RobotCub

The *RobotCub* Cognitive Architecture: Foundations, Insights, and Challenges

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Cogsys
Cognitive Systems

Robotic Open-Architecture for Cognition, Understanding, and Behaviours

RobotCub

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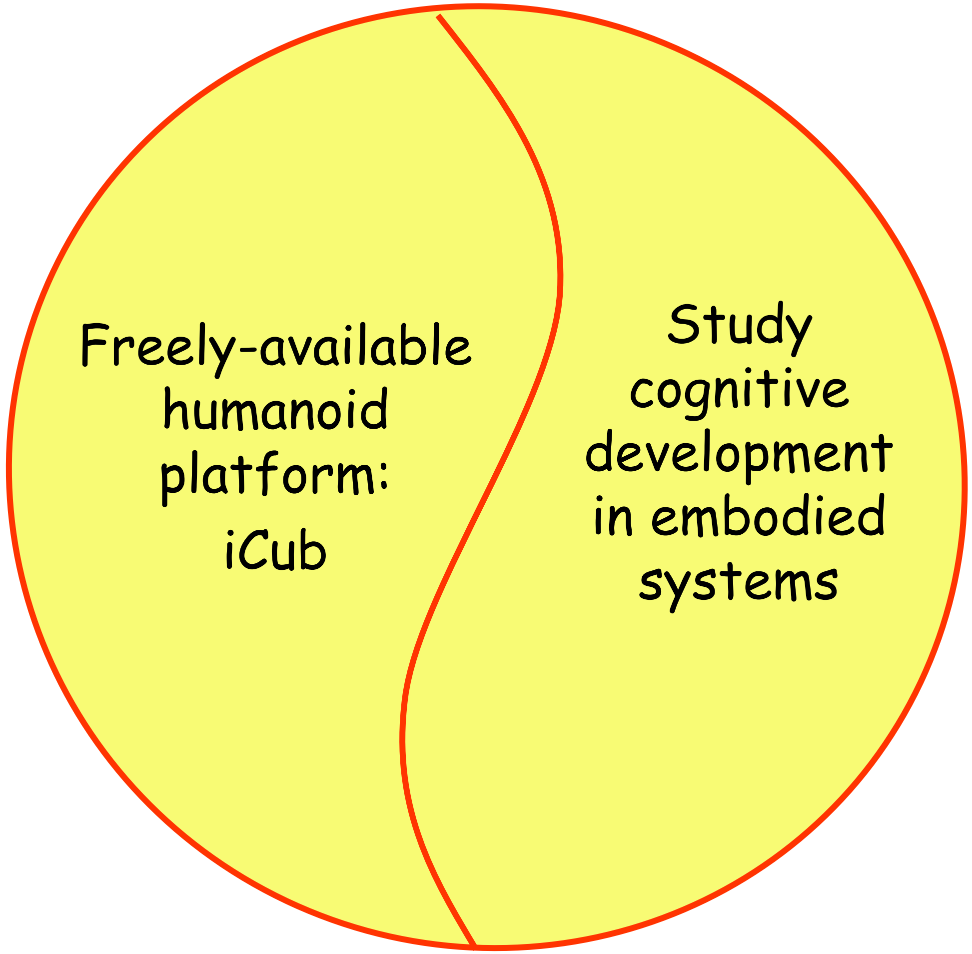
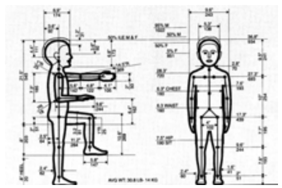
Two Complementary Goals



RobotCub

GOAL
53 degree of freedom
cognitive humanoid robot

PRACTICAL VALIDATION
Hand-eye coordination
Grasp and manipulate lightweight objects
Crawl on all fours and sit up



TARGET DOMAIN
Open research platform:
humanoid robot size & shape
of a 2 year old child
(FDL & GPL)

FOCUS
Co-development of cognitive skills
through **exploration** and **manipulation**

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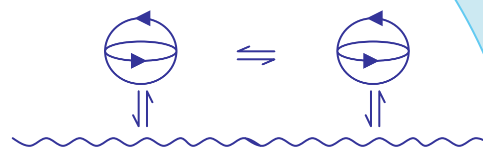
RobotCub

CORE IDEA

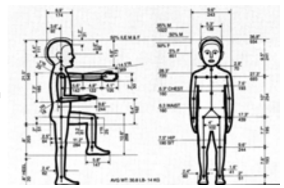
Cognition emerges through exploratory learning and co-development through embodied physical interaction



CRITICAL ISSUES

Phylogenic configuration *vs* Ontogenic development:

The Cognitive Architecture



CORE IDEA

Initially deals with immediate events

Increasingly acquires a predictive capability

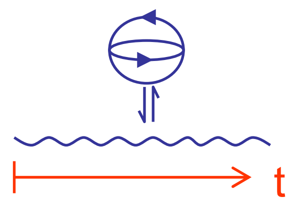
CRITICAL ISSUES

Exploration

Manipulation

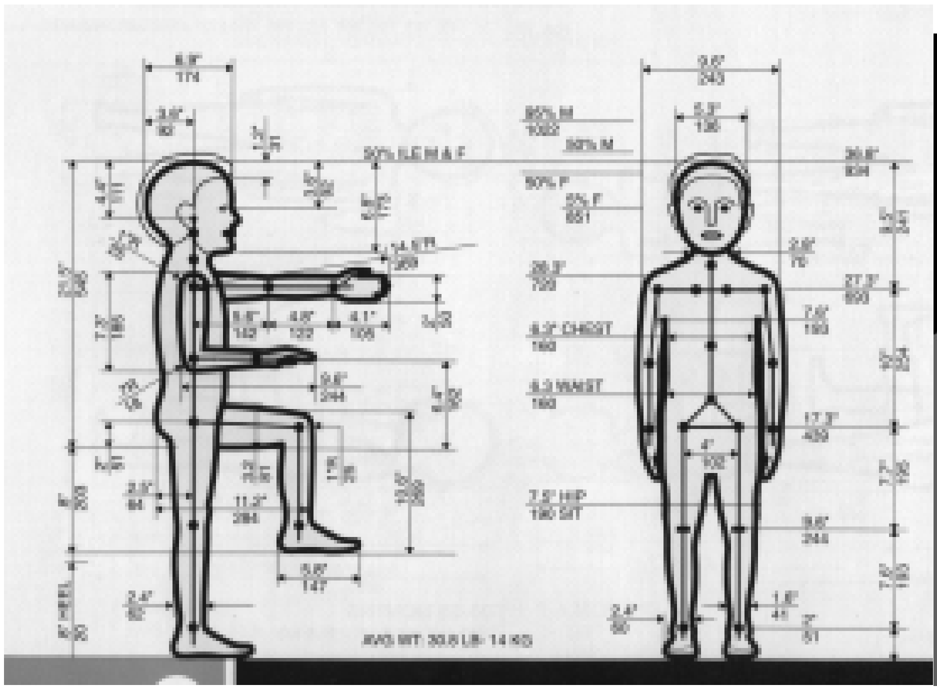
Imitation

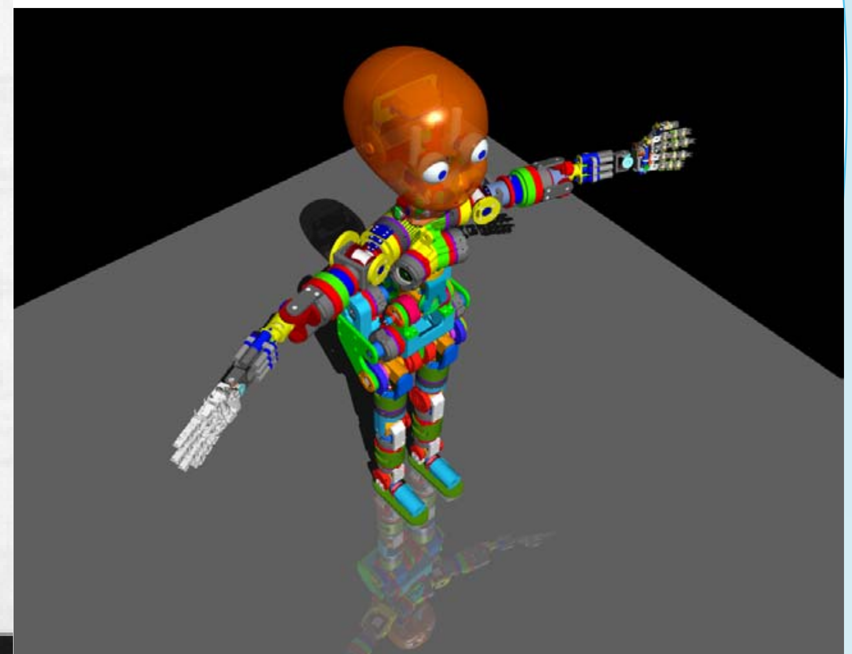
Gestural Communication



Anticipation / Planning / Deliberation / Prediction

iCub
Open Cognitive Humanoid Robot





iCub
Open Cognitive Humanoid Robot

- The iCub will be a full humanoid robot sized as a two and half year-old child
- The total height is estimated to be around 90cm
- It will have 53 degrees of freedom (dof), including articulated hands to be used for manipulation and gesturing
- The robot will be able to crawl and sit and autonomously transition from crawling to sitting and vice-versa.

iCub
Open Cognitive Humanoid Robot

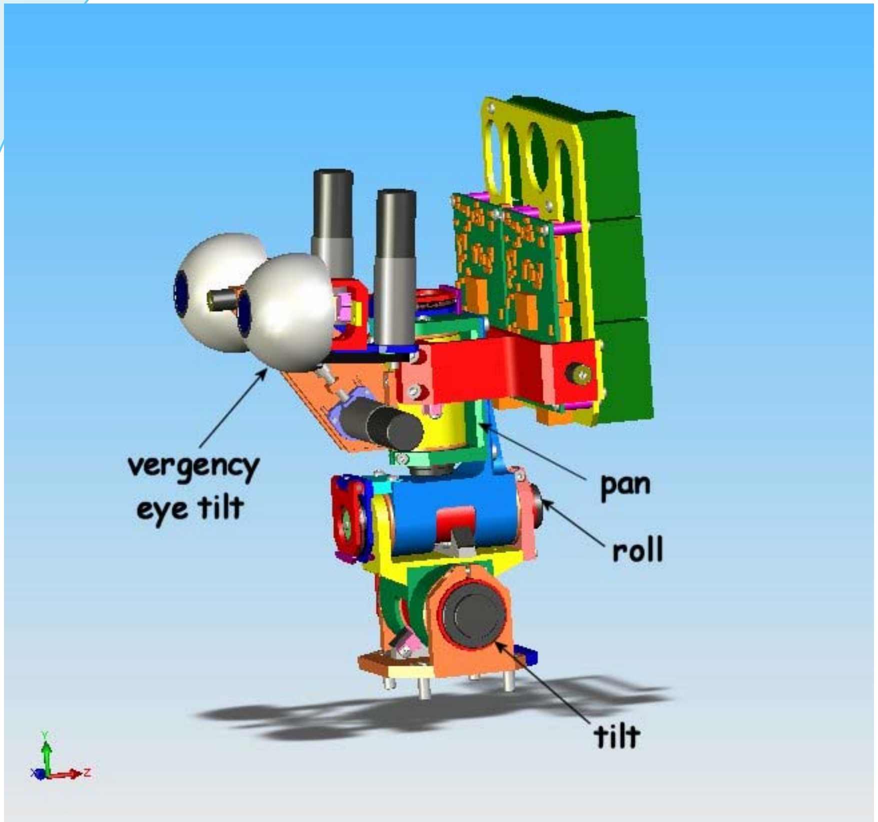
I from "I-Robot"

Cub from "man-cub" (Kipling's 'Jungle Book')

1. Trademark registration procedure has been started for the name iCub
2. Internet Domain Names have been registered

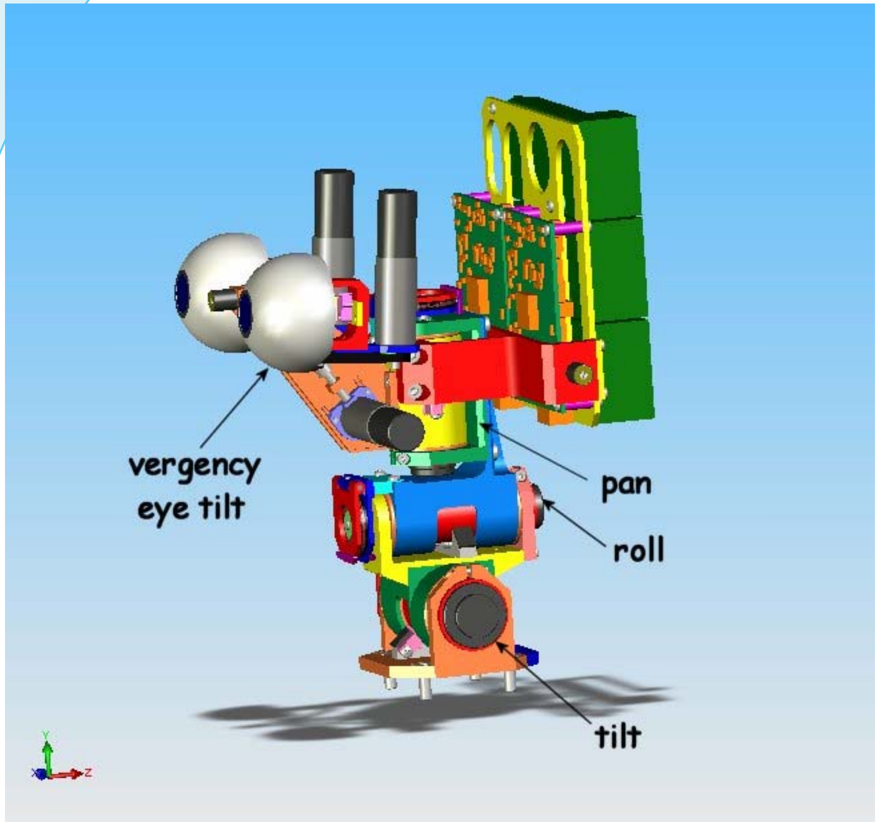
iCub

Open Cognitive Humanoid Robot



- 3 DOF serial neck
- modular design
- indipendent vergency (2dofs)
- eye tilt
- overload protection on neck
- absolute sensors on neck
- integrated sensors and electronics

