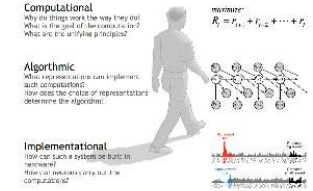
Cognitive architectures

A cognitive architecture is a formal theory of how the mind works, which can be implemented computationally.

Understanding information processing systems at three levels of analysis (Marr, 1982)



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Newell, 1990
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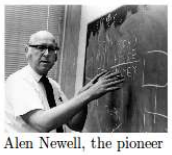

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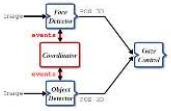

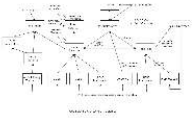

Top-down, Bottom-up and Modern approaches

Top-down, representation-based approches

A complex internal representation of a task is decomposed into sub-tasks to be executed, recursively

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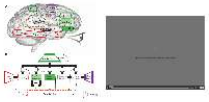

Pros and cons of top-down approaches

✚ High-level symbolic reasoning

▬ Poor embodiement and autonomy

Embodimentis more than connecting symbolic reasoning to a body

Bottom-up, behavior-based approches

A variety of simple behaviors are built into the robot's repertoire. These behaviors are layered and organized into a hierarchy, with more abstract goals farther up the heirarchy.

Can you drive only with a motor engine?

Embodiment is the surprisingly radical hypothesis that the brain is not the sole cognitive resource we have available to us to solve problems. Our bodies and their perceptually guided motions through the world do much of the work required to achieve our goals, replacing the need for complex internal mental representations. This simple fact utterly changes our idea of what "cognition" involves, and thus embodiment is not simply another factor acting on an otherwise disembodied cognitive processes.

Wilson and Golonka, *Embodied Cognition is Not What you Think it is*, Frontiers in Psychology, 2013

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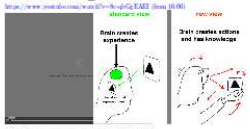

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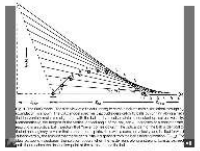
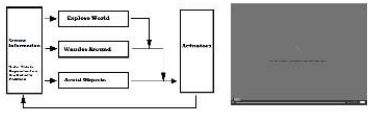


The world is its own best model (Rodney Brooks)

Combining embodied behaviors



Subsumption architecture (Brooks, 1986)

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A key challenge is to bridge both approaches, referred as the symbol-grounding problem.

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Top-down representation-based vs. Bottom-up behavior-based

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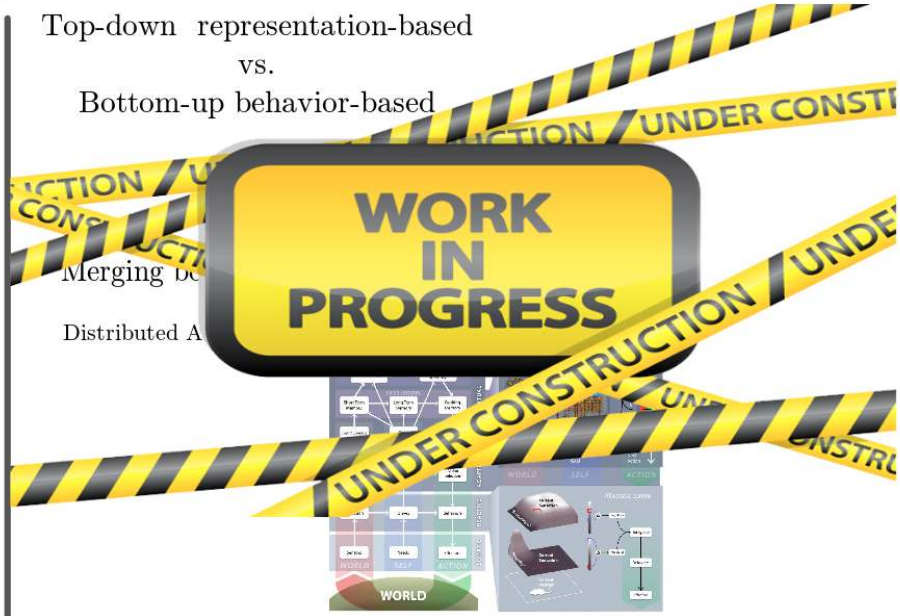

