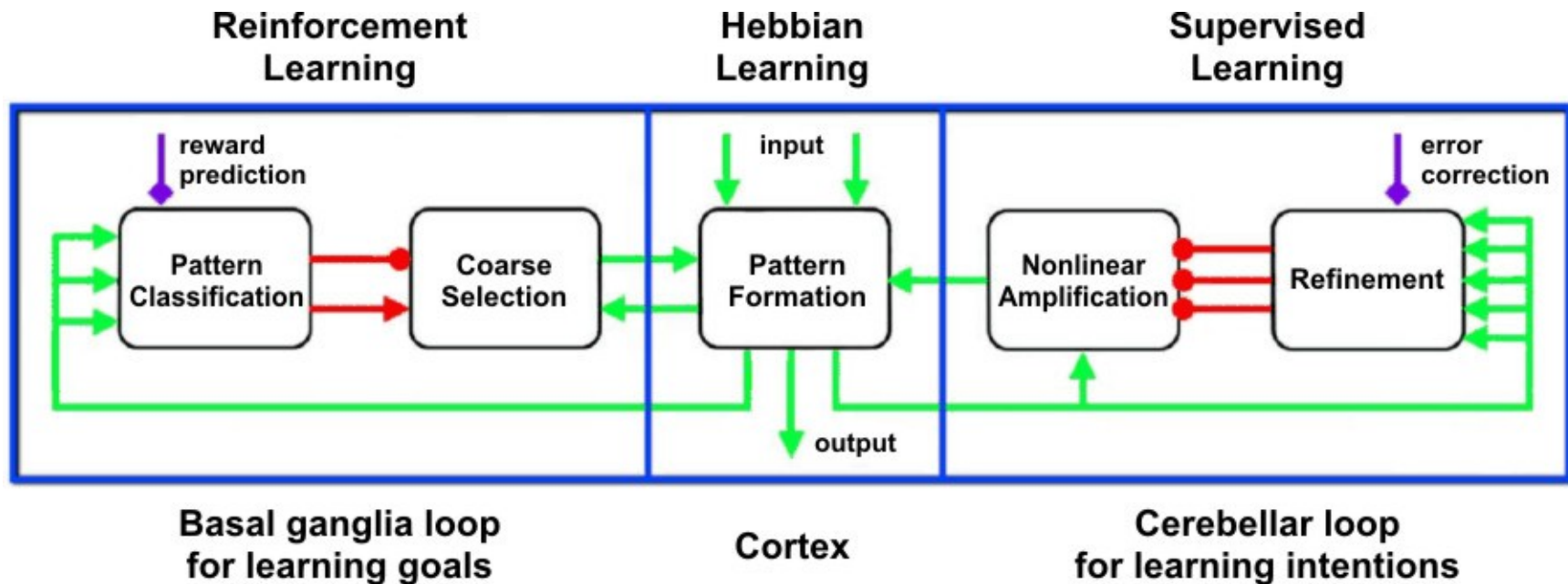
# Three Methods of Learning



## Hypothesis by Doya (2000).

- **Cerebral cortex:** Unsupervised learning, as proposed by Donald Hebb.
- **Basal ganglia:** Reinforcement learning, with a dopamine reward.
- **Cerebellum:** Supervised learning, with cerebral cortex as supervisor.

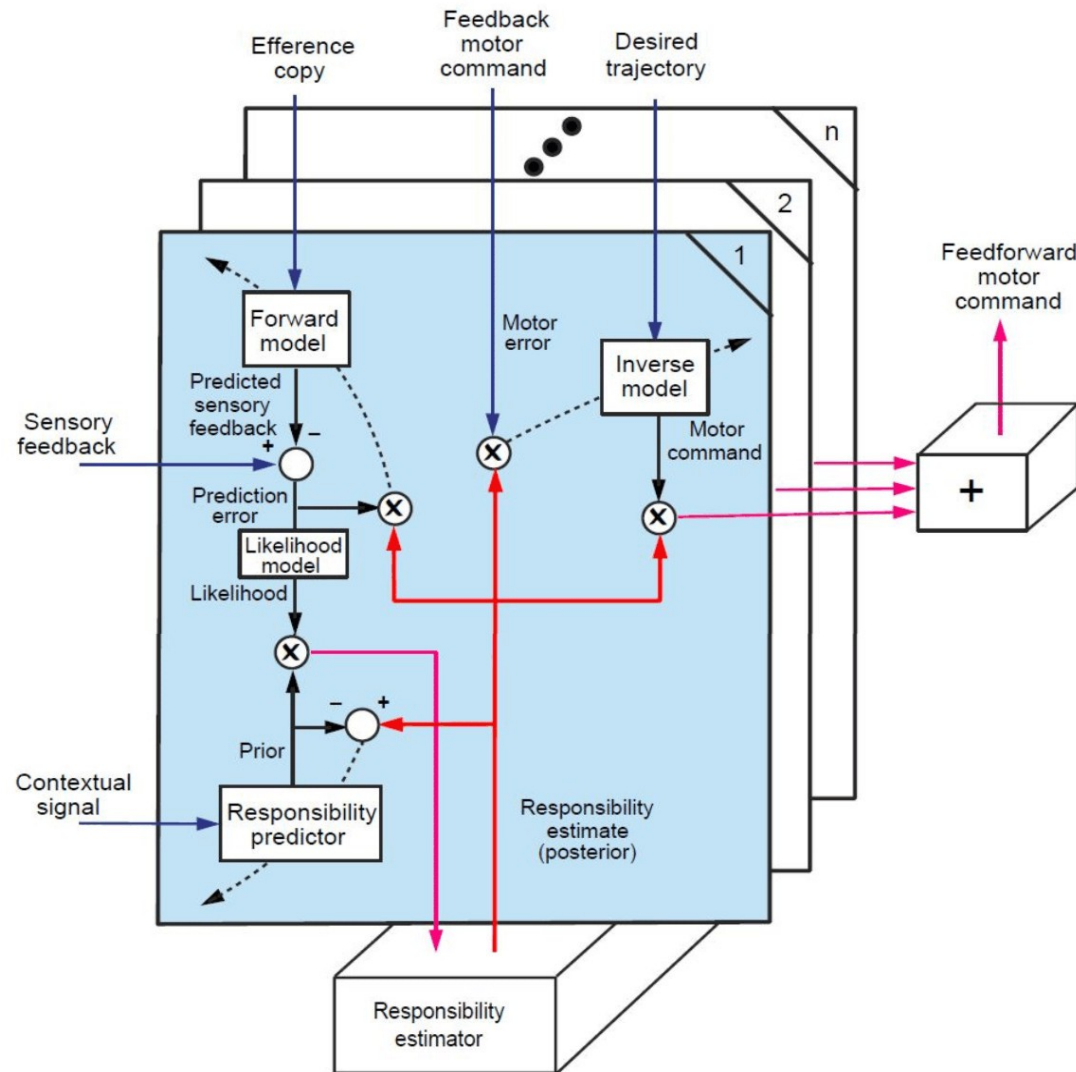
# Updated Version



**Caligiore et al. (2016) revised and extended Doya's diagram:**

- **Cerebral cortex:** Learn patterns by Hebbian-style learning.
- **Basal ganglia:** Learn production rules (if-then style) with dopamine rewards generated by a signal from the cortex to the substantia nigra.
- **Cerebellum:** Supervised learning with the cortex as supervisor.
- **Arrows with a pointed end** add or strengthen a pattern.
- **Arrows with a circular end** delete or inhibit a pattern.
- **Arrows with a diamond end** may strengthen or inhibit.

# Prediction and Responsibility



**The cerebellum can make predictions (forward reasoning) or determine responsibility (backward reasoning). It relates perception and intention. \***

\* Diagram from Wolpert, Miall, & Kawato (1998).

See also Roth, Synofzik, & Lindner (2013) The Cerebellum optimizes perceptual predictions .

# Learning Perceptual and Motor Patterns

Drawing shows Purkinje neurons (A) and granule neurons (B). \*

Cerebellum has about 50 billion granule cells, each with about 4 dendrites.

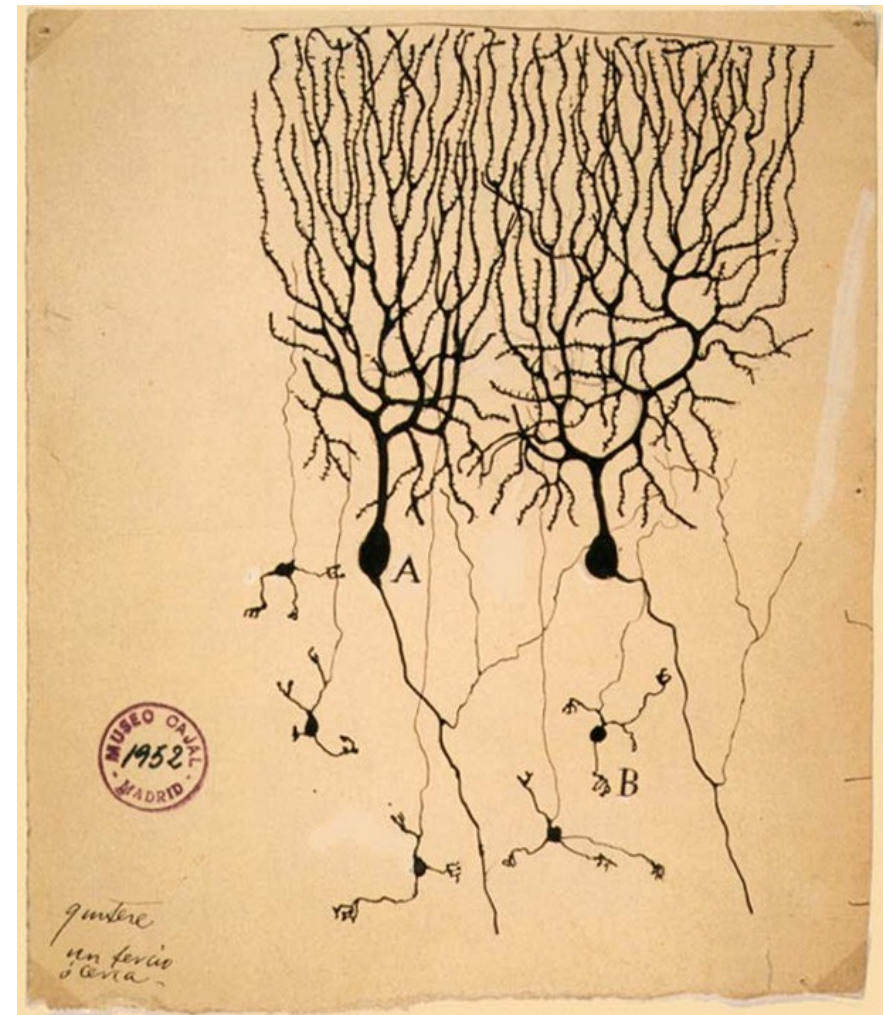
It has much fewer Purkinje cells, but each one has over 100,000 synapses.

Marr, Albus, and others suggested that granule cells form networks that learn perceptual and motor patterns.

Purkinje cells transmit that information from the granule cells to the cerebrum.

The cerebrum builds on the perceptual patterns as the basis for cognitive learning, reasoning, and language.

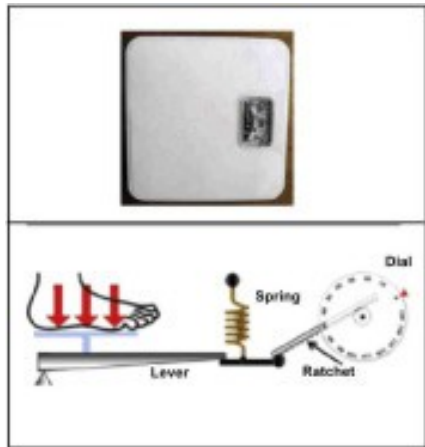
The cerebrum is a general-purpose processor, and the cerebellum behaves like a computationally intensive graphics processor.



\* Drawing by Santiago Ramón y Cajal, copy from Wikipedia.



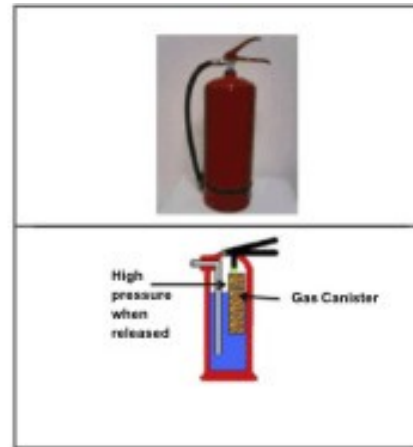
# Perceptual and Cognitive Learning



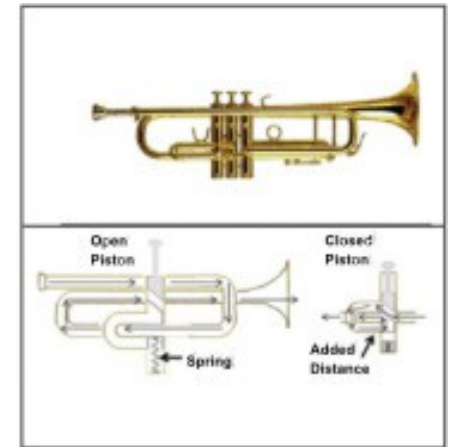
Bathroom Scale



Disc Brake System



Fire Extinguisher



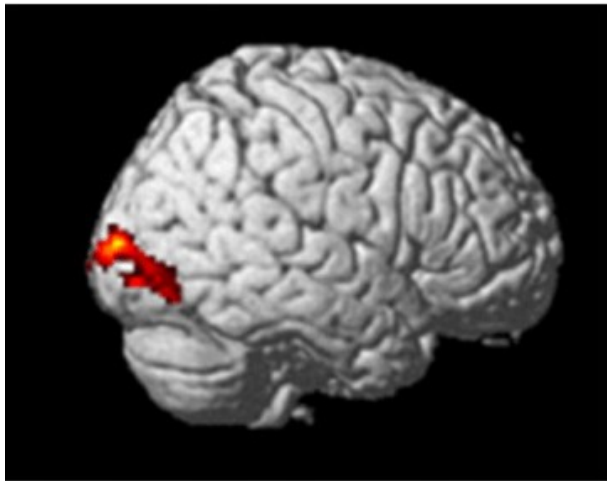
Trumpet

**14 participants studied how four devices work: bathroom scale, fire extinguisher, disc brake system, and trumpet. \***

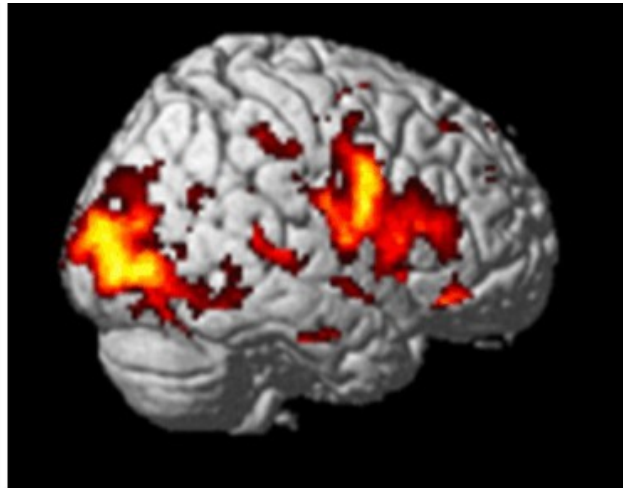
- **Subjects:** college students who were not science or engineering majors.
- **Mutple training sessions and test sesions with each of the four devices.**
- **During test sessions, an fMRI scanner recorded patterns of brain activity.**
- **An early training session just showed pictures and named the parts: *A bathroom scale consists of a spring, a lever, a ratchet, and a dial.***
- **Later sessions explained structural and causal relations: *The spring pulls a ratchet which rotates a gear attached to a measurement dial.***

\* R. A. Mason & M. A. Just (2015) [Physics instruction induces changes in neural representation.](#)

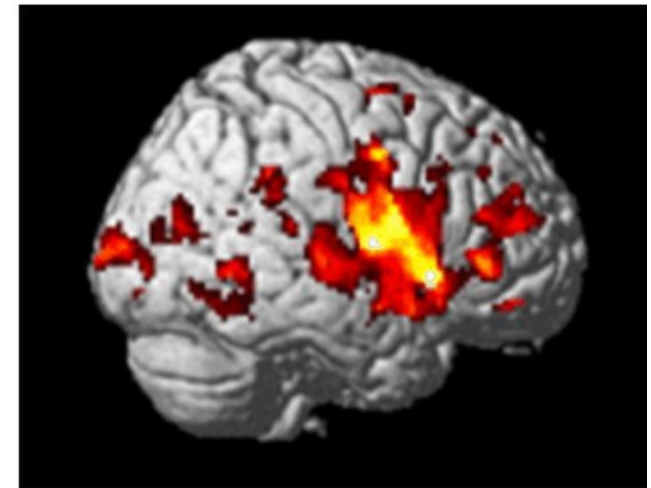
# Cognitive Learning



1. Visual perception



2. Thinking about structure



3. Thinking about causality

## Neural activity in the right hemisphere during test sessions:

- All 14 students showed similar neural activations.
- Questions about the objects and parts activated the visual cortex, the occipital lobes in the back of the brain (image #1).
- Questions about structural relations activated the parietal lobes, which link vision to all sensory and motor regions (image #2).
- Questions about the causal effects of someone operating the system activated the frontal lobes and connections across the brain (image #3).
- **Summary:** Cognitive learning involves structural and causal relations that link and coordinate perception, action, and reasoning.