iCub
Open Cognitive Humanoid Robot



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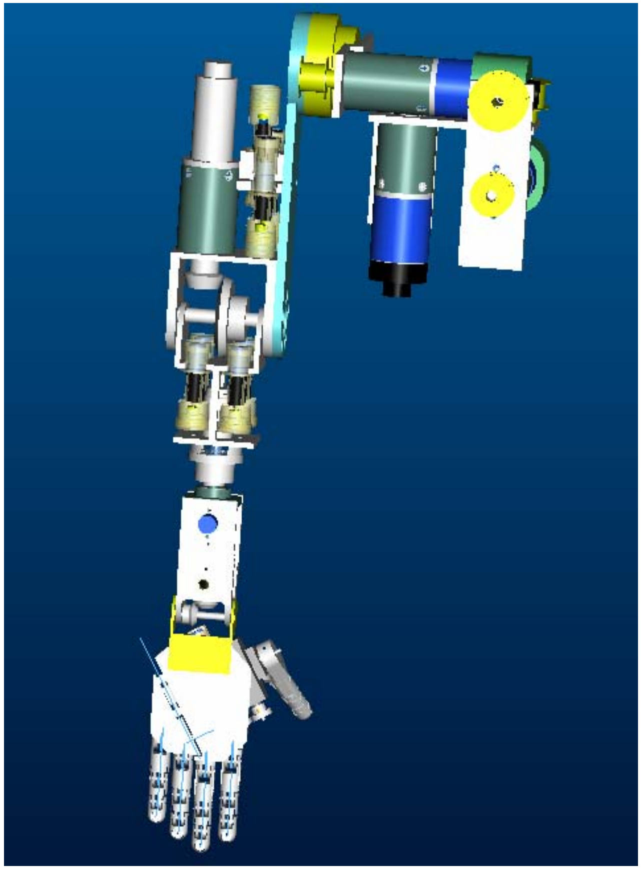
Cogsys Cognitive Systems



iCub

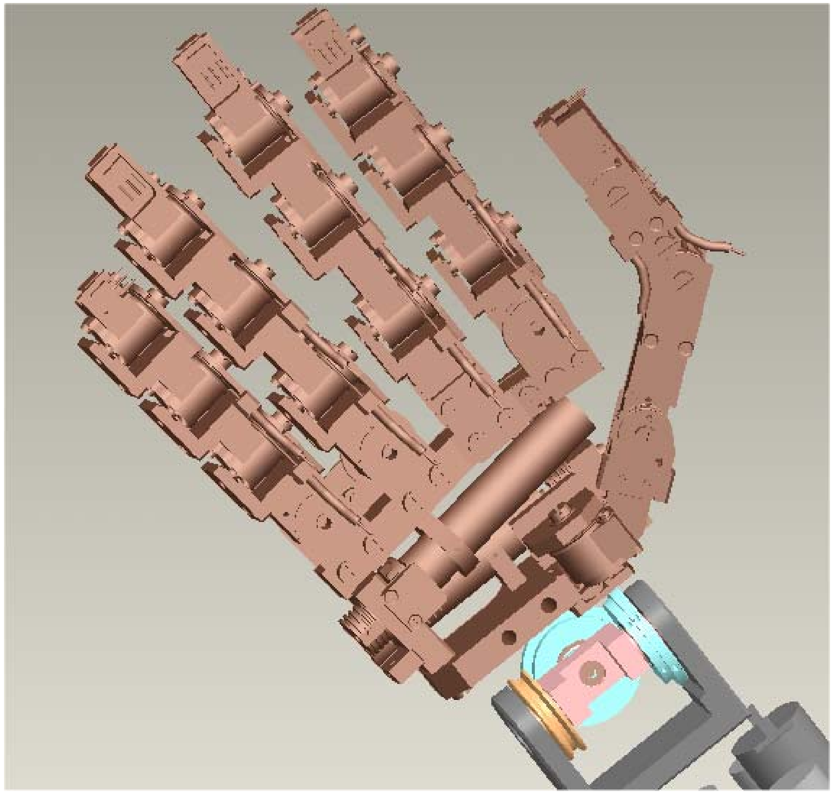
Open Cognitive Humanoid Robot

3 DOF shoulder timing belt driven

1 DOF elbow conical gear driven

3 DOF wrist(mixed transmission)

hand actuator relocation along the arm



iCub

Open Cognitive Humanoid Robot

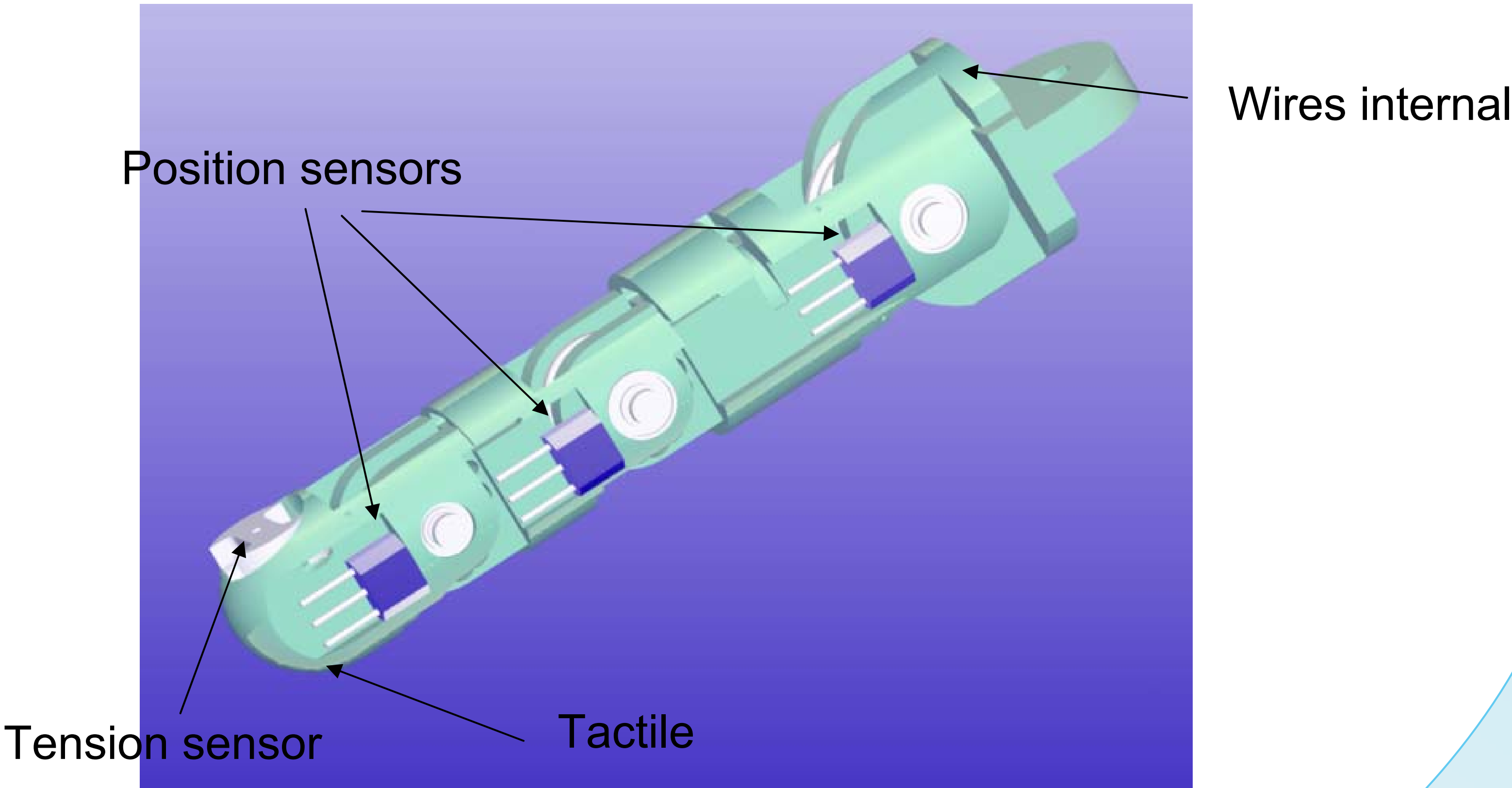
9 controlled DOF on hand

finger underactuation (21 DOF in total)

absolute position sensor on finger joint

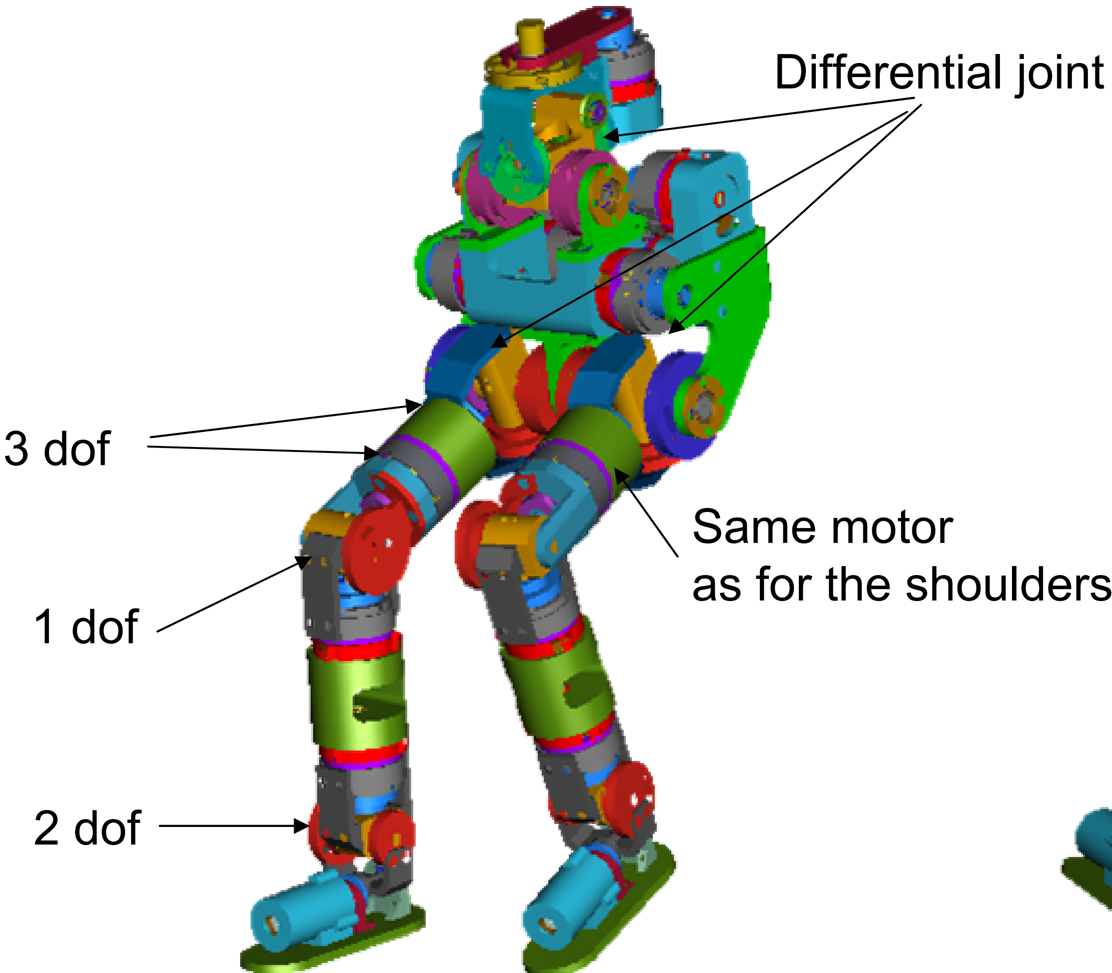
tension sensor on finger tendons

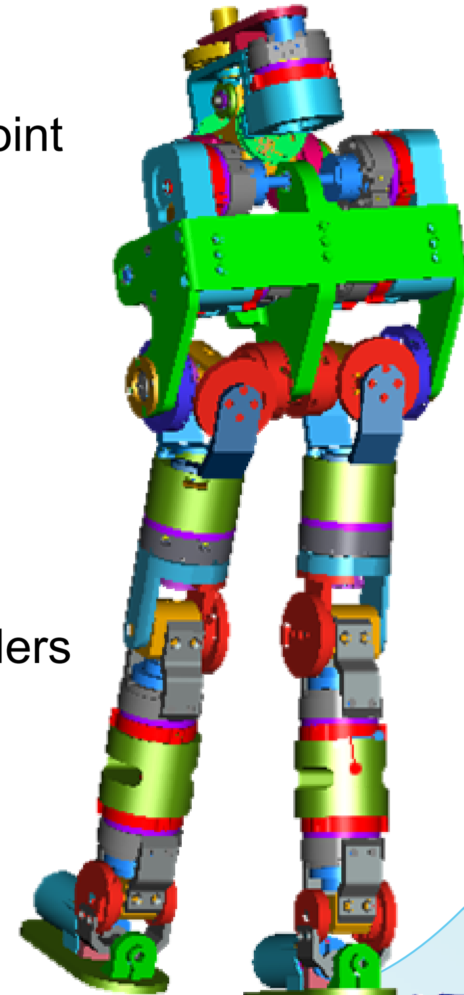
tactile sensor (still under implementation)