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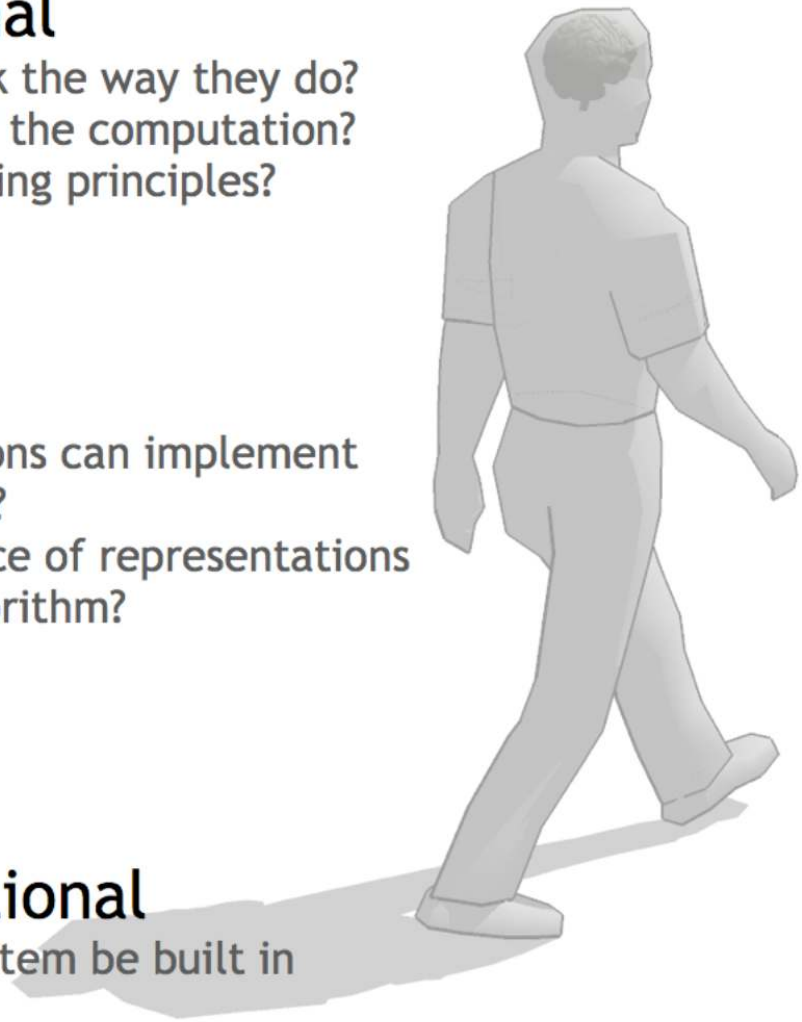
Understanding information processing systems at three levels of analysis (Marr, 1982)

Computational

Why do things work the way they do?
What is the goal of the computation?
What are the unifying principles?



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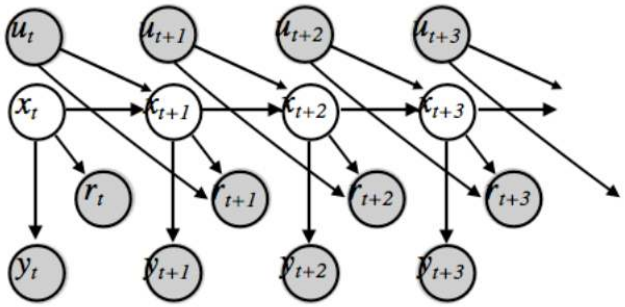
$$R_t = r_{t+1} + r_{t+2} + \cdots + r_T$$

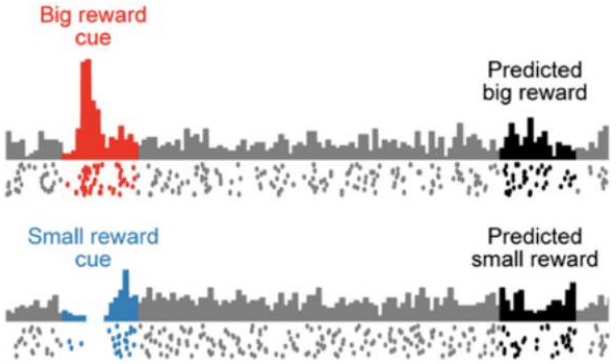
Algorithmic

What representations can implement such computations?
How does the choice of representations determine the algorithm?



Implementational

How can such a system be built in hardware?
How can neurons carry out the computations?



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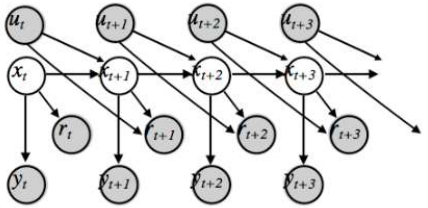

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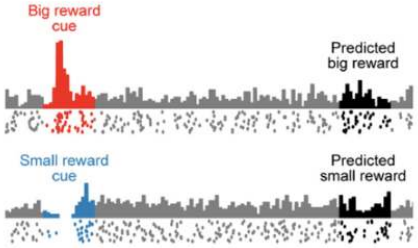