# Arthropod Brains

The arthropoda, which include crustaceans and insects, split from the vertebrates over 550 million years ago.

But they have many common genes for related neural functions.

**Convergent evolution for spatial memory and navigation:**

- The “mushroom bodies” of the arthropod brain correspond to the hippocampus in vertebrates. \*
- London taxi drivers, who have to memorize all the streets in the city, have an enlarged hippocampus.
- Birds that forage long distances have a larger hippocampus than birds of the same species that live where food is more abundant.
- Honey bees that forage outside the hive have an enlarged calyx of their mushroom bodies compared to bees that work inside the hive.

**The architecture of an animal’s brain is adapted to the way its body and sense organs interact with the environment.**

\* Nicholas Strausfeld (2012) *Arthropod Brains: Evolution, Functional Elegance, and Historical Significance*, Cambridge, MA: Belknap Press. (p. 548)

# Feelings and Emotions

## Damasio and Carvalho (2013),

- **“Feelings are mental experiences of body states.”**
- **“They signify physiological need, tissue injury, optimal function, threats to the organism, or specific social interactions.”**
- **“Feelings constitute a crucial component of the mechanisms of life regulation, from simple to complex.”**
- **“Their neural substrates can be found at all levels of the nervous system, from individual neurons to subcortical nuclei and cortical regions.”**

## Damasio (2014), \*

- **“I’m ready to give the very teeny brain of an insect – provided it has the possibility of representing its body states – the possibility of having feelings.”**
- **“Of course, what flies don’t have is all the intellect around those feelings that could make use of them: to found a religious order, or develop an art form, or write a poem.”**

\* Interview, <http://www.technologyreview.com/qa/528151/the-importance-of-feelings/>

# Mental Imagery and Feelings

**Nothing in the cerebellum is conscious, but projections of the VR to the cerebral cortex can be conscious.**

**Antonio Damasio (2010):**

**The distinctive feature of brains such as the one we own is their uncanny ability to create maps... But when brains make maps, they are also creating images, the main currency of our minds. Ultimately consciousness allows us to experience maps as images, to manipulate those images, and to apply reasoning to them.**

**Damasio and Carvalho (2013),**

- Feelings are mental experiences of body states.**
- They signify physiological need, tissue injury, optimal function, threats to the organism, or specific social interactions.**
- Feelings constitute a crucial component of the mechanisms of life regulation, from simple to complex.**
- Their neural substrates can be found at all levels of the nervous system, from individual neurons to subcortical nuclei and cortical regions.**

# Consciousness

**Damasio (2010) proposed a 3-level theory of consciousness.**

**The foundation is a *protoself* maintained by the brain stem:**

- Brain stem integrates and relates all sensory inputs and motor outputs.
- For a frog, the brain stem and cerebellum are sufficient for jumping on a lily pad and catching flies.
- For a person talking on a cell phone, the cerebellum can bypass the cerebrum and control walking or driving (!) without conscious thought.

**The *core self* integrates the protoself with the body image:**

- All sensory and motor areas process information about the body.
- An infant learns to relate the body to images of the self and others.
- The core self is the protoself intimately aligned with the body image.

**The *autobiographical self* can think and talk about the core self:**

- Contains all the thoughts and memories about the self throughout a lifetime – what people call their *mind*.
- Language casts the self as the protagonist of a narrative.

# 3. Semiotic Foundation

**Charles Sanders Peirce was a polymath:**

- He published research in mathematics, physics, astronomy, and psychology.
- He was also an associate editor of the *Century Dictionary*, for which he wrote or edited over 16,000 definitions.
- 63 years before Alan Turing, he published an article on artificial intelligence (called “Logical Machines”) in the *American Journal of Psychology*.
- And he was a pioneer in logic who developed a general theory of signs that characterizes reasoning by the minds or “quasi-minds” of all living things.

**Peirce’s semiotic spans the full range of cognitive issues:**

- Perception, action, and mental imagery are fundamental.
- The symbols of natural languages “grow” from those images.
- The notations for mathematics and logic are abstractions from the symbols and patterns in natural languages.
- Peirce’s continuity of minds is related to Aristotle’s hierarchy of psyches from plants, to sponges, to worms, to fish, to mammals, to humans.

**Peirce’s *phaneroscopy*, a kind of phenomenology, is a method for analyzing the VR that is projected to conscious awareness.**

# Phaneroscopy or Phenomenology

**Peirce's phaneron is a conscious awareness of the VR:**

**“Phaneroscopy is the description of the *phaneron*; and by the *phaneron* I mean the collective total of all that is in any way or in any sense present to the mind, quite regardless of whether it corresponds to any real thing or not. If you ask present *when*, and to *whose* mind, I reply that I leave these questions unanswered, never having entertained a doubt that those features of the phaneron that I have found in my mind are present at all times and to all minds. So far as I have developed this science of phaneroscopy, it is occupied with the formal elements of the phaneron.”**  
(CP 1.284)

**He sometimes used the word *phenomenology*:**

**“Phenomenology is that branch of philosophy which endeavours to describe in a general way the features of whatever may come before the mind in any way... The work of discovery of the phenomenologist, and most difficult work it is, consists in disentangling or drawing out, from human thought, certain threads that are seen through it, and in showing what marks each has that distinguishes it from every other.”** (MS 693a)

**See Leila Haaparanta (1994), [Charles Peirce and the drawings of the mind](#)**



# Phenomenology and Virtual Reality

## Different, but related versions:

- The word *phänomenologie* was used by Hegel and Husserl.
- Peirce coined the word *phaneroscopy*, and he sometimes used the word *phenomenology* to recognize the common themes. \*
- But he had disagreements with both Hegel and Husserl, which caused him to vacillate in his choice of words.
- AI researchers sometimes agree with, but more often disagree with Hubert Dreyfus (1992) about the use of phenomenology to criticize AI.

## Phenomenology studies “everyday lived experience”. \*\*

- By any name, it's compatible with the virtual reality of the mind.
- Perception, action, and feelings are the primary sources of experience.
- The cerebellum relates all those sources to generate the VR.
- It can predict the temporal sequence of the stages in the VR.
- Mental models are the conscious interpretation of that VR. \*

\* André De Tienne (2004) [Phaneroscopy as a pre-semiotic science](#)

\*\* Sean D. Kelly (2002) [Edmund Husserl and phenomenology](#)

# The Cerebellum Generates the Phaneron

**Perception is instantaneous, but the phaneron is continuous:**

- Objects are experienced as persisting through time.
- Their motions across space are experienced as continuous paths.
- A sequence of “snapshots” is experienced as a unified event.
- How are fleeting sensations integrated as continuous experience? \*

**A patient, Sidney Bradford, who had been blind from infancy: \*\***

- After an operation at age 52, he could see, and he quickly learned to recognize colors and visual patterns.
- But he had difficulty in relating moving images to his actions.
- When he was blind, he walked in traffic by himself. But when he could see, he was terrified of traffic, even with a friend holding his arm.

**Unlike Jon Keleher, Bradford had a normal cerebellum.**

- His cerebellum could relate sound, touch, and kinesthesia to motion.
- But it had not been trained to relate vision to motion.
- Like Keleher, Bradford was easily confused by complex moving images.

\* Sean D. Kelly (2005) [The puzzle of temporal experience](#).

\*\* R. L. Gregory & J. G. Wallace (1963) [Recovery from early blindness: A case study](#).

# Peirce's Triads

**While studying Kant, Peirce analyzed the patterns of triads in Kant's table of 12 categories (4 x 3).**

**He discovered metalevel patterns underlying those categories:**

- **First: Quality expressible by a monadic predicate.**
- **Second: Reaction expressible by a dyadic relation.**
- **Third: Mediation that relates a first and a second.**

**Peirce's basic triad: Some observable Mark (1) that can be interpreted as a Token (2) of some Type (3). \***

- **The phaneron: “whatever is throughout its entirety open to direct observation” (Peirce, MS 337, 1904).**
- **It's a continuum of possible marks prior to any interpretation.**
- **Peirce compared phaneroscopy to the work of artists who can see and draw marks with little or no interpretation.**
- **That talent enables artists to imagine what people will see and feel as they walk through buildings that have not yet been built.**

\* See [Signs and Reality](#) (Sowa 2015) for examples and discussion of Peirce's categories.

# Intentionality

**Without life, there is no meaning in the universe.**

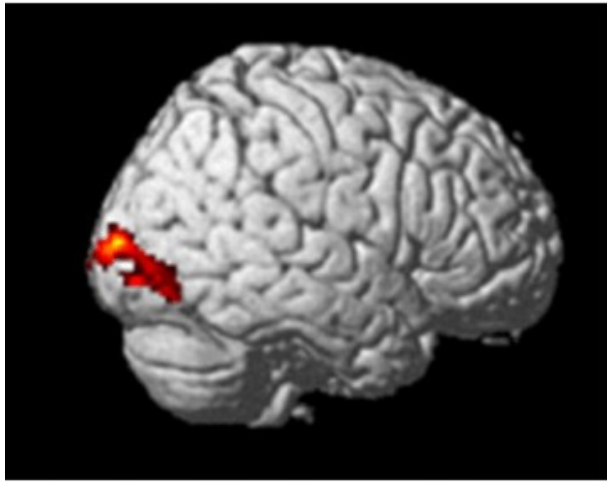
- **Philosopher Franz Brentano:** Intentionality is *“the directedness of thought toward some object, real or imagined.”*
- **Biologist Lynn Margulis:** *“The growth, reproduction, and communication of these moving, alliance-forming bacteria become isomorphic with our thought, with our happiness, our sensitivities and stimulations.”* \*
- **A bacterium swimming upstream in a glucose gradient marks the beginning of goal-directed intentionality.**

**In Peirce’s categories, intentionality is a mediating Third.**

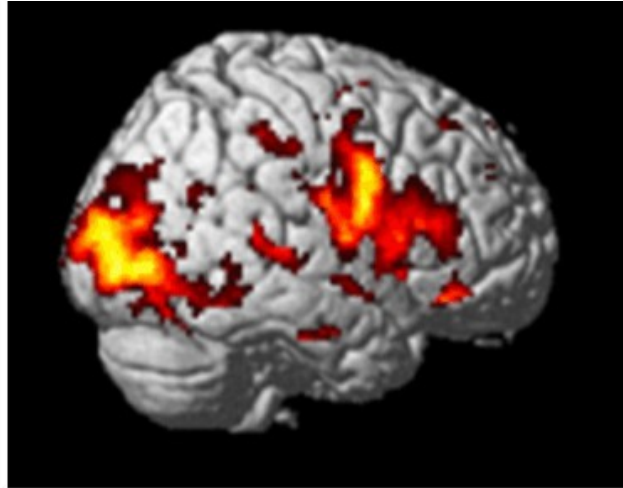
- **It’s the reason why some mind or quasi-mind directs attention toward some mark, which it interprets as a token of some type.**
- **Some interpretation by some agent makes some mark (an aspect of the universe) meaningful in some way for that agent.**
- **All laws, communications, explanations, value judgments, and social relations depend on the intentions of some agent.**

\* Margulis (1995) Gaia is a tough bitch, <http://edge.org/documents/ThirdCulture/n-Ch.7.html>

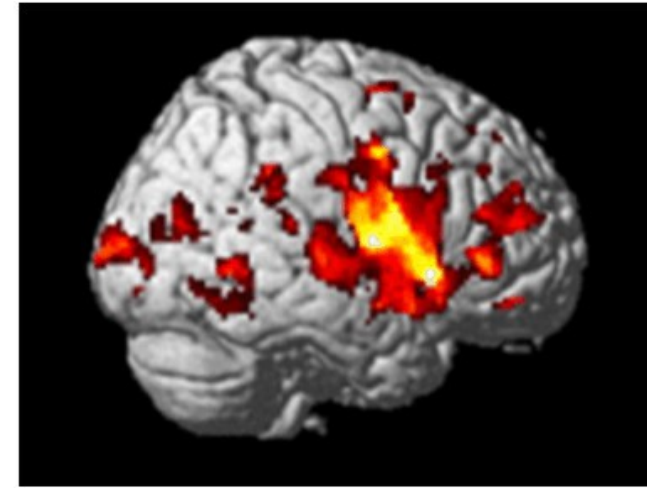
# Neural Correlates



1. Visual perception



2. Thinking about structure

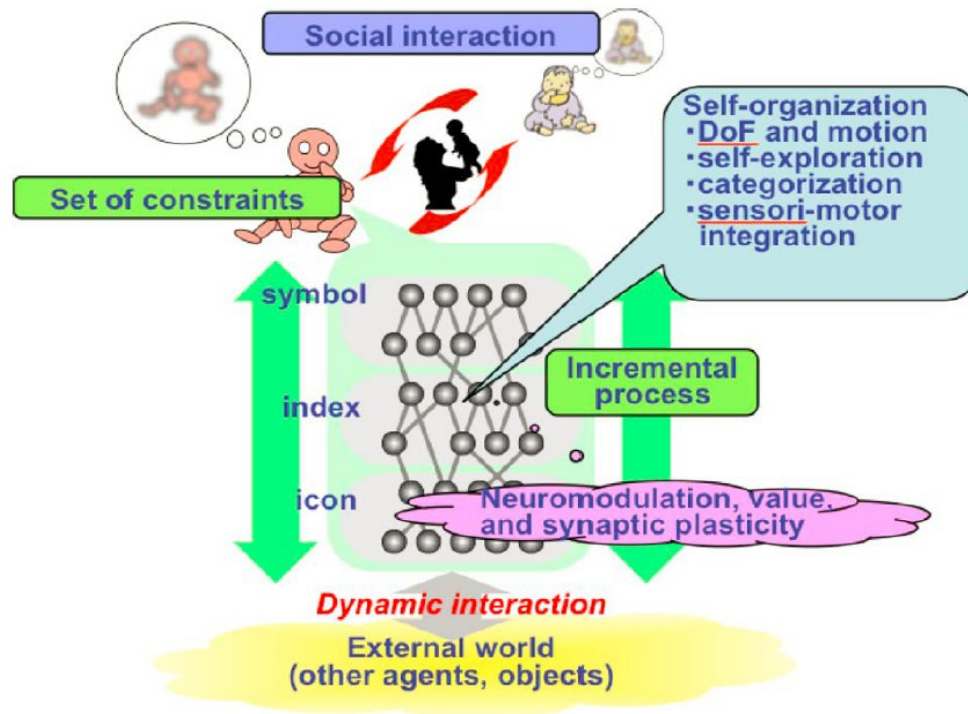


3. Thinking about causality

## Neural correlates of Firstness, Secondness, and Thirdness:

- Perception is based on localized percepts or prototypes. It classifies phenomena by the monadic predicates of Firstness (fMRI image #1).
- Long-distance connections in the parietal lobes support dyadic relations that connect all sensory and motor modalities. They represent the structures of Secondness (image #2).
- The frontal lobes process the mediating Thirdness in reasoning, planning, causality, and intentionality (image #3).
- Much more detail must be analyzed and explained, but the examples in slides 45, 46, and this one illustrate promising directions to explore.