Wires internal
Position sensors
Tension sensor
Tactile

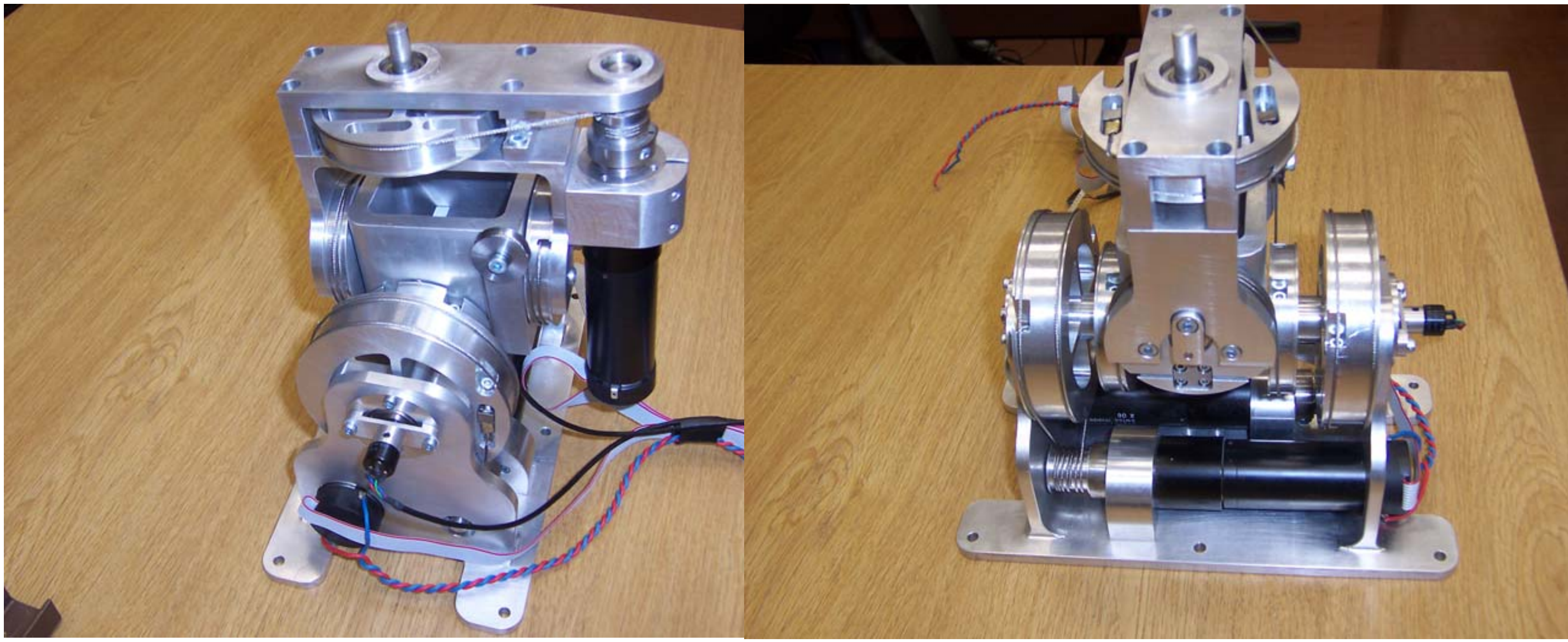
iCub

Open Cognitive Humanoid Robot



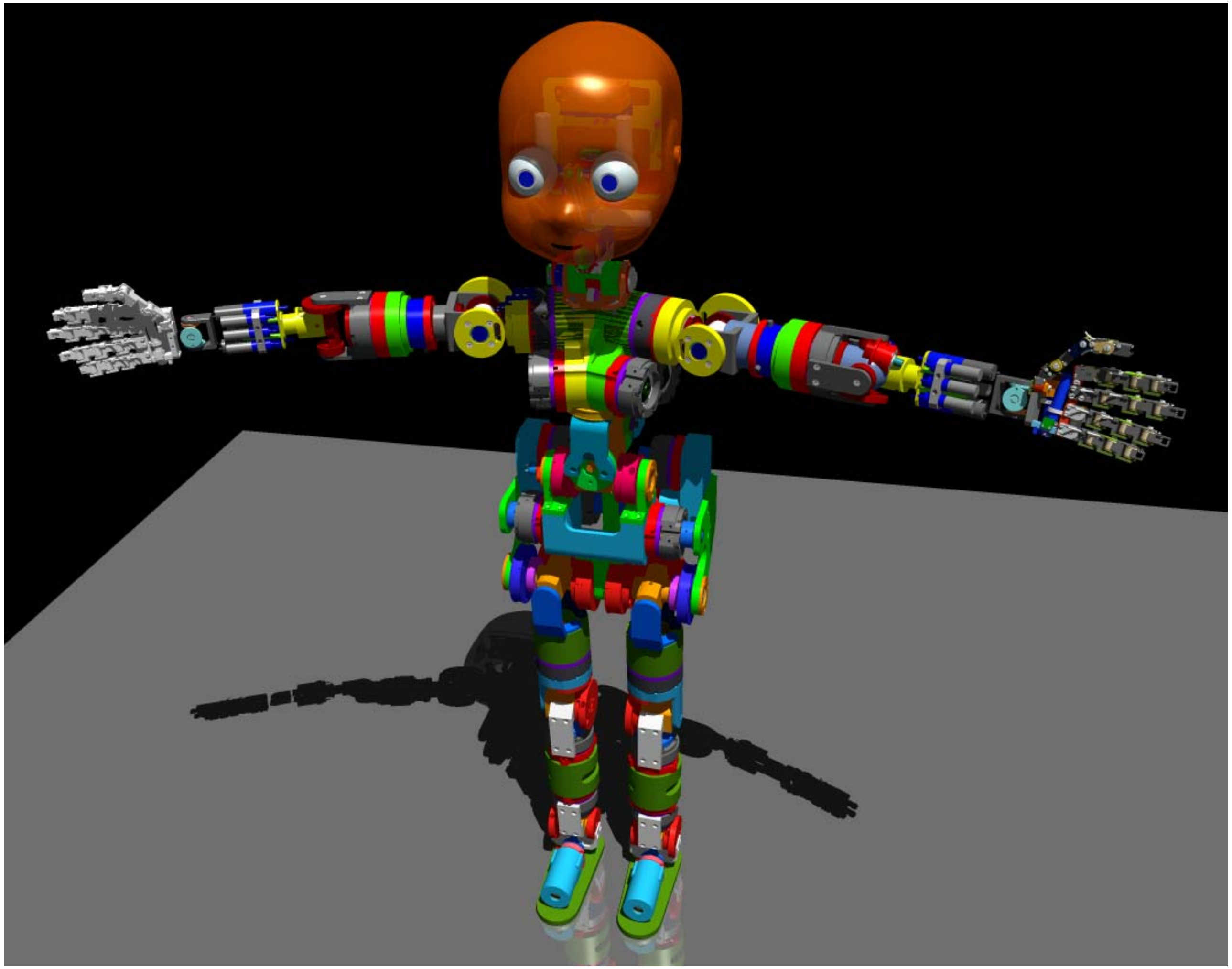


RobotCub



Waist prototype

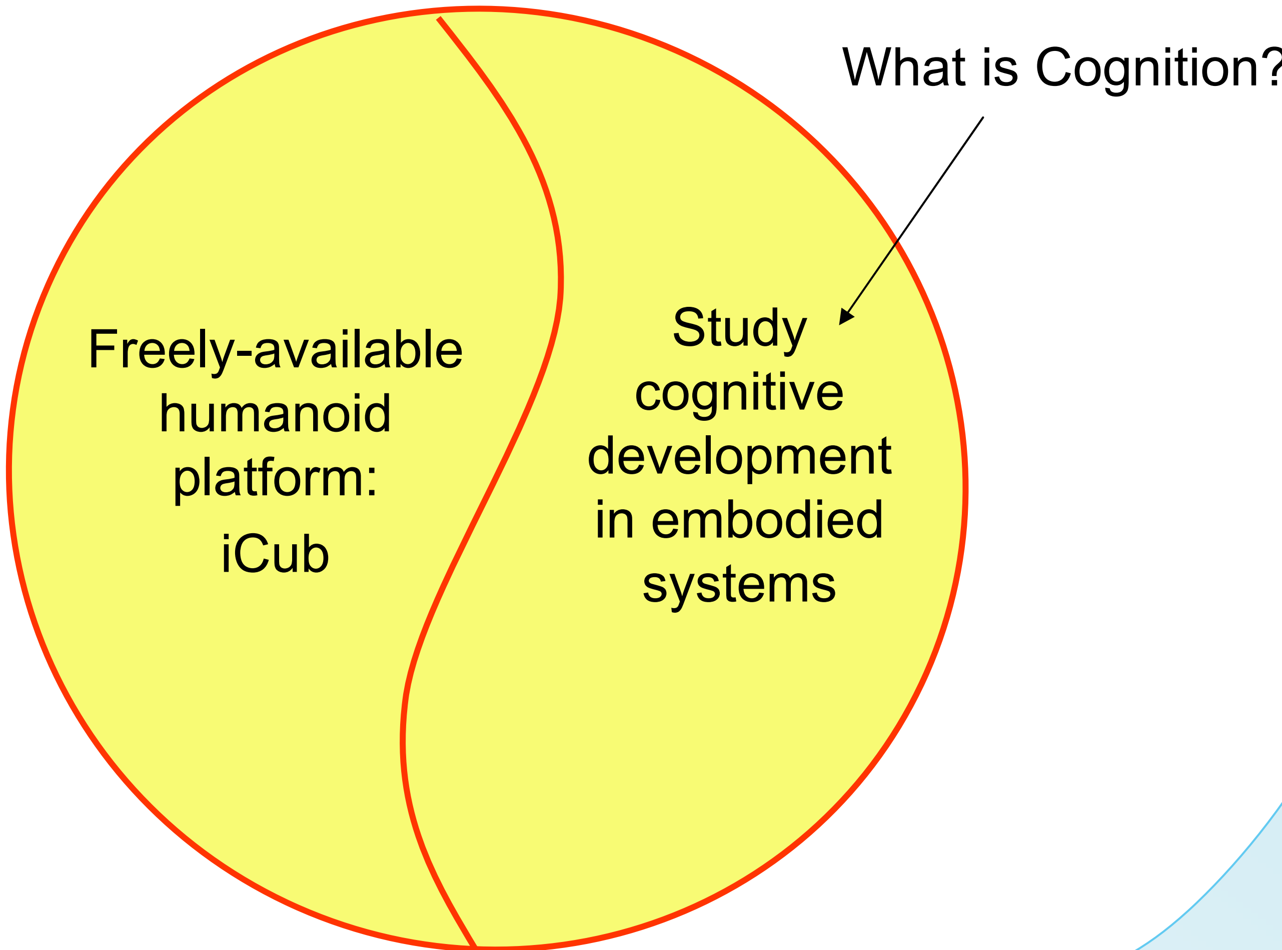
RobotCub



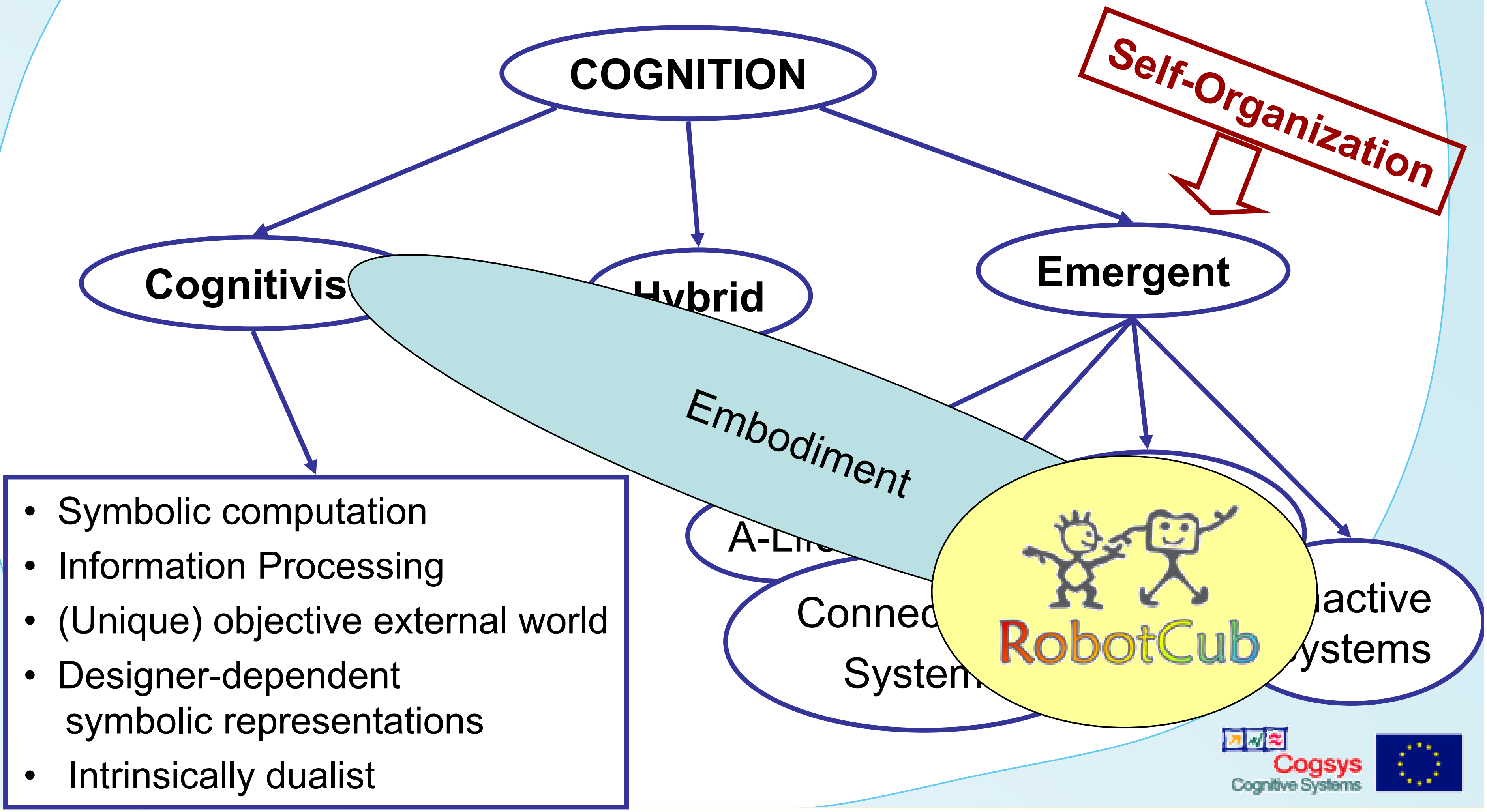
iCub

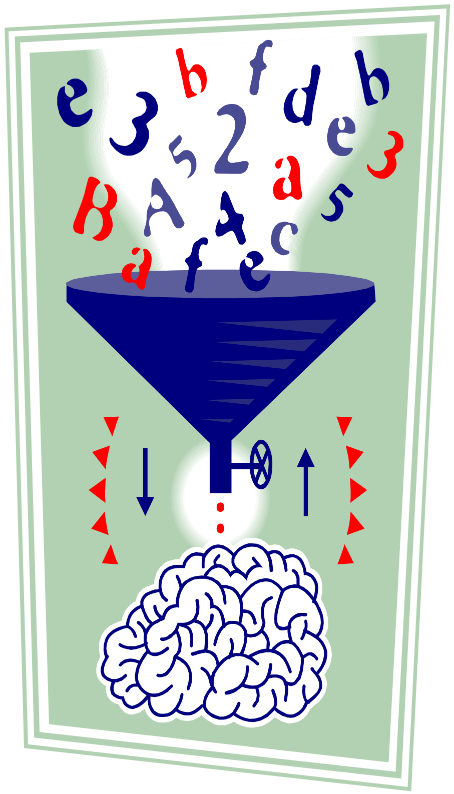
Open Cognitive Humanoid Robot

Cogsys Cognitive Systems


What is Cognition?
Freely-available humanoid platform:
iCub
Study cognitive development in embodied systems

