A **Standard Model of the Mind***: Toward a Common Computational Framework across Artificial Intelligence, Cognitive Science, Neuroscience, and Robotics

John E. Laird, Christian Lebiere, Paul S. Rosenbloom

(* since 2018 a.k.a. Common Model of Cognition)

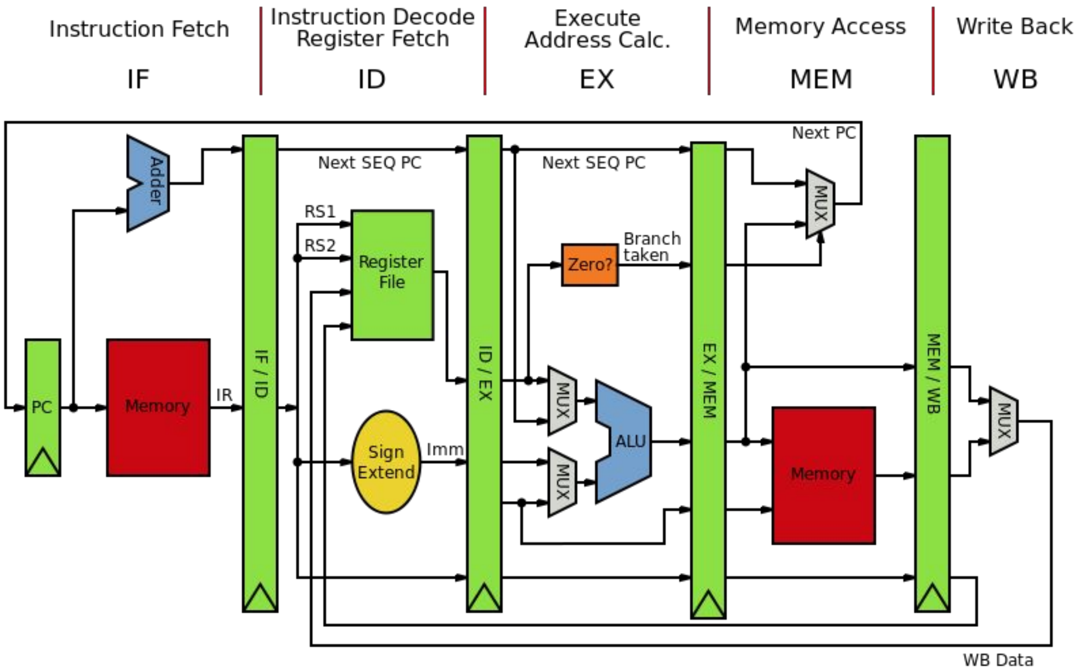
Presenters: Suzanne Lewis & Satpreet Singh

Introduction

- AI Magazine article emerging out of discussions at AAAI Conference 2013 organized by authors
- Motivation: Convergence in thinking about "minds" across various disciplines
    - *A **"Mind"** is a functional entity that can think, and thus support intelligent behavior*
- Different approaches within different disciplines
    - AI
    - Cognitive Science
    - Neuroscience
    - Robotics
- Models vs. Architectures
    - *Consensus* rather than *completeness*
    - SMM: "human-like" vs. optimal (AI)

Cognitive Architectures

- Cognitive Architecture: "a theory for simulating and understanding human cognition"
- Analogy with Computer / Microprocessor Architectures
- In this paper:
  - ACT-R
  - Soar
  - Sigma
- Notable others
  - Spaun, Leabra
  - DeepMind DRL (not really)



MIPS Computer Architecture
https://en.wikipedia.org/wiki/Computer_architecture

ACT-R

- "Adaptive Control (Character?) of Thought - Rational"
- tasks (e.g., Tower of Hanoi, list of words, language comprehension, aircraft controlling)
- traditional measures of cognitive psychology:
  - time to perform the task,
  - accuracy in the task, and,
  - neurological data