# Cognitive Development



## Can or should robots learn to think and talk like children? \*

- Piaget's stages: Sensorimotor (0-2 years old); preoperational (2-7); concrete operations (7-12); formal operations (12-adulthood).
- Even adults go through similar stages when they encounter something new (see previous slide).
- ML algorithms can often beat humans in learning patterns from large data sets, but they are not as general, flexible, or extendible.
- Major weakness of ML: Explaining causality and intentionality.

\* See the [review article](#) (Asada et al. 2009) and [slides](#) (Asada 2012).

# Classification of Signs

	1. Quality	2. Indexicality	3. Mediation
1. Material	<p><b>Mark</b></p> <p><i>A quality which is a sign.</i></p>	<p><b>Token</b></p> <p><i>An actual existent thing or event which is a sign.</i></p>	<p><b>Type</b></p> <p><i>A principle, habit, or law which is a sign.</i></p>
2. Relational	<p><b>Icon</b></p> <p><i>Refers by virtue of some similarity to object.</i></p>	<p><b>Index</b></p> <p><i>Refers by virtue of being affected by object.</i></p>	<p><b>Symbol</b></p> <p><i>Refers by virtue of some law or association.</i></p>
3. Formal	<p><b>Predicate</b></p> <p><i>A sign of qualitative possibility.</i></p>	<p><b>Proposition</b></p> <p><i>A sign of actual existence.</i></p>	<p><b>Argument</b></p> <p><i>A sign of law.</i></p>

## Peirce's three basic triads (the *triple trichotomy*):

- Living things from bacteria to humans perceive and communicate via signs in the material triad.
- Birds and mammals appear to use relational signs.
- Formal signs are used by animals with language (*zôa logon echonta*).
- Other kinds of signs are derived by combinations of these nine.

# The Relational and Formal Triads

## The relational triad: Icons, indexes, and symbols.

- An icon has a structural resemblance to its referent.
- An index points to its referent by some connection.
- A symbol indicates its referent by a habit or convention.

## The formal triad: Predicates, Propositions, and Arguments.

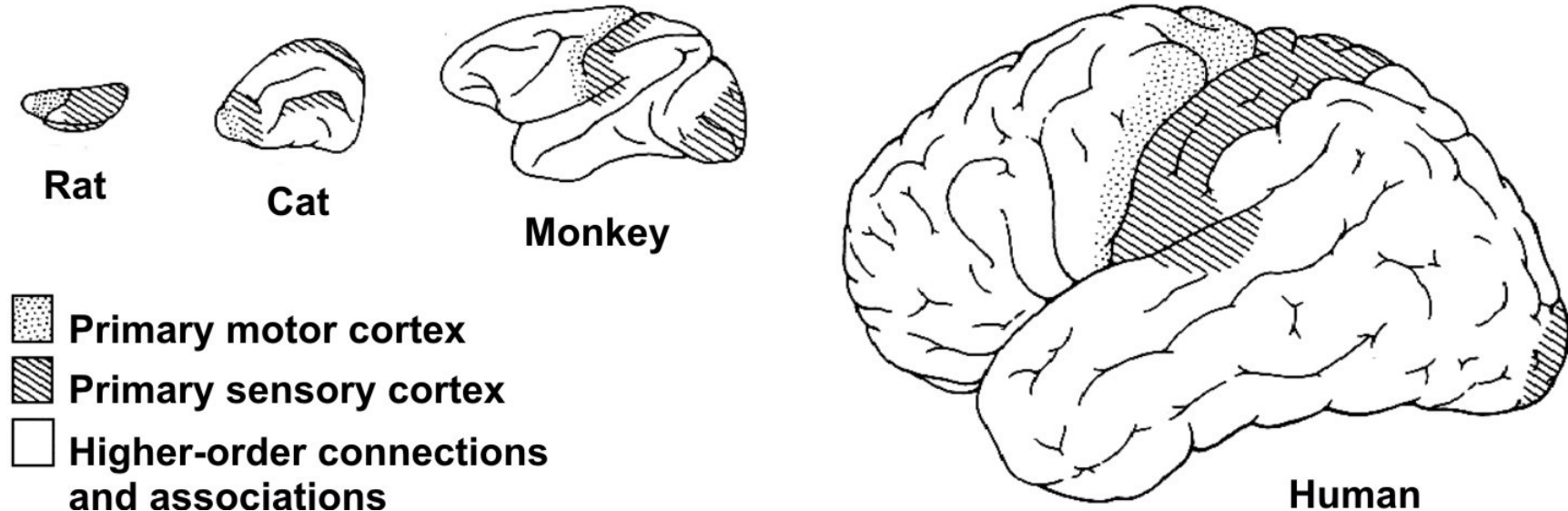
- Constructed from patterns of icons, indexes, and symbols.
- May be one-dimensional strings (natural and artificial languages).
- May be diagrams in two or more dimensions.
- A photograph, for example, is an icon.
- A labeled photo is a proposition that says something about the icon.

## Diagrams can encode far more information than strings.

- A road map is an icon of a road system with symbolic labels.
- A movie is a diagram that uses time as one of its dimensions.
- A musical score is a diagram that states a proposition that describes some composition and its possible performances.



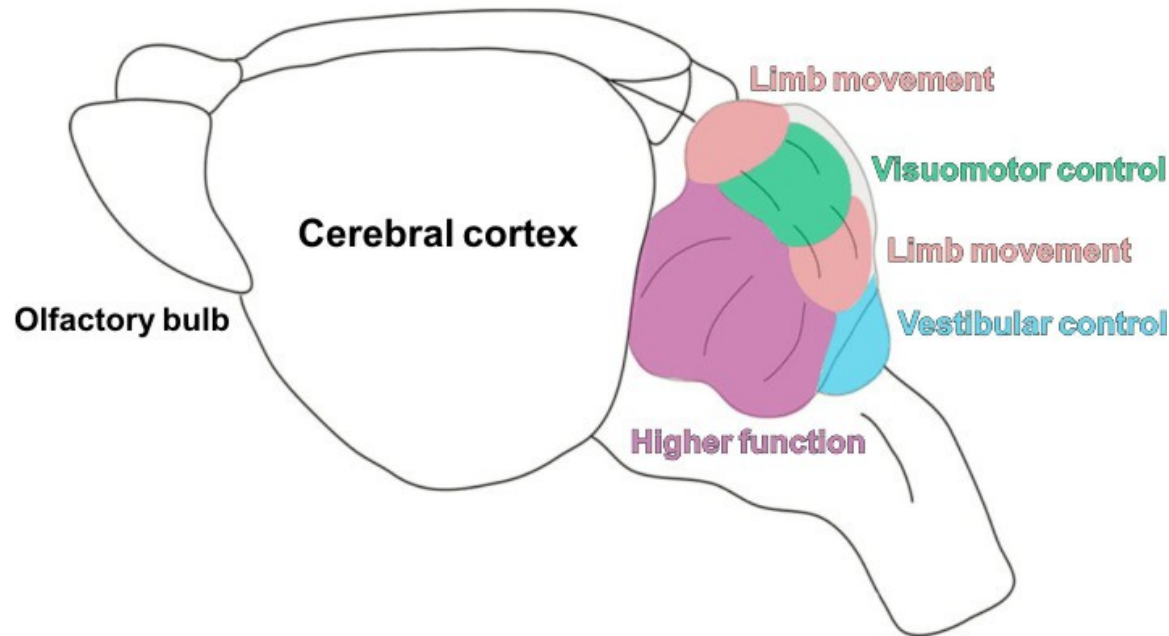
# Association Areas in the Cortex



## Peirce emphasized continuity in levels of intelligence:

- “All human knowledge, up to the highest flight of science, is but the development of our inborn animal instincts.” (CP 2.754, 1883)
- “When one’s purpose lies in the line of novelty, invention, generalization, theory — in a word, improvement of the situation... instinct and the rule of thumb manifestly cease to be applicable.” (CP 2.178, 1902)
- As he said, “symbols grow” — from patterns of icons in sensory areas to more general and flexible patterns of symbols in association areas.
- The enormous association areas of the human cortex support the formal patterns of patterns of symbols in languages, natural and artificial.

# Rodent Brains

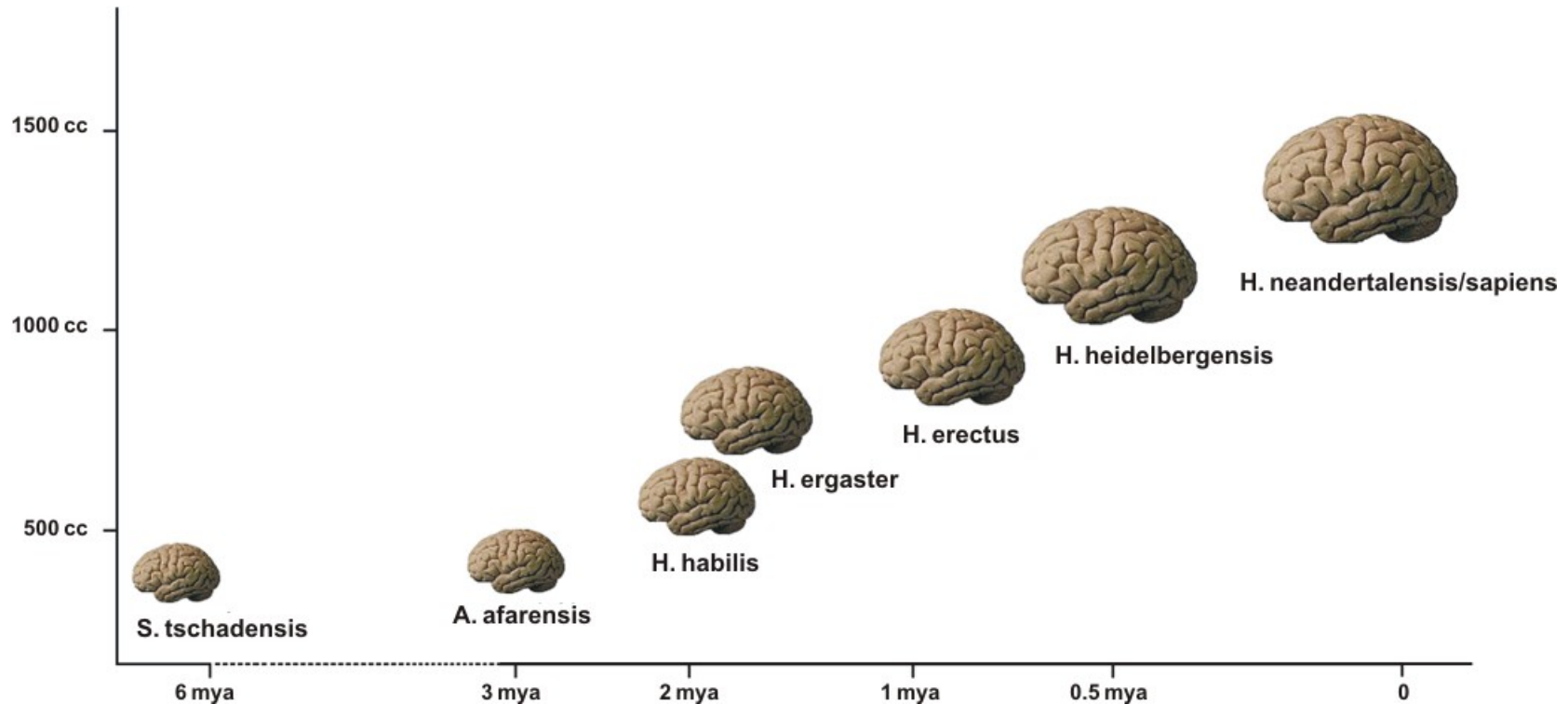


## The rodent brain, relative to a human brain:

- Much smaller association area implies a limited use of symbols.
- Large olfactory bulb implies a sensitive nose for finding food.
- Large cerebellum (in color) enables complex aerobatics by squirrels.
- Large hippocampus implies good episodic memory, especially for places.
- It enables squirrels to bury nuts, remember them, and later find them.

**As Jakob von Uexküll (1934) would say, the rodent's brain is well adapted to its Umwelt (environment and way of life).**

# Origins of Language



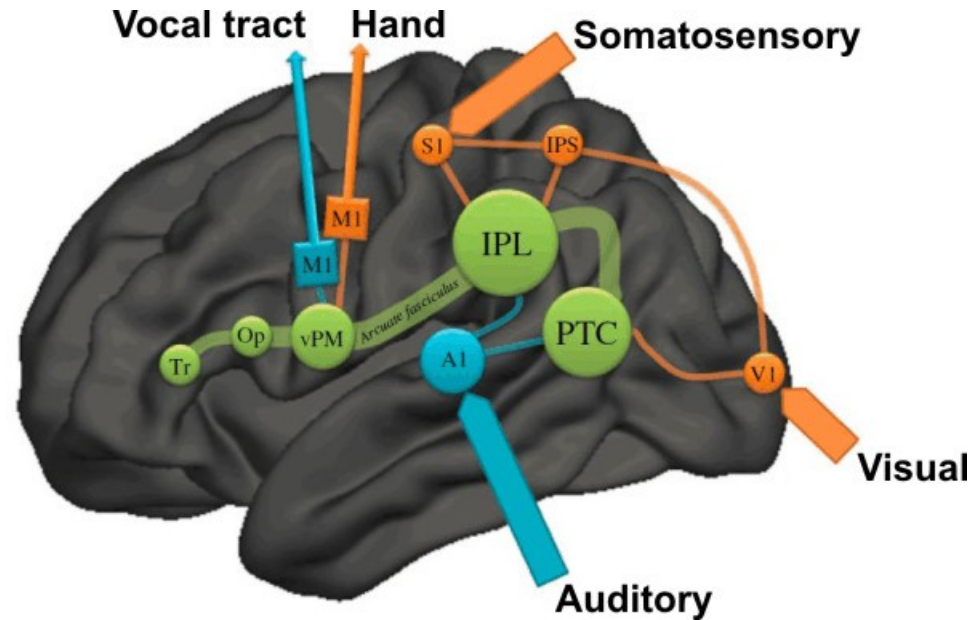
**When did early humans begin to use language?**

**Note the sudden jump in brain size about 2 million years ago:**

- Hominins began to walk on two legs around 6 mya.
- But from 6 mya to 3 mya, there was almost no change in brain size.
- Why did that sudden jump occur with *Homo habilis*?

**Deacon (1997): “Co-evolution of language and the brain.”**

# Evolution of Language and Tools



## Areas of the cerebral cortex involved in language and tool use: \*

- Green areas are active in both.
- Blue areas are highly active in speech, but not tool use.
- Orange areas are highly active in tool use, but not speech.