Paradigms of Cognitive Systems





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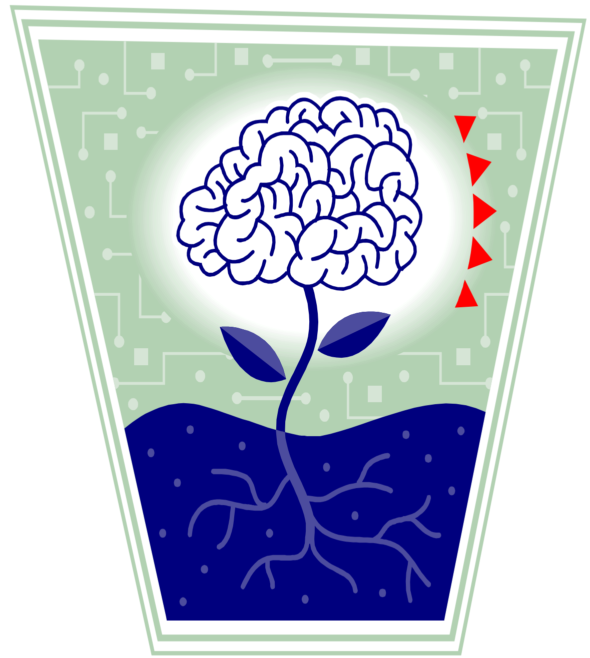


The RobotCub Approach

Guiding Philosophy

- Cognition cannot be hand-coded (can't short-circuit ontogeny)
- Necessarily the product of a process of embodied development
- Initially dealing with immediate events ⟼ t
- Increasingly acquiring a predictive capability ⟼ t

Cognition and perception are functionally-dependent on the richness of the action interface

The RobotCub Approach

Emergent embodied cognitive systems:

- Given a rich set of innate action and perception capabilities
- Develop over time an increasing range of cognitive abilities
- Recruiting ever more complex actions
- Achieving an increasing degree of prospection (and, hence, adaptability and robustness)

The RobotCub Approach

Cognitive development involves several phases

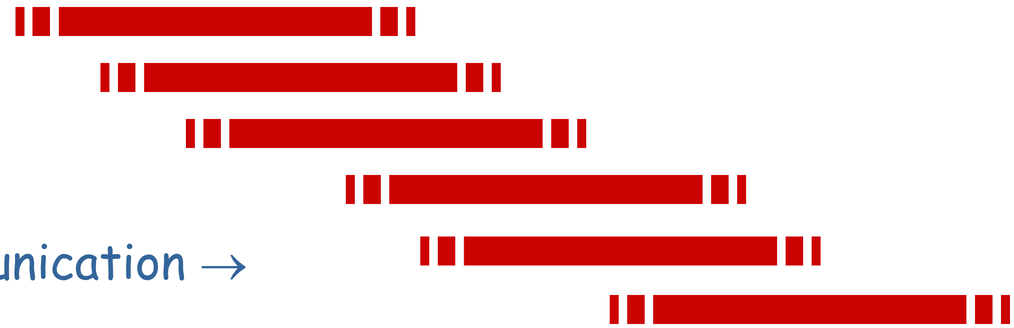
1. Coordination of eye-gaze, head attitude, hand placement when reaching

2. Dexterous manipulation of the environment: learn the affordances in the context of one's own developing capabilities

3. Ideally, communicate through gestures, simple expressions of its understanding, achieved through
   - rich manipulation-based exploration & social contact
   - imitation
   - multi-agent social interaction

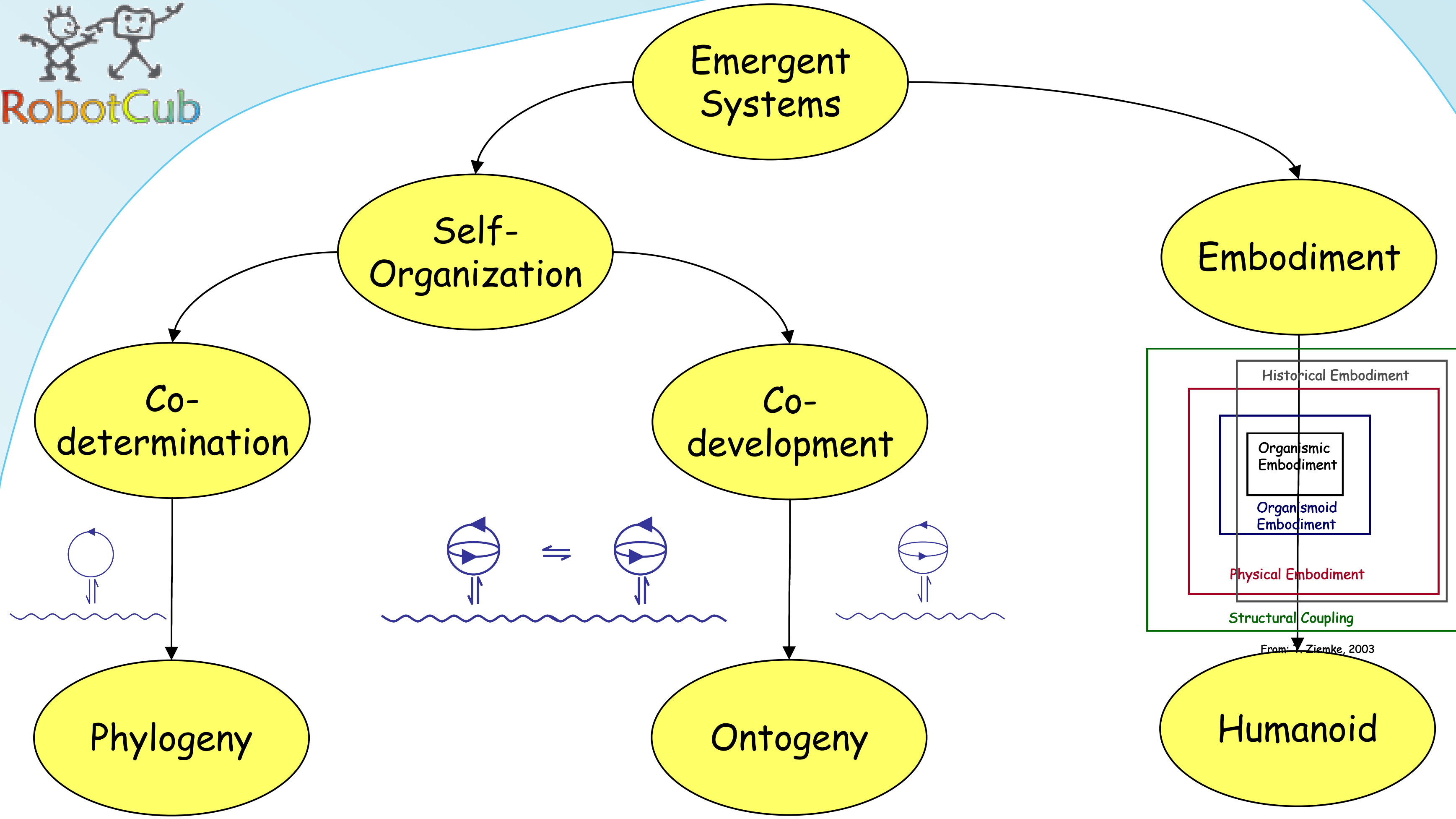
More complex and revealing exploratory use of action

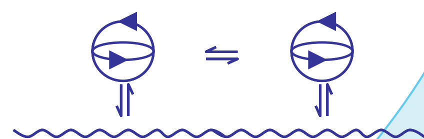
reaching →
grasping →
manipulation →
imitation →
gestural communication →
language



Scientific Framework

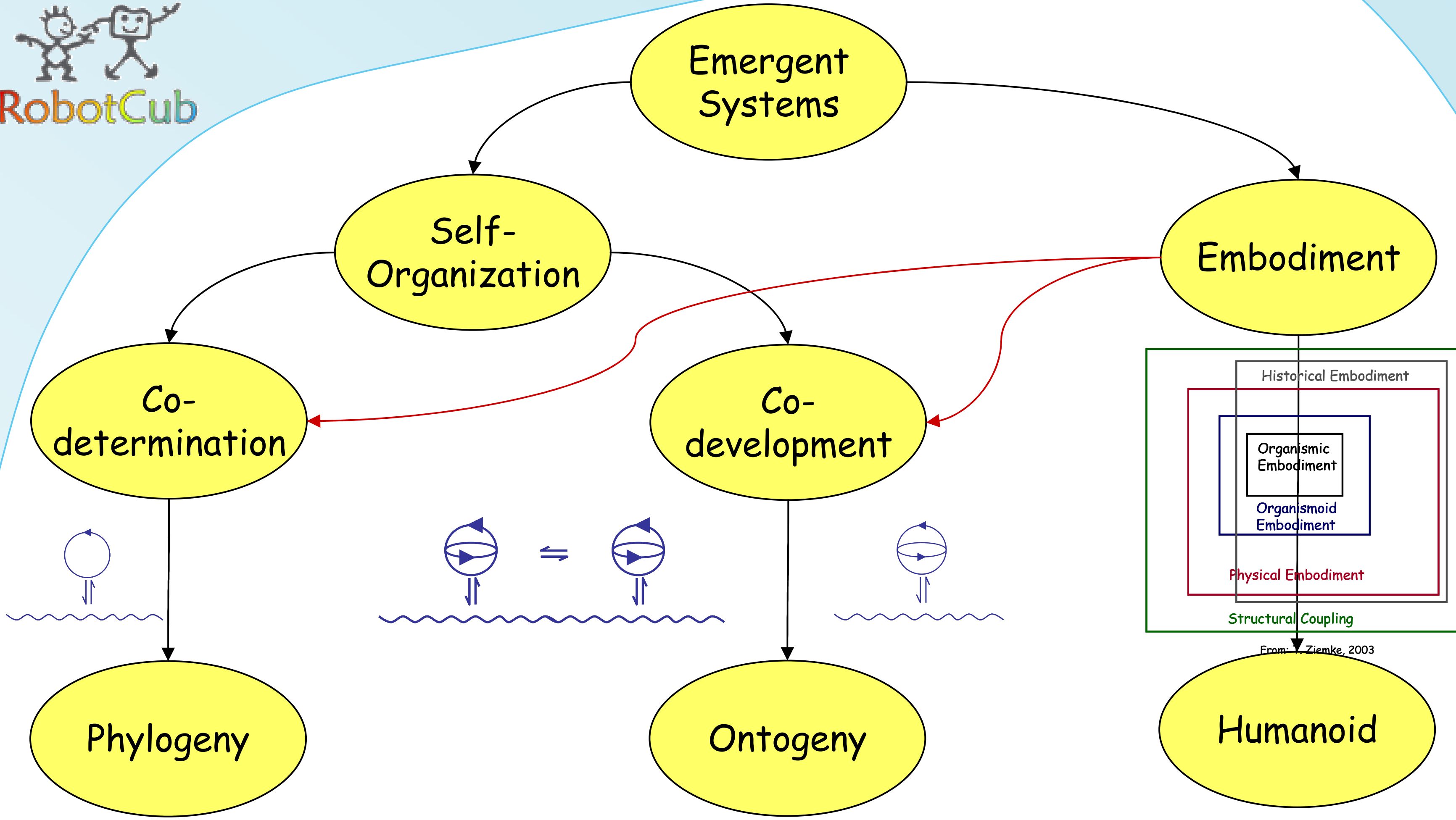
(Why development in humanoid form is important for cognition)



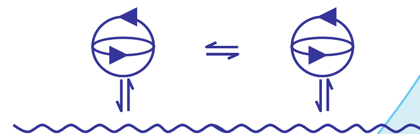


Meaning emerges through interaction

Therefore, we require a humanoid embodiment
to effect mutually-consistent meanings

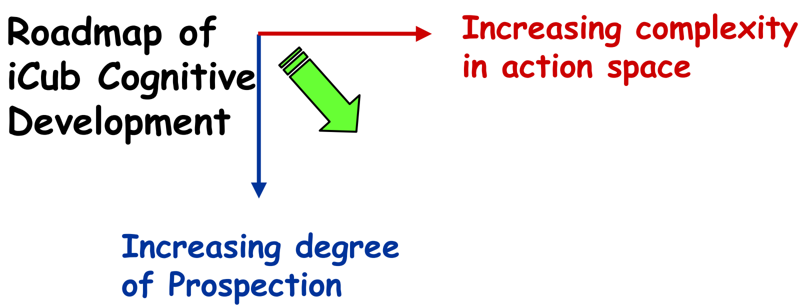


Morphology impacts on both phylogeny and ontogeny:



Ontogenic Development: Gradual acquisition of a prospective capability

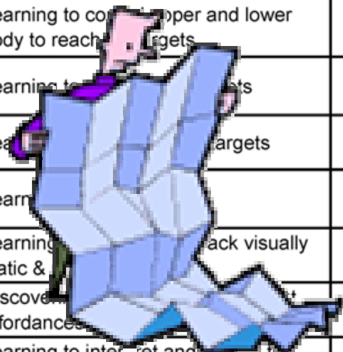
1. Body Movement / Locomotion
2. Eye-Head-Hand Coordination
3. Bi-manual co-operation
4. Affordances
5. Imitation
6. Gestural Communication



Roadmap of iCub Cognitive Development
The Space of Ontogeny: Action & Prospection

Recruited Actions → Increasing complexity in action space

Ontogenic Development ↓ Increasing degree of Prospection



		Locomotion	Eye-head-hand Coordination	Bimanual Cooperation	Interaction and Affordance	Interaction and Imitation	Interaction and Communication
Discovering the manipulation abilities of its own body	Learning to co[illegible]pper and lower body to reach[illegible]rgets						
	Learnin[illegible]ts						
	Le[illegible]argets						
	Learn[illegible]						
Discovering and representing the shape of objects	Learning[illegible]ack visually static & [illegible]						
	Discove[illegible] affordance[illegible]						
Recognizing manipulation abilities of others and relating those to one's own manipulation abilities	Learning to interpret and [illegible] gestures of others						
	Learning motor skills & affordances by imitating manipulation tasks						
	Learning what to imitate & when to imitate others' gestures						
Learning regulating interaction dynamics	Approach, avoidance, turn-taking, and social spaces						
	Learning to use gesture as a means of communication						
Developing personality via autobiographic memory based on interaction histories	Learning about meaningful events in the lifetime of the robot						
	Sharing memory (events) during interaction						

The Phylogeny and Ontogeny of Natural Cognitive Systems

(Identify the iCub Phylogeny and Ontogeny)

Development of Cognition in Nature
Neonatal Cognitive Systems

Actions organize cognitive behaviour

Actions are:

- Motivated
- Guided by prospection … predictive control
- Neonatal movements are action-based
- Actions vs. reflexes

Development of Posture and Locomotion

M3	First sign of being able to control gravity (prone)
M6-8	Sitting (control of sway of head and trunk) Transfer from two-handed to one-handed reaching
M12	Infants who stand are very sensitive to peripheral visual information; sensitivity decreases with experience

Development of Cognition in Nature
Neonatal Cognitive Systems

Development of Looking

M0	Vestibular gaze stabilization
M0	Saccadic eye movement, develops rapidly to M6
M0	Very limited smooth pursuit ability
M0	Attentional processes: Gaze directed towards attractive objects (novelty)
M1.5	Rapid improvement of smooth pursuit
M3-4	Infants achieve adult level of smooth pursuit

Development of Cognition in Nature
Neonatal Cognitive Systems

Development of Reaching and Manipulation

M0	Visual control of arm; no control of fingers for grasping Arm & finger motion coupled; hand is open when extending arm
M2	Coupling of global arm & finger motions broken; hand is fisted when extending arm
M2-3	Open hand when reaching but only when visually-guided; hand closing when close to object
M4-5	Reaching and grasping
M5	Hand not adjusted to size of object when reaching
M9	Onset of adjustment of hand size when reaching
M9-10	Differentiated finger grasping (e.g. pincer grasp)
M13	Grasping starts when reaching

Development of Cognition in Nature
Neonatal Cognitive Systems

Development of Social Abilities

M3-6	Can detect approximately-correct gaze direction
M10-12	Can follow gaze

Observations and Insights

Perception is action-dependent

Perception is prospective

Perception is highly integrated among sensory modalities

Perception is task specific

Perceptual abilities are developed (both phylogenic and ontogenic)

Perception of humans is critical (face, emotion, gaze ..)

