The Cognitive Systems Approach in Robotics

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Cognitive Robotics

Cognitive … ?

Intelligent …

Embodied …

Situated …

Adaptive ...

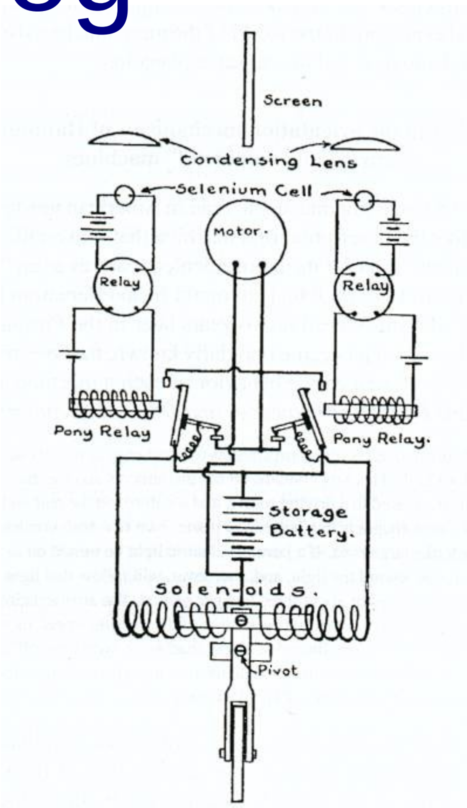
Roads to Cognition

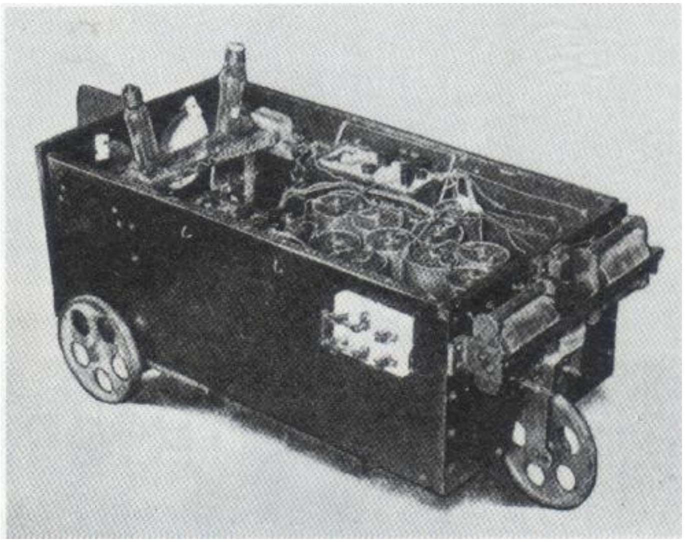
- History repeating: behaviours to AI and back again
- Two Paths
  - Developmental / epigenetic / evolutionary robotics - the embodied perspective
  - Cognitive systems perspective
- Cognitive robotics work at Vienna
- What works: success stories in robotics

First true robot in history – guesses anyone?

Seleno the Electric Dog

- John Hammond, Benjamin Miessner (1912)
- Phototaxis (move to or avoid light)
- Technical realisation of theories of phototaxis (heliotropism) in animals by Jacques Loeb
- "... inherit almost superhuman intelligence"
- ".. the dog promptly, almost fearfully, backed away."
- "Mechanical creature that will fight burglars, sweep and dust and be generally useful."

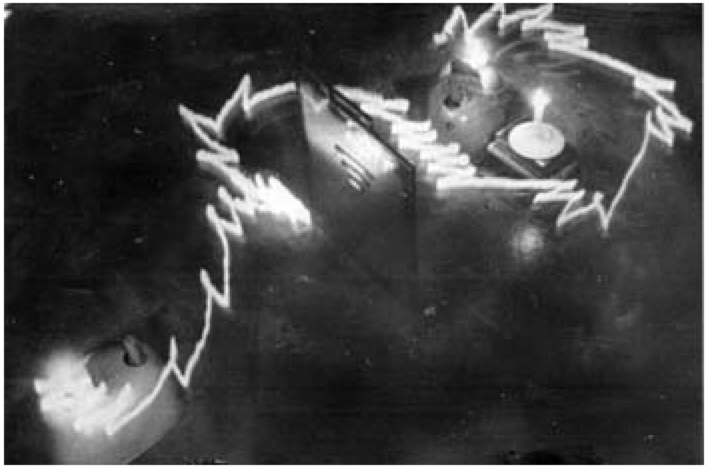




[http://cyberneticzoo.com]

Turtles

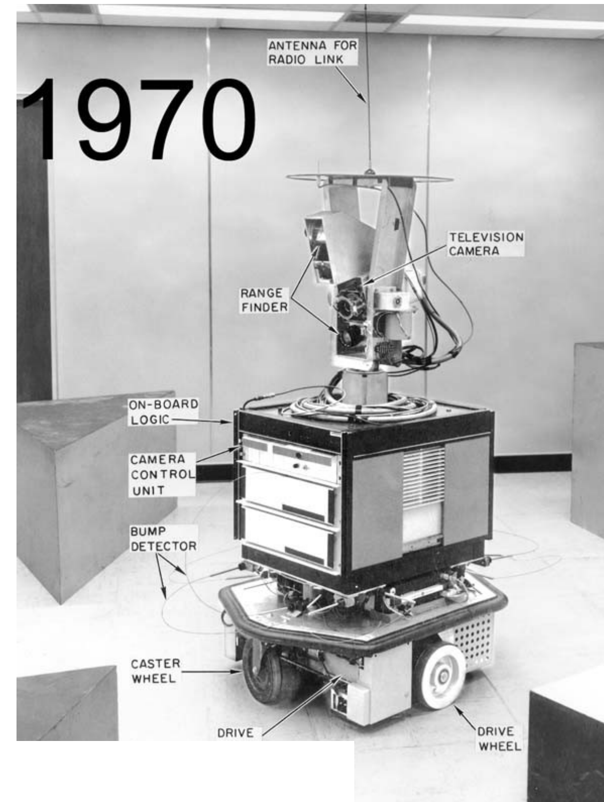
- William Grey Walter (~1950)
- Turtles Elmer and Elsie
- Phototaxis to find recharging station
- “social interaction” between 2 robots



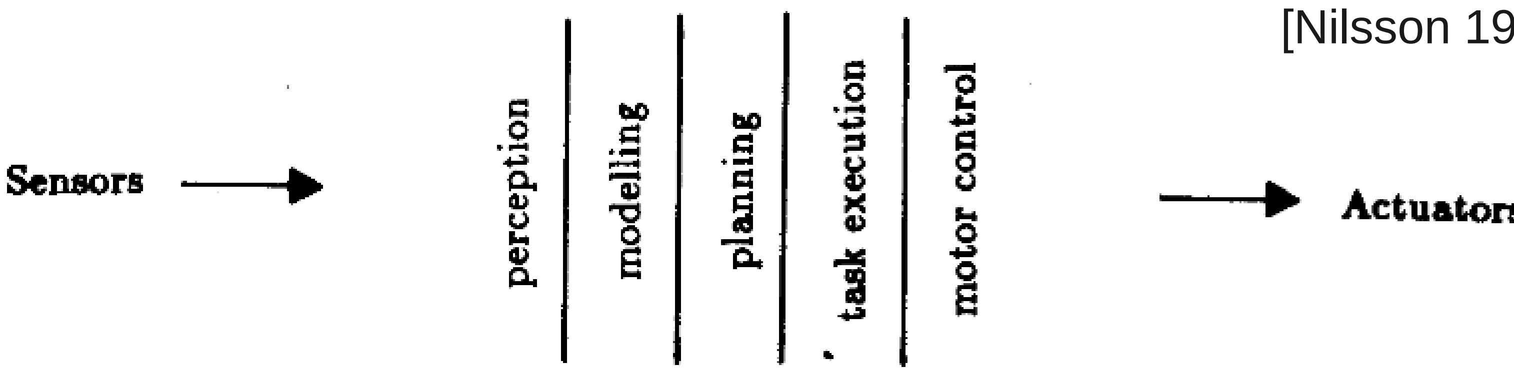
www.ias.uwe.ac.uk/Robots/gwonline/gwonline.html

Shakey

- Stanford Cart, SRI Shakey
- Computer controlled
- From simple behaviours towards symbolic AI
- Sense-think-act

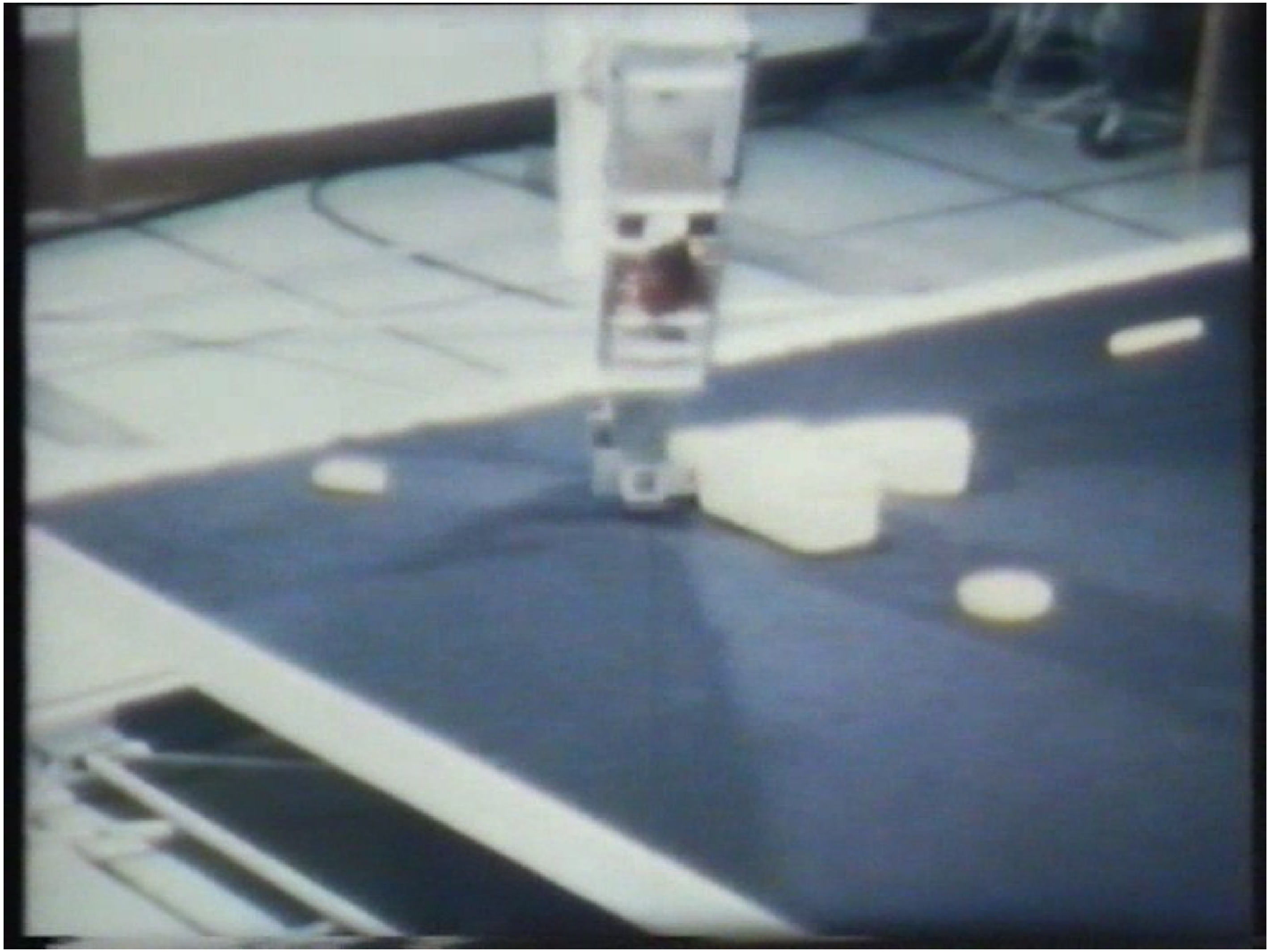


[Nilsson 1984]



[Brooks 1986]

Edinburgh Freddy II



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Embodied Vision to overcome failure (1966-73)