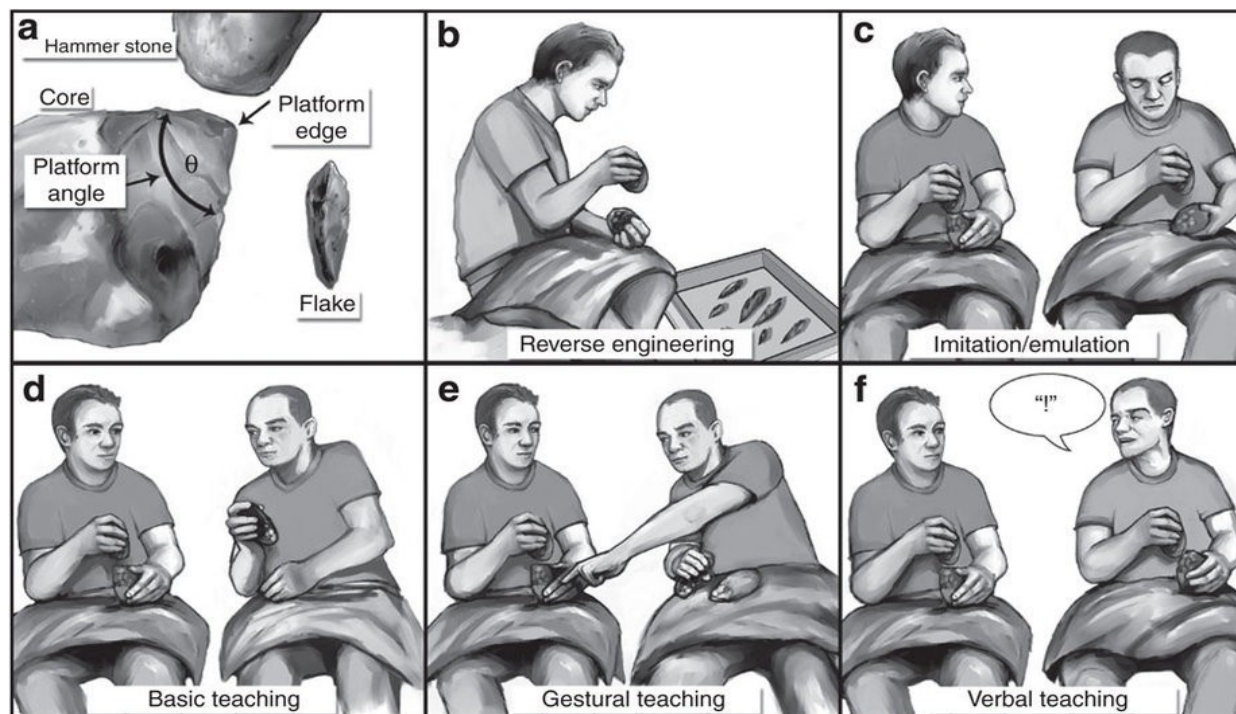
## Language and tool use stimulated the evolution of the brain:

- Australopithecus made crude stone tools about 3.3 mya. \*\*
- Homo habilis (2.5 mya) and Homo erectus (1 mya) made better tools.

\* Stout & Chaminade (2012) [Stone tools, language, and the brain in human evolution](#) .

\*\* Lewis & Harmand (2016) [An earlier origin for stone tool making](#).

# Methods of Learning and Teaching

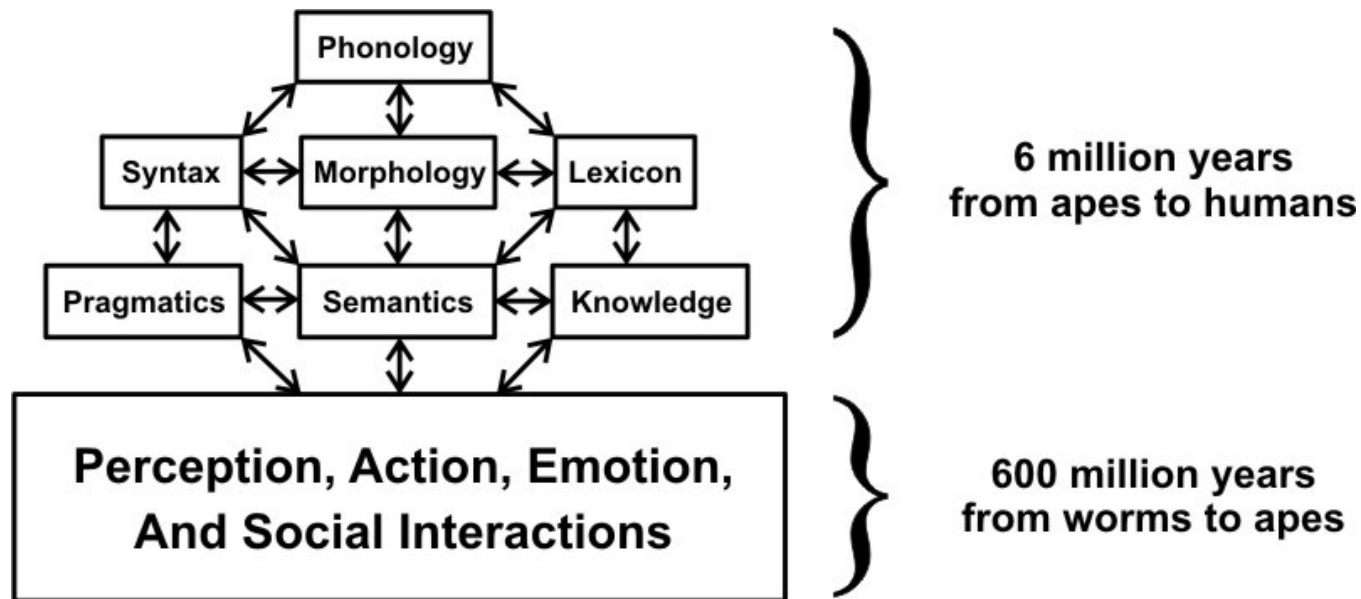


## Experiments with modern students show the value of language.\*

- Oldowan tools (2.5 mya) show considerable skill and consistency across generations, but earlier tools (3.3 mya) are crude and inconsistent.
- “Performance increases with teaching and, particularly, language.”
- “Little evidence that imitation or emulation” is sufficient.
- The complexity of Acheulian tools (1.7 mya) indicates “a capacity for teaching — and potentially simple proto-language.”

\* T. J. H. Morgan et al. (2015) <http://www.nature.com/articles/ncomms7029>

# The Foundation for Language



**The human verbal system evolved in an unusually short time.**

- The perception-action foundation took 99% of evolutionary time.
- As a result, the human perception, action, emotional, and social patterns remain similar to the chimpanzee and bonobo versions.

**Those shared patterns are sufficient to support a protolanguage.**

- The great apes can learn and use a subset of human sign language.
- Australopithecus may have had a vocal supplement to sign language.
- Homo habilis and erectus probably had protolanguages that enabled them to teach tool making and other skills to their children.

# Protolanguages

## **Great apes — chimpanzees, bonobos, gorillas, and orangutans**

- Use vocalization at about the same level as monkeys.
- But they use gestures to plan and organize social interactions.
- All four species of apes have learned subsets of human sign language.
- And they can understand a larger subset of human spoken language than they can express with the sign language. \*

## **Stages in the evolution of language before *Homo habilis*:**

- Bipedal hominins (before 4 mya) could carry things while walking.
- Vocalization enabled them to communicate while their hands were full.
- Their vocal forms could have become as expressive as their gestures.
- Implication: *Australopithecus* may have had an early protolanguage.

## **Development of child language — and probably protolanguage:**

1. Single words, similar to commands by shepherds to their dogs.
2. Two-word phrases, similar to the sign language learned by apes.
3. Simple grammars (short sentences without recursion).

\* Stanley I. Greenspan & Stuart G. Shanker (2004) *The First Idea*.

# **Symbols, Chunks, and Serial Order**

**Zoosemiotics: All animals recognize and respond to signs:**

- **Icons (images), indexes (links), symbols (habits and associations).**
- **Objection: a “homunculus” would be needed to decode symbols.**
- **Peirce’s hypothesis: all sign tokens are perceived in the same way.**
- **A symbol has a perceptible image, which is linked to association areas of the brain by the same mechanisms as any other image.**

**Chunks, maps, groups, schemata, and hierarchies:**

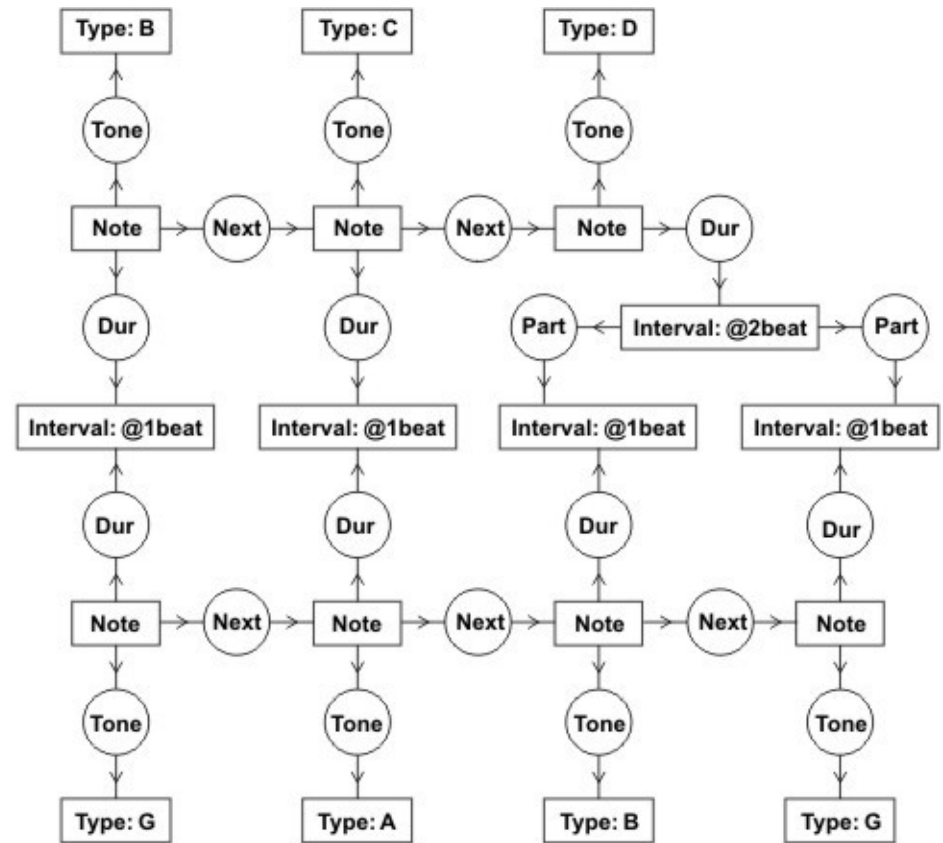
- **Tolman (1948): “Cognitive maps in rats and men.”**
- **Patterns of perception and action form chunks of arbitrary size.**
- **Miller (1956): Short-term memory holds about seven chunks.**

**Time-dependent serial order in all animal behavior:**

- **Order in walking, flying, hunting, feeding, courting, and nest building.**
- **Lashley (1951): Action schemata instead of stimulus-response chains.**
- **Music: Unique to humans. It has close connections to language in its symbolic, melodic, and emotional aspects.**



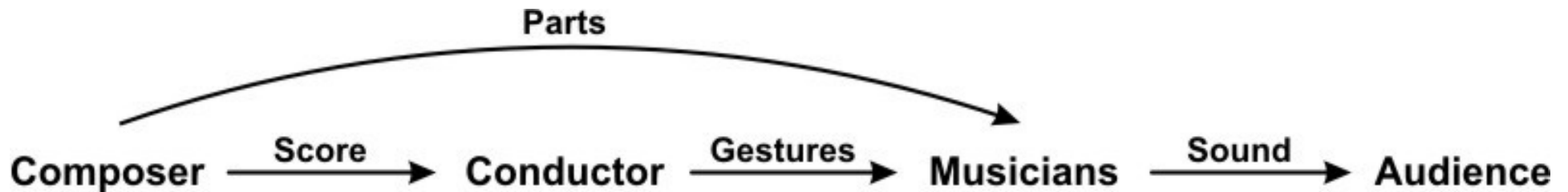
# The Logic and Ontology of Music



## Musical notation represents the logic and ontology:

- Each note is a symbol of duration, such as 1 beat or 2 beats.
- Vertical position is an iconic representation of tone (higher or lower).
- Horizontal position is an iconic representation of time sequence.
- A symbolic notation, such as predicate calculus, is very hard to read.
- A graph is more iconic, but musical notation is even better.

# Conducting an Orchestra



## **An orchestra conductor communicates by gestures. \***

- The composer writes a score with parts for each of the musicians.
- The conductor interprets the complete score – and adds feeling.
- During a rehearsal, the conductor communicates the interpretation with a combination of language, gestures, and some singing or humming.
- During a performance, the conductor communicates by gestures.
- Sarah Platte, a musician and conductor, used instruments to measure and record the motions and physiology of the conductor and musicians.
- She analyzed the effects of the conductor's style on the musicians' physical responses (motions and feelings) and the resulting sound.

\* Platte (2016) [The maestro myth](#) – exploring the Impact of conducting gestures on the musician's body and the sounding result.

# **Semantics of Natural Languages**

**Human language is based on the way people think about everything they see, hear, feel, and do.**

**And thinking is intimately integrated with perception and action.**

**The semantics and pragmatics of a language are**

- **Situated in time and space,**
- **Distributed in the brains of every speaker of the language,**
- **Dynamically generated and interpreted in terms of a constantly developing and changing context,**
- **Embodied and supported by the sensory and motor organs.**

**These points summarize current views by psycholinguists.**

**Philosophers and logicians have debated the issues:**

- **A continuum between natural languages and formal logics or a sharp dichotomy between NLs and logic.**

# Continuum Between Logic and Language

**Richard Montague (1970): A continuum with logic as primary.**

**“I reject the contention that an important theoretical difference exists between formal and natural languages.”**

**Hans Kamp (2001): A qualified continuum.**

**“The basic concepts of linguistics — and especially those of semantics — have to be thought through anew... Many more distinctions have to be drawn than are dreamt of in current semantic theory.”**

**Barbara Partee (2005): More qualifications.**

**“The present formalizations of model-theoretic semantics are undoubtedly still rather primitive compared to what is needed to capture many important semantic properties of natural languages...”**

**Peirce and Wittgenstein: A continuum with NLs as primary.**

- Every artificial notation is an abstraction from some aspects of NLs.**
- No version of logic has all the semantic properties of NLs.**
- Any formal logic is just one among many possible language games.**

# Relating Language to Logic

**Peirce wrote a succinct summary of the issues:**

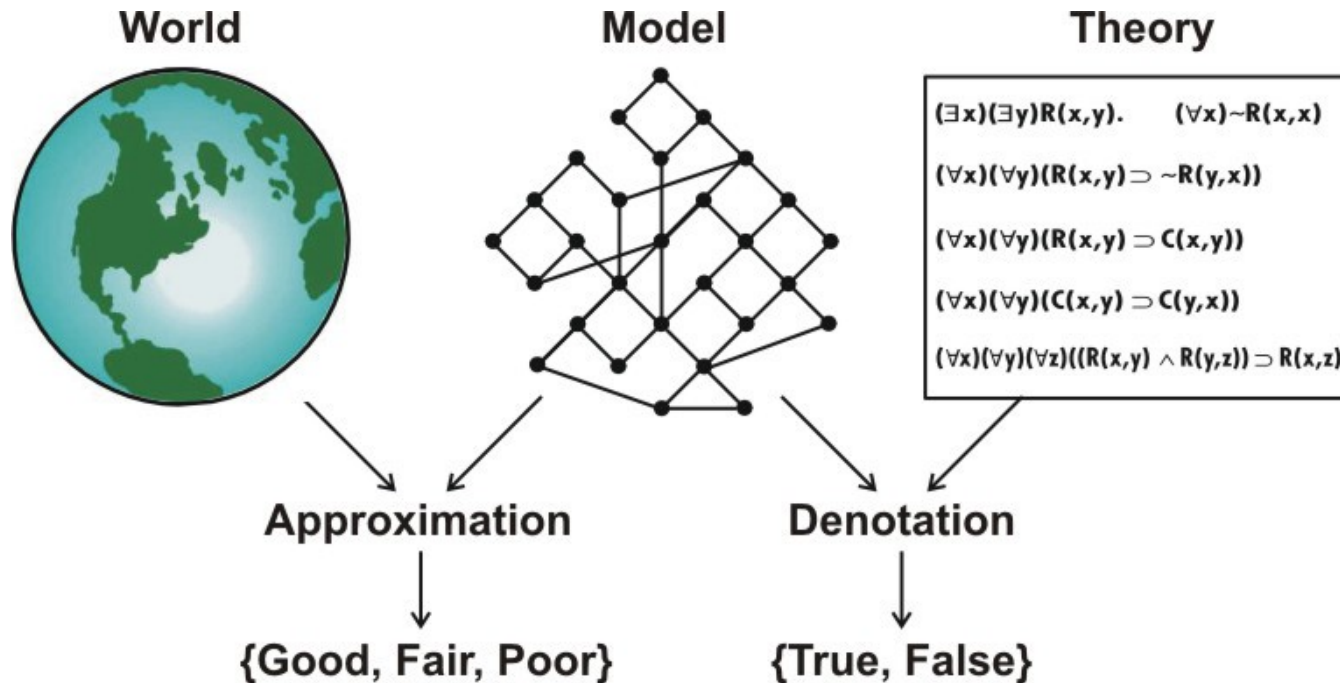
*“It is easy to speak with precision upon a general theme. Only, one must commonly surrender all ambition to be certain. It is equally easy to be certain. One has only to be sufficiently vague. It is not so difficult to be pretty precise and fairly certain at once about a very narrow subject.” (CP 4.237)*

**Implications:**

- **A precise formal ontology of everything can be stated in logic, but it’s almost certainly false in critical details.**
- **A looser classification, such as WordNet or Roget’s *Thesaurus*, can be more flexible for representing lexical patterns.**
- **A specification in logic can be “pretty precise and fairly certain” only for a very narrow subject.**

**A formal logic cannot be vague. But no finite set of symbols can precisely describe every aspect of a continuous world.**

# Symbol Grounding



**Model-theoretic semantics determines truth in terms of a model:**

- But a symbolic model is an approximation to the world.
- As engineers say, “All models are wrong, but some are useful.”