Perception of affordances is learned

Different modes of perception:
    local/focal perception (first) vs. global/ambient perception (later)

Perception requires unsupervised on-line learning

Neuroscience of Cognition in Nature

(Identify the iCub Phylogeny and Ontogeny)

Neuroscience of Cognition in Nature

Co-dependence of action and perception

- Conventional thinking
  - Ventral stream: object recognition
  - Dorsal stream: spatial location
  - Posterior parietal cortex: unique site of space perception
- Recent results
  - No general purpose space map
  - Space perception: joint activity of several fronto-parietal circuits
  - Space encoded in different ways in different circuits based on different motor/effector needs and different sensory input
  - Motor system is also involved in semantic understanding of percepts
  - **Same issues also apply to the issue of "object" perception**

Neuroscience of Cognition in Nature

Co-dependence of action and perception (Selective Attention)

- Dependence on oculo-motor programming
  - Eye is close to limit of rotation
  - Can't saccade any further in one direction

  } Visual attention is attenuated in that direction

- Ability to detect an object is enhanced when appearance coincides with grasp configuration of a subject preparing to grasp

  } Subject's actions condition its perceptions

Take-home Message:

No single multi-purpose centre in the brain which knows everything and directs attention;

Instead, to direct attention we use potential actions (activate representations of action)

Work-in-Progress Models

RobotCub

Recruited Actions → Increasing complexity in action space

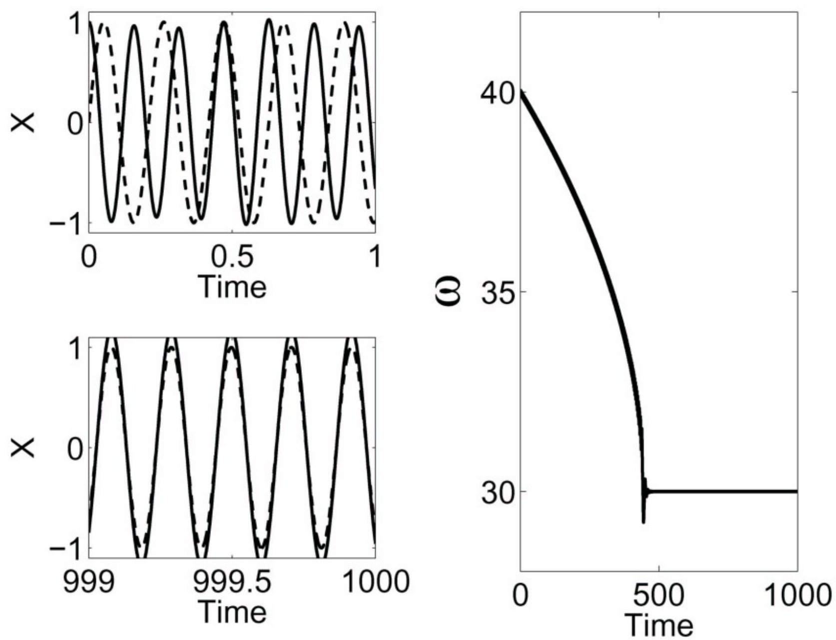
Ontogenic Development ↓ Increasing degree of Prospection

		Locomotion	Eye-head-hand Coordination	Bimanual Cooperation	Interaction and Affordance	Interaction and Imitation	Interaction and Communication
Discovering the manipulation abilities of its own body	Learning to control upper and lower body to reach for targets	✓	✓	✓		✓	
	Learning to reach static targets	✓	✓	✓		✓	
	Learning to reach moving targets	✓	✓	✓	✓		
	Learning to balance	✓	✓				
Discovering and representing the shape of objects	Learning to recognize & track visually static & moving targets		✓		✓		
	Discovering and representing object affordances				✓		
Recognizing manipulation abilities of others and relating those to one's own manipulation abilities	Learning to interpret and predict the gestures of others	✓	✓		✓	✓	✓
	Learning motor skills & affordances by imitating manipulation tasks					✓	
	Learning what to imitate & when to imitate others' gestures					✓	
Learning regulating interaction dynamics	Approach, avoidance, turn-taking, and social spaces		✓		✓	✓	✓
	Learning to use gesture as a means of communication					✓	✓
Developing personality via autobiographic memory based on interaction histories	Learning about meaningful events in the lifetime of the robot						✓
	Sharing memory (events) during interaction						✓

Self-Adaptive (Programmable) CPG

Adaptive Hopf Oscillator

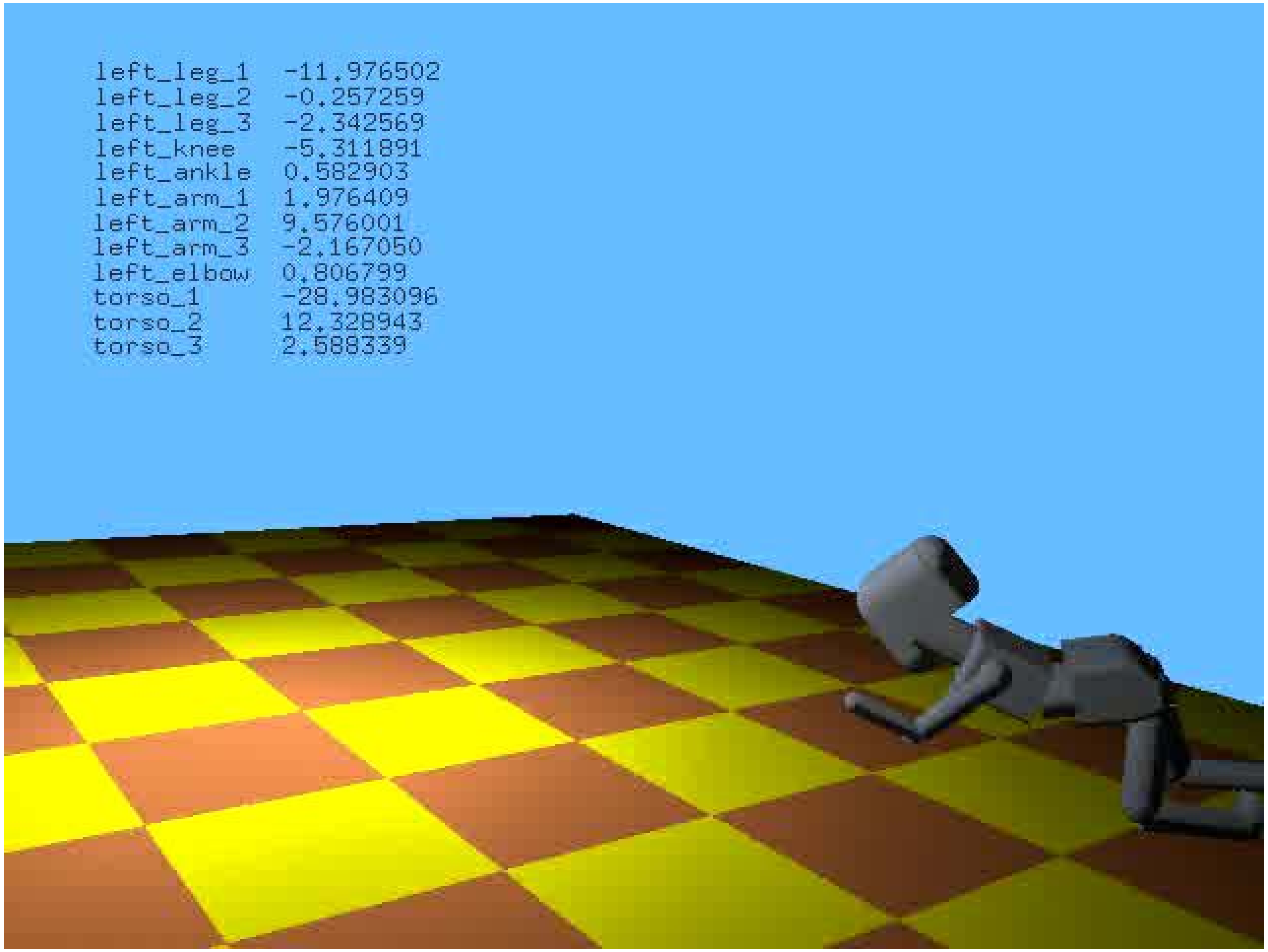
$$\begin{aligned}\dot{x} &= \gamma(\mu - (x^2 + y^2))x - \omega y + \epsilon F(t) \\ \dot{y} &= \gamma(\mu - (x^2 + y^2))y + \omega x \\ \dot{\omega} &= -\epsilon F(t) \frac{y}{\sqrt{x^2 + y^2}}\end{aligned}$$



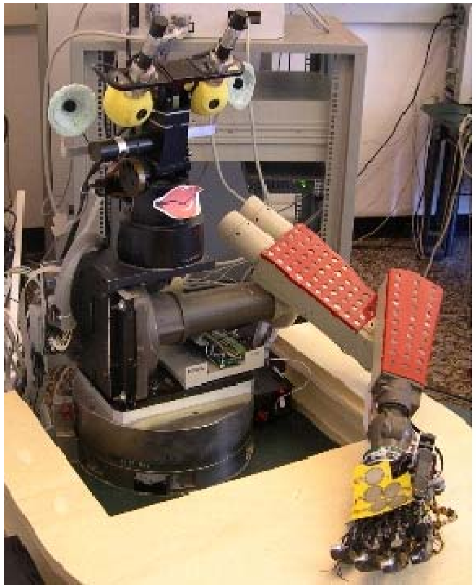
- Easy learning of any periodic signal
- Stability against perturbations
- Easy modulation of the pattern
- Synchronization properties (with other CPGs, with the environment or with the body dynamics)

Construct CPG using ADAPTIVE coupled oscillators

École Polytechnique Fédérale de Lausanne



University of Genoa

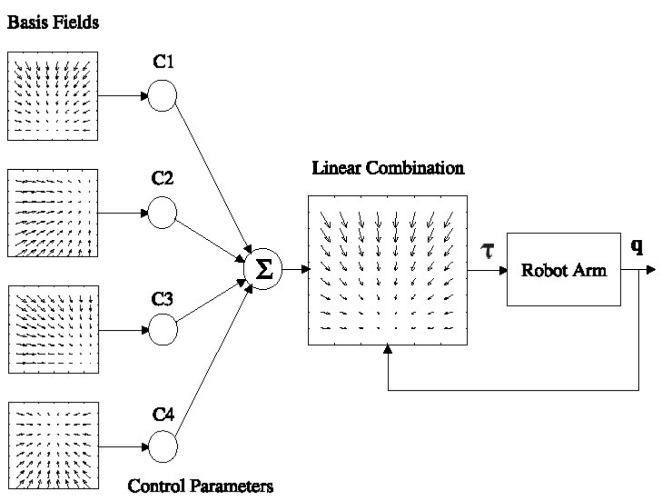


Visually-guided Reaching and Grasping

Assume fixation point -> object

Map eye-head proprioceptive data to arm control parameters (trained by fixating on hand)

Control parameters modulate linear combination of basis torque fields (i.e. torque to be applied to group of actuators to achieve a particular equilibrium point)



Eye-hand motor commands:
- Direct gaze at fixation point
- Control arm motors

Motor-motor control

Colour segmentation &
Log-polar sensor

Reaching Movement Imitation

Predicting human motion is key to human-robot interaction

RobotCub

Recruited Actions → Increasing complexity in action space

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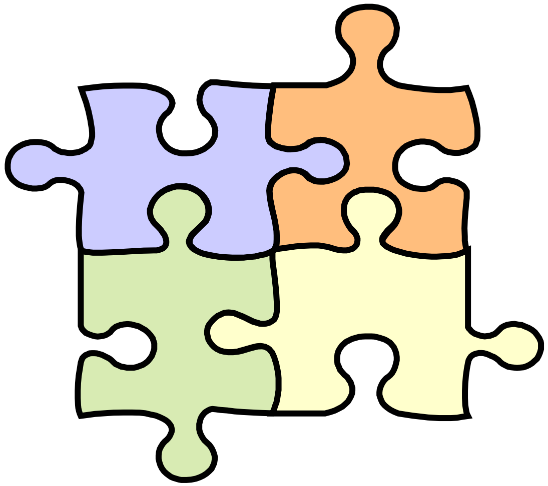
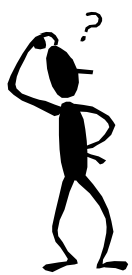
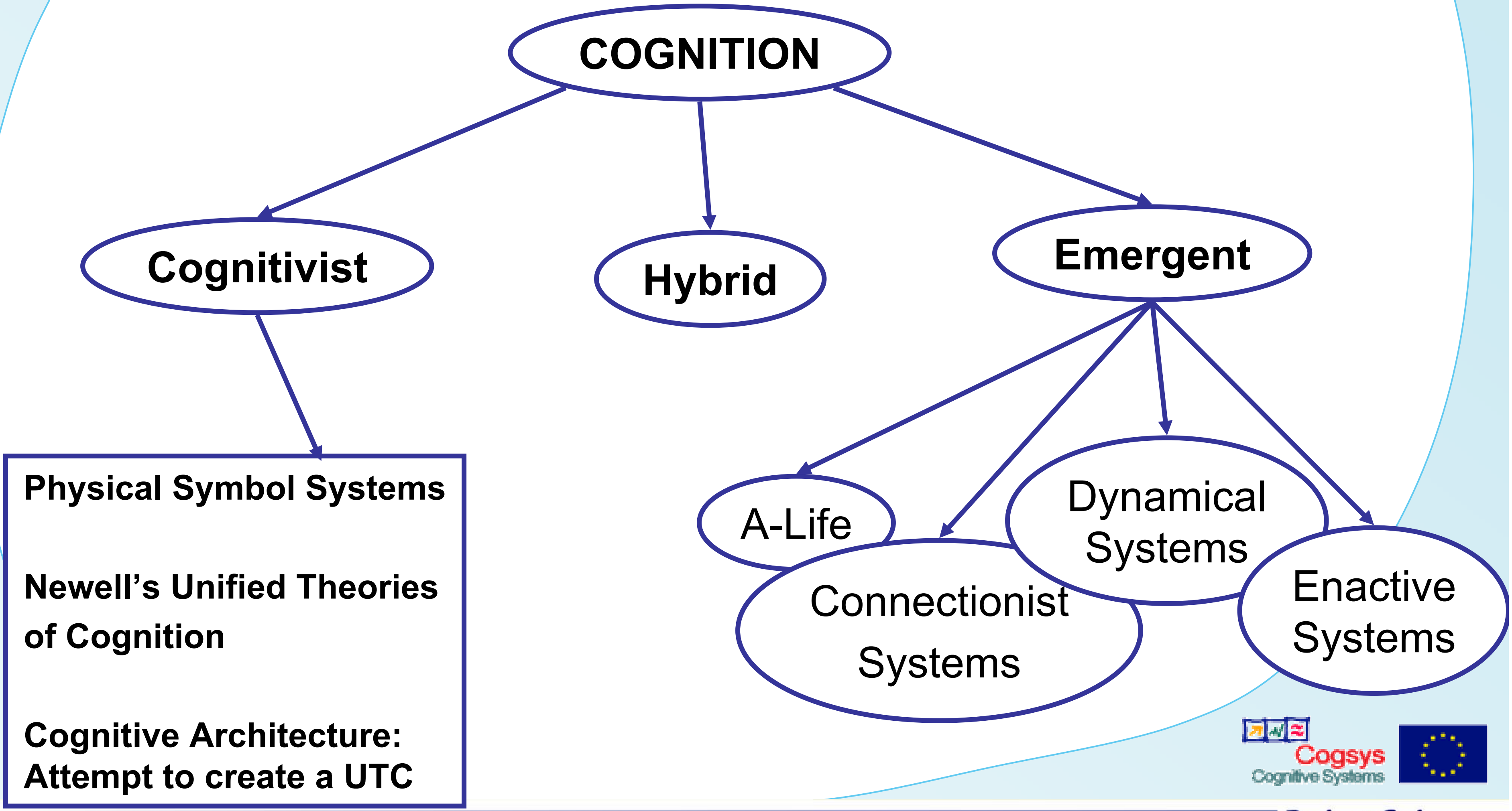
Cognitive Architecture