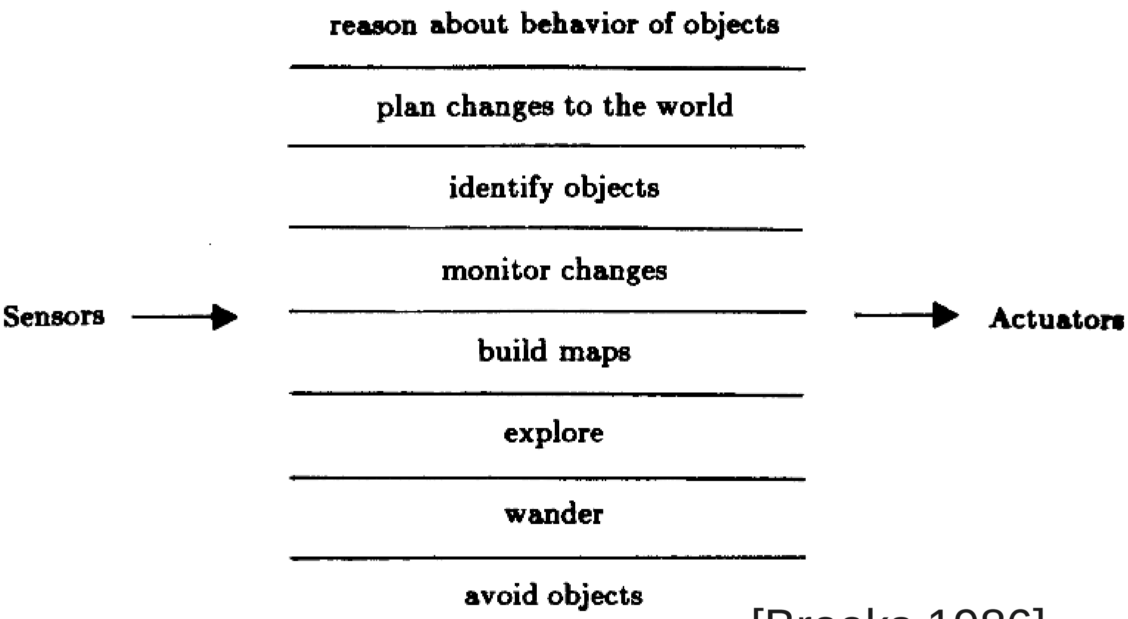
http://www.aiai.ed.ac.uk/project/freddy

[Ambler, 1973]

.. and back again: Subsumption

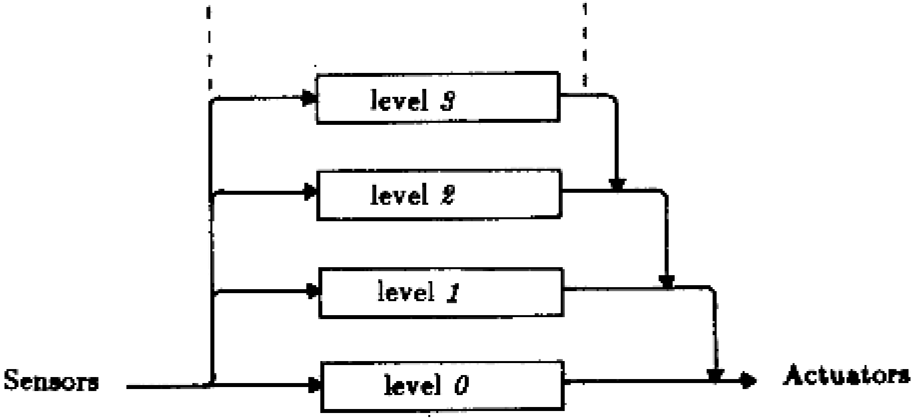
- Rodney Brooks (1986): decomposition by activity

Ghengis



[Brooks 1986]

- Subsumption architecture: higher layers subsume lower layers, always complete control system
- Intelligence without representation (1991): The world is its own best model



[Brooks 1986]

… and again ...

- Intelligence with representation (Steels 2003)
- Behaviours don't scale up – higher level tasks require some form of representation / conceptualisation
- Where do representations / concepts come from? How do they acquire meaning (for a robot(s) and its user)?
- External representations instead of purely abstract entities, constructed commonly by a group of agents
- *“Representations … organisers of activity rather than abstract models of some aspects of reality”* (example of trodden path on lawn)

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Embodiment and Behaviours

- Braitenberg: Vehicles (1984)
- Rather direct coupling between sensing and acting => dynamical system
- Behaviour *emerges* in conjunction with environment
- Continuous adaptation to ever-changing environment => robust behaviours
- Self-organisation emerges in groups of agents

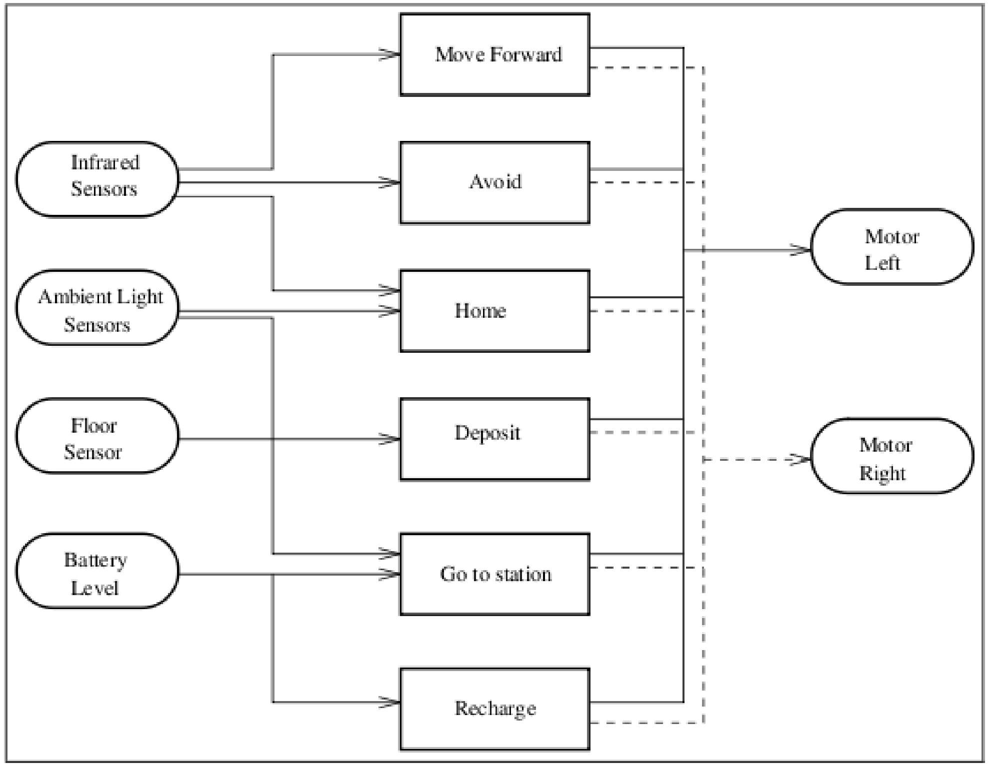
Design Principles

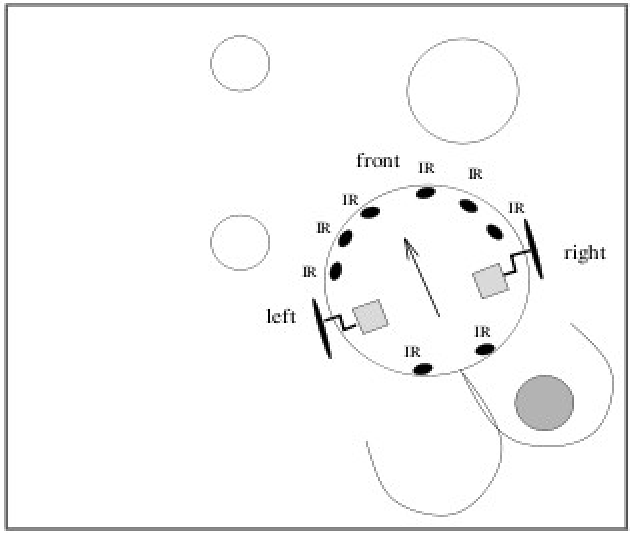
Pfeifer, Scheier: Understanding Intelligence (1999)

- Definition of ecological niche
- Definition of desired behaviours
- Complete agent principle
- Principle of parallel, loosely coupled processes
- Principle of sensory-motor coordination
- Principle of cheap design
- Redundancy principle
- Principle of ecological balance
- Value principle

Extended Braitenberg Architecture

- Lambrinos, Scheier (1995)
- Problem of action selection with several tasks (recharge, collect garbage)
- Parallel processes all contribute to output activity
- Time-dependent motivation functions, avoid getting stuck
- cheap design: bent wires as “object categorisers”





[Lambrinos 1995]

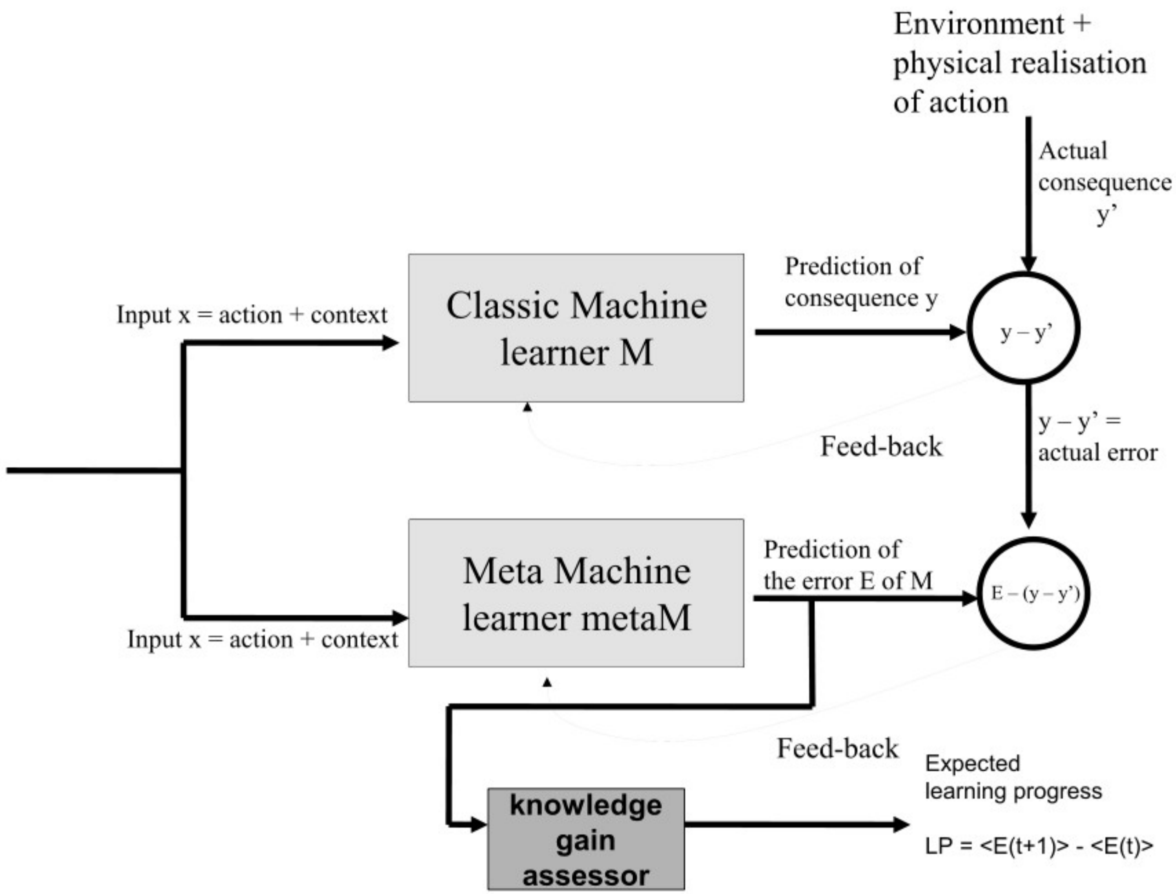
Turtles revisited

- Steels (1996, 2003)
- Phototaxis to recharging station
- Added motivation to “work”: push boxes to reduce drain on charge
- Adaptation: learn the “importance” of work
- Collective dynamics: social injustice emerges!

