Universidad Carlos III de Madrid
Escuela Politécnica Superior – Departamento de Informática

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Evaluation and Development of Consciousness in Artificial Cognitive Systems

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Contents

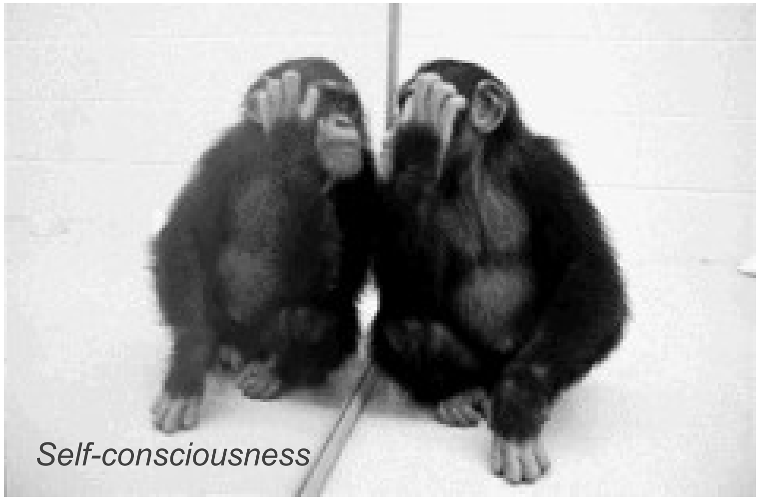
Consciousness in Artificial Cognitive Systems

- **Introduction**
  - **What is consciousness?**
  - Working hypotheses
  - Objectives
- State of the Art
- CERA-CRANIUM
- *ConsScale*
- Artificial Qualia
- Experimentation
- Conclusions

What is consciousness?

"The state of being characterized by sensation, emotion, volition, and thought"

"The quality or state of being aware especially of something within oneself"



Self-consciousness

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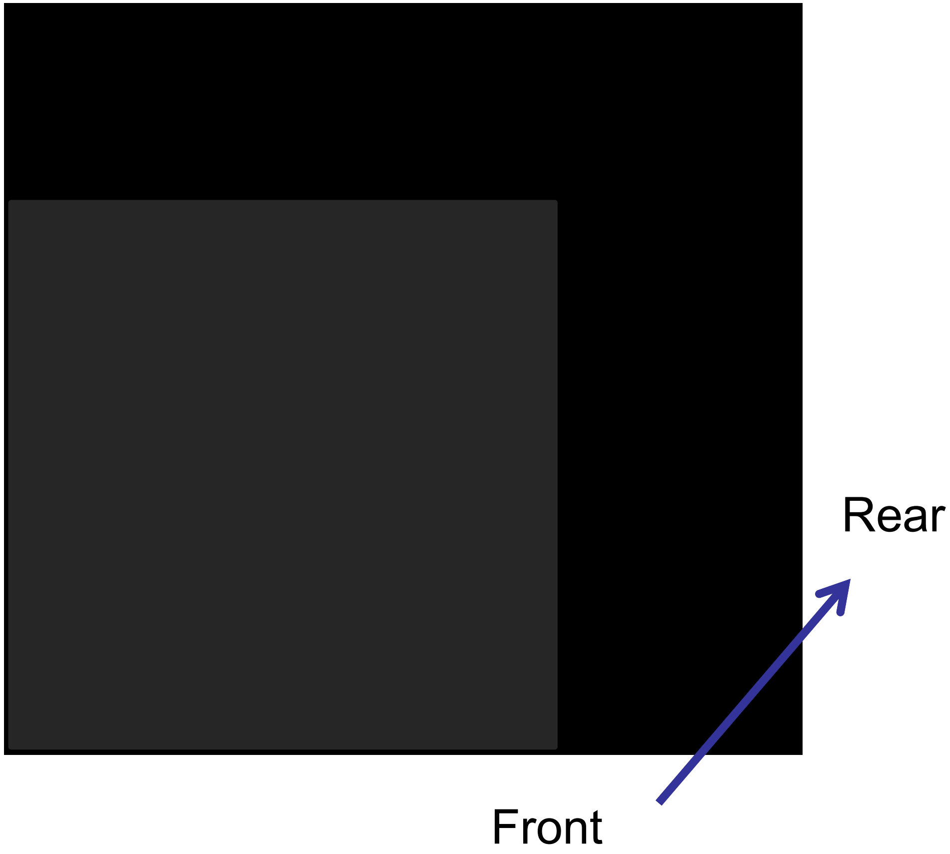
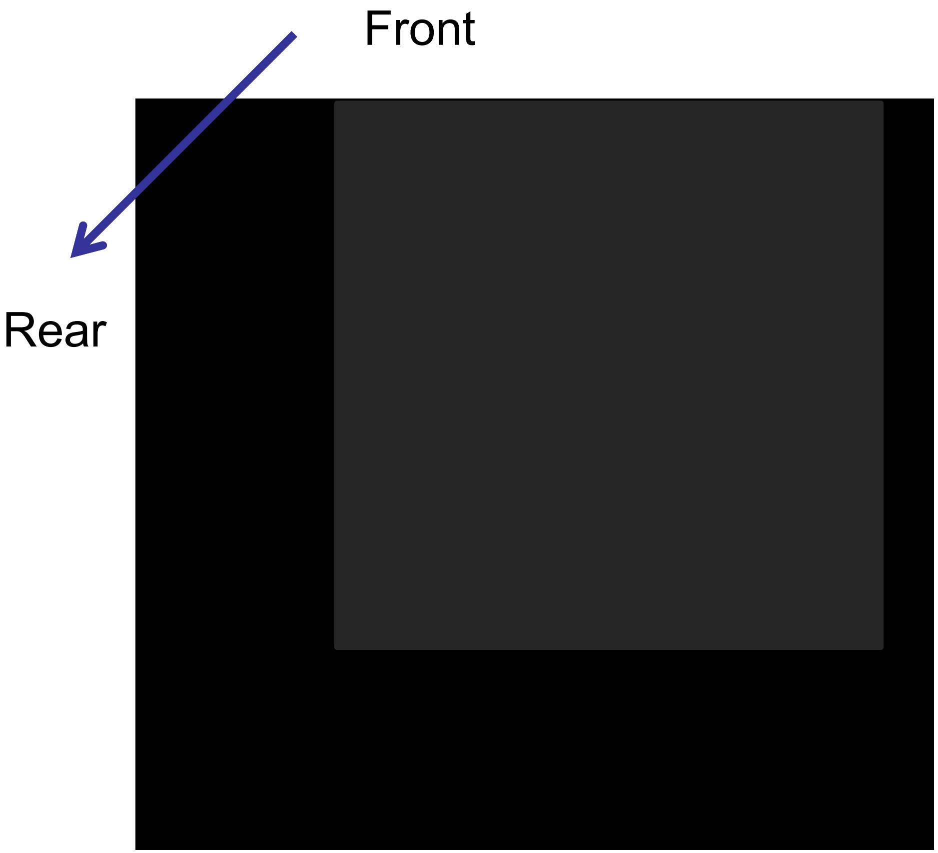
What is consciousness?

Senses ←→ Conscious Experience

What is consciousness?



What is consciousness?



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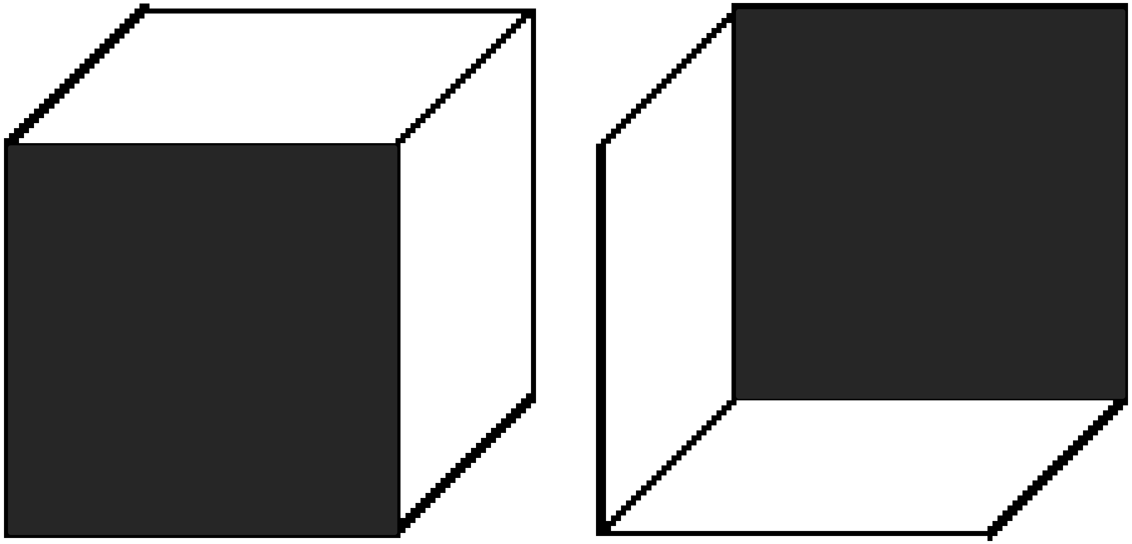

Bistable Perception

What goes on inside the brain when we perceive the color RED?

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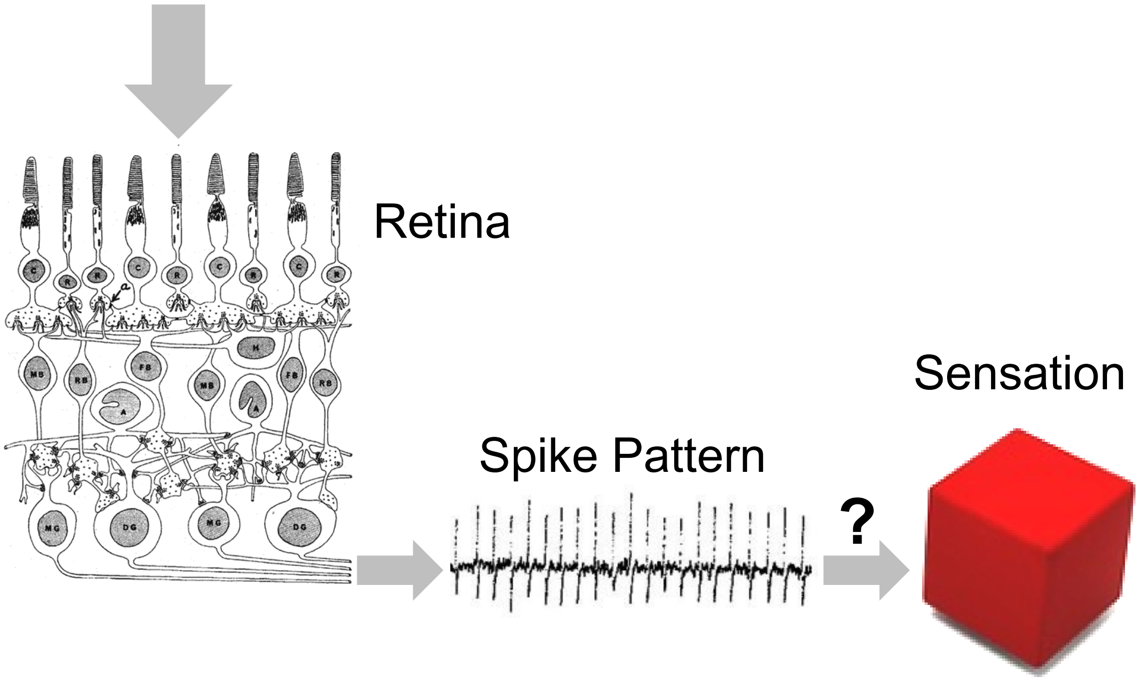
What is consciousness?



LIGHT

Retina

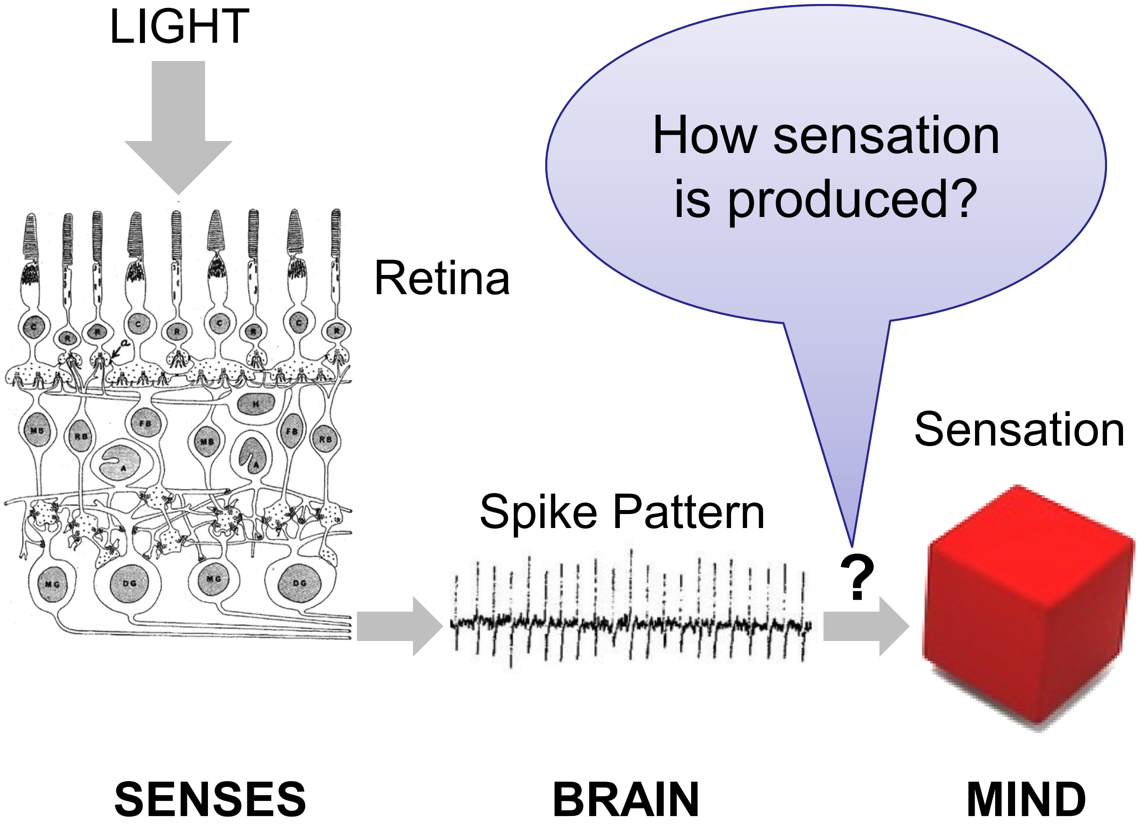
Sensation

Spike Pattern

?

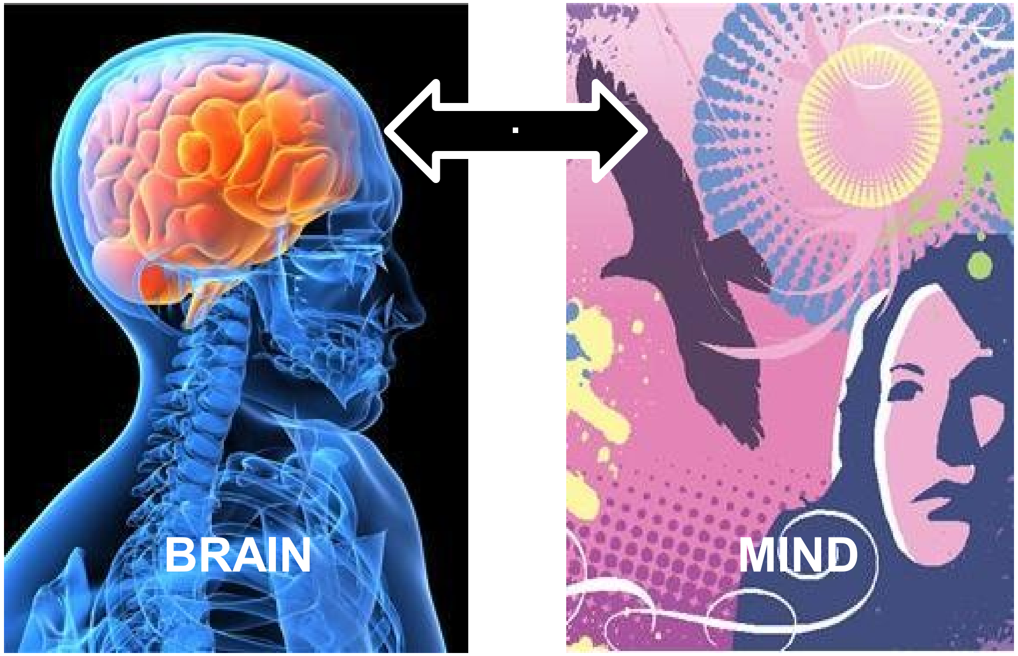
SENSES **BRAIN** **MIND**

What is consciousness?



What is consciousness?

Mind-Body Problem



Material
Observable

Immaterial
Private

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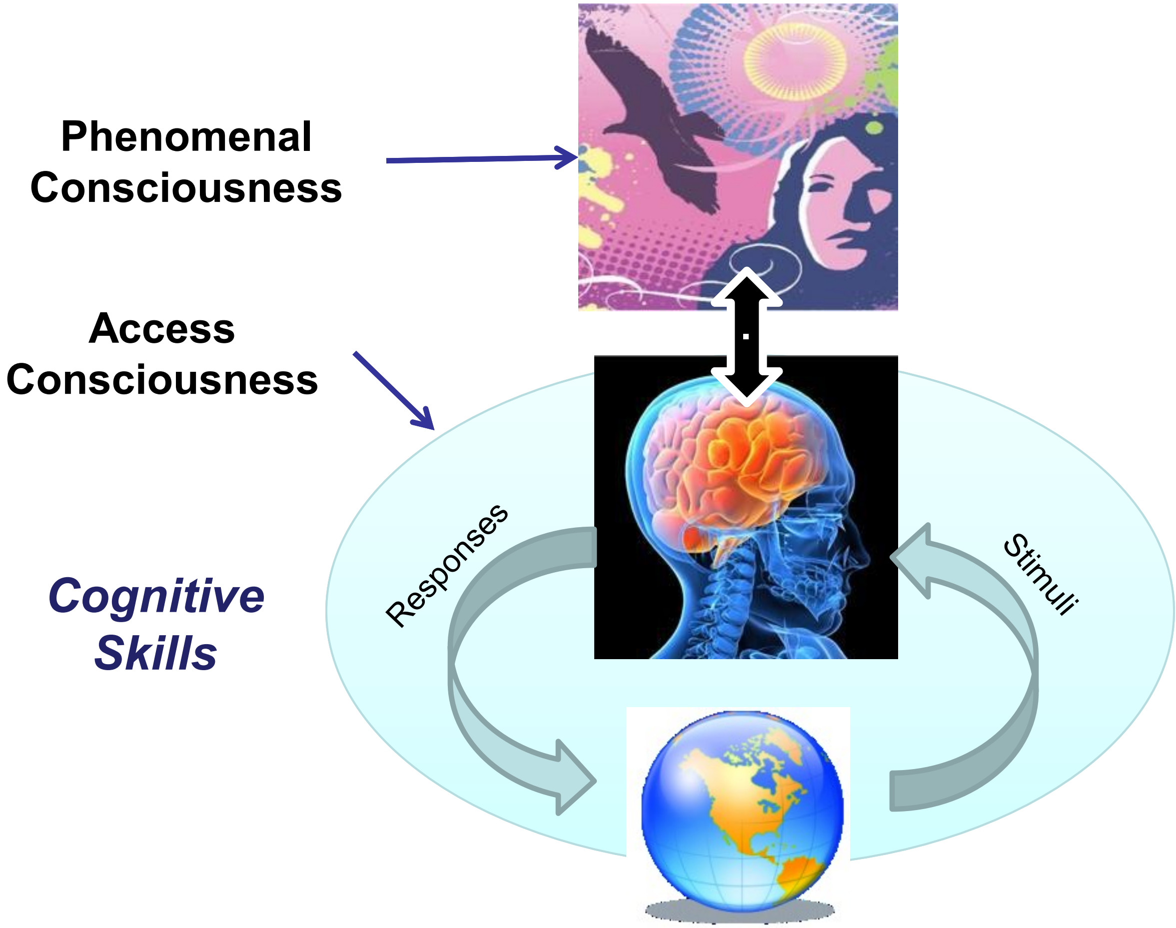
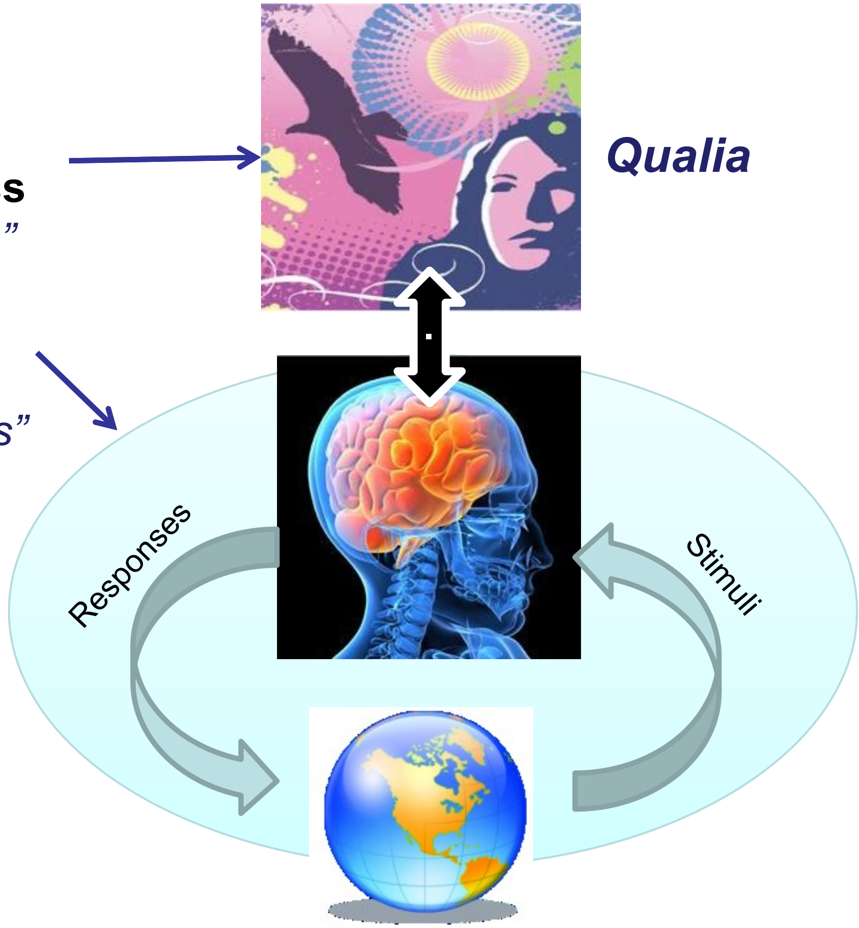


Phenomenal Consciousness

Access Consciousness

Cognitive Skills

What is consciousness?



Phenomenal Consciousness
"Hard Problem"

Access Consciousness
"Easy Problems"

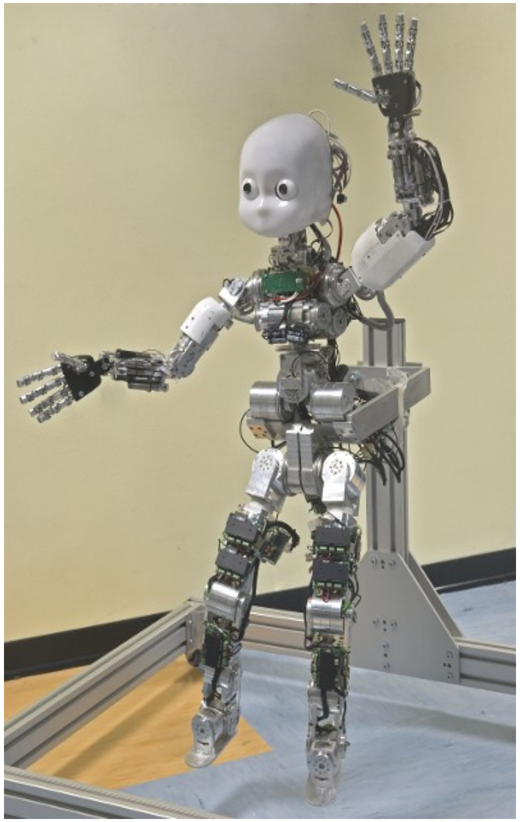
Cognitive Functions

(Block, 1995)
(Chalmers, 1995)

Consciousness in Artificial Cognitive Systems

Cognitive Skills

- ☐ Functional dimension of:
  - ☐ Attention
  - ☐ Planning
  - ☐ Imagination
  - ☐ Emotions
  - ☐ Theory of Mind
  - ☐ Introspection
  - ☐ …



"Easy Problems"

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What are Qualia?

"Enjoying a song"

"The redness of red"

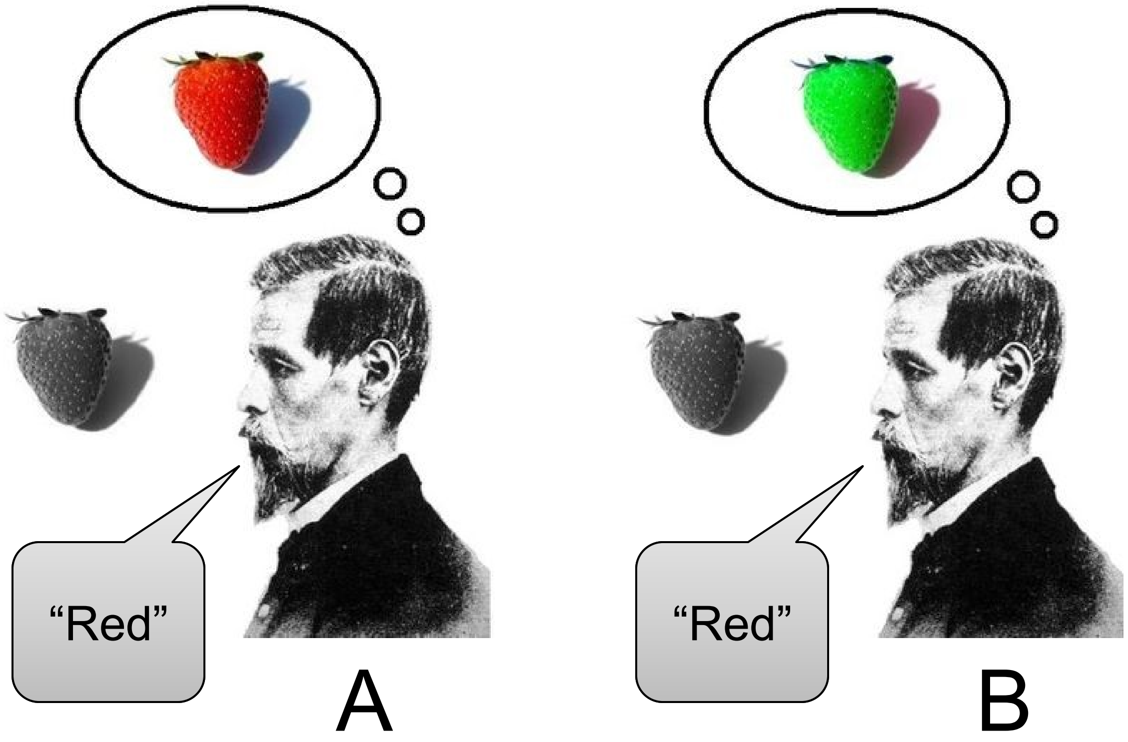
"The taste of ice-cream"

"A headache"

Integrated
Ineffable
Qualia
Private
Structured
Presence
Sensations

"Hard Problem"

What are *Qualia*?



Working Hypotheses

What is consciousness.

How can it be scientifically studied.

How can it be measured.

↓

Machine Consciousness

Objectives

Prove or refute the working hypotheses

Cognitive architecture based on a model of consciousness

Framework for the evaluation of the level of consciousness of artificial systems

Consciousness in Artificial Cognitive Systems

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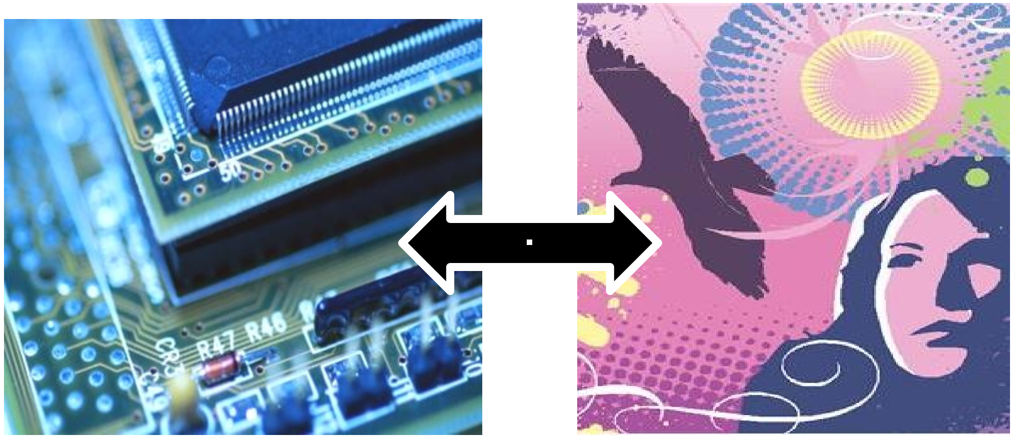
Objectives

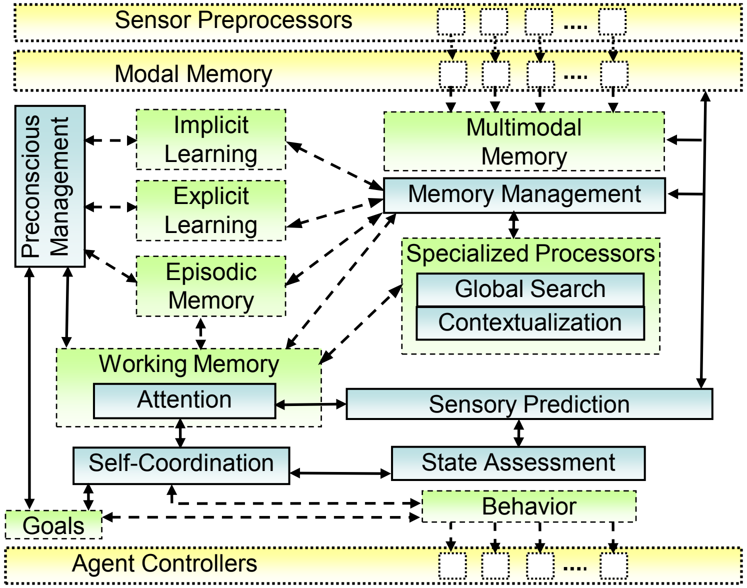
I. To demonstrate that phenomenal consciousness can be studied using artificial systems.



