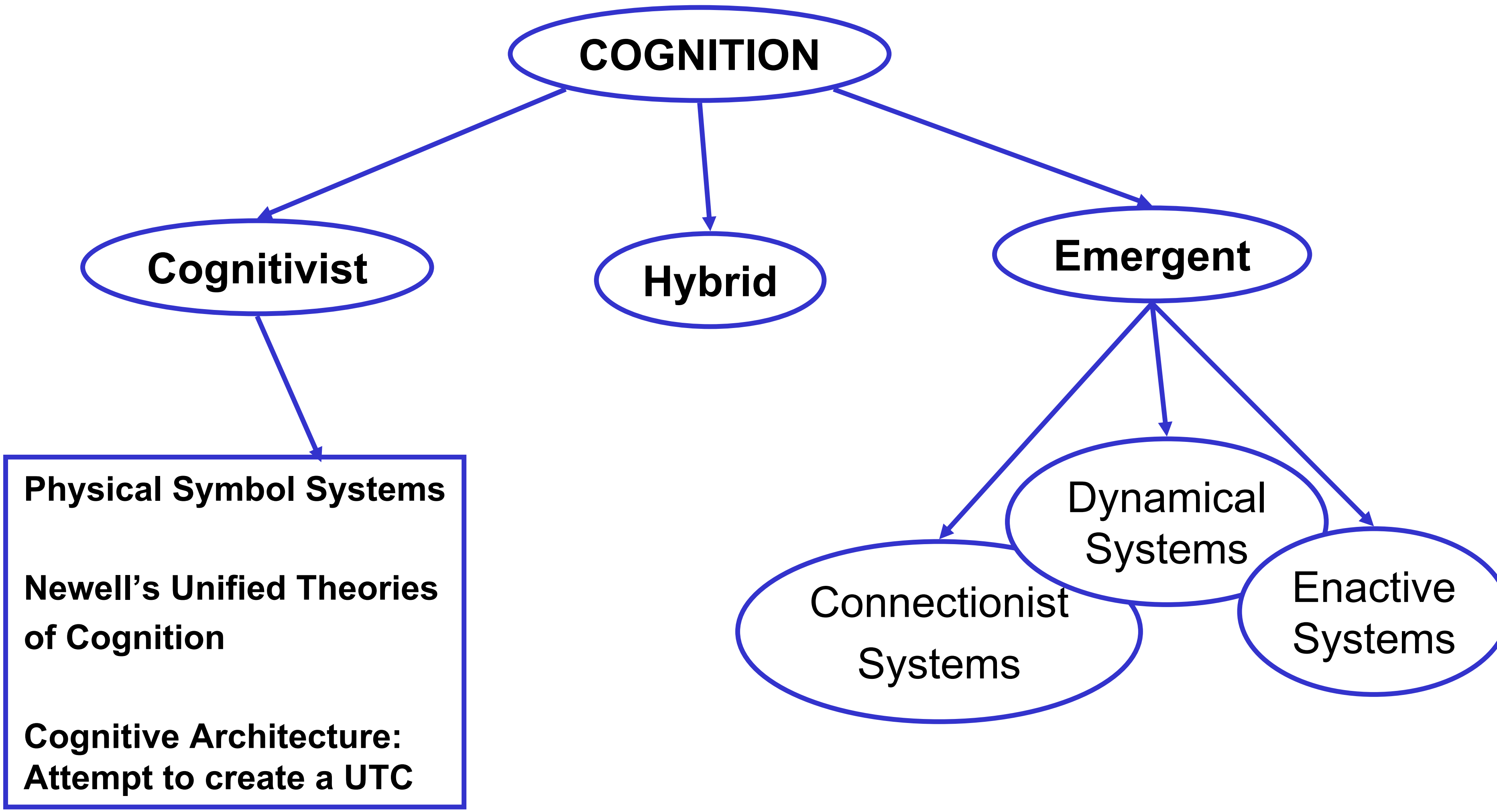
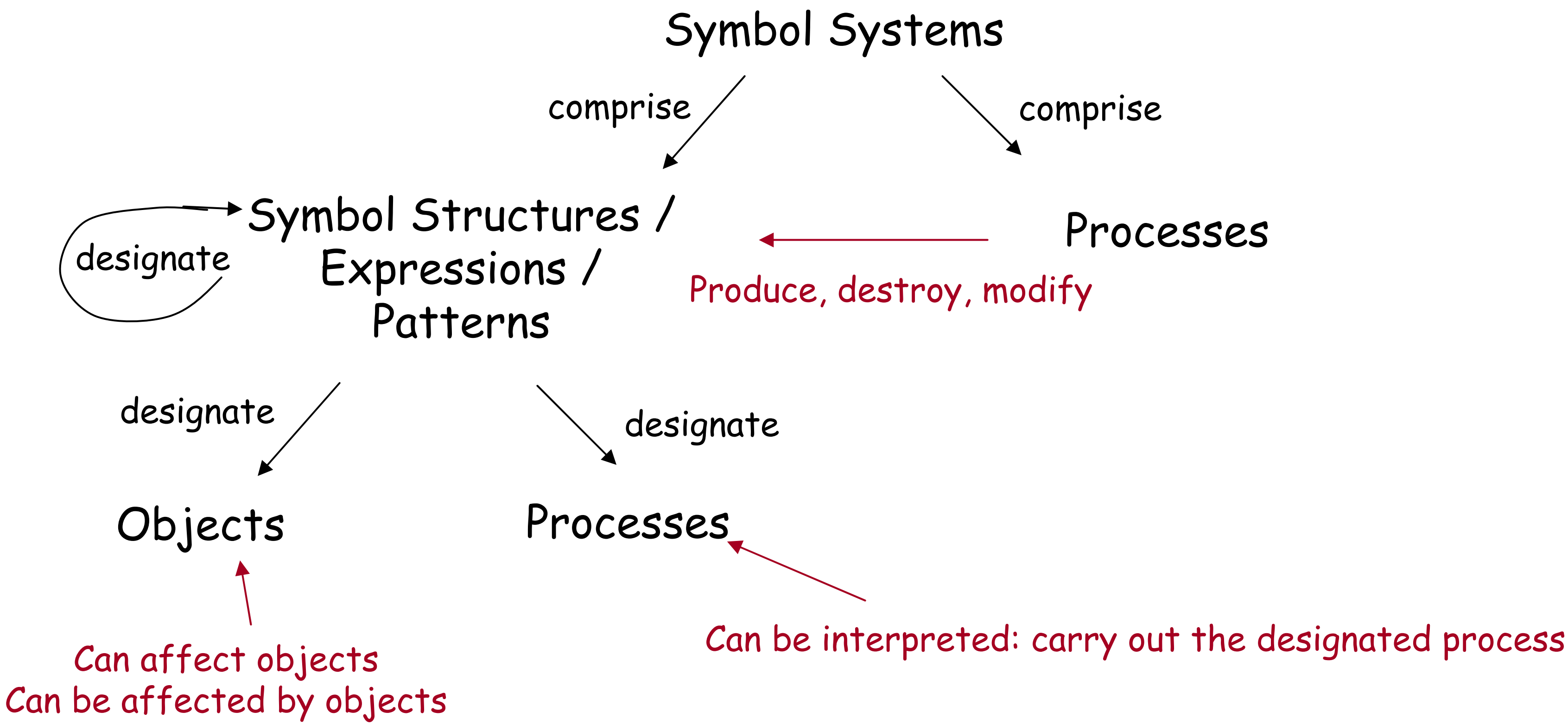
Cognitive Architectures


COGNITION
Cognitivist
Hybrid
Emergent
Physical Symbol Systems
Newell's Unified Theories of Cognition
Cognitive Architecture: Attempt to create a UTC
Dynamical Systems
Connectionist Systems
Enactive Systems

Cognitive Architecture

- Physical Symbol Systems [Newell and Simon 1975]



Cognitive Architecture

UTC (i.e. theories covering a broad range of cognitive issues)

- Attention
- Memory
- Problem solving
- Decision making learning
- …

from several aspects

- Psychology
- Neuroscience
- computer science
- …

[Byrne 03]

Cognitive Architecture

An embodiment of a scientific hypothesis about those aspects of human cognition that are

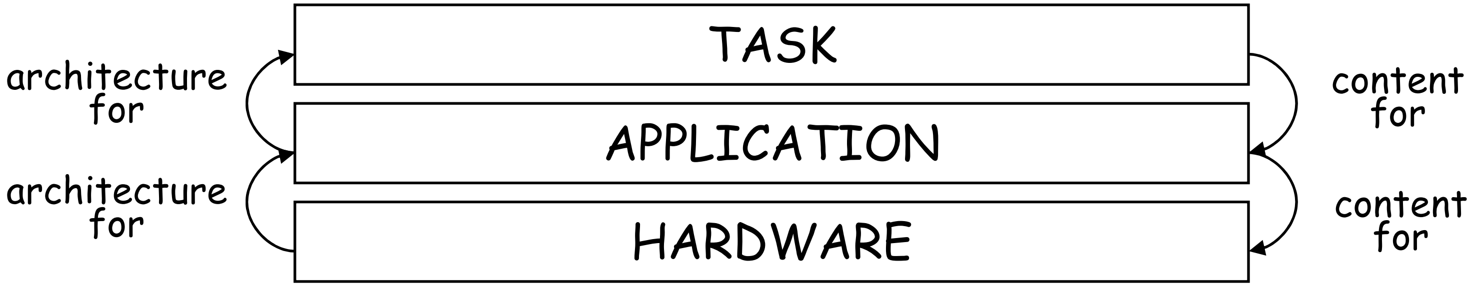
relatively constant over time and

relatively independent of task

[Ritter & Young 01]

Cognitive Architecture

- Theory of the fixed set of mechanisms and structures
- Needs content to get behaviour



BEHAVIOR = ARCHITECTURE X CONTENT

Factor out what's common across cognitive behaviours across the phenomena explained by micro-theories

Lehman et al 97, also Anderson & Labiere 98, Newell 90

Cognitive Architecture

Computational Infrastructure

- Constant across different domains
- Constant across different knowledge bases

Commitment to formalisms for

- Short-term & long-term memories that store the agent's beliefs, goals, and knowledge
- Representation & organization of structures embedded in memory
- Functional processes that operate on these structures
  - Performance / utilization
  - Learning
- Programming language to construct systems embodying the architectures assumptions

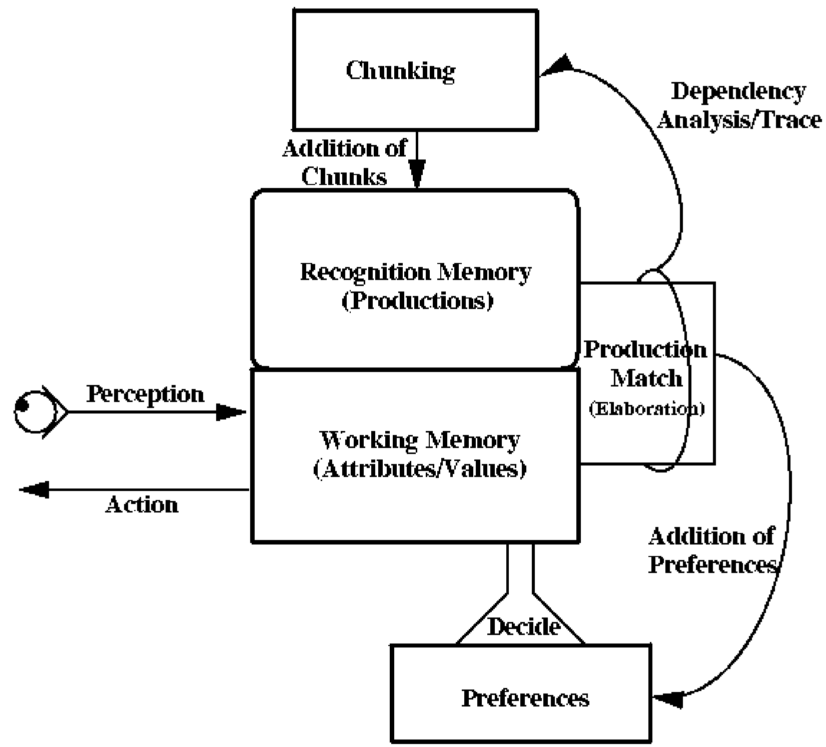
[Langley 05, Langley 06]

Cognitive Architecture	Embodiment	Perception	Action	Anticipation	Adaptation	Motivation	Autonomy
Cognitivist							
Soar				+	+		
Epic		+	+	+			
ACT-R		+	+	+	+		
ICARUS		+	+	+	×		
ADAPT	×	×	×	+	+		
GLAIR		+	+		+		+
CoSy		+	+		+	+	
Emergent							
AAR	×	×	×			+	×
Global Workspace	+	+	+	×		×	×
I-C SDAL	+	+	+	+	+	×	×
SASE	×	×	×	+	×	×	×
Darwin	×	×	+		+	×	×
Cognitive-Affective	×	×	×	×	×	×	×
Hybrid							
HUMANOID	×	×	×	+	+	+	
Cerebus	×	×	×	+	+		
Cog: Theory of Mind	×	×	×	+			
Kismet	×	×	×			×	
LIDA	+	+	+	×	×	+	+
CLARION		+	+	×	×	+	+
PACO-PLUS	×	×	×		×		

Cognitive Architectures

Soar [Newell 96]

- (sitemaker.umich.edu/soar)
- Newell's candidate UTC
- 1983 – 2005 … (v 8.5)
- Production system
- Cyclic operation
  - Production firing (all)
  - Decision (cf preferences)
- Fine-grained knowledge representation
- Universal sub-goaling (dealing with impasse)
- General-purpose learning (encapsulates resolution of impasse)

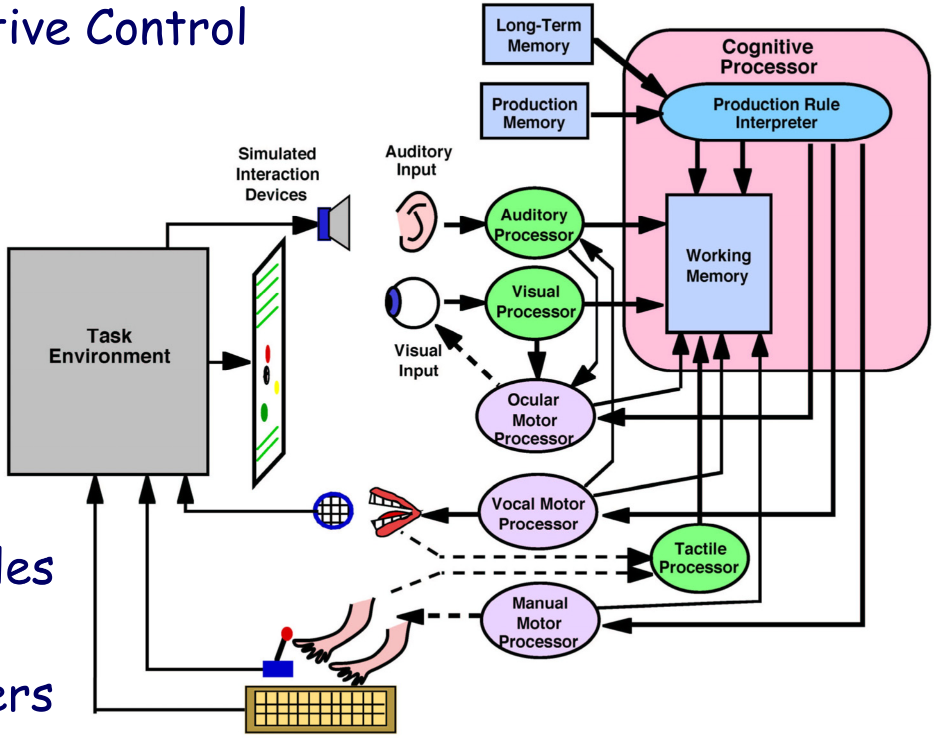


(Based on Figure 3.1, pg 20, The Soar's User Manual, Version 6)

Cognitive Architectures

EPIC [Kieras & Meyer 97]

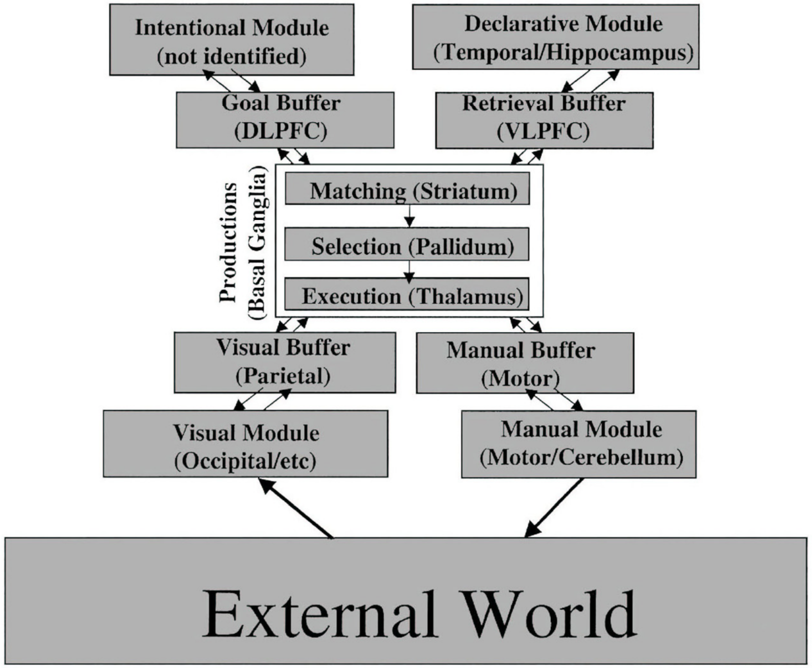
- Executive Process Interactive Control
- Link high-fidelity models of perception and motor mechanisms with a production system
  - Only the timing!
- Knowledge in production rules
- Perceptual-motor parameters
- All processors run in parallel
- No learning



Cognitive Architectures

ACT-R 5.0 [Anderson et al. 04]

- Adaptive Character of Thought [96]->
- Adaptive Control of Thought-Rational [04
- Production system
- Execute on production per cycle
  - Arbitration
- Declarative memory
  - Symbols (cf. Soar)
  - Activation values
  - Probability of reaching goal
  - Time cost of firing
  - Combined to find best trade-off

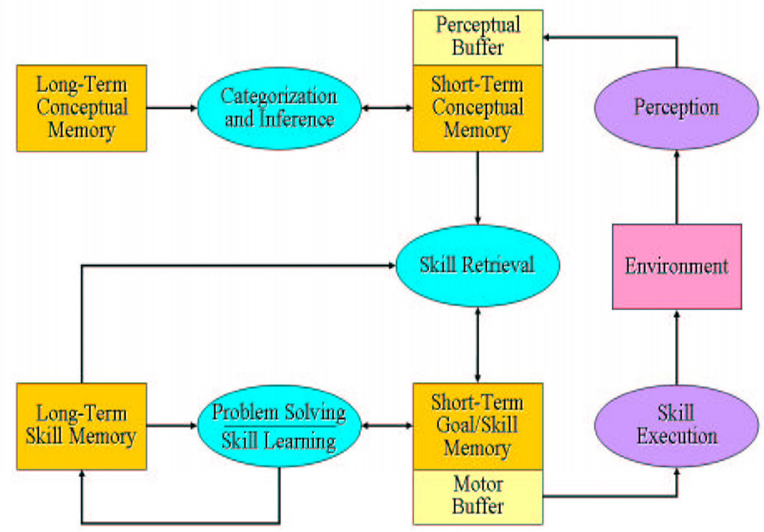


- Activation based on Bayesian analysis of probability of invocation
- Learning ('Rational Analysis')
  - Includes sub-symbolic:
    P(Goal), C(fire), Activation level, context association

Cognitive Architectures

ICARUS [Langley 05, Langley 06]