[Steels 1996]

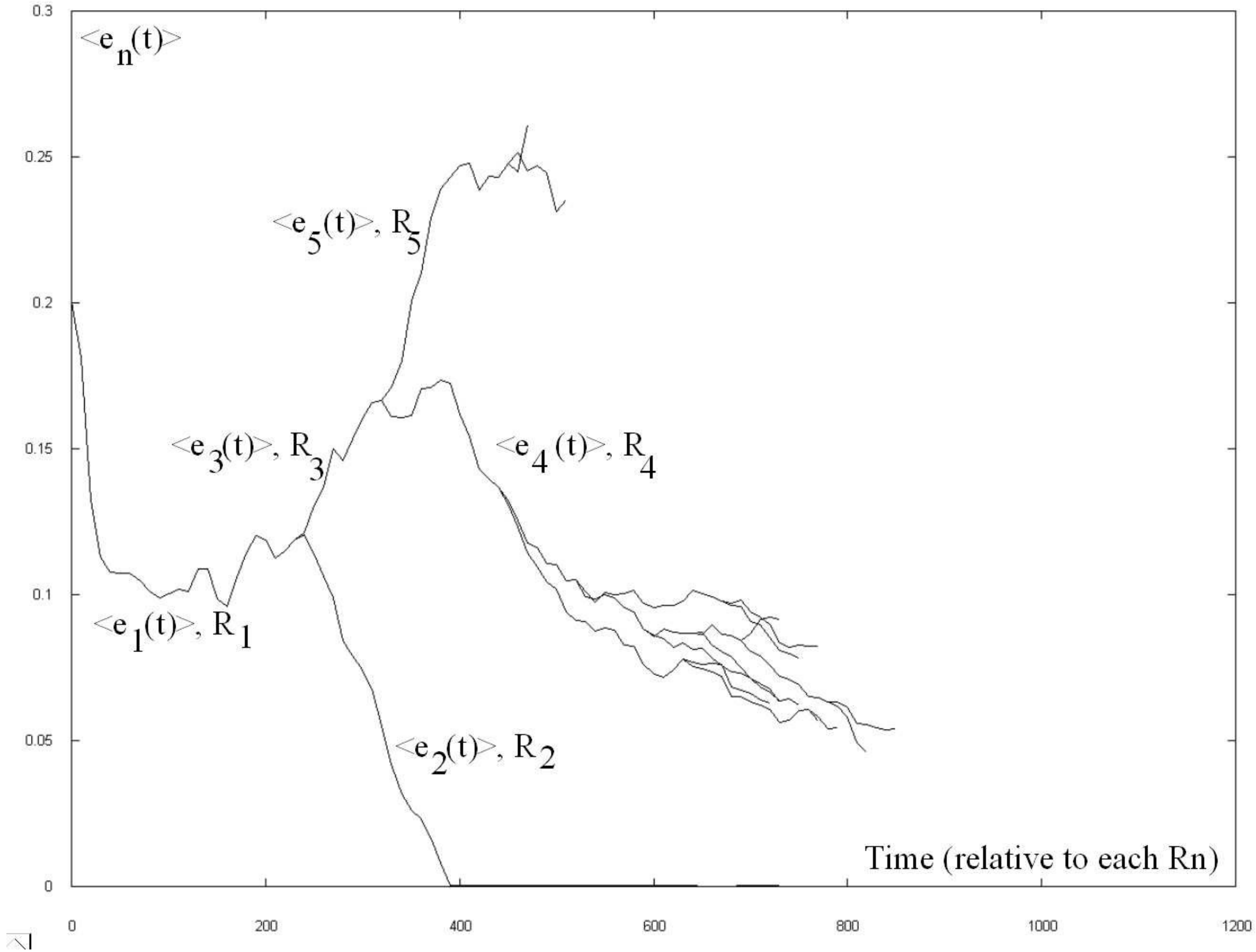
Curiosity Driven Exploration

- Oudeyer et al. (2007)
- Infants don't learn randomly, they seek out interesting situations and repeat until bored
- Curiosity as intrinsic motivation – Intelligent Adaptive Curiosity



[Oudeyer ea 2007]

Assessing "interestingness"



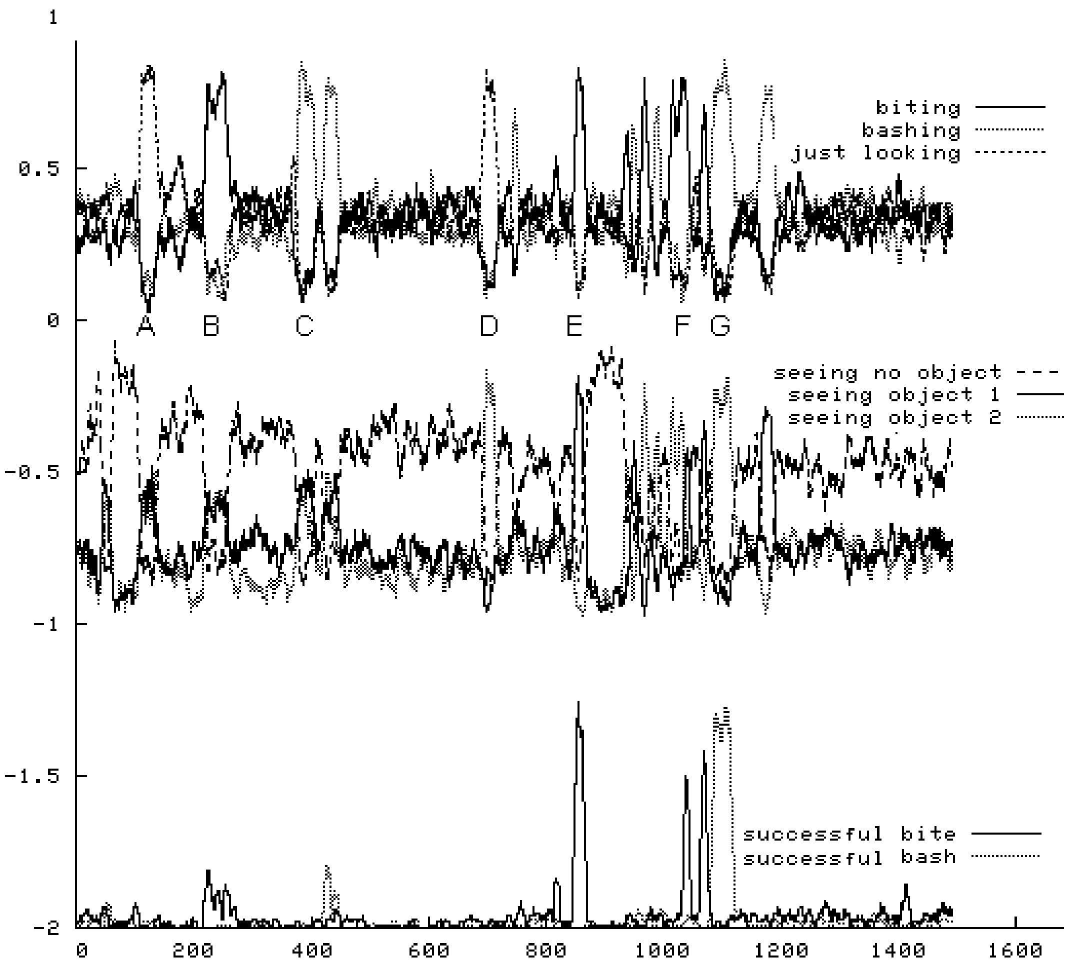
Evolution of prediction error rate drives exploration

[Oudeyer ea 2007]

A curious dog

- Developmental stages with predominant behaviours
- Increasing complexity
- Stages of development

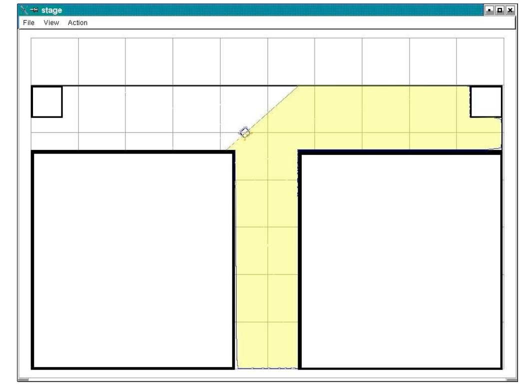
Aibo robot:
Looks at, bashes, bites
objects



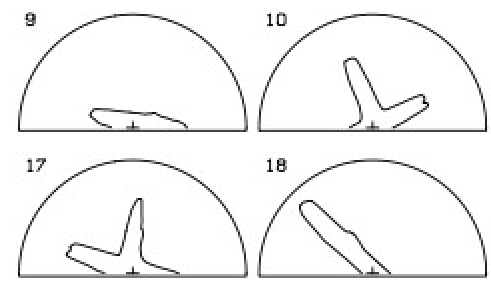
[Oudeyer ea 2007]

Abstraction

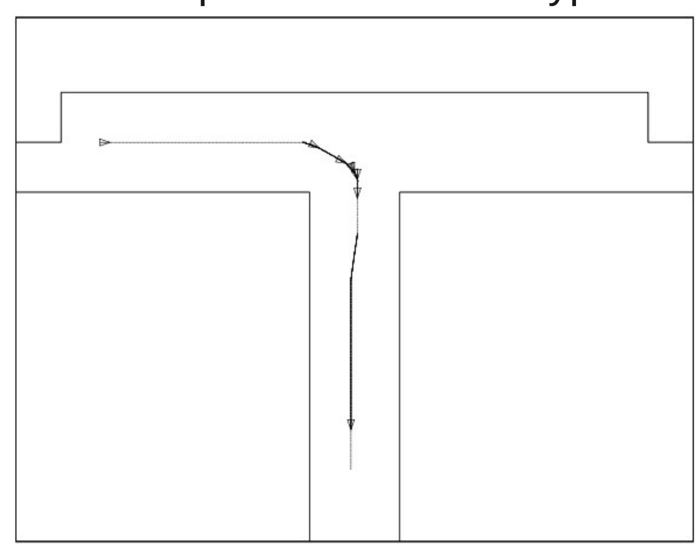
- Provost et al (2006): Self-Organizing Distinctive State Abstraction (SODA)
- Reduce “problem diameter”
- Learn prototypical situations via vector-quantization, define perceptual neighborhood
- Hill climbing to distinctive state
- Trajectory following from one dist. state into neighborhood of another