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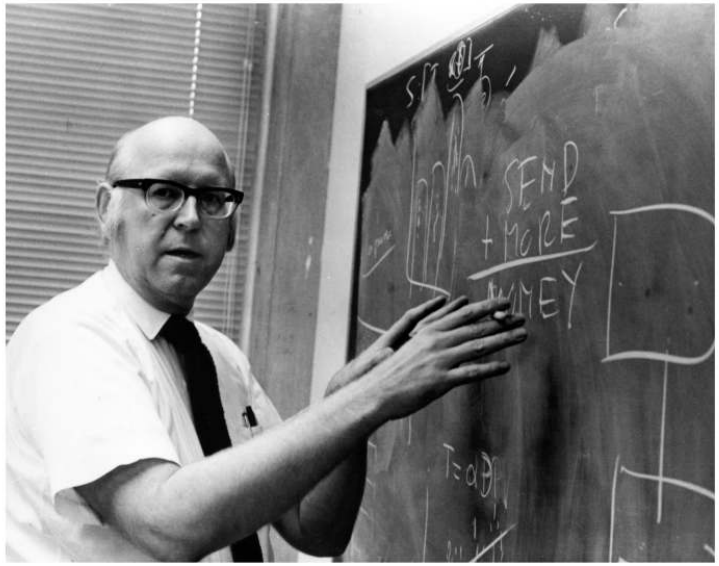

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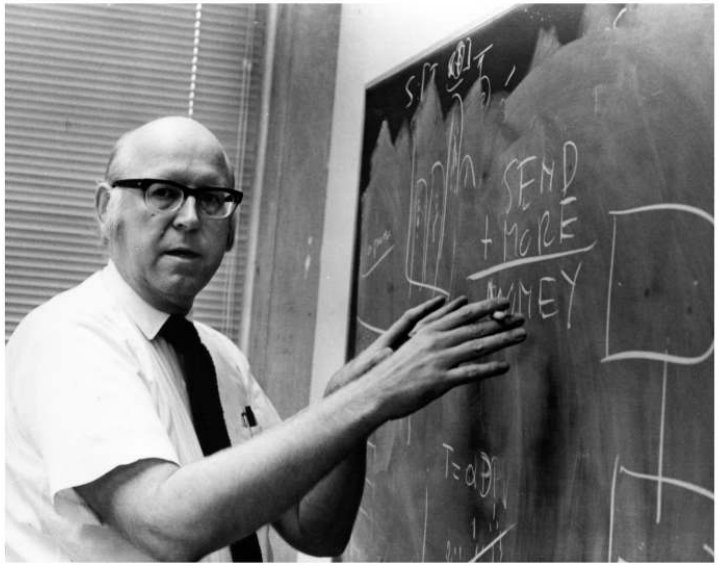

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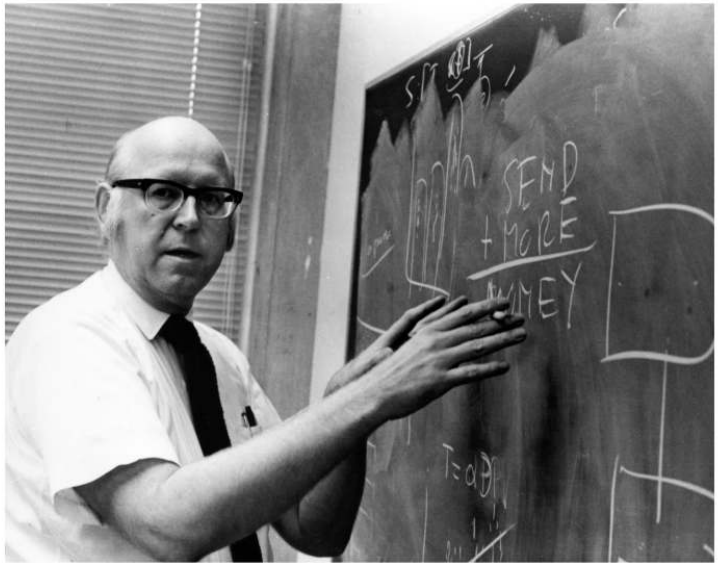

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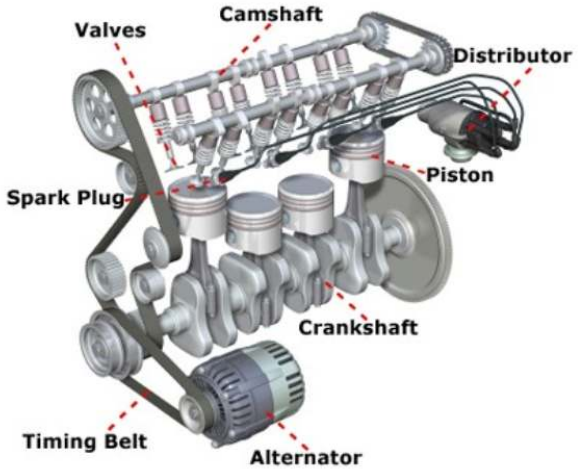

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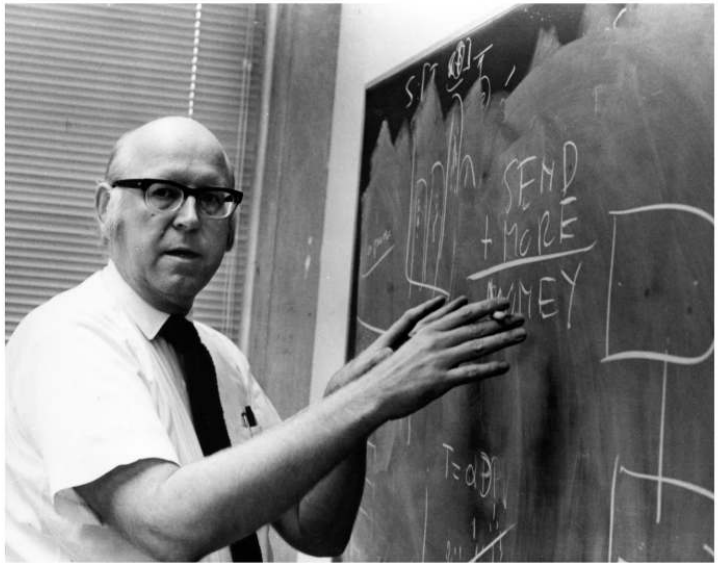