What is a Cognitive Architecture?

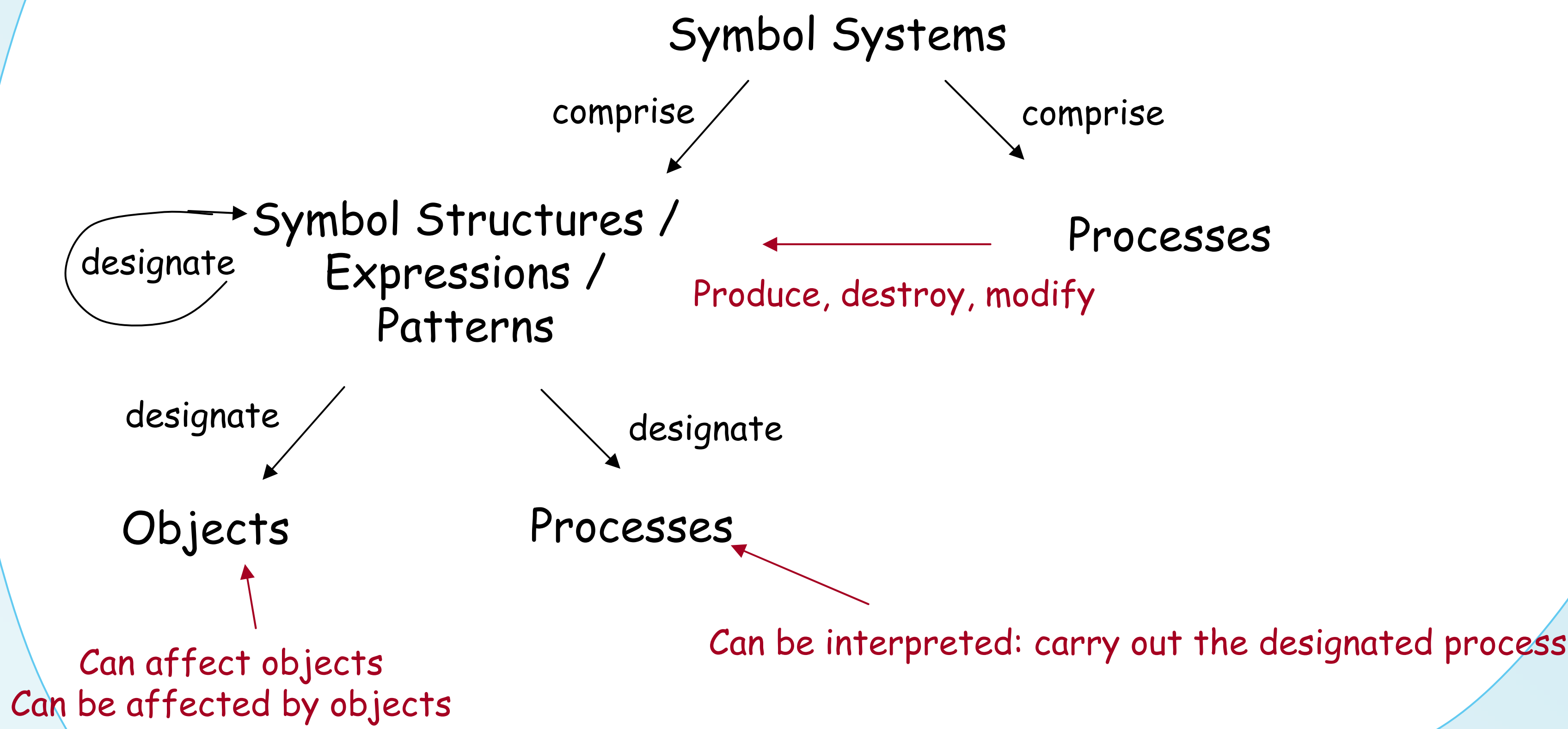


Cognitive Architecture



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

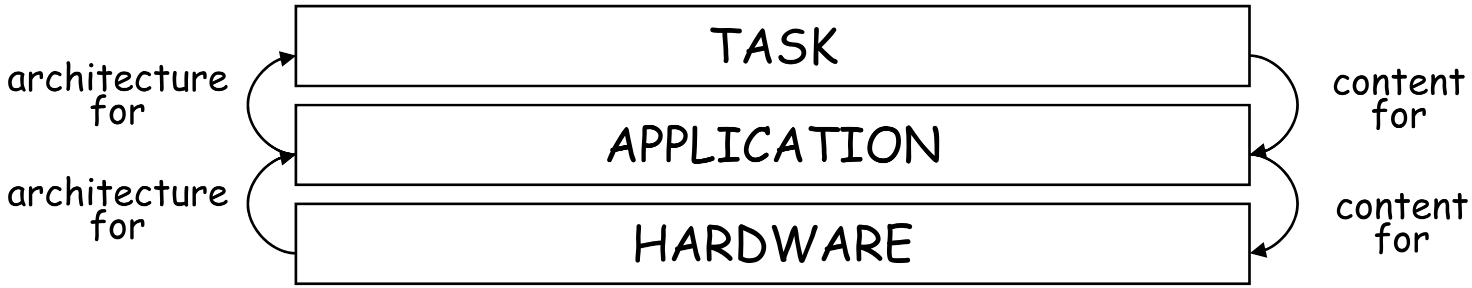
relatively constant over time and

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

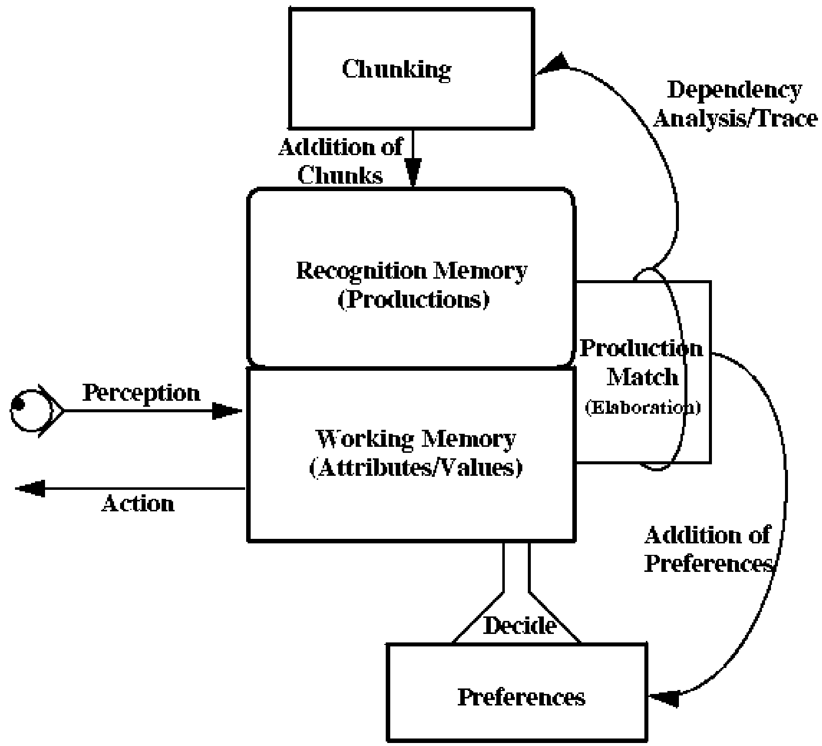
- Short-term & long-term memories that store the agent's beliefs, goals, and knowledge
- Representation & organization of structures embedded in memory
- Functional processes that operate on these structures
  - Performance / utilization
  - Learning
- Programming language to construct systems embodying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

[Langley 05, Langley 06]

Cognitive 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 preference
- Fine-grained knowledge rep
- Universal sub-goaling (dealing with impasse)
- General-purpose learning (encapsulates resolution of impasse)

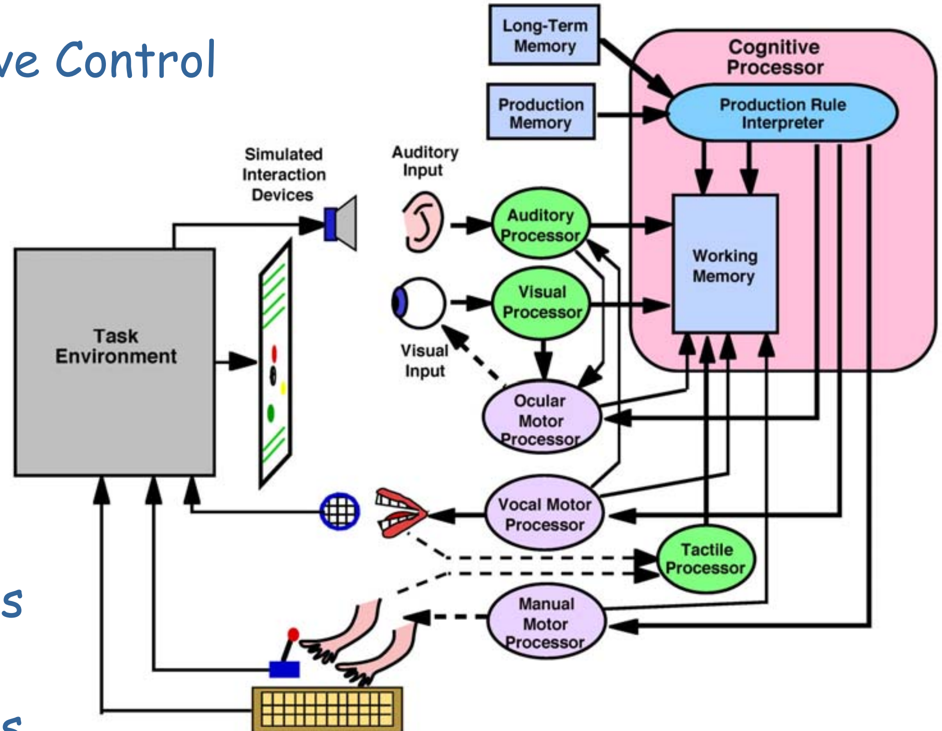


(Based on Figure 3.1, pg 20, The Soar's User Manual, Version 6)

Cognitive Architectures

EPIC [Kieras & Meyer 97]

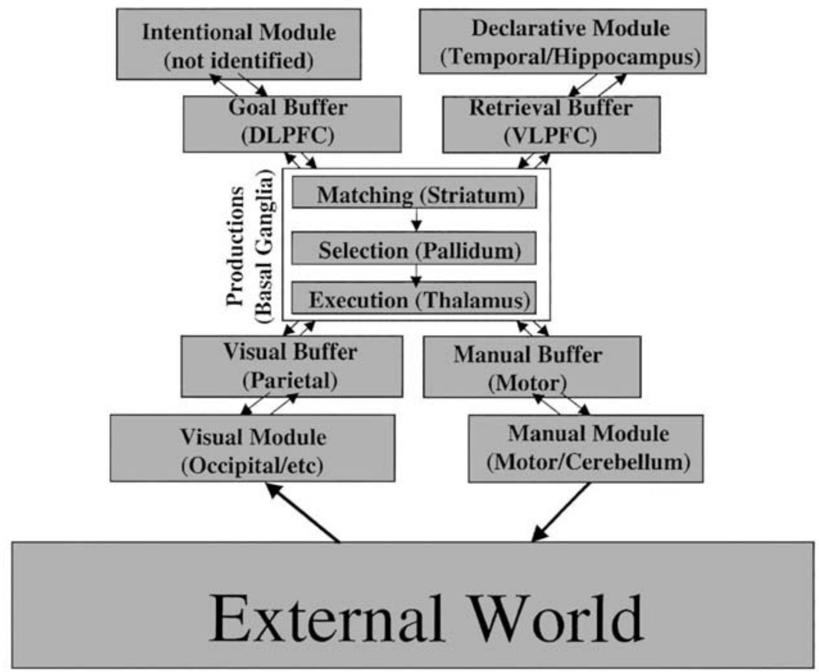
- Executive Process Interactive Control
- Link high-fidelity models of perception and motor mechanisms with a production system
  - Only the timing!
- Knowledge in production rules
- Perceptual-motor parameters
- All processors run in parallel
- No learning