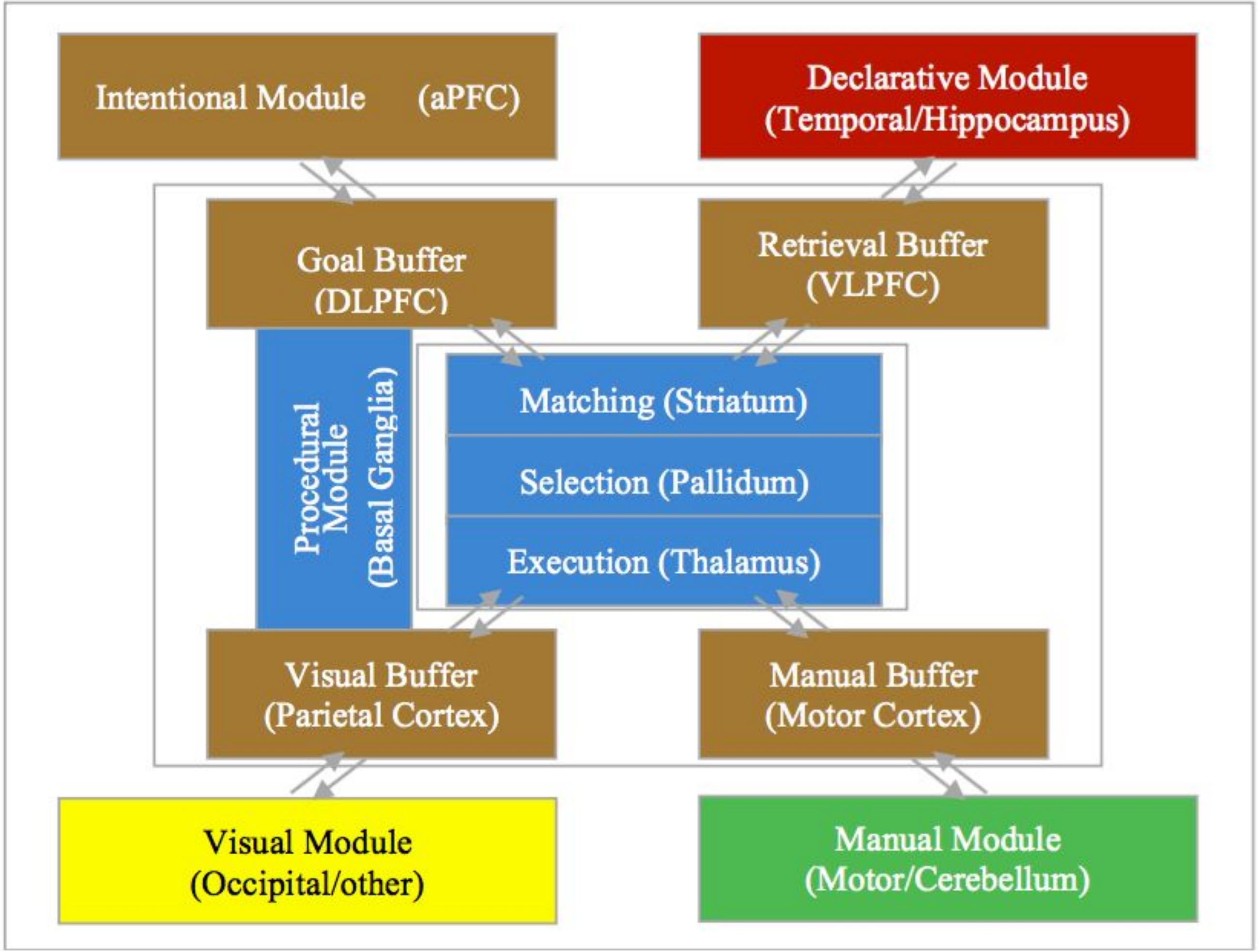


Figure 1. ACT-R cognitive architecture.

