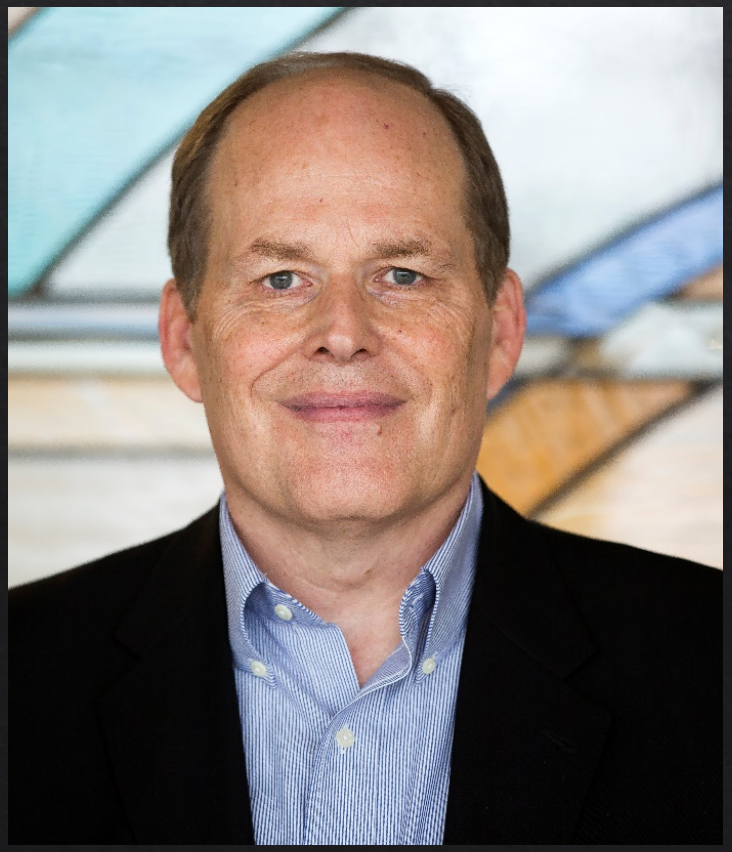
VISCA-2020
June 4-5, 2020
Hosted by the Soar Research Group
University of Michigan

Introduction to Cognitive Architecture

VISCA-2020



John E. Laird

John L. Tishman Professor of Engineering
Computer Science and Engineering
University of Michigan

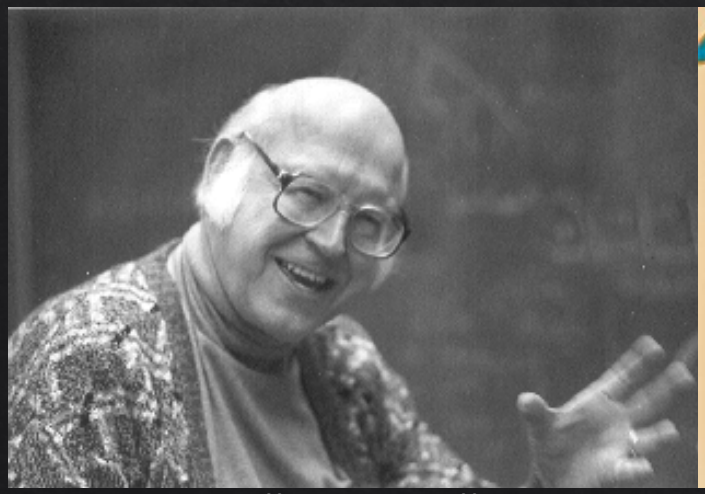
Email: laird@umich.edu
Website: laird.engin.umich.edu