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 Architecture

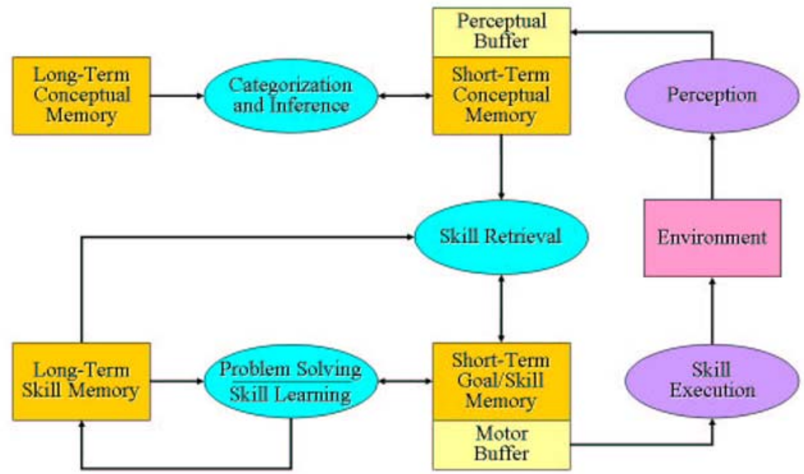
"There is reason to suppose that the nature of cognition is strongly determined by its perceptual and motor processes, as the proponents of embodied and situated cognition have argued"

[Anderson 04]

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 Architecture

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 Architecture

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. Parser
  4. Inference network

- Implements reflective knowledge: knowledge of its own structure and capabilities

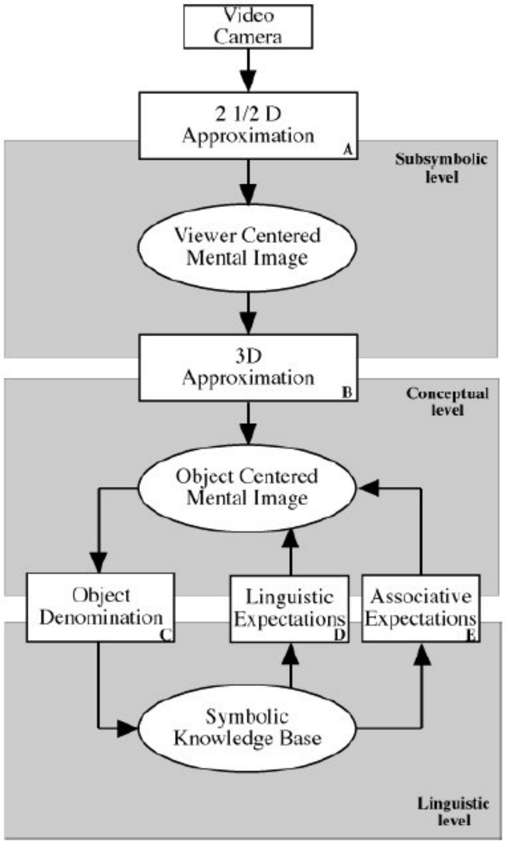
Cognitive Architectures

Other (weaker) cognitive architectures

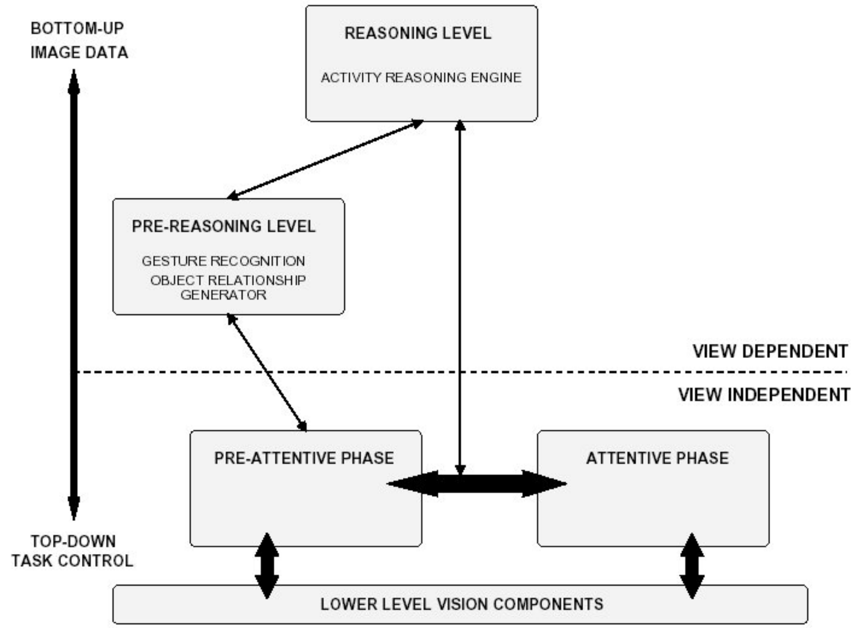
- Vision [Chella et al. 97]
- Vision [Buxton et al. 02]
- Vision [Town & Sinclair 03]
- Vision [Nagel 04]
- Robotic Hand Posture Learning [Infantino et al 05]
- Action-based perception [Granlund 05]

Some Cognitivist Systems

- Cognitive Vision System
  (Chella Frixione Gaglio 97)
  - 3D representations based on superquadrics models
  - Symbolic knowledge using first order predicate logic

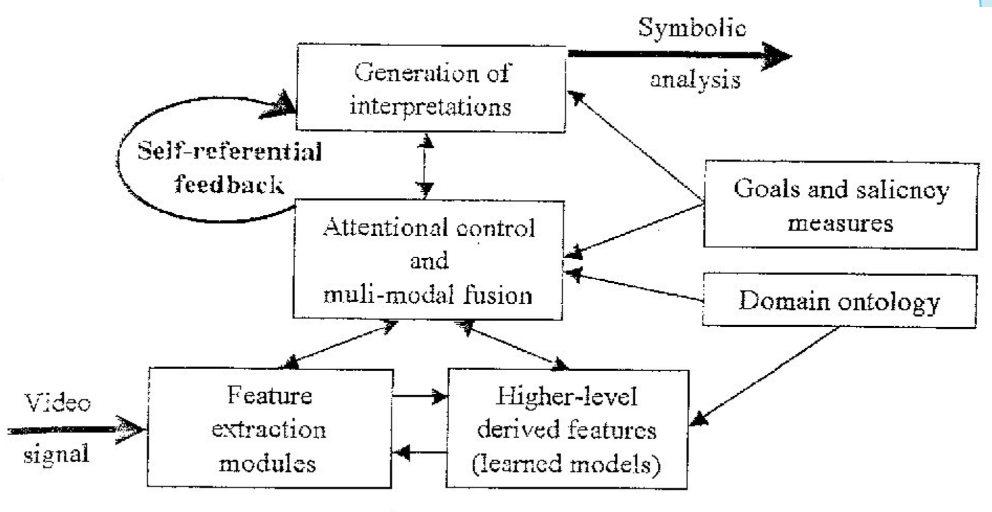


- Cognitive Vision System
  (Buxton Howell Sage 02)
  - Gesture recognition
  - Uses probabilistic (statistical) models
  - Dynamic Decision Networks (extension of Bayesian Belief Networks)
  - Time Delay Radial Basis Function Networks (TDRBFN)
  - Hidden Markov Models (HMM)
  - Uses learning to create the gesture models
  - Still requires system designer to identify constraints and dependencies



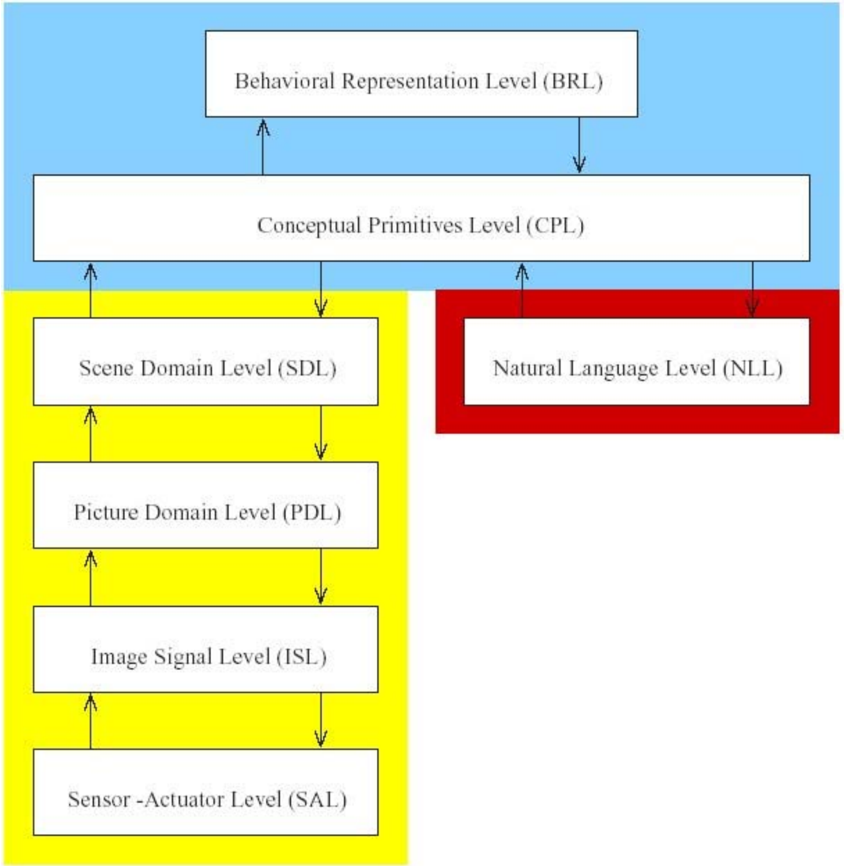
Some Cognitivist Systems

- Cognitive Vision System
  (Town Sinclair 03)
  - Combines low-level processing
    - Motion estimation
    - Edge tracking
    - Region classification
    - Face detection
    - Shape models
    - Perceptual grouping
  - And high-level processing
    - Language-based ontology
    - Adaptive Bayesian Networks
  - Self-referential
    - Maintains internal representation of its goa and hypotheses
  - Visual inference: process sentence structures in the ontological language
  - Requires the designer to identify the 'right structural assumptions' and prior probability distributions



Cognitive Architectures

- Cognitive Vision System
  (Nagel 2004)
  - Model based system for interpreting videos of traffic
  - Signal representations to symbolic representations
    - Optical flow
    - Edge detection
    - 3D model fitting
    - Vehicle trajectories (Kalmann filtering)
    - Vehicle manoeuvers
    - Vehicle behaviours (situation graph trees)
    - Interpretation via logic programming (based on SGT)

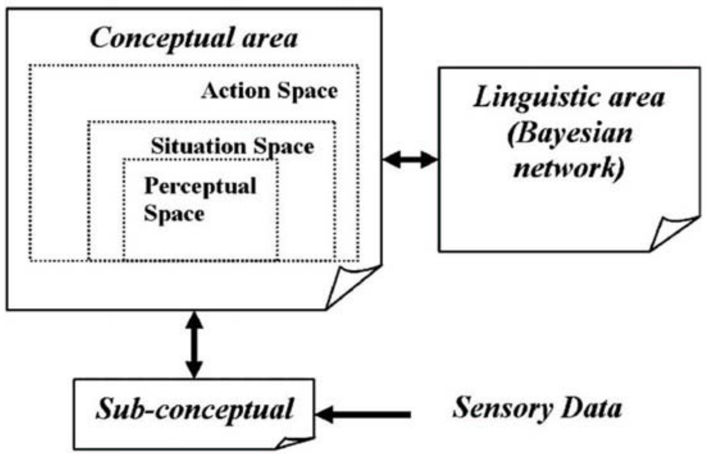


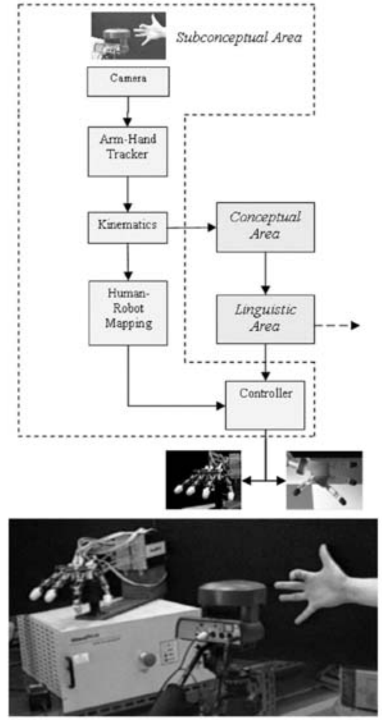
RobotCub

Cognitive Architectures

Robotic Hand Posture Learning

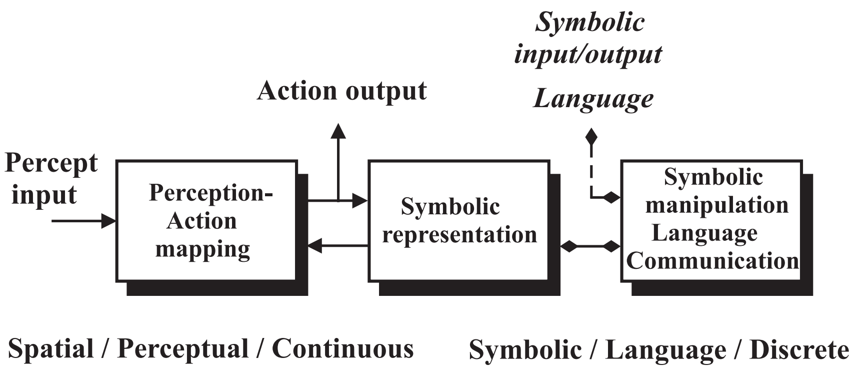
[Infantino et al. 06]

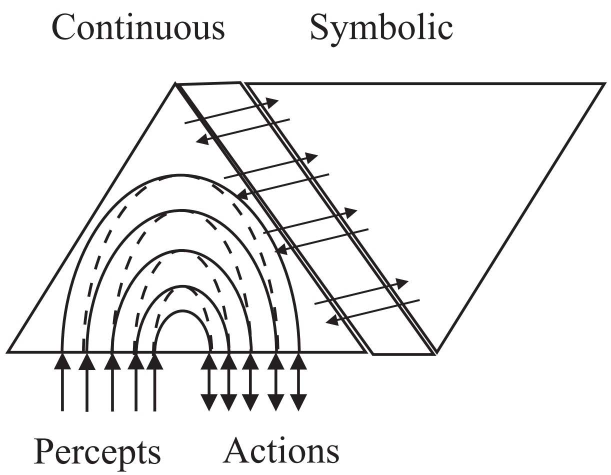




Cognitive Architectures

Action-based Perception [Granlund 05]





Cognitive Architecture

Still Problems!!!