**Phenomenology relates thoughts and models to the world:**

- As Peirce said, “Every thought is a sign.”
- Phenomenology analyzes the way signs and combinations of signs are related to perception of the world and action upon it.
- It can explain symbol grounding in humans, animals, and robots.

# Implicit Information in an Icon



**To answer a question by looking at a map:**

- **Which country is closer to Africa: Canada or the USA?**
- **Observe the two congruent lines, which are determined by 4 data points.**
- **The possible observations grow as  $D^n$  — where  $D$  is the number of data points in the icon, and  $n$  is the number used in the observation.**

**The information implicit in an icon can be far greater than the information explicitly encoded in symbols and indexes.**

# Icons and Diagrams

**The relational triad: Icons, indexes, and symbols:**

- An icon has a structural resemblance to its referent.
- An index points to its referent by some kind of connection.
- A symbol indicates its referent by some habit or convention.

**Algebraic notations use symbols for the operators and letters (variables) for the indexes.**

**Diagrams use icons to represent relations:**

- A road map is an icon of a road system with symbolic labels.
- A topographic map is a labeled icon of a land surface.
- A map of roads plus topography can combine both.

**Peirce's observation about Euclid's *Elements*: \***

- Every theorem has a new diagram.
- Every corollary uses the same diagram as the main theorem.
- The creative insight is the visualization of a new diagram.

\* See <http://www.jfsowa.com/talks/ppe.pdf>



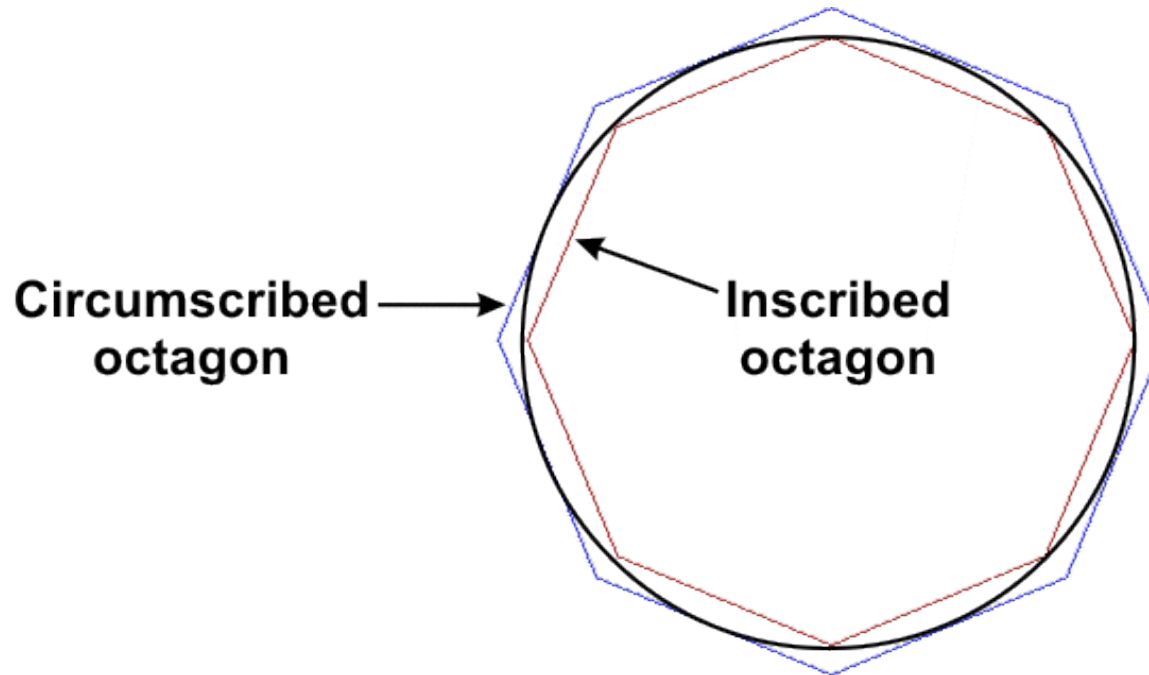
# Archimedes' Eureka Moment



**Insight: A submerged body displaces an equal volume of water.**

- It's a mathematical principle, a property of Euclidean space.
- Scientists and engineers have used it ever since.
- They don't prove it. They use it to define *incompressible fluid*.

# Determining the Value of $\pi$

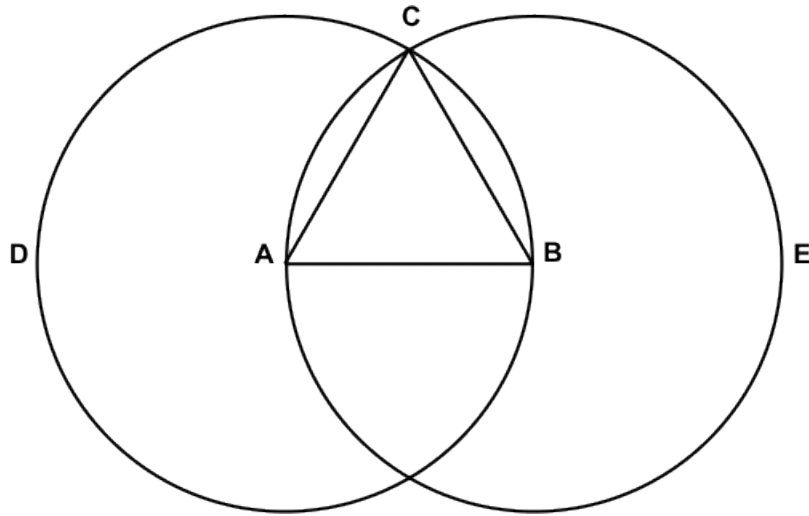


**Archimedes had two creative insights, both inspired by images:**

- **The circumference of the circle is greater than the perimeter of the inner polygon and less than that of the outer polygon.**
- **As the number of sides increases, the inner polygon expands, and the outer polygon shrinks. They converge to the circle.**

**Given these insights, a good mathematician could compute  $\pi$  to any desired precision. Archimedes used 96-gons.**

# Euclid's Proposition 1



**Euclid's statement, as translated by Thomas Heath:**

- **On a given finite straight line, to draw an equilateral triangle.**

**The creative insight is to draw two circles:**

- **The circle with center at A has radii AB and AC.**
- **The circle with center at B has radii BA and BC.**
- **Since all radii of a circle have the same length, the three lines AB, AC, and BC form an equilateral triangle.**

# 4. Natural Logic

**Symbolic logic isn't as “natural” as Aristotle's or Euclid's logic.**

**Cognitive scientists have been searching for a natural logic:**

- Linguists such as Lakoff (1970) and Fodor (1975) used language as a model for a natural logic or a language of thought.
- Logicians such as Gentzen (1935), Montague (1970), and van Benthem (2008) used algebraic notations for all versions, natural or formal.
- The formal linguists Kamp and Reyle (1993) developed Discourse Representation Structure (DRS) for a better mapping to language.
- Some philosophers, psychologists, and neuroscientists claim that mental maps or models are the basis for language and reasoning.

**Peirce's existential graphs (EGs) support all of the above:**

- EG notation is as general and expressive as any algebraic notation.
- The FOL subset of EGs is isomorphic to the Kamp-Reyle DRS notation.
- EG rules of inference subsume Gentzen's version of natural deduction.
- With icons, generalized EGs can directly represent mental models.

# Existential Graphs

**Charles Sanders Peirce (1880, 1885) invented the algebraic notation for first-order and higher-order predicate calculus. \***

**In 1897, he invented existential graphs (EGs) as a “more iconic” representation for “the atoms and molecules of logic.”**

- Even more important than the notation, EGs support simple, elegant, and general rules of inference.**
- When the relations in EGs are represented only by symbols, they have the same expressive power as the algebraic notation.**
- The Existential Graph Interchange Format (EGIF) can serve as an intermediate notation between EGs and linear notations for logic.**
- But Generalized EGs may also include arbitrary icons.**
- For example, they can include Euclid’s diagrams (in two or more dimensions) in the axioms, theorems, and proofs.**
- They can even support proofs in natural languages without a preliminary translation to any formal notation.**

\* Hilary Putnam (1982) Peirce the logician, <http://www.jfsowa.com/peirce/putnam.htm>

# A Minimal Notation for FOL

A line for existence. An oval for negation. Conjunction is implicit.

Existence: —

Negation: 

Relations: Cat- -On- -Under- -With- -Mat

*A cat is on a mat:* Cat—On—Mat

*Something is under a mat:* —Under—Mat

*Some cat is not on a mat:* Cat——Mat

*Some cat is on something that is not a mat:* Cat—On——Mat

# Icons and Diagrams

**Three kinds of signs: Icons, indexes, and symbols.**

- An icon has a structural resemblance to its referent.
- An index points to its referent by some kind of connection.
- A symbol indicates its referent by some habit or convention.

**Algebraic notations combine symbols and indexes with linear icons for the operators and transformation rules.**

**Diagrams use complex icons to represent relations:**

- A road map is an icon of a road system with symbolic labels.
- A topographic map is a labeled icon of some land surface.
- A map of roads plus topography can combine both.

**Peirce's existential graphs are logic diagrams.**

- Icons represent existence, identity, conjunction, negation, and scope.
- But generalized EGs can also use icons to represent relations.
- Perception and action can relate EGs to the outside world.

For more detail about EGs: <http://www.jfsowa.com/talks/egintro.pdf>

# Peirce's Rules of Inference

Peirce's rules support the simplest, most general reasoning method ever invented for any logic.

Three pairs of rules, which insert or erase a graph or subgraph:

1. Insert/Erase: (i) insert anything in a negative area (shaded); (e) erase anything in a positive area (unshaded).
2. Iterate/Deiterate: (i) iterate (copy) anything into the same area or any nested area; (e) deiterate (erase) any such copy.
3. Double negation: (i) insert or (e) erase a double negation (a shaded area with nothing in it) around any graph in any area.

There is only one axiom: the empty graph, which is always true.

Peirce stated these rules in terms of EGs.

But they can be adapted to many notations, including predicate calculus, natural languages, and Euclid's diagrams.



# Issues of Mapping Language to Logic

Hans Kamp observed that the features of predicate calculus do not have a direct mapping to and from natural languages. \*

**Pronouns can cross sentence boundaries, but variables cannot.**

- Example: *Pedro is a farmer. He owns a donkey.*
- $(\exists x)(\text{Pedro}(x) \wedge \text{farmer}(x)). (\exists y)(\exists z)(\text{owns}(y,z) \wedge \text{donkey}(z)).$
- There is no operator that can relate  $x$  and  $y$  in different formulas.

**The rules for scope of quantifiers are different.**

- Example: *If a farmer owns a donkey, then he beats it.*
- In English, quantifiers in the if-clause govern the then-clause.
- But in predicate calculus, the quantifiers must be moved to the front.
- Formula:  $(\forall x)(\forall y)((\text{farmer}(x) \wedge \text{donkey}(y) \wedge \text{owns}(x,y)) \supset \text{beats}(x,y)).$

**Note: Proper names are rarely unique identifiers. Kamp and Peirce mapped names to monadic relations.**

\* Hans Kamp & Uwe Reyle (1993) *From Discourse to Logic*, Dordrecht: Kluwer.

# Linking Existential Quantifiers

To relate existential quantifiers in different statements, EGs (left) and DRS (right) support equivalent operations:

Pedro  
|  
farmer

x  
Pedro(x) farmer(x)

— owns — donkey

y z  
owns(y,z) donkey(z)

By connecting EG lines or merging DRS boxes,

Pedro  
|  
— owns — donkey  
farmer

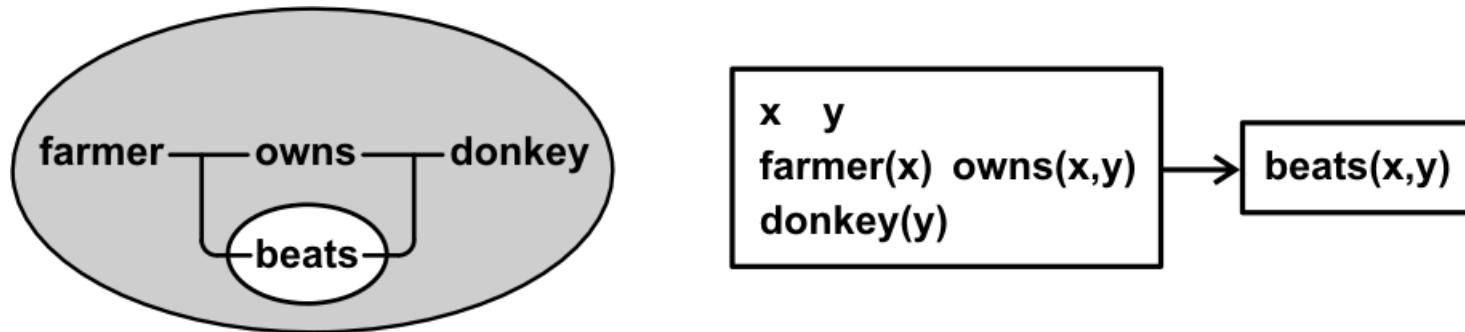
x y z x=y  
Pedro(x) farmer(x)  
owns(y,z) donkey(z)

# Quantifiers in EG and DRS

**Peirce and Kamp independently chose isomorphic structures.**

- Peirce chose nested ovals for EG with lines to show coreference.
- Kamp chose boxes for DRS with variables to show coreference.
- But the boxes and ovals are isomorphic: they have the same constraints on the scope of quantifiers, and they support equivalent operations.