Consciousness in Artificial Cognitive Systems

Objectives

II. To demonstrate that the functional role of consciousness is integration and adaptation.



Consciousness in Artificial Cognitive Systems

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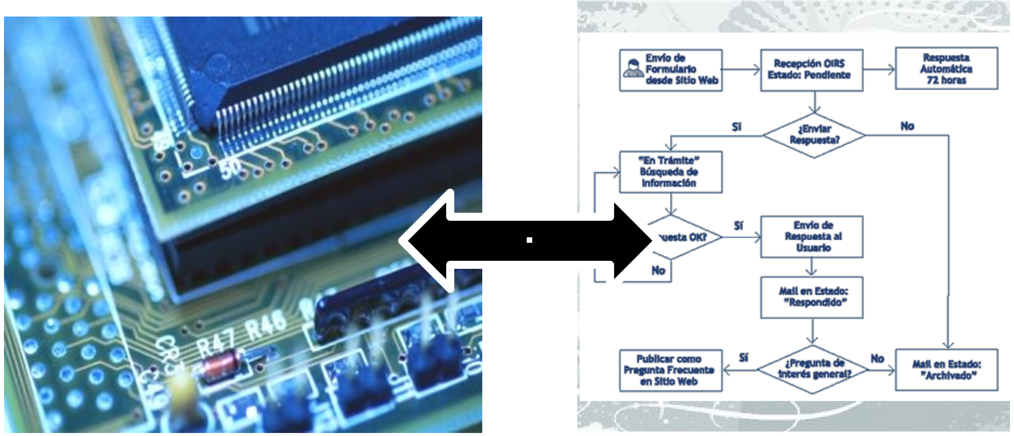
Objectives

III. To demonstrate that consciousness is a process, not a property of matter.



Consciousness in Artificial Cognitive Systems

Objectives

IV. To demonstrate that there is no direct correlation between computational power and cognitive power.

Consciousness in Artificial Cognitive Systems

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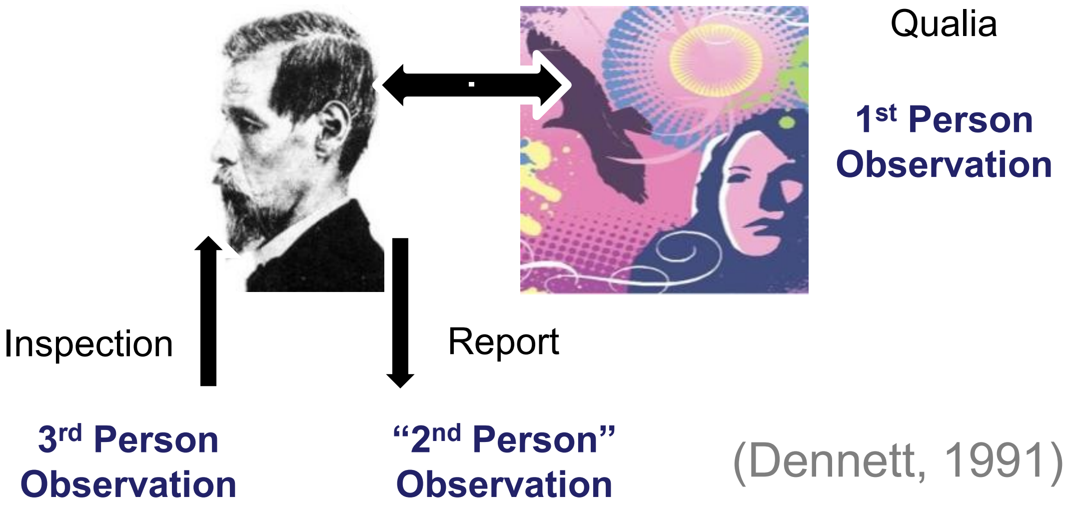
Objectives

V. To demonstrate that consciousness can be scientifically studied using the *heterophenomenology* method.



Qualia

1st Person Observation

Inspection

Report

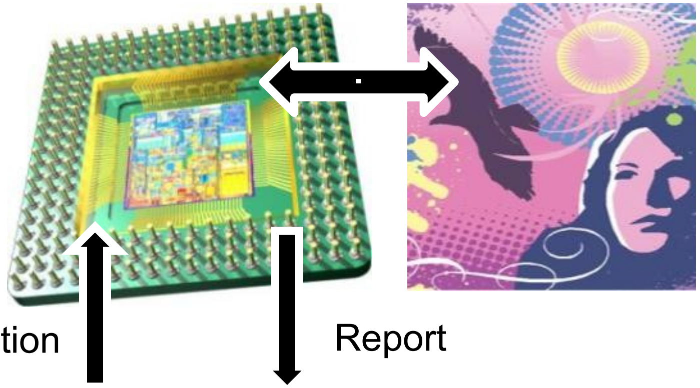
3rd Person Observation

“2nd Person” Observation

(Dennett, 1991)

Objectives

V. To demonstrate that consciousness can be scientifically studied using the *heterophenomenology* method.



(Dennett, 1991)

Consciousness in Artificial Cognitive Systems

- **Introduction**
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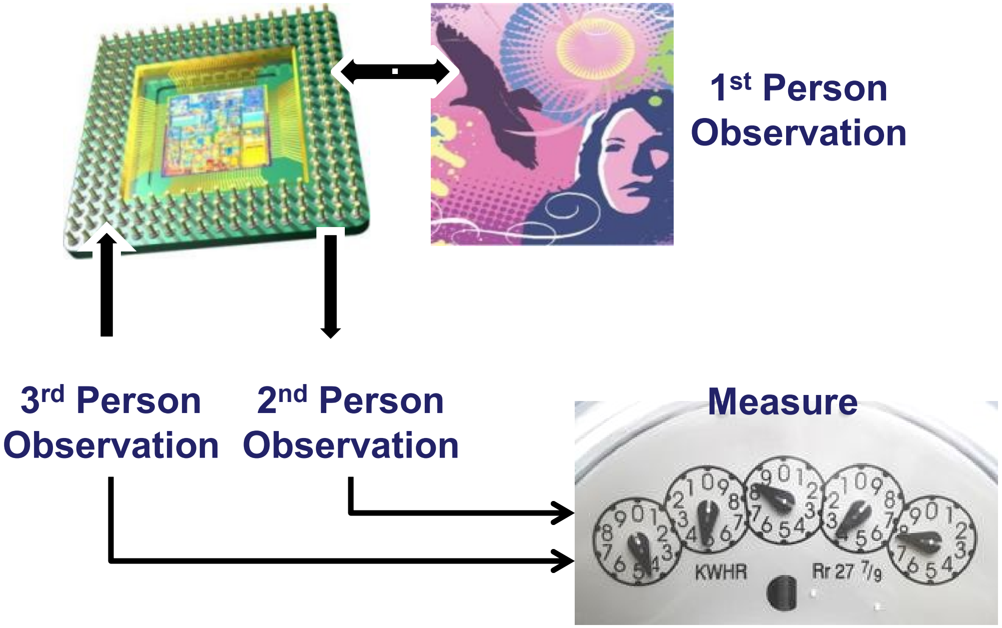
Objectives

VI. To demonstrate that the level of consciousness of an artificial system can be measured.



1st Person Observation

3rd Person Observation

2nd Person Observation

Measure

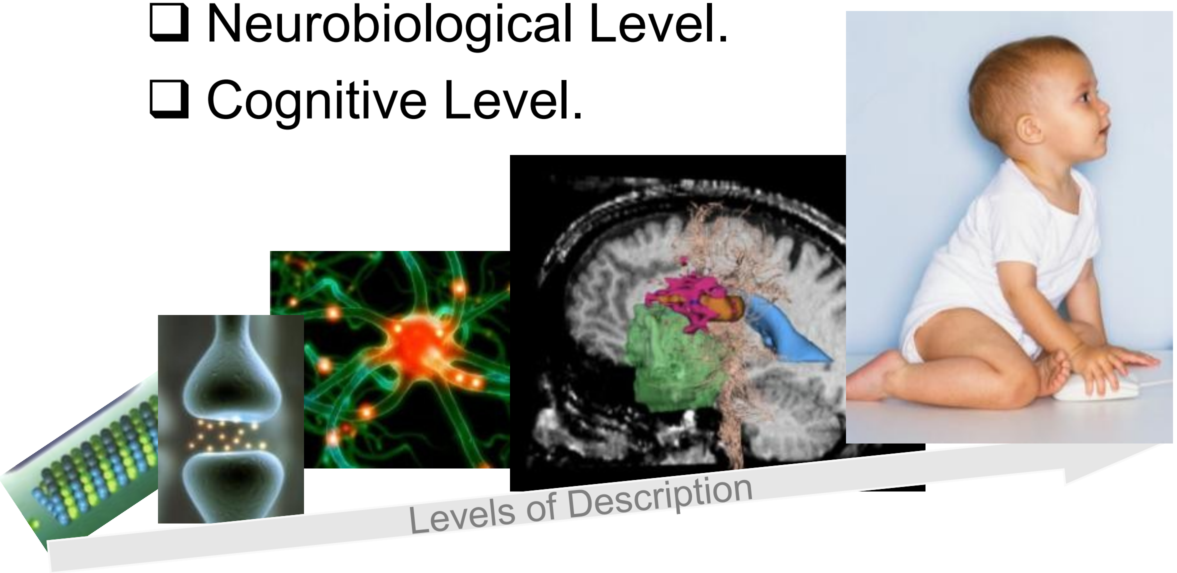
Contents

Study of Consciousness

- ☐ Problems and Scientific Challenges
  - ☐ Applicability of the scientific method.
  - ☐ Relative immatureness.
  - ☐ Definition of consciousness.

Study of Consciousness

- ☐ Main levels of study:
  - ☐ Physical Level.
  - ☐ Neurobiological Level.
  - ☐ Cognitive Level.



Consciousness in Artificial Cognitive Systems

- **Introduction**
- **State of the Art**
  - **Study of Consciousness**
  - **Machine Consciousness**
  - Measuring Consciousness
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- *ConsScale*
- Artificial Qualia
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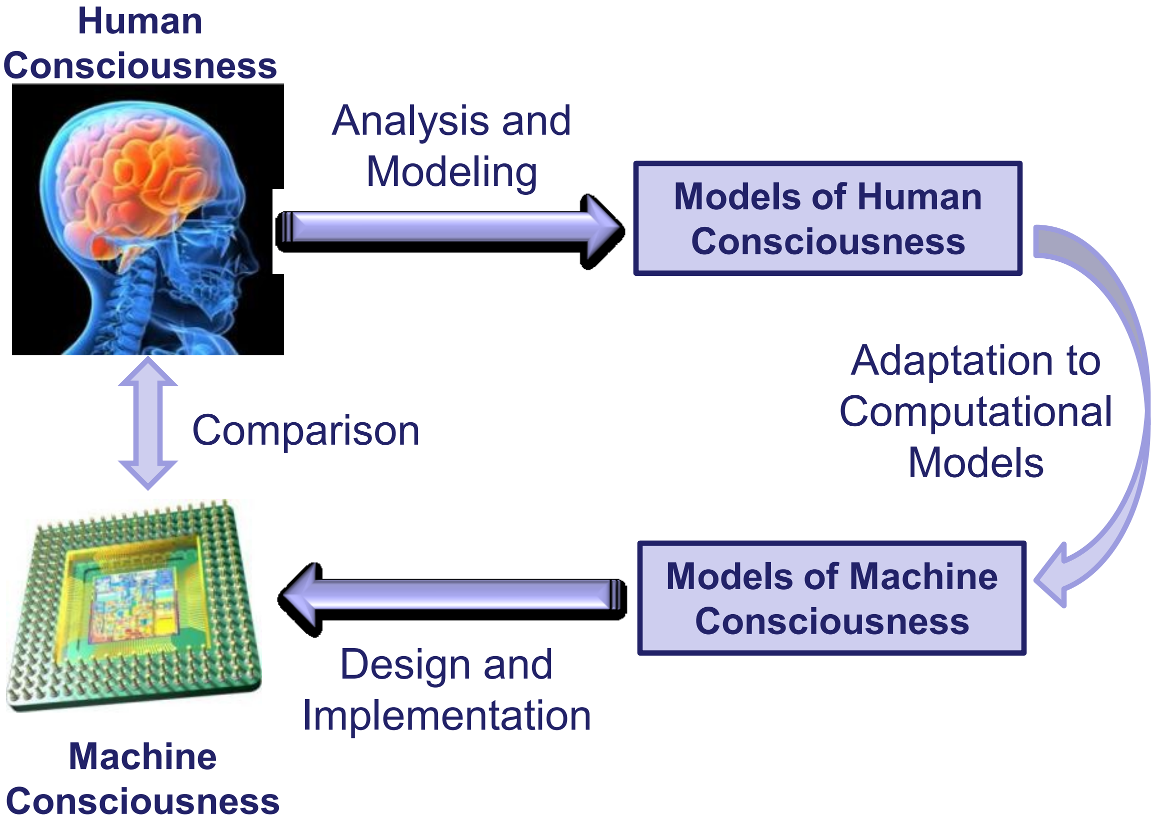
- Conclusions

Machine Consciousness



Human Consciousness

Analysis and Modeling

Models of Human Consciousness

Adaptation to Computational Models

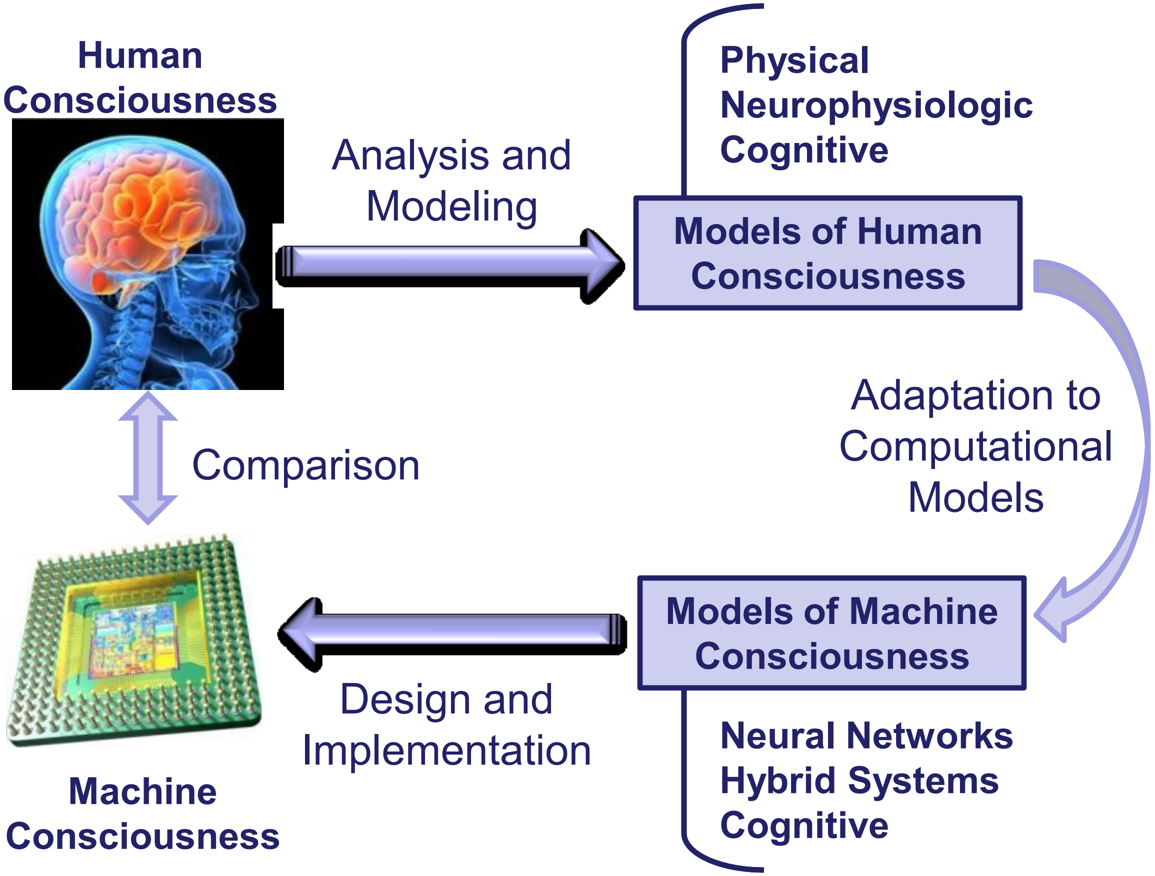
Models of Machine Consciousness

Design and Implementation

Comparison

Machine Consciousness

Machine Consciousness



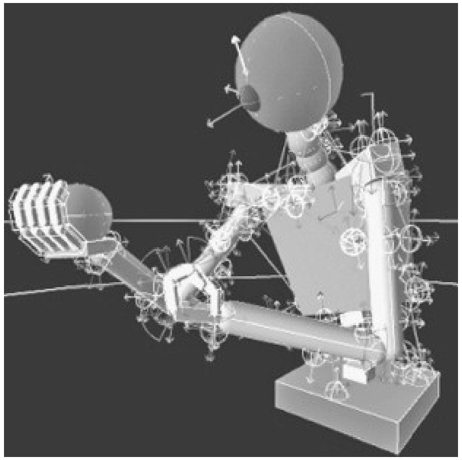
Machine Consciousness

- ❑ Artificial Neural Networks
- ❑ Hybrid Systems
  - ❑ ANN, RBS, GA, …
- ❑ Cognitive Architectures
  - ❑ IDA (Franklin, 1998), LIDA (Franklin, 2007),
  - ❑ CogPrime (Goertzel, 2009),
  - ❑ Haikonen (Haikonen, 2007),
  - ❑ CRONOS (Holland, 2007),
  - ❑ CiceRobot (Chella, 2009) ,
  - ❑ ...

Machine Consciousness

❑ Main Areas of Application

- ❑ Cognitive Robotics.
- ❑ Synthetic Phenomenology (Chrisley, 2009).



Consciousness in Artificial Cognitive Systems

- **Introduction**
- **State of the Art**
  - **Study of Consciousness**
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Measuring Consciousness

- ☐ Main Approaches:
  - ☐ In humans.
  - ☐ In other animals.
  - ☐ In machines.
- ☐ Main Tools:
  - ☐ Verbal report.
  - ☐ Observed behavior.
  - ☐ Neurophysiologic markers (EEG, fMRI, JFK-revised, etc.).

Measuring Consciousness

- ☐ Problems
  - ☐ Verbal report?
  - ☐ Neurophysiologic markers?
  - ☐ Observed behavior?

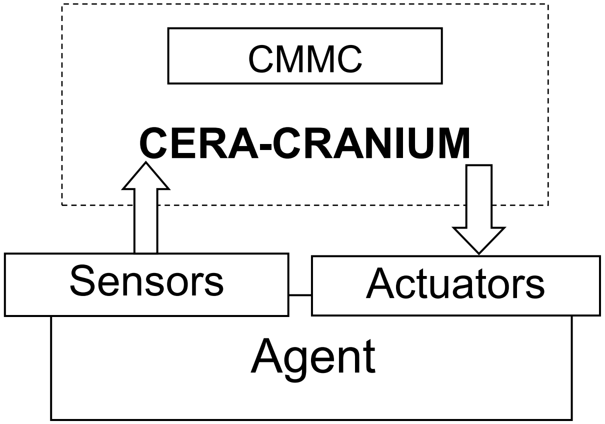
Measuring Machine Consciousness

- ☐ Extant proposals:
  - ☐ Turing Test (Turing, 1950).
  - ☐ Cognitive tests (mirror test [Gallup, 1977]).
  - ☐ Axioms (Aleksander, 2003).
  - ☐ Ordinal Probability Scale (Gamez, 2005).
  - ☐ Information Integration Φ (Tononi, 2008).

Contents

CERA-CRANIUM

- Framework for the experimentation with Cognitive Models of Machine Consciousness (CMMC).
  - Applicable to different agents.
  - Applicable to different domains.



CERA-CRANIUM

- ☐ CERA

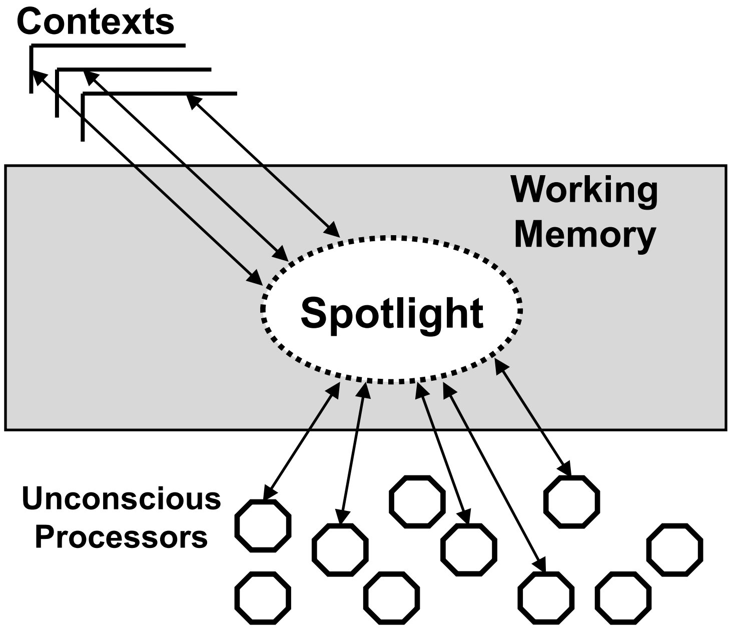
  (Conscious and Emotional Reasoning Architecture)
  - ☐ Layered control architecture.

- ☐ CRANIUM

  (Cognitive Robotics Architecture Neurologically Inspired Underlying Manager)
  - ☐ Runtime environment for the creation and management of large amounts of parallel processes that share a common workspace.

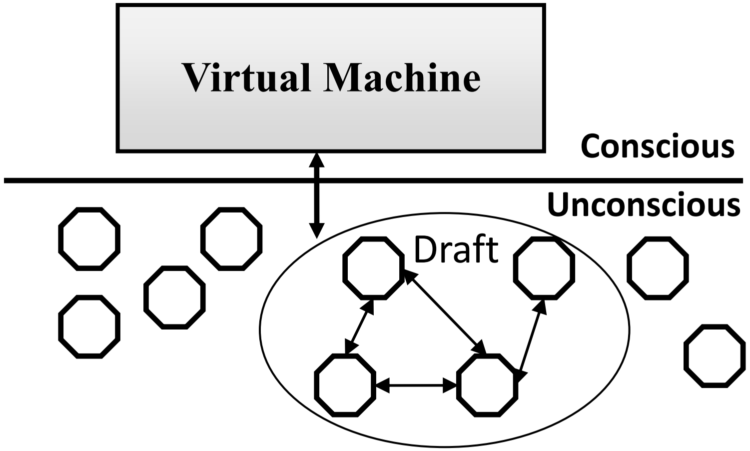
CERA-CRANIUM

- ☐ Inspired by cognitive theories
  - ☐ Global Workspace Theory (Baars, 1988, 1997).



CERA-CRANIUM

- ☐ Inspired by cognitive theories
  - ☐ Multiple Draft Model (Dennett, 1991).



CERA-CRANIUM

☐ Both metaphors agree that:

“A set of specialized processors compete/collaborate in order to generate the conscious contents of the mind”.

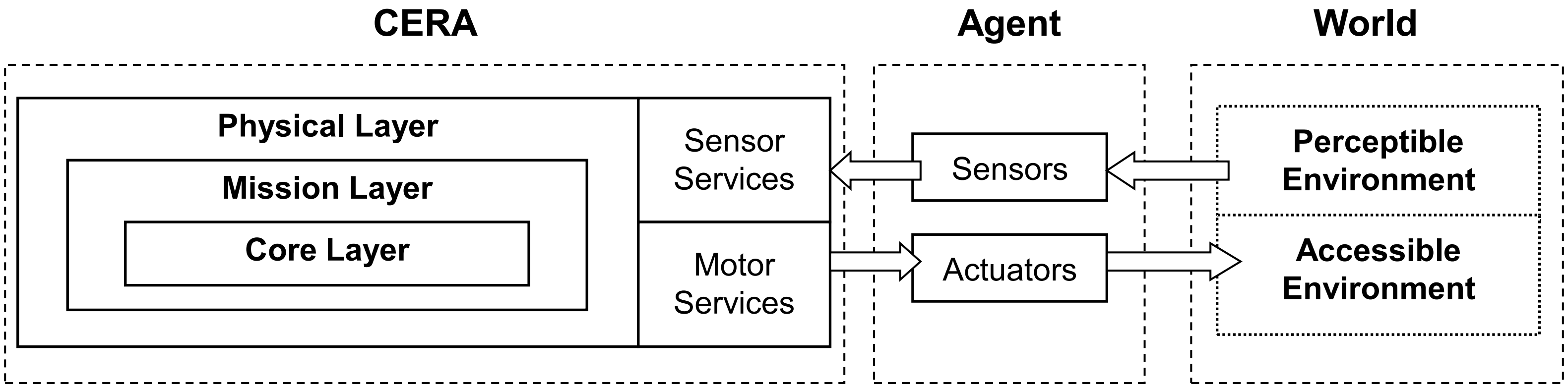
☐ CERA-CRANIUM provides a specific design and implementation.

Consciousness in Artificial Cognitive Systems

- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
  - **Introduction**
  - **CERA-CRANIUM**

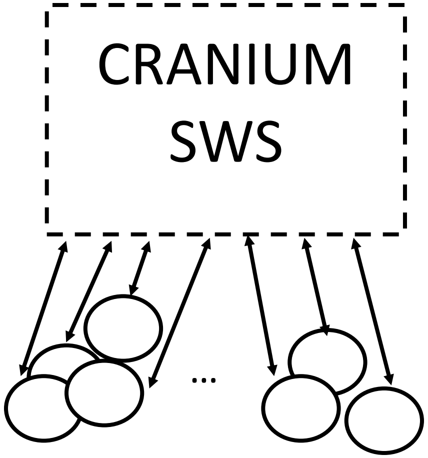
CERA

- ☐ CERA provides answers for these questions:
  - ☐ What should be the next action?
  - ☐ What should be the next conscious content of the mind?



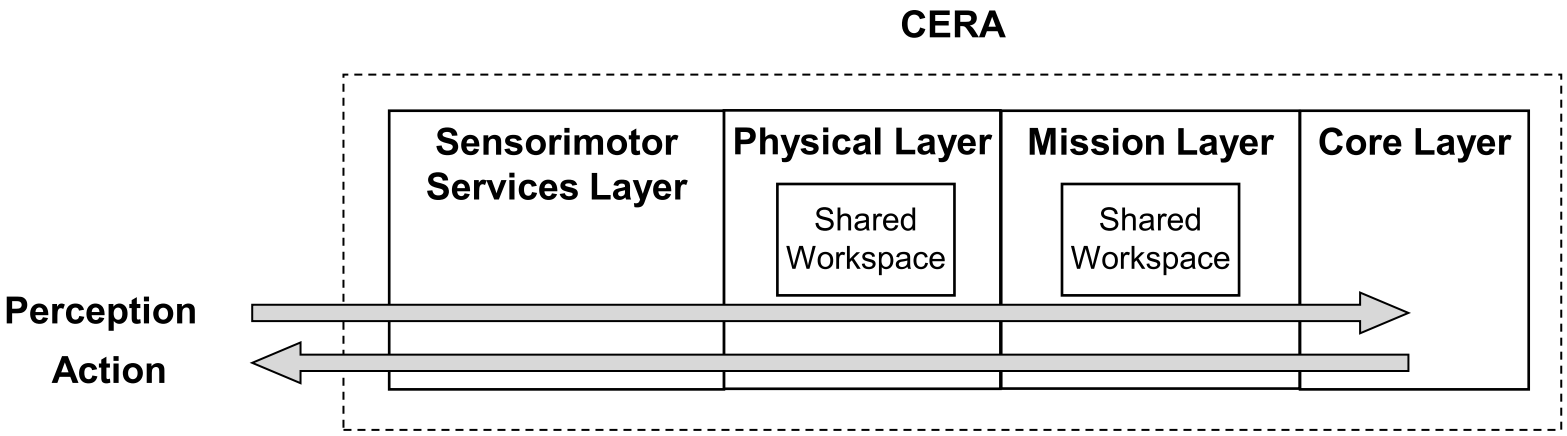
CRANIUM

☐ SWS (Shared Workspace).



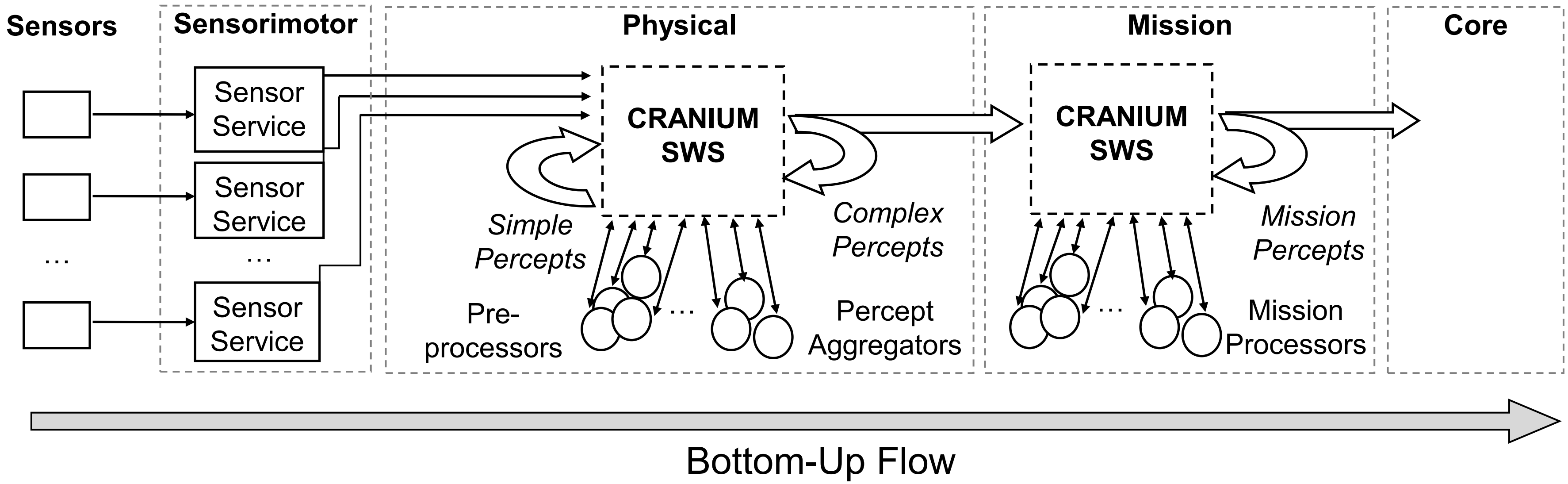
CERA

- CERA supports two flows of information:
  - Bottom-Up: Perception.
  - Top-Down: Action.



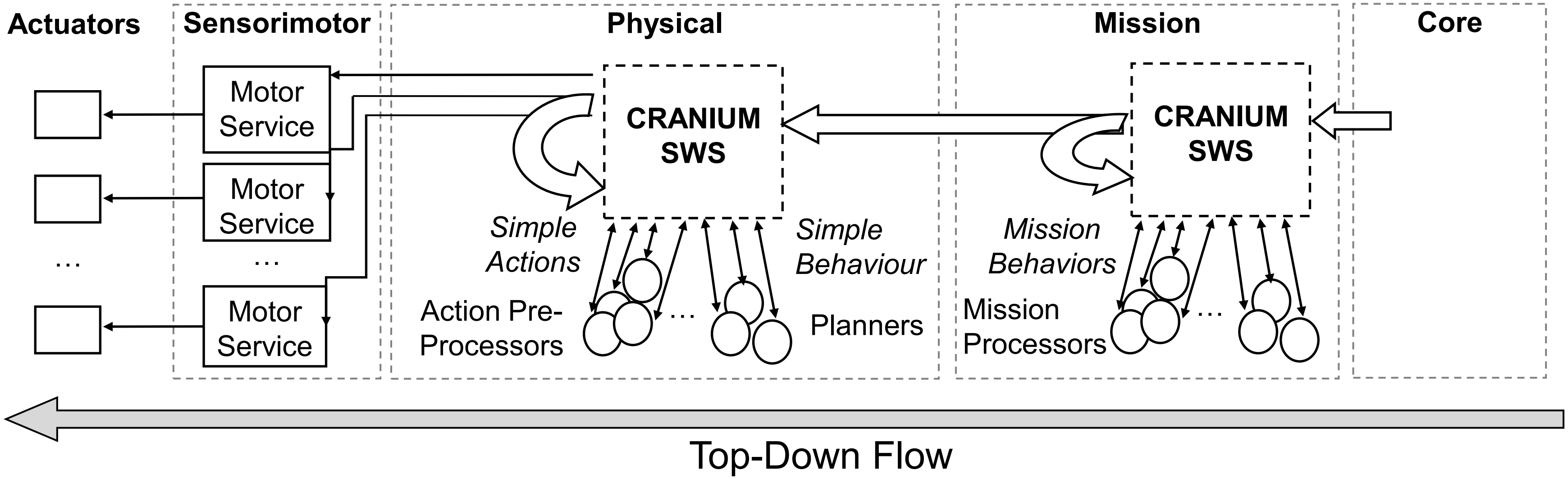
CERA-CRANIUM

- ❑ Bottom-Up Flow:
  - ❑ Percept Generation.