ACT-R Concepts

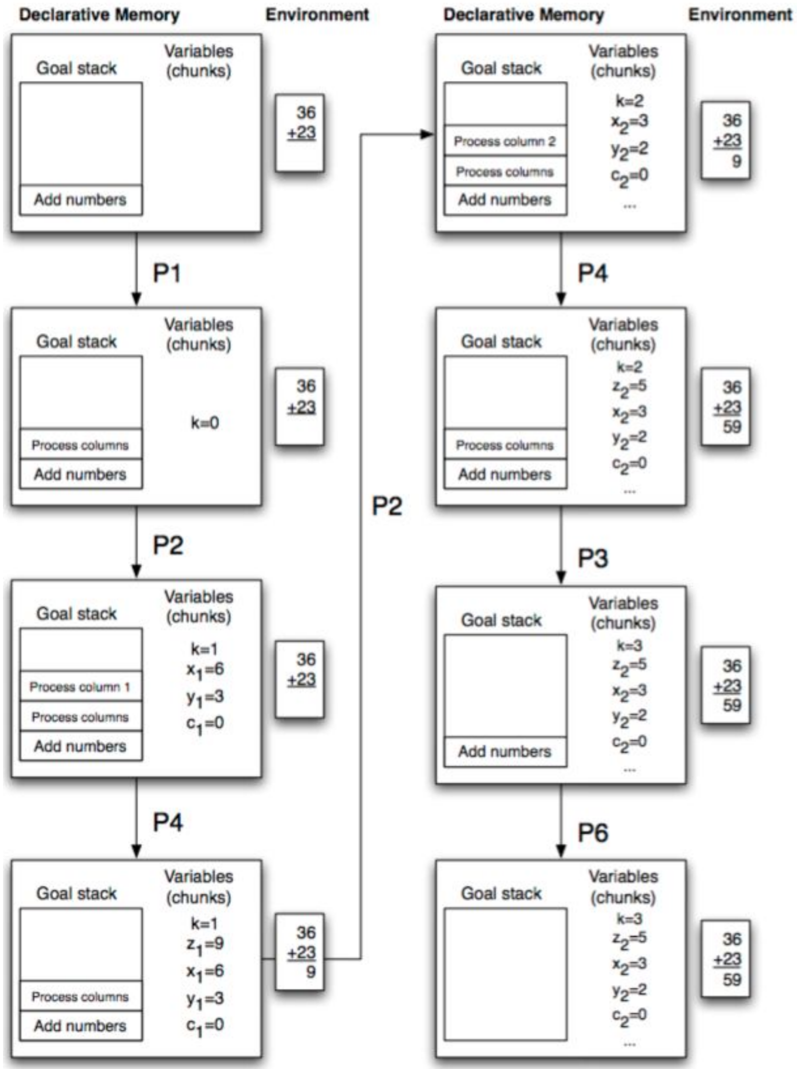
- Declarative Memory
  - **Chunks** (Variables)
  - "The **bank** is **closed** on **Sunday**"
  - **Goals** (goal chunks)
- Procedural Memory
  - **Production Rules**: **if/then** statements that specific how a particular **goal** can be achieved when a **precondition** is met

Production Rules

P1	If	the goal is to add two numbers
	Then	push a subgoal to process each of the columns with $k = 0$.
P2	If	the goal is to process each of the columns
	and	the last processed column was k (counted from the right)
	and	column $k+1$ exists
	Then	push a subgoal to process column $k+1$.
P3	If	the goal is to process each of the columns
	and	the last processed column was k (counted from the right)
	and	column $k+1$ does not exist
	Then	pop subgoal.
P4	If	the goal is to process column k
	and	the digits in the column are x_k, y_k, and carry c_k,
	and	$z_k = x_k + y_k + c_k < 10$,
	Then	write z_k below column k; pop subgoal.
P5	If	the goal is to process column k
	and	the digits in the column are x_k, y_k, and carry c_k,
	and	$z_k = x_k + y_k + c_k \geq 10$,
	Then	write the one's digit of z_k below column k; set c_{k+1} to 1 (adding a column of 0's as necessary); pop subgoal.
P6	If	the goal is to add two numbers
	and	all the columns have been processed
	Then	pop the goal.