**Example:** *If a farmer owns a donkey, then he beats it.*

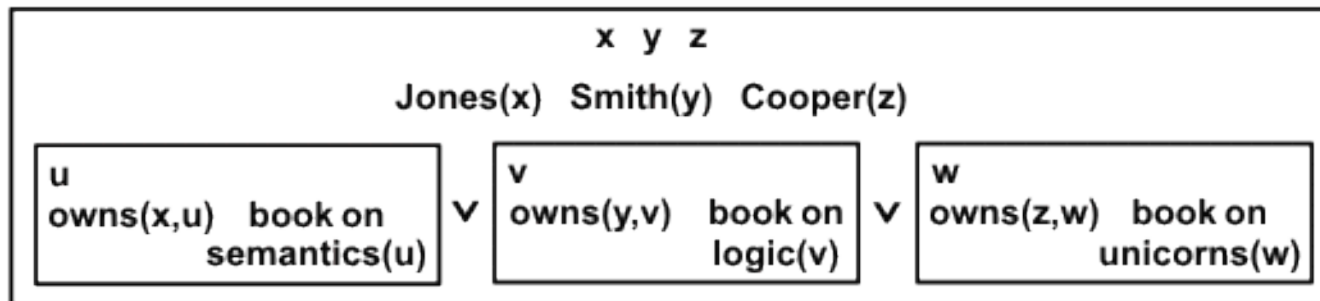
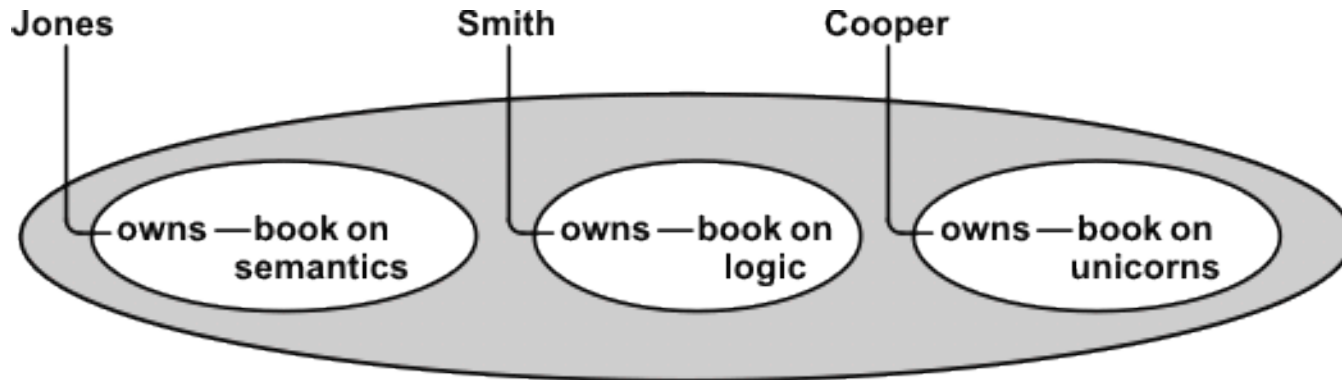


**In both EG and DRS, quantifiers in the *if*-area are existential, and they include the *then*-area within their scope.**

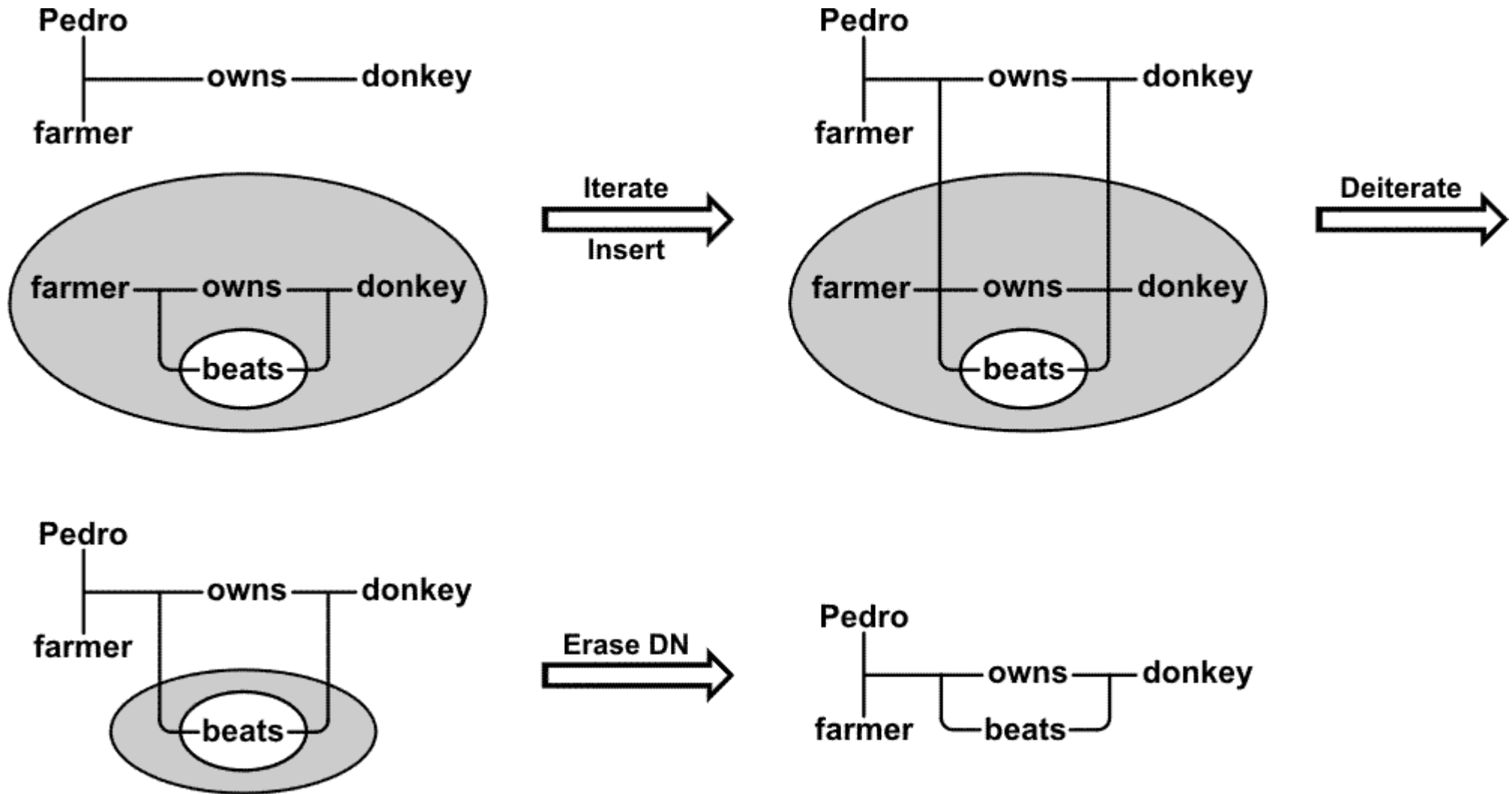
# Disjunctions in EG and DRS

Example by Kamp and Reyle (1993):

*Either Jones owns a book on semantics, or Smith owns a book on logic, or Cooper owns a book on unicorns.*



# A Proof by Peirce's Rules



**Conclusion:** *Pedro is a farmer who owns and beats a donkey.*

# Applying Peirce's Rules to Other Notations



**If a cat is on a mat, then it is happy.**

**Start with a sentence that can be mapped to any version of FOL:**

- **Draw ovals around negated areas.**
- **Draw the ovals through words like *not, if, then, every, either, or.***
- **Shade negative areas, and leave positive areas unshaded.**

**A generalization of Peirce's first pair of rules:**

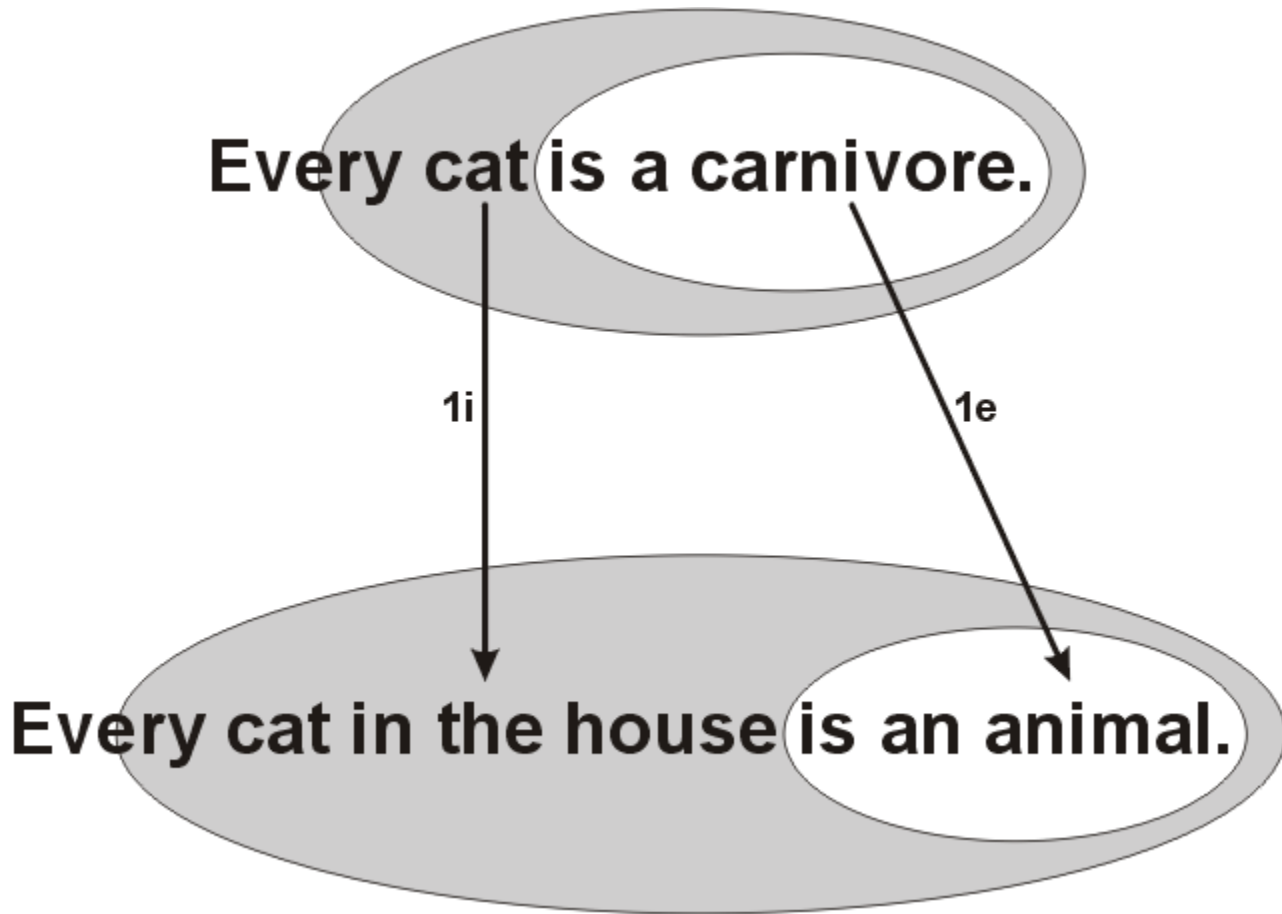
- **Insert:** In a negative context (shaded), any propositional expression may be replaced by a more specialized expression.
- **Erase:** In a positive context (unshaded), any propositional expression may be replaced by a more general expression.

# Peirce's Rules Applied to English

Use shading to mark the positive and negative parts of each sentence.

Rule 1i specializes 'cat' to 'cat in the house'.

Rule 1e generalizes 'carnivore' to 'animal'.



This system of inference is sound and complete for sentences that can be translated to and from FOL, DRS, or EGs.

# A Proof in English

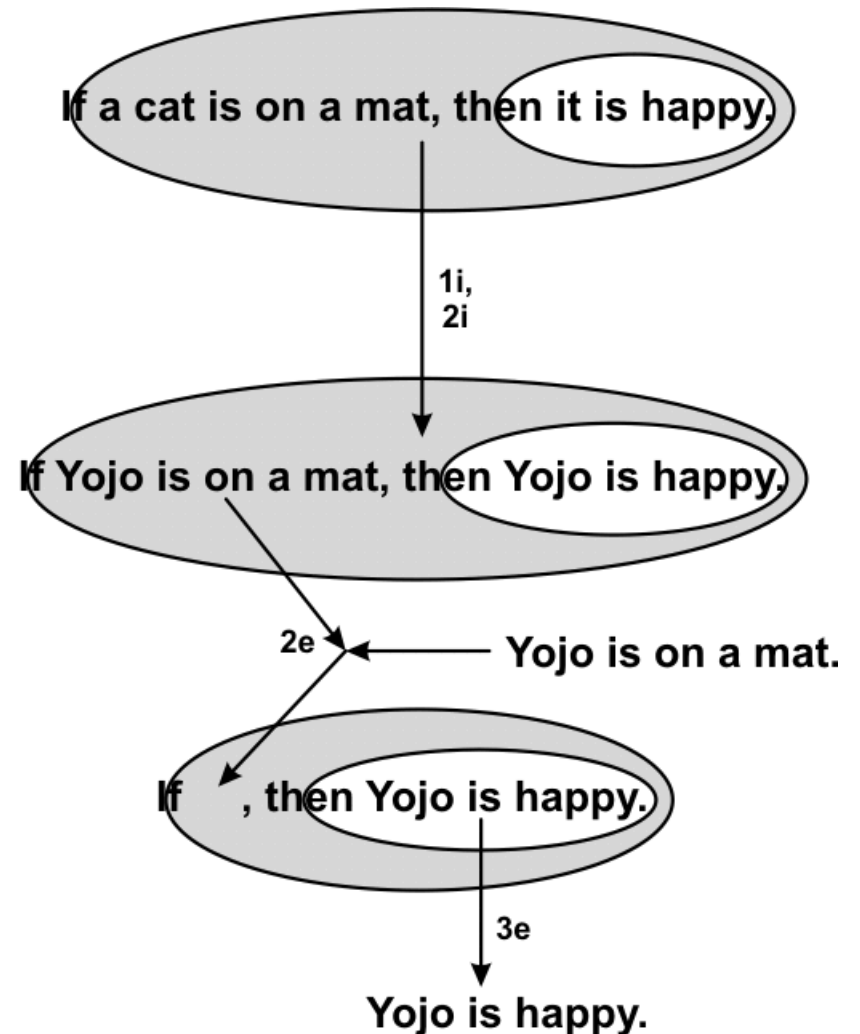
Use shading to mark positive and negative parts of each sentence.

Rule 1i specializes 'a cat' to 'Yojo', and Rule 2i iterates 'Yojo' to replace the pronoun 'it'.

Rule 2e deiterates the nested copy of the sentence 'Yojo is on a mat'.

As a result, there is nothing left between the inner and outer negation of the if-then nest.

Finally, Rule 3e erases the double negation to derive the conclusion.





# Theoretical Issues

**Peirce's rules have some remarkable properties:**

- **Simplicity:** Each rule inserts or erases a graph or subgraph.
- **Symmetry:** Each rule has an exact inverse.
- **Depth independence:** Rules depend on the positive or negative areas, not on the depth of nesting.

**They allow short proofs of remarkable theorems:**

- **Reversibility Theorem.** Any proof from  $p$  to  $q$  can be converted to a proof of  $\sim p$  from  $\sim q$  by negating each step and reversing the order.
- **Cut-and-Paste Theorem.** If  $q$  can be proved from  $p$  on a blank sheet, then in any positive area where  $p$  occurs,  $q$  may be substituted for  $p$ .
- **Resolution and natural deduction:** Any proof by resolution can be converted to a proof by Peirce's version of natural deduction by negating each step and reversing the order.