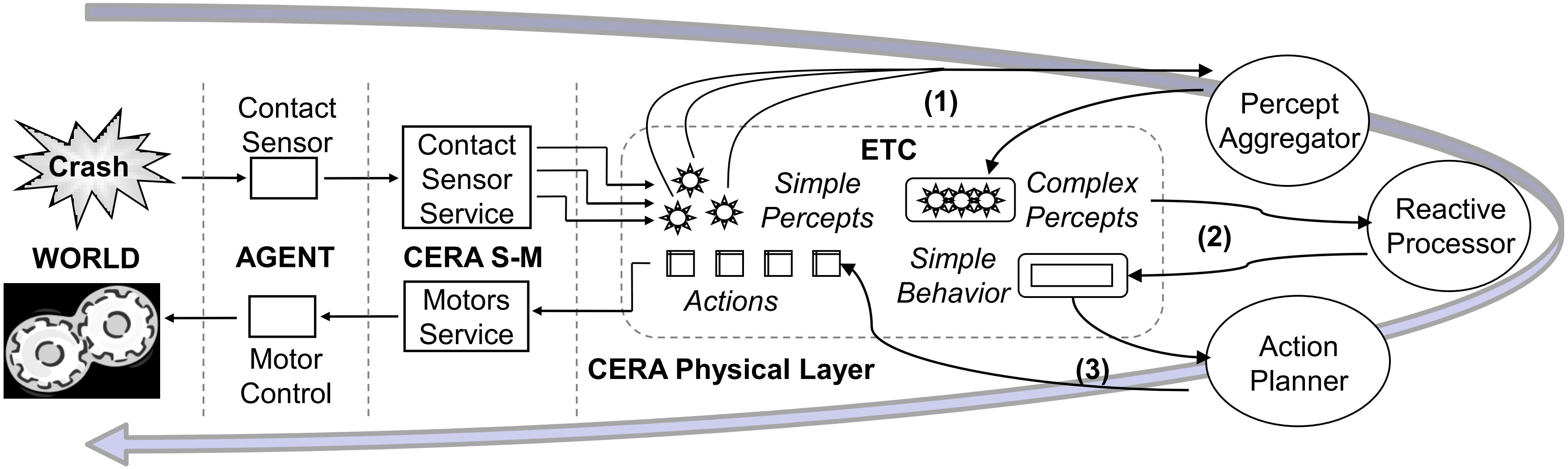
CERA-CRANIUM

- ❑ Top-Down Flow:
  - ❑ Action Generation.



CERA-CRANIUM

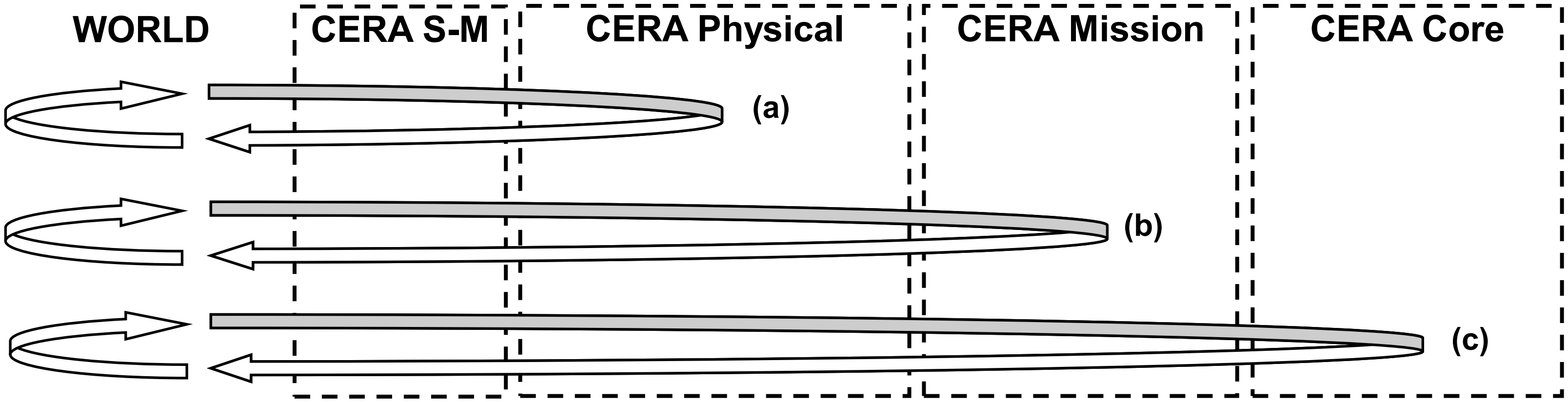
- ❑ Specialized Processors
  - ❑ Preprocessors
  - ❑ Aggregators
  - ❑ Planners
  - ❑ Forecasters
  - ❑ …



CC-Bot Example

CERA-CRANIUM

- ☐ Control loops:
  - ☐ Adaptive responses at different levels.



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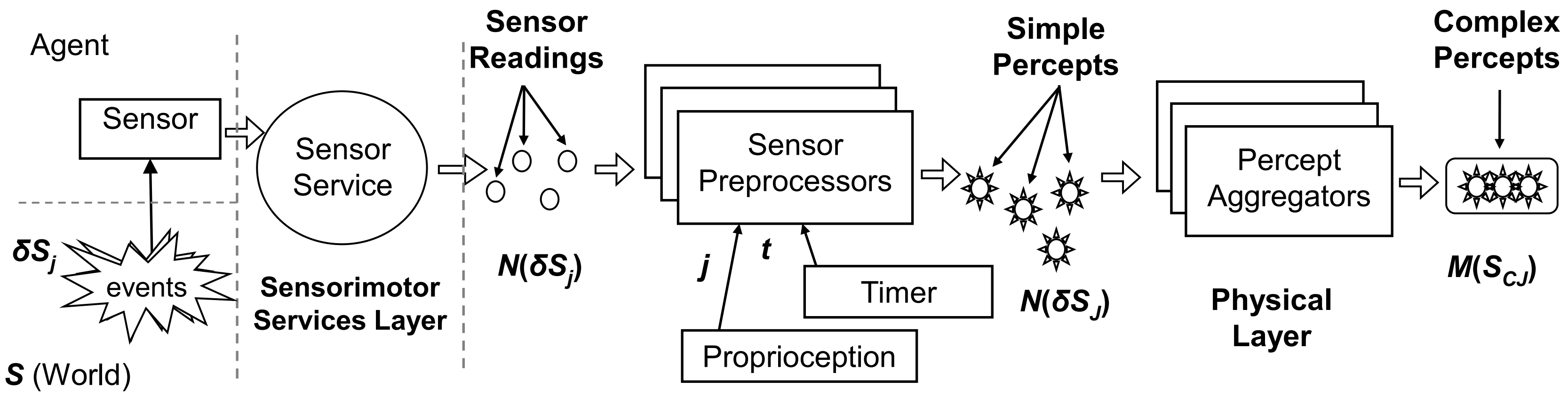
- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
  - **Introduction**
  - **CERA-CRANIUM**
  - **Representation**

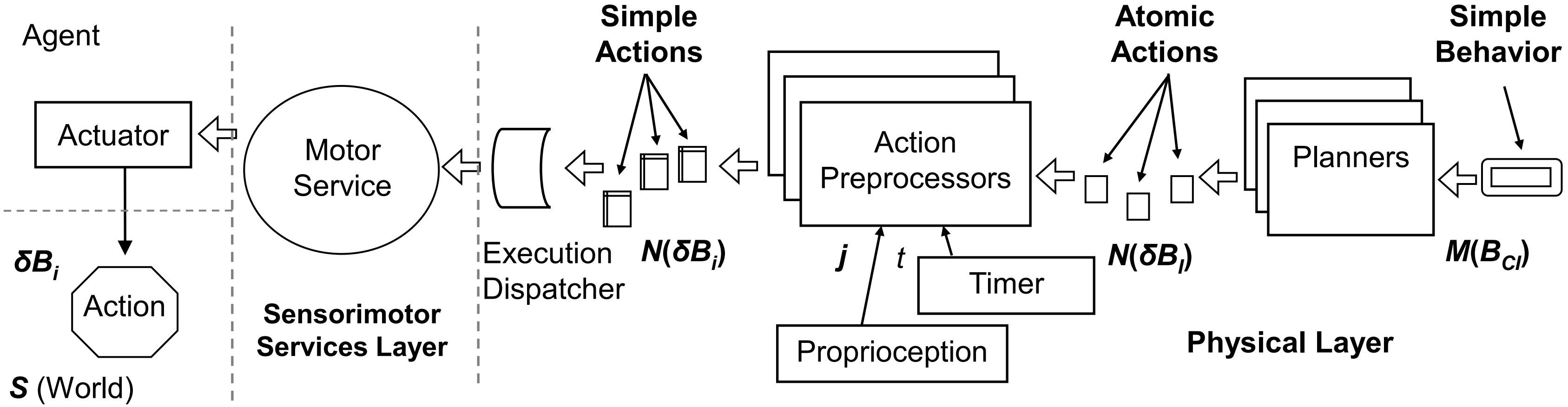
Knowledge Representation

- ☐ Readings → Simple P. → Complex P.
- ☐ Indexed percepts: *j, t* → *J* → *CJ*



Knowledge Representation

- ☐ Simple Behavior → Atomic A. → Simple A.
- ☐ Indexed Behaviors: *CI* → *I* → *j*, *t*

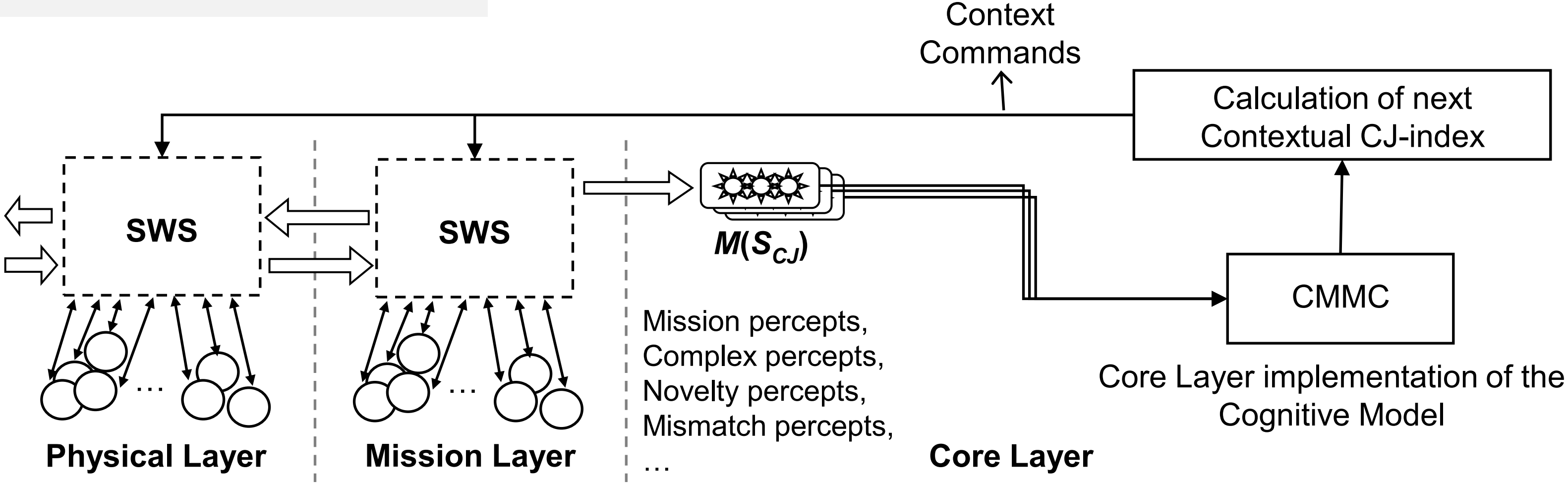


Contextualization

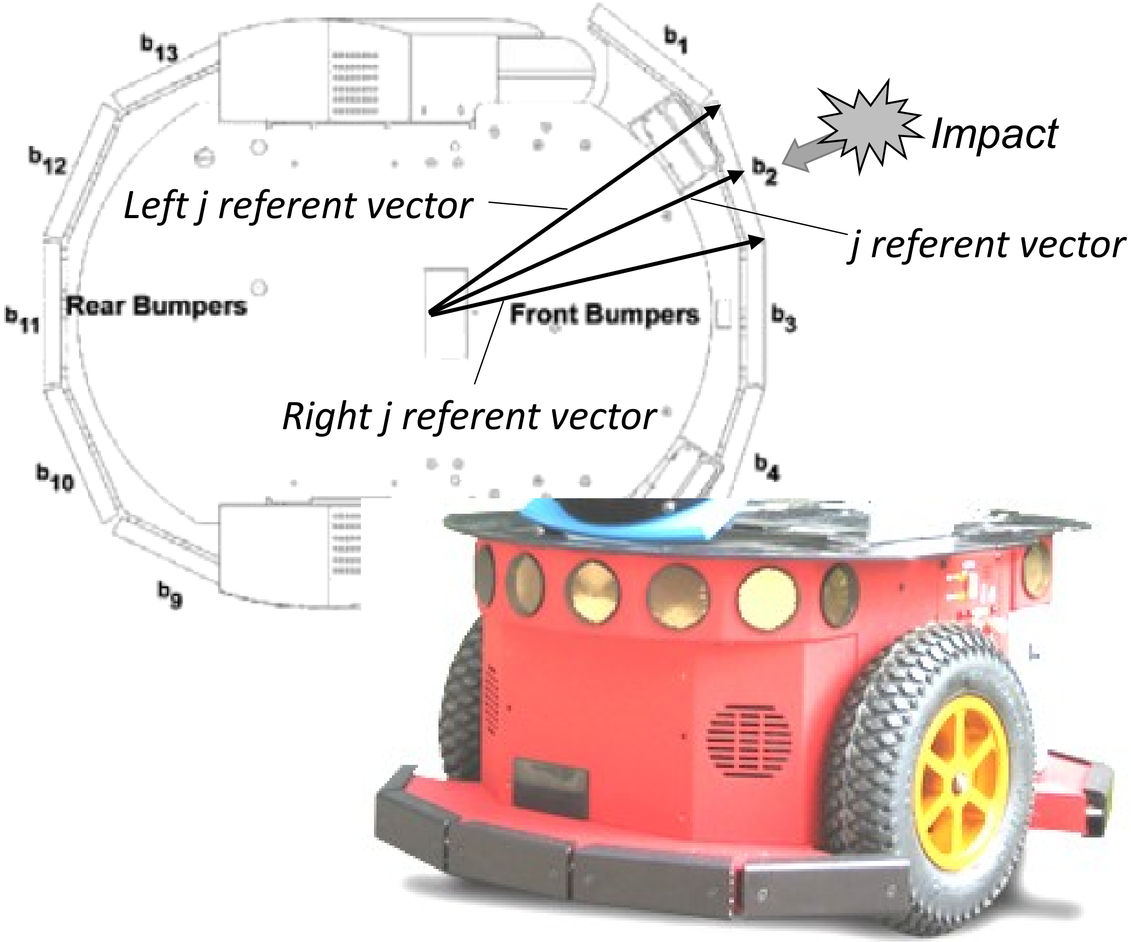
- ☐ Bottom-Up:
  - ☐ “Native” context application, such as spatiotemporal contexts.
- ☐ Top-Down:
  - ☐ Specific context induction from the Core Layer.

Modulation

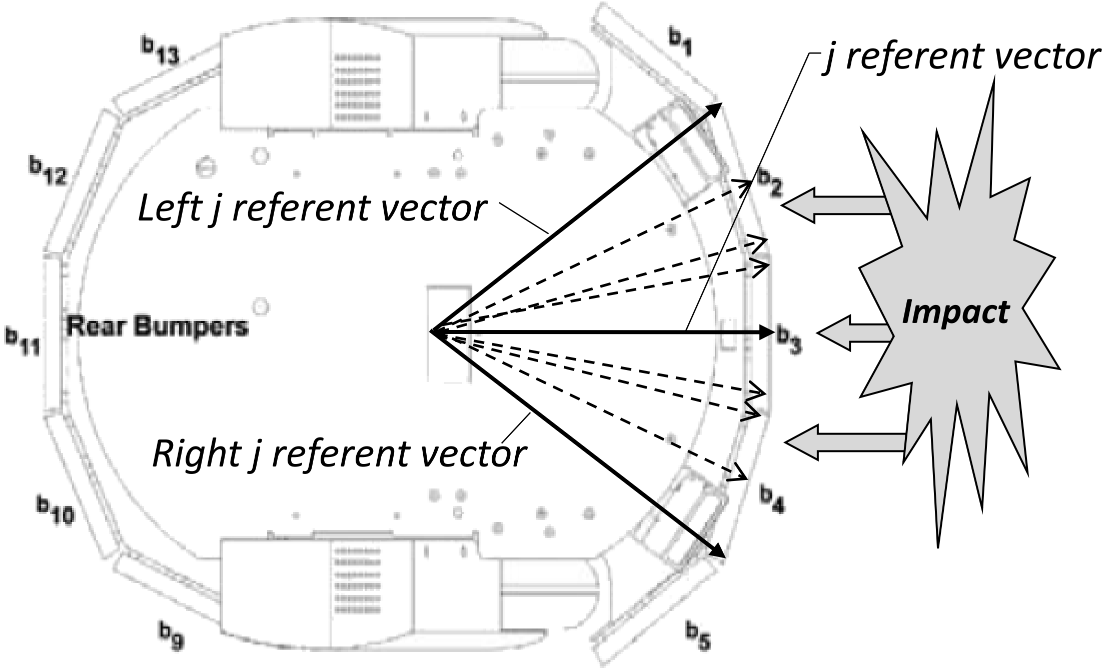
- ☐ Modulation induced by Core Layer:
  - ☐ Context Commands.
  - ☐ ***CJ-index***: Region of interest within the sensorimotor space of the agent.



Sensory Fusion Example



Sensory Fusion Example



Contents

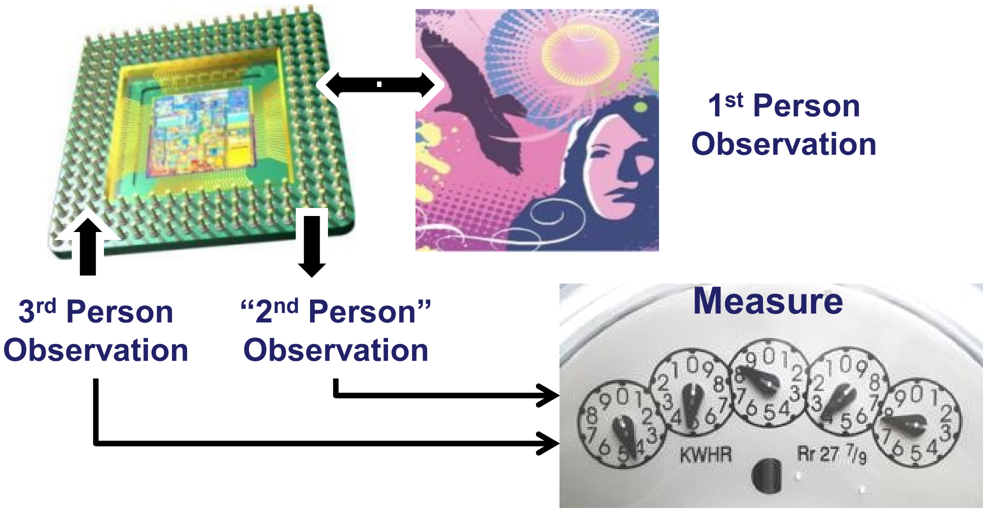
- ✓ **Introduction**
- ✓ **State of the Art**
- ✓ **CERA-CRANIUM**
- ❖ ***ConsScale***
- ❑ Artificial Qualia
- ❑ Experimentation
- ❑ Conclusions

Consciousness in Artificial Cognitive Systems

- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
  - Levels
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

ConsScale

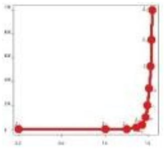
- Scale designed to measure the cognitive development of consciousness in agents.
- Based on cognitive functions synergy and the heterophenomenolgy approach.



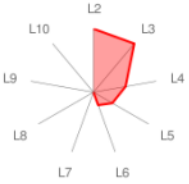
ConsScale

❑ *ConsScale* allows the characterization of the level of development of consciousness based on:

An ordered list of levels (from -1 to 11).



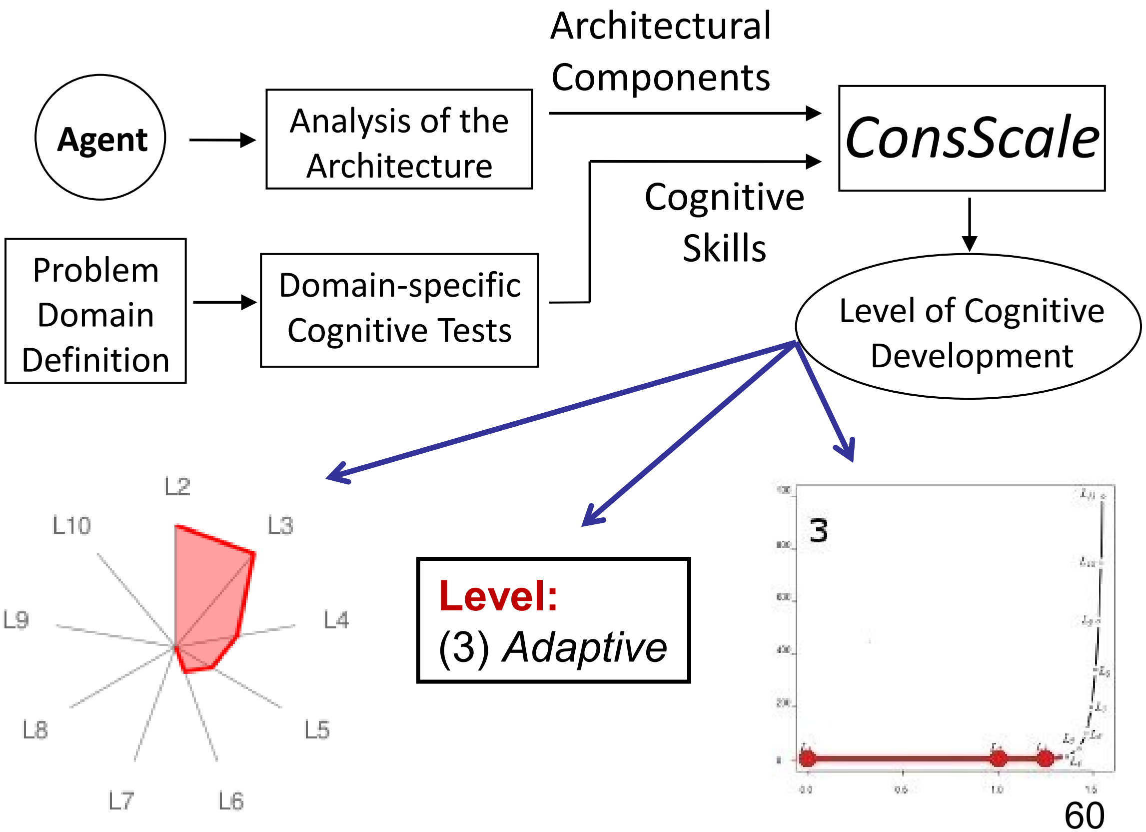
A quantitative score (CQS: from 0 to 1000).



A graphical cognitive profile.

ConsScale

- ☐ Evaluation of the cognitive development of an agent using *ConsScale.*



Agent

Analysis of the Architecture

Architectural Components

ConsScale

Problem Domain Definition

Domain-specific Cognitive Tests

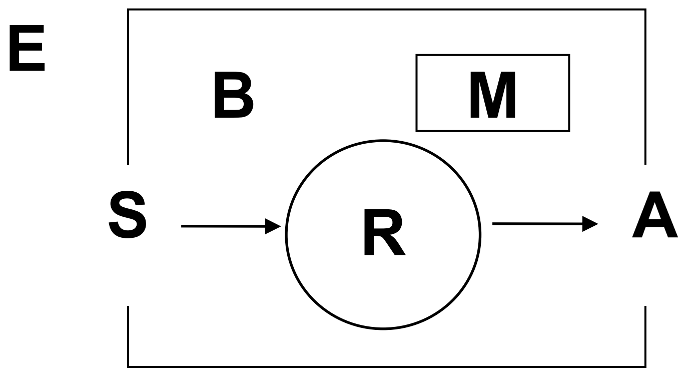
Cognitive Skills

Level of Cognitive Development

Level:
(3) *Adaptive*

Abstract Architecture

- ☐ Abstract architectural components (Wooldridge, 1999):
  - ☐ B, E, S, A, R, M
  - ☐ Att, M^n, SsA, I, O, AR, AVR, R^n



Cognitive Skills ($CS_{i,j}$)

Level (L_i)	**Cognitive Skills**
2	$CS_{2,1}$: Fixed reactive responses (“reflexes”).
3	$CS_{3,1}$: Autonomous acquisition of new adaptive reactive responses.
	$CS_{3,2}$: Usage of proprioceptive sensing for embodied adaptive responses.
	$CS_{3,3-5}$: Selection of relevant sensory / motor / memory information.
	$CS_{3,6}$: Evaluation (positive or negative) of selected objects or events.
	$CS_{3,7}$: Selection of what needs to be stored in memory.
4	$CS_{4,1}$: Trial and error learning. Re-evaluation of selected objects or events.
	$CS_{4,2}$: Directed behavior toward specific targets like following or escape.
	$CS_{4,3}$: Evaluation of the performance in the achievement of a single goal.
	$CS_{4,4}$: Basic planning capability: calculation of next n sequential actions.
	$CS_{4,5}$: Ability to build depictive representations of percepts for each available sensory modality .
5	$CS_{5,1}$: Ability to move back and forth between multiple tasks.
	$CS_{5,2}$: Seeking of multiple goals.
	$CS_{5,3}$: Evaluation of the performance in the achievement of multiple goals.
	$CS_{5,4}$: Autonomous reinforcement learning (emotional learning).
	$CS_{5,5}$: Advanced planning capability considering all active goals.
	$CS_{5,6}$: Ability to generate selected mental content with grounded meaning integrating different modalities into differentiated explicit percepts.
6	$CS_{6,1}$: Self-status assessment (background emotions).
	$CS_{6,2}$: Background emotions cause effects in agent’s body.
	$CS_{6,3}$: Representation of the effect of emotions in organism and planning (feelings).
	$CS_{6,4}$: Ability to hold a precise and updated map of body schema.
	$CS_{6,5}$: Abstract learning (learned lessons generalization).
	$CS_{6,6}$: Ability to represent a flow of integrated percepts including self-status.
7	$CS_{7,1-3}$: Representation of the relation between self and perception / action / feelings.
	$CS_{7,4}$: Self-recognition capability.
	$CS_{7,5}$: Advance planning including the self as an actor in the plans.
	$CS_{7,6}$: Use of *imaginational* states in planning.
	$CS_{7,7}$: Learning of tool usage.
	$CS_{7,8}$: Ability to represent and self-report mental content (continuous inner flow of percepts - inner imagery).
8	$CS_{8,1}$: Ability to model others as subjective selves.
	$CS_{8,2}$: Learning by imitation of a counterpart.
	$CS_{8,3}$: Ability to collaborate with others in the pursuit of a common goal.
	$CS_{8,4}$: Social planning (planning with socially aware plans).
	$CS_{8,5}$: Ability to make new tools.
	$CS_{8,6}$: Inner imagery is enriched with mental content related to the model of others and the relation between the self and other selves.
9	$CS_{9,1}$: Ability to develop Machiavellian strategies like lying and cunning.
	$CS_{9,2}$: Social learning (learning of new Machiavellian strategies).
	$CS_{9,3}$: Advanced communication skills (accurate report of mental content as basic inner speech).
	$CS_{9,4}$: Groups are able to develop a culture.
	$CS_{9,5}$: Ability to modify and adapt the environment to agent’s needs.
10	$CS_{10,1}$: Accurate verbal report. Advanced linguistic capabilities. Human-like inner speech.
	$CS_{10,2}$: Ability to pass the Turing test.
	$CS_{10,3}$: Groups are able to develop a civilization and advance culture and technology.
11	$CS_{11,1}$: Ability to manage several streams of consciousness.

Consciousness in Artificial Cognitive Systems

- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
  - Levels
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

Cognitive Skills ($\mathbf{CS_{i,j}}$)

Level (L_i)	**Cognitive Skills**
2	$CS_{2,1}$: Fixed reactive responses (“reflexes”).
3	$CS_{3,1}$: Autonomous acquisition of new adaptive reactive responses. $CS_{3,2}$: Usage of proprioceptive sensing for embodied adaptive responses. $CS_{3,3-}$: Selection of relevant sensory / motor / memory information. $CS_{3,6}$: E luation (positive or negative) of selected objects or events. $CS_{3,7}$: Se n of what needs to be stored in memory.
4	$CS_{4,1}$: Trial r learning. Re-evaluation of selected objects or events. $CS_{4,2}$: Directe r toward specific targets like following or escape. $CS_{4,3}$: Evaluatio formance in the achievement of a single goal. $CS_{4,4}$: Basic plan calculation of next n sequential actions. $CS_{4,5}$: Ability to bu sentations of percepts for each available sensory modality .
5	$CS_{5,1}$: Ability to move ween multiple tasks. $CS_{5,2}$: Seeking of multi $CS_{5,3}$: Evaluation of the p ement of multiple goals. $CS_{5,4}$: Autonomous reinfo learning). $CS_{5,5}$: Advanced planning ca als. $CS_{5,6}$: Ability to generate selec d meaning integrating different modalities into differentiated explicit percepts.
6	$CS_{6,1}$: Se $CS_{6,2}$: B $CS_{6,3}$: R $CS_{6,4}$: A $CS_{6,5}$: A $CS_{6,6}$: A
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$CS_{3,3}$: Selection of relevant sensory information.

Consciousness in Artificial Cognitive Systems

- Introduction
- State of the Art
- CERA-CRANIUM
- *ConsScale*
  - Introduction
  - Levels
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

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7	**$CS_{7,1-3}$**: **$CS_{7,4}$**: S **$CS_{7,5}$**: A **$CS_{7,6}$**: U **$CS_{7,7}$**: Le **$CS_{7,8}$**: Ability to represent an ntinuous inner flow of percepts - inner imagery).
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11	**$CS_{11,1}$**: Ability to manage several streams of consciousness.

$CS_{8,5}$: Ability to make new tools.