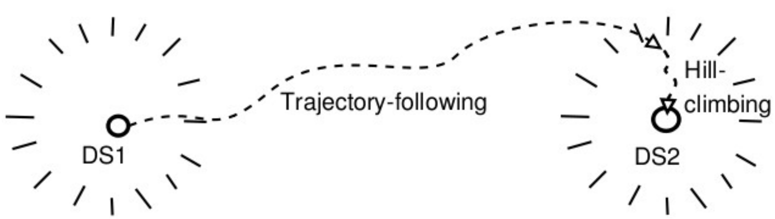


Simulated Environment



Example Learned Prototypes





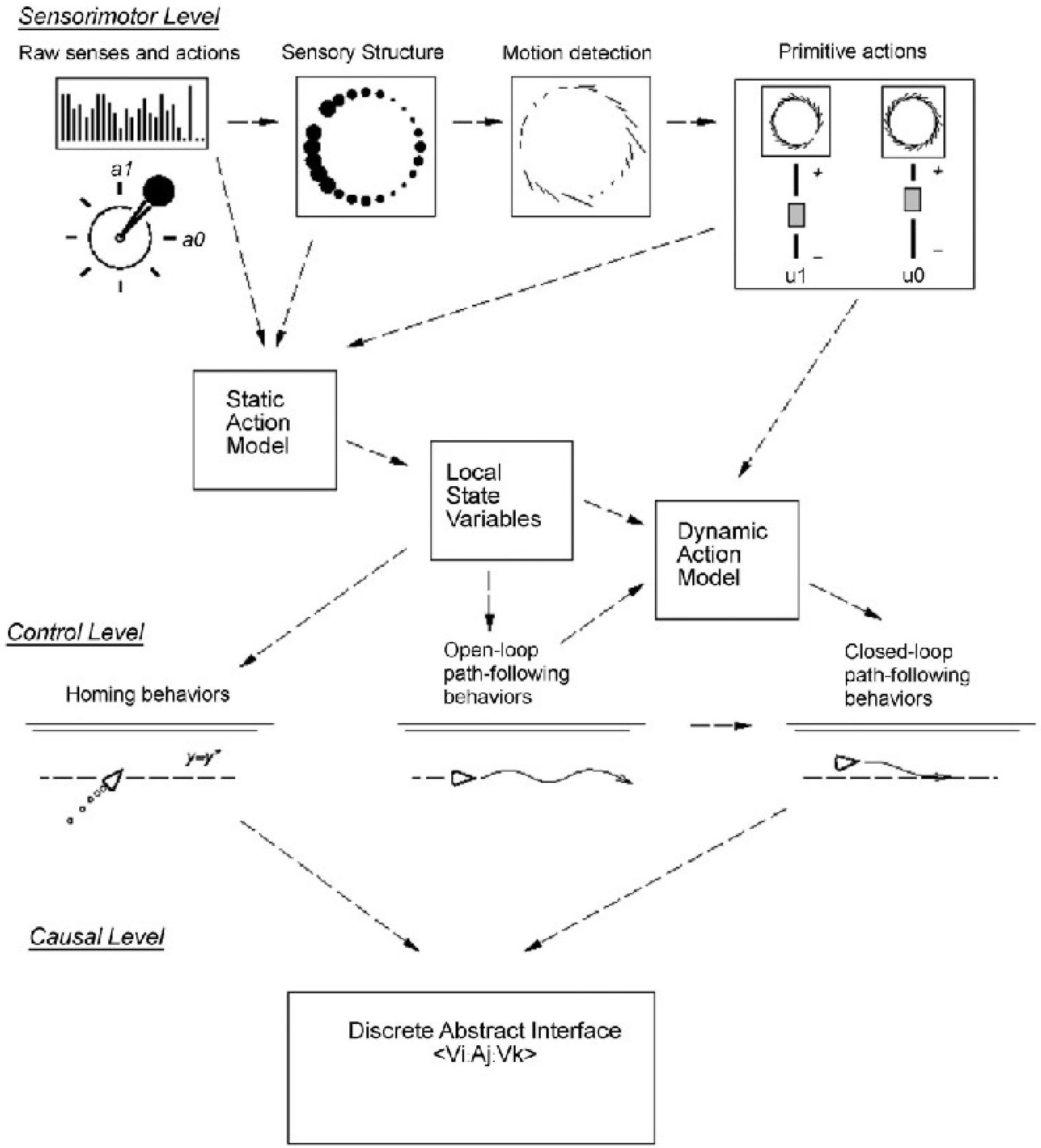
Navigation using learned abstraction

[Provost ea 2006]

Bootstrapping Representations

- Intentionality Problem: Where does meaning come from?
- Firehose of Experience: “... extremely high bandwidth stream of sensor data that the agent must cope with, continually.” [Kuipers 2008]
- Trackers point from spatio-temporal region of the input stream to stable symbolic representation
- Kuipers (2000, 2008): Spatial Semantic Hierarchy (SSH)
- Distinctive states defined by behaviours of the dynamical system given by the agent, its environment and control laws
- From raw uninterpreted sensor data to navigation in topological maps via several hierarchies of abstraction

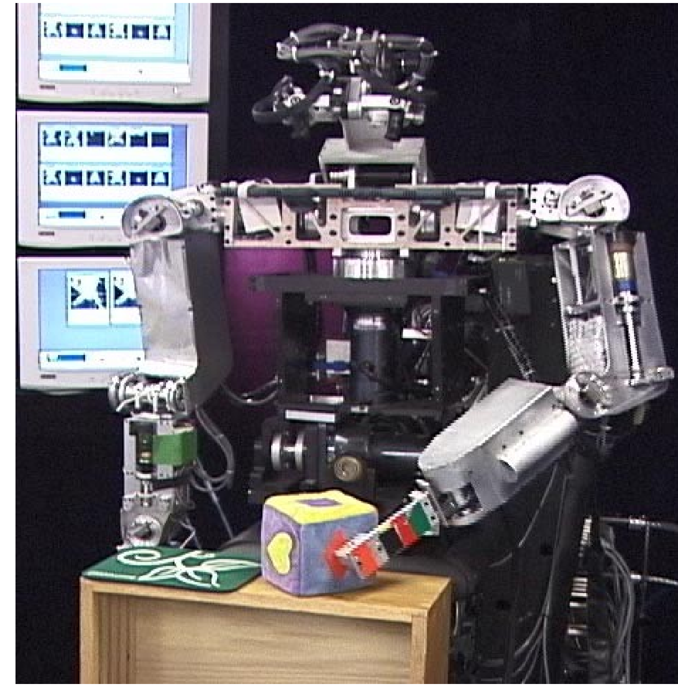
SSH - Lattice of Learning Methods



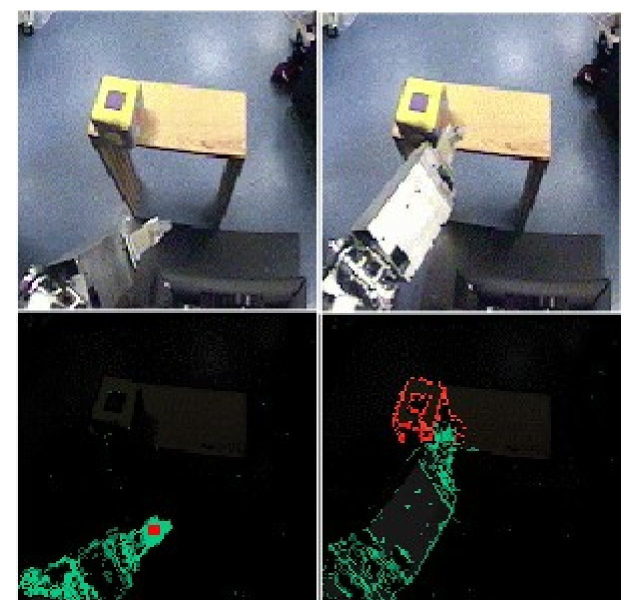
[Kuipers 2008]

Learning causal effects

- Metta, Fitzpatrick (2003)
- Learn to distinguish between self and environment based on temporal correlation between self-generated action and observed changes
- Active scene segmentation by observing pushing
- Learn affordances of objects (rolling w.r.t. principal axis)

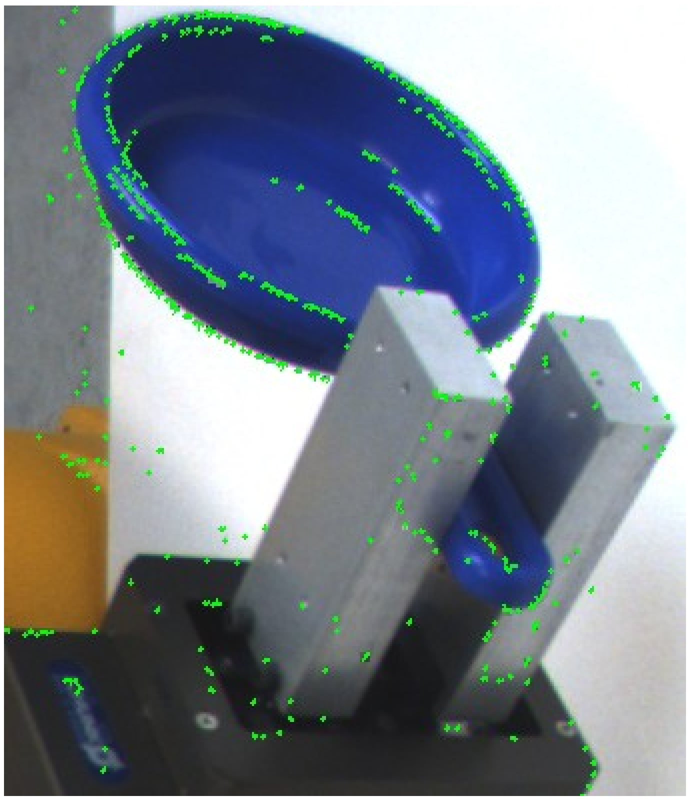


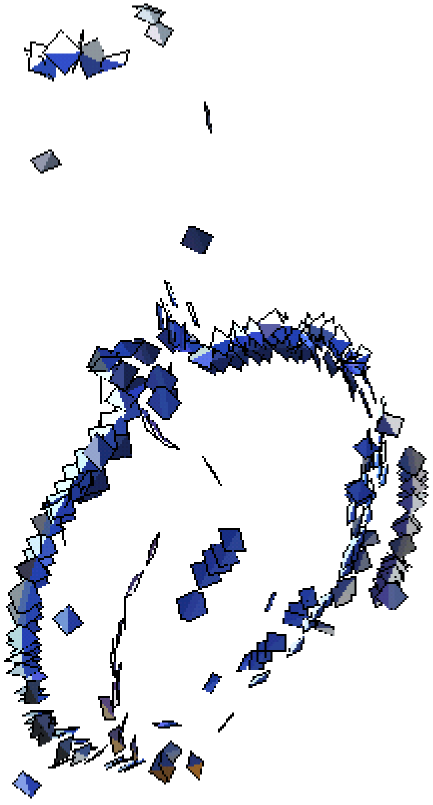
MIT's cog [Brooks ea 1999]



[Metta 2003]

More Active Segmentation





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“Birth of the object” (Kraft, 2008)

Learning Grasp Affordances

(0.59)

Learned 6DOF grasp density

http://www.csc.kth.se/~detryr/research.php

[Detry, 2011]

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Cognitive Systems

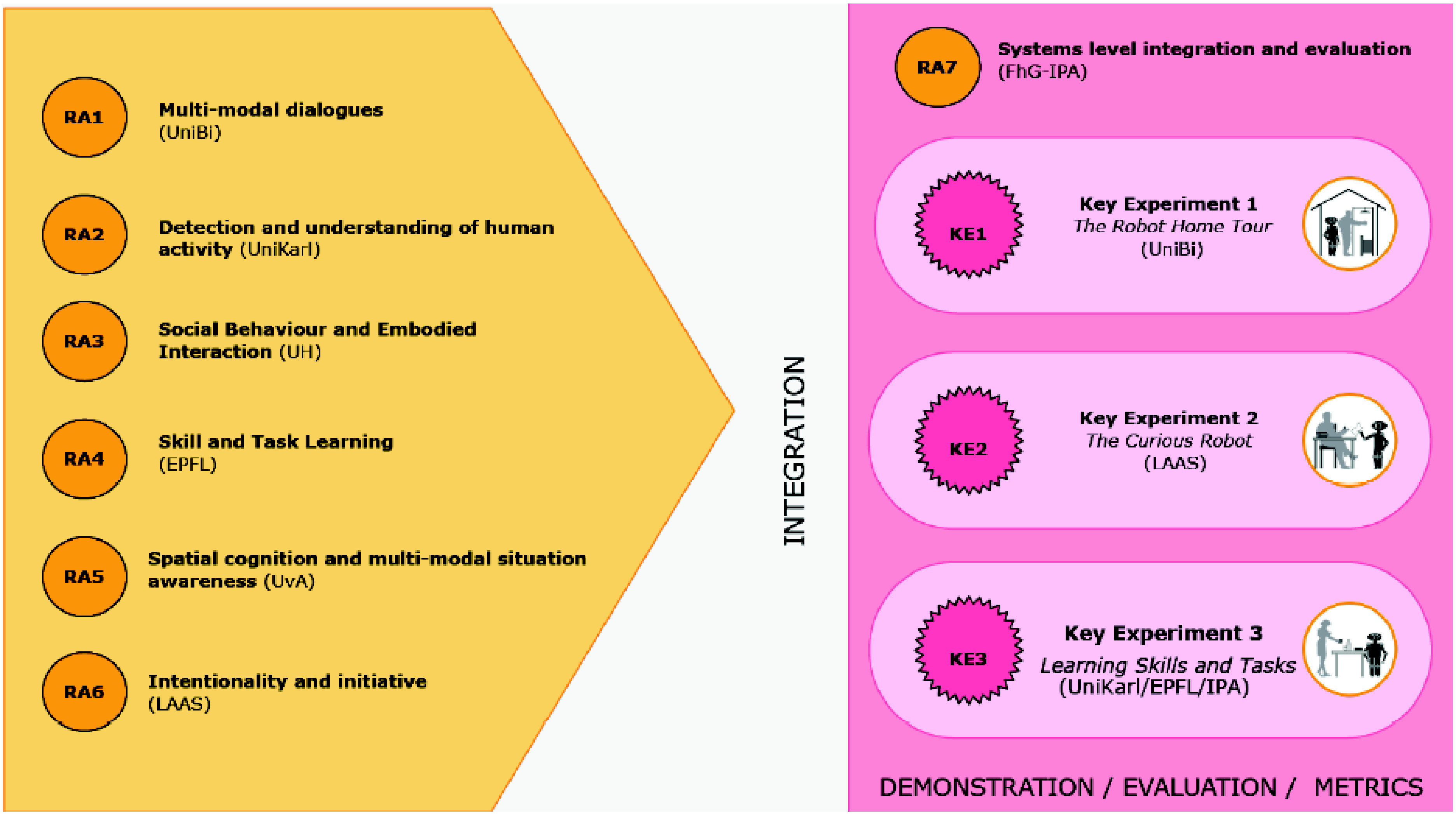
- Human-assistive tasks (robotic butlers)
- (Large) multidisciplinary projects
- Natural language communication
- Open-ended learning