**For proofs of these theorems and further discussion of the issues, see Section 6 of <http://www.jfsowa.com/pubs/egtut.pdf>**

# Natural Deduction

**Gerhard Gentzen developed a proof procedure that he called *natural deduction*.**

**But Peirce's method is a version of natural deduction that is simpler and more general than Gentzen's:**

<b>Peirce's Method</b>	<b>Gentzen's Method</b>
<b>6 rules</b>	<b>16 rules</b>
<b>3 symmetric pairs</b>	<b>Many irregularities</b>
<b>Simple operations</b>	<b>Requires provability</b>
<b>Straight-line proofs</b>	<b>Complex bookkeeping</b>
<b>Date: 1897-1909</b>	<b>Date: 1935</b>

For details, see pp. 24 to 26 of <http://www.jfsowa.com/pubs/egtut.pdf>

# Gentzen's Natural Deduction

	Introduction Rules	Elimination Rules
$\wedge$	$\frac{A, B}{A \wedge B}$	$\frac{A \wedge B}{A} \quad \frac{A \wedge B}{B}$
$\vee$	$\frac{A}{A \vee B} \quad \frac{B}{A \vee B}$	$\frac{A \vee B, A \vdash C, B \vdash C}{C}$
$\supset$	$\frac{A \vdash B}{A \supset B}$	$\frac{A, A \supset B}{B}$
$\sim$	$\frac{A \vdash \perp}{\sim A} \quad \frac{\perp}{A}$	$\frac{A, \sim A}{\perp} \quad \frac{\sim \sim A}{A}$
$\forall$	$\frac{A(a)}{(\forall x)A(x)}$	$\frac{(\forall x)A(x)}{A(t)}$
$\exists$	$\frac{A(t)}{(\exists x)A(x)}$	$\frac{(\exists x)A(x), A(a) \vdash B}{B}$

Like Peirce, Gentzen assumed only one axiom: a blank sheet of paper.

But Gentzen had more operators and more complex, nonsymmetric pairs of rules for inserting or erasing operators.

# Role of the Empty Sheet

**Both Peirce and Gentzen start a proof from an empty sheet.**

**In Gentzen's syntax, a blank sheet is not a well-formed formula.**

- Therefore, no rule of inference can be applied to a blank.
- A method of making and discharging an assumption is the only way to begin a proof.

**But in EG syntax, an empty graph is a well-formed formula.**

- Therefore, a double negation may be drawn around a blank.
- Then any assumption may be inserted in the negative area.

**Applying Peirce's rules to predicate calculus:**

- Define a blank as a well-formed formula that is true by definition.
- Define the positive and negative areas for each Boolean operator.
- Show that each of Gentzen's rules is a derived rule of inference in terms of Peirce's rules.

**Then any proof by Gentzen's rules is a proof by Peirce's rules.**

# A Problem in Automated Reasoning

**Larry Wos (1988), a pioneer in automated reasoning methods, stated 33 unsolved problems. His problem 24:**

*Is there a mapping between clause representation and natural-deduction representation (and corresponding inference rules and strategies) that causes reasoning programs based respectively on the two approaches or paradigms to attack a given assignment in an essentially identical fashion?*

**The answer in terms of Peirce's rules is yes:**

- **The inference rules for Gentzen's clause form and natural deduction are derived rules of inference in terms of the EG rules.**
- **Any proof in clause form (by resolution) can be converted, step by step, to a proof by EG rules.**
- **Any such proof can be converted to a proof by Peirce's version of natural deduction by negating each step and reversing the order.**
- **Convert the proof by Peirce's rules to a proof by Gentzen's rules.**

# Psychological Issues

**Endorsement by the psychologist Philip Johnson-Laird (2002):**

*Peirce's existential graphs... anticipate the theory of mental models in many respects, including their iconic and symbolic components, their eschewal of variables, and their fundamental operations of insertion and deletion.*

*Much is known about the psychology of reasoning... But we still lack a comprehensive account of how individuals represent multiply-quantified assertions, and so the graphs may provide a guide to the future development of psychological theory. \**

**Johnson-Laird published a book on mental models.**

**His comments on that topic are significant, and the option of using icons in generalized EGs strengthens the claim.**

\* See <http://mentalmodels.princeton.edu/papers/2002peirce.pdf>

# Reasoning with Mental Models

## From Damasio and other neuroscientists:

- **Mental models are patterns in the sensory projection areas that resemble patterns derived from perception.**
- **But the stimuli that generate mental models come from the frontal lobes, not from sensory input.**
- **The content of the mental models is generated by assembling fragments of earlier perceptions in novel combinations.**

## From suggestions by Johnson-Laird:

- **The nodes of an existential graph could represent images or fragments of images from long-term memory.**
- **The connecting lines of an EG would show how those fragments are assembled to form a mental model.**
- **The logical features of EGs could be used to represent rules and constraints for reasoning about those models.**

# Induction and Analogy

## Quotations by George Polya (1954):

- *Demonstrative reasoning is safe, beyond controversy, and final.*
- *Plausible reasoning is hazardous, controversial, and provisional.*
- *Demonstrative reasoning [however] is incapable of yielding new knowledge about the world.*

## Some mathematicians quoted by Polya:

- **Euler:** *The properties of the numbers known today have been mostly discovered by observations... long before their truth has been confirmed by rigid demonstrations.*
- **Laplace:** *Even in the mathematical sciences, our principal instruments to discover the truth are induction and analogy.*

**Polya's books had a strong influence on the methods of heuristics in artificial intelligence.**

**They are consistent with Peirce's many observations about induction, abduction, deduction, and analogy.**



# The Foundation for Natural Logic

**Peirce called existential graphs “the logic of the future.”**

**Computer graphics and virtual reality can implement them:**

- **The icons in two-dimensional maps can be generalized to three dimensions and even 3+1 dimensions for motion and change.**
- **Conjunctions and lines of identity can be represented in any dimension.**
- **For negation, the ovals can be generalized to closed shapes in any number of dimensions.**

**Peirce’s claim is consistent with neuroscience:**

- **As Damasio said, images are “the main currency of our minds.”**
- **As Johnson-Laird observed, Peirce’s rules of inference insert and erase graphs and subgraphs — operations that neural processes can perform.**
- **Generalized EGs can include arbitrary images in the graphs.**
- **When Peirce claimed that EGs represent “a moving picture of the action of the mind in thought,” he may have imagined something similar. \***

\* Pietarinen, Ahti-Veikko (2011) Moving pictures of thought II, *Semiotica* 186:1-4, 315–331, <http://www.helsinki.fi/~pietarin/publications/Semiotica-Diagrams-Pietarinen.pdf>

# 5. The Cognitive Cycle

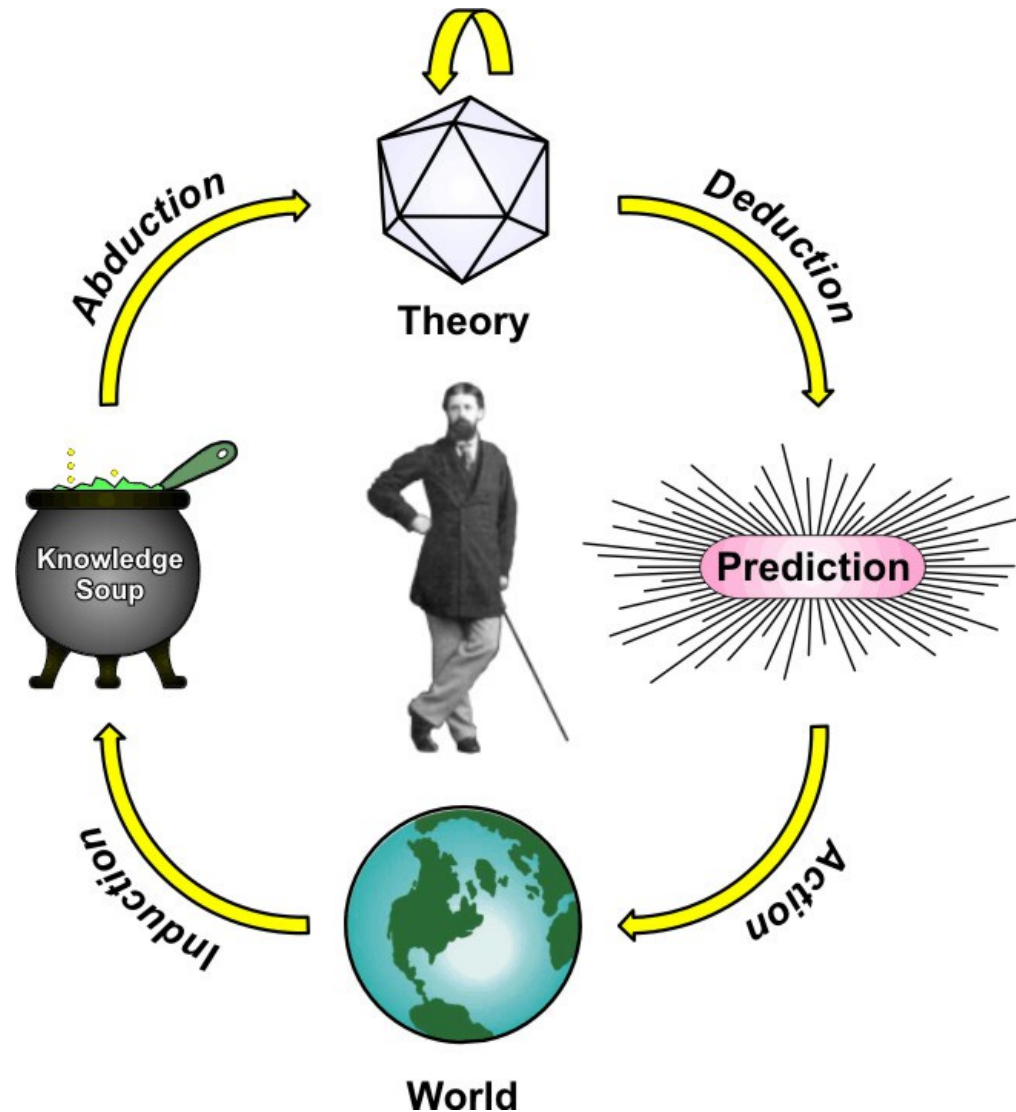
**All learning, from simple habits to scientific research, is based on patterns of perception and purposeful action.**

**By trial and error, people revise and extend their beliefs to make better predictions about the world, society, and themselves:**

- **Observations generate low-level facts.**
- **Induction derives general axioms from multiple facts.**
- **A mixture of facts and axioms is an unstructured *knowledge soup*.**
- **Abduction selects facts and axioms to form a hypothesis (theory).**
- **Analogies may relabel a theory of one topic and apply it to another.**
- **Deductions from a theory generate predictions.**
- **Actions test the predictions against reality.**
- **Effects of the actions lead to new observations.**
- **Frequently used perception-action patterns become habits — overlearned responses that are computed by the cerebellum.**

**Cycles within cycles may be traversed at any speed — from milliseconds to hours to research projects that take years.**

# Observing, Learning, Reasoning, Acting



**The logic of pragmatism by Charles Sanders Peirce.  
Similar cycles occur in science and everyday life.**

# Knowledge Soup

**A heterogeneous, loosely linked mixture: \***

- Fluid, lumpy, and dynamically changing.
- Many lumps are or can be structured in a computable form.
- But they may be inconsistent or incompatible with one another.

**In anybody's head, knowledge soup is**

- The totality of everything in the brain, including the cerebellum, the brain stem, and all signals from and about the body.

**In the WWW, knowledge soup is**

- The totality of everything people downloaded from their heads, recorded automatically, or derived by any computable method.

**Linked Open Data is useful for finding and classifying anything in the soup – whether loose items or structured lumps.**

**But understanding the contents of the LOD poses the same challenge as understanding natural language.**

\* Sowa (2004) [The challenge of knowledge soup](#).

# Language is Central to Human Learning

**People use language to express every aspect of life.**

**The cognitive cycle integrates linguistic and nonlinguistic data:**

- **New data (experiences) accumulate from observations in life.**
- **Statistical methods are useful for finding generalizations.**
- **But those generalizations must be integrated with previous knowledge.**
- **Routine abduction may use statistics to select patterns from the soup.**
- **But creative abduction is necessary to invent new patterns.**
- **Belief revision integrates various patterns into larger, better structured patterns called hypotheses or theories.**
- **Deduction generates predictions from the theories.**
- **Actions in and on the world test the predictions.**
- **New observations provide supervision (rewards and punishments).**

**Language is essential for expressing novel patterns and for learning the novel patterns discovered by other people.**

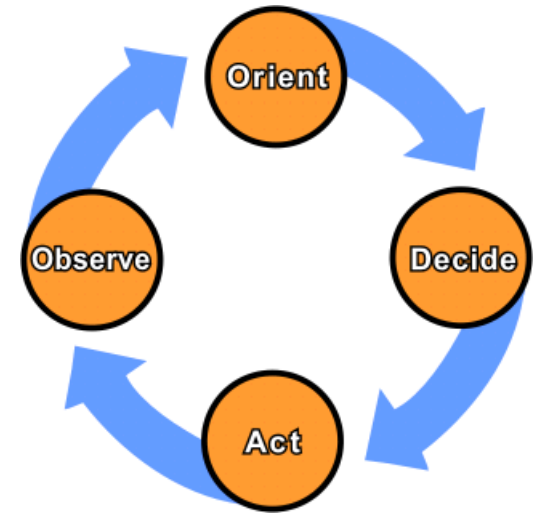
# Boyd's OODA Loop

John Boyd drew a four-step diagram for training fighter pilots to observe and respond rapidly.

The first two steps – Observe and Orient – involve the occipital, parietal, and temporal lobes.

The next two steps – Decide and Act – involve the frontal lobes for reasoning and motor control.

The four steps and the associated brain areas:

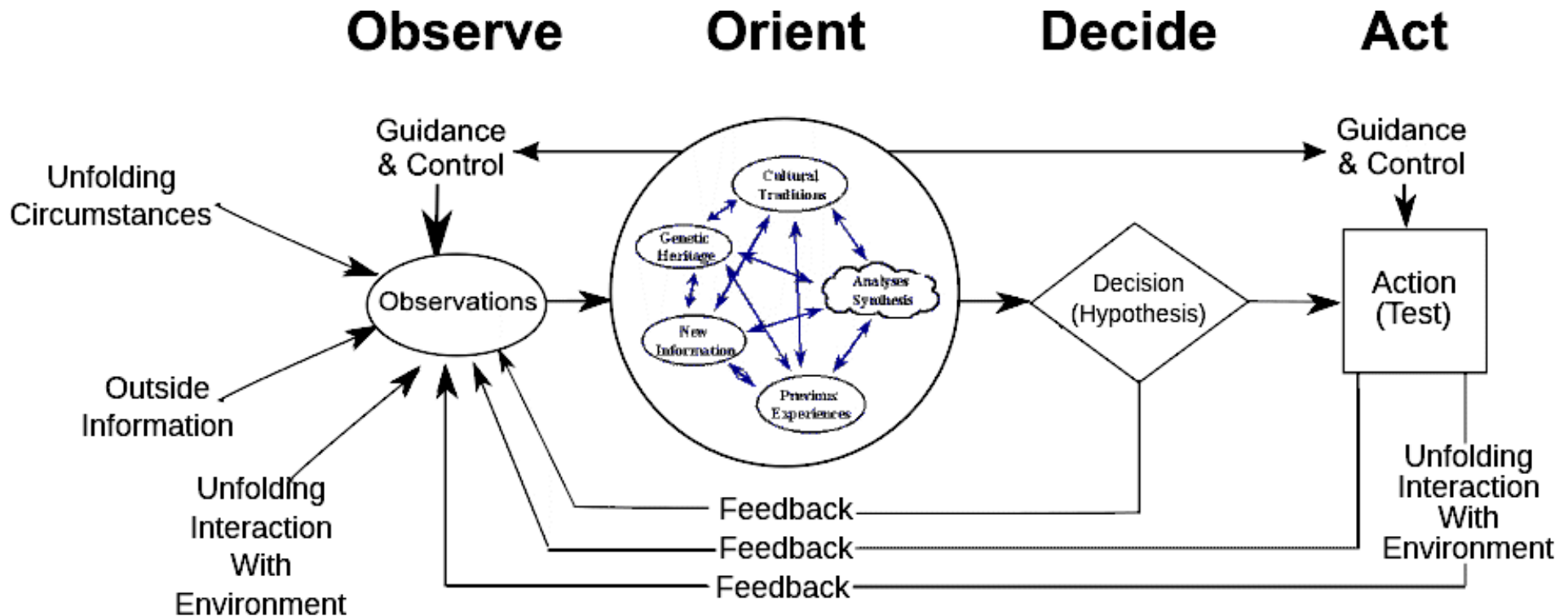


1. **Observe:** Visual input goes to the primary visual cortex (occipital lobes), but object recognition and naming involve the temporal lobes.
2. **Orient:** Parietal lobes relate vision, touch, and sound in “cognitive maps.”
3. **Decide:** Reasoning is under the control of the frontal lobes, but other areas store the “knowledge soup” and the “mental models.”
4. **Act:** “Action schemata” are patterns in the premotor cortex of the frontal lobes. Signals from the motor cortex go to the muscles.