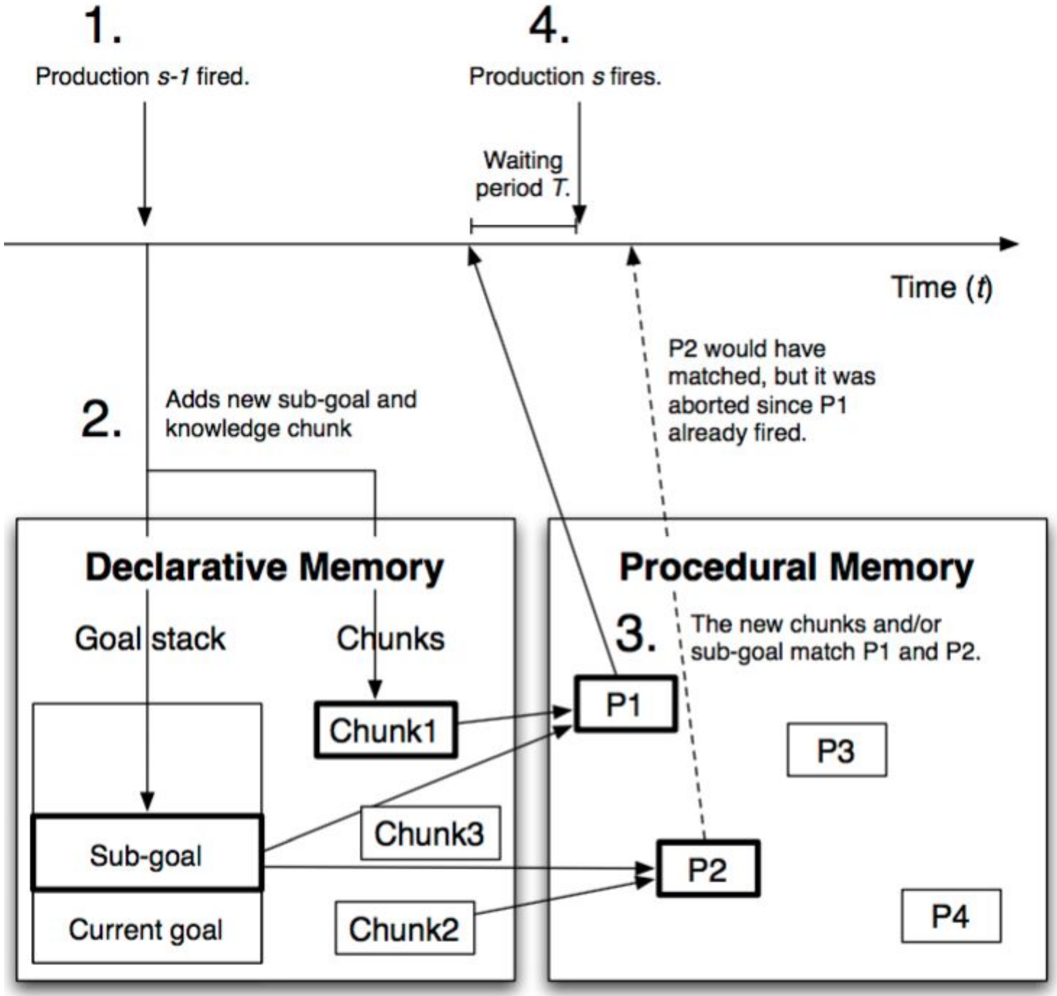
ACT-R Cognitive Cycle

- Declarative Memory
  - Chunks & Variables
  - Goals
  - **Goal stack**
- Procedural Memory
  - Production Rules
  - Matching
  - "Firing" (next slide)
- Environment
- Actions



ACT-R Rule Selection

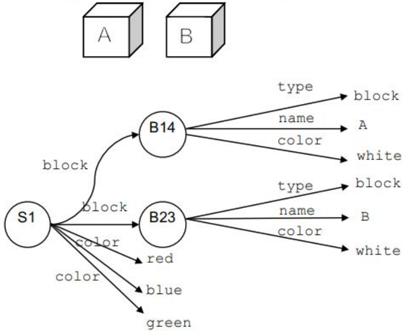
- Rules fire when
  - Preconditions (Chunks + Goals) match
  - Win out over other matched rules
- Firing
  - Executes logic
  - Adds chunks/goals
  - Performs actions
- Matching → Firing
  - Expected Value: $V = pG - C$
  - Waiting period + Retrieval time/Latency
- Learning mechanisms
  - Activation/Latency updates
  - Updating/New Chunks + PRs