- Cognition is grounded in perception and action
- Concepts and skills are distinct cognitive structures
- Skill and concept hierarchies are acquired cumulatively
- Long-term memory is organized hierarchically
- LT & ST structures have a strong correspondence
- Symbolic cognitive structures are modulated with numeric functions



Cognitive Architectures

BUT …

"Cognitive architectures do not easily support certain paradigms of perception and control that are mainstream in robotics [such as] adaptive dynamics and active perception"

[Benjamin et al. 04]

Cognitive Architectures

Robots are distributed systems; multiple sensory, reasoning, and motor control processes

- run in parallel
- loosely-coupled
- separate limited representation of the world and task

Not realistic to constantly synchronize them with a central knowledge base

[Horswill 01]

Cognitive Architectures

ADAPT [Benjamin et al. 04]

- Adaptive Dynamics & Active Perception for Thought
- Production-based with working memory (cf. Soar)
- Declarative memory for sensory-motor schemas (cf. ACT-R)
- Processors operate in parallel (cf. EPIC)
  - Place low-level sensory data in working memory
- 2 Types of GOALS:
  1. Task goals (find blue block)
  2. Architecture goals (start schema to scan scene)
- 2 Types of ACTIONS:
  1. Task action (pick up blue block)
  2. Architecture goals (start grasp schema)

Many goals & many actions (schemas)

1 goal and 1 action represented procedurally (productions)

Cognitive Architectures

Cerebus [Horswill 06]

- Scale behaviour-based robots to higher-level cognitive tasks WITHOUT a traditional planning system

    1. Behaviour-based sensory-motor system
    2. Marker-passing semantic network
    3. Inference network
    4. Parser

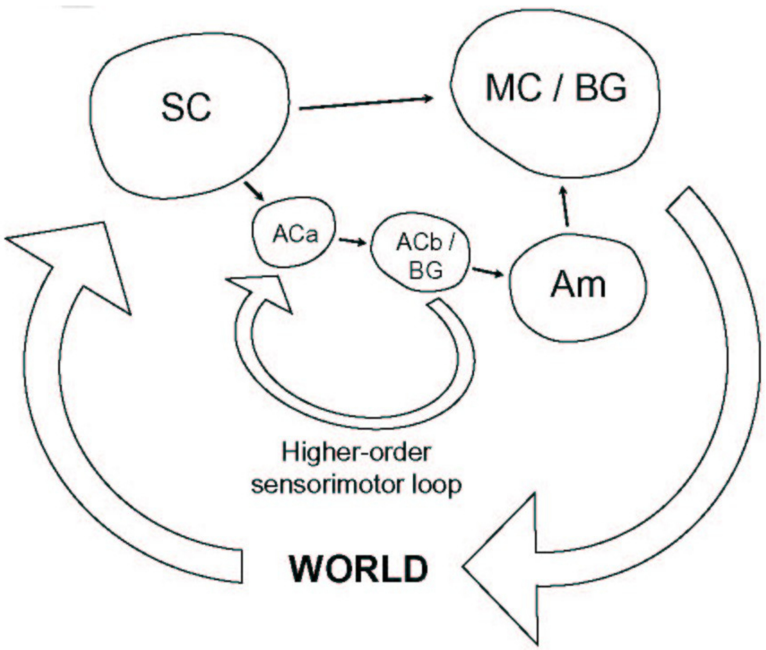
- Implements reflective knowledge: knowledge of its own structure and capabilities and the ability to reason about its capabilities

Cognitive Architectures

Shanahan's Global Workspace Architecture

[Shanahan06,ShanahanBaars06,Shanahan05a,Shanahan05b]

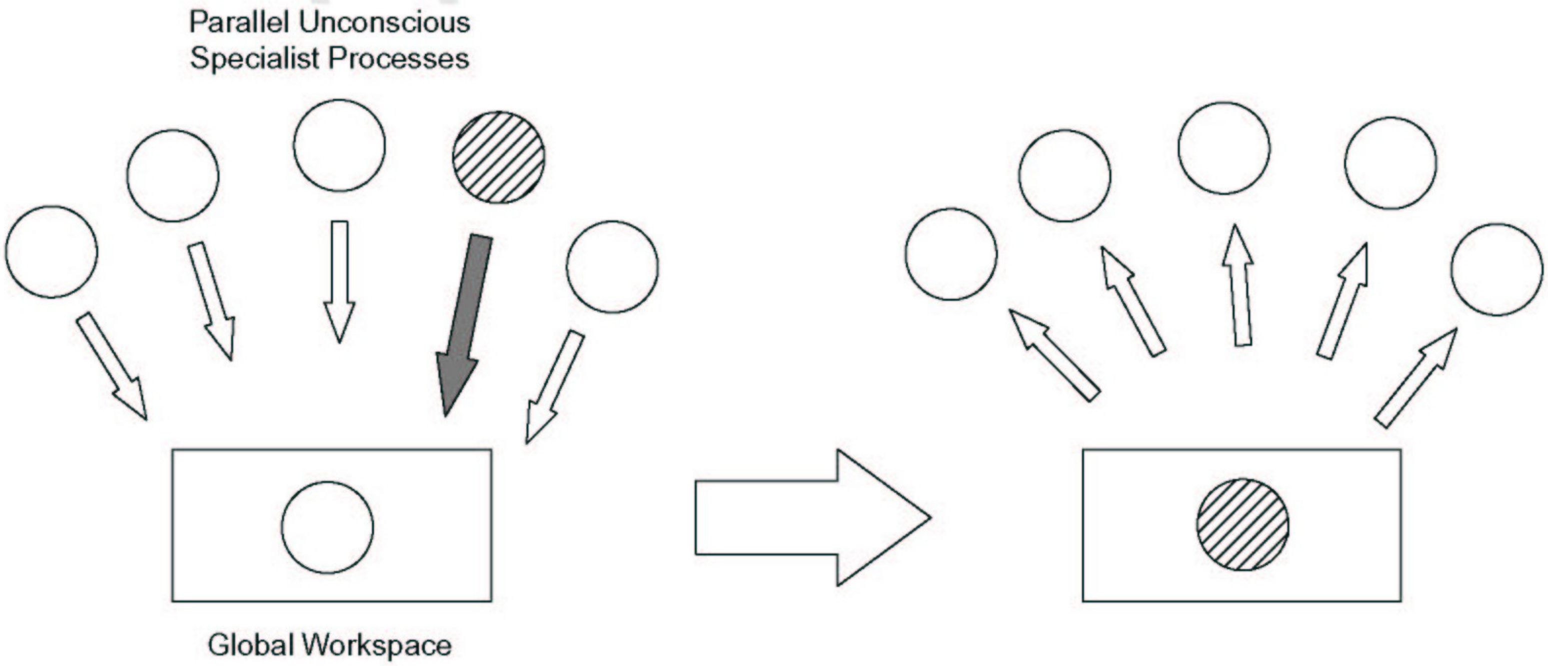
- Anticipation and planning achieved through internal simulation
- Action selection (internal and external) mediated by affect
- Analogical representation (-> small semantic gap & easier grounding)
- Global workspace model: parallelism is a fundamental component of the architecture, not an implementation issue



SC Sensory Cortex
MC Motor Cortex
BG Basal Ganglia (action selection)
AC Association Cortex
Am Amygdala (affect)

Cognitive Architectures

Global workspace model: sequence of states emerge from multiple competing and cooperating parallel processes

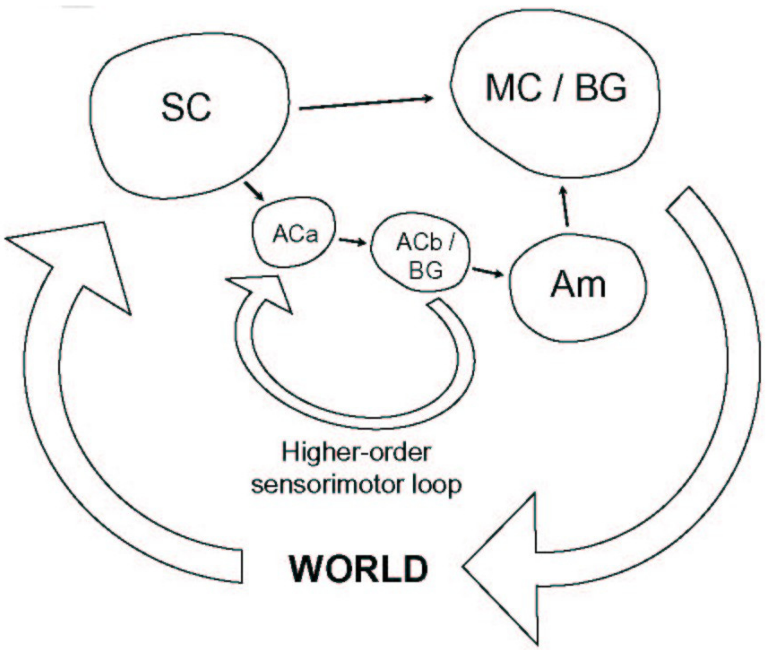


Cognitive Architectures

Shanahan's Global Workspace Architecture

[Shanahan06,ShanahanBaars06,Shanahan05a,Shanahan05b]

- Implemented using G-RAMS (generalized random access memories)
- Global workspace and cortical assemblies define an attractor landscape
- Perceptual categories define attractors
- Higher-order loop allows the GW to visit these attractors



SC Sensory Cortex
MC Motor Cortex
BG Basal Ganglia (action selection)
AC Association Cortex
Am Amygdala (affect)

Still Problems!!!

Architectures not focussed on development in the sense of the gradual acquisition of cognitive skills over an extended period

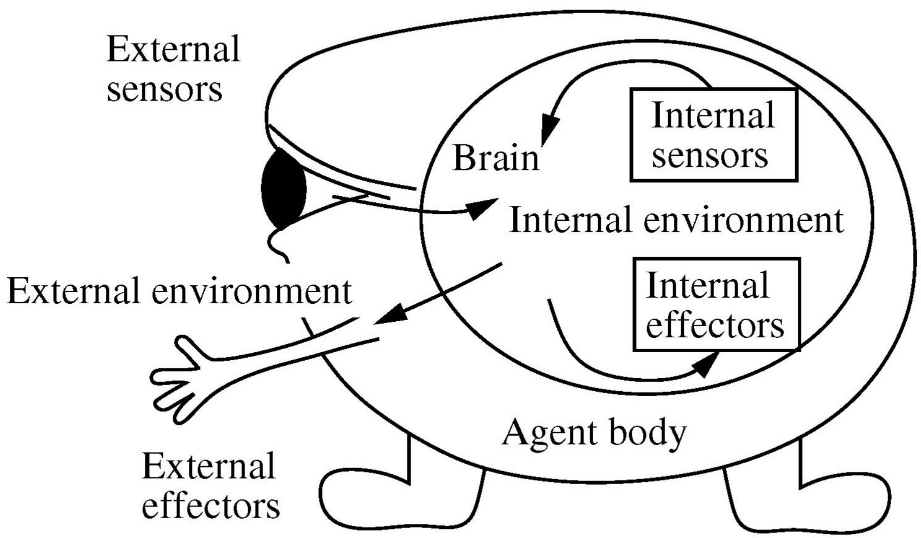
[Weng 02, Weng & Zhang 02, Weng 04a, Weng 04b]

(but also consider Anderson 04 / ACT-R 5.0)

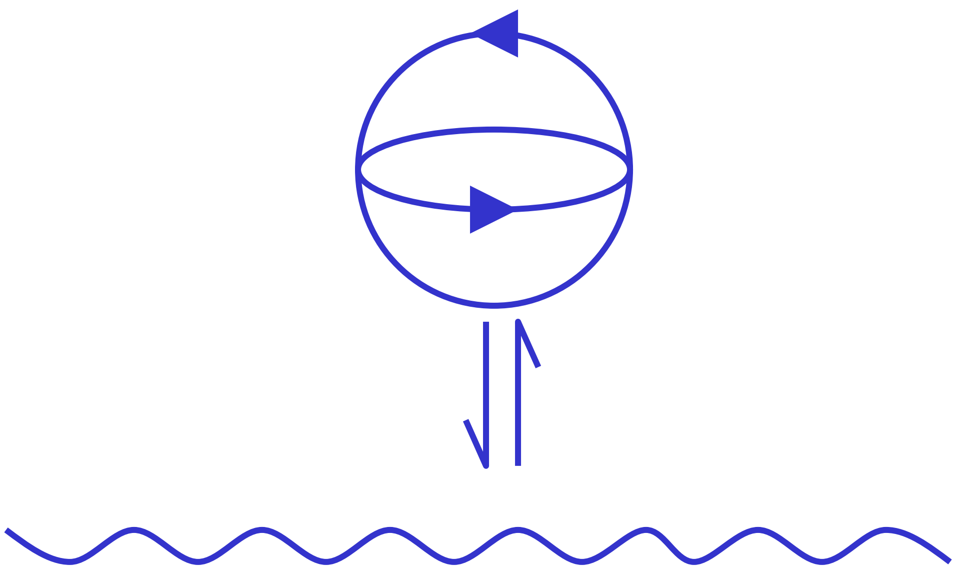
Cognitive Architectures

AMD Autonomous Mental Development
[Weng et al. 01, Weng 02,
Weng & Zhang 02, Weng 04a, Weng 04b]

Self-aware self-effecting (SASE) agent



Enactive Cognition



Cognitive system: operationally-closed system with a nervous system;

Nervous system perturbed by both environment and system (of receptors & NS)

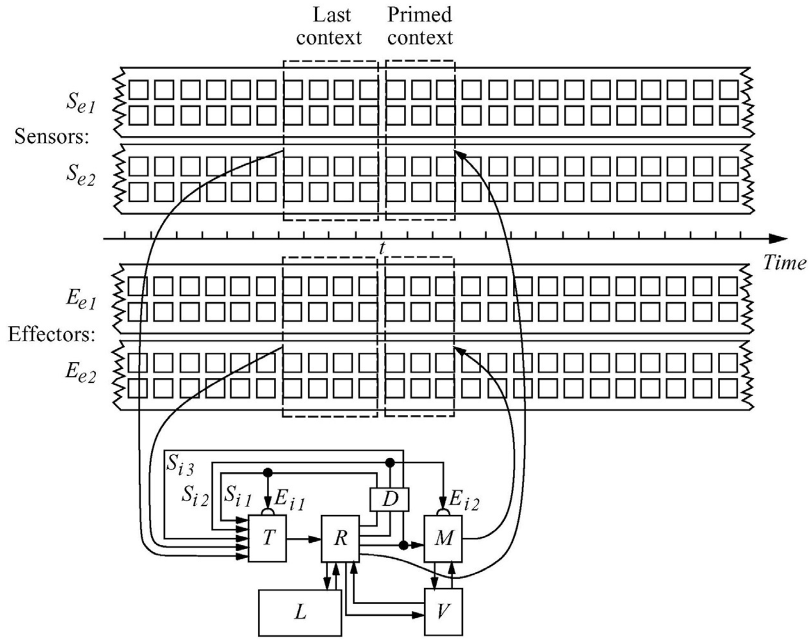
Level 2 Autopoiesis implies the facility to self-modify [Maturana & Varela 87]

Recursive self-maintenance [Bickhard 00]

Cognitive Architectures

Theory of Developmental Architecture [Weng 04b]

- Progression of 6 types of architecture (based on Markov Decision Process MDP)
- Type 4: Observation-driven SASE MDP
- Type 5: Developmental observation-driven SASE MDP: DOSASE MDP



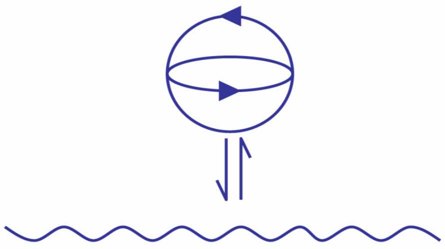
Cognitive Architecture for Developmental Systems

Krichmar's Design Principles for Developmental Systems

1. Address connectivity and interaction between circuits/regions in the brain
2. Effect perceptual categorization, without a priori knowledge (a model generator, rather than a model fitter, cf [Weng 04])
3. Embodied & capable of exploration
4. Minimal set of innate behaviours
5. Value system (set of motivations) to govern development

Each with own limited encodings

Network of cooperating/competing circuits



Learning: to tune phylogenetic skills

Development: change system dynamics new action spaces

Self-modification

Model Generation

Cognitive Architecture

implies some phylogenetic configuration

Exploratory motives

Novel regularities in the world

Potential of own actions

agent interaction: mutually-constructed patterns of behaviour

Social motives

Unsupervised

Supervised

Reinforcement

Learning

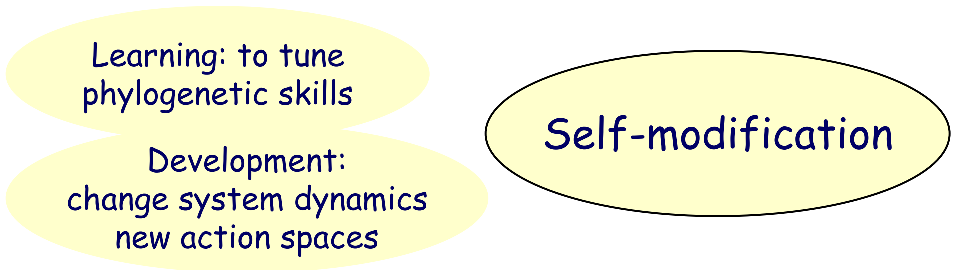
Moderate actual behaviour

Mechanism to rehearse hypothetical scenarios

Action-Perception Couplings

Embodiment

Key Issue:
Development



- Improve the predictive performance
- Increase the space of viable actions

Key Issue:
Internal Simulation

Three purposes of internal simulation:

1. Prediction: future events

   Moderate actual behaviour

   Mechanism to rehearse hypothetical scenarios

2. Reconstruction: explaining observed events (imagining a causal chain leading to that event)

3. Imagination: internal simulation as a way of imagining new ideas

Key Issue:
Exogenous and Endogenous

Exogenous: curiosity

Novel regularities in the world

Potential of own actions

Exploratory motives

Sensori-motor learning

Endogenous: experimentation

Experience-based *generative* development & operation

ENACT

A Cognitive Architecture for the iCub Humanoid Robot

"It's better to lay a single brick than to draw up plans that are too great"