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

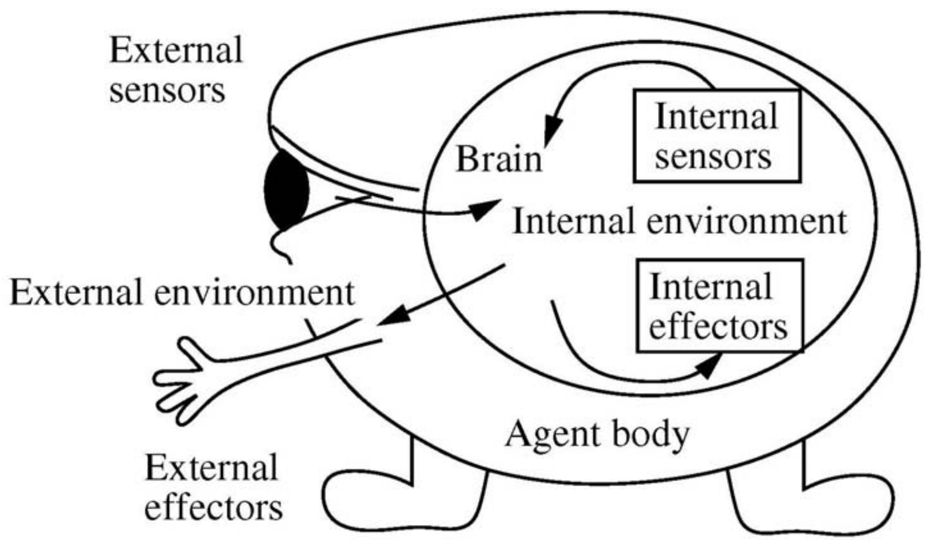
[Weng 02, Weng & Zhang 02, Weng 04a, Weng 04b]

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

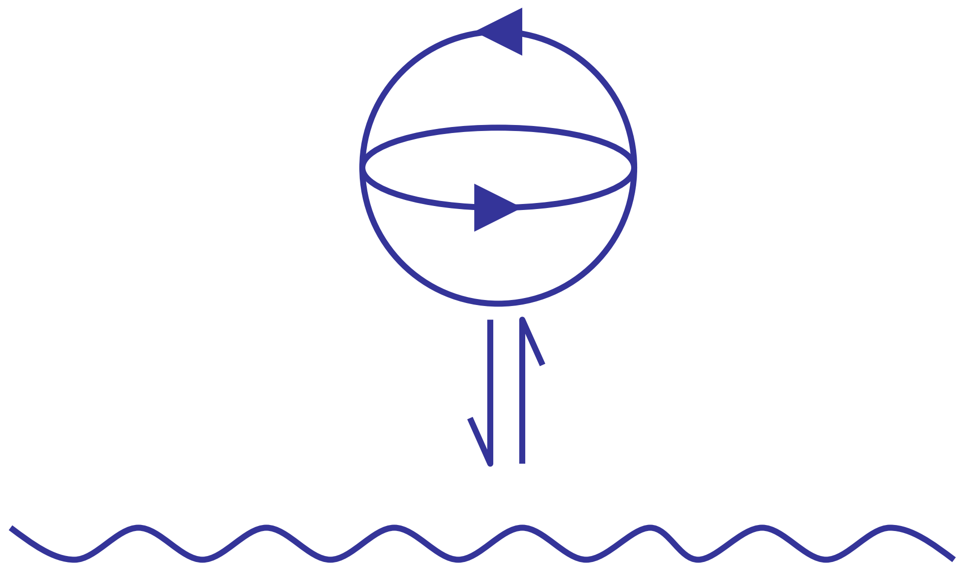
Cognitive Architectures

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)

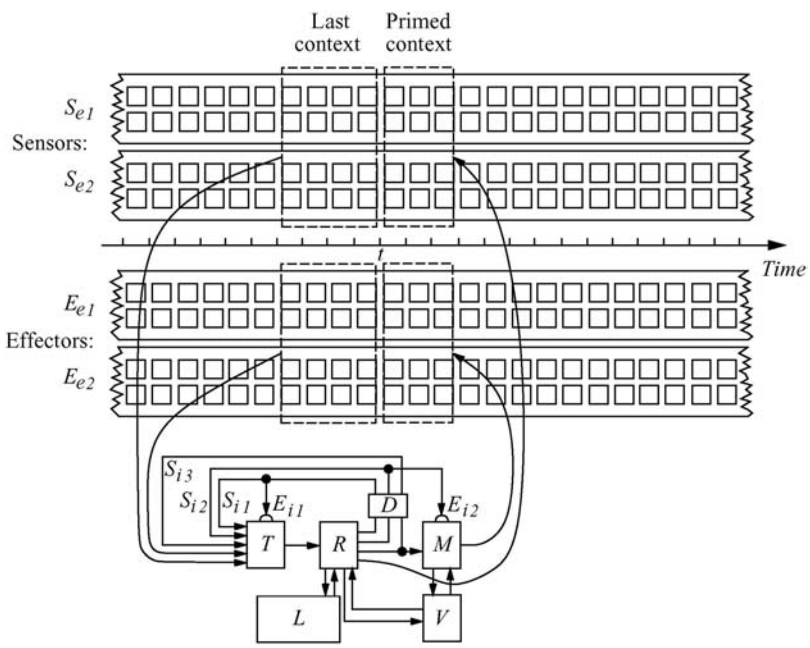
Level 2 Autopoiesis implies the facility to self-modify [Maturana & Varela 87]

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



iCub Cognitive Architecture

Grounded in neuroscience and psychology

Rooted in action-dependent perception

Focussed on scaffolding prospective capabilities

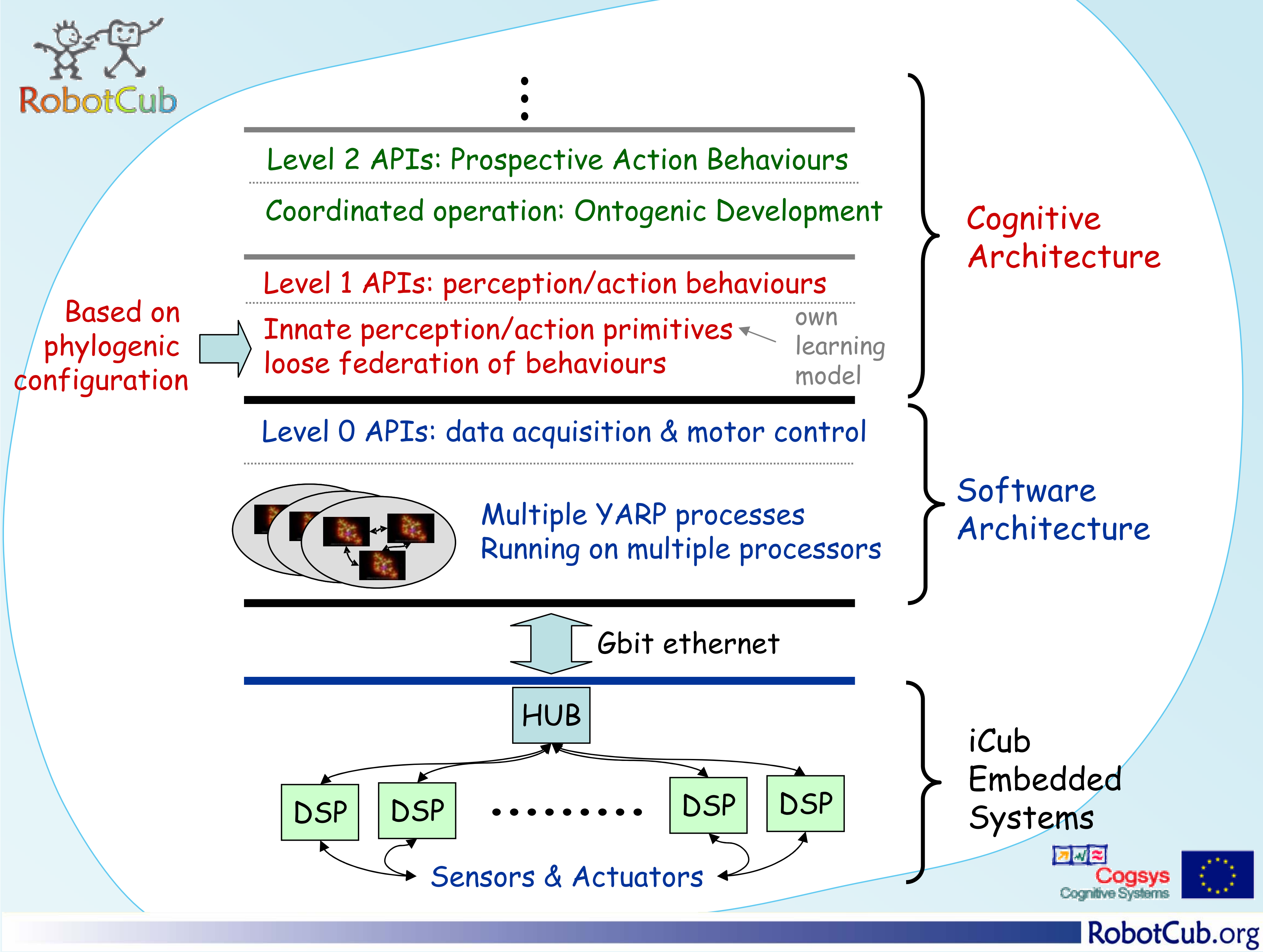
Designed to facilitate development

iCub Cognitive Architecture

Freely-accessible AND open to change by others

$\Rightarrow$ degrees of commitment to a theory in the cognitive architecture

Robotic Open-Architecture for Cognition, Understanding, and Behaviours


RobotCub
Level 2 APIs: Prospective Action Behaviours
Coordinated operation: Ontogenic Development
Cognitive Architecture
Level 1 APIs: perception/action behaviours
Based on phylogenic configuration
Innate perception/action primitives
loose federation of behaviours
own learning model
Level 0 APIs: data acquisition & motor control
Multiple YARP processes
Running on multiple processors
Software Architecture
Gbit ethernet
HUB
DSP
DSP
DSP
DSP
iCub Embedded Systems
Sensors & Actuators
Cogsys
Cognitive Systems
RobotCub.org

M0	Visual acuity is only 3-2% of adult level
M0	Vestibular gaze stabilization
M0	Saccadic eye movement, develops rapidly to M6
M0	Very limited smooth pursuit ability
M0	Attentional processes: gaze directed towards attractive objects (novelty)
M0	Visual control of arm; no control of fingers for grasping
	Arm & finger motion coupled; hand is open when extending arm
M1	Ability to process colour
M1.5	Rapid improvement of smooth pursuit
M2	Ability to process motion information
M3	Ability to perceive binocular depth
M3	First sign of being able to control gravity (prone)
M3-4	Infants achieve adult level of smooth pursuit
M3-6	Can detect approximately-correct gaze direction
M5	Visual acuity reaches adult level
M6-8	Sitting (control of sway of head and trunk)
	Transfer from two-handed to one-handed reaching
M12	Sensitivity to peripheral visual information
M2	Coupling of global arm & finger motions broken; hand is fisted when extending arm
M2-3	Open hand when reaching but only when visually-guided; hand closing when close to object
M4-5	Reaching and grasping
M5	Hand not adjusted to size of object when reaching
M9	Onset of adjustment of hand size when reaching; hand closes when in vicinity of object
M9-10	Differentiated finger grasping (e.g. pincer grasp)
M10-12	Can follow gaze
M13	Grasping starts when reaching (i.e. one integrated reach-grasp act)

iCub Cognitive Architecture

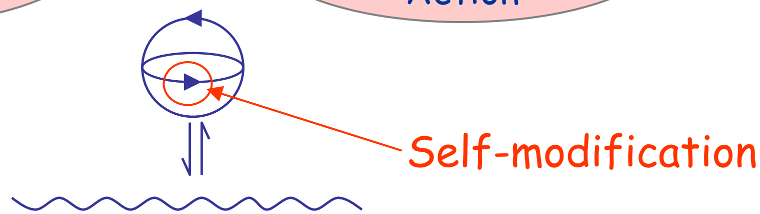
Coordinated operation: Ontogenic Development:

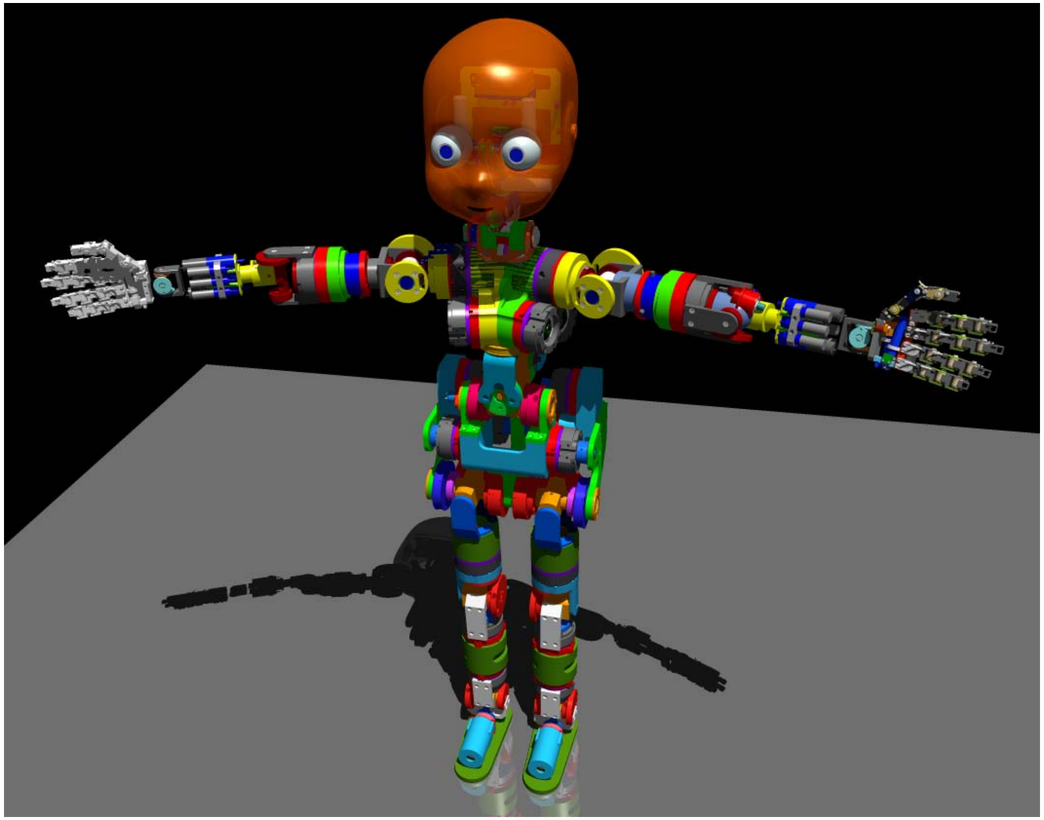
What mechanisms / structures / dynamics?

1. Coupling mechanism between P/A primitives (AAM?)
2. Metric of order/regularity in total confederation of P/A primitives
3. Development mechanism to adjust coupling
4. Metric of consistency of expectations with experiences

Action

Social Contact





For further information see www.robotcub.org or www.icub.org