SOAR

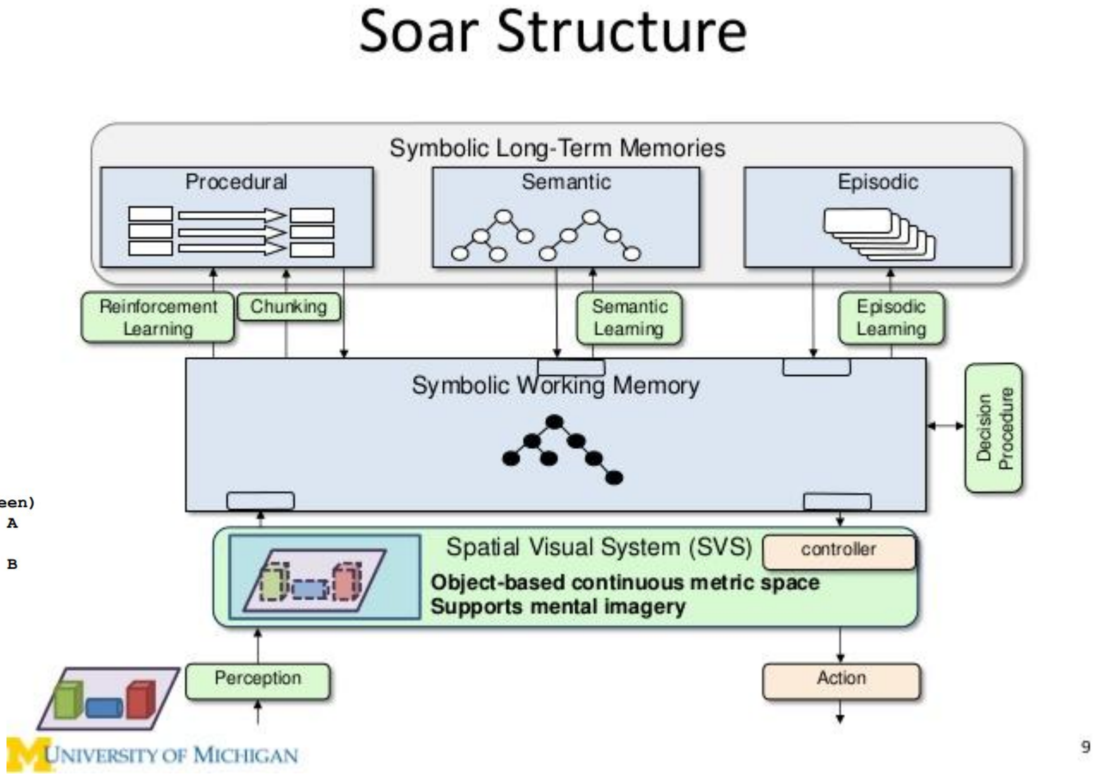
Current-goal: make both blocks red

State: blocks [color, name]
paint brushes for specific colors [color]




```
(S1 ^block B14)
(S1 ^block B23)
(S1 ^color red)
(S1 ^color blue)
(S1 ^color green)
(B14 ^type block)
(B14 ^name A)
(B14 ^color white)
(B23 ^type block)
(B23 ^name B)
(B23 ^color white)

(S1 ^block B14 B23
    ^color red blue green)
(B14 ^type block ^name A
     ^color white)
(B23 ^type block ^name B
     ^color white)
```



http://web.eecs.umich.edu/~soar/ijcai16/Tutorial-2016-basic.pdf
https://www.slideshare.net/diannepatricia/laird-ibmsmall

SMM: Structure and Processing

- **Common Cognitive Cycle:**
  - **Perception**
  - **PM examine WM**
  - **PM modify WM**
    - **Retrieve more PM**
    - **Initiate operations/actions**
- **Bounded Rationality Hypothesis**
- **Complex behavior as sequence of cycles**
- **Does not specify module descriptions**

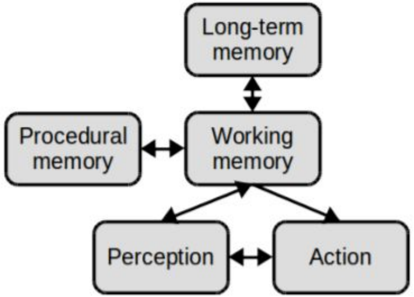


Figure 1: A graphical representation of the Standard Model of the Mind, as proposed by Laird et al. (2017)

A. Structure and Processing

1. The purpose of architectural processing is to support bounded rationality, not optimality
2. Processing is based on a small number of task-independent modules
3. There is significant parallelism in architectural processing
   a. Processing is parallel across modules
      i. ACT-R & Soar: asynchronous; Sigma: synchronous
   b. Processing is parallel within modules
      i. ACT-R: rule match, Sigma: graph solution, Soar: rule firings
4. Behavior is driven by sequential action selection via a cognitive cycle that runs at ~50 ms per cycle in human cognition
5. Complex behavior arises from a sequence of independent cognitive cycles that operate in their local context, without a separate architectural module for global optimization (or planning).