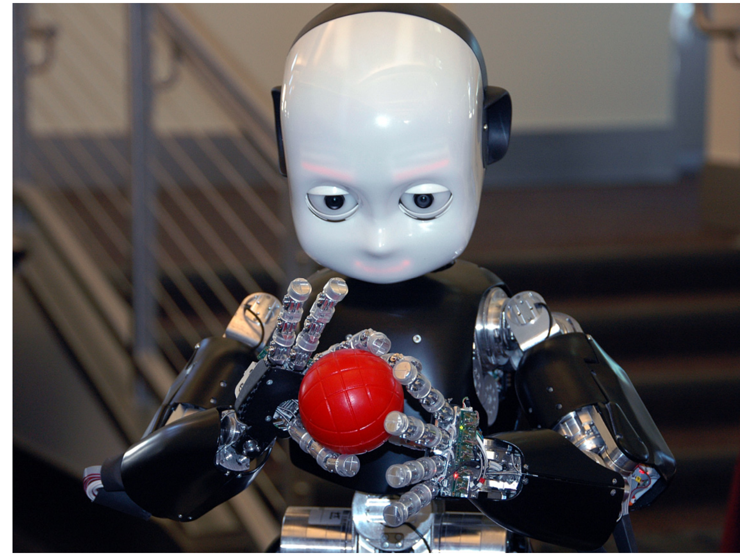
Alquist in R.U.R. (Rossum's Universal Robots), Karel Čapek, 1921

iCub.org

an open source cognitive humanoid robotic platform

iCub

Open-Systems Platform

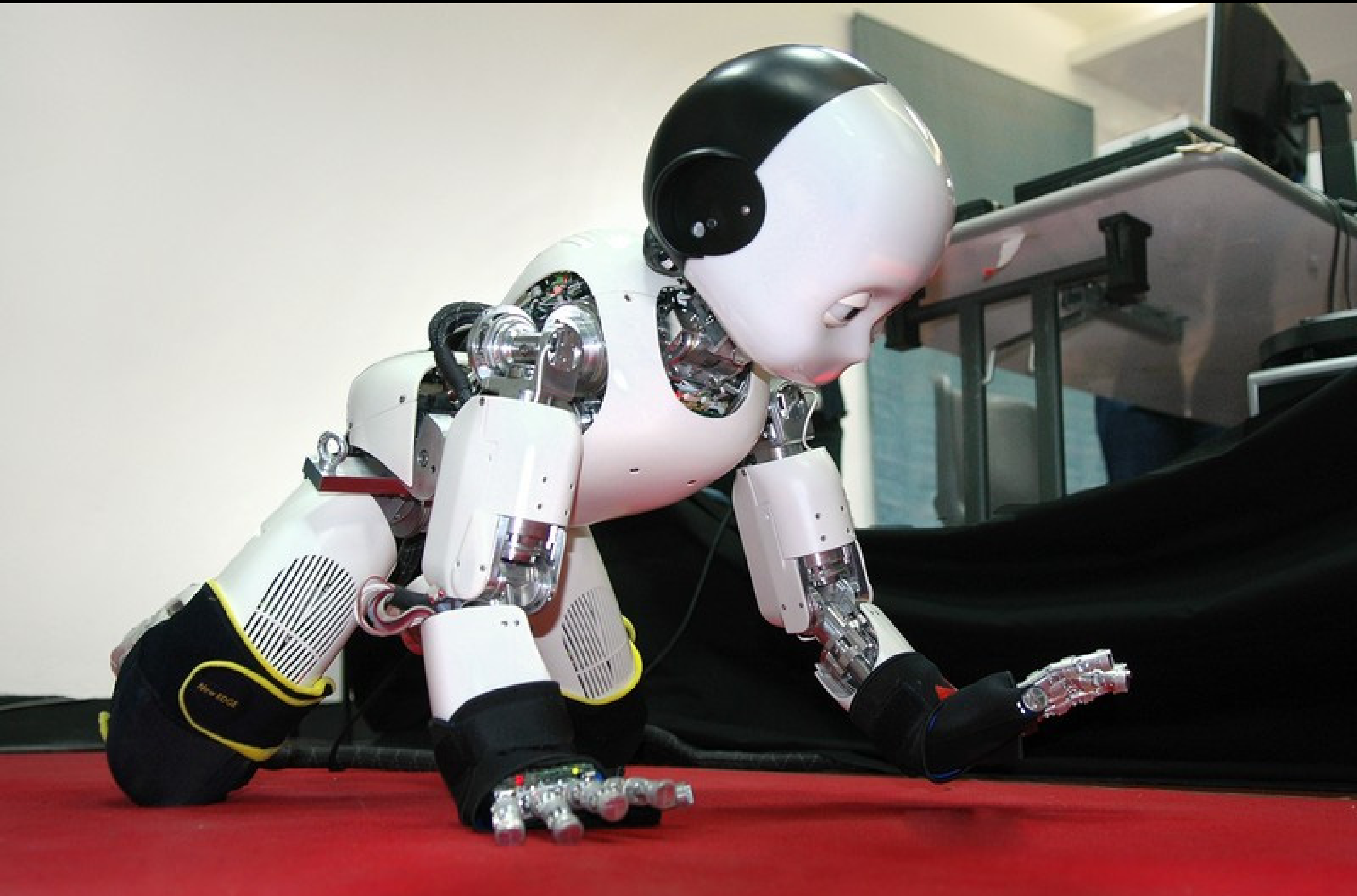


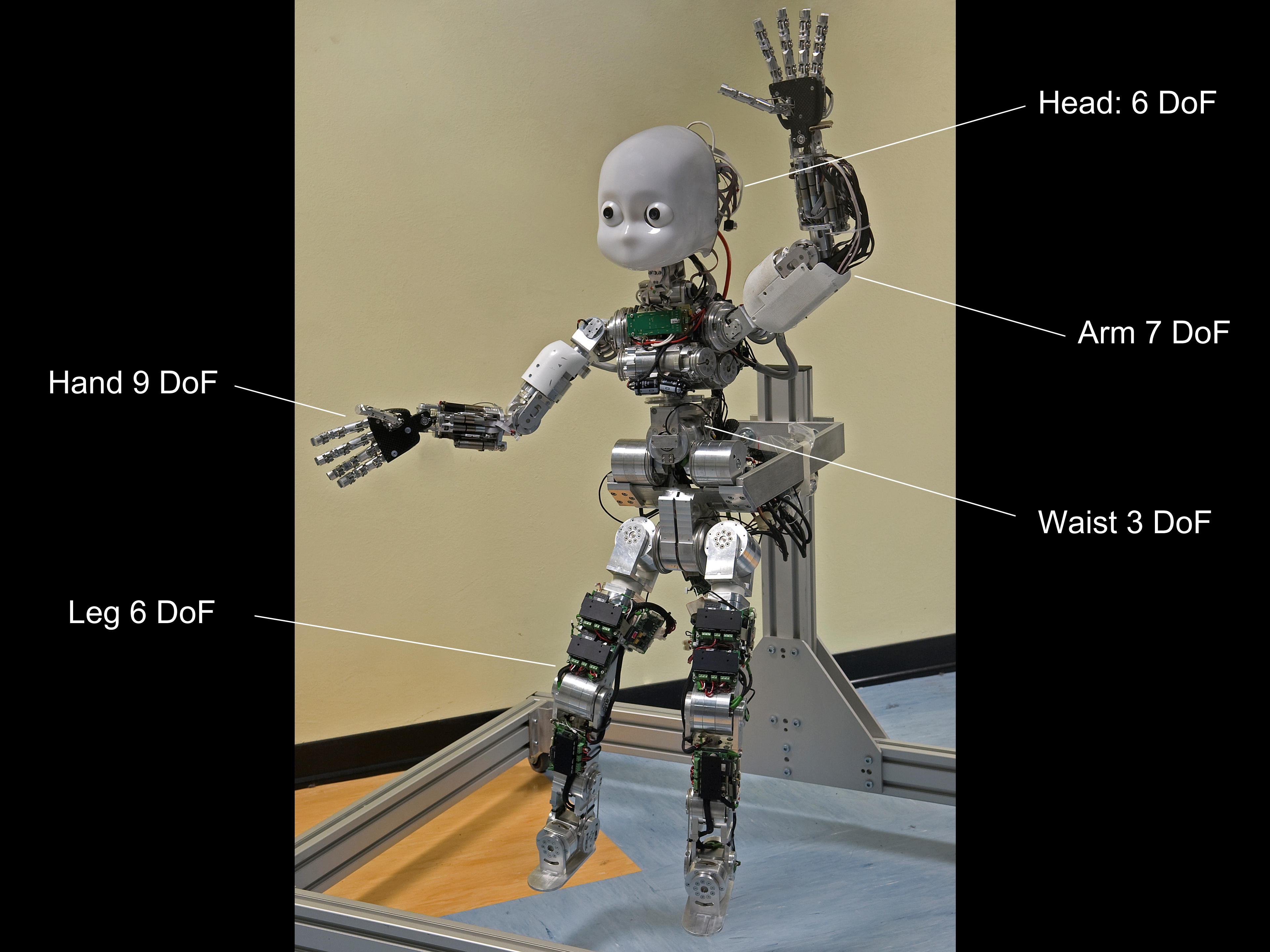
Created to support Community research on embodied cognition

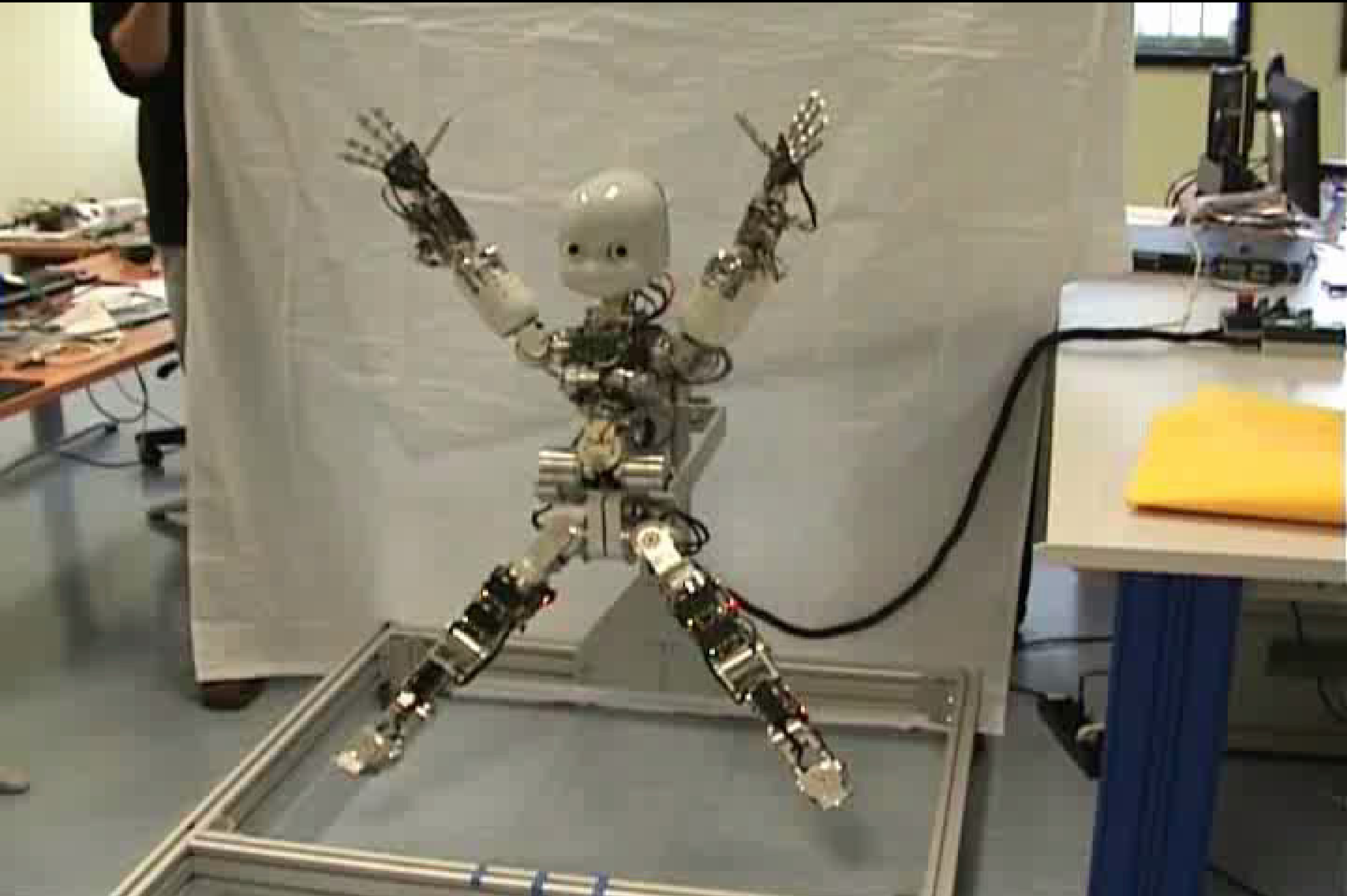
Goal: research platform of choice

- Exploit it quickly and easily
- Collaborate & Share results
- Benefit from the work of other users

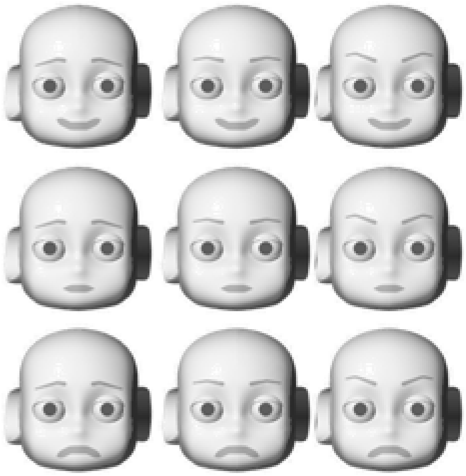
- Humanoid robot sized: two and half year-old child
- Total height: approx. 94cm
- 53 degrees of freedom
- crawl and sit
- The robot is GPL/FDL

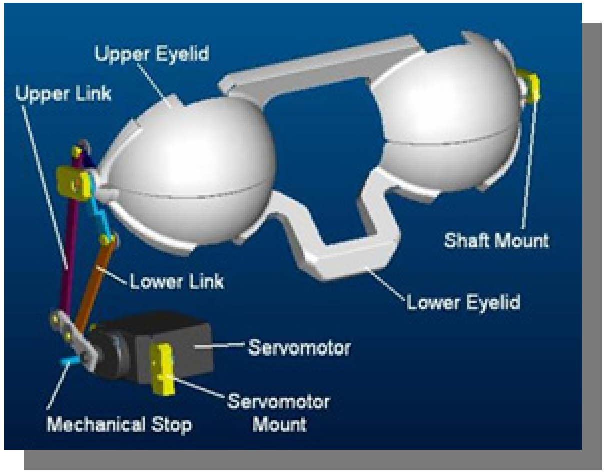



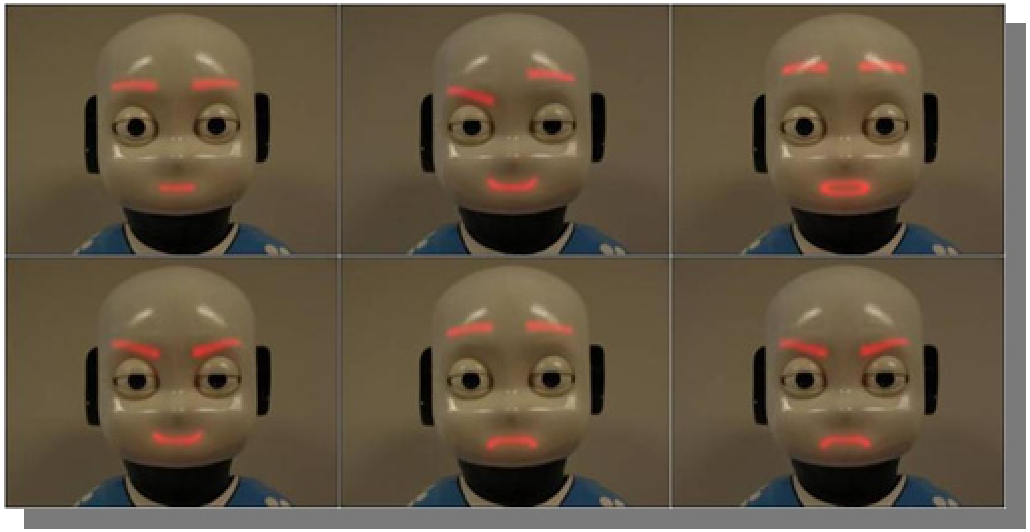

Head: 6 DoF
Arm 7 DoF
Hand 9 DoF
Waist 3 DoF
Leg 6 DoF

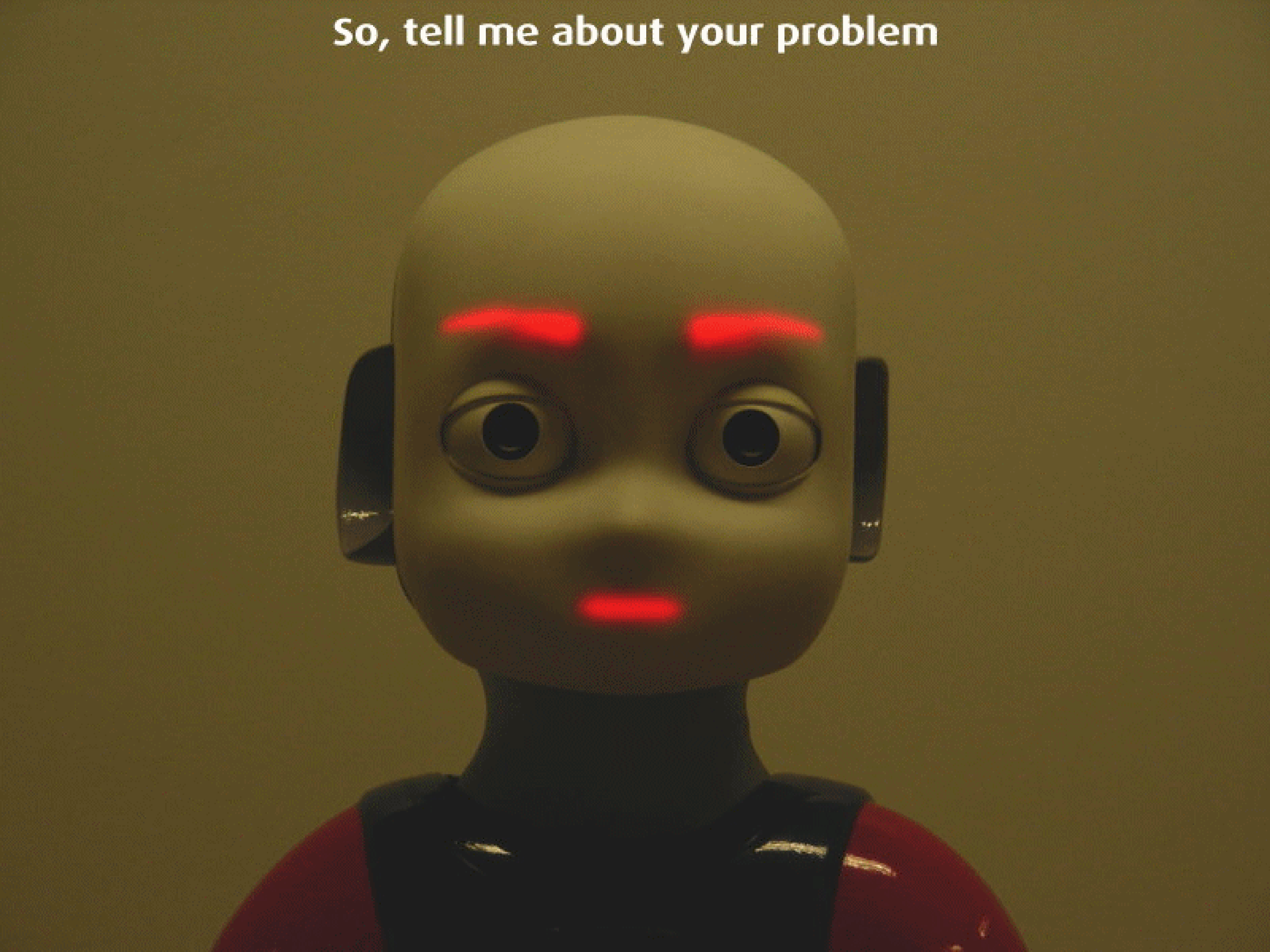


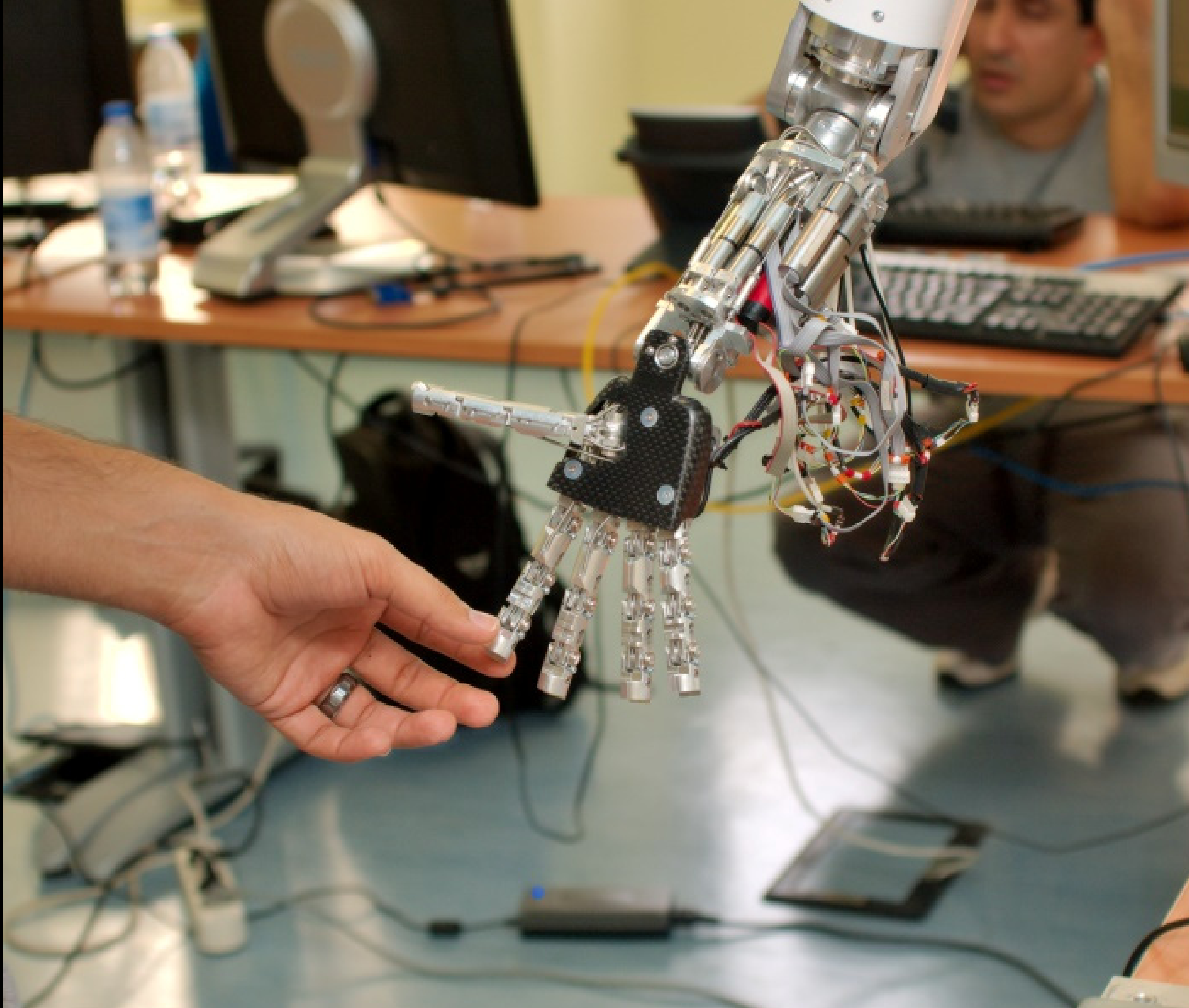
Facial Expressions
(IST)