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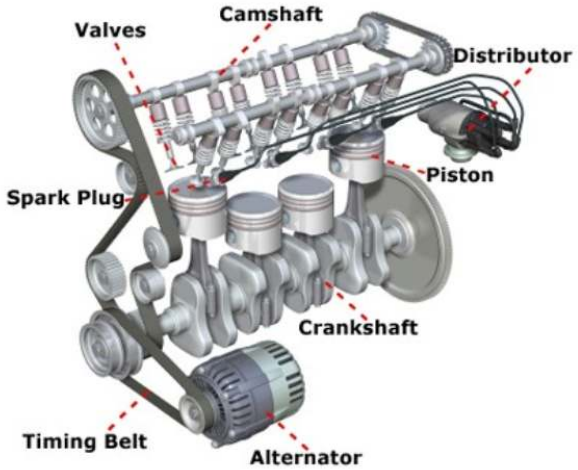
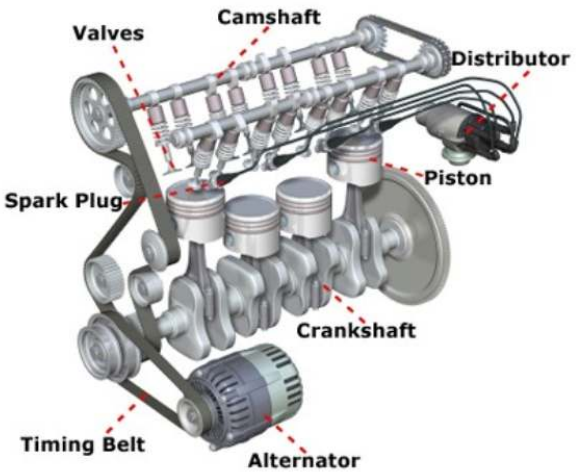


Newell's Functional Criteria for a Human Cognitive Architecture

1. Behave as an (almost) arbitrary function of the environment
2. Operate in real time
3. Exhibit rational, i.e., effective adaptive behavior
4. Use vast amounts of knowledge about the environment
5. Behave robustly in the face of error, the unexpected, and the unknown
6. Integrate diverse knowledge
7. Use (natural) language
8. Exhibit self-awareness and a sense of self
9. Learn from its environment
10. Acquire capabilities through development
11. Arise through evolution

What are the parts of the cognition engine?



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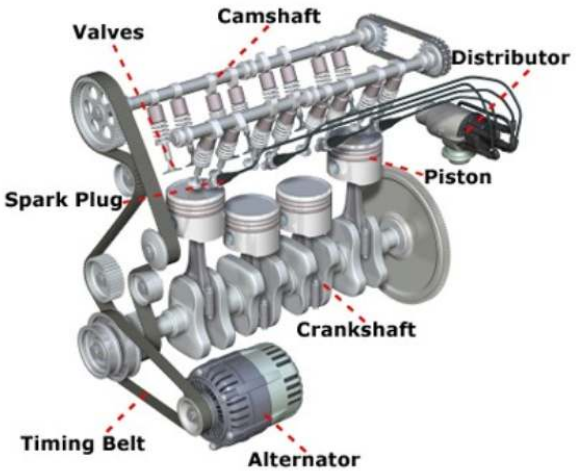