June 4, 2020

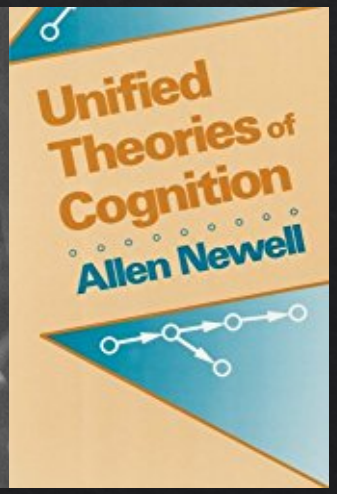
Cognitive Architecture Hypothesis

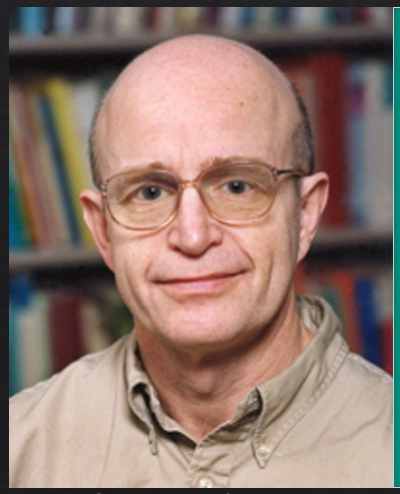
- "Our ultimate goal is a unified theory of human cognition. This will be expressed, I have maintained, as a theory of the architecture of human cognition – that is, of the fixed (or slowly varying) structure that forms the framework for the immediate processes of cognitive performance and learning." – Newell, 1990.

- Complex cognition arises from a combination of:
  - a fixed set of task-independent computational mechanisms: perception, memories, representations, learning, motor
  - knowledge (innate and learned through experience).