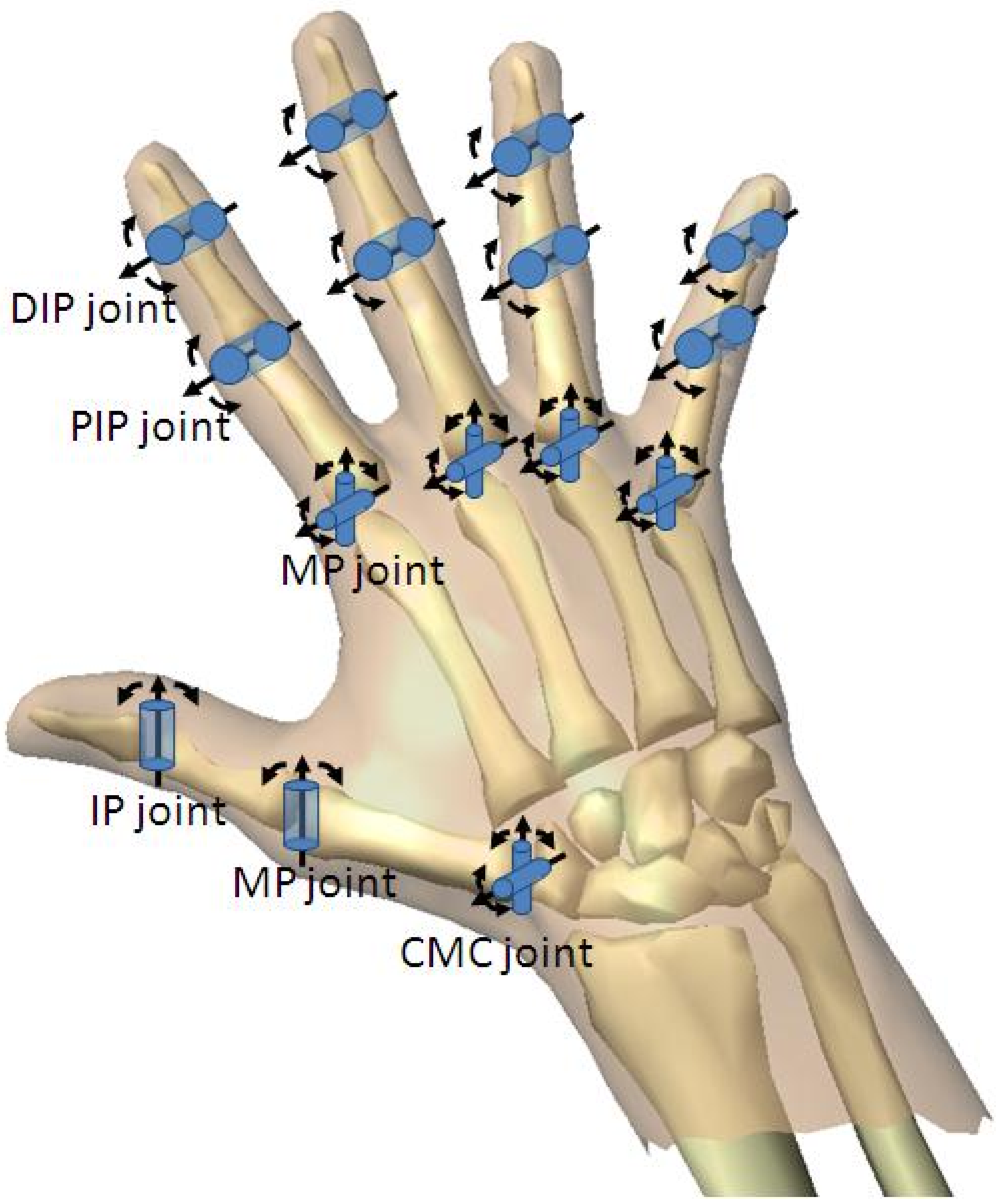


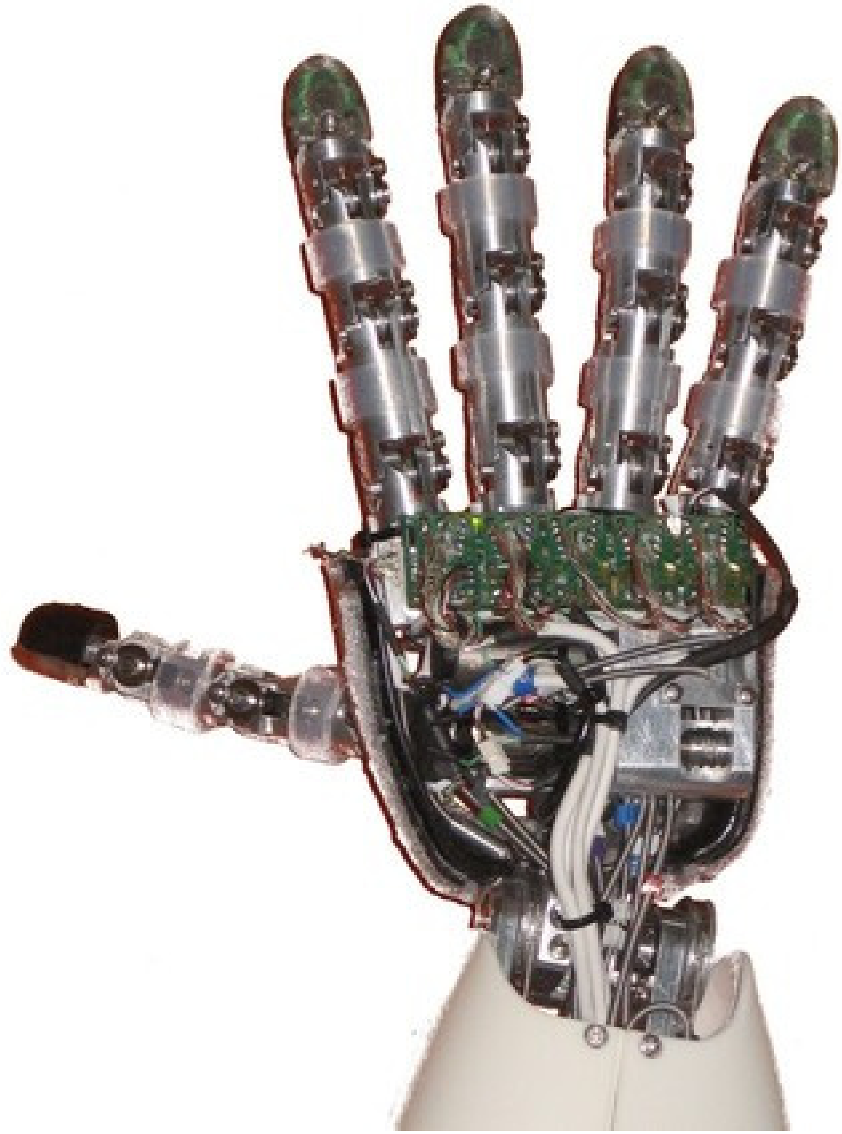


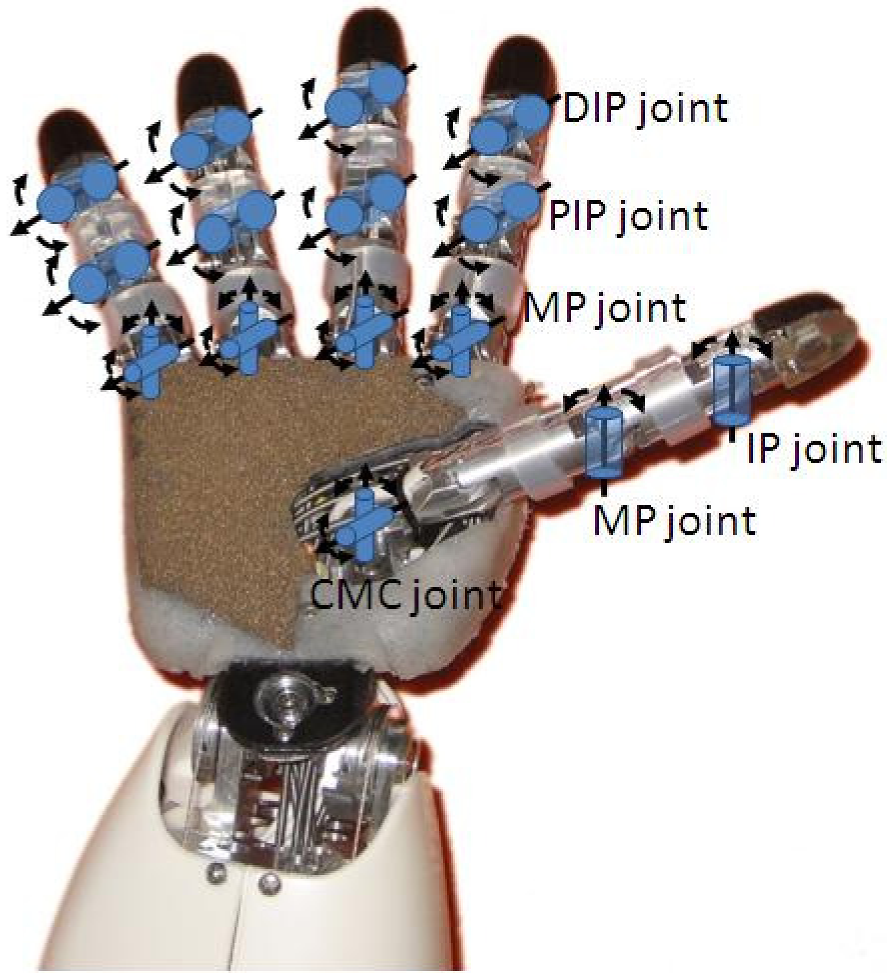


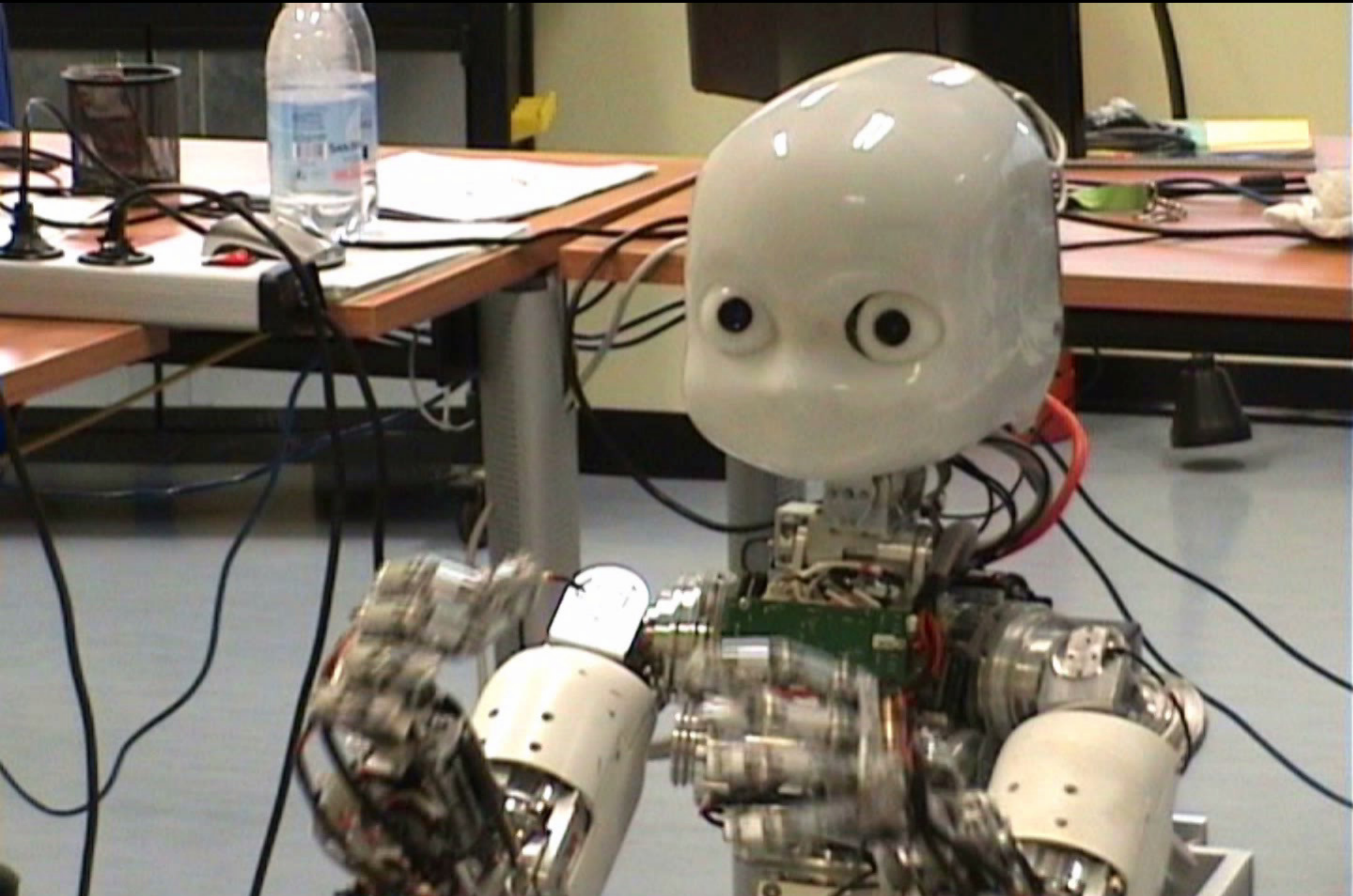

So, tell me about your problem

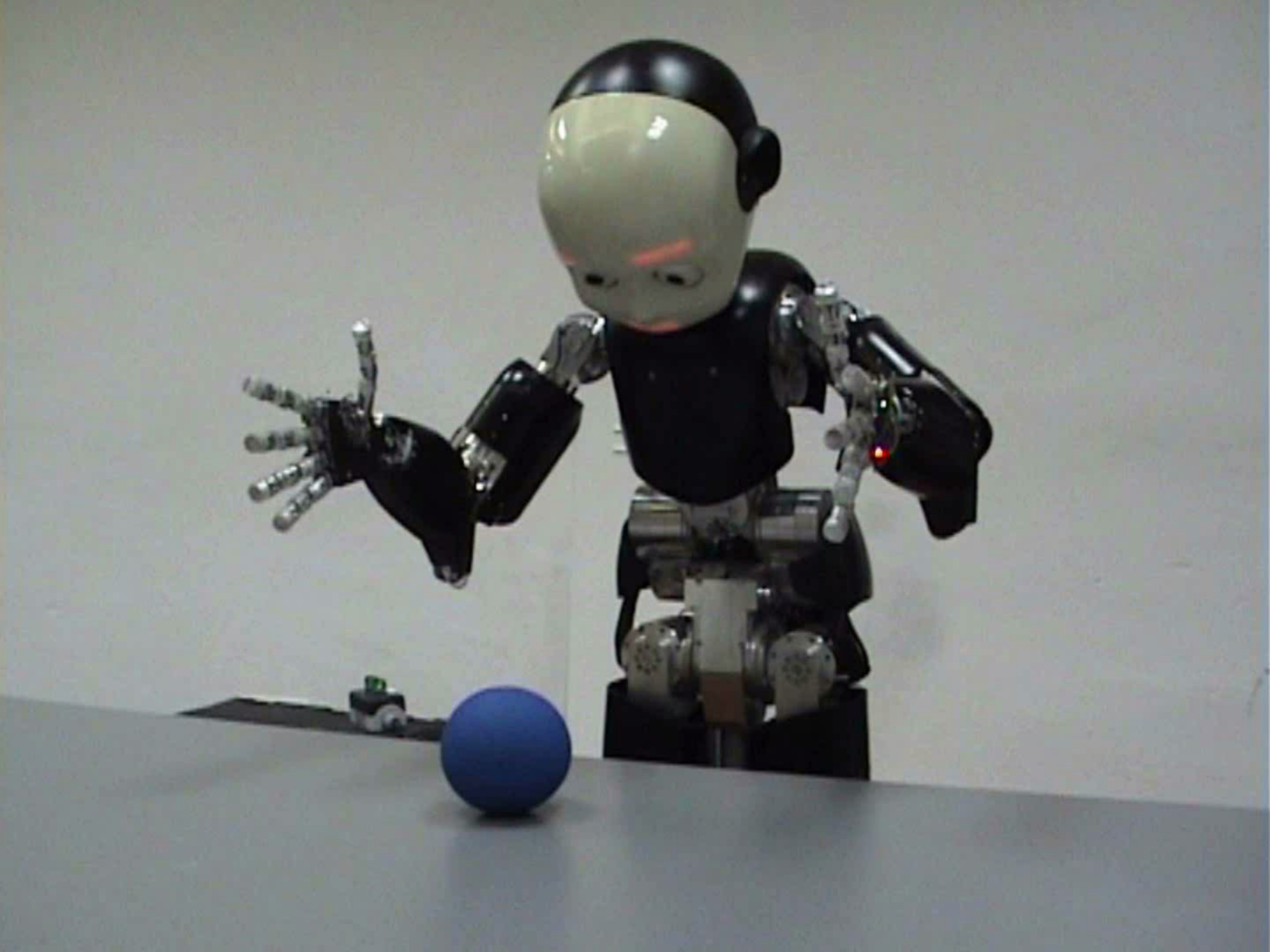



DIP joint
PIP joint
MP joint
IP joint
MP joint
CMC joint



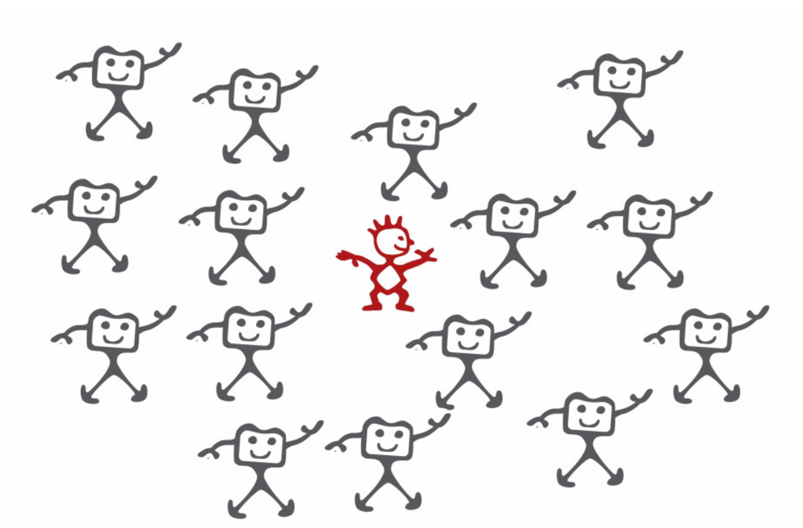

DIP joint
PIP joint
MP joint
IP joint
MP joint
CMC joint



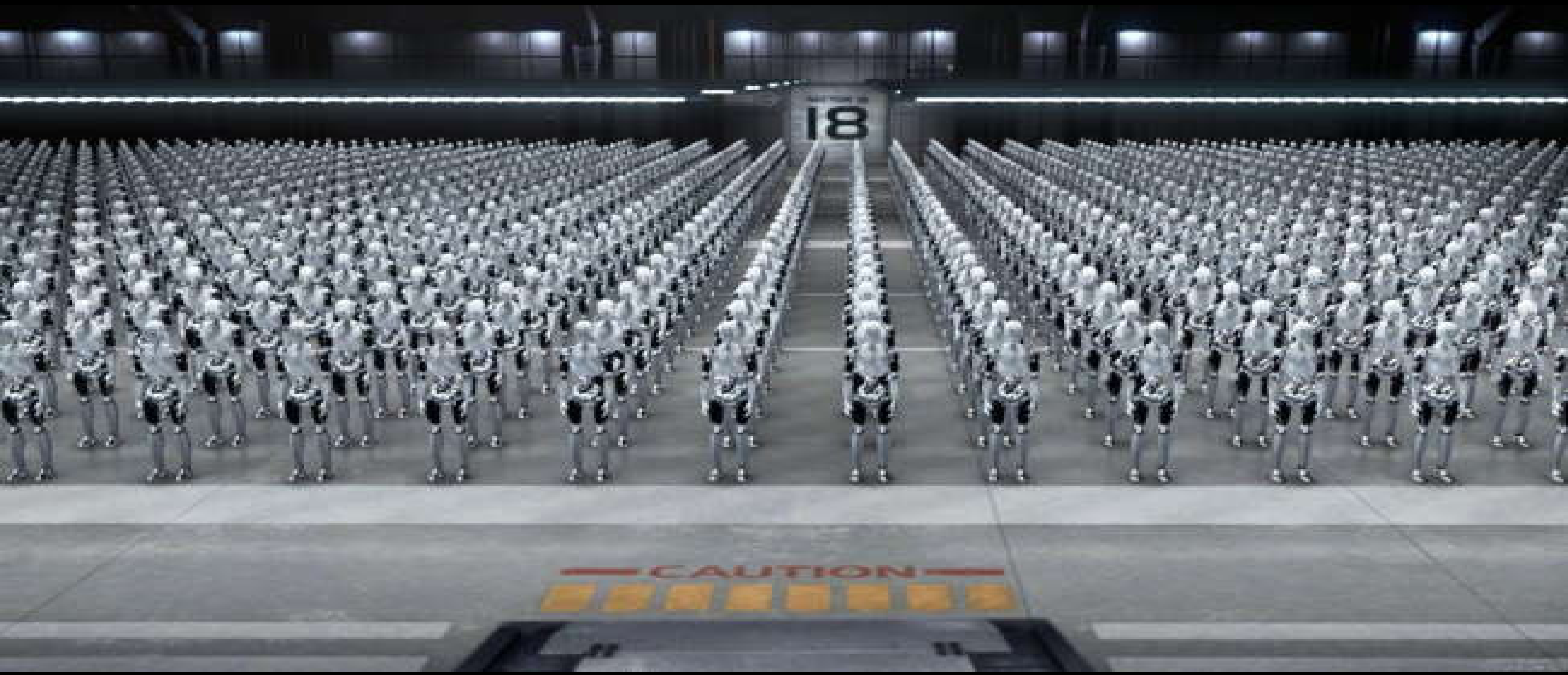


iCub production

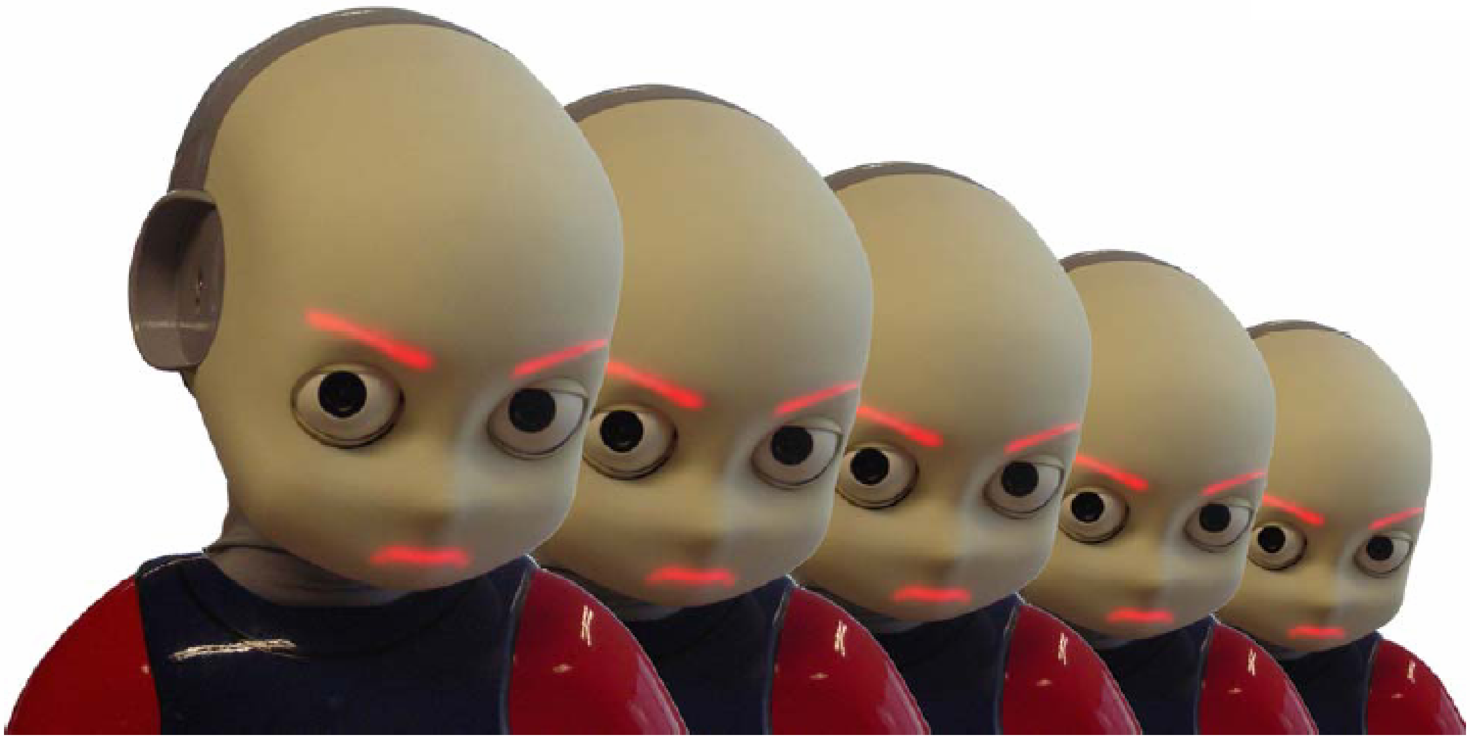




19 iCubs completed and 1 more in production