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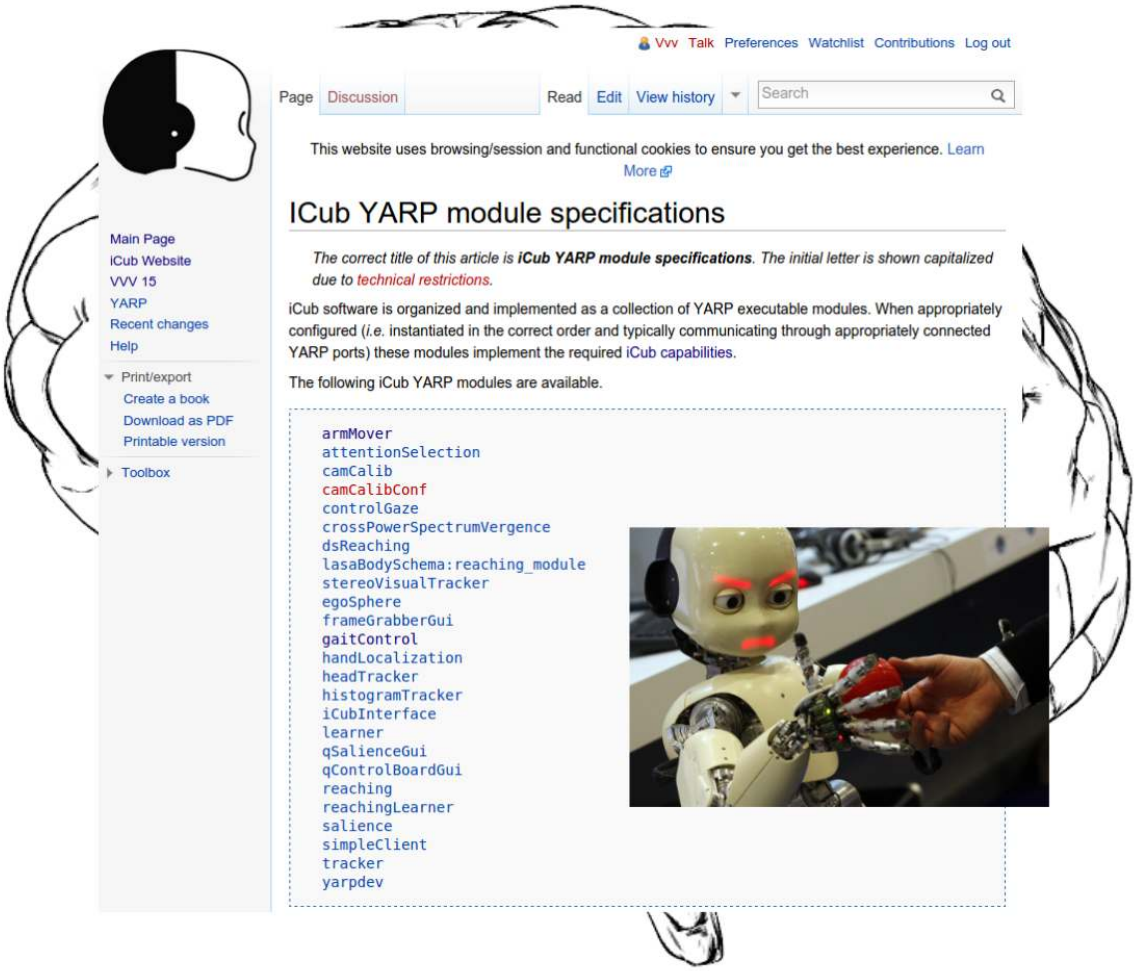

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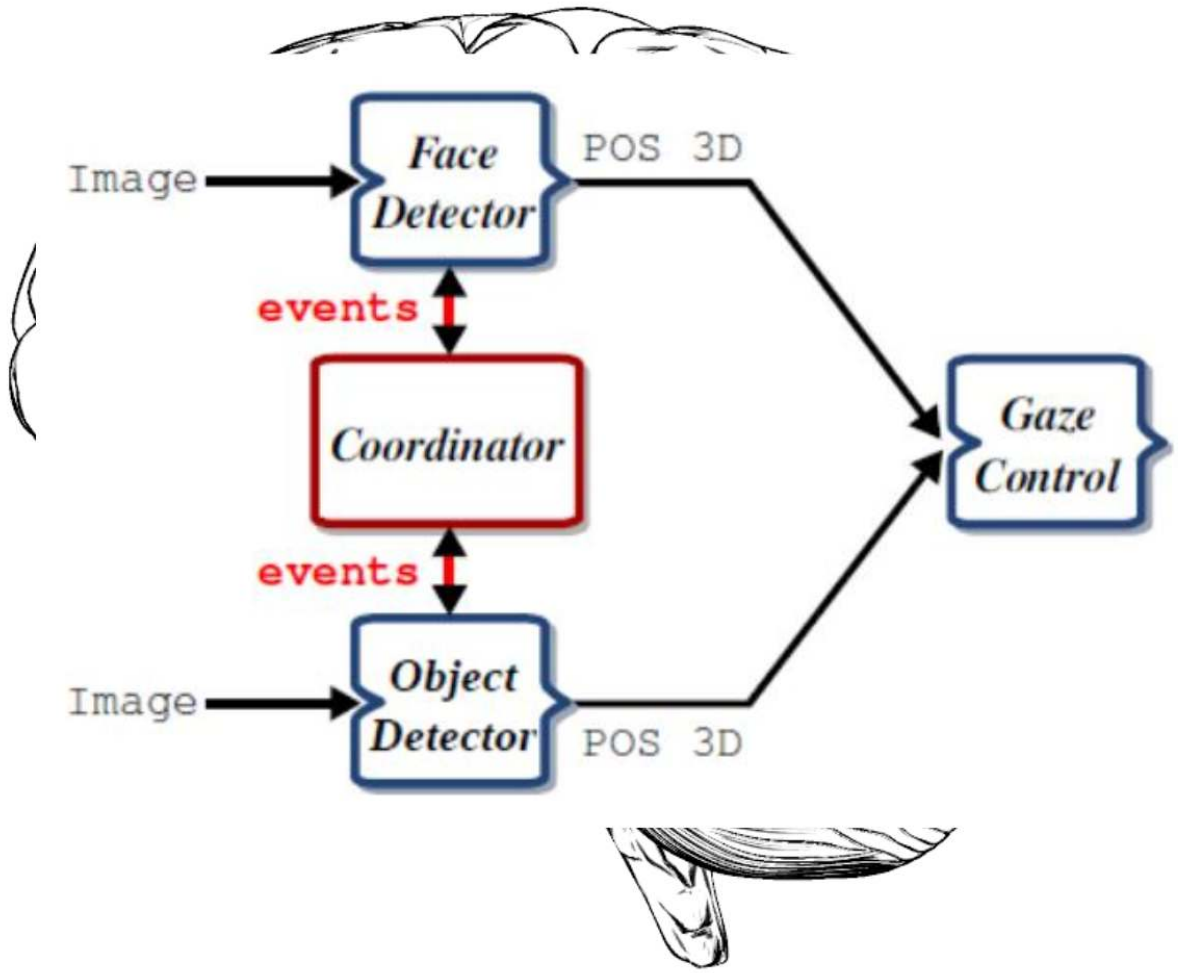