COGNIRON - The Cognitive Robot Companion

- Learning and understanding space, objects
- Interaction with people, understanding their actions and expressing intentions
- Learning skills
- Making decisions and taking initiatives

http://www.cogniron.org

COGNIRON Architecture



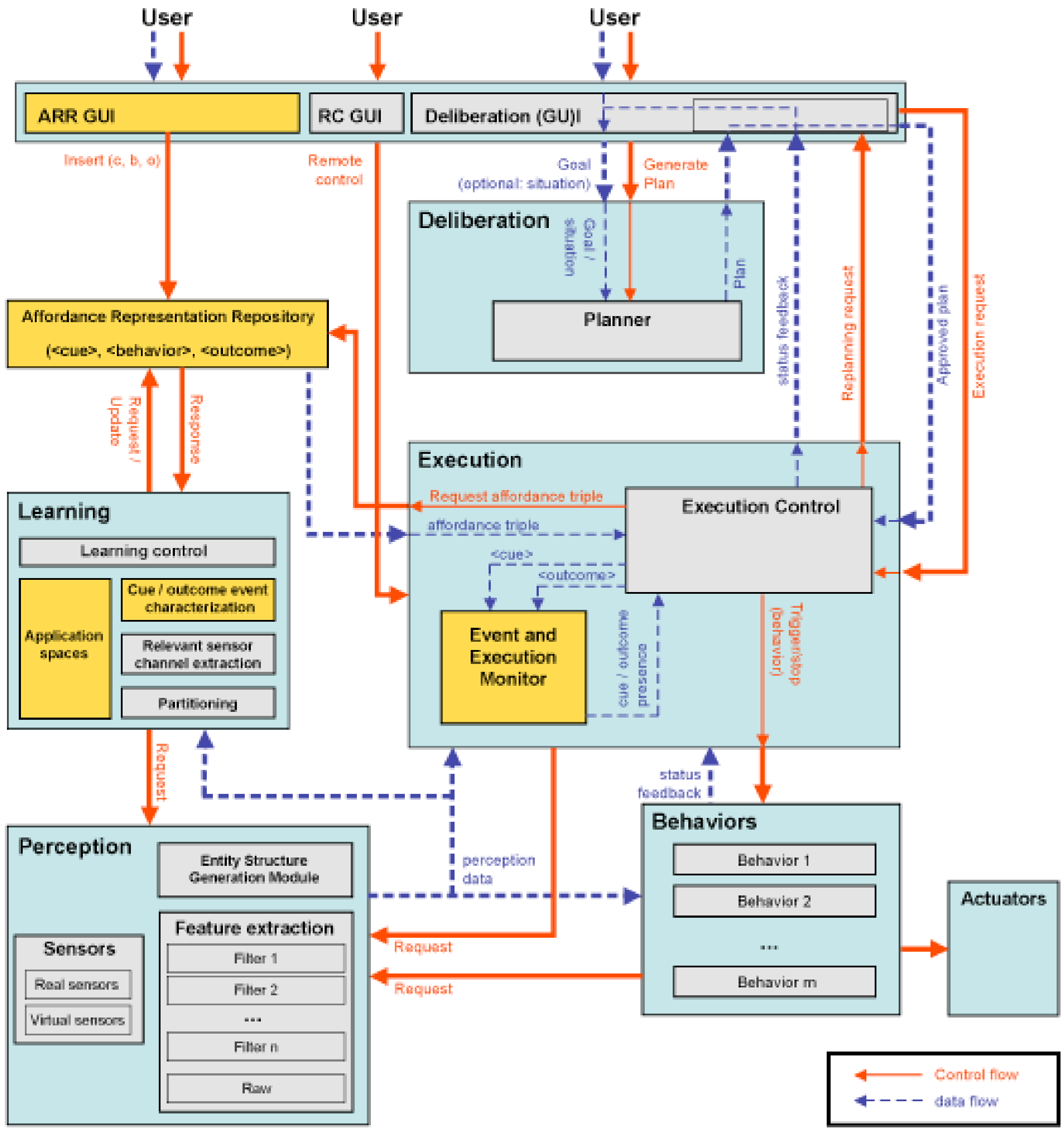
MACS - Exploring and Exploiting the Concept of Affordances for Robot Control

- “The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill.” (Gibson 1979)
- “Perceiving an affordance means perceiving an interaction possibility … The same object / thing / entity can offer different functions for different animals ...” (MACS webpage)
- Leads to feature-based perception of (object) functions (as opposed to appearance based recognition)

http://www.macs-eu.org

Kurt3D and its affordances

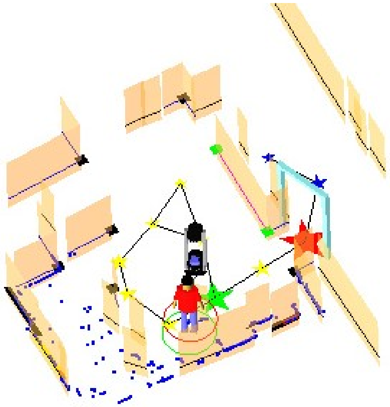
MACS System Overview



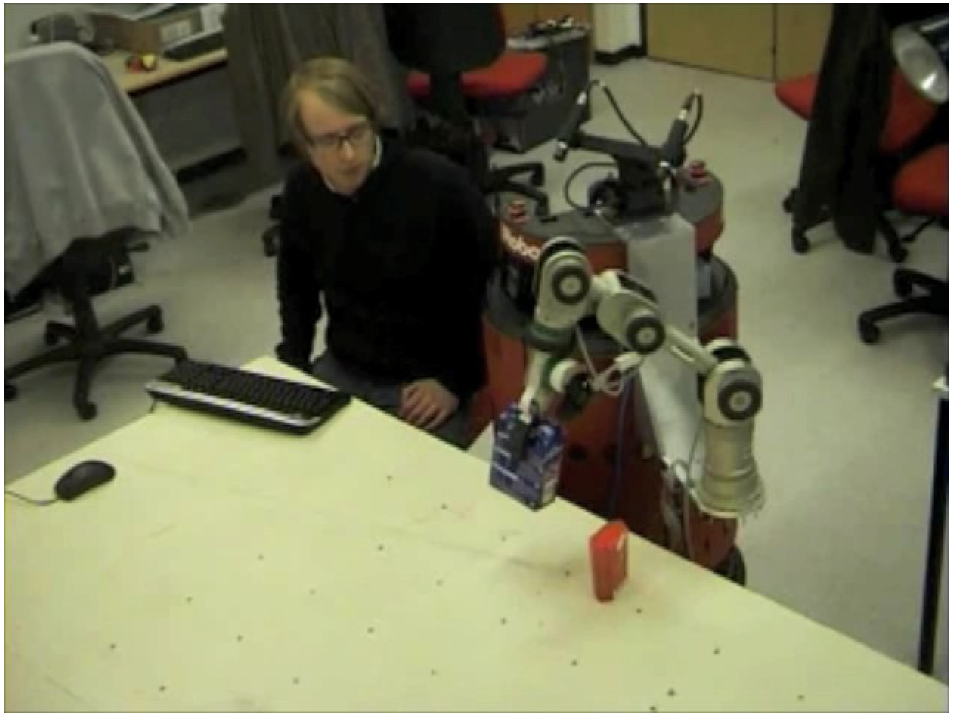
Bratislava AI Seminar 19.3.2012 - Zillich

http://www.macs-eu.org

CoSy - Cognitive Systems for Cognitive Assistants

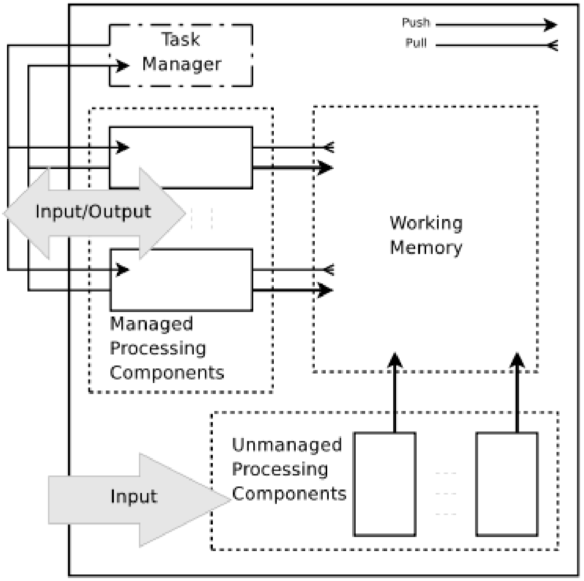


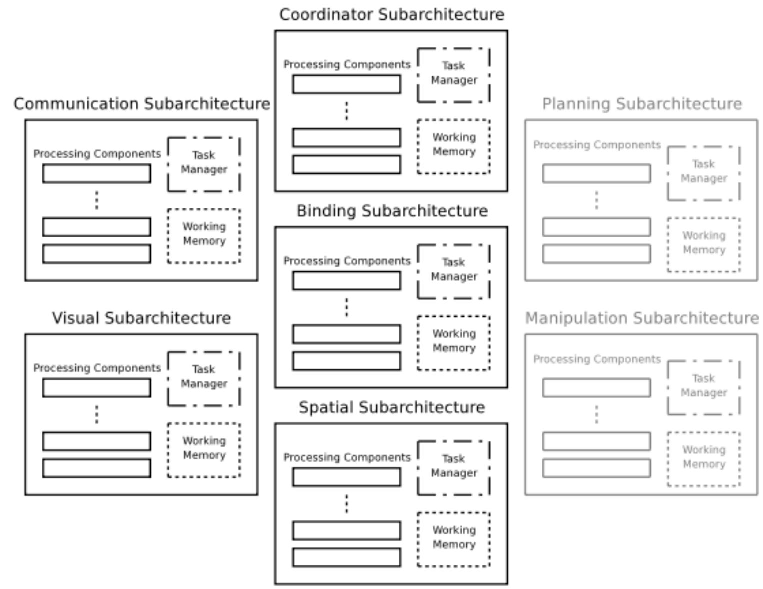
- “.. multi-disciplinary investigation of *requirements*, design options and trade-offs for human-like, autonomous, integrated, physical (e.g. robot) systems ..”
  “.. succession of increasingly ambitious working robot systems to test and demonstrate the ideas ..”
- Build capabilities over time
- Perform and *understand* tasks
- Scenarios to test theories and foster integration (playmate, explorer)
- Requirements => theory => implementation => scenario => revise ..