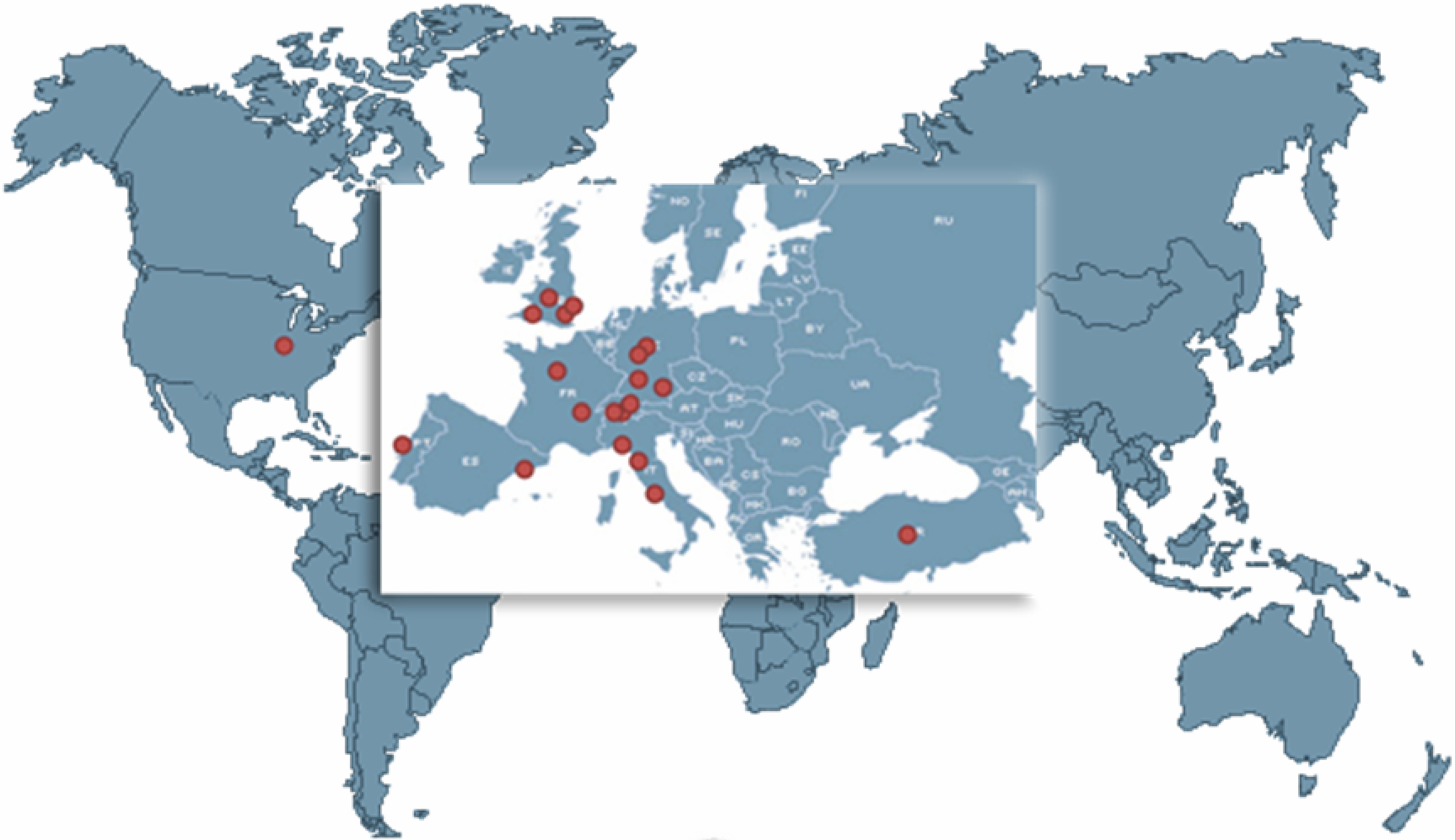

18
CAUTION

Laugh now but one day we'll be in charge



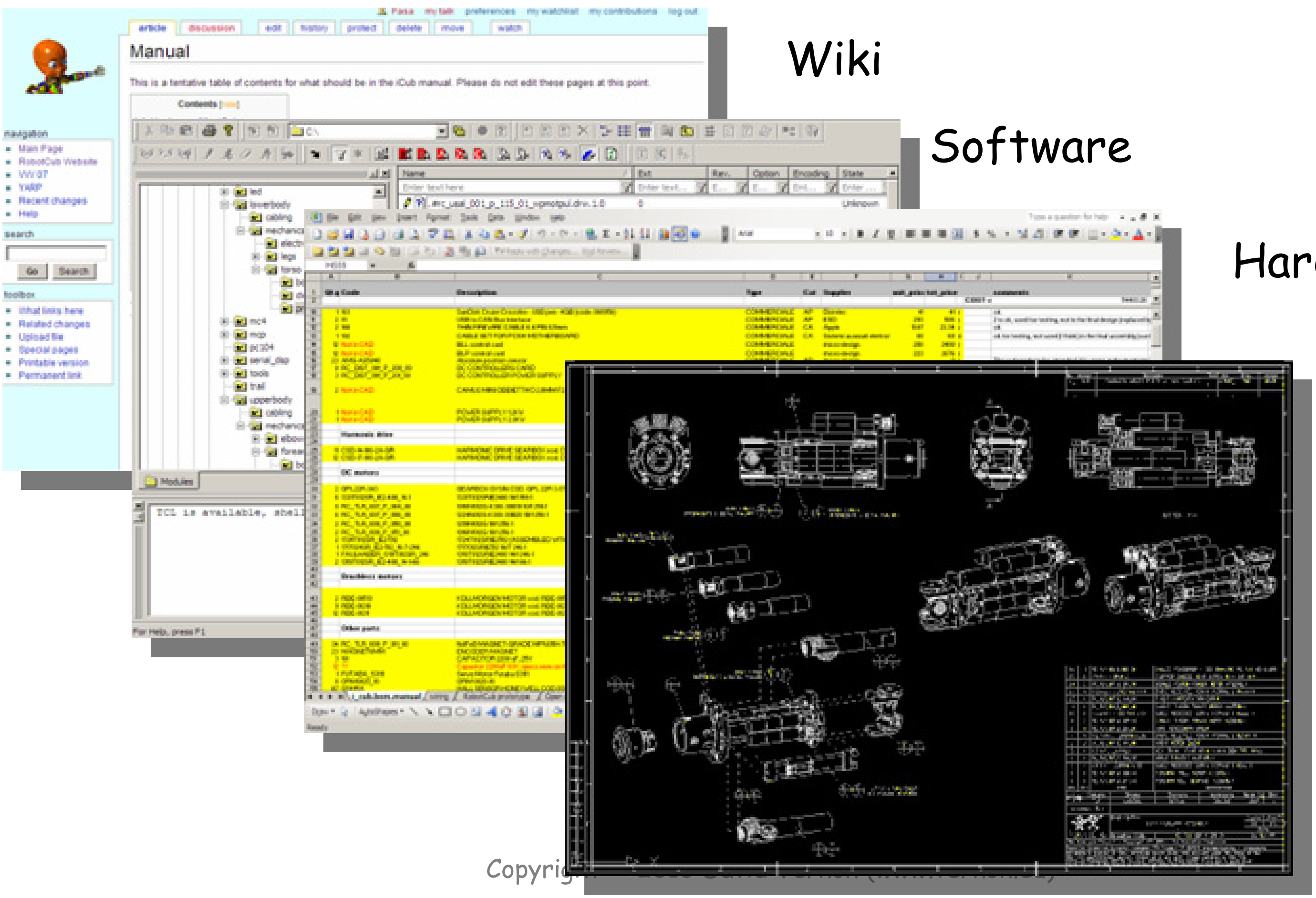
iCub.org

iCub locations



iCub.org

open source™

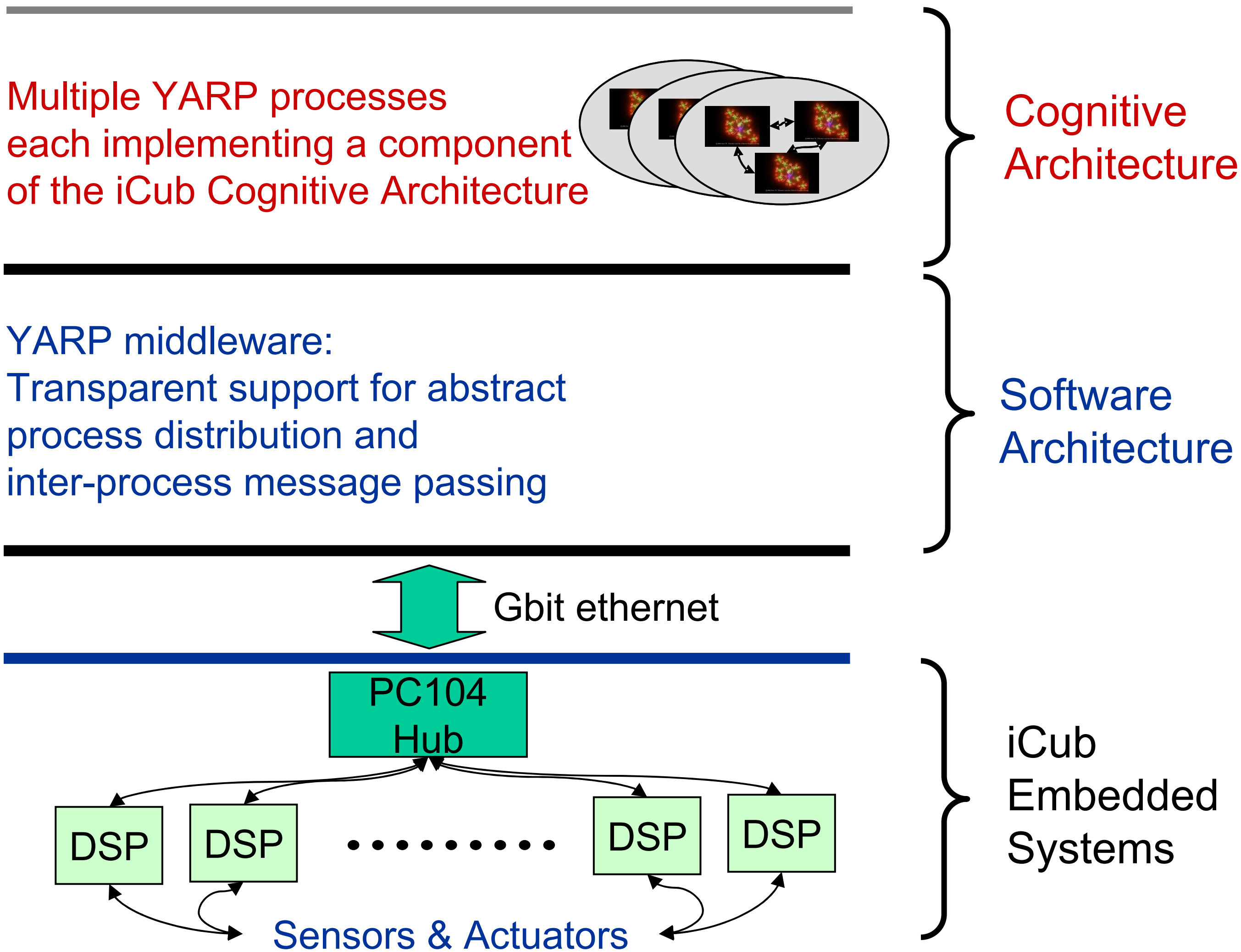


Wiki

Software

Hardware

Drawings


Multiple YARP processes
each implementing a component
of the iCub Cognitive Architecture
Cognitive
Architecture
YARP middleware:
Transparent support for abstract
process distribution and
inter-process message passing
Software
Architecture
Gbit ethernet
PC104
Hub
DSP
DSP
DSP
DSP
Sensors & Actuators
iCub
Embedded
Systems