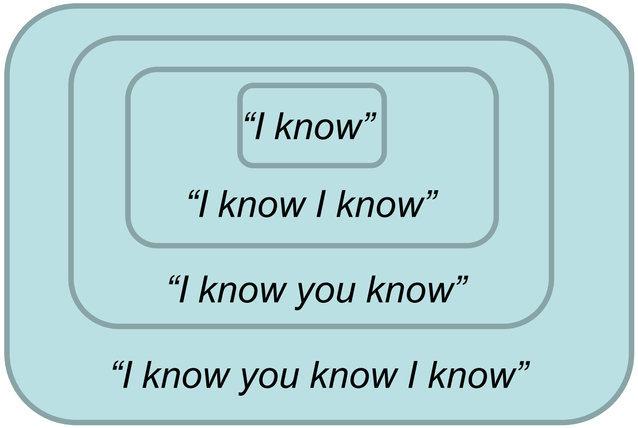
Cognitive Skills

- ☐ Cognitive skills associated with consciousness:
  - ☐ Theory of Mind (Vygotsky, 1980).
  - ☐ Executive Function (Perner, 1999).
  - ☐ Modulating Function of Emotions (Damasio, 1999).
  - ☐ Learning Mechanisms.

Consciousness in Artificial Cognitive Systems

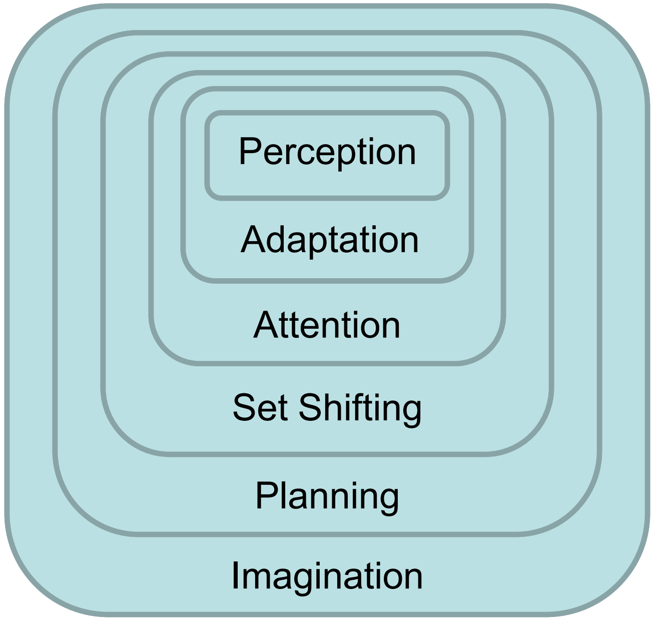
Cognitive Skills

☐ Cognitive Hierarchy for the Theory of Mind (Lewis, 2003):



Cognitive Skills

☐ Cognitive Hierarchy of the Executive Function:



Perception

Adaptation

Attention

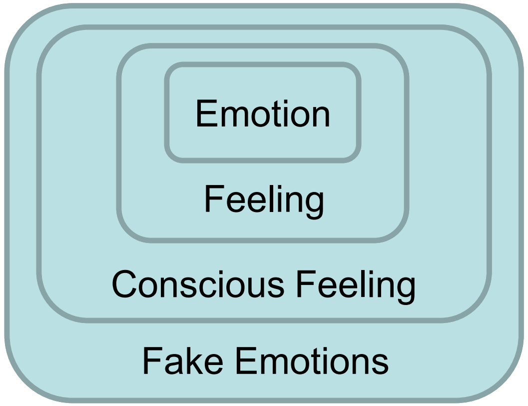
Set Shifting

Planning

Imagination

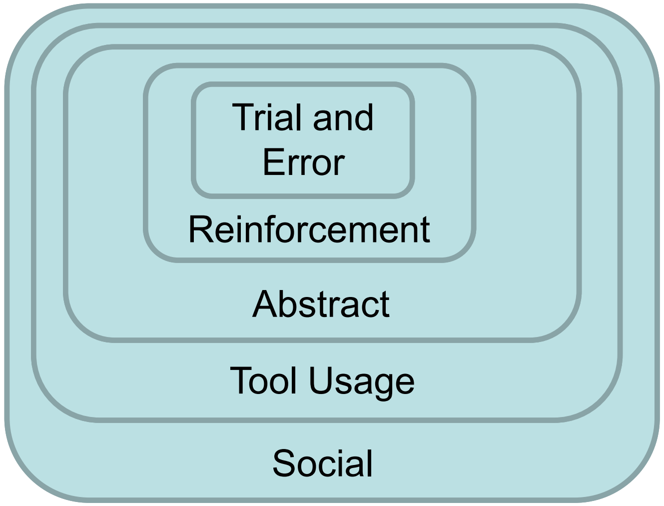
Cognitive Skills

❑ Cognitive Hierarchy of Emotions:



Cognitive Skills

☐ Cognitive Hierarchy of Learning:



Trial and Error

Reinforcement

Abstract

Tool Usage

Social

Consciousness in Artificial Cognitive Systems

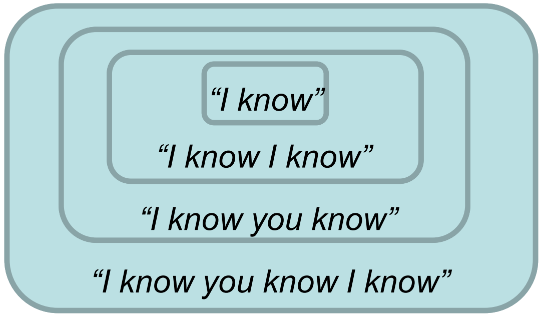
- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
    - **Introduction**
    - Levels
    - CQS
    - Cognitive Profiling
    - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

Cognitive Skills

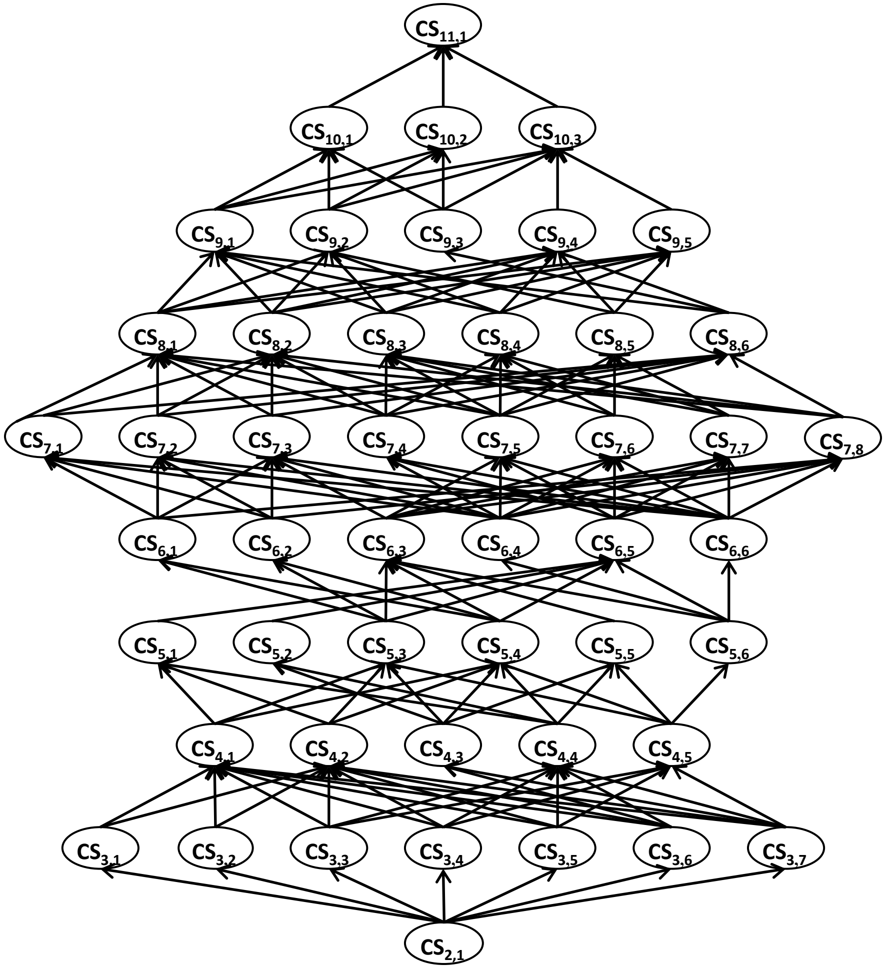
- Cognitive Hierarchy characterizes as a *poset (CSS, <).*

$$CS_{6,1-6} < CS_{7,1-5} < CS_{8,1-4} < CS_{9,1-2}$$

- $CS_{6,1-6}$ (*"I know"*) < $CS_{7,1-5}$ (*"I know I know"*)
- $CS_{7,1-5}$ (*"I know I know"*) < $CS_{8,1-4}$ (*"I know you know"*)
- $CS_{8,1-4}$ (*"I know you know"*) < $CS_{9,1-2}$ (*"I know you know I know"*)



Cognitive Skills



Consciousness in Artificial Cognitive Systems

- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
  - Levels
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

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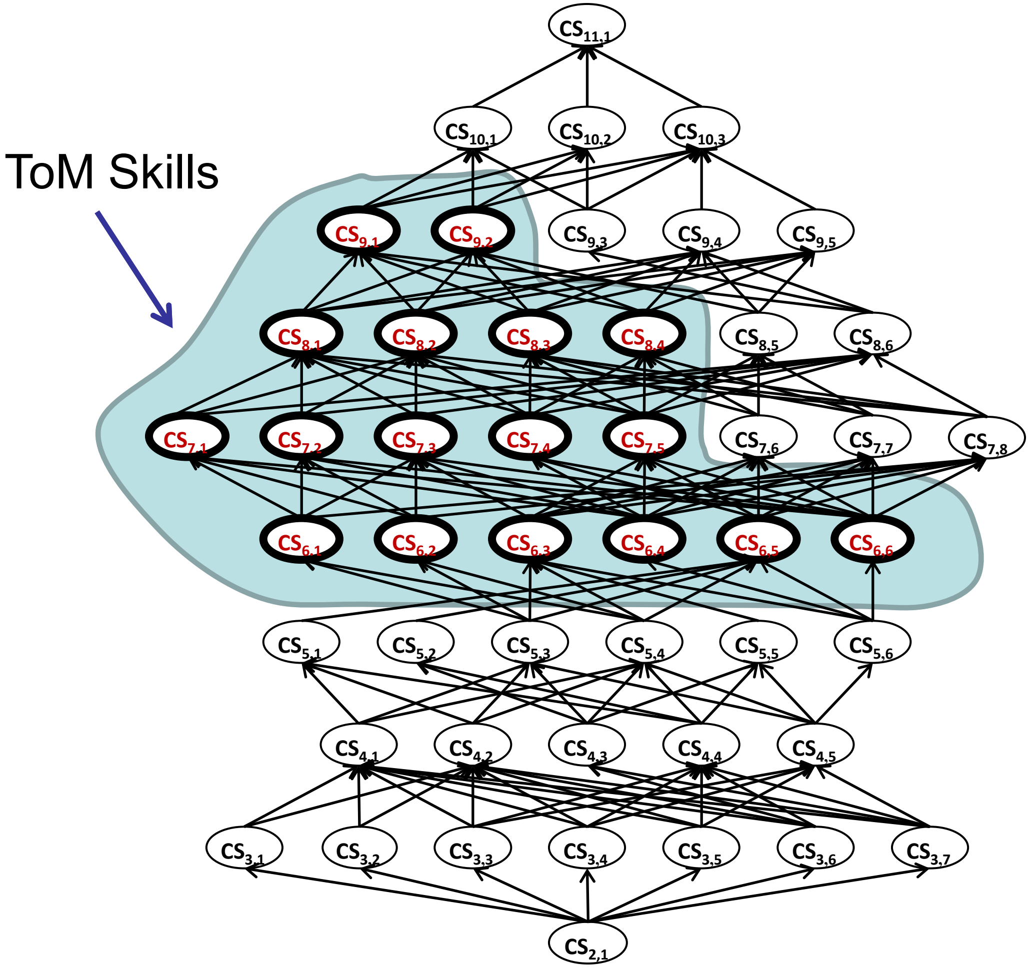
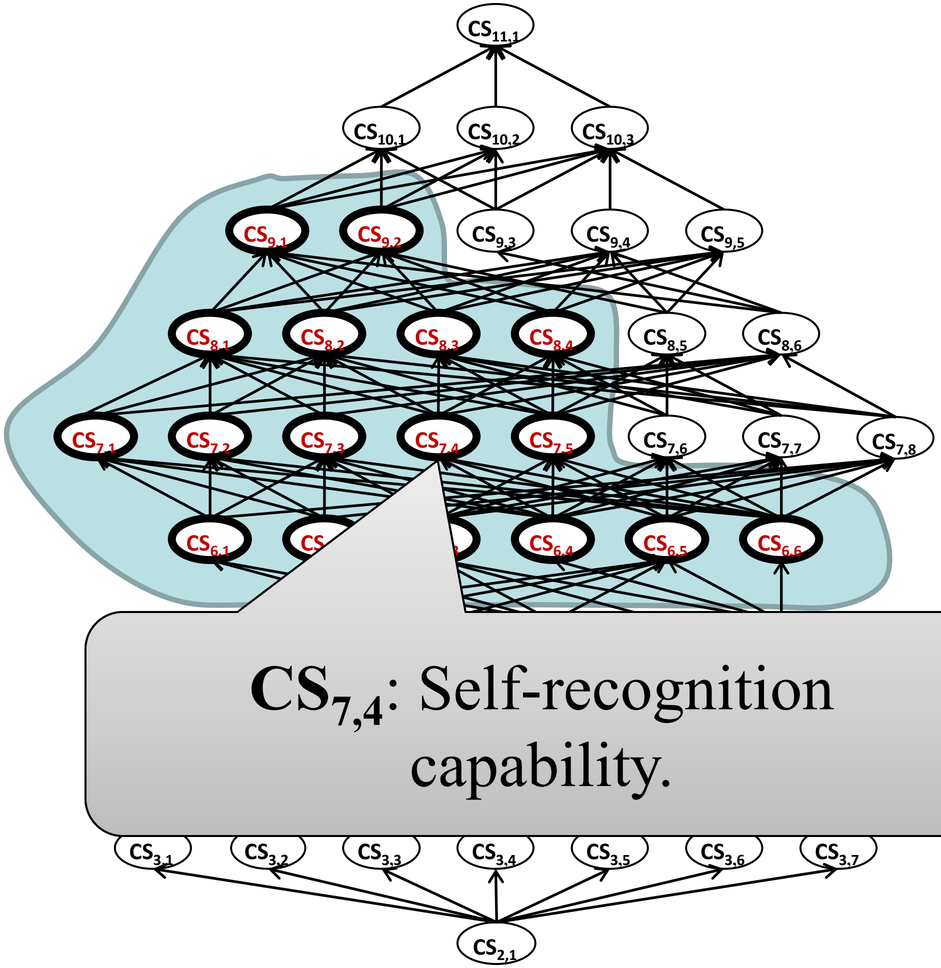


Consciousness in Artificial Cognitive Systems

- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
  - Levels
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

Cognitive Skills

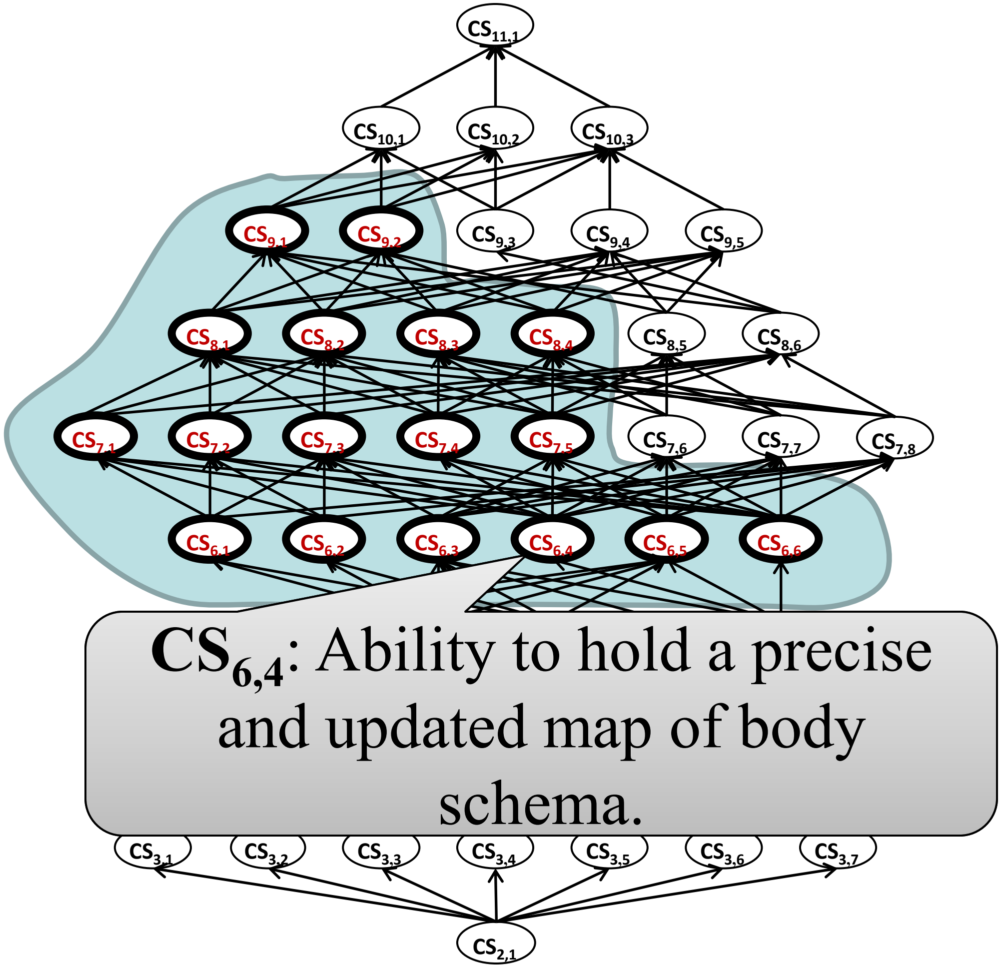


$CS_{7,4}$: Self-recognition capability.

Consciousness in Artificial Cognitive Systems

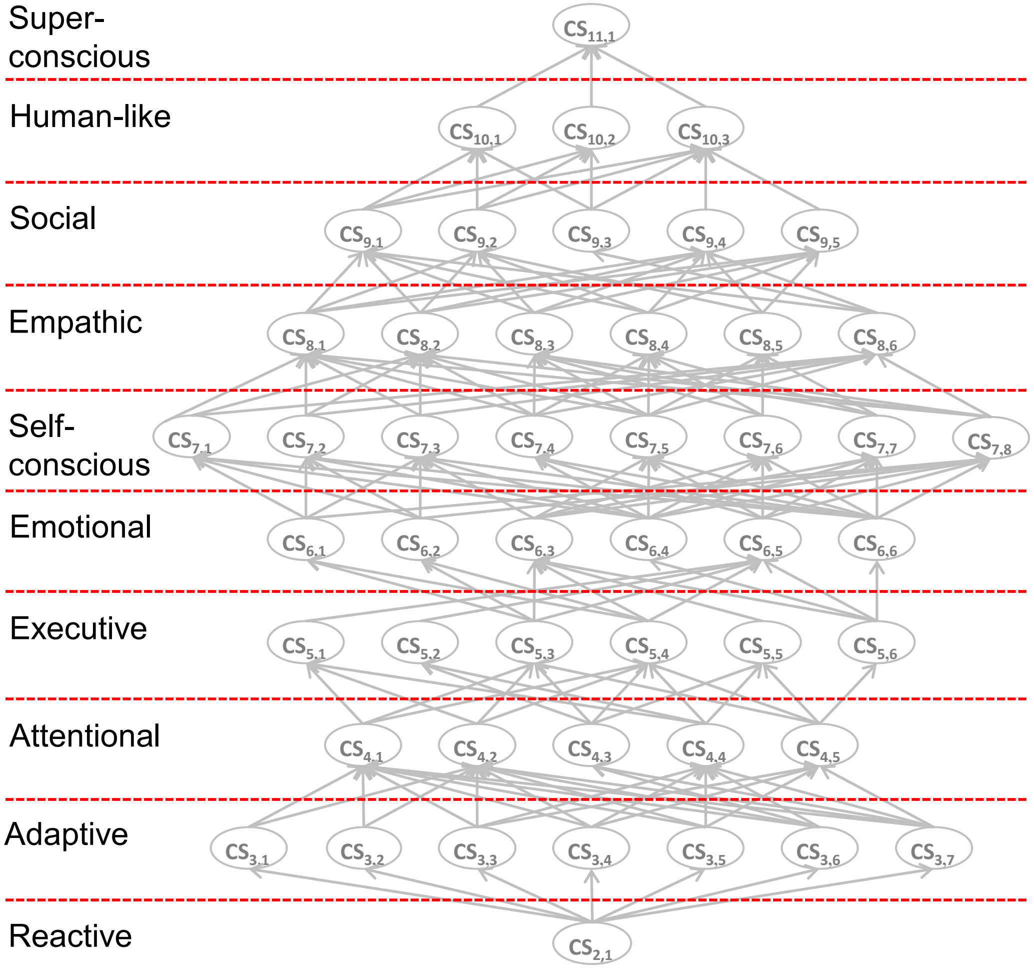
- Introduction
- State of the Art
- CERA-CRANIUM
- *ConsScale*
  - Introduction
  - Levels
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

Habilidades Cognitivas



$CS_{6,4}$: Ability to hold a precise and updated map of body schema.

ConsScale Levels



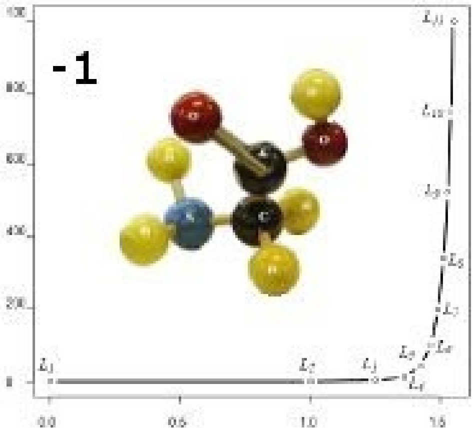
Consciousness in Artificial Cognitive Systems

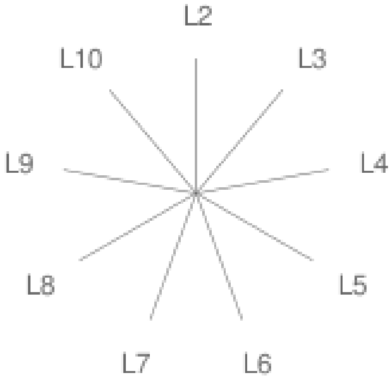
- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
  - **Levels**
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

Level -1. Disembodied

- ☐ Behavior: not a situated agent.
- ☐ Phylogeny: amino acid.

E **B**





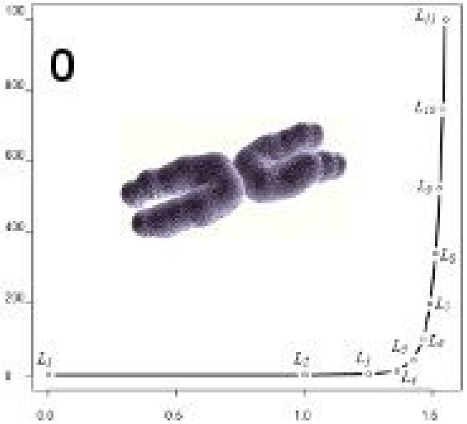
Consciousness in Artificial Cognitive Systems

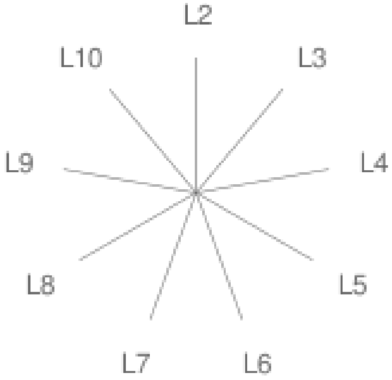
- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
  - **Levels**
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

Level 0. Isolated

- ☐ Behavior: not a situated agent.
- ☐ Phylogeny: isolated chromosome.

E **B**

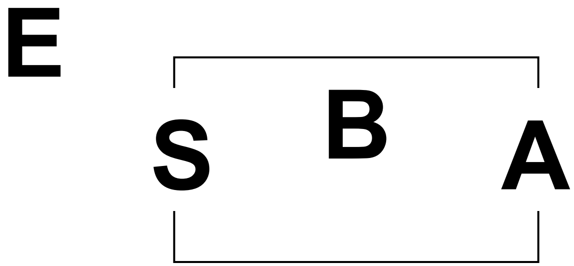


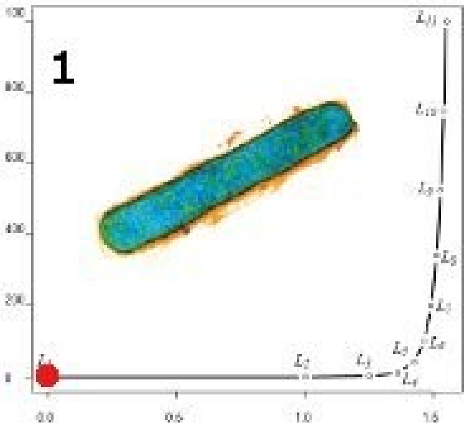


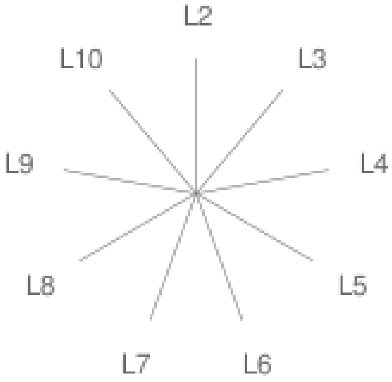
Consciousness in Artificial Cognitive Systems

Level 1. Pre-Functional

- ☐ Behavior: not a situated agent.
- ☐ Phylogeny: dead bacteria.



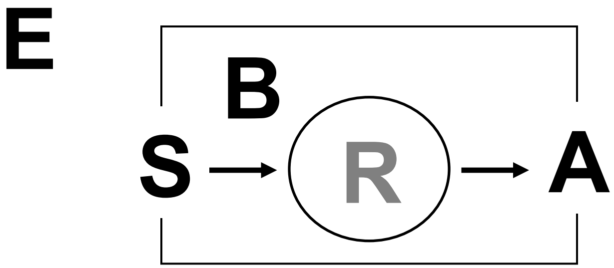


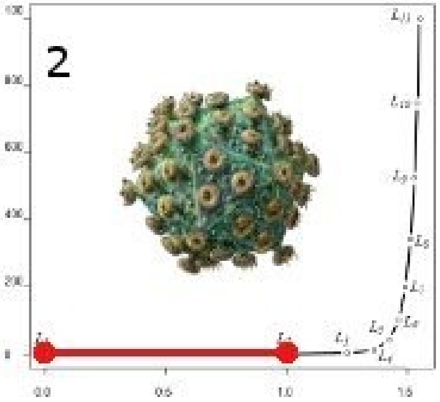


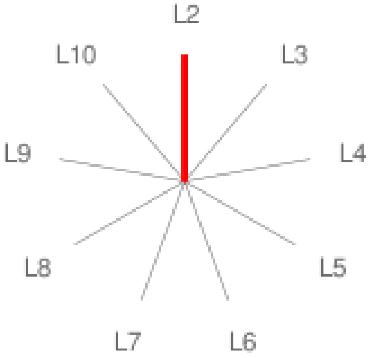
Consciousness in Artificial Cognitive Systems

Level 2. Reactive

- Behavior: reflexes.
- Phylogeny: virus.

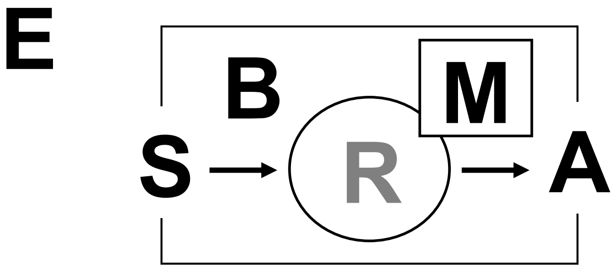


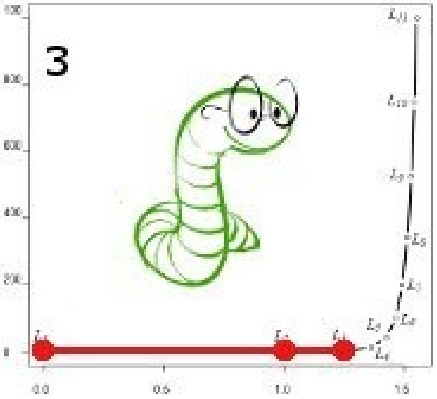


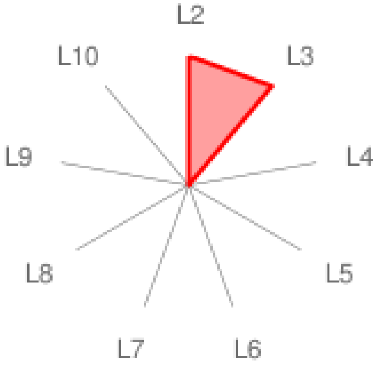


Level 3. Adaptive

- ☐ Behavior: learning of new reflexes.
- ☐ Phylogeny: earthworm.





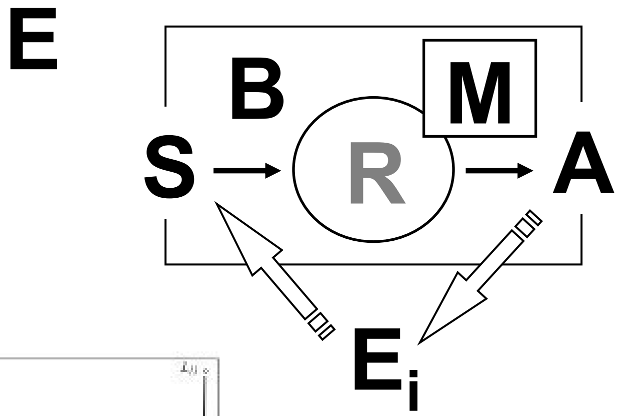


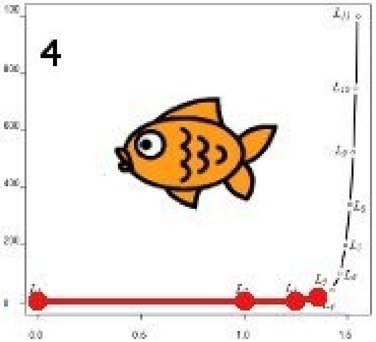
Consciousness in Artificial Cognitive Systems

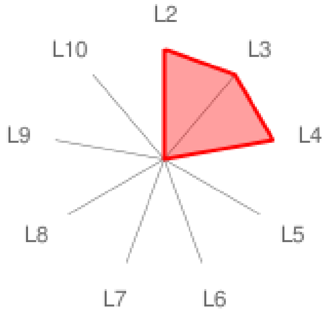
- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
  - **Levels**
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

Level 4. Atenttional

- ❑ Behavior: Attack and escape. Attention + emotion.
- ❑ Phylogeny: fish.