www.cognitivesystems.org

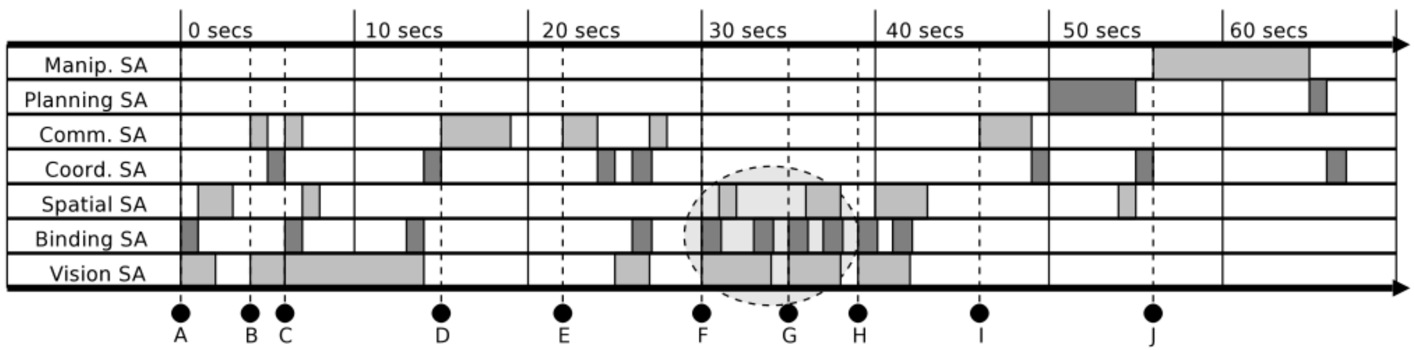
CoSy Architecture

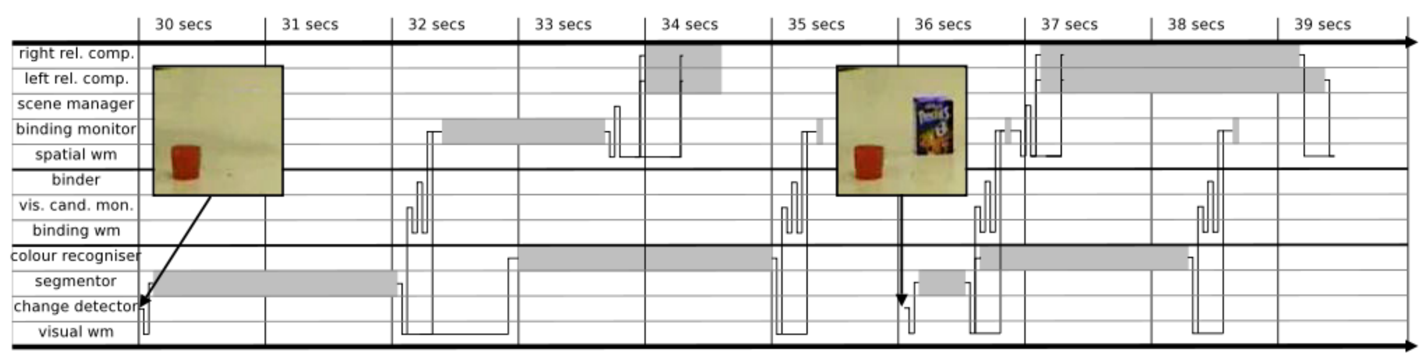




A Red object placed on table.
B Tutor (T): "This is a red thing."
C Red object replaced with blue object.
D Robot (R): "Is that red?"
E T: "No, this is a blue thing."
F Blue object replaced with red object.
G Blue object placed to right of red object.
H Blue object placed to left of red object.
I T: "Put the blue things to the left of the red thing."
J R moves right hand blue object to left of red object.

Single subarchitecture



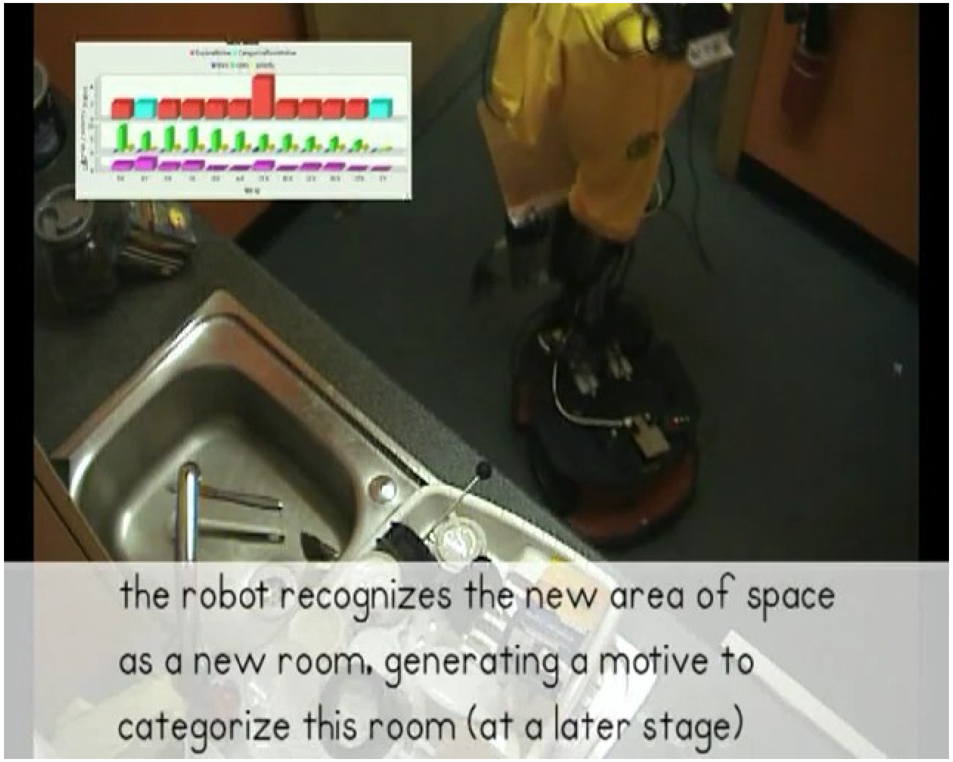


Flow of processing across subarchs in interaction with human

CogX - Cognitive Systems that Self-Understand and Self-Extend

- “.. unified theory of self-understanding and self-extension with a convincing instantiation and implementation of this theory in a robot ..”
- Emphasis on representing *missing* knowledge and actions to extend knowledge
- Maintain set of *beliefs* (private, attributed, shared)

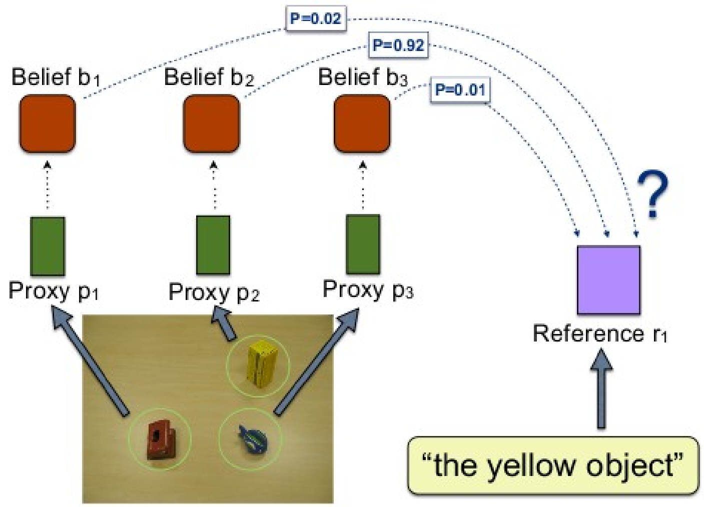
(1:20, 3:43)



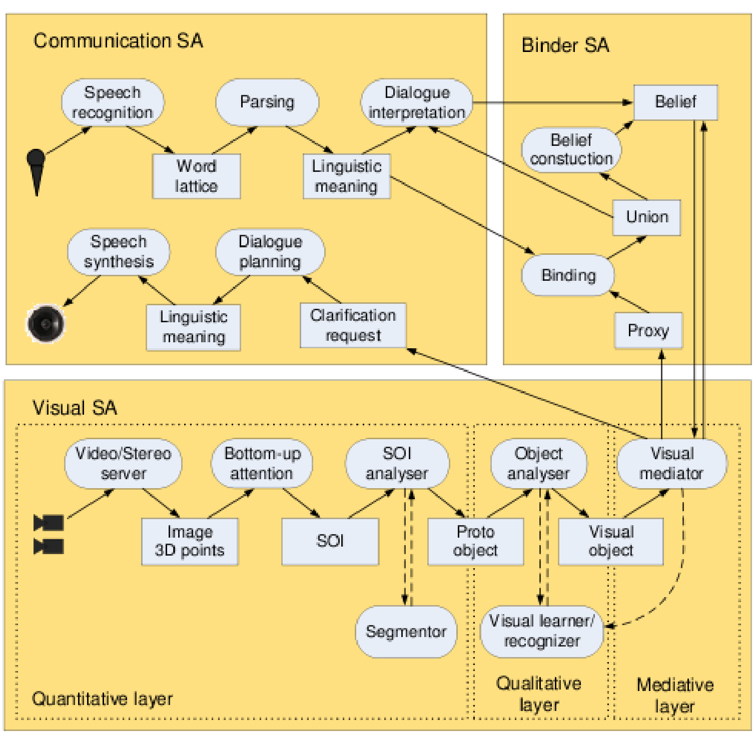
(1:40)

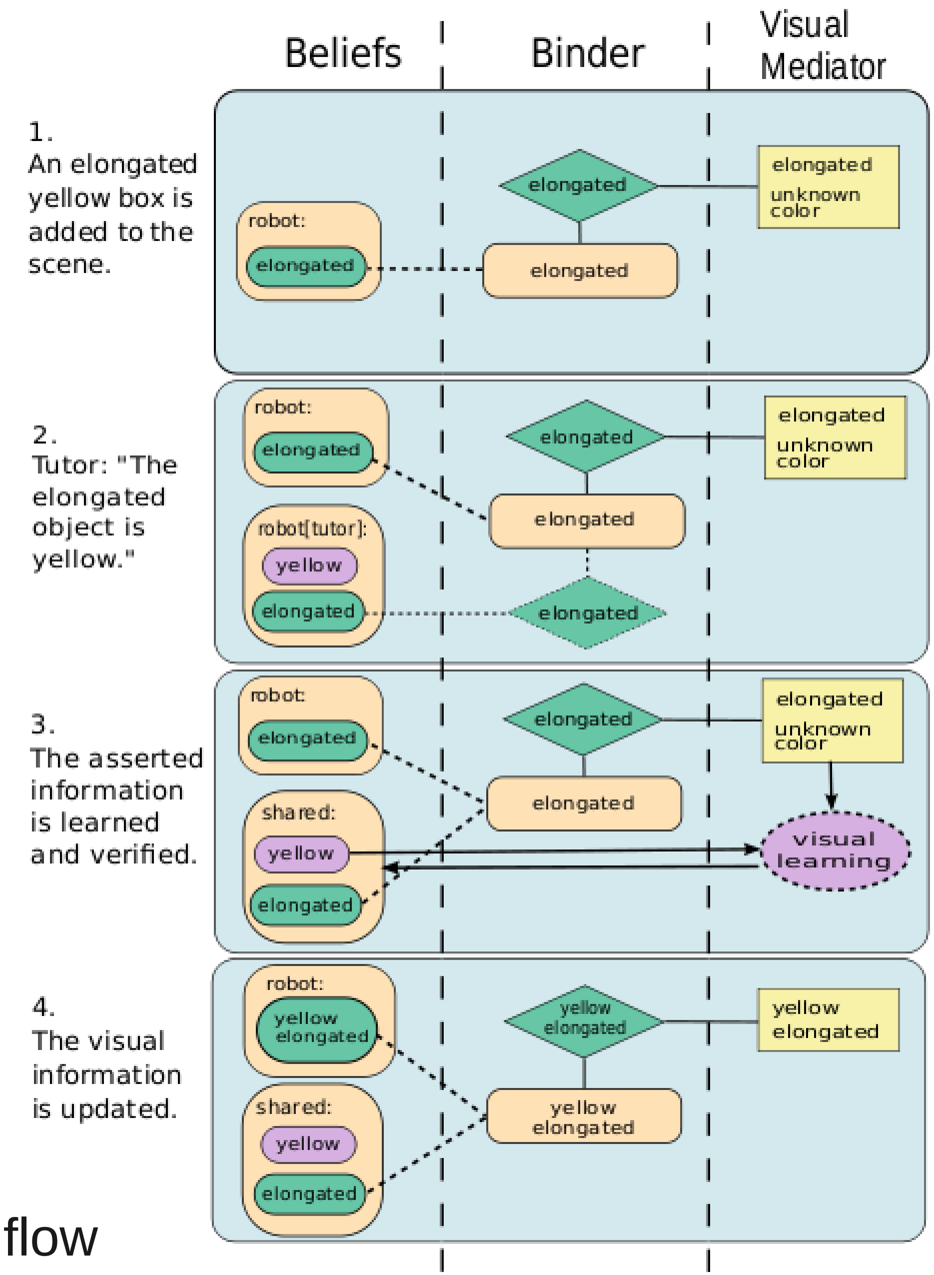
http://cogx.eu

CogX Architecture



The binding problem





Process flow

[Skocaj 2010]