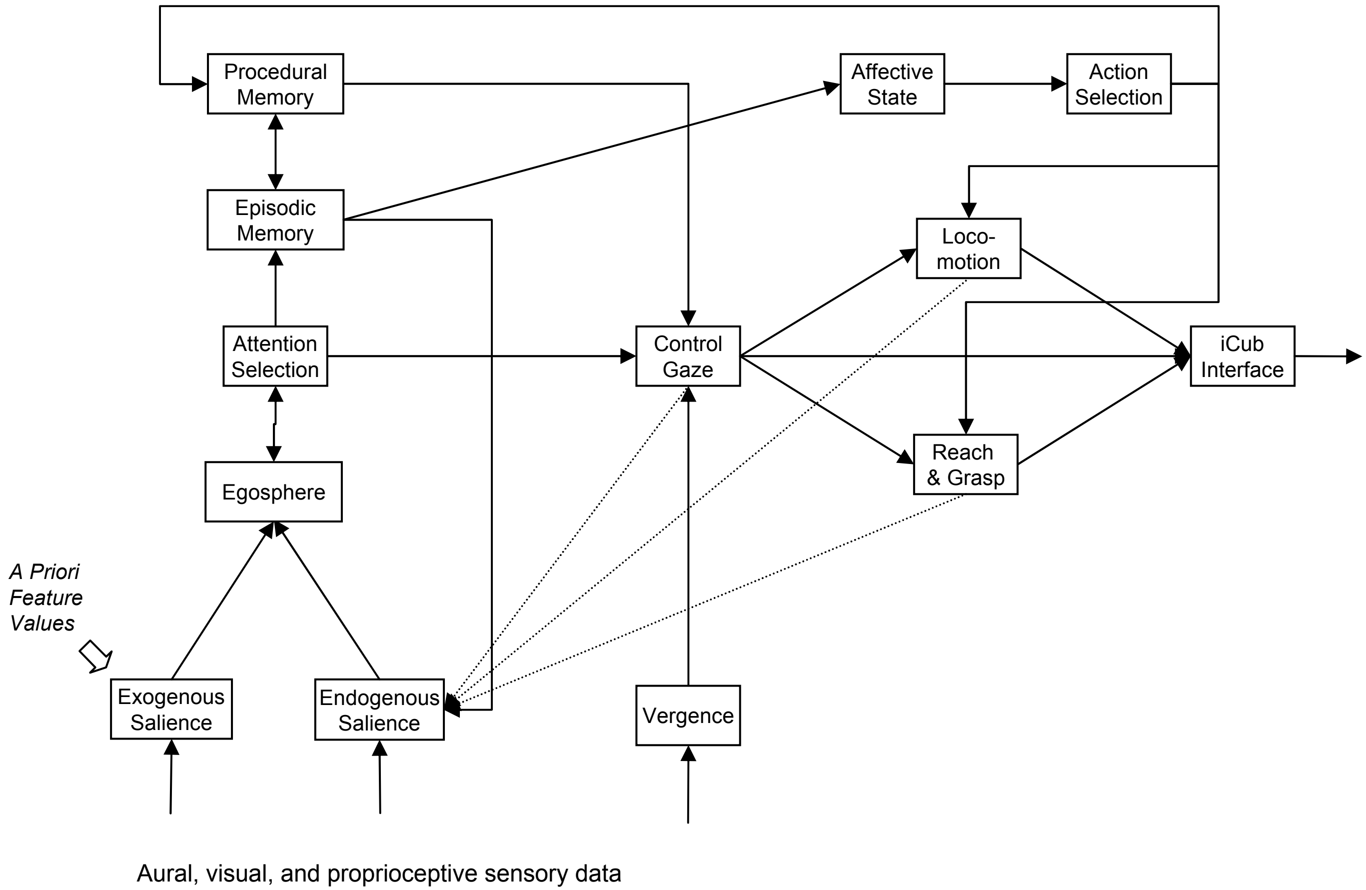
ENACT
A Cognitive Architecture for the iCub Humanoid Robot

1. **Cognition** is the process by which an autonomous self-governing agent acts effectively in the world in which it is embedded

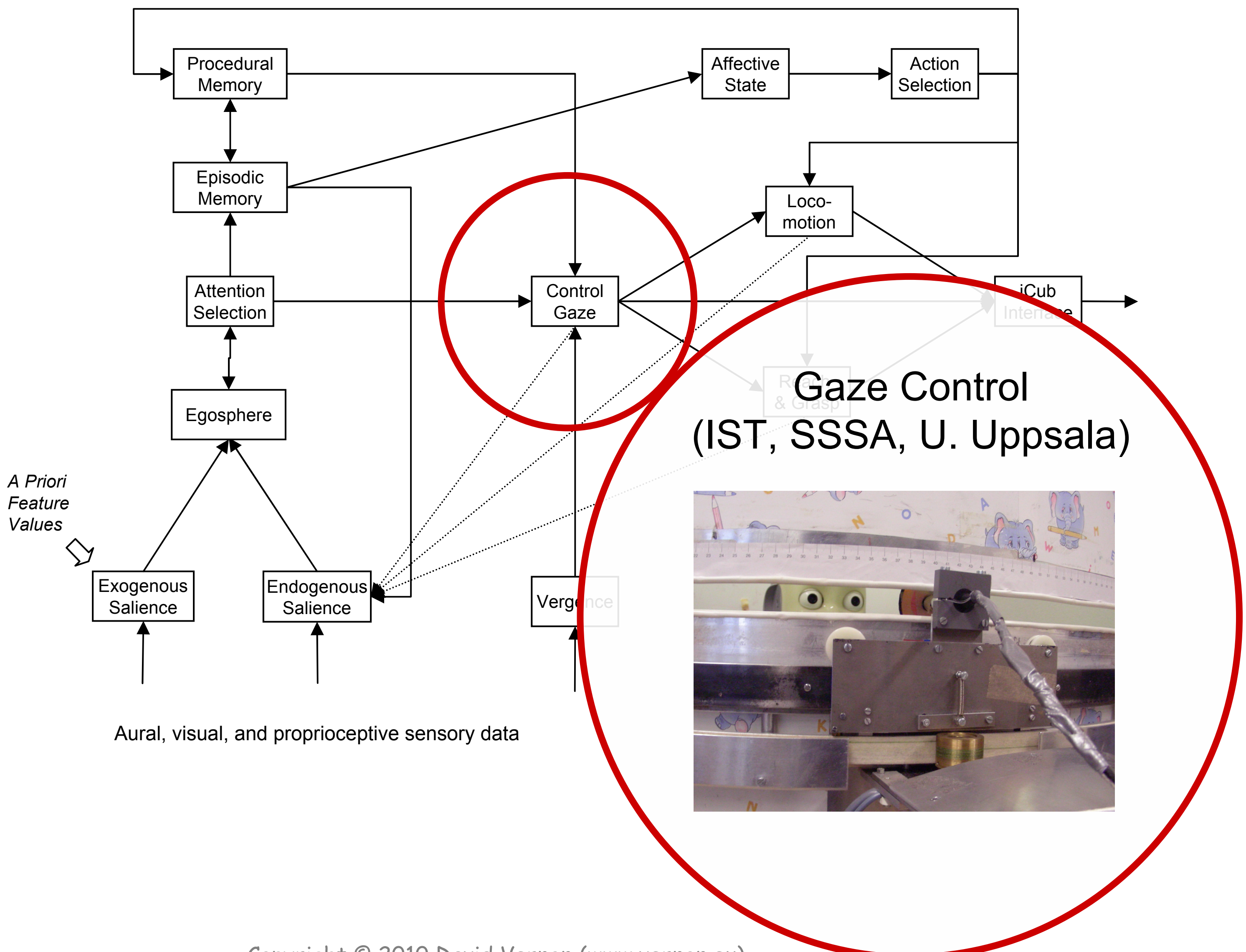
2. **Dual purpose:**

   1. Increase agent's repertoire of effective actions
   2. Increase agent's power to anticipate the need for future actions and their outcomes

3. **Development** plays an essential role in the realization of cognitive capabilities



Procedural Memory
Affective State
Action Selection
Episodic Memory
Loco-motion
Attention Selection
Control Gaze
iCub Interface
Reach & Grasp
Egosphere
A Priori Feature Values
Exogenous Salience
Endogenous Salience
Vergence
Aural, visual, and proprioceptive sensory data


Procedural Memory
Affective State
Action Selection
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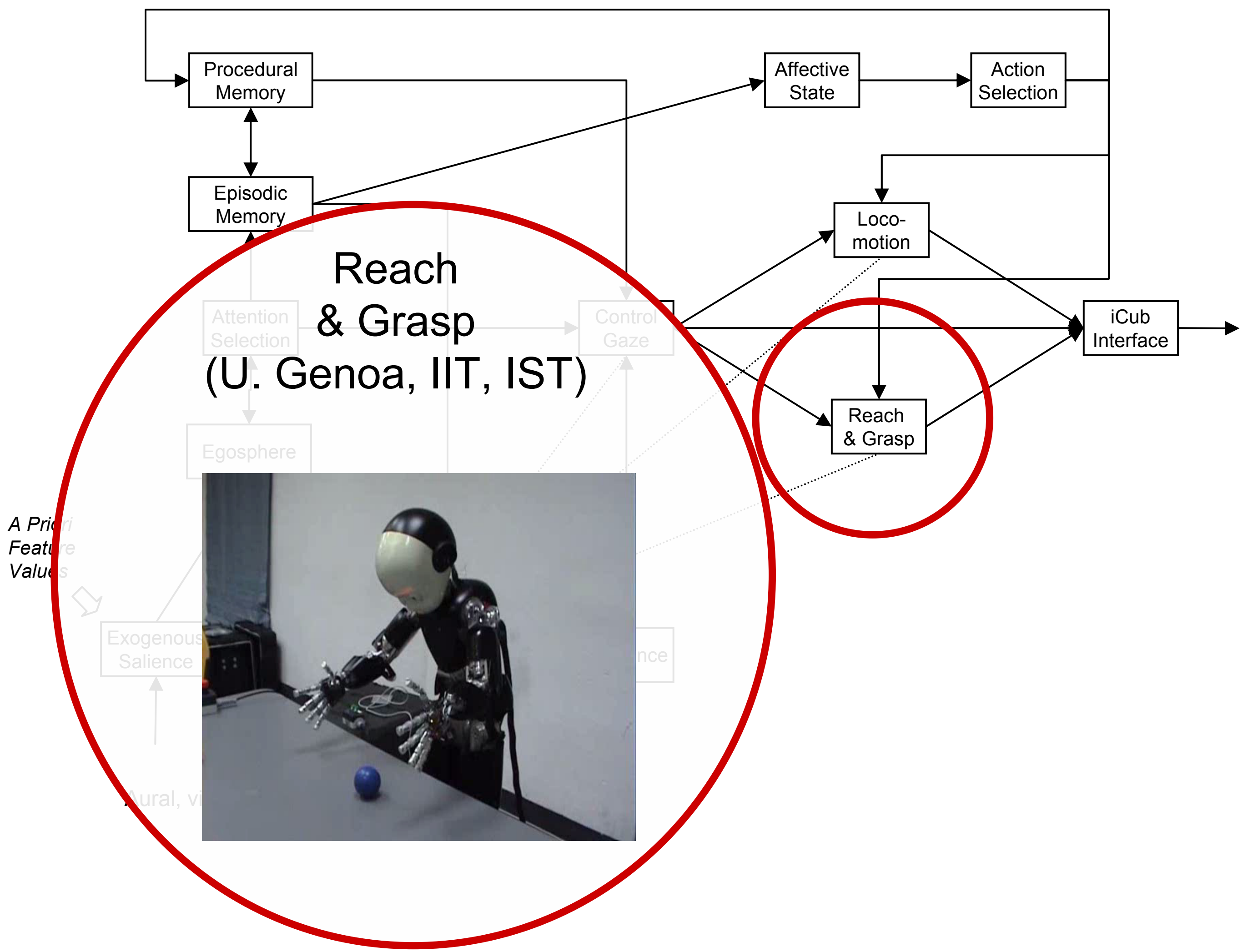
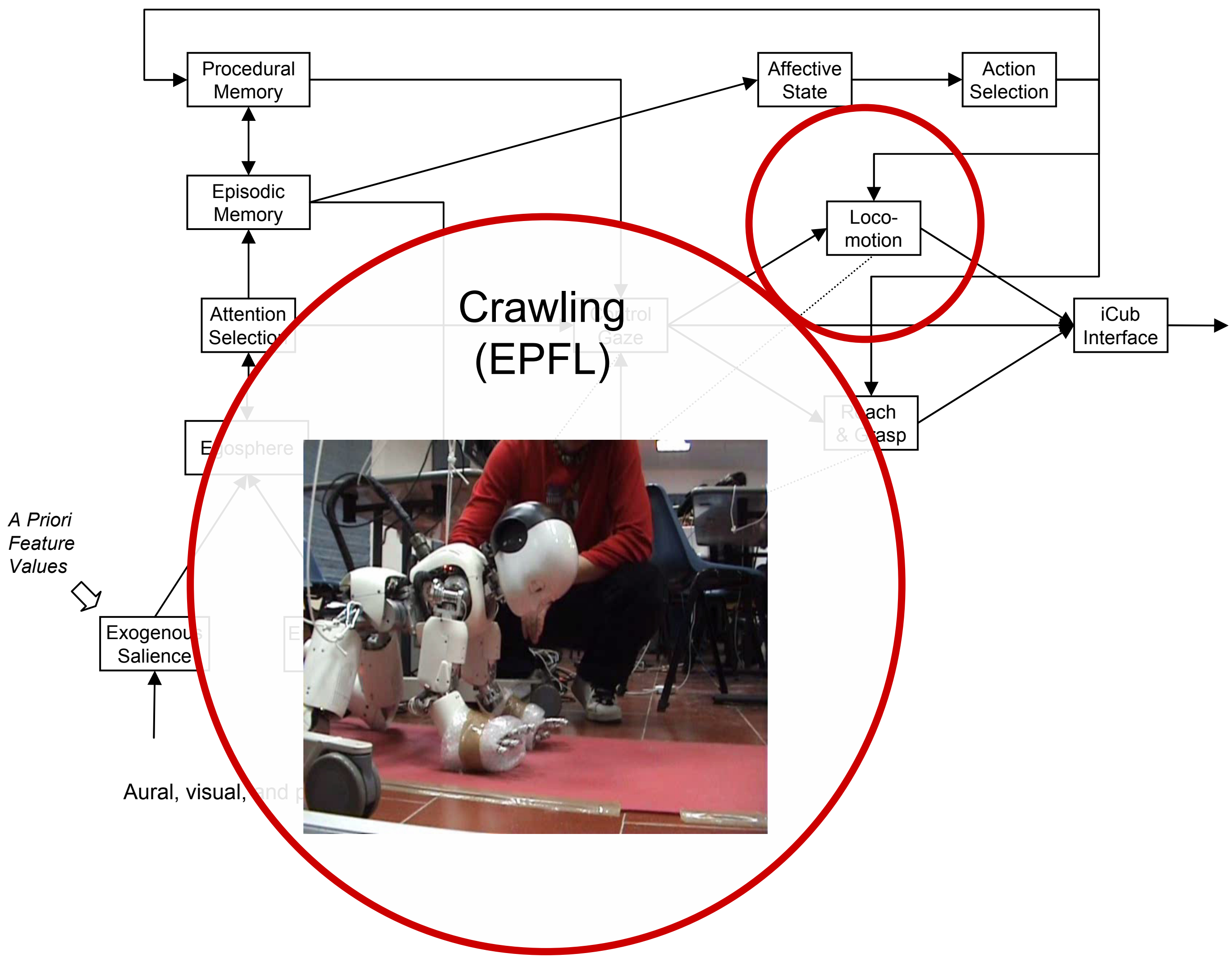
Attention Selection
Control Gaze
iCub
Egosphere
Gaze Control
(IST, SSSA, U. Uppsala)
A Priori Feature Values
Exogenous Salience
Endogenous Salience
Vergence
Aural, visual, and proprioceptive sensory data


Procedural Memory
Affective State
Action Selection
Episodic Memory
Loco-motion
iCub Interface
Reach & Grasp
Reach
& Grasp
(U. Genoa, IIT, IST)
Attention Selection
Control Gaze
Egosphere
Exogenous Salience