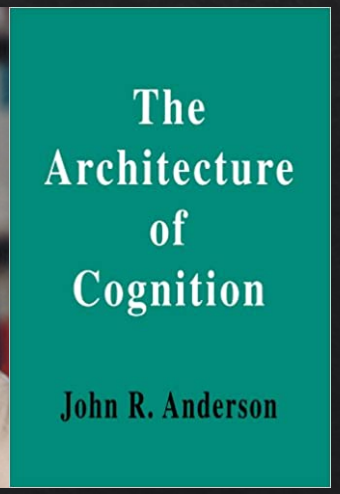


Allen Newell

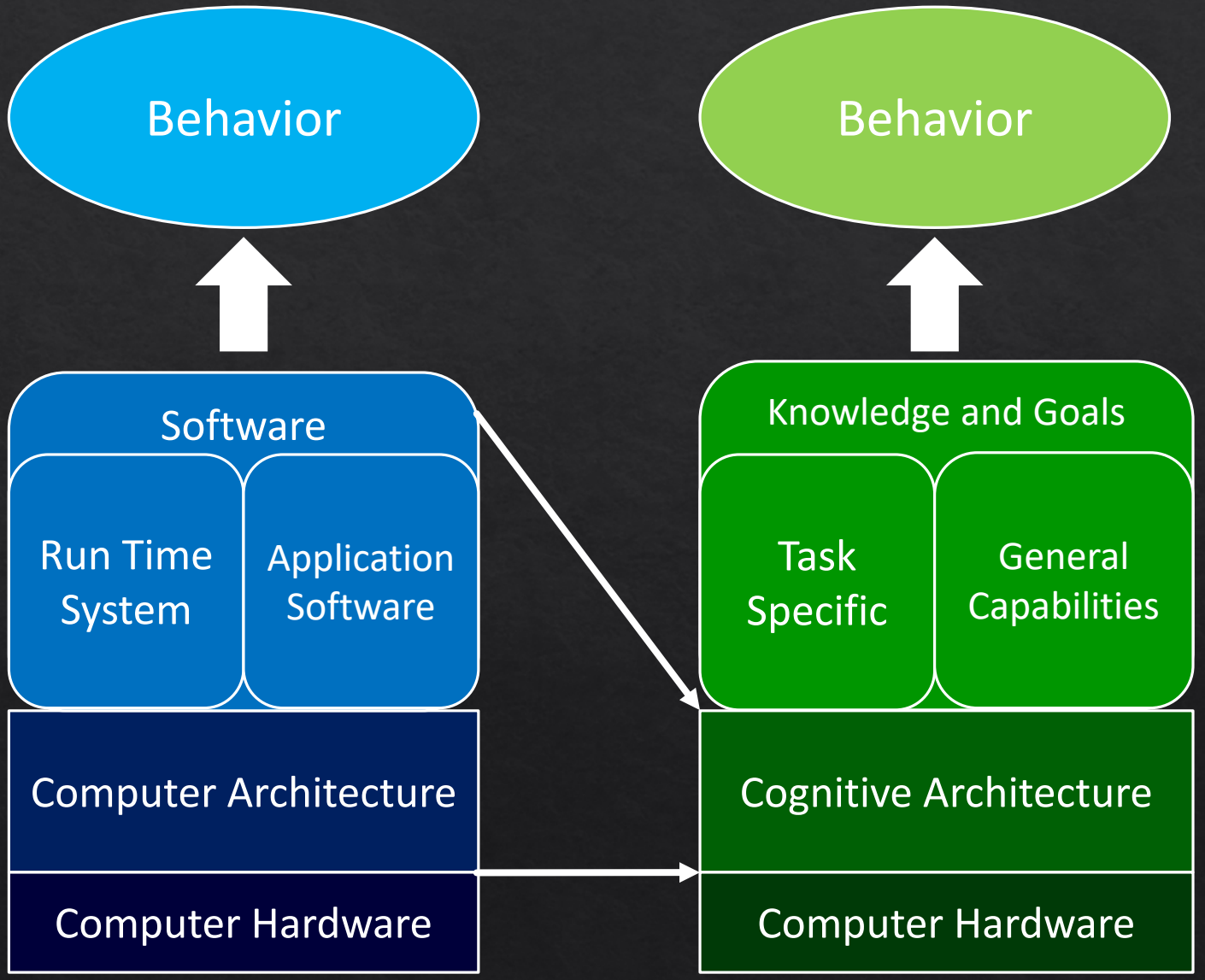




John Anderson



Computer and Cognitive Architectures



Newell's Time Scale of Human Action

Scale (sec)	Time Units	System	Band	
10^7	months			
10^6	weeks		Social	
10^5	days			
10^4	hours	Task		
10^3	10 min	Task	Rational	
10^2	minutes	Task		System 2
10^1	10 sec	Unit task		
10^0	1 sec	Compositional	Cognitive	System 1
10^{-1}	100 ms	Deliberate act		
10^{-2}	10 ms	Neural Circuit		System 0
10^{-3}	1 ms	Neuron	Biological	
10^{-4}	100 µs	Organelle		

Different regularities at different time scales.

Cognitive Band

Time Units	System	Cognitive Capabilities
10 sec	Unit tasks	Meta Reasoning Complex Reasoning Complex Analogy Planning
1 sec	Compositional acts	Simple Reasoning Language Processing Skilled Behavior
100 ms	Deliberate acts	Primitive Internal Actions Access Long-term Memories

- Intermixing of cognitive capabilities.
- Ubiquitous learning: automatic and continuous.
  - "Compiles" System 2 to System 1.

AI Tasks

Chess

Go

Starcraft

Poker

Fortnite

Jeopardy

Autonomous Driving

Diagnostic imaging analysis

Detect patterns in patient records for screening and treatment

Literature analysis and summarization

AI Tasks

Chess
Starcraft
Go
Poker
Fortnite
Jeopardy
Autonomous Driving
Diagnostic imaging analysis
Detect patterns in patient records for screening and treatment
Literature analysis and summarization

All AI Task Abilities

Results: Task Specific AI Programs

- Customized sensing, representations, processing, and learning.
- Advantages: Improved efficiency
  - Faster processing by eliminating irrelevant reasoning.
  - Optimize size, structure, and content of memories to needs of task.
- Disadvantages: Limits on generality and robustness
  - Over fit to the task: may need to redesign or retrain for small deviations.
  - Still lots of (expert) human involvement: formulation, parameter tuning...
  - Limits to knowledge transfer and reuse.

Powerful but often brittle solutions to specific task/problems.

Human Tasks and Knowledge

Shared Goals of Cognitive Architecture Research

- Develop the task-independent, fixed computational mechanisms underlying all intelligence – a unified theory of cognition.
- Support for the encoding and use of a multiplicity of types of knowledge (innate and learned) in support of simple to complex cognitive capabilities.