Community, community, community

- Willow Garage's PR2 robot
- ROS (Robot Operating System)
- Large repertoire of specific purpose components
- Allows rapid prototyping to plug together application scenarios

Fetching beer video (1 week hackathon) [Willow Garage]

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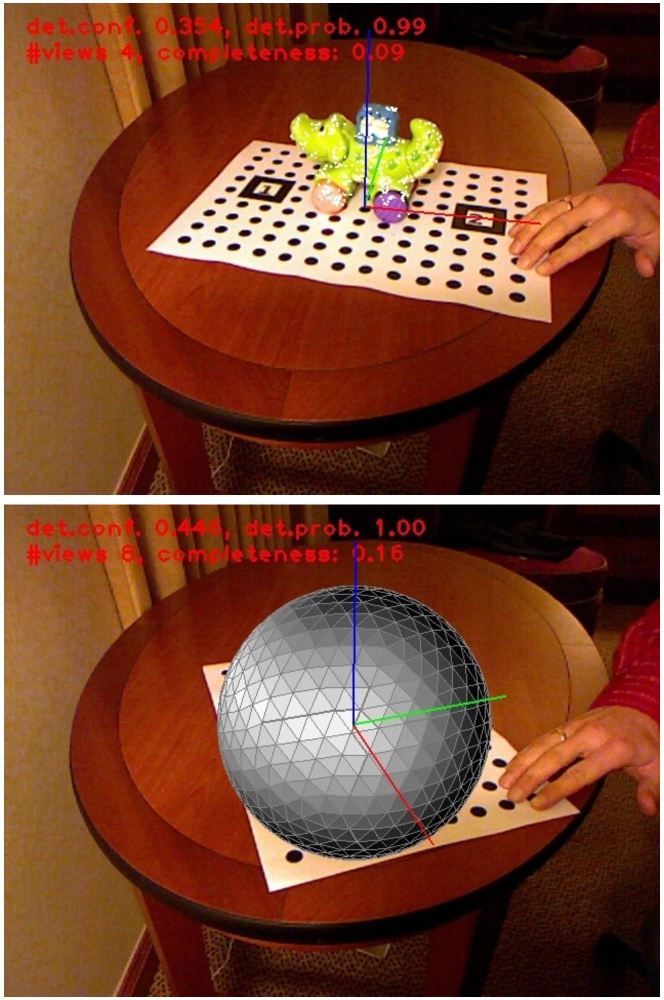
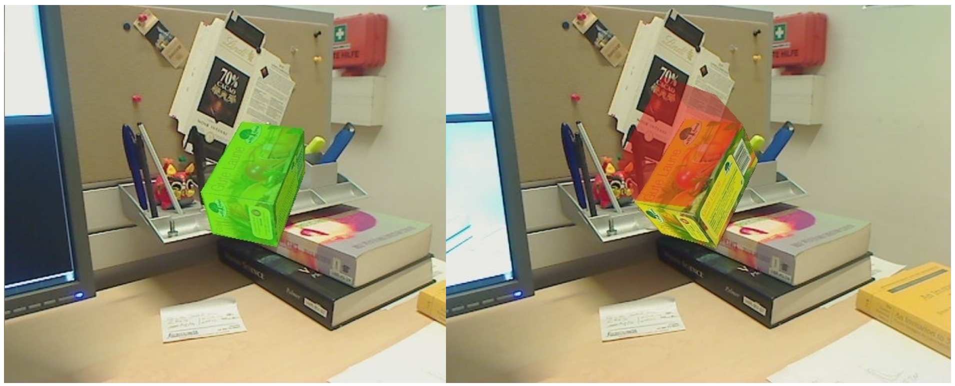
Representing Gaps

- Incremental acquisition of 3D object models for open-ended learning scenarios
- Exploration-exploitation dilemma: when have I learned enough?
- Probabilistic measures of *observed detection success*, *predicted detection success*, *model completeness*
- Support reasoning when to extend model, where to look next
- Predict the probability of successful detection given the model learned so far

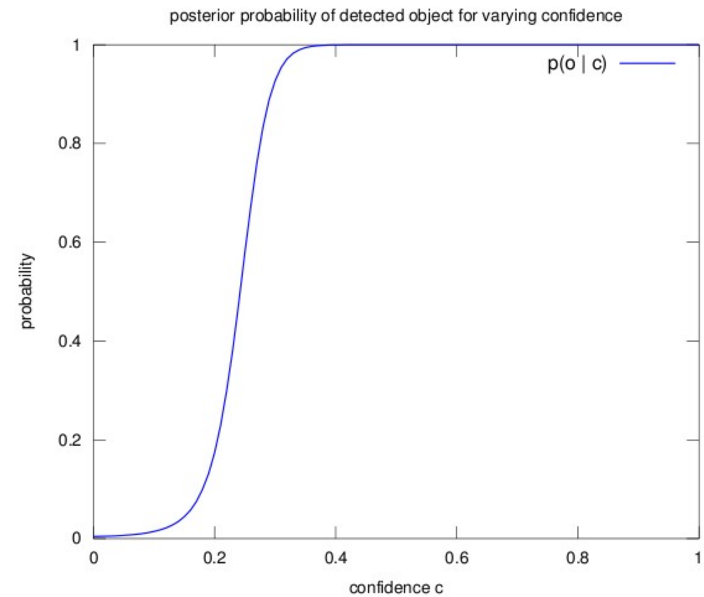


[Zillich, 2011]

Supporting knowledge acquisition



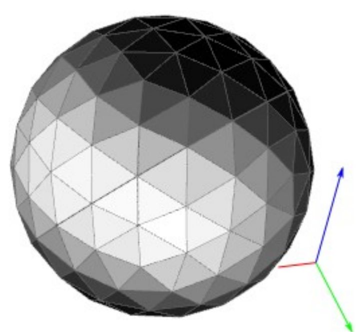
Virtual training examples



$$p(o \,|\, c) = \frac{p(c \,|\, o)\ p(o)}{p(c)}$$

$$= \frac{p(c \,|\, o)\ p(o)}{\sum_{k \in \{t,f\}} p(c \,|\, o = k)}$$

Observed detection success

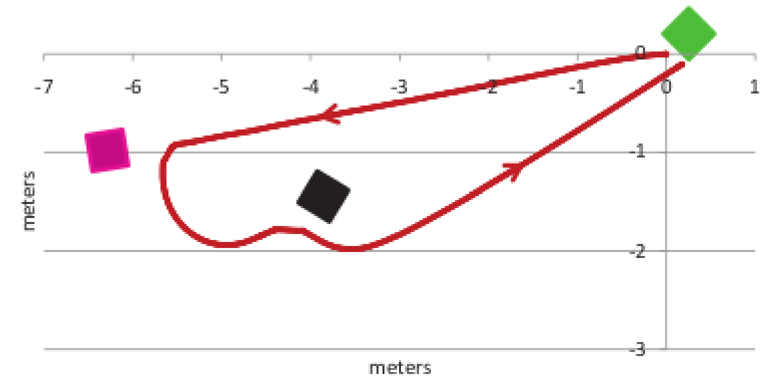


$$\hat{p}(o) = \sum_{\theta} \max_{j} p(o_j \,|\, \theta) p(\theta)$$

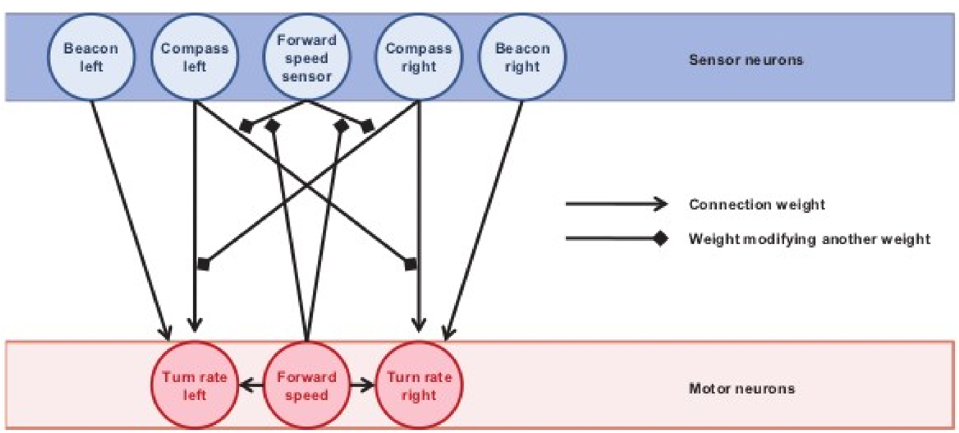
Model completeness

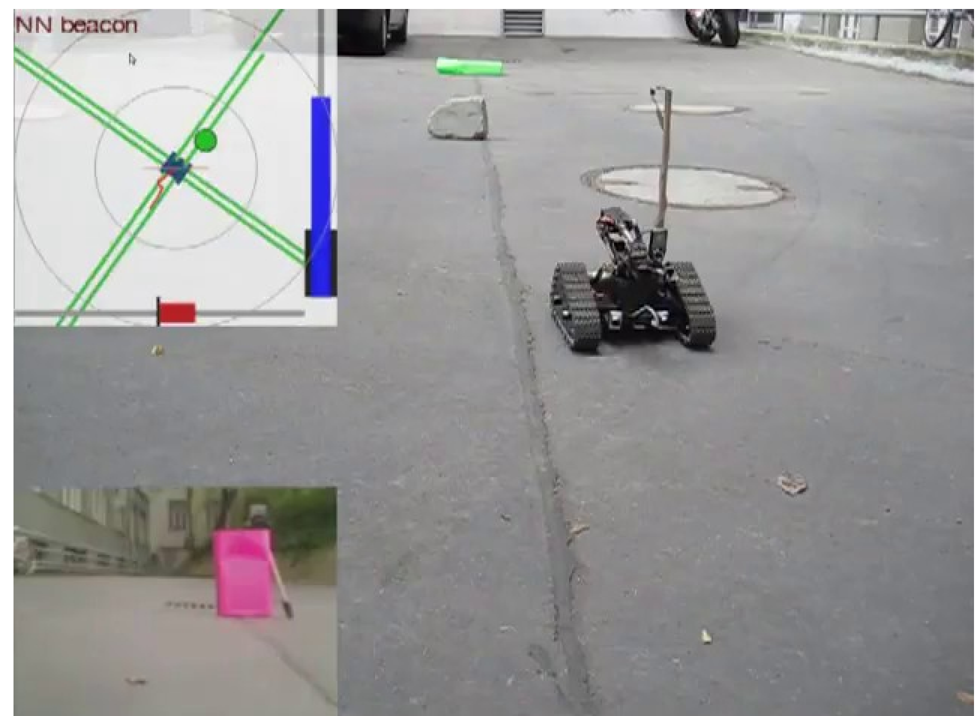
Ant Navigation

- Implement path integration in Sahara Desert ant (Cataglyphis bicolor)
- ModCTRNN (Modified Continuous Time Recurrent Neural Network) [Vickerstaff, 2007]
- Simple model, replicates foraging behaviour
- No claim to biological plausiblity



Example run

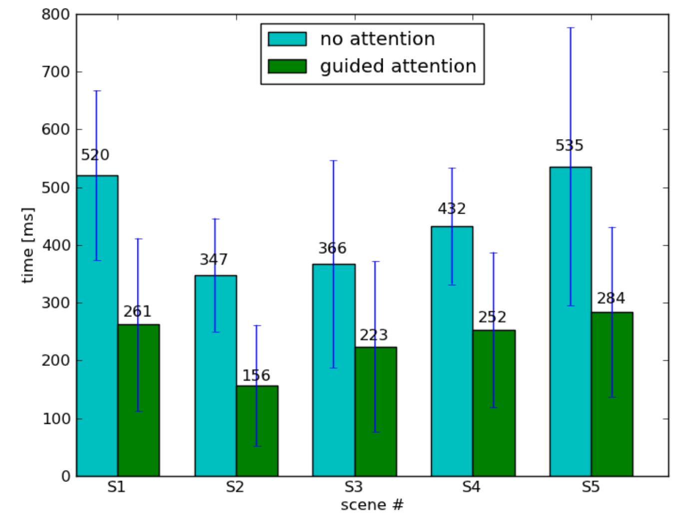




[Papauschek, 2010]

Integrated Language and Vision

- HRI poses tight timing requirements on visual and natural language processing to allow for natural interactions
- Rapidly and incrementally integrate perceptual context
- Top-down attention modulated via partially parsed linguistic utterances directs visual processing
- Computationally heavy processes work incrementally, so they can be interrupted and reconfigured



Improved detection speed

Is there a short red object?