Procedural Memory
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Action Selection
Episodic Memory
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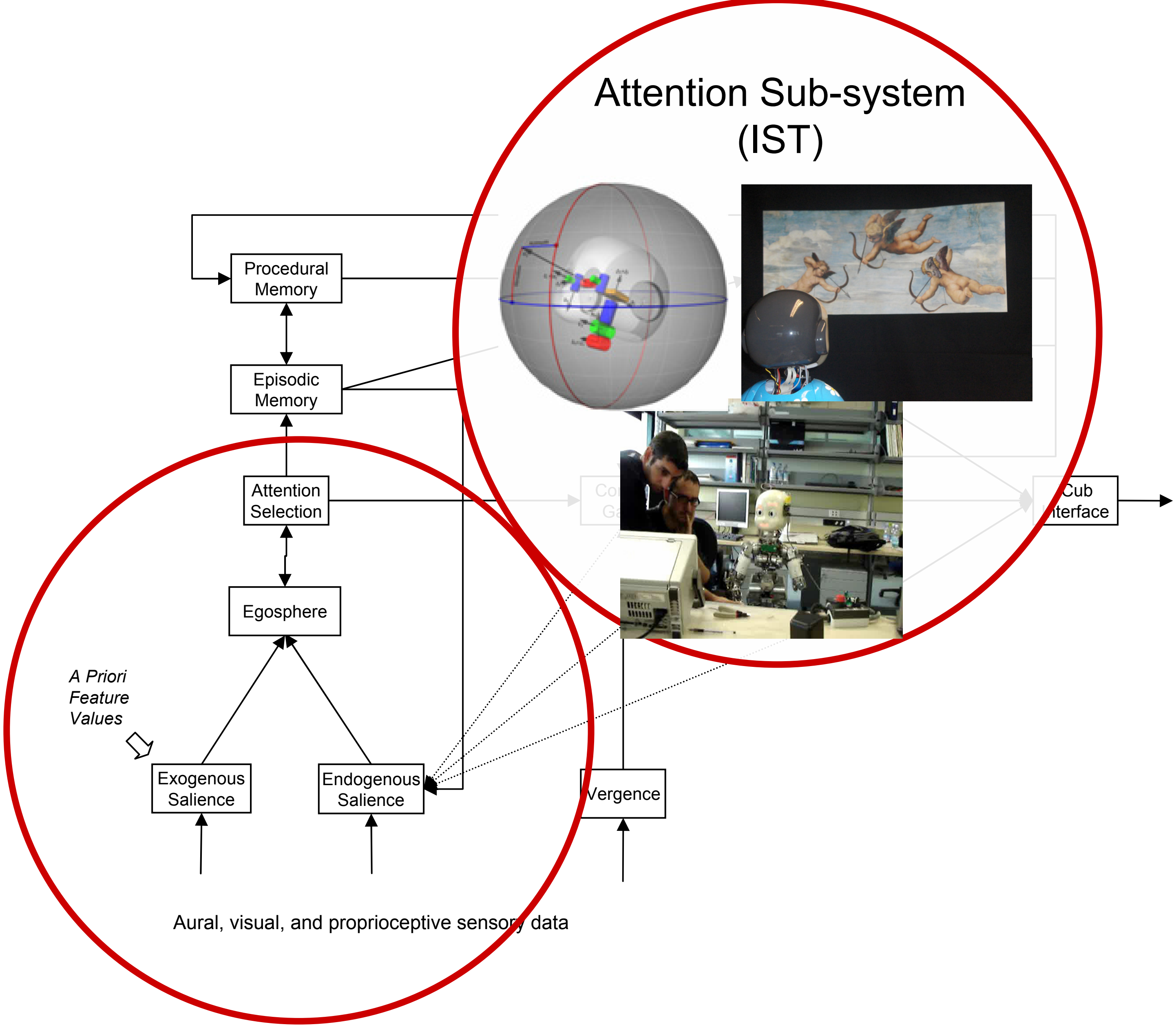
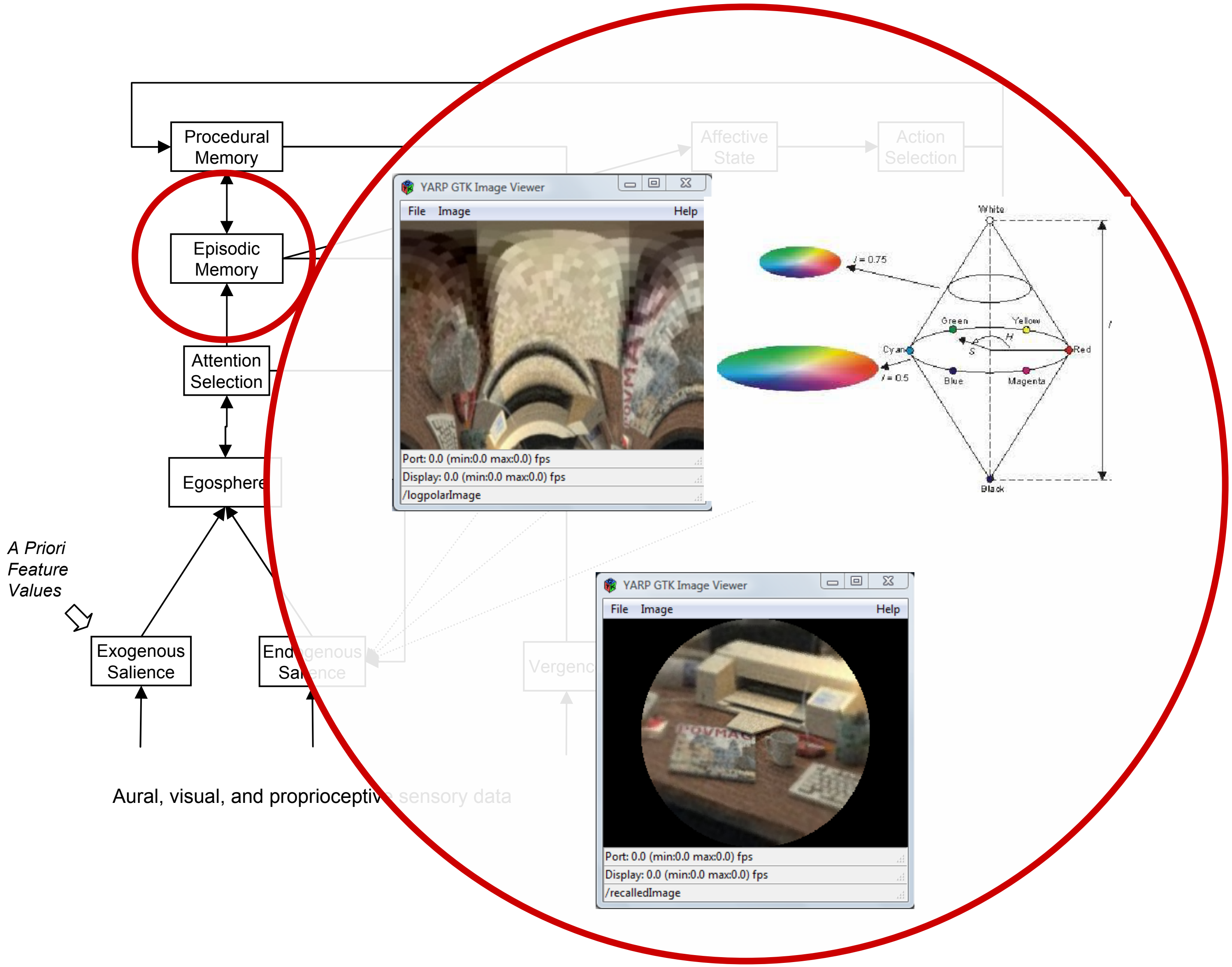
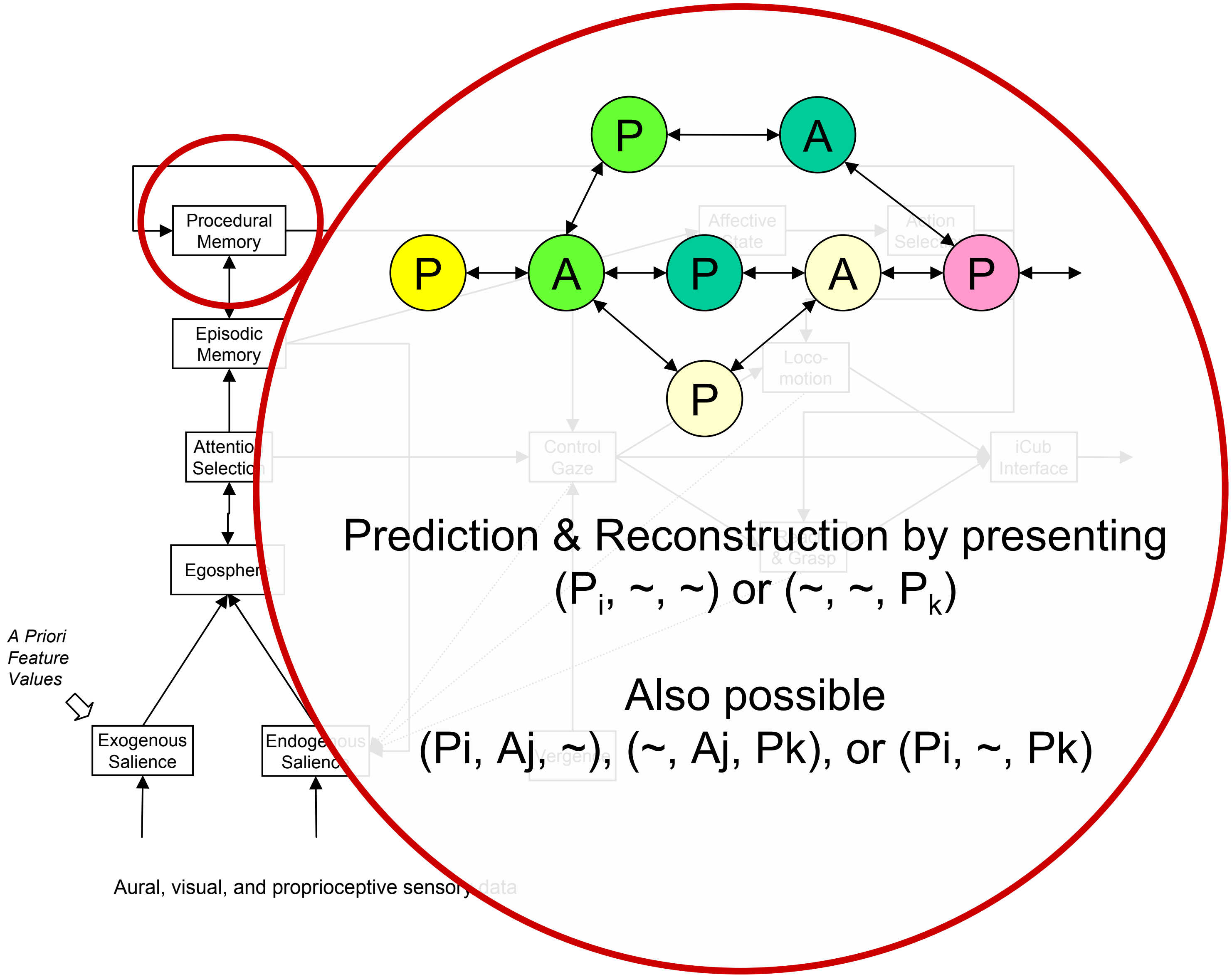
Exogenou
Salience
Aural, visual,


Attention Sub-system
(IST)
Procedural Memory
Episodic Memory
Attention Selection
Egosphere
A Priori Feature Values
Exogenous Salience
Endogenous Salience
Vergence
Aural, visual, and proprioceptive sensory data



Procedural Memory
Affective State
Action Selection
Episodic Memory
Attention Selection
Egosphere
A Priori Feature Values
Exogenous Salience
Endogenous Salience
Aural, visual, and proprioceptive sensory data
YARP GTK Image Viewer
File Image Help
Port: 0.0 (min:0.0 max:0.0) fps
Display: 0.0 (min:0.0 max:0.0) fps
/logpolarImage
White
Green
Yellow
Cyan
Red
Blue
Magenta
Black
I = 0.75
I = 0.5
H
S
I
YARP GTK Image Viewer
File Image Help
Port: 0.0 (min:0.0 max:0.0) fps
Display: 0.0 (min:0.0 max:0.0) fps
/recalledImage



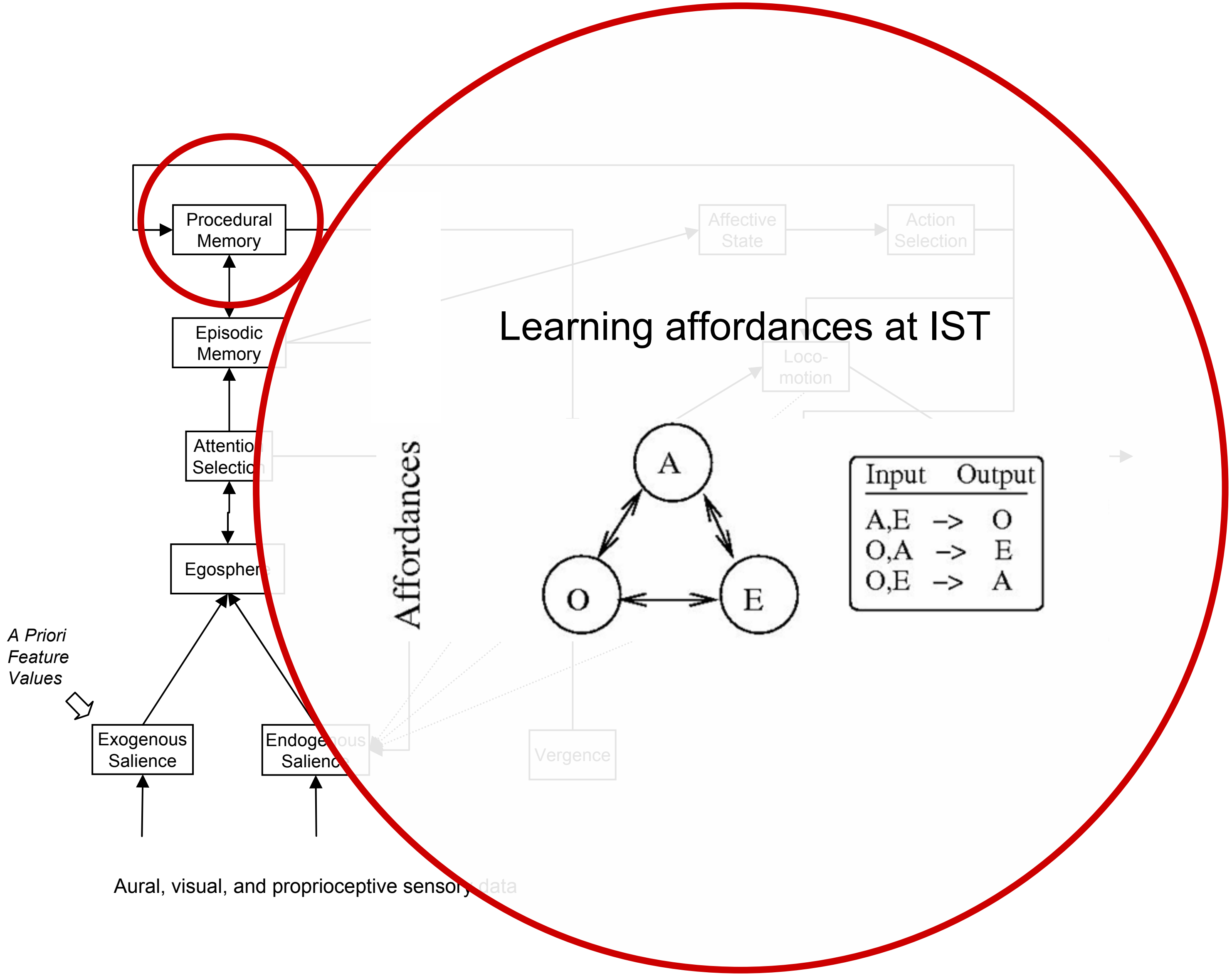
Prediction & Reconstruction by presenting

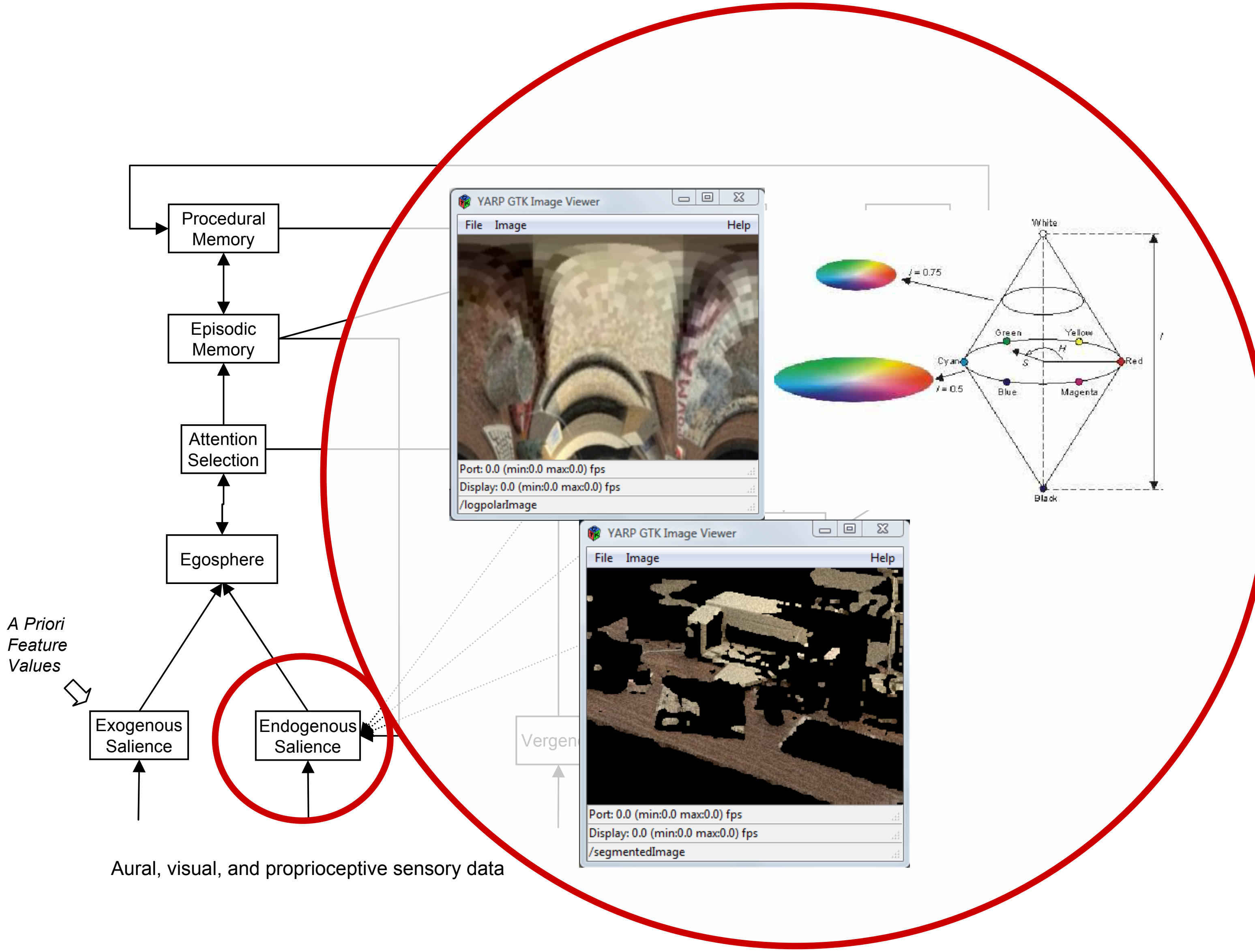
$(P_i, \sim, \sim)$ or $(\sim, \sim, P_k)$

Also possible

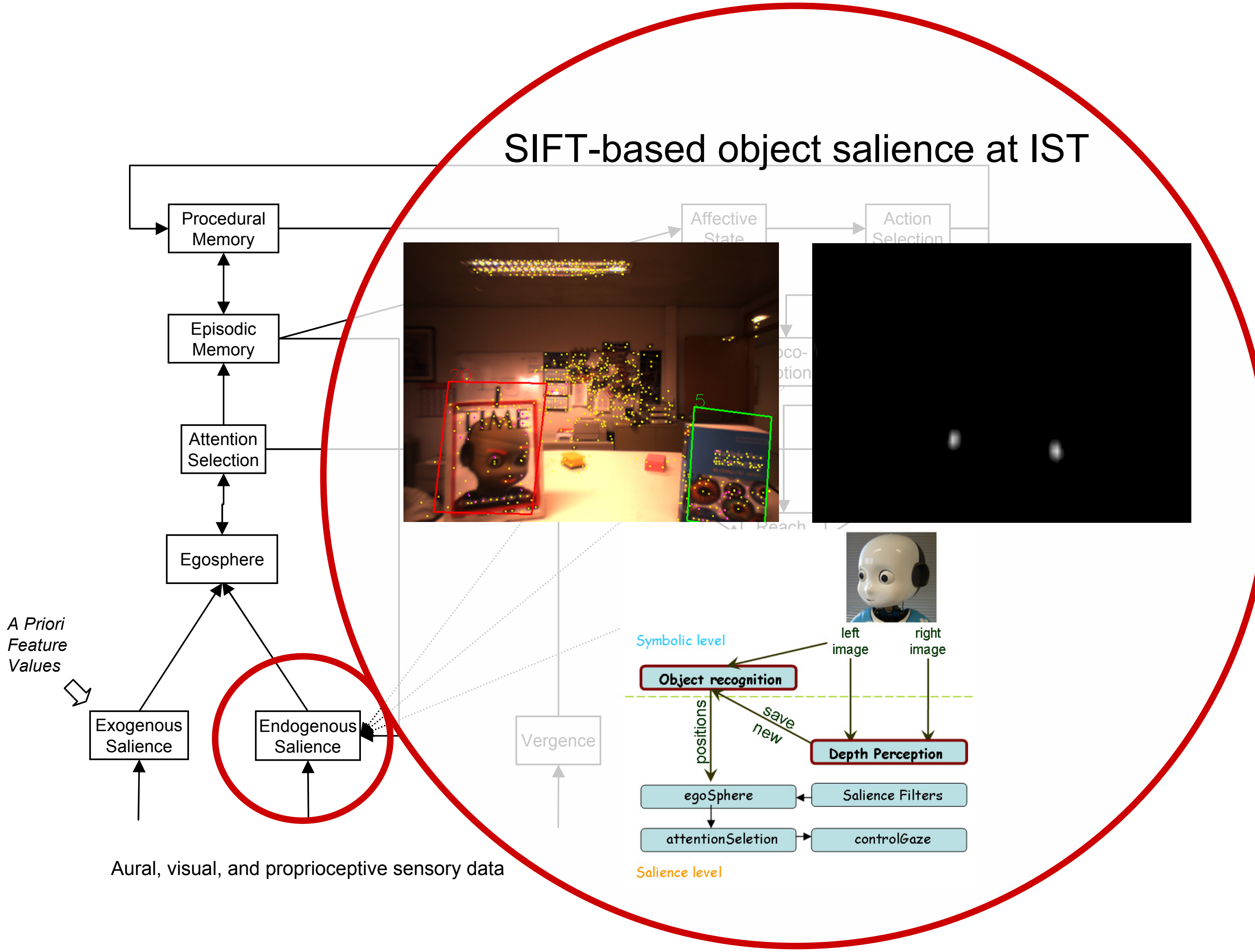
(Pi, Aj, ~), (~, Aj, Pk), or (Pi, ~, Pk)