In emergencies, each step must be traversed in milliseconds.

The fastest responses are controlled by the VR in the cerebellum.

# Extended OODA Loop

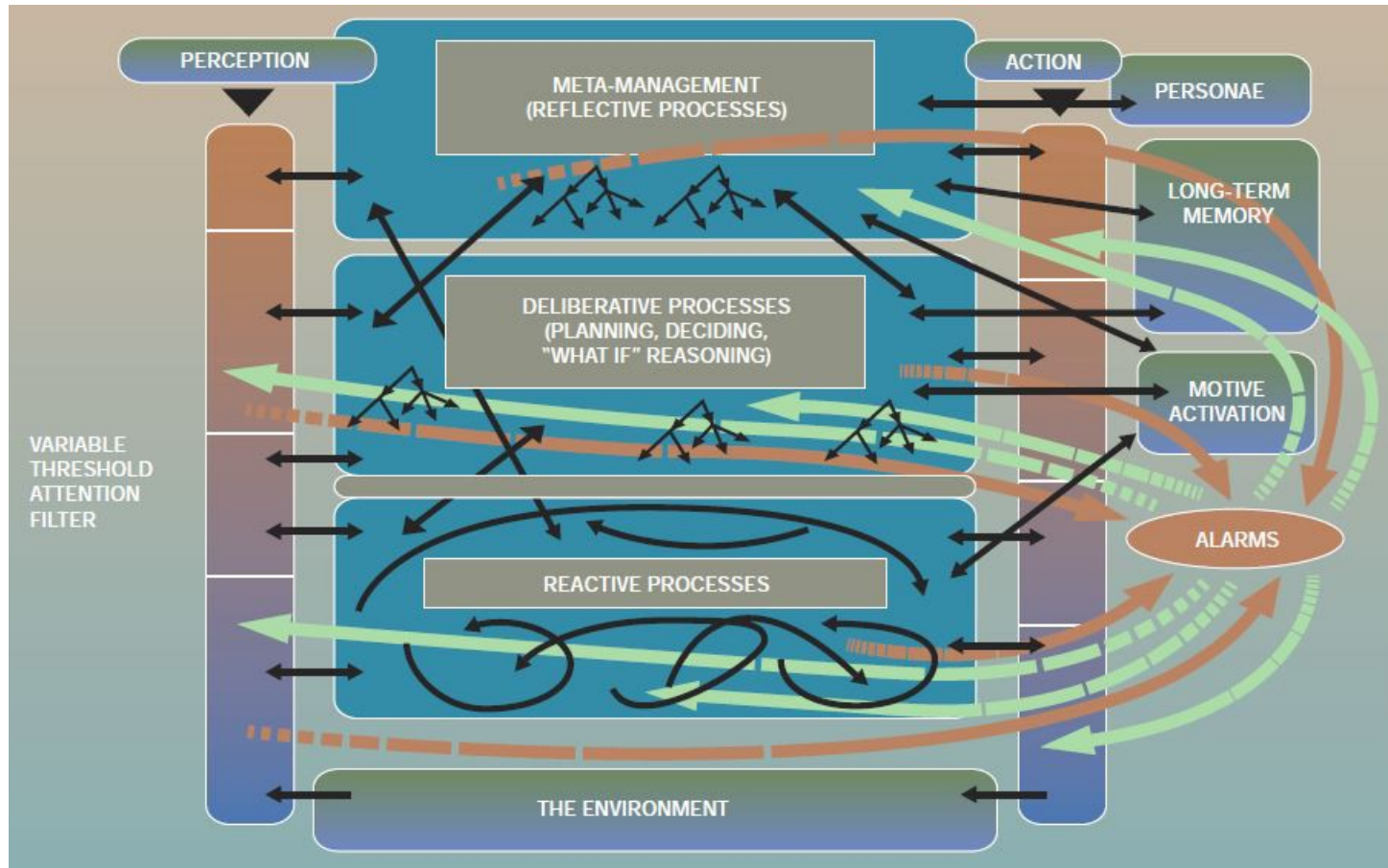


**Cycles are self-correcting: Any error in one cycle can be detected and corrected in later cycles.**

**Over the years, Boyd added more detail to the OODA Loop and applied it to decision-making processes of any kind.**

**Both versions are compatible with Peirce's cycles.**

# The H-Cogaff Architecture

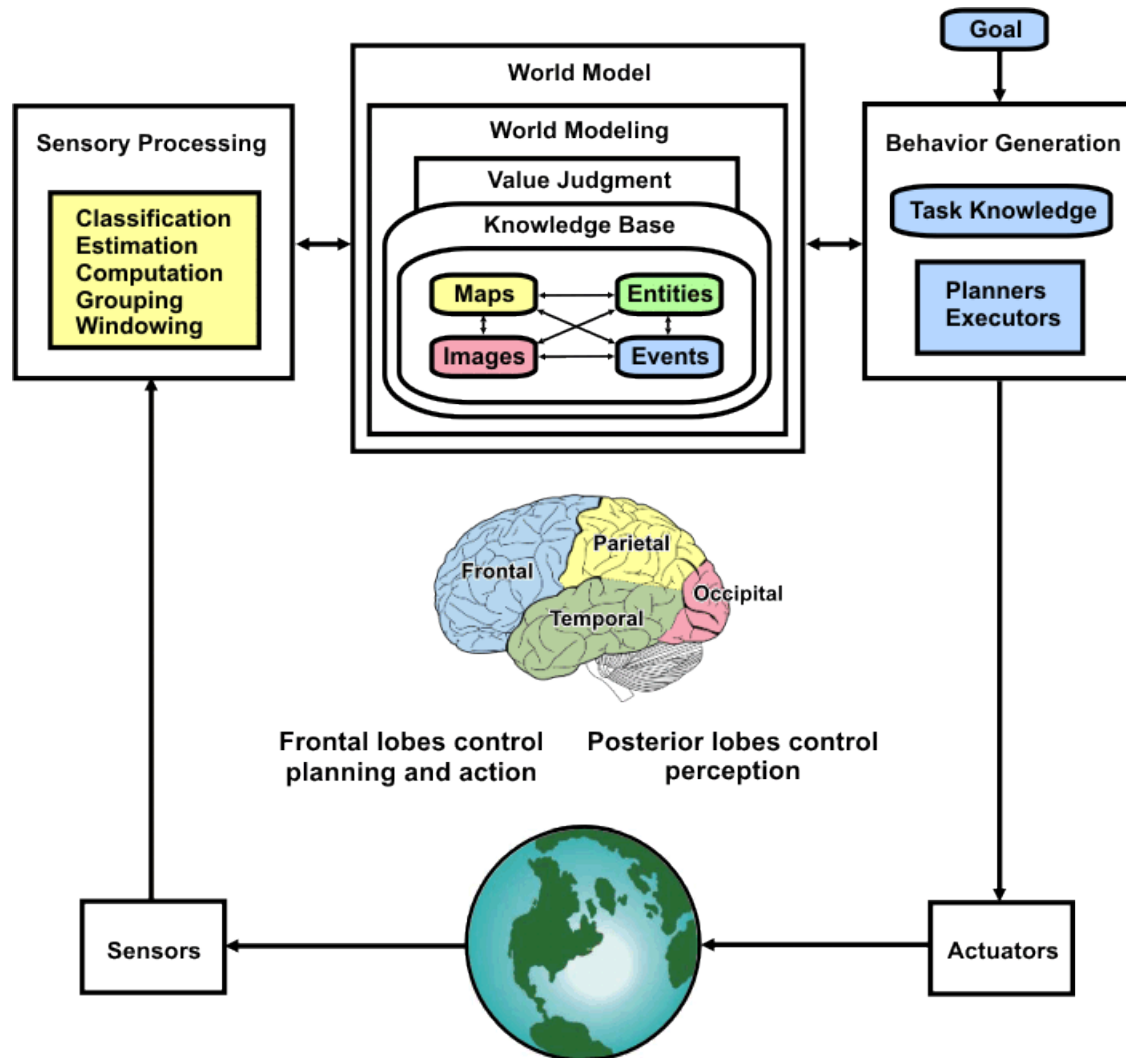


The Hierarchical Cognition Affect architecture by Aaron Sloman includes a cycle similar to Peirce's or Boyd's. \*

\* From [An architecture of diversity for Commonsense Reasoning](#) by McCarthy, Minsky, Sloman, et al. (2002)



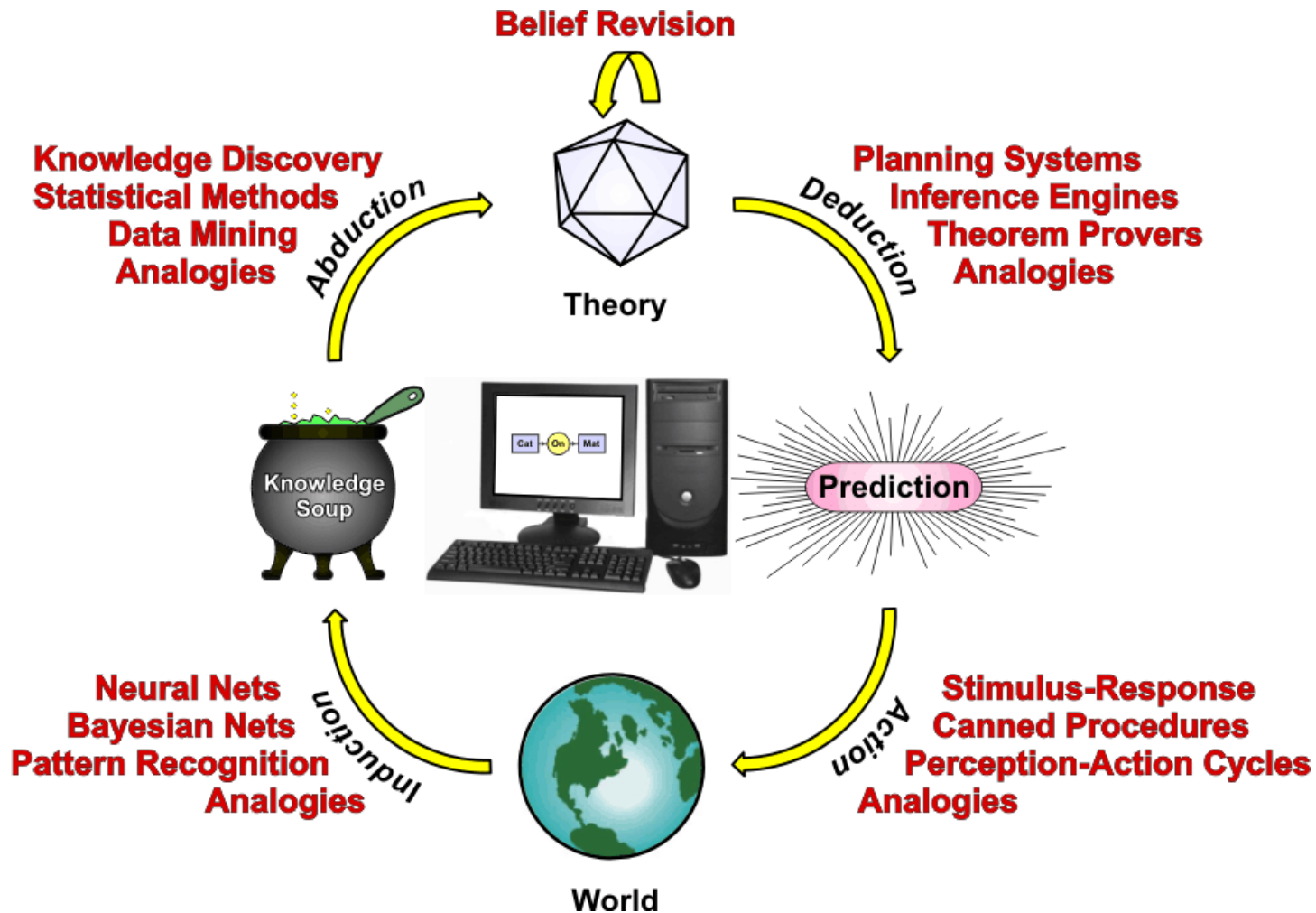
# Albus Cognitive Architecture



A cycle that resembles those by Peirce, Boyd, and Sloman.

See Albus (2010), <http://www.james-albus.org/docs/ModelofComputation.pdf>

# Implementing the Cycles



An open-ended variety of methods for learning and reasoning.

# Knowledge Discovery

## Observation by Immanuel Kant:

*Socrates said he was the midwife to his listeners, i.e., he made them reflect better concerning that which they already knew, and become better conscious of it. If we always knew what we know, namely, in the use of certain words and concepts that are so subtle in application, we would be astonished at the treasures contained in our knowledge...*

*Platonic or Socratic questions drag out of the other person's cognitions what lay within them, in that one brings the other to consciousness of what he actually thought.*

From his *Vienna Logic*

**We need tools that can play the role of Socrates.**

**They could help us discover the implicit knowledge in data from any source, especially the WWW.**

# Conclusion

**Many theories capture important aspects of cognition:**

- **Symbolic methods support formal deduction and computation.**
- **Embodied theories emphasize the dependence of mind on body.**
- **Dual coding theories relate the symbolic and embodied methods.**
- **The cerebellum supports virtual reality as a foundation for cognition.**
- **Artificial neural networks are valuable for pattern recognition.**
- **Cognitive linguistics relates language to all of the above.**
- **Biosemiotics emphasizes the continuity from bacteria to humans.**
- **Philosophers have analyzed and debated these issues for millennia.**

**Peirce's semiotic relates and integrates everything:**

- **Signs are the basis for all aspects of perception, learning, cognition, reasoning, communication, and action by all living things.**
- **His research in logic, philosophy, science, mathematics, lexicography, psychology, and early computing devices gave him the insights. \***

\* See <http://www.jfsowa.com/pubs/csp21st.pdf>

# Related Readings

For more information, most slides have URLs or citations.  
For the general bibliography, see <http://www.jfsowa.com/bib.htm>

## Publications by John F. Sowa:

The virtual reality of the mind (2016) <http://www.jfsowa.com/pubs/vrmind.pdf>

Signs and reality (2015) <http://www.jfsowa.com/pubs/signs.pdf>

The role of logic and ontology in language and reasoning (2010)  
<http://www.jfsowa.com/pubs/rolelog.pdf>

From existential graphs to conceptual graphs (2013)  
<http://www.jfsowa.com/pubs/eg2cg.pdf>

Peirce's tutorial on existential graphs (2011)  
<http://www.jfsowa.com/pubs/egtut.pdf>

Signs, processes, and language games: Foundations for ontology (1999)  
<http://www.jfsowa.com/pubs/signproc.pdf>

## Slides of presentations:

Peirce, Polya, and Euclid: Integrating logic, heuristics, and geometry (2015)  
<http://www.jfsowa.com/talks/ppe.pdf>

Natural logic (2016) <http://www.jfsowa.com/talks/natlog.pdf>

Cognitive Memory (2018) <http://www.jfsowa.com/talks/cogmem.pdf>