Differing Goals of Cognitive Architecture Research

Biological modeling:

- Model what we know about the brain: neurons, neural circuits, …
- Predict neural activity and cognitive behavior
- Shorter time scales
- Examples: LEABRA, SPAUN, …

Psychological modeling:

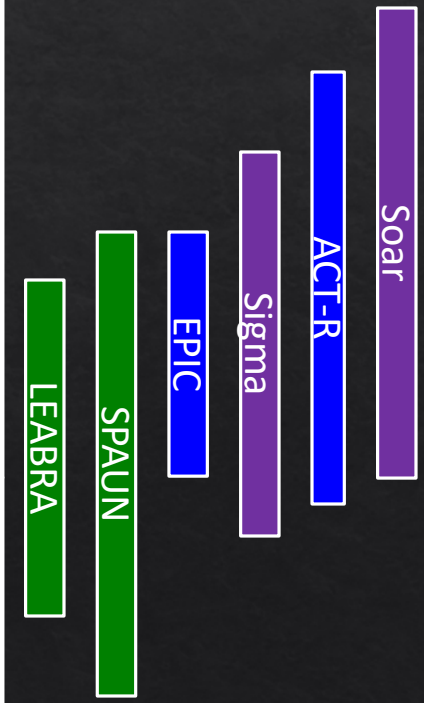
- Model human performance in a wide range of cognitive tasks
- Predict human reaction time and error rates for psychological tasks
- Tasks that take seconds to minutes
- Examples: ACT-R, EPIC, CLARION, LIDA, CHREST, 4CAPS, …

AI Functionality:

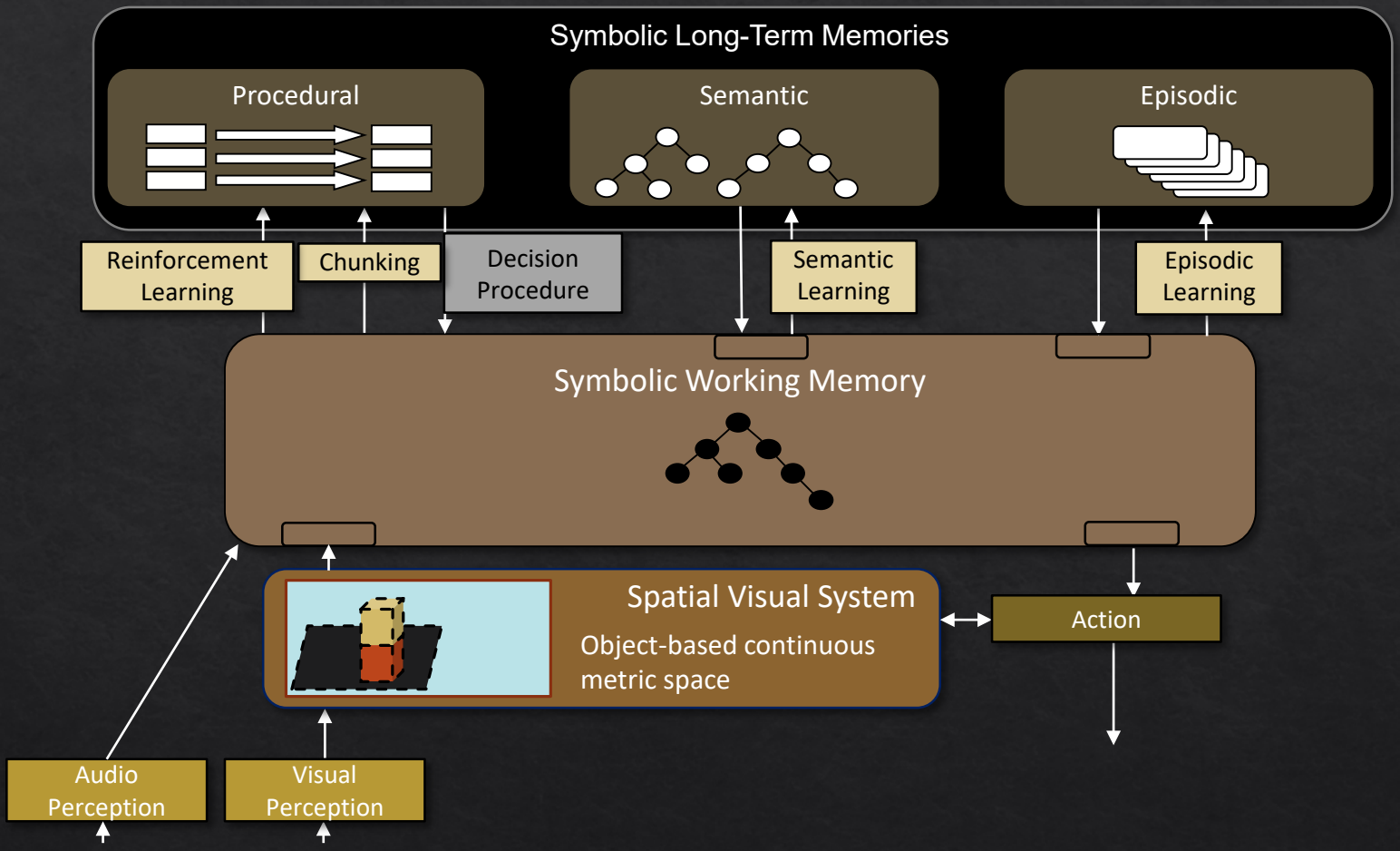
- Toward human-level intelligence, often *inspired* by psychology and biology
- Emphasizes more complex cognitive processing, longer time scales
- Examples: Soar, Companions, Sigma, ICARUS, CogPrime, PUG, …