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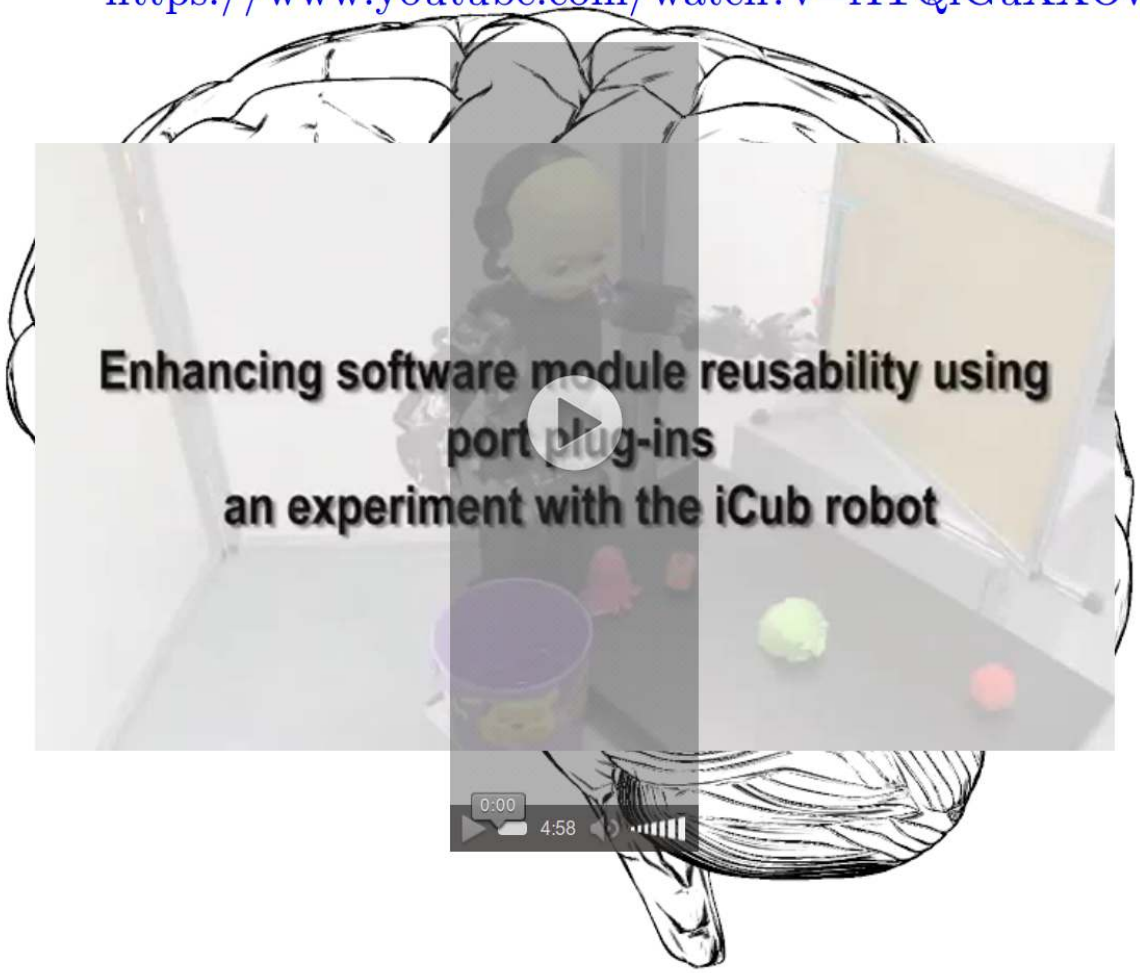
https://www.youtube.com/watch?v=rITQlGuXXOw