Learning affordances at IST

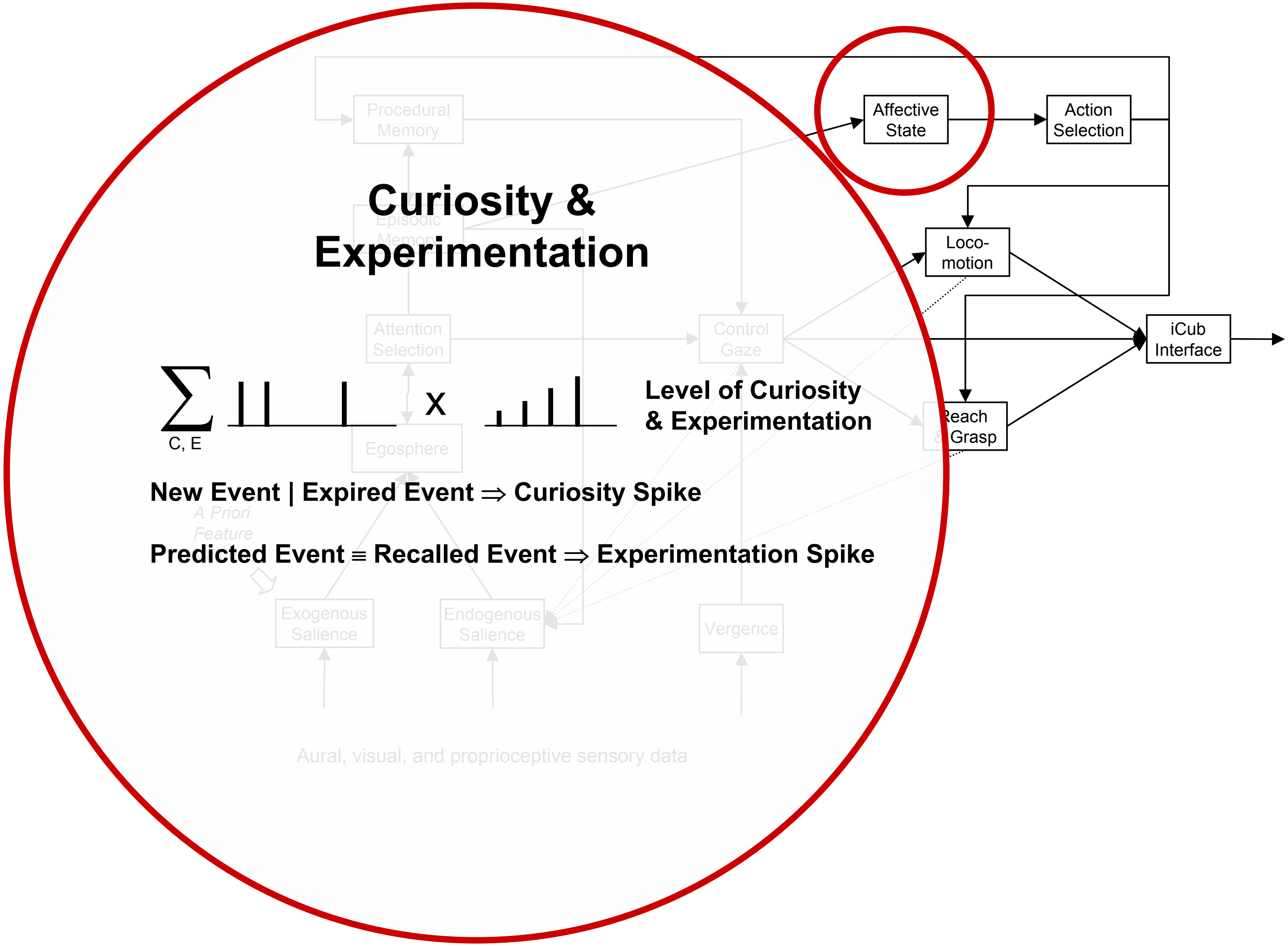



Procedural Memory
Episodic Memory
Attention Selection
Egosphere
A Priori Feature Values
Exogenous Salience
Endogenous Salience
Aural, visual, and proprioceptive sensory data
YARP GTK Image Viewer
File Image Help
Port: 0.0 (min:0.0 max:0.0) fps
Display: 0.0 (min:0.0 max:0.0) fps
/logpolarImage
YARP GTK Image Viewer
File Image Help
Port: 0.0 (min:0.0 max:0.0) fps
Display: 0.0 (min:0.0 max:0.0) fps
/segmentedImage
White
I = 0.75
Green
Yellow
Cyan
Red
Blue
Magenta
I = 0.5
Black

SIFT-based object salience at IST



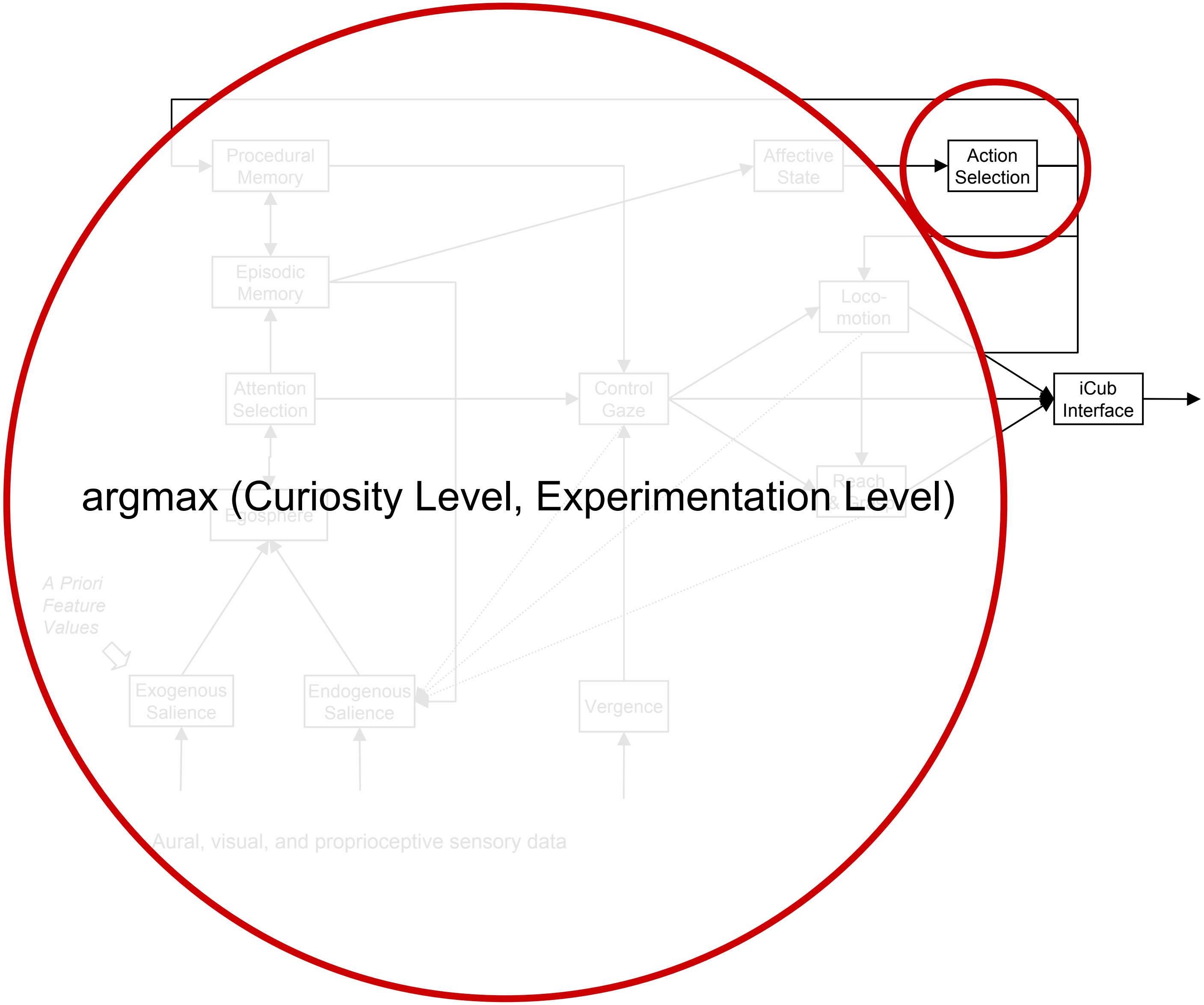
Curiosity & Experimentation

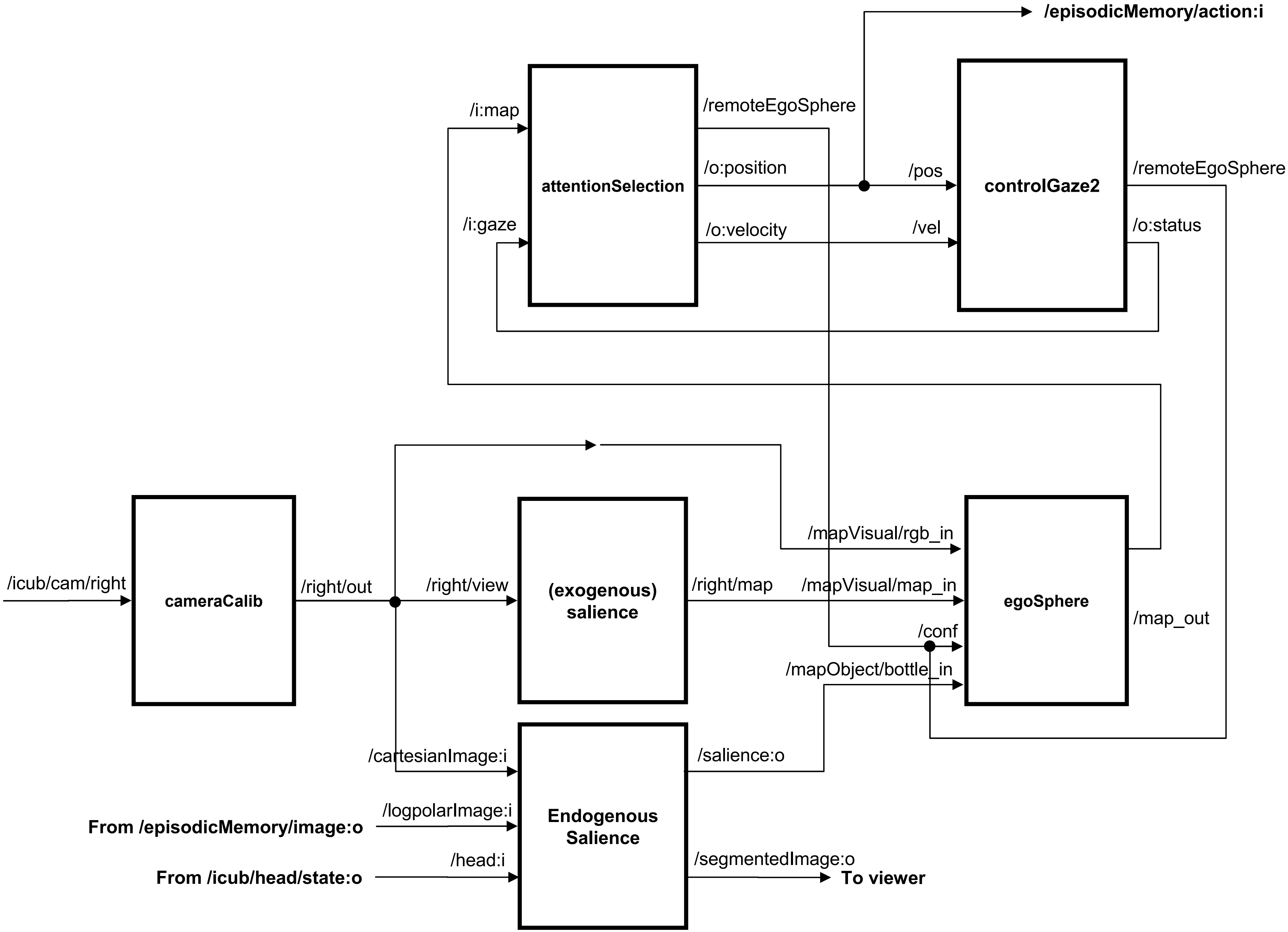


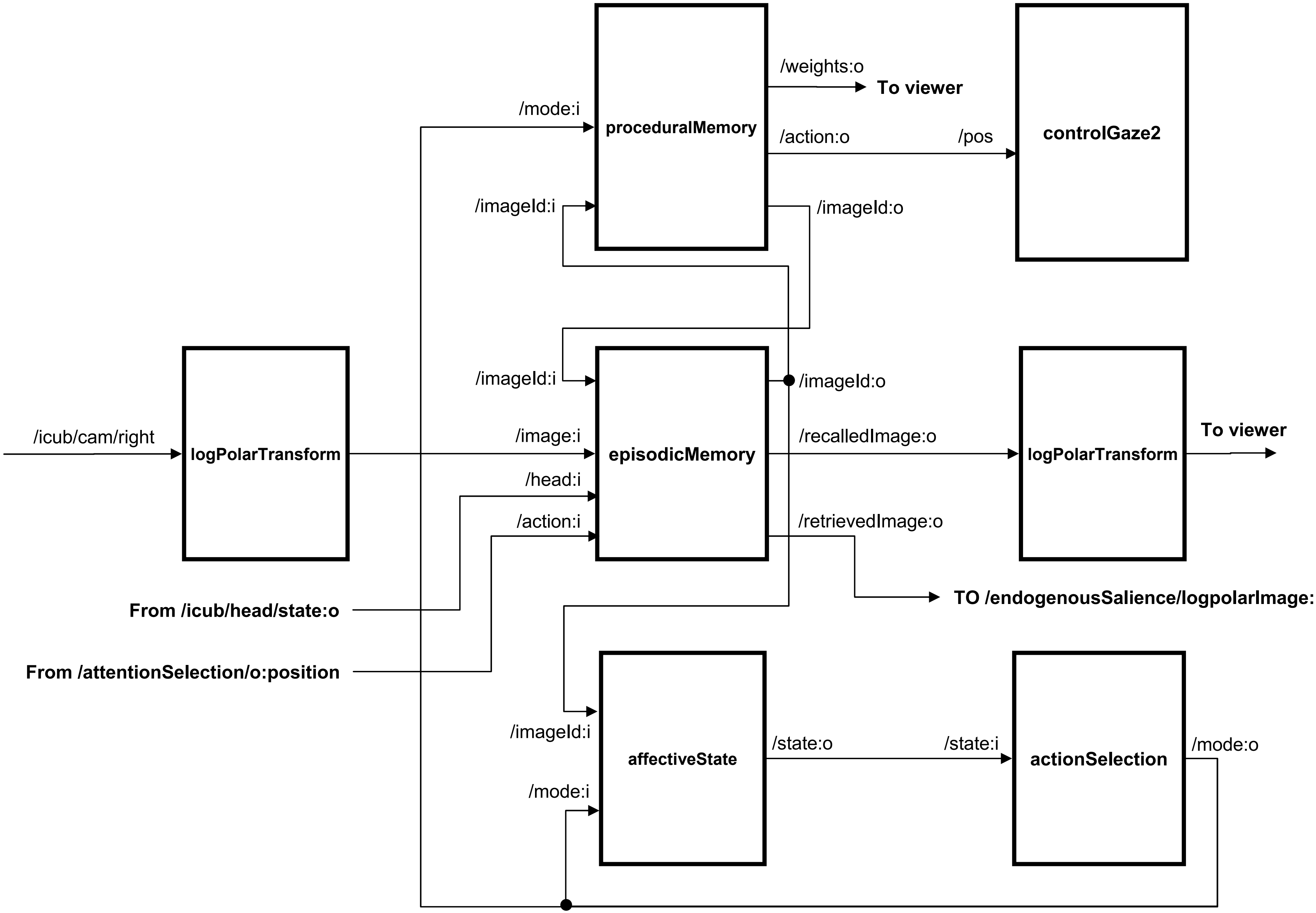
Level of Curiosity & Experimentation

New Event | Expired Event ⇒ Curiosity Spike

Predicted Event ≡ Recalled Event ⇒ Experimentation Spike


Procedural Memory
Affective State
Action Selection
Episodic Memory
Loco-motion
Attention Selection
Control Gaze
iCub Interface
Reach & Grasp
Egosphere
A Priori Feature Values
Exogenous Salience
Endogenous Salience
Vergence
Aural, visual, and proprioceptive sensory data
argmax (Curiosity Level, Experimentation Level)


/episodicMemory/action:i
attentionSelection
/i:map
/remoteEgoSphere
/o:position
/i:gaze
/o:velocity
/pos
/vel
controlGaze2
/remoteEgoSphere
/o:status
/mapVisual/rgb_in
/icub/cam/right
cameraCalib
/right/out
/right/view
(exogenous) salience
/right/map
/mapVisual/map_in
egoSphere
/map_out
/conf
/mapObject/bottle_in
/cartesianImage:i
/salience:o
/logpolarImage:i
From /episodicMemory/image:o
Endogenous Salience
/head:i
From /icub/head/state:o
/segmentedImage:o
To viewer



proceduralMemory
/mode:i
/imageId:i
/weights:o
To viewer
/action:o
/pos
controlGaze2
/imageId:o
logPolarTransform
/icub/cam/right
/imageId:i
/imageId:o
/image:i
episodicMemory
/recalledImage:o
logPolarTransform
To viewer
/head:i
/action:i
/retrievedImage:o
TO /endogenousSalience/logpolarImage:i
From /icub/head/state:o
From /attentionSelection/o:position
/imageId:i
affectiveState
/state:o
/state:i
actionSelection
/mode:o
/mode:i

Guidelines for the Phylogeny of a Developmental Cognitive System		
Number	**Guideline**	**iCub**
	Embodiment	
1	Rich array of physical sensory and motor interfaces	+
3	Humanoid morphology	×
13	Morphology integral to the model of cognition	+
	Perception	
12 (32)	Attention fixated on the goal of an action	×
15	Perception of objecthood	
16	Discrimination & addition of small numbers; groups of large numbers	
19	Attraction to people (faces, their sounds, movements, and features)	+
20	Preferential attention to biological motion	
21	Recognition of people, expression, and action	+
22	Prolonged attention when a person engages in mutual gaze	
23	Perceive & communicate emotions by facial gesture and engage in turn-taking	+
26	Involvement of the motor system in discrimination between percepts	+
27	Mechanism to learn hierarchical representations	
28	Pre-motor theory of attention —spatial attention	
29	Pre-motor theory of attention —selective attention	
	Action	
10	Movements organized as actions	×
14	Early movements constrained to reduce the number of degrees of freedom	
17	Navigation based on dynamic ego-centric path integration	×
18	Re-orientation based on local landmarks	+
36	Action selection modulated by affective motivation mechanisms	×
42	Hierarchically-structured representations of action-sequence skills	
	Anticipation	
8, 35	Internal simulation to predict, explain, & imagine events, and scaffold knowledge	×
	Adaptation	
4	Self-modification to expand actions and improve prediction	+
5	Autonomous generative model construction	+
7 (25, 41)	Learning affordances	×
9 (40)	Grounding internal simulations in actions	×
33	Learn from experience the motor skills associated with actions	×
38	Transient and generalized episodic memories of past experiences	+
39	Procedural memory of actions and outcomes associated with episodic memories	×
	Motivation	
6 (11, 31)	Social and explorative motives	+
34	Affective drives associated with autonomy-preserving processes of homeostasis	+
	Autonomy	
2	Autonomy-preserving processes of homeostasis	+
24	Encode space in motor & goal specific manner	+
30	Minimal set of innate behaviours for exploration and survival	+
37	Separate representations associated with each component / sub-system	+
43	Concurrent competitive operation of components and subsystems	×