Newell's Time Scale of Human Action

Scale (sec)	Time Units	System	Band
10^7	months		
10^6	weeks		Social
10^5	days		
10^4	hours	Task	
10^3	10 min	Task	Rational
10^2	minutes	Task	
10^1	10 sec	Unit task	
10^0	1 sec	Compositional	Cognitive
10^{-1}	100 ms	Deliberate act	
10^{-2}	10 ms	Neural Circuit	
10^{-3}	1 ms	Neuron	Biological
10^{-4}	100 µs	Organelle	



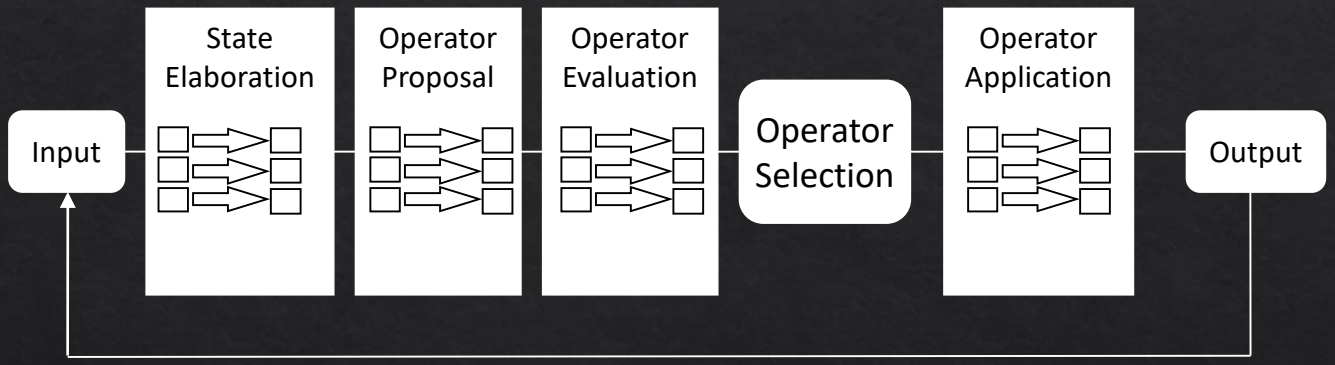
Soar


Symbolic Long-Term Memories
Procedural
Semantic
Episodic
Reinforcement Learning
Chunking
Decision Procedure
Semantic Learning
Episodic Learning
Symbolic Working Memory
Spatial Visual System
Object-based continuous metric space
Action
Audio Perception
Visual Perception

Cognitive Architecture

Not just a programming language…

- A fixed, continual processing cycle
  - Serial and parallel processing with no program counter
  - Conditional action is the norm instead of the exception