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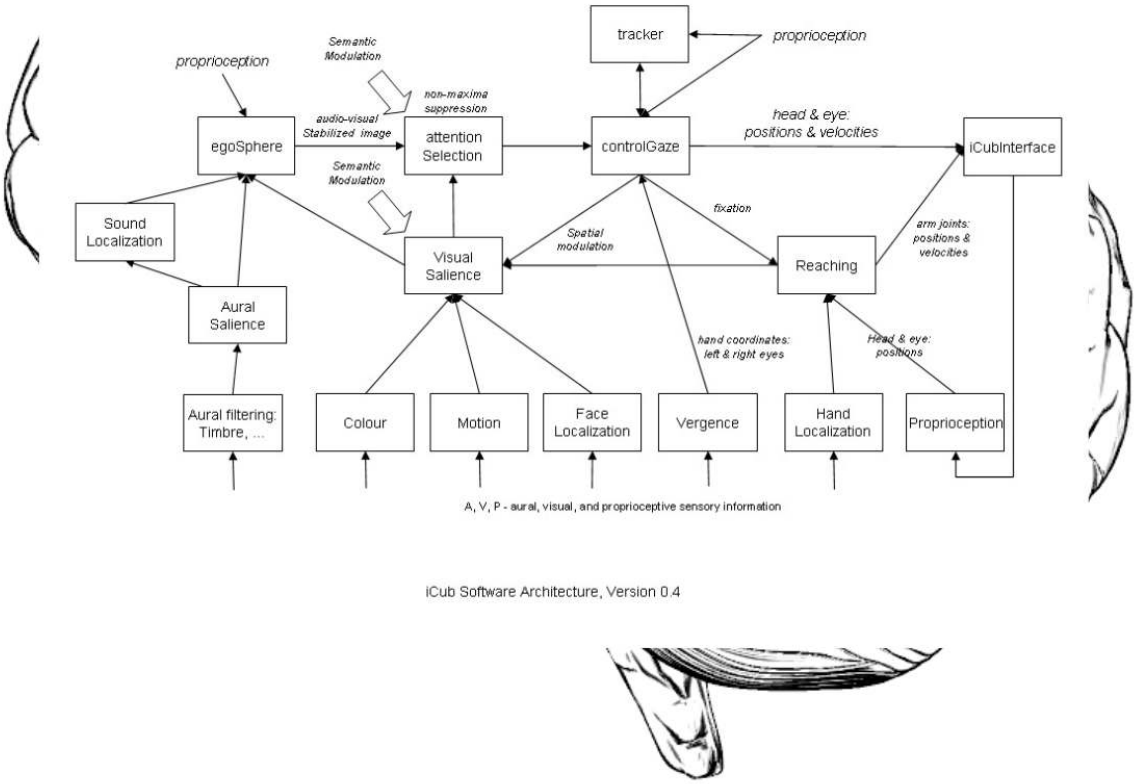

iCub Software Architecture, Version 0.4

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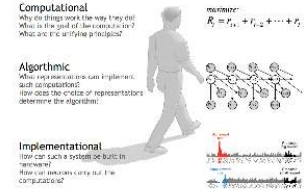

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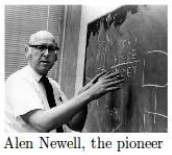

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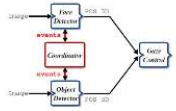

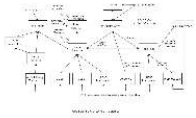

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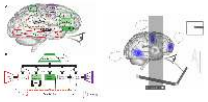

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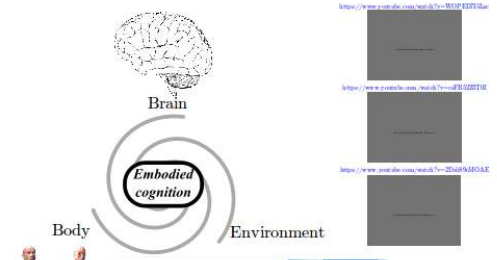

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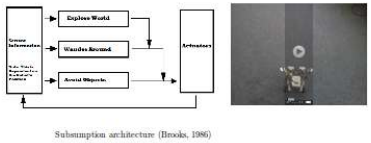

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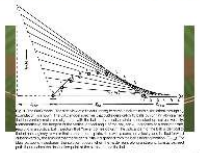

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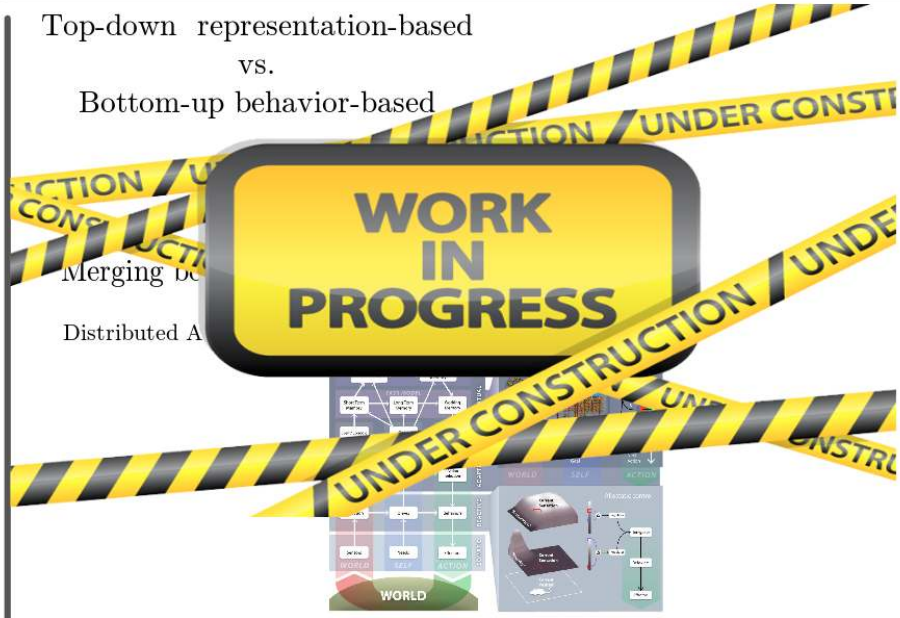