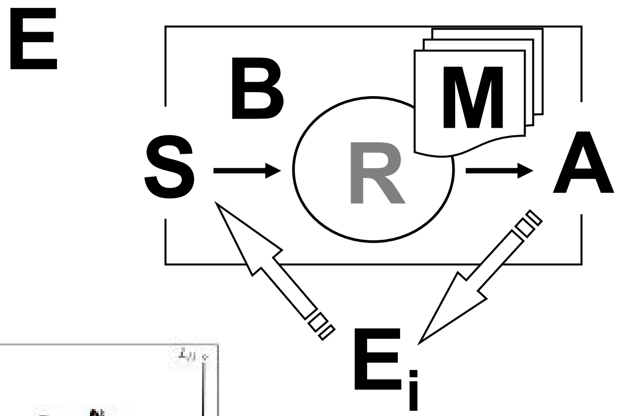


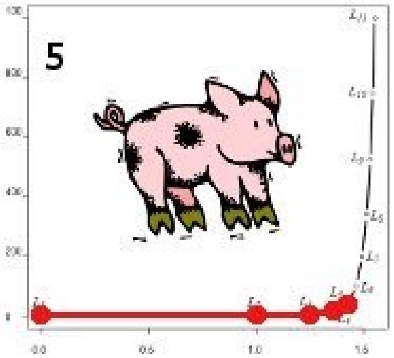


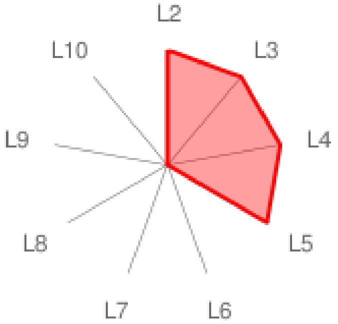


Level 5. Executive

- ❑ Behavior: Set shifting. Emotional learning.
- ❑ Phylogeny: quadruped mammal.





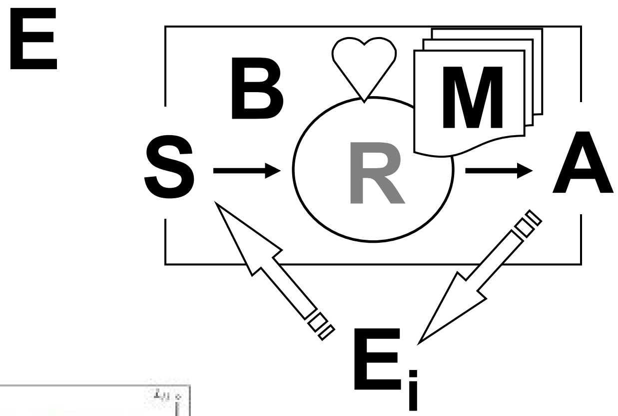


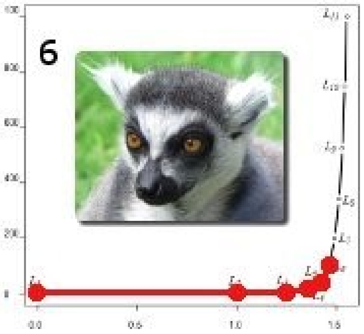
Consciousness in Artificial Cognitive Systems

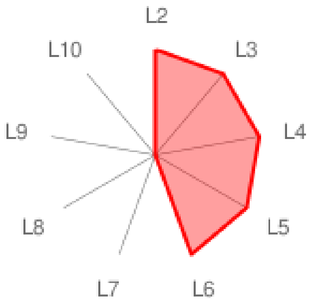
- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
  - **Levels**
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

Level 6. Emotional

- ❑ Behavior: modulated by feelings. “I know”.
- ❑ Phylogeny: monkey.

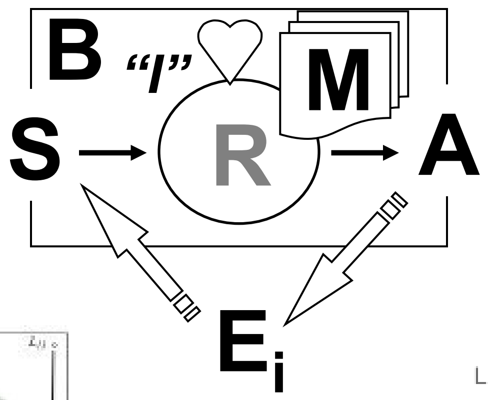


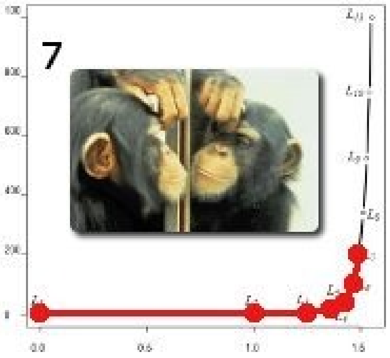


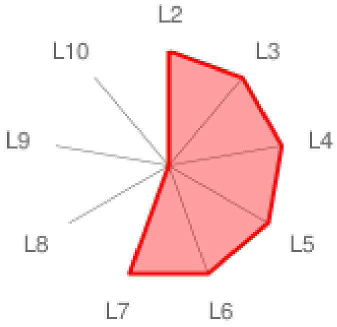


Level 7. Self-conscious

- ❑ Behavior: advanced planning. Tools usage. "I know I know".
- ❑ Phylogeny: monkey.



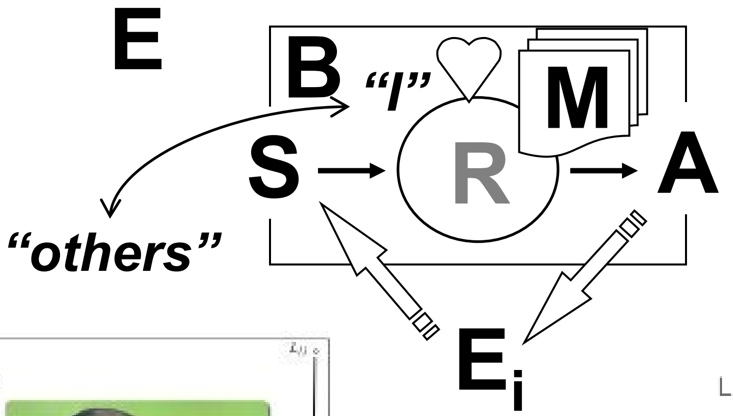


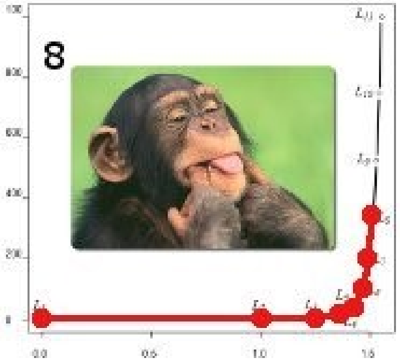


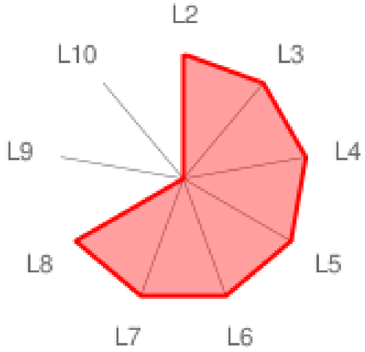
Consciousness in Artificial Cognitive Systems

Level 8. Empathic

- ☐ Behavior: making of tools and social. "I know you know".
- ☐ Phylogeny: chimpanzee.







Consciousness in Artificial Cognitive Systems

- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
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  - **Levels**
  - CQS
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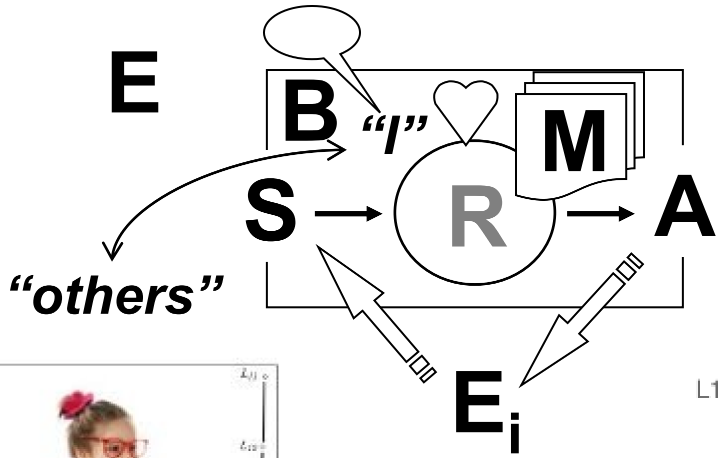
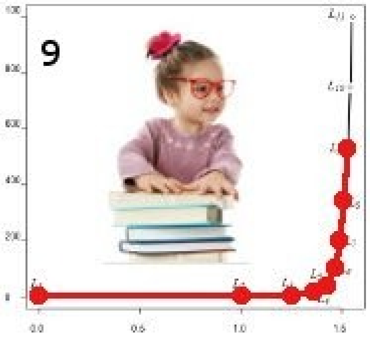
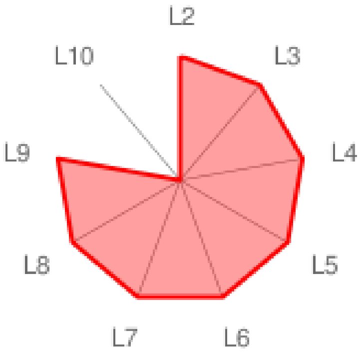
- Experimentation
- Conclusions

Level 9. Social

- ☐ Behavior: linguistic capabilities. Culture. "I know you know I know".
- ☐ Phylogeny: human.







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- **State of the Art**
- **CERA-CRANIUM**
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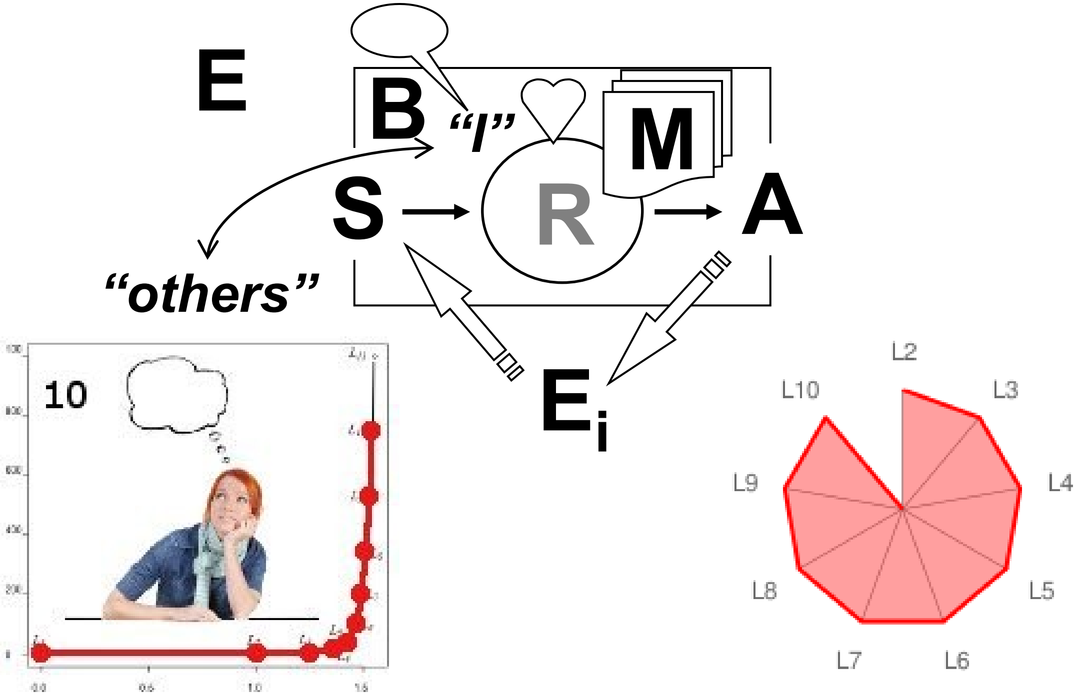
Level 10. Human-like

- ☐ Behavior: accurate verbal report. Technology. Adapted environment.
- ☐ Phylogeny: human.



Consciousness in Artificial Cognitive Systems

- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
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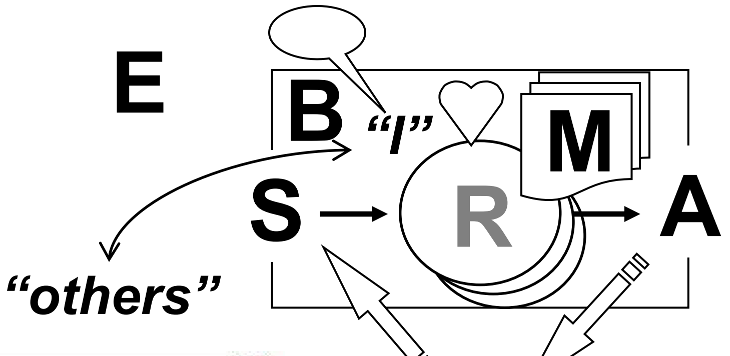
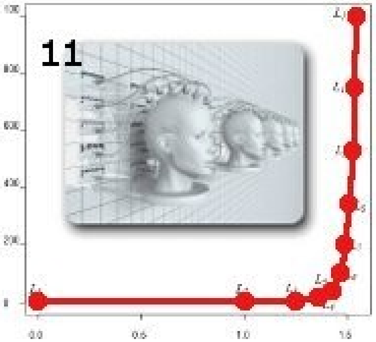
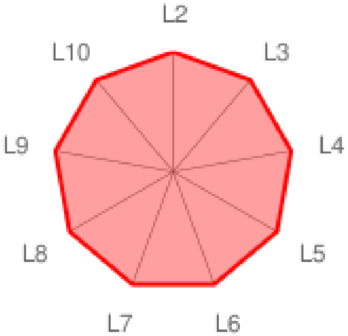
Level 11. Super-conscious

- ❑ Behavior: several coordinated threads of consciousness.
- ❑ Phylogeny: n/a.

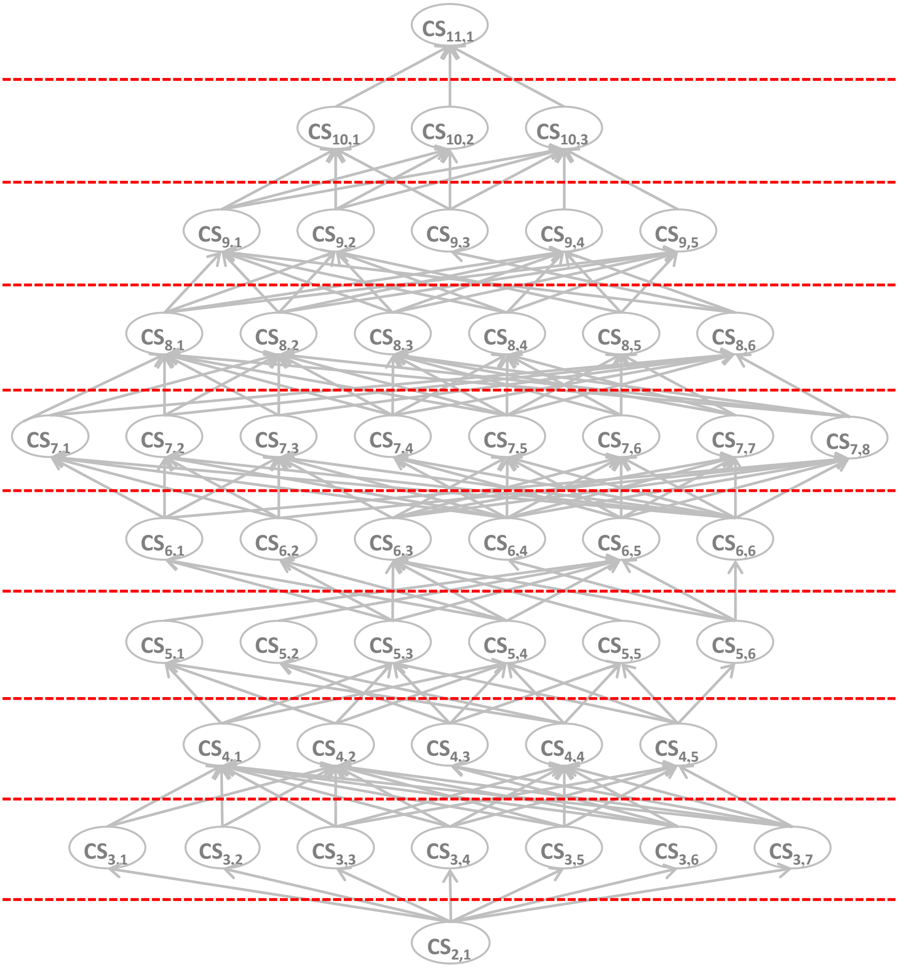






Consciousness in Artificial Cognitive Systems

CQS Quantitative Score



1000.00	11
745.74	10
524.54	9
341.45	8
200.03	7
101.08	6
41.23	5
12.21	4
2.22	3
0.18	2

CQS Quantitative Score

- ☐ **L_i**

  Score for each *i* level.

- ☐ **CLS**

  Cumulative score.

- ☐ **CQS**

  ConsScale Quantitative Score.

Consciousness in Artificial Cognitive Systems

- Introduction
- State of the Art
- CERA-CRANIUM
- *ConsScale*
  - Introduction
  - Levels
  - CQS
  - Cognitive Profiling
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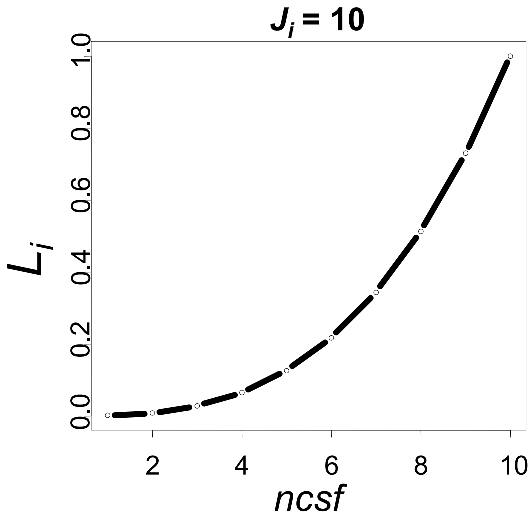
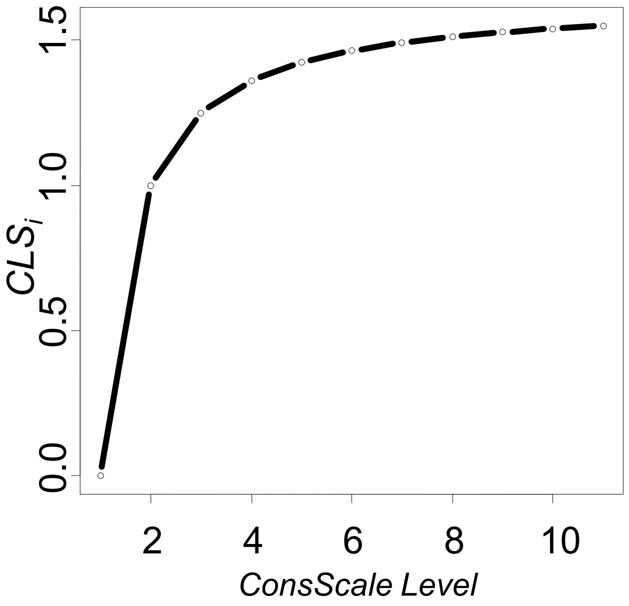
CQS Quantitative Score

$$L_i = \begin{cases} 0 & \text{if } ncsf \text{ is } 0 \\ \dfrac{(ncsf + (J - J_i))^3}{10^3} & \text{otherwise} \end{cases}$$



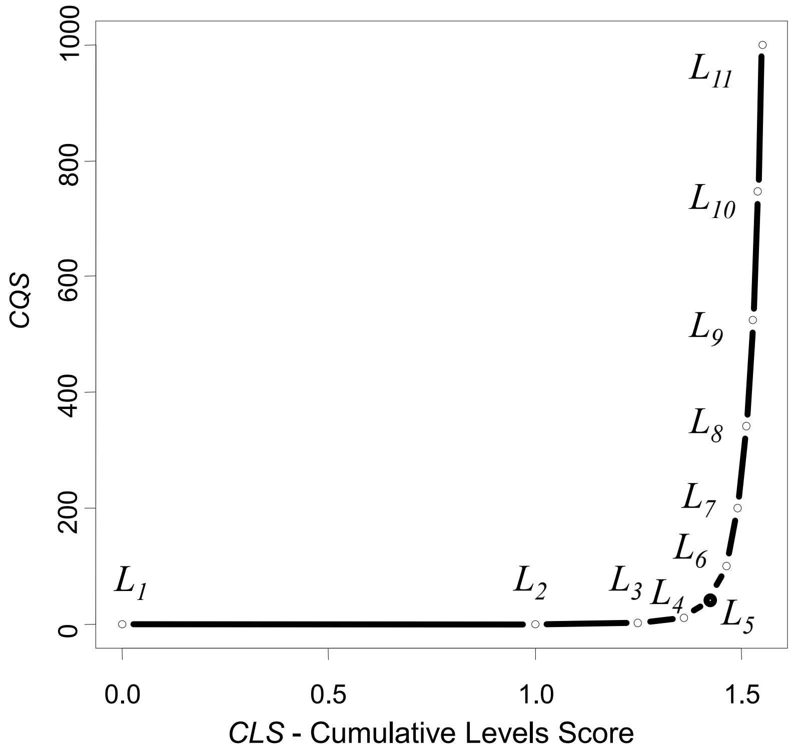
CQS Quantitative Score

$$CLS = \sum_{i=2}^{11} \left(\frac{L_i}{i-1} \right)^2$$



CQS Quantitative Score

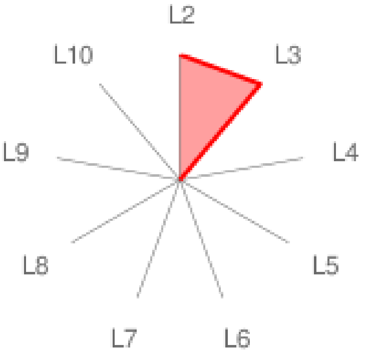
$$CQS = \frac{e^{\left(CLS^5/K\right)} + a}{10}$$



Consciousness in Artificial Cognitive Systems

Cognitive Profiling

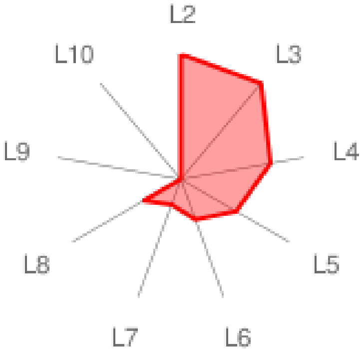
- ☐ An agent is said to comply with level *n* **if and only if** it satisfies both *n* and all lower levels.



Agent L3

Level: 3 – *Adaptive* (canonical)

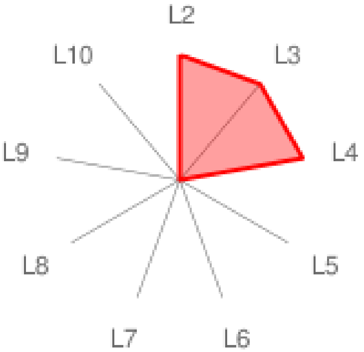
`CQS: 2.22`



Agent L3+

Level: 3 – *Adaptive* (non-canonical)

`CQS: 9.04`



Agent L4

Level: 4 – *Attentional* (canonical)

`CQS: 12.21`

Consciousness in Artificial Cognitive Systems

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- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
  - **Introduction**
  - **Levels**
  - **CQS**
  - **Cognitive Profiling**
  - **Instantiations**
- Artificial Qualia
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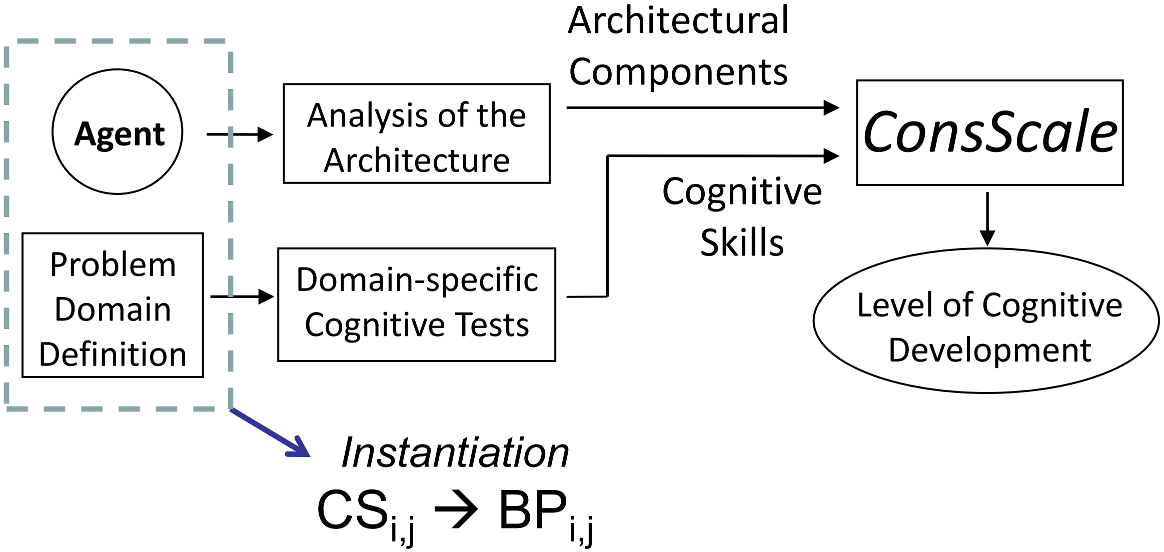
- Conclusions

ConsScale Instantiation



Agent

Analysis of the Architecture

Problem Domain Definition

Domain-specific Cognitive Tests

Architectural Components

Cognitive Skills

ConsScale

Level of Cognitive Development

Instantiation

$CS_{i,j}$ → $BP_{i,j}$

Generic Cognitive Skills ($CS_{i,j}$) → Domain-specific ($DCS_{i,j}$)

Domain-specific CS → Behavior Profiles ($BP_{i,j}$)

Behavior Profiles → **Behavioral Tests**

ConsScale FPS

First-Person Shooter Video Game Bots

☐ **DCS**$_{3,3}$: Ability to ignore sensory input not critical to current task.

☐ **BP**$_{3,3}$: Bot ignores detected ammo reloading kits when involved in a firefight and no more ammo is needed.

ConsScale Calculator

- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
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    - **Levels**
    - **CQS**
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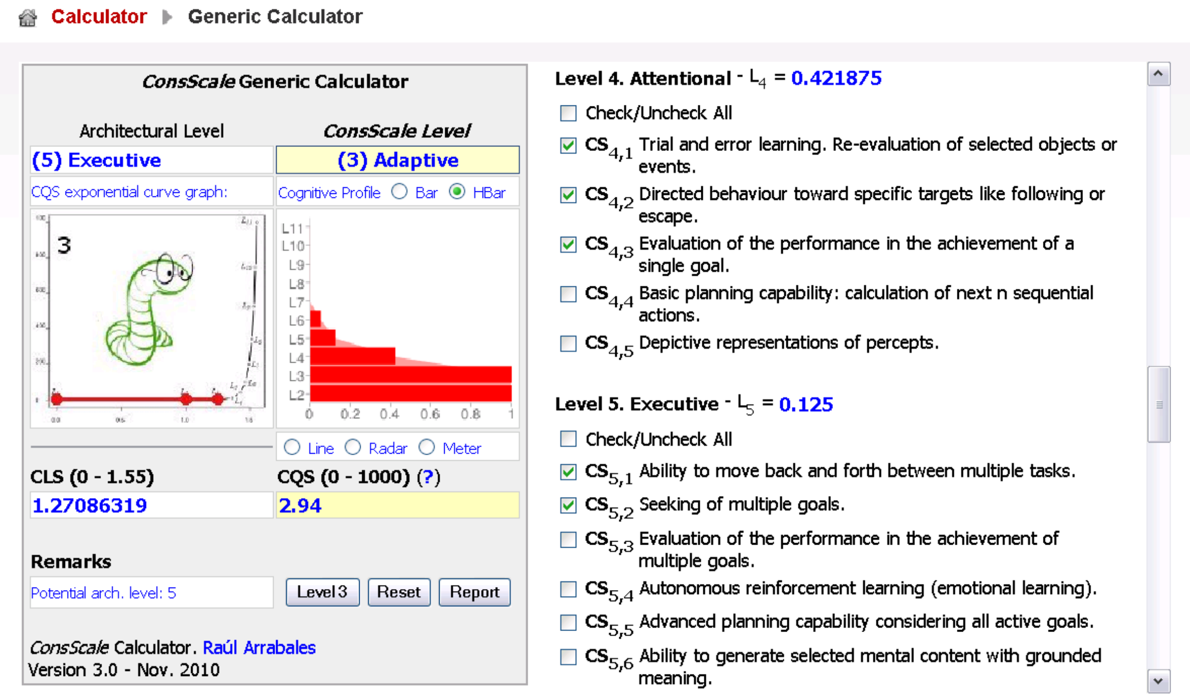


Calculator ▸ **Generic Calculator**

ConsScale Generic Calculator

Architectural Level: **(5) Executive**

ConsScale Level: **(3) Adaptive**

CQS exponential curve graph:

Cognitive Profile ○ Bar ● HBar

○ Line ○ Radar ○ Meter

CLS (0 - 1.55): **1.27086319**

CQS (0 - 1000) (?): **2.94**

Remarks

Potential arch. level: 5

ConsScale Calculator. Raúl Arrabales
Version 3.0 - Nov. 2010

Level 4. Attentional - L_4 = 0.421875

☐ Check/Uncheck All

☑ **$CS_{4,1}$** Trial and error learning. Re-evaluation of selected objects or events.

☑ **$CS_{4,2}$** Directed behaviour toward specific targets like following or escape.

☑ **$CS_{4,3}$** Evaluation of the performance in the achievement of a single goal.

☐ **$CS_{4,4}$** Basic planning capability: calculation of next n sequential actions.

☐ **$CS_{4,5}$** Depictive representations of percepts.

Level 5. Executive - L_5 = 0.125

☐ Check/Uncheck All

☑ **$CS_{5,1}$** Ability to move back and forth between multiple tasks.

☑ **$CS_{5,2}$** Seeking of multiple goals.

☐ **$CS_{5,3}$** Evaluation of the performance in the achievement of multiple goals.

☐ **$CS_{5,4}$** Autonomous reinforcement learning (emotional learning).

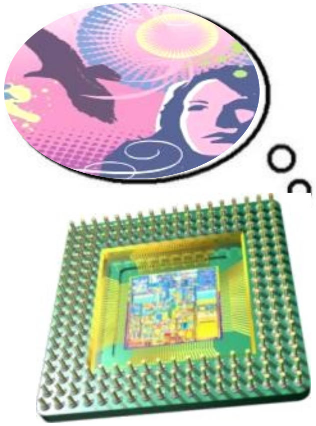
☐ **$CS_{5,5}$** Advanced planning capability considering all active goals.

☐ **$CS_{5,6}$** Ability to generate selected mental content with grounded meaning.