SMM: Memory and Content

- Working, procedural, declarative
- Physical Symbol System
- Metadata
- Not specified
    - Memory structure
    - Metacognition
    - Learning across modules
    - Integrate rules to select action

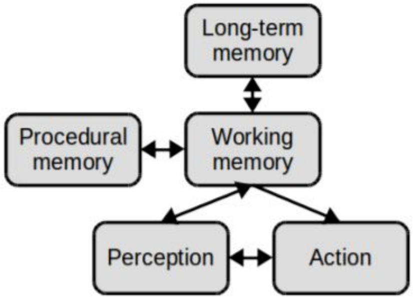


Figure 1: A graphical representation of the Standard Model of the Mind, as proposed by Laird et al. (2017)

B. Memory and Content

1. Declarative and procedural long-term memories contain symbol structures and associated quantitative metadata
    a. ACT-R: chunks with activations and rules with utilities; Sigma: predicates and conditionals with functions; Soar: triples with activations and rules with utilities
2. Global communication is provided by a short-term working memory across all cognitive, perceptual, and motor modules
3. Global control is provided by procedural long-term memory
    a. Composed of rule-like conditions and actions
    b. Exerts control by altering contents of working memory
4. Factual knowledge is provided by declarative long-term memory
    a. ACT-R: single declarative memory; Sigma: unifies with procedural memory; Soar: semantic and episodic memories

SMM: Learning

- Create and Tune PM and WM
- Does not specify all learning mechanisms
  - RL and chunking
- Learn through backward flow of information

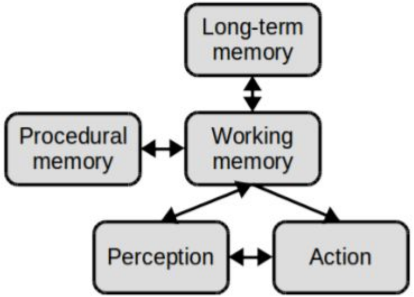


Figure 1: A graphical representation of the Standard Model of the Mind, as proposed by Laird et al. (2017)

C. Learning

1. All forms of long-term memory content, whether symbol structures or quantitative metadata, are learnable
2. Learning occurs online and incrementally, as a side effect of performance and is often based on an inversion of the flow of information from performance
3. Procedural learning involves at least reinforcement learning and procedural composition
   a. Reinforcement learning yields weights over action selection
   b. Procedural composition yields behavioral automatization
      i. ACT-R: rule composition; Sigma: under development; Soar: chunking
4. Declarative learning involves the acquisition of facts and tuning of their metadata
5. More complex forms of learning involve combinations of the fixed set of simpler forms of learning

SMM: Perception and Motor

- **Perception**
  - **Nonsymbolic->symbolic**
  - **Inflow constrained**
  - **Does not specify input structure/processing or top-down detail**
- **Motor**
  - **symbolic->environmental interaction**