- Fixed small set of primitive data representations of the world
  - Symbolic lists or graphs and non-symbolic values
- Has multiple long-term memories and learning mechanisms
- Can have significant innate knowledge

40 Years of Cognitive Architectures:

Core Cognitive Abilities and Practical Applications

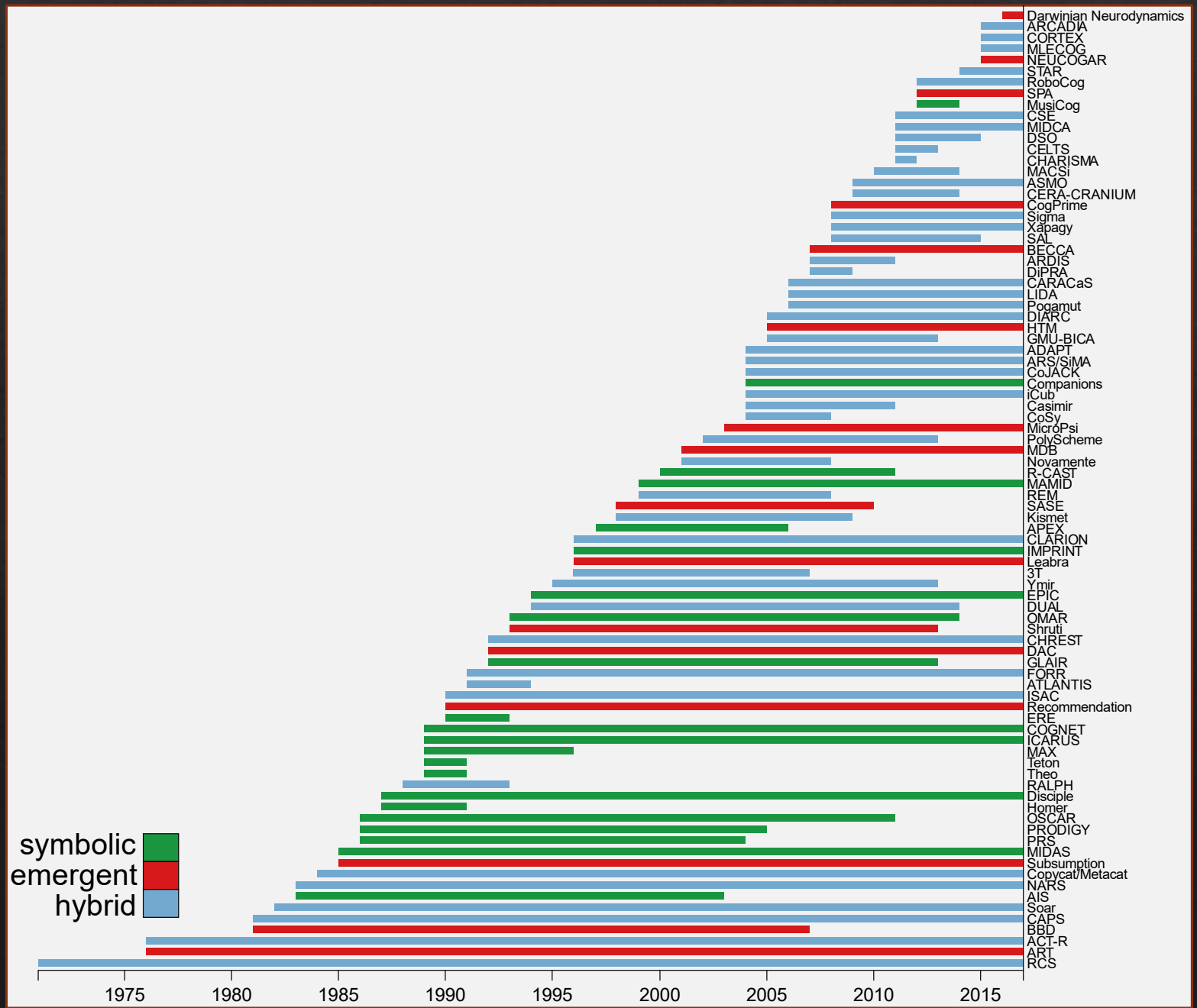
Iuliia Kotseruba and John K. Tsotsos

Artificial Intelligence Review 53, 17-94 (2020)