Contents

Artificial Qualia

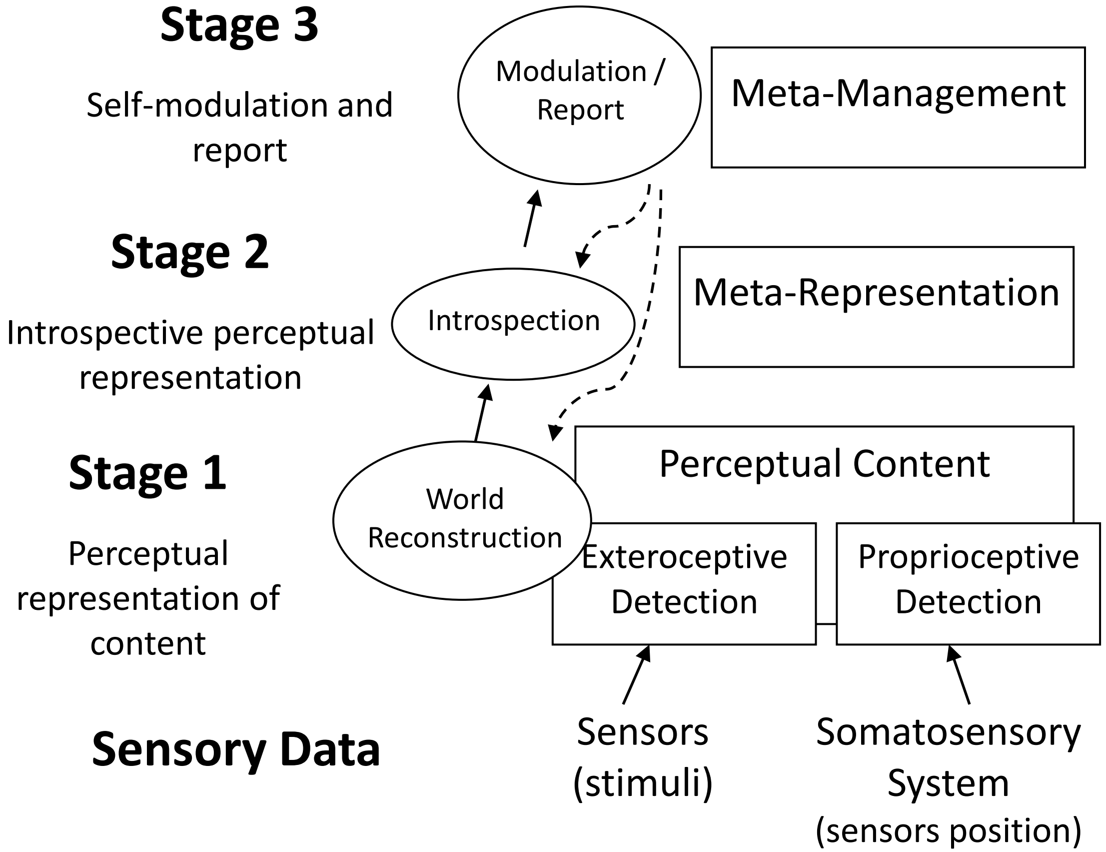
- ☐ How qualia can be generated in a machine?
- ☐ Would artificial qualia be comparable to human subjective experience?



Hypotheses about qualia

- ☐ They are processes that are present in relation with cognitive abilities.
- ☐ They have associated functionality.
- ☐ Qualia are the ultimate result of the perception process.

Proposed model



Stage 3

Self-modulation and report

Stage 2

Introspective perceptual representation

Stage 1

Perceptual representation of content

Sensory Data

Consciousness in Artificial Cognitive Systems

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- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
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  - **Introduction**
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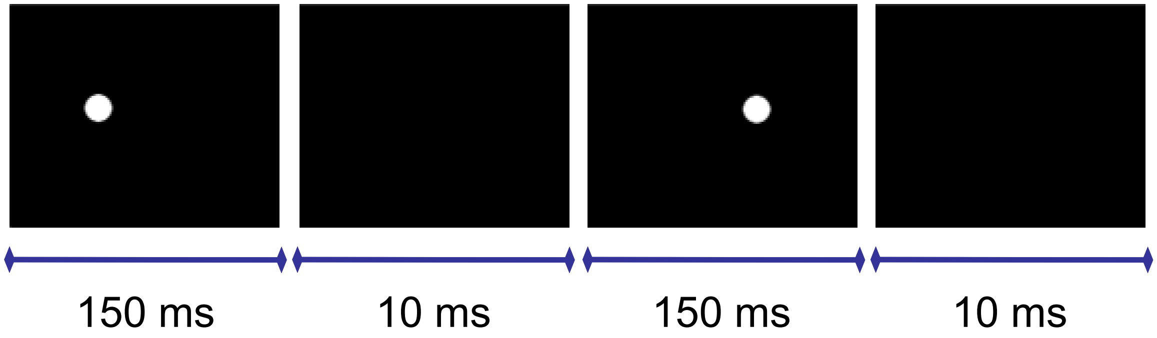
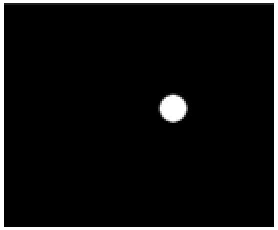
Application to Visual Experience





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- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
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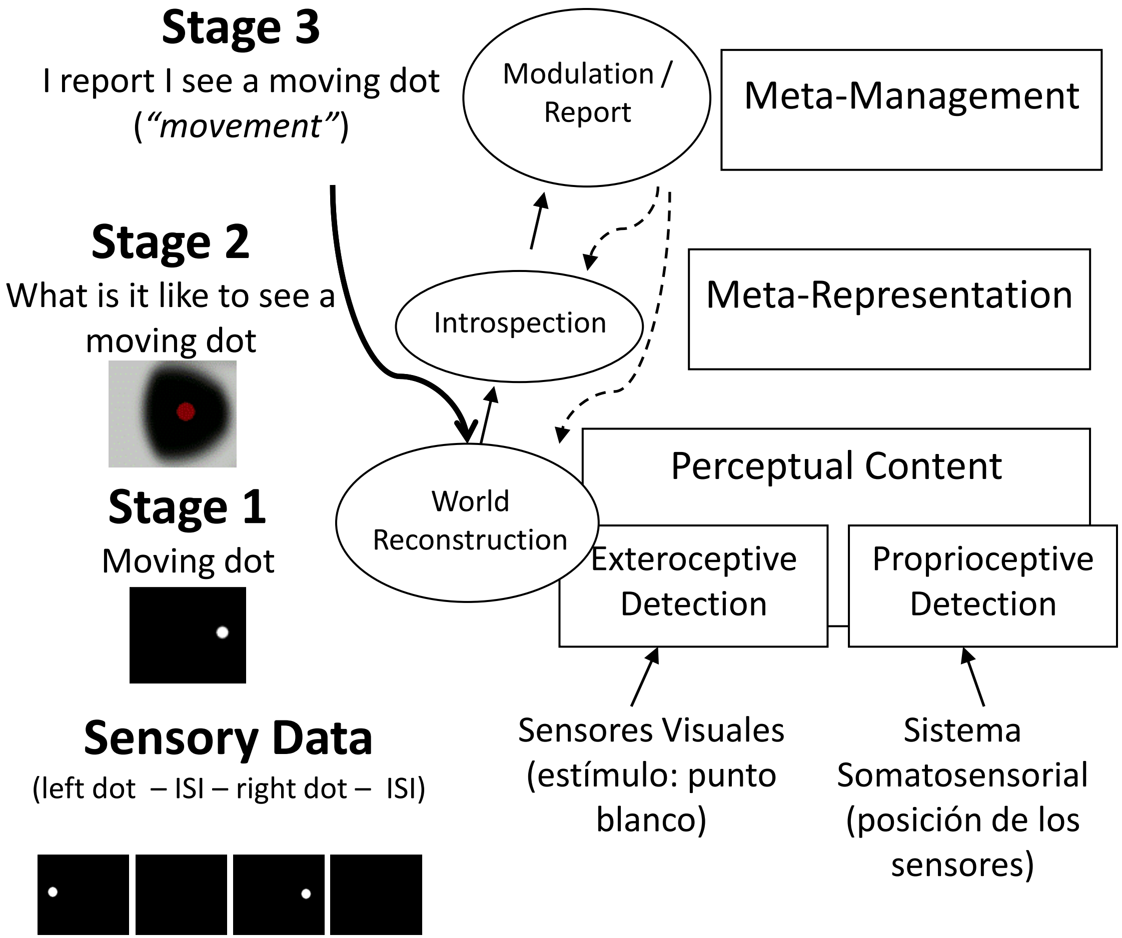
Proposed model



Stage 3

I report I see a moving dot (*“movement”*)

Stage 2

What is it like to see a moving dot

Stage 1

Moving dot

Sensory Data

(left dot – ISI – right dot – ISI)

Modulation / Report

Introspection

World Reconstruction

Meta-Management

Meta-Representation

Perceptual Content

Exteroceptive Detection

Proprioceptive Detection

Sensores Visuales (estímulo: punto blanco)

Sistema Somatosensorial (posición de los sensores)

Contents

Domains of Experimentation

☐ Application of CERA-CRANIUM to the control of autonomous agents.

☐ Application of CERA-CRANIUM to synthetic phenomenology.

☐ Application of *ConsScale* to the evaluation of machine consciousness models and implementations.

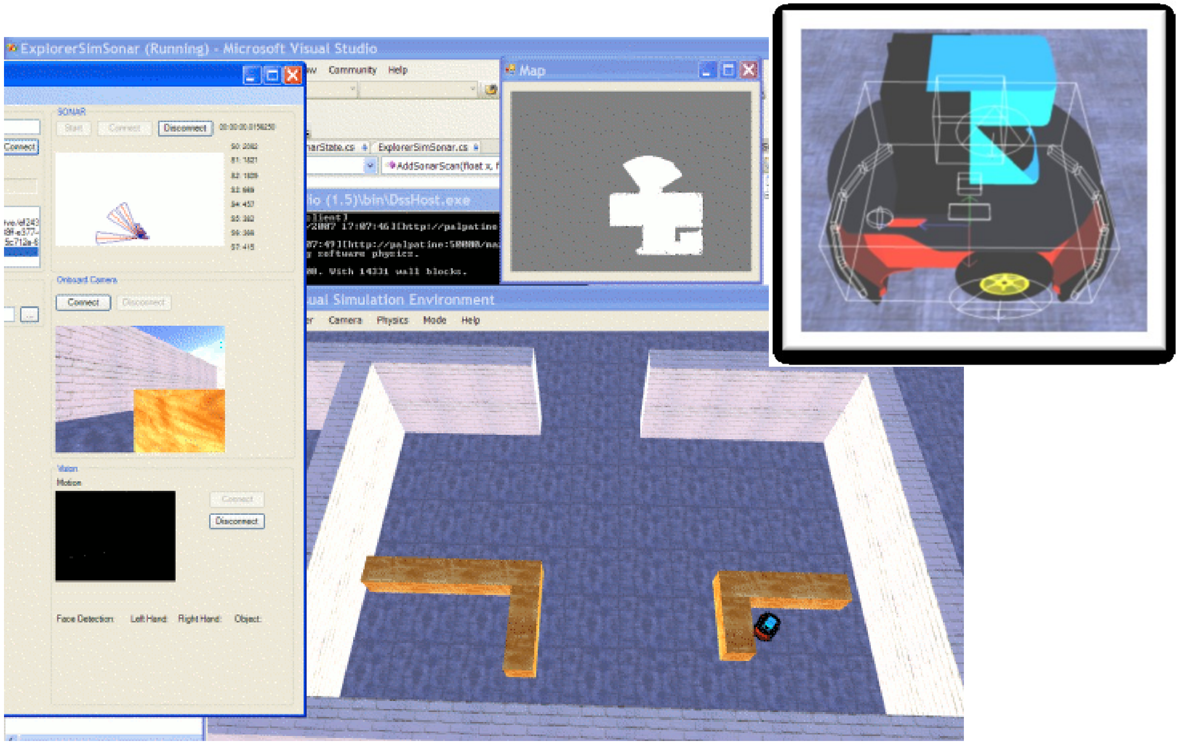
Domains of Experimentation

❑ Application of CERA-CRANIUM to the control of autonomous agents.

- ❑ CERA-CRANIUM Explorer *(CC-Explorer)* → Exploration task.
- ❑ CERA-CRANIUM Chaser *(CC-Chaser)* → Chasing task.
- ❑ CERA-CRANIUM Bot *(CC-Bot)* → FPS playing task.

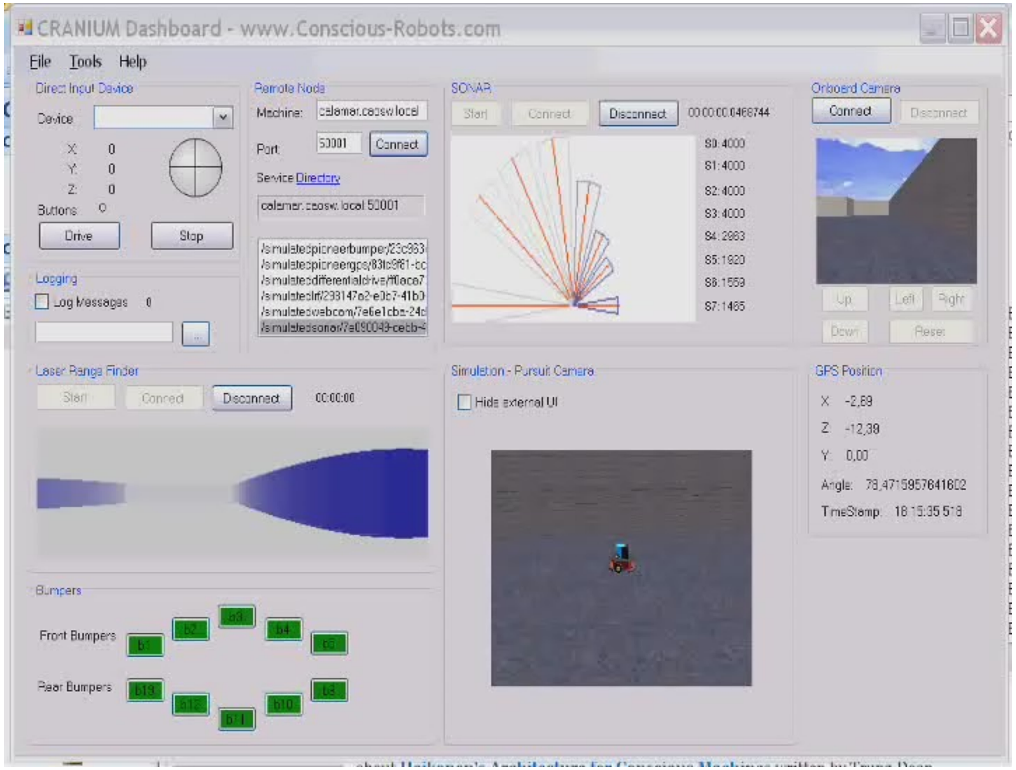
CERA-CRANIUM Explorer

- ☐ Autonomous exploration (no SLAM).
- ☐ Using both simulated and real P-3DX robots.



CERA-CRANIUM Explorer

- ☐ Autonomous exploration (no SLAM).
- ☐ Use of frontal sonar ring for mapping.



Device

X: 0

Y: 0

Z: 0

Buttons 0

Machine: calamar.ceosw.local

Port 50001 Connect

Service Directory

calamar.ceosw.local:50001

/simulatedpioneerbumper/23c963
/simulatedpioneergps/83fc9f61-bc
/simulateddifferentialdrive/ff0ace7
/simulatedlrf/238147e2-e0b7-41b0
/simulatedwebcam/7e6e1cba-24c
/simulatedsonar/7a090049-cebb-

☐ Log Messages 0

00:00:00.0468744

S0:4000
S1:4000
S2:4000
S3:4000
S4:2983
S5:1920
S6:1559
S7:1465

00:00:00

☐ Hide external UI

X -2,69

Z -12,39

Y 0,00

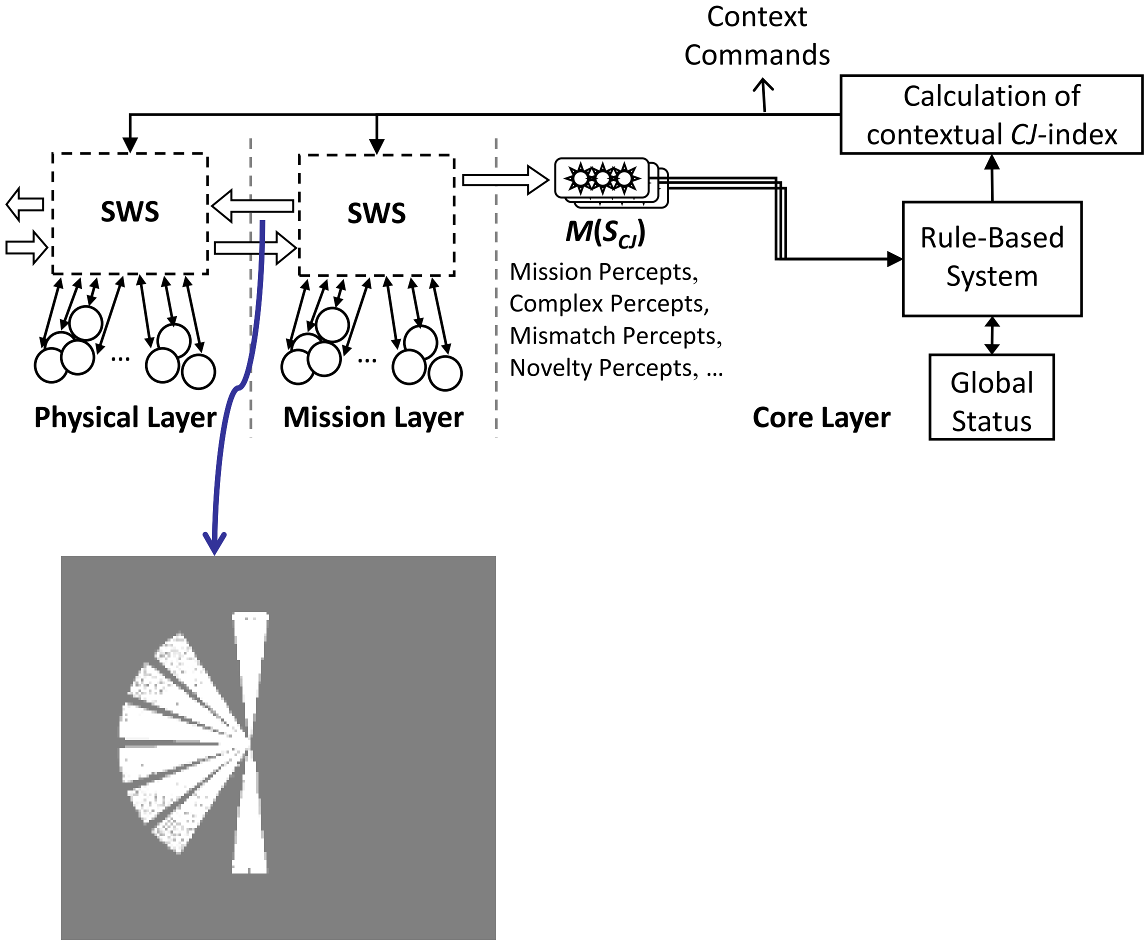
Angle: 78,4715957641602

TimeStamp: 18:15:35 518

CERA-CRANIUM Explorer

- ☐ CC-Explorer implementations
  - ☐ **CCE-1**: physical layer only (obstacle avoidance reflex).
  - ☐ **CCE-2**: Attention focus toward areas free of obstacles.
  - ☐ **CCE-3**: Attention focus toward unexplored areas.

CERA-CRANIUM Explorer



Context Commands

Calculation of contextual *CJ*-index

SWS

SWS

$M(S_{CJ})$

Mission Percepts, Complex Percepts, Mismatch Percepts, Novelty Percepts, …

Rule-Based System

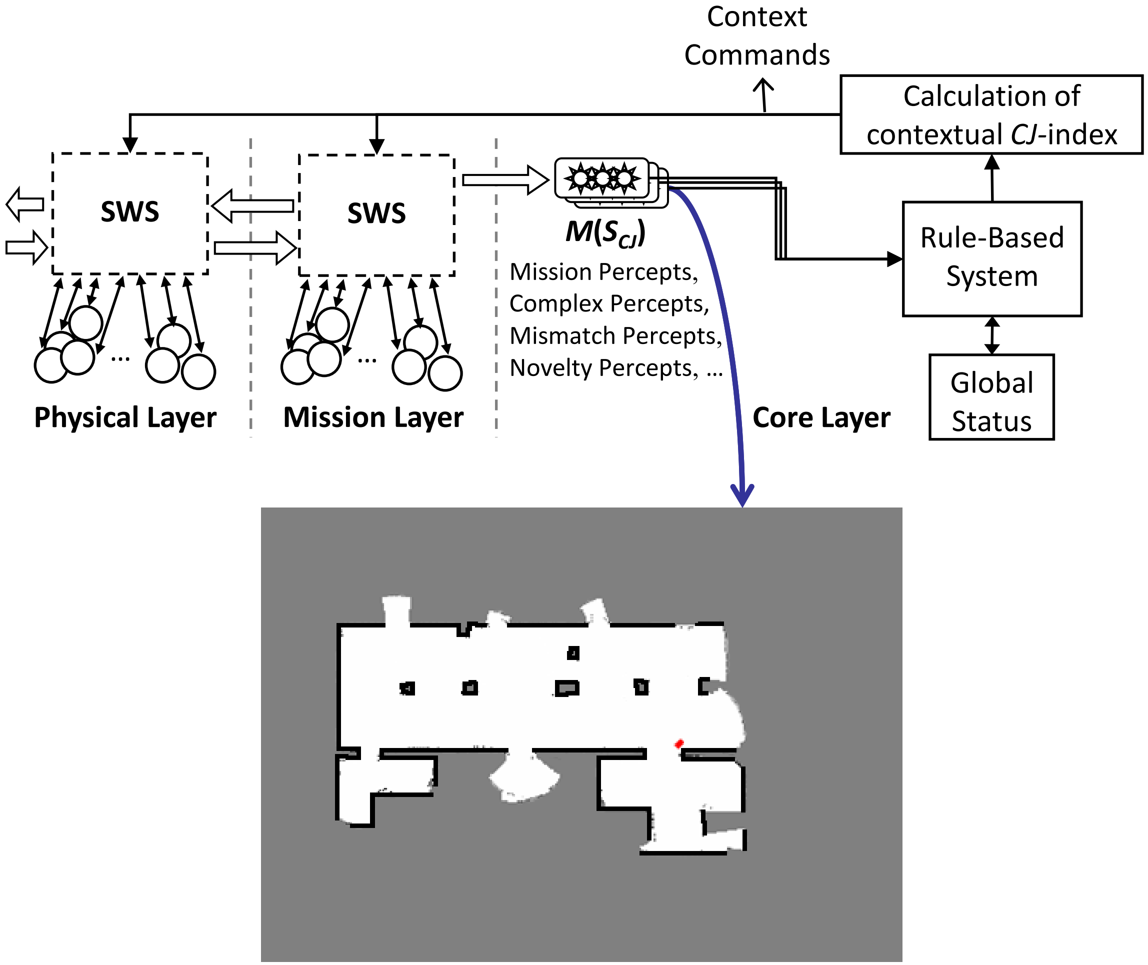
Global Status

Physical Layer

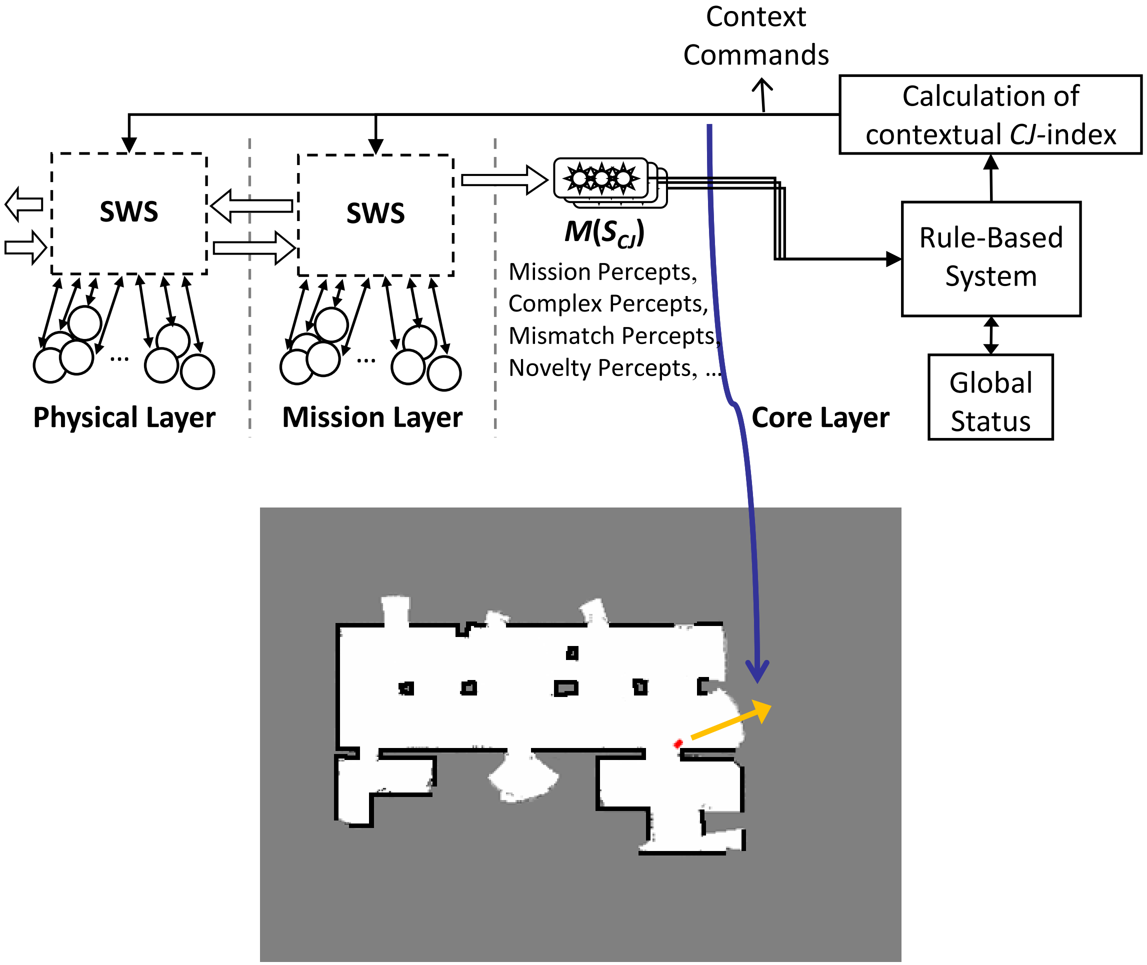
Mission Layer

Core Layer

CERA-CRANIUM Explorer



CERA-CRANIUM Explorer



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M(S_{CJ})

Mission Percepts,
Complex Percepts,
Mismatch Percepts,
Novelty Percepts, …

Rule-Based System

Global Status

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- **State of the Art**
- **CERA-CRANIUM**
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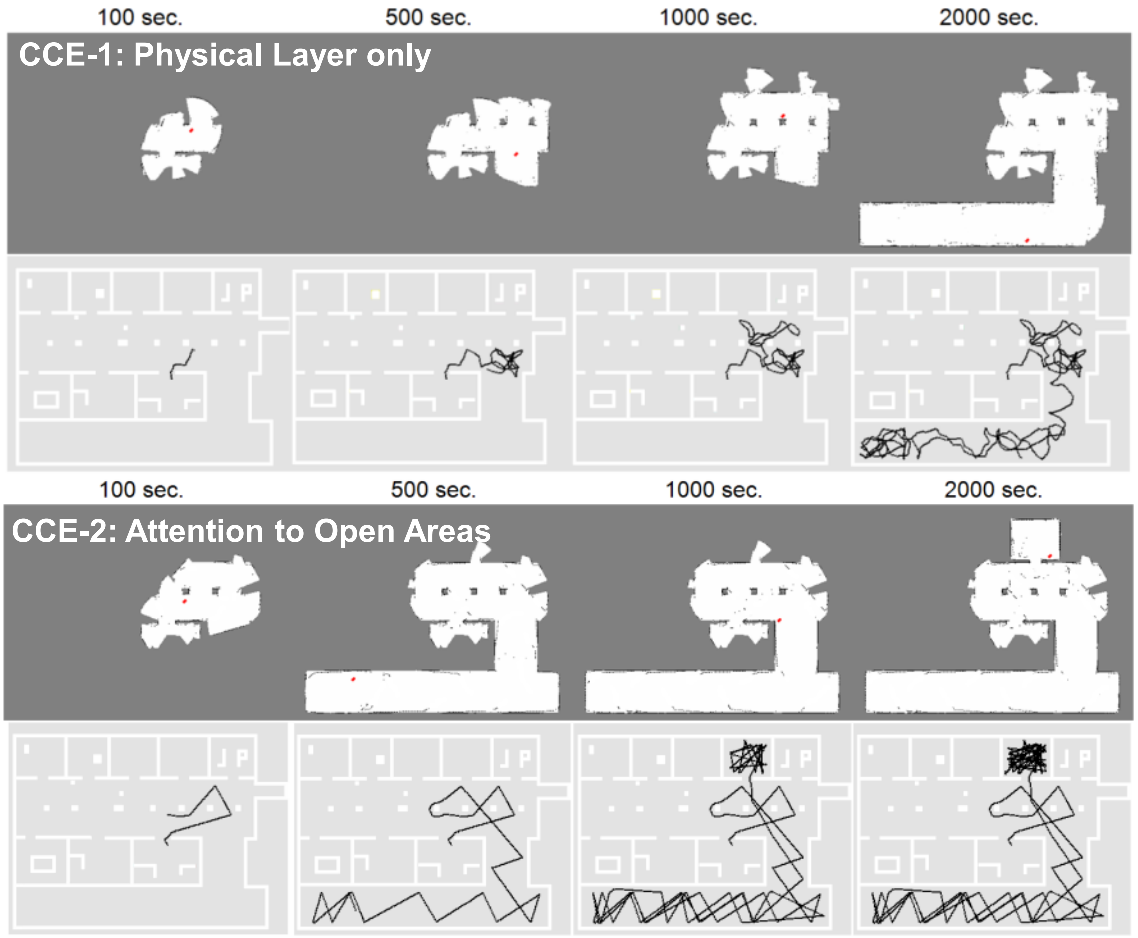
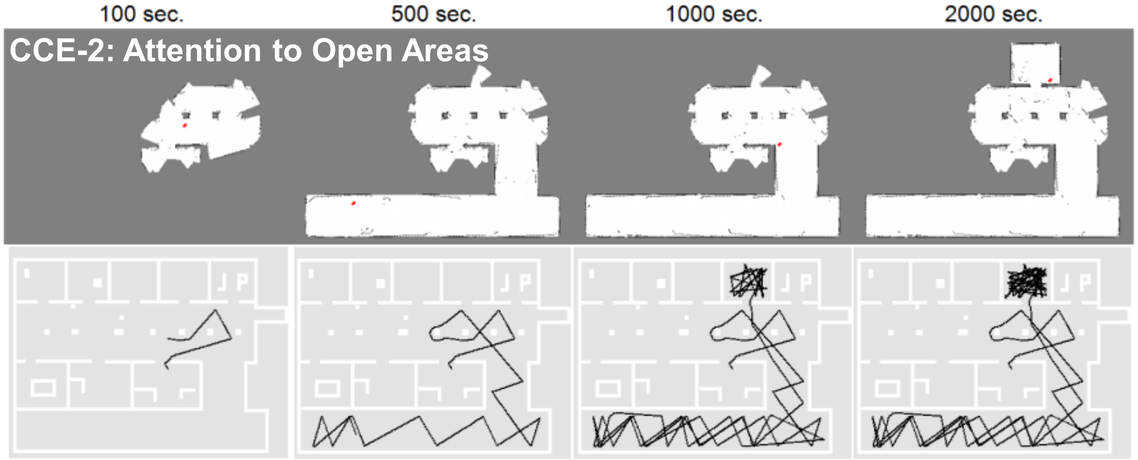
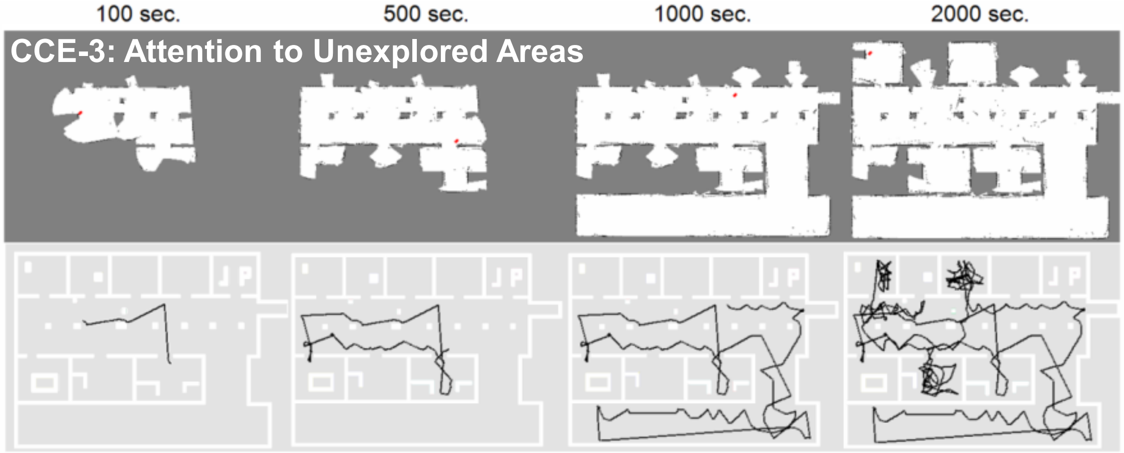
  - CC-Bot
  - CC-Observer
  - *ConsScale*
- Conclusions