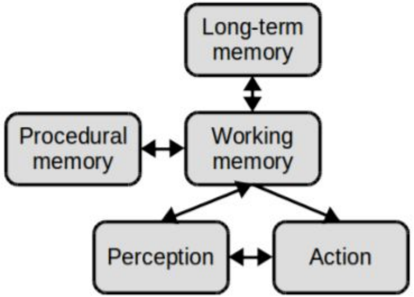


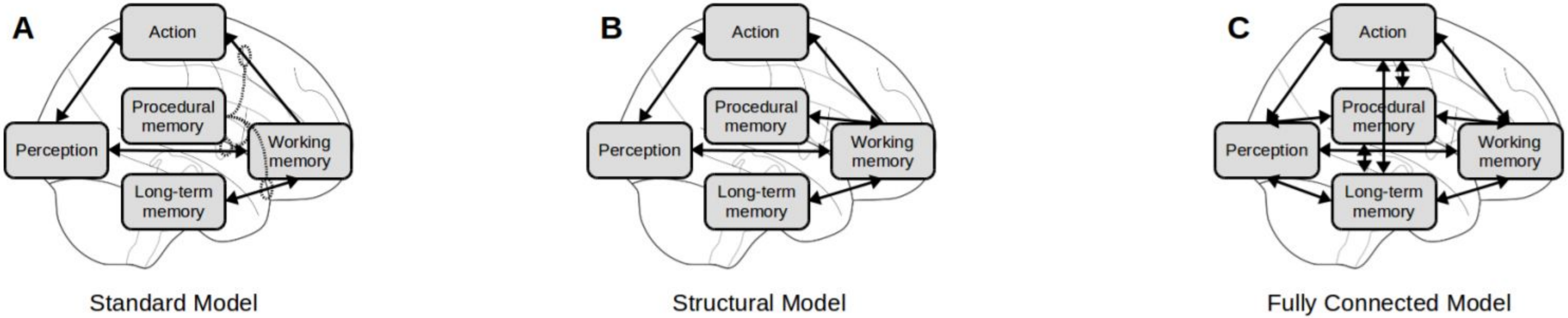
Figure 1: A graphical representation of the Standard Model of the Mind, as proposed by Laird et al. (2017)

D. Perception and Motor

1. Perception yields symbol structures with associated metadata in specific working memory buffers
   a. There can be many different such perception modules, each with input from a different modality and its own buffer
   b. Perceptual learning acquires new patterns and tunes existing ones
   c. An attentional bottleneck constrains the amount of information that becomes available in working memory
   d. Perception can be influenced by top-down information provided from working memory
2. Motor control converts symbolic relational structures in its buffers into external actions
   a. As with perception, there can be multiple such motor modules
   b. Motor learning acquires new action patterns and tunes existing ones

SMM mapped to brain

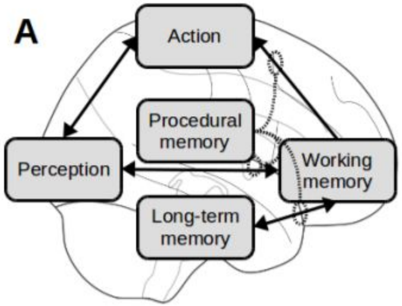
- Look at SMM structure of components/ connectivity compared to fMRI data across different tasks
- Map modules to brain regions- PM is basal ganglia



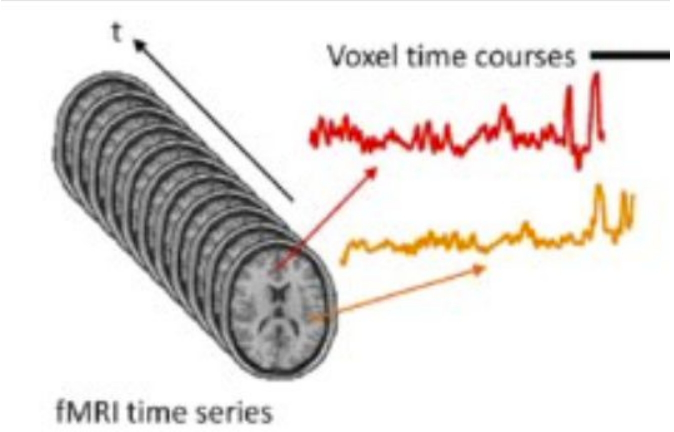
3. Global control is provided by procedural long-term memory
   a. Composed of rule-like conditions and actions
   b. Exerts control by altering contents of working memory

DCM:

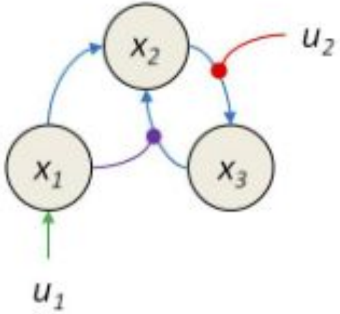
- Evaluate effective/directional connectivity
- Compare to functional architecture/ connectivity SMM