York University

- A survey of 84 cognitive architectures (49 actively developed)
- Based on over 2,500 publications covering 40 years of research
- Provides a timeline and taxonomy of cognitive architectures
- Examines core cognitive abilities: perception, attention, action selection, memory, learning, reasoning and metacognition
- Categorizes over 900 practical applications of cognitive architectures
- Interactive visualizations and full bibliography are available at: *http://jtl.lassonde.yorku.ca/project/cognitive_architectures_survey/*

Timeline of cognitive architectures

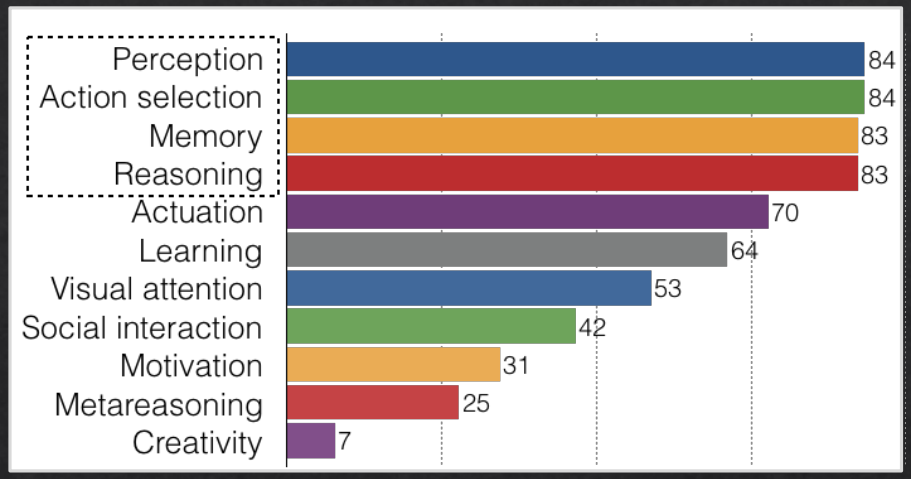


Kotseruba & Tsotsos 2020

Where are we now?

- Wide spectrum of cognitive abilities and applications
- Engineered and biomimetic approaches
- Focus on high-level cognition: action selection, memory, and learning
- Gap between bio-inspired and engineered architectures
- Gap between cognitive architectures and narrow AI (deep learning)

Number of architectures (84 total) implementing core cognitive abilities



What is missing?

- Realistic perception and life-long learning
- Communication and social skills
- Metacognition and episodic memory
- Performance and scalability
- Rigorous experimental validation
- Reproducibility of the results