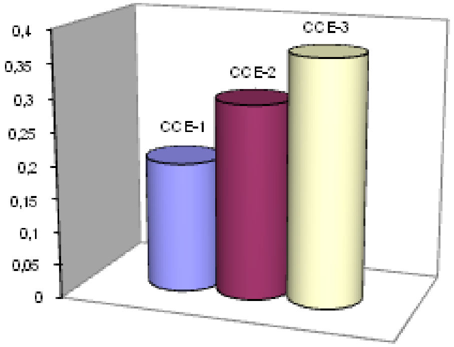
CERA-CRANIUM Explorer

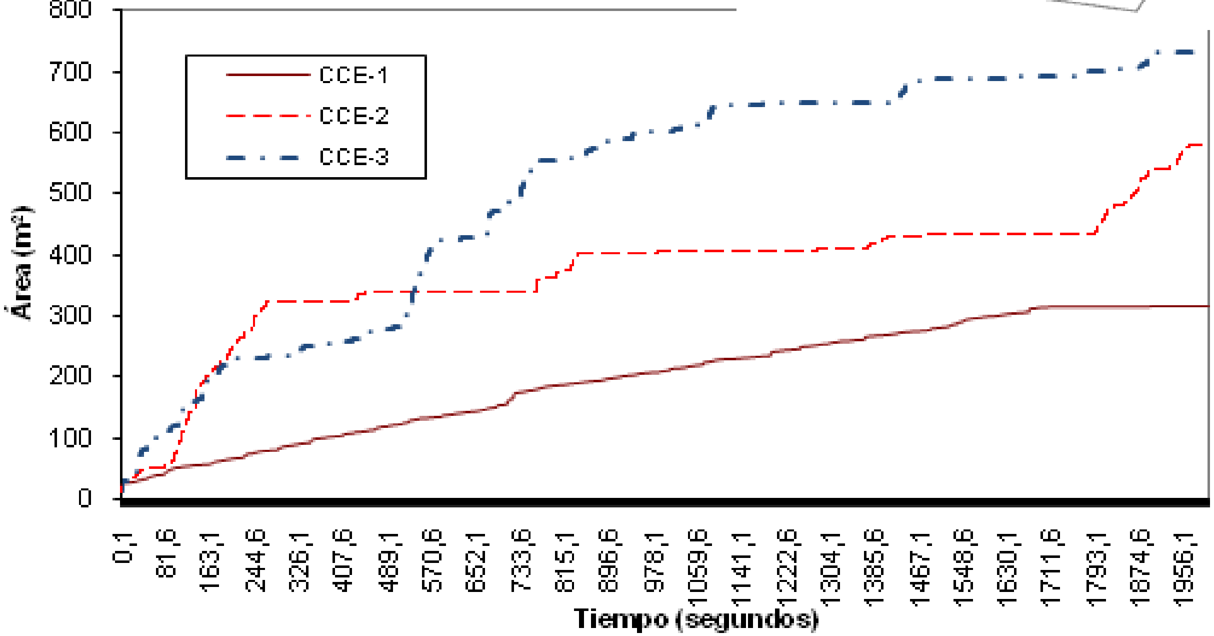




CERA-CRANIUM Explorer

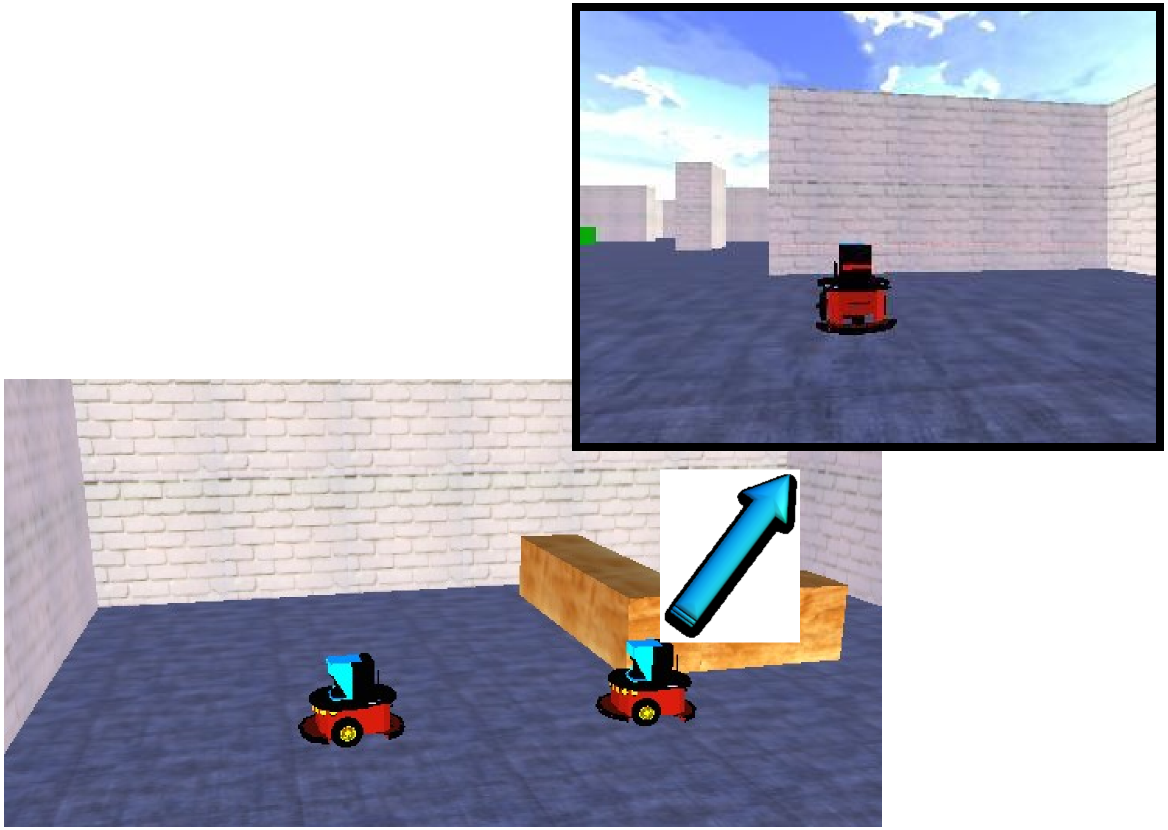
CCE-1 (no attention): 0.19 m^2/s
CCE-2 (open areas): 0.29 m^2/s
CCE-3 (unexplored): 0.36 m^2/s





CERA-CRANIUM Chaser

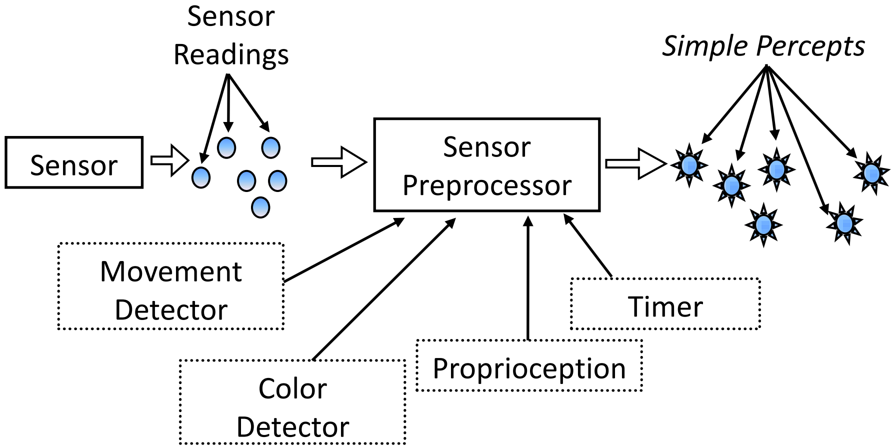
- ☐ Simple pursuing task.



CERA-CRANIUM Chaser

❑ Additional parameter for context formation:

  ❑ *t* (time), *j* (relative position),
  ❑ *c* (color), *m* (movement).



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- **State of the Art**
- **CERA-CRANIUM**
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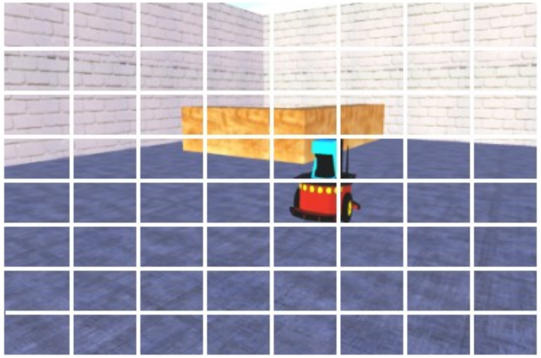
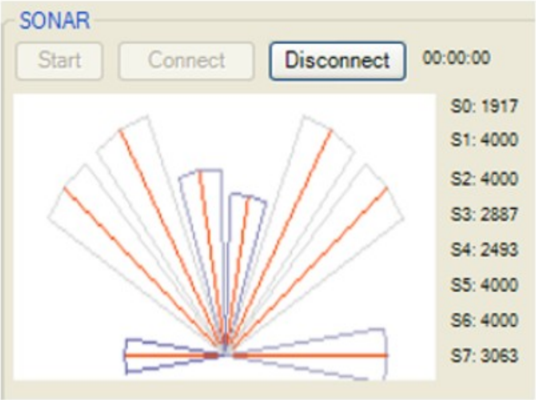
CERA-CRANIUM Chaser

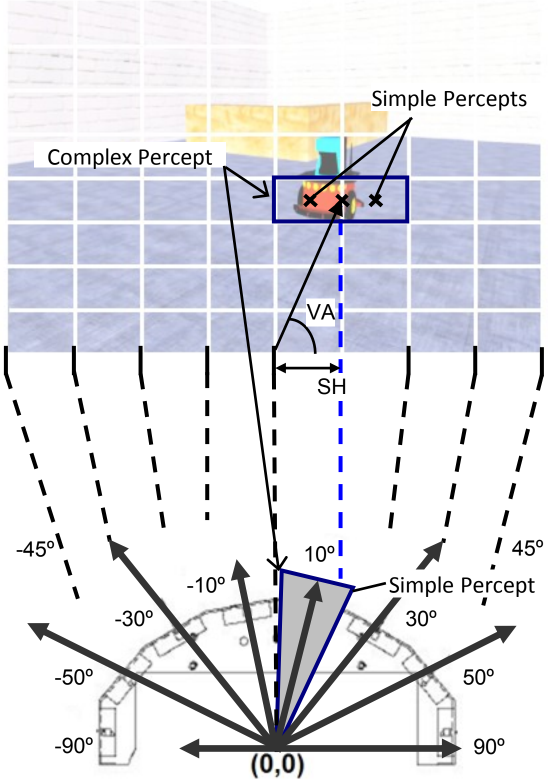
Multimodal Sensory Fusion





00:00:00

S0: 1917
S1: 4000
S2: 4000
S3: 2887
S4: 2493
S5: 4000
S6: 4000
S7: 3063



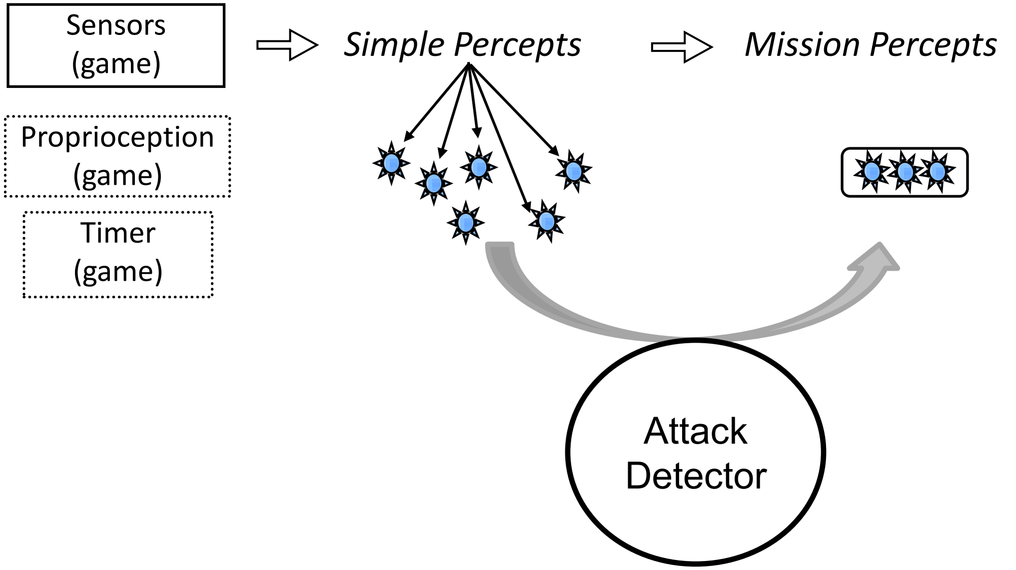
CERA-CRANIUM Bot

- Environment
  - Unreal Tournament 2004
  - Pogamut

- Implementations
  - CC-Bot1:
    - Qualification trials at 2K BotPrize 2009.
  - CC-Bot2:
    - Winner of the 2K BotPrize 2010.

CERA-CRANIUM Bot

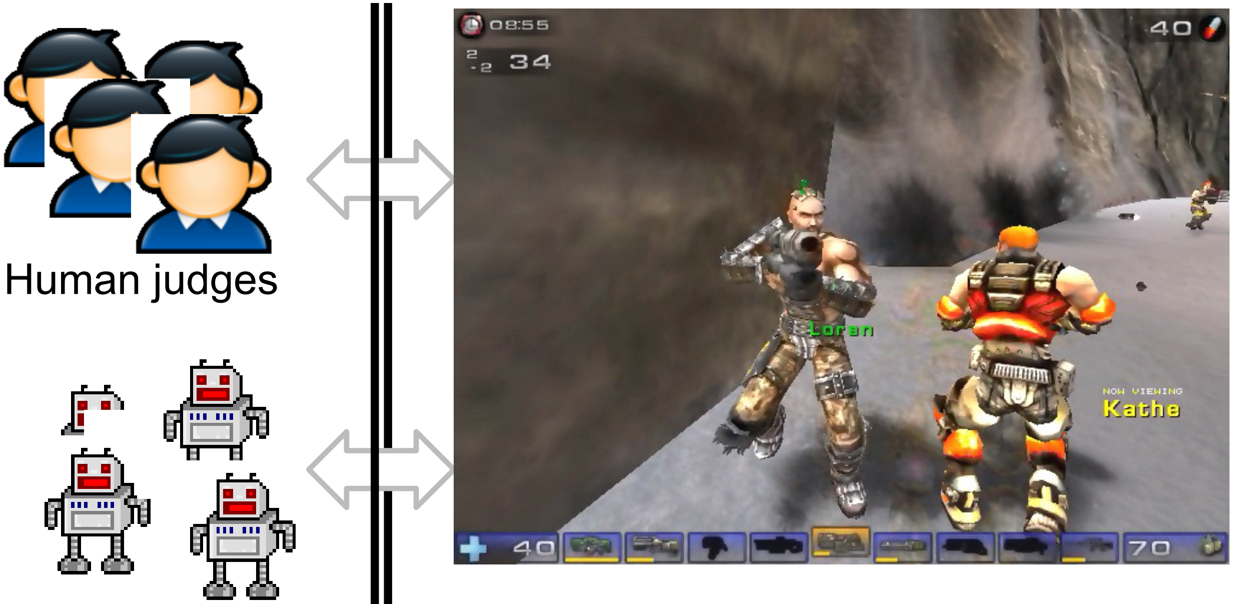
Mission Percepts



"I am being damaged"
\+
"I see an enemy" ⇨ "Enemy attacking"
\+
"Enemy is approaching"

CERA-CRANIUM Bot

BotPrize – Turing Test Adapted to FPS game



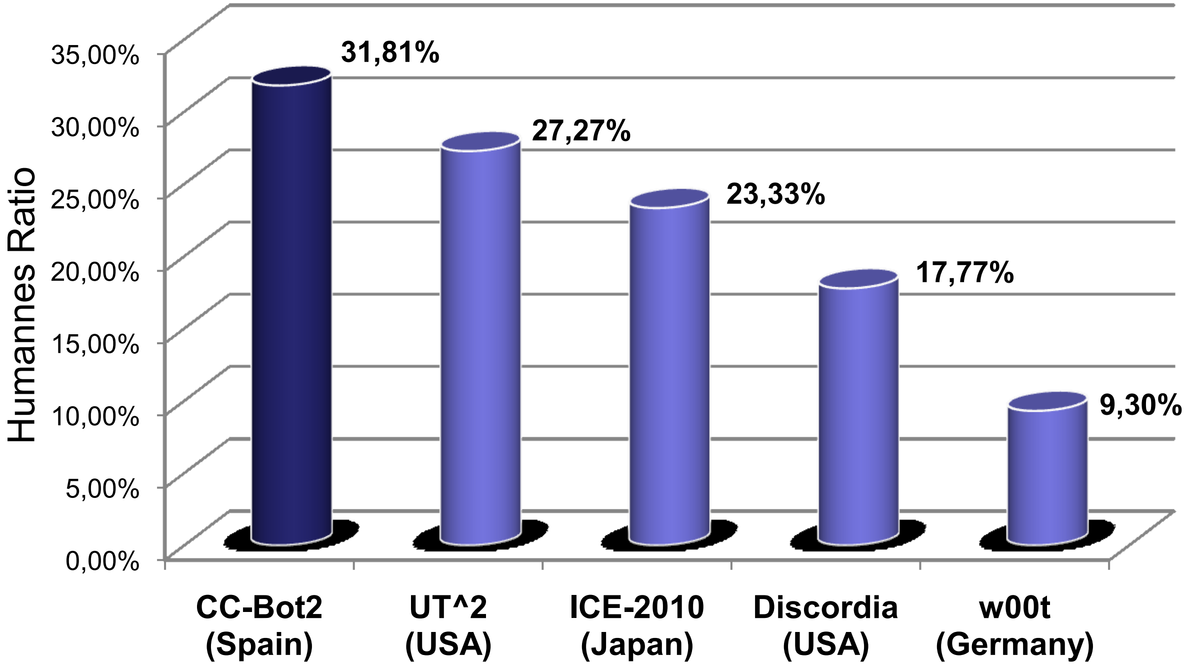
Human judges

Artificial Bots

Unreal Tournament deathmatch game

CERA-CRANIUM Bot

2K BotPrize 2010 Results



Consciousness in Artificial Cognitive Systems

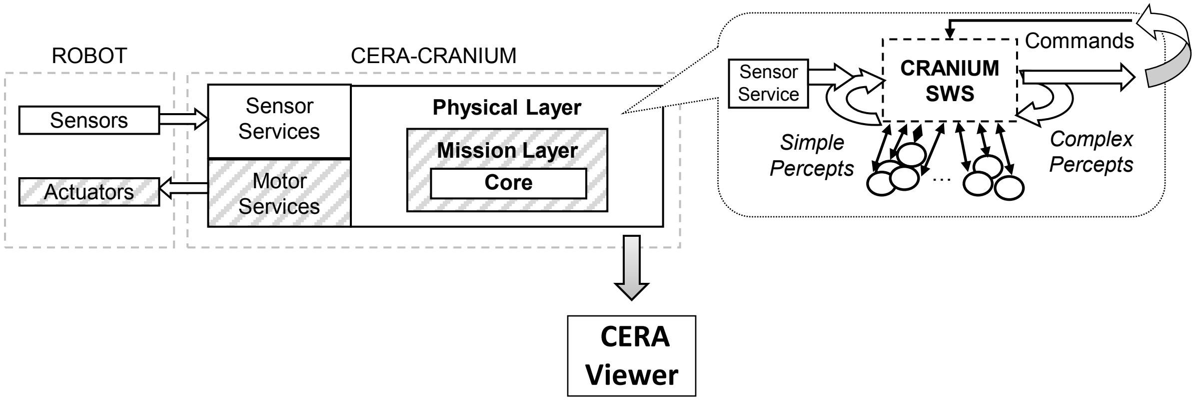
- **Introduction**
- **State of the Art**
- **CERA-CRANIUM**
- ***ConsScale***
- **Artificial Qualia**
- **Experimentation**
  - **Introduction**
  - **CC-Explorer**
  - **CC-Chaser**
  - **CC-Bot**
  - **CC-Observer**
  - *ConsScale*
- Conclusions

CERA-CRANIUM Observer

Synthetic Phenomenology

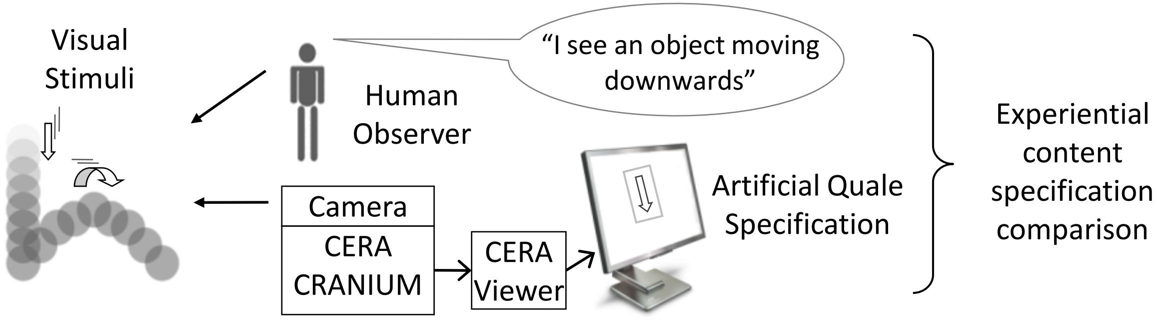
☐ Specification of the content of conscious experience.

☐ Minimal implementation CERA-CRANIUM.



CERA-CRANIUM Observer

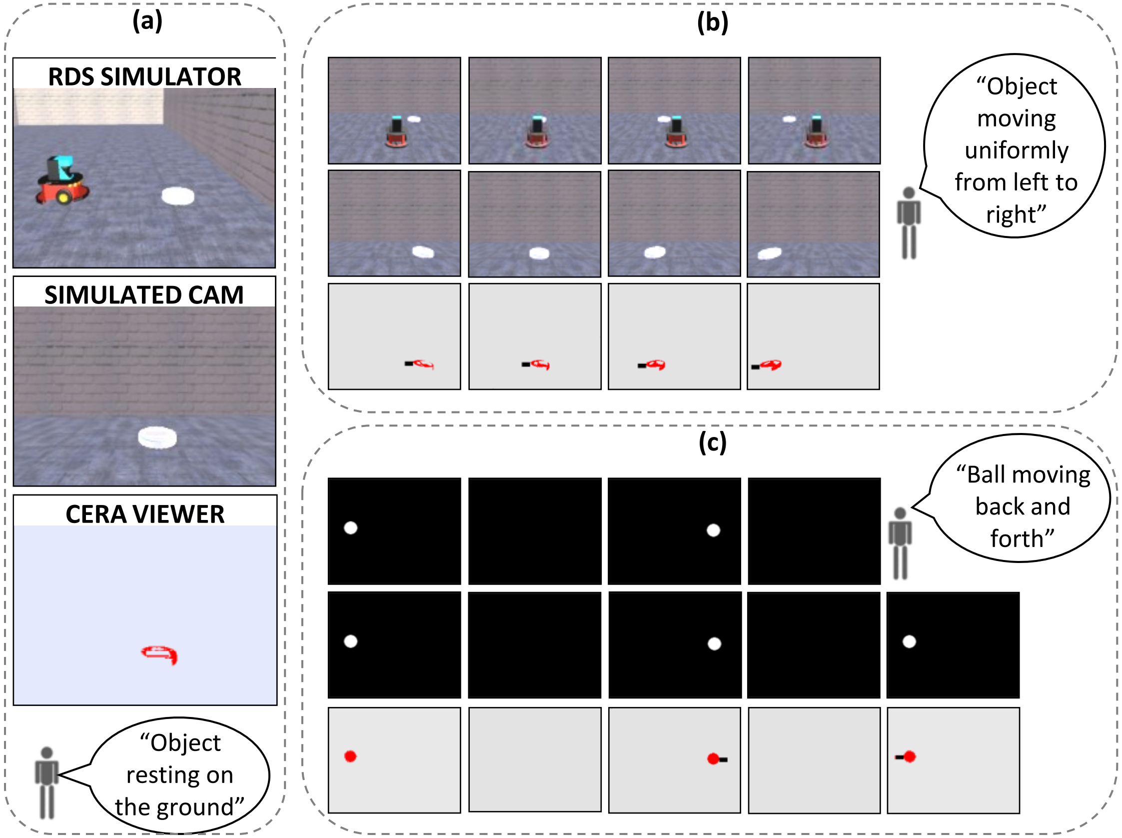
Visual Experience



- ❑ Three visual stimuli:
  - ❑ **S1**: Static white object resting on a dark background.
  - ❑ **S2**: White object moving along a linear trajectory.
  - ❑ **S3**: Two white stationary blinking dots.

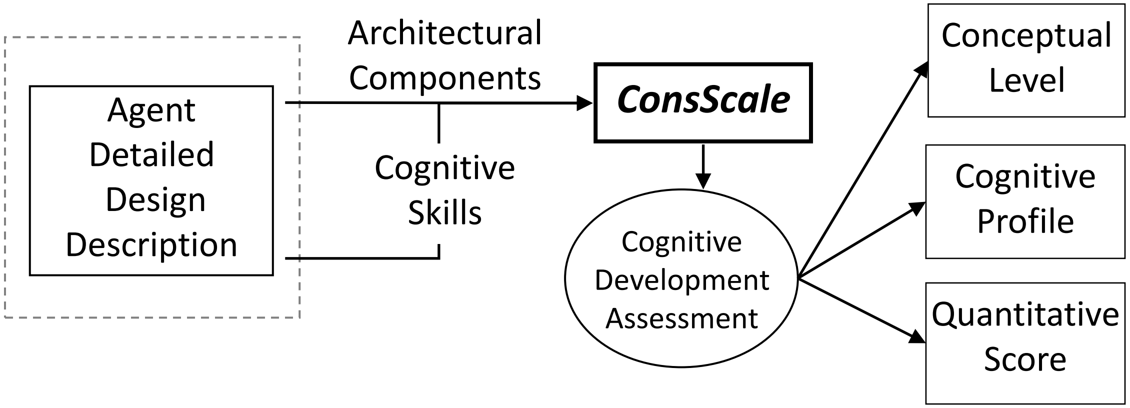
CERA-CRANIUM Observer

Results



Agent evaluation using *ConsScale*

Simplified Rating Process

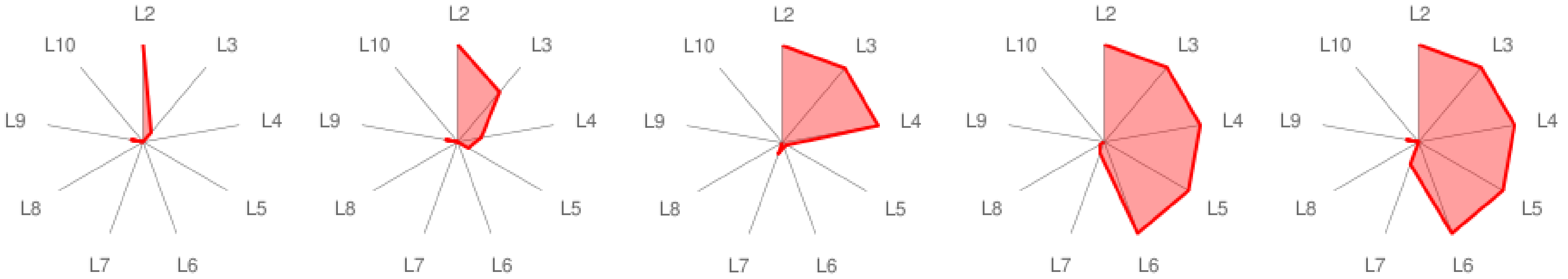


Agent evaluation using *ConsScale*

- ☐ **Eliza**. Conversational agent (Weizembaun, 1966).
- ☐ **CC-Bot1.** Adaptive agent fot UT2004 (Arrabales, 2009).
- ☐ **MAFI.** Minimal Architecture for Functional Imagination in CRONOS (Marques, 2009).
- ☐ **LIDA.** Cognitive architecture based on the GWT (Franklin, 2007).
- ☐ **Haikonen.** Haikonen cognitive architecture (Haikonen, 2007).