Do you see the tall object on the left?

[Potapova, 2012]

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Robotic Success Stories

Roomba and colleagues

- Braitenberg vehicles with a purpose
- Cheap and very simple

irobot

Samsung

Robot toys: Sony AIBO, Pleo, (Paro)

- More complex, programmable
- Interesting for early adopters and technophiles

Aibo

Pleo

Paro

Robot Success Stories

Google Self-driving car project

- DARPA grand challenges starting 2004
- Sebastian Thrun (Stanford), Chris Urmson (CMU, Google)
- fleet of self-driving cars, >160000 miles on public roads in California and Nevada, including downtown San Francisco and Los Angeles

Robot Success Stories

Big Dog

- Marc Raibert (MIT, Boston Dynamics)
- Work starting mid eighties

http://www.youtube.com/watch?v=cNZPRsrwumQ

Quadruped 1987

Big Dog 2010

Conclusions

The embodied perspective

- + "Deep" theories
- + Solid grounding of concepts
- - *"Oooh, look what it just did!"* - surprise at emergent behaviours

The Cognitive systems perspective

- + Tackles real world problems
- Draws from solid results in many disciplines
- - *"Howdy partner, how are you doing today?"* - shallow demos not grounded in actual solid capabilities

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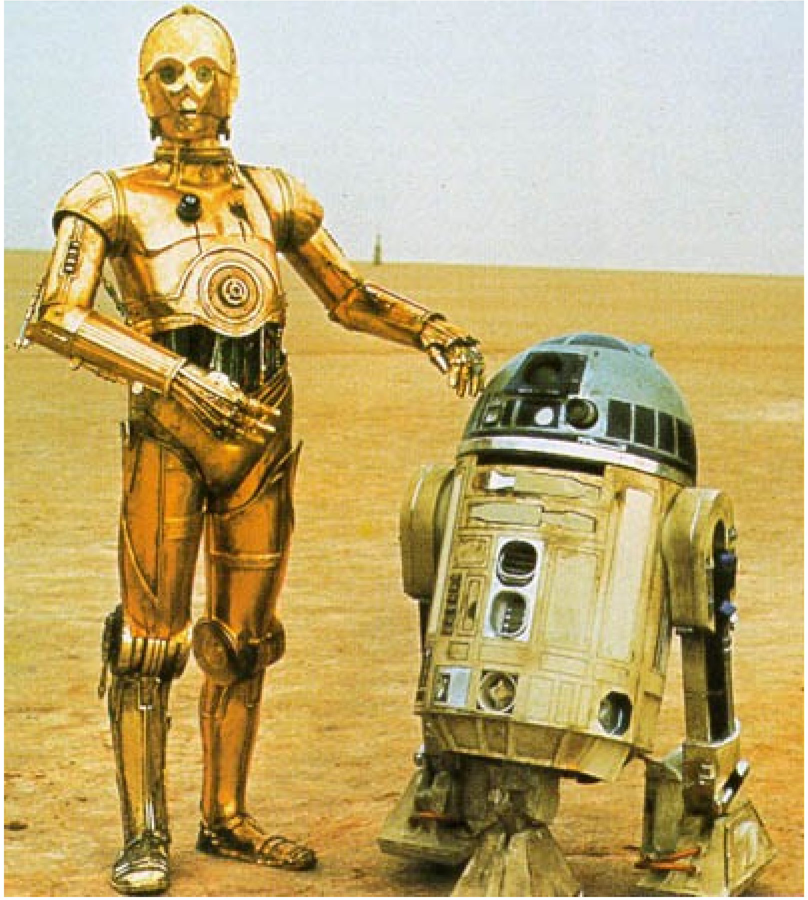
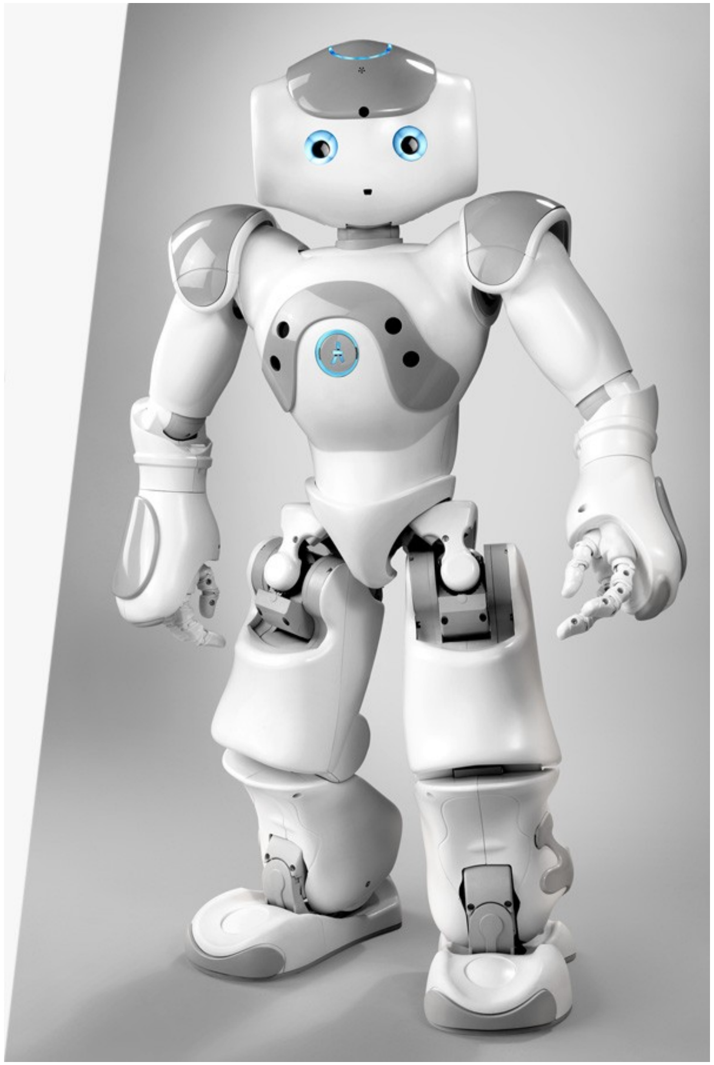
A Caveat

Cognition is ***not*** about looking human



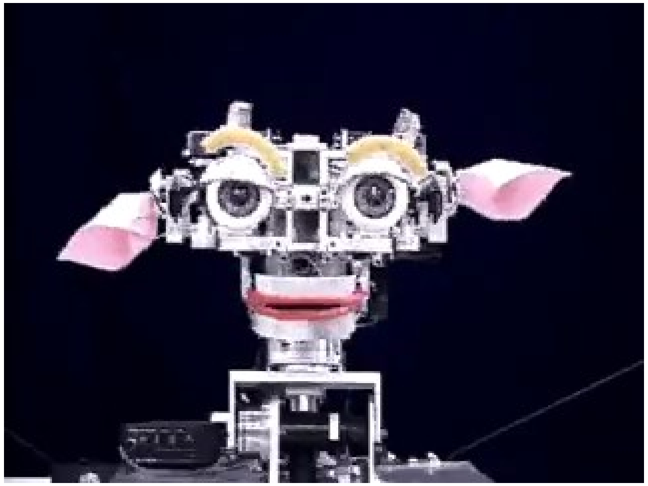
Who's smarter?



Aldebaran Nao

Look out for fake “intelligence”!

Don't trust rubber lips, eyebrows and ping-pong eyes



Kismet [Breazeal 1998]

HRP-4C [Nat. Inst. Adv. Ind. Sci. & Tech, Japan 2009]

References

[Ambler, 1973] A. P. Ambler, H. G. Barrow, C. M. Brown, R. M. Burstall, and R. J. Popplestone, A Versatile Computer-Controlled Assembly System, Proc. Third Int. Joint Conf. on AI, Stanford, California, pp. 298-307, 1973.

[Braitenberg, 1984] Braitenberg, V. Vehicles: Experiments in Synthetic Psychology, 1984. Bradford Books, 1984.

[Brooks, 1986] Brooks, R. A Robust Layered Control System for a Mobile Robot. IEEE Journal of Robotics and Automation, 2(1), 1986.

[Brooks, 1991] Brooks, R. A. Intelligence without representation. Artificial Intelligence, 47():139-159, 1991.

[Detry, 2011] Detry, R., Kraft, D., Kroemer, O., Bodenhagen, L., Peters, J., Krüger, N., & Piater, J. (2011). Learning Grasp Affordance Densities. Paladyn. Journal of Behavioral Robotics, 2(1), 1–17

[Gibson, 1979] Gibson, J. J. The ecological approach to visual perception, Boston, MA, 1979. Houghton Mifflin, Boston, MA, 1979.

[Kraft, 2003] Kraft, D., Pugeault, N., Baseski, E., Popovic, M., Kragic, D., Kalkan, S., Wörgötter, F., and Krüger, N. (2008). Birth of the object: Detection of objectness and extraction of object shape through object action complexes. Special Issue on ``Cognitive Humanoid Robots'' of the International Journal of Humanoid Robotics (IJHR), 2008, 5(2):247–265.

[Kuipers, 2008] Kuipers, B. Drinking from the firehose of experience. Artificial Intelligence in Medicine, 44:155-170, 2008.

[Lambrinos and Scheier, 1995] Lambrinos, D. and Scheier, C. Extended Braitenberg Architectures. AILab Technical Report, 95-10, University of Zurich, Switzerland, 1995.

[Metta et al., 2003] Metta, G., Metta, G., Fitzpatrick, P. and Fitzpatrick, P. Early integration of vision and manipulation. Adaptive Behavior, 11:109--128, 2003.

[Nilsson, 1984] Nilsson, N. J. Shakey the robot. Technical report, 323, AI Center, SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025, 1984.

[Oudeyer et al., 2007] Oudeyer, P.-Y., Kaplan, F. and Hafner, V. Intrinsic Motivation Systems for Autonomous Mental Development. IEEE Transactions on Evolutionary Computation, 11(2):265--286, 2007.

[Papauschek, 2010] Papauschek, C., Zillich, M. (2010). Biologically inspired navigation on a mobile robot. 2010 IEEE International Conference on Robotics and Biomimetics (ROBIO) (pp. 519 – 524).

[Potapova, 2012] Potapova, E., Krause, E., Cantrell, R., Zillich, M., Vincze, M., & Scheutz, M. (2012). Integrated Incremental Visual and Natural Language Processing for Human-Robot Interaction, CogSys'2012 (Poster)

[Pfeifer and Scheier, 1999] Pfeifer, R. and Scheier, C. Understanding Intelligence, Boston, 1999. MIT Press, Boston, 1999.

[Provost et al., 2006] Provost, J., Kuipers, B. J. and Miikkulainen, R. Developing navigation behavior through self-organizing distinctive state abstraction. Connection Science, 18(2), 2006.

[Skocaj et al., 2010] Skocaj, D., Janicek, M., Kristan, M., Kruijff, G.-J. M., Leonardis, A., Lison, P., Vrecko, A. and Zillich, M. A basic cognitive system for interactive continuous learning of visual concepts. ICRA 2010 Workshop ICAIR - Interactive Communication for Autonomous Intelligent Robots, pages 30-36. Anchorage, AK, USA, 2010.

[Steels, 1996] Steels, L. Discovering the competitors. Adaptive Behavior, 4(2):173--199, 1996.

[Steels, 2003] Steels, L. Intelligence with representation. Philosoph. Trans. Roy. Soc., 361(1811):2381-2395, 2003.

[Zillich, 2011] Zillich, M., Prankl, J., Mörwald, T., & Vincze, M. (2011). Knowing Your Limits - Self-evaluation and Prediction in Object Recognition. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).