Kotseruba & Tsotsos, 2020

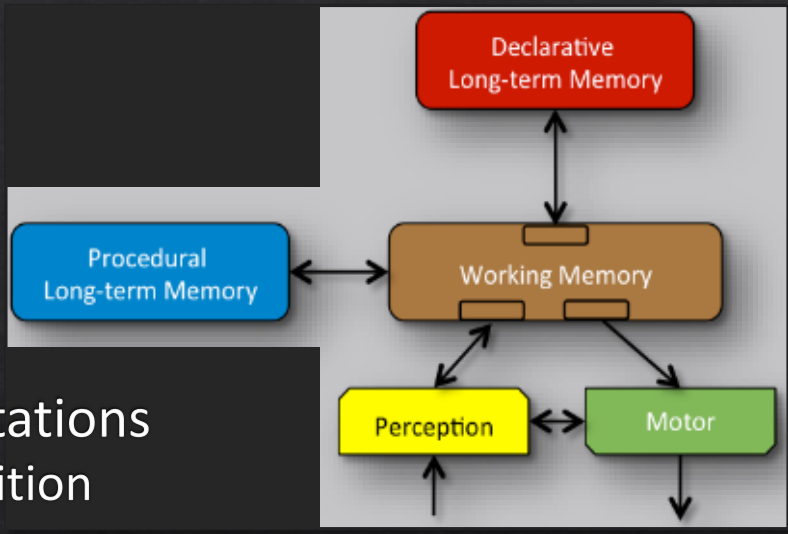
Common Issues/Controversies

1. What are fixed mechanisms vs. learnable knowledge?
   - Architecture: optimized/efficient, universal, access to metadata.
   - Knowledge: adaptable, task specific, …
   - Ex: Innate mechanisms for declarative goal structures, metareasoning, …
2. Multiple mechanisms vs. single more general mechanism
   - Ex: Single declarative long-term memory vs. semantic and episodic
3. Commitments to underlying implementation technology
   - Ex: Commitment to neural realization of higher architectural levels
4. Support of reasoning and learning over modality-specific representations
   - Ex: Inclusion of mental imagery
5. Explicit representations of symbols vs. implicit representation
6. Commitment to real-world, real-time implementations vs. simulations vs. theoretical specifications

20

Common Model of Cognition

- An abstract specification of human-like cognitive architecture
  - Community consensus/agreement
  - Not itself a cognitive architecture
  - Still missing many components

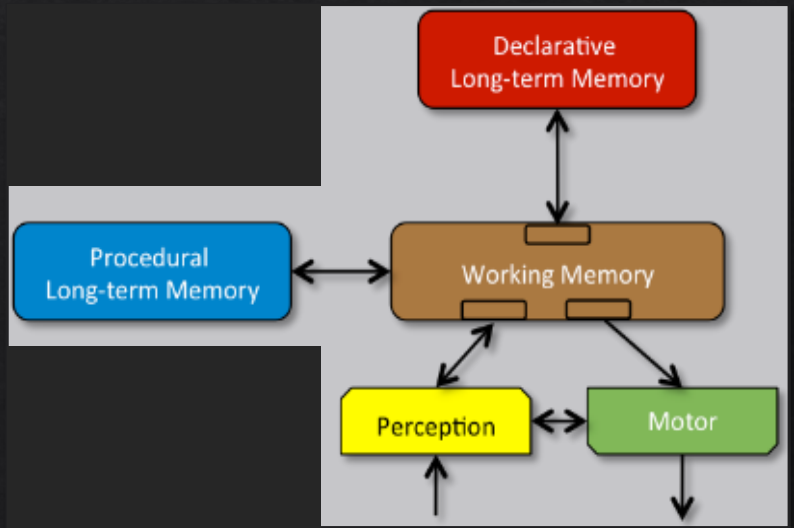


- A set of communicating modules
  - But not just undifferentiated stuff
  - Specific processing, interfaces, representations
  - No additional modules for complex cognition
- Potential benefits
  - Coherent baseline to facilitate shared cumulative progress
  - Guidance in extending research on individual components & constructing intelligent applications
  - Testable theory for different structures and functions of the mind

Laird, J. E., Lebiere, C. & Rosenbloom, P. S. (2017). A Standard Model for the Mind: Toward a Common Computational Framework across Artificial Intelligence, Cognitive Science, Neuroscience, and Robotics , *AI Magazine 38(4).*

Common Model Structure and Processing

1. Processing based on a few task-independent modules
2. Cognitive cycle runs at ~50 ms per cycle in humans that drives behavior via sequential action selection
3. Parallelism throughout architectural processing
   a. Processing is parallel across modules
   b. Processing is parallel within modules
4. Complex behavior arises from a sequence of independent cognitive cycles
5. Learning mechanisms are associated with every memory



Other Relevant 2020 Meetings

- Artificial General Intalligence: AGI
  - June 23-26, 2020, Virtual and St. Petersburg, Russia
  - http://agi-conference.org/
- International Conference on Cognitive Modeling: ICCM
  - July 22-31: Virtual
  - http://mathpsych.org/conferences/2020/
- Advances in Cognitive Systems: ACS
  - August 10-12: Virtual and possibly Palo Alto, CA
  - http://www.cogsys.org/conference/2020/
- Brain-Inspired Cognitive Architectures for Artificial Intelligence: BICA*AI
  - Nov 10-15: Virtual and Natal, Brazil
  - https://bica2020.org/