Standard Model



DCM



References

- A Standard Model of the Mind: Toward a Common Computational Framework Across Artificial Intelligence, Cognitive Science, Neuroscience, and Robotics. Laird, John E; Lebiere, Christian; Rosenbloom, Paul S. AI Magazine; Vol. 38, Iss. 4, (Winter 2017)
- Understanding ACT-R – an Outsider's Perspective (Jacob Whitehill) https://arxiv.org/abs/1306.0125
- Marinier III, R. P., Laird, J. E., & Lewis, R. L. (2009). A computational unification of cognitive behavior and emotion. *Cognitive Systems Research*, *10*(1), 48-69.
- Jilk, D. J., Lebiere, C., O'Reilly, R. C., & Anderson, J. R. (2008). SAL: An explicitly pluralistic cognitive architecture. *Journal of Experimental and Theoretical Artificial Intelligence*, *20*(3), 197-218.
- Stocco, A., Laird, J., Lebiere, C., & Rosenbloom, P. (2018). Empirical Evidence from Neuroimaging Data for a Standard Model of the Mind. In Proceedings of the 40th Annual Meeting of the Cognitive Science Society (pp. 1094-1099).
- http://web.eecs.umich.edu/~soar/ijcai16/Tutorial-2016-basic.pdf
- https://www.slideshare.net/diannepatricia/laird-ibmsmall
- https://soar.eecs.umich.edu/tutorial18/Tutorial-2018-SW-basic.pdf

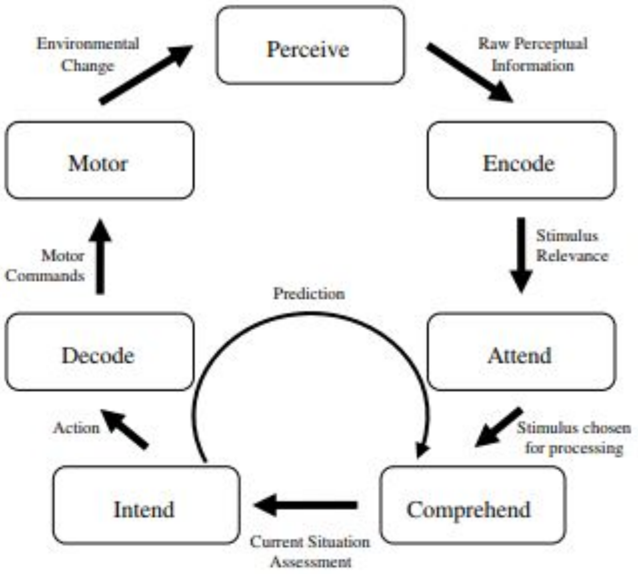


Fig. 1. Basic PEACTIDM cycle. The agent repeats this cycle forever. The output from a step primarily feeds into the next step, but the output of Intend also feeds into the next cycle's Comprehend. Tasking (not shown) competes with Attend. Tasking modifies the current goal, which also serves as an input to the Encode and Comprehend cycles.

Sigma

- “Modules” via functionalization driven by specialization and combination
- Single, general learning mechanisms
    - Learn different kinds of knowledge because all have the same structure
    - Translate meaning of different memories to determine LTM vs PM

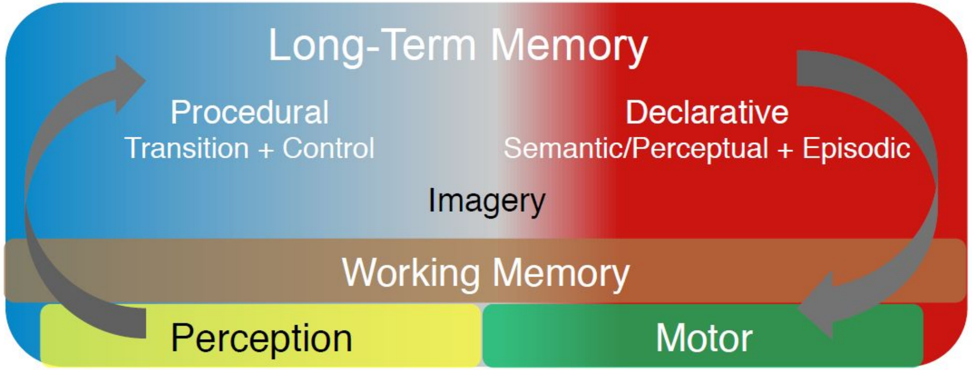


Figure 3. Sigma cognitive architecture.