Agent evaluation using *ConsScale*

ELIZA	*CC-Bot1*	MAFI	LIDA	Haikonen
$cs_{2,1}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{9,3}$.	$cs_{2,1}$; $cs_{3,1}$; $cs_{3,2}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{3,6}$; $cs_{4,1}$; $cs_{4,5}$; $cs_{5,2}$; $cs_{5,4}$.	$cs_{2,1}$; $cs_{3,1}$; $cs_{3,2}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{3,6}$; $cs_{3,7}$; $cs_{4,1}$; $cs_{4,2}$; $cs_{4,3}$; $cs_{4,4}$; $cs_{4,5}$; $cs_{5,4}$; $cs_{6,4}$; $cs_{7,1}$; $cs_{7,2}$; $cs_{7,5}$; $cs_{7,6}$.	$cs_{2,1}$; $cs_{3,1}$; $cs_{3,2}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{3,6}$; $cs_{3,7}$; $cs_{4,1}$; $cs_{4,2}$; $cs_{4,3}$; $cs_{4,4}$; $cs_{4,5}$; $cs_{5,1}$; $cs_{5,2}$; $cs_{5,3}$; $cs_{5,4}$; $cs_{5,5}$; $cs_{5,6}$; $cs_{6,1}$; $cs_{6,2}$; $cs_{6,3}$; $cs_{6,4}$; $cs_{6,5}$; $cs_{6,6}$; $cs_{7,1}$; $cs_{7,2}$; $cs_{7,3}$; $cs_{7,6}$; $cs_{8,1}$.	$cs_{2,1}$; $cs_{3,1}$; $cs_{3,2}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{3,6}$; $cs_{3,7}$; $cs_{4,1}$; $cs_{4,2}$; $cs_{4,3}$; $cs_{4,4}$; $cs_{4,5}$; $cs_{5,1}$;$cs_{5,2}$; $cs_{5,3}$; $cs_{5,4}$; $cs_{5,5}$; $cs_{5,6}$; $cs_{6,1}$; $cs_{6,2}$; $cs_{6,3}$; $cs_{6,4}$; $cs_{6,5}$; $cs_{6,6}$; $cs_{7,1}$; $cs_{7,2}$; $cs_{7,3}$; $cs_{7,4}$; $cs_{7,8}$; $cs_{9,3}$.
CQS: **0.19** 2 (*reactive*)	CQS: **0.51** 2 (*reactive*)	CQS: **12.37** 4 (*attentional*)	CQS: **102.27** 6 (*emotional*)	CQS: **114.39** 6 (*emotional*)



Agent evaluation using *ConsScale*

ELIZA	***CC-Bot1***	**MAFI**	**LIDA**	**Haikonen**
$cs_{2,1}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{9,3}$.	$cs_{2,1}$; $cs_{3,1}$; $cs_{3,2}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{3,6}$; $cs_{4,1}$; $cs_{4,5}$; $cs_{5,2}$; $cs_{5,4}$.	$cs_{2,1}$; $cs_{3,1}$; $cs_{3,2}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{3,6}$; $cs_{3,7}$; $cs_{4,1}$; $cs_{4,2}$; $cs_{4,3}$; $cs_{4,4}$; $cs_{4,5}$; $cs_{5,4}$; $cs_{6,4}$; $cs_{7,1}$; $cs_{7,2}$; $cs_{7,5}$; $cs_{7,6}$.	$cs_{2,1}$; $cs_{3,1}$; $cs_{3,2}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{3,6}$; $cs_{3,7}$; $cs_{4,1}$; $cs_{4,2}$; $cs_{4,3}$; $cs_{4,4}$; $cs_{4,5}$; $cs_{5,1}$; $cs_{5,2}$; $cs_{5,3}$; $cs_{5,4}$; $cs_{5,5}$; $cs_{5,6}$; $cs_{6,1}$; $cs_{6,2}$; $cs_{6,3}$; $cs_{6,4}$; $cs_{6,5}$; $cs_{6,6}$; $cs_{7,1}$; $cs_{7,2}$; $cs_{7,3}$; $cs_{7,6}$; $cs_{8,1}$.	$cs_{2,1}$; $cs_{3,1}$; $cs_{3,2}$; $cs_{3,3}$; $cs_{3,4}$; $cs_{3,5}$; $cs_{3,6}$; $cs_{3,7}$; $cs_{4,1}$; $cs_{4,2}$; $cs_{4,3}$; $cs_{4,4}$; $cs_{4,5}$; $cs_{5,1}$;$cs_{5,2}$; $cs_{5,3}$; $cs_{5,4}$; $cs_{5,5}$; $cs_{5,6}$; $cs_{6,1}$; $cs_{6,2}$; $cs_{6,3}$; $cs_{6,4}$; $cs_{6,5}$; $cs_{6,6}$; $cs_{7,1}$; $cs_{7,2}$; $cs_{7,3}$; $cs_{7,4}$; $cs_{7,8}$; $cs_{9,3}$.
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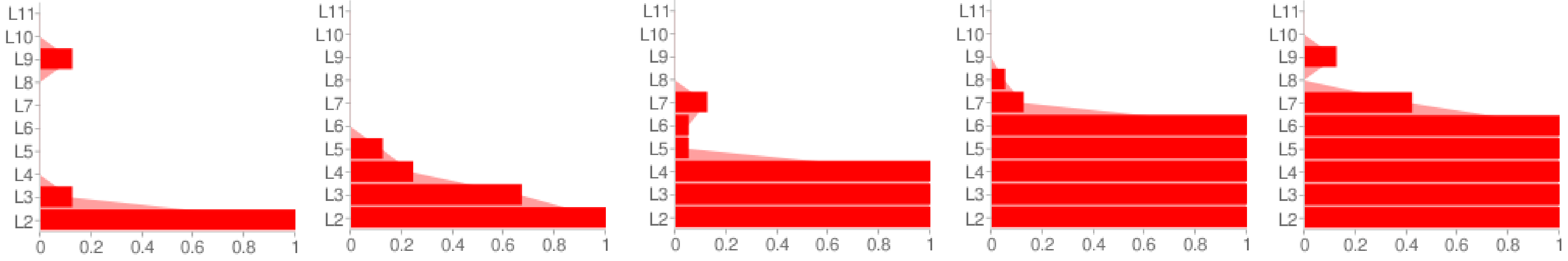
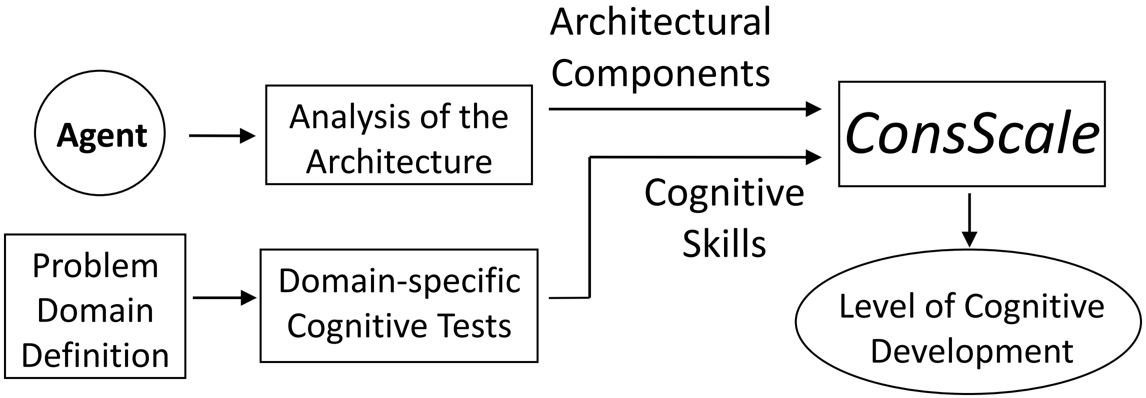
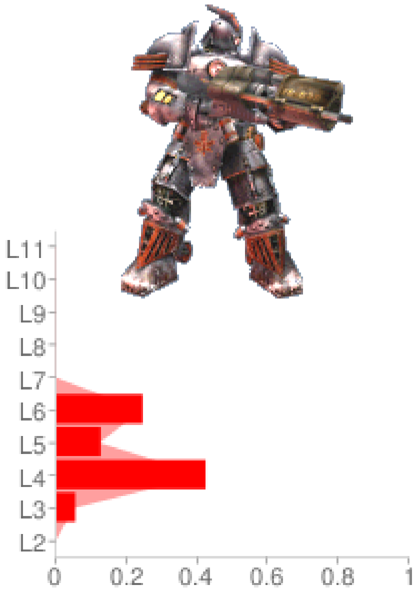


Agent evaluation using *ConsScale FPS*

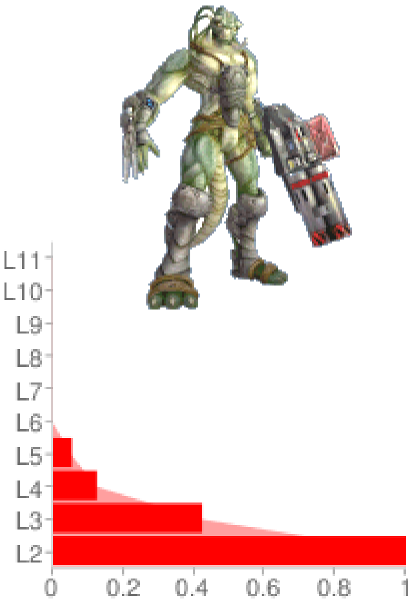
Standard Evaluation Process



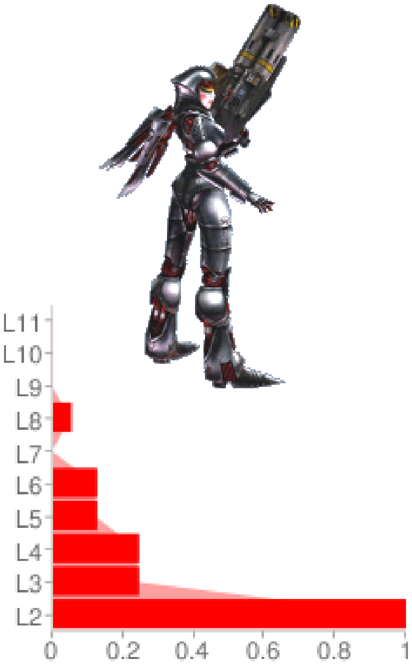
Agent evaluation using *ConsScale* FPS



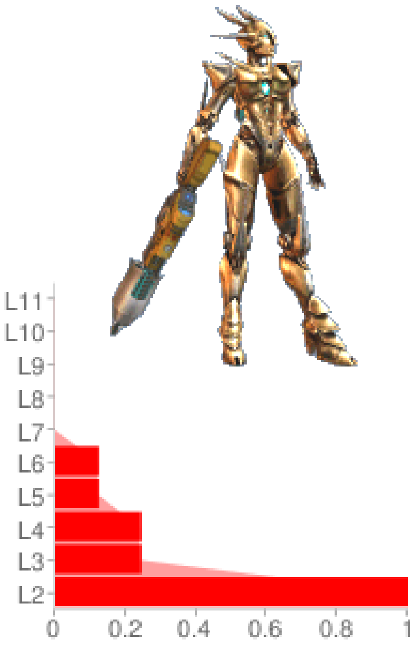
Discordia (CQS = 0.00)



ICE-2010 (CQS = 0.26)



UT^2 (CQS = 0.22)



CC-Bot2 (CQS = 0.22)

Contents

Conclusions

- ☐ Several cognitive functions associated with consciousness have been identified and integrated in an artificial architecture.
- ☐ Consciousness has been characterized as an integrative "super-function".
- ☐ A practical framework for the assessment of the level of consciousness of artificial agents has been proposed.

Conclusions

- ☐ CERA-CRANIUM application to:
  - ☐ Simple tasks (autonomous exploration and target following).
  - ☐ Human-like video game bots (2K BotPrize).
  - ☐ Synthetic phenomenology.
- ☐ *ConsScale* application to:
  - ☐ Assessment and comparison of models and implementations designed for different domains.

Conclusions

- ☐ We don't know yet what phenomenal states exactly are, however:
  - ☐ Artificial Qualia can contribute to the understanding of human consciousness.
  - ☐ Qualia have been functionally characterized proposing a model of consciousness as an integrator and self-regulating function.
- ☐ The heterophenomenology approach has been put in practice.
  - ☐ It is possible to characterize and measure the level of consciousness of artificial agents.

Future Work

☐ CERA-CRANIUM mechanisms:

- ✓ **Attention**
- ✓ **Global Access**
- ✓ **Preconscious Management**
- ✓ **Contextualization**
- ✓ **Self-Regulation**
- ☐ Self-state Assessment
- ☐ Sensorimotor Prediction
- ☐ Long Term Memory Management
- ☐ Learning Mechanisms
- ☐ Verbal Mental State Report

Future Work

- ☐ To enhance the experimentation in synthetic phenomenology with more complex stimuli and better representation mechanisms.
- ☐ To improve the believability of CC-Bot.
- ☐ To refine the definition of *ConsScale* and to use it in other problem domains.
- ☐ To use *ConsScale* as a roadmap.

Consciousness in Artificial Cognitive Systems

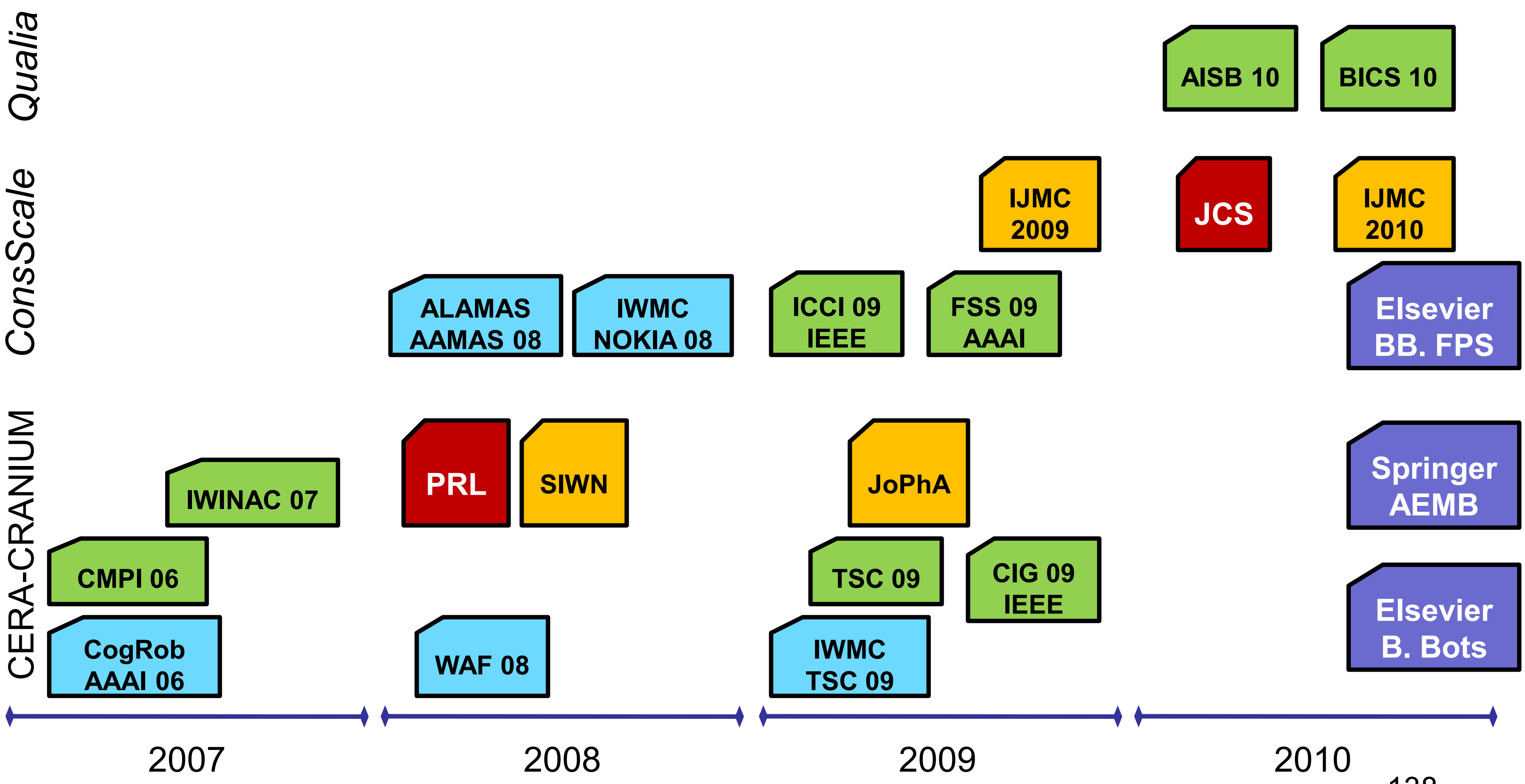
JCR

Book Ch.

Journal

Conf.

Workshop



Qualia

AISB 10

BICS 10

ConsScale

IJMC 2009

JCS

IJMC 2010

ALAMAS AAMAS 08

IWMC NOKIA 08

ICCI 09 IEEE

FSS 09 AAAI

Elsevier BB. FPS

CERA-CRANIUM

IWINAC 07

PRL

SIWN

JoPhA

Springer AEMB

CMPI 06

TSC 09

CIG 09 IEEE

Elsevier B. Bots

CogRob AAAI 06

WAF 08

IWMC TSC 09

2007

2008

2009

2010

Thank you for your attention

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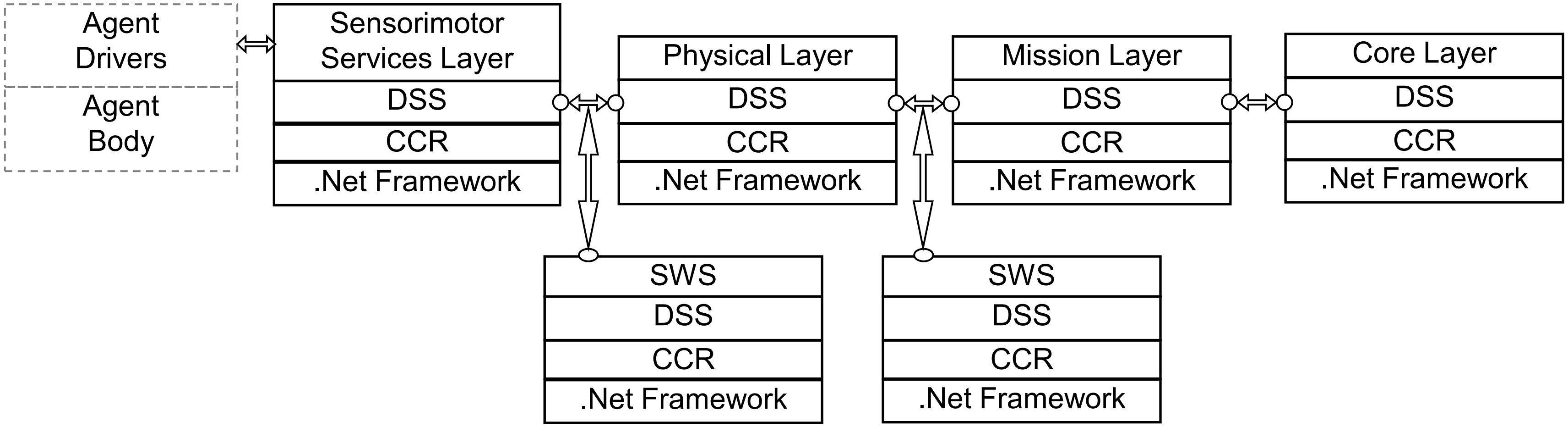
ANNEXES

Additional Slides

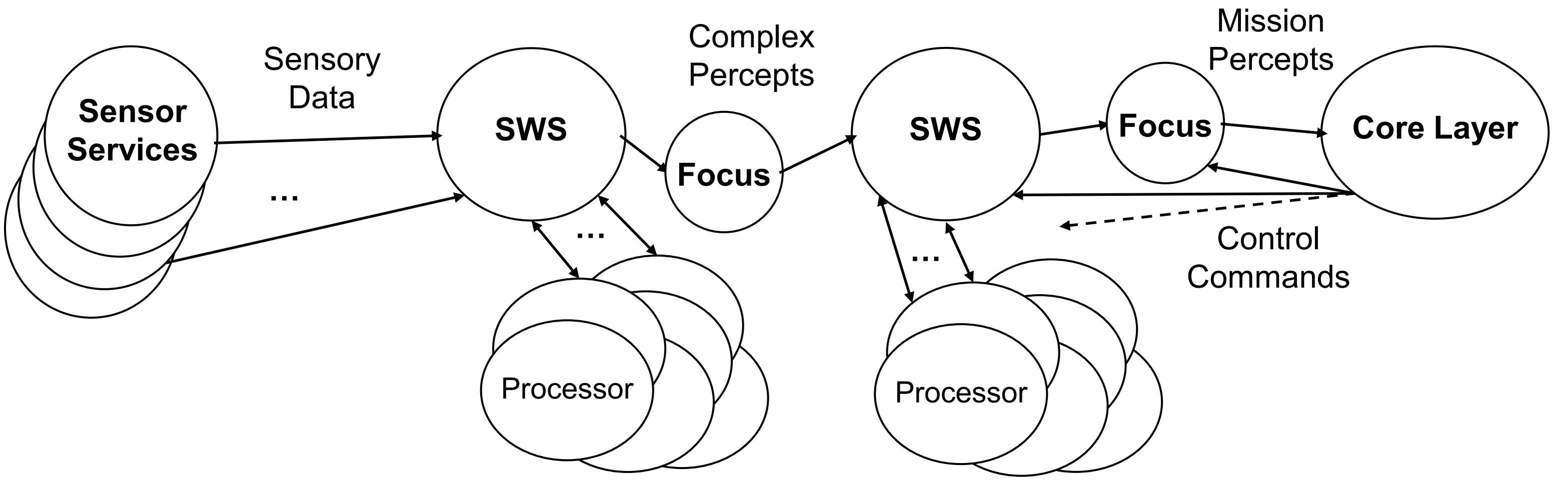
CERA-CRANIUM

- ☐ Software Architecture
  - ☐ Based on *Robotics Developer Studio*



CERA-CRANIUM

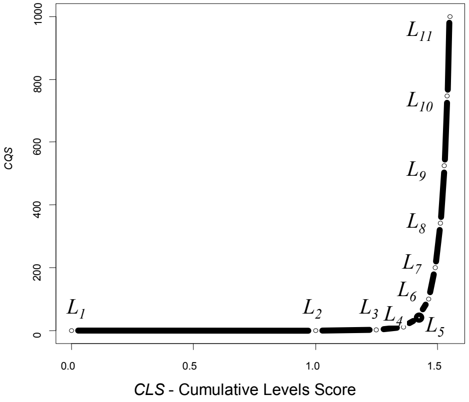
- ❑ Software Architecture
  - ❑ Service-Oriented Architecture



Consciousness in Artificial Cognitive Systems

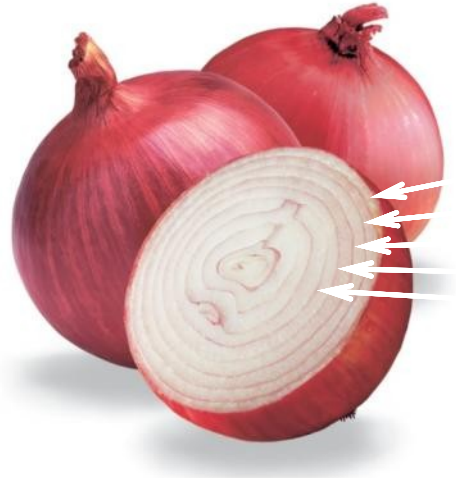
Calculation of *a* and *K*

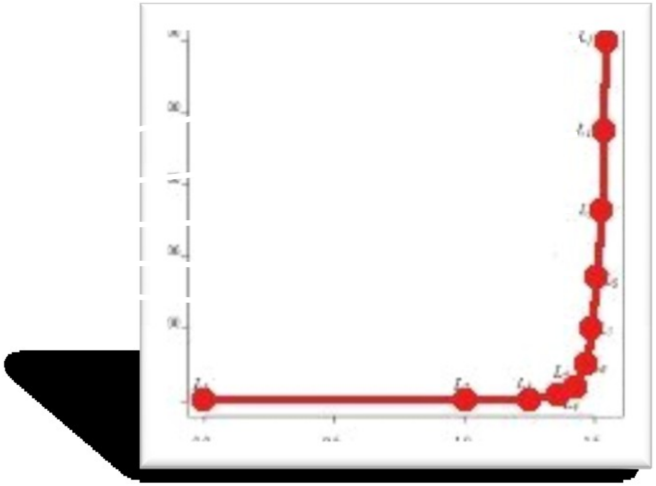
$$\left\{ \begin{array}{l} \dfrac{e^{0/K}+a}{10}=0 \\ \dfrac{e^{c^5/K}+a}{10}=1000 \end{array} \right\}$$



ConsScale as a Roadmap

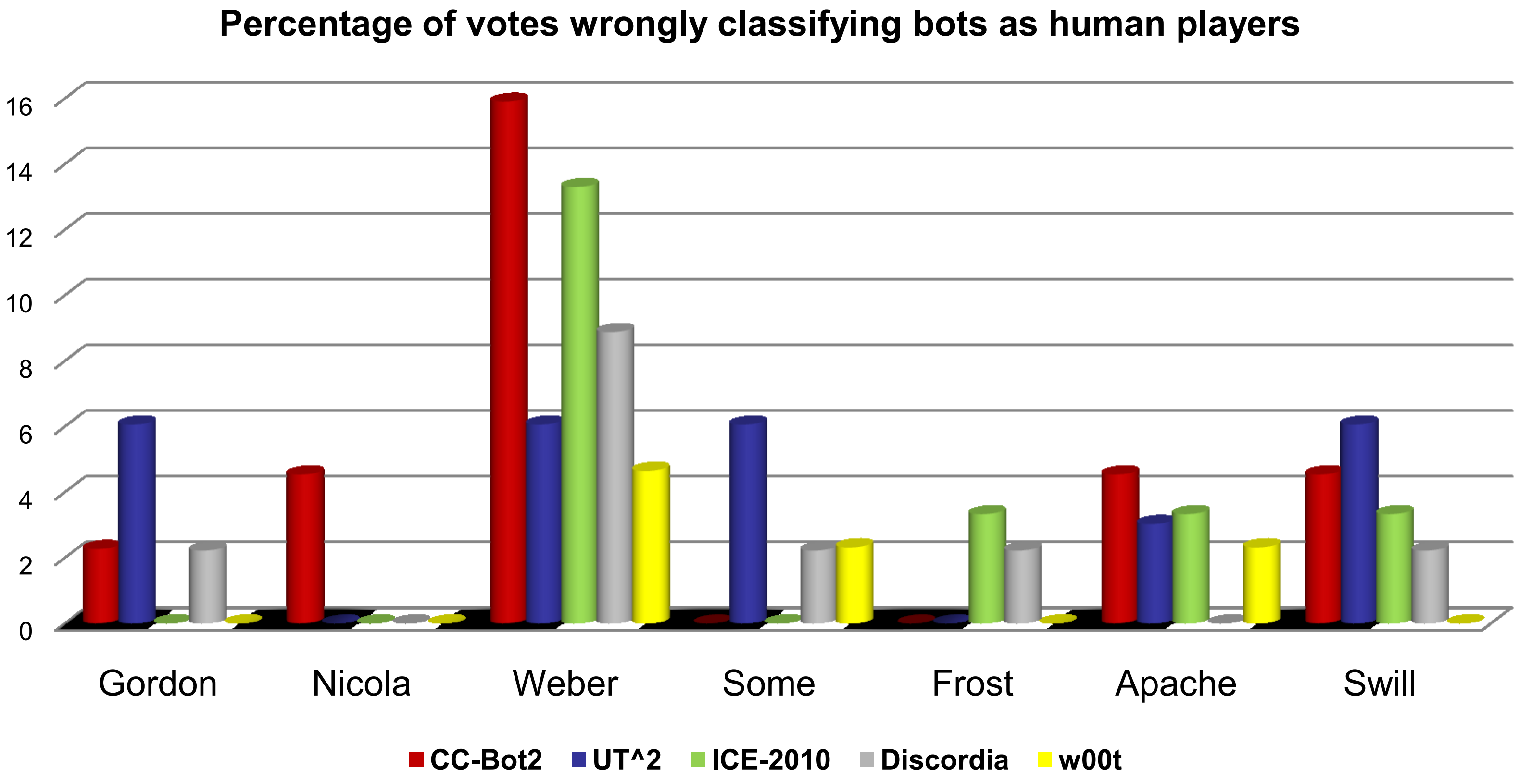
- ☐ Consciousness in an integrator.
- ☐ Inspired by evolution and development.
- ☐ Cognitive functions are considered synergistically. Cognitive dependency.



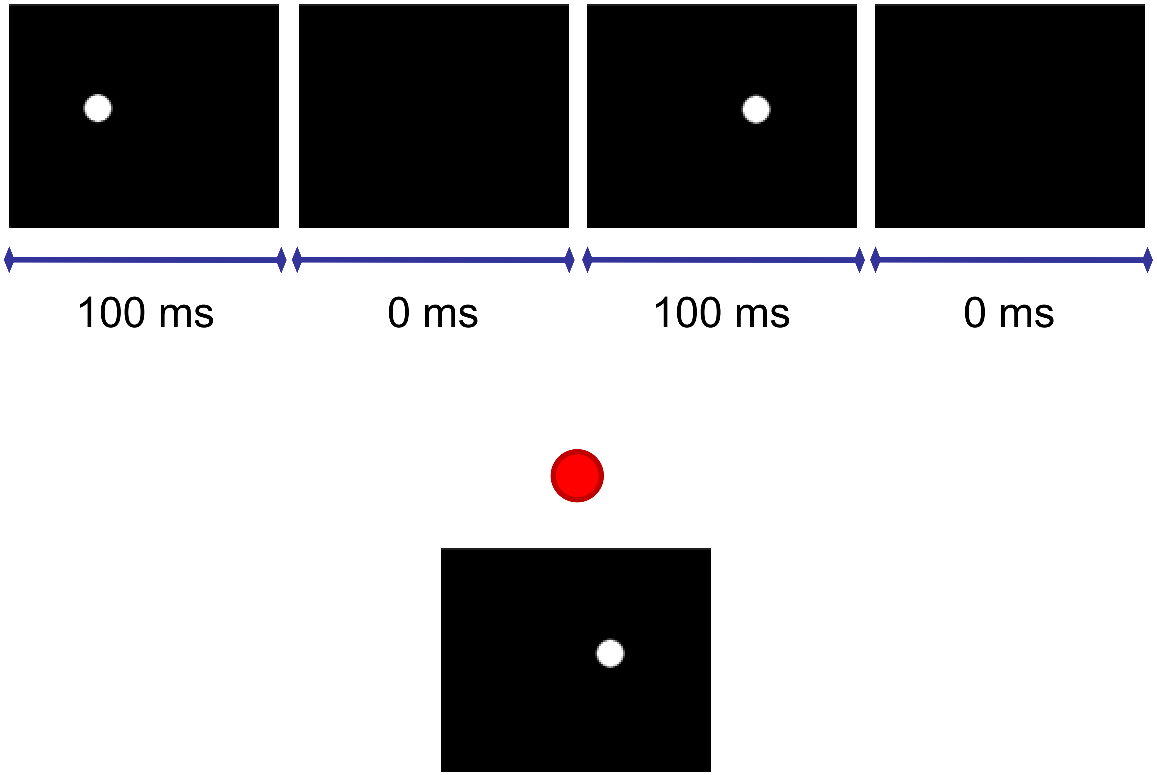


CERA-CRANIUM Bot

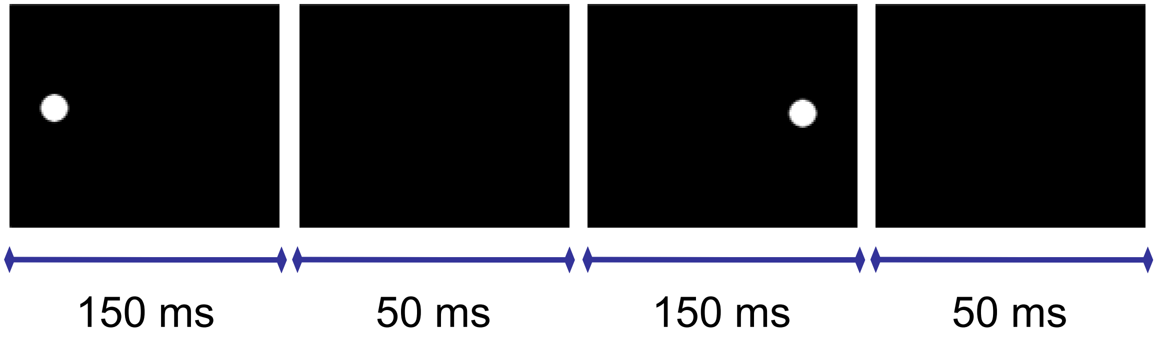
2k BotPrize 2010 Judging Results

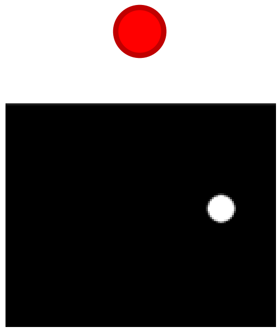


Aplicación a la Experiencia Visual



Aplicación a la Experiencia Visual





Consciousness in Artificial Cognitive Systems

CERA-CRANIUM Observer

Synthetic Phenomenology