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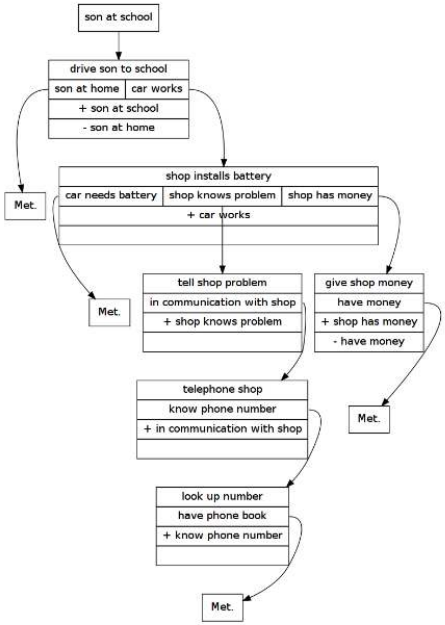

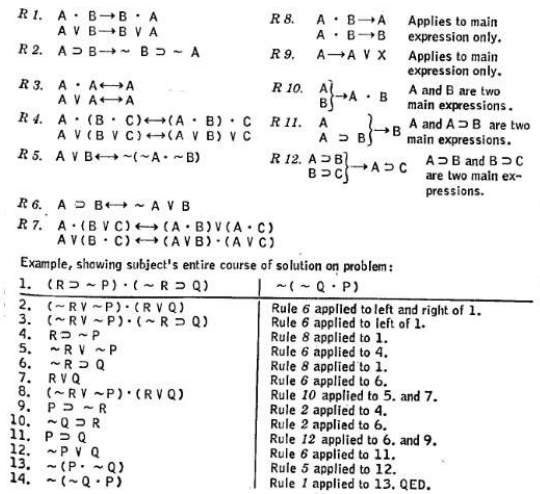

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R 2. $A \supset B \rightarrow \sim B \supset \sim A$

R 3. $A \cdot A \longleftrightarrow A$; $A \vee A \longleftrightarrow A$

R 4. $A \cdot (B \cdot C) \longleftrightarrow (A \cdot B) \cdot C$; $A \vee (B \vee C) \longleftrightarrow (A \vee B) \vee C$

R 5. $A \vee B \longleftrightarrow \sim(\sim A \cdot \sim B)$

R 6. $A \supset B \longleftrightarrow \sim A \vee B$

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R 8. $A \cdot B \rightarrow A$; $A \cdot B \rightarrow B$ — Applies to main expression only.

R 9. $A \rightarrow A \vee X$ — Applies to main expression only.

R 10. $A, B \rightarrow A \cdot B$ — A and B are two main expressions.

R 11. $A, A \supset B \rightarrow B$ — A and $A \supset B$ are two main expressions.

R 12. $A \supset B, B \supset C \rightarrow A \supset C$ — $A \supset B$ and $B \supset C$ are two main expressions.

Example, showing subject's entire course of solution on problem:

1.	$(R \supset \sim P) \cdot (\sim R \supset Q)$	$\sim(\sim Q \cdot P)$
2.	$(\sim R \vee \sim P) \cdot (R \vee Q)$	Rule *6* applied to left and right of 1.
3.	$(\sim R \vee \sim P) \cdot (\sim R \supset Q)$	Rule *6* applied to left of 1.
4.	$R \supset \sim P$	Rule *8* applied to 1.
5.	$\sim R \vee \sim P$	Rule *6* applied to 4.
6.	$\sim R \supset Q$	Rule *8* applied to 1.
7.	$R \vee Q$	Rule *6* applied to 6.
8.	$(\sim R \vee \sim P) \cdot (R \vee Q)$	Rule *10* applied to 5. and 7.
9.	$P \supset \sim R$	Rule *2* applied to 4.
10.	$\sim Q \supset R$	Rule *2* applied to 6.
11.	$P \supset Q$	Rule *12* applied to 6. and 9.
12.	$\sim P \vee Q$	Rule *6* applied to 11.
13.	$\sim(P \cdot \sim Q)$	Rule *5* applied to 12.
14.	$\sim(\sim Q \cdot P)$	Rule *1* applied to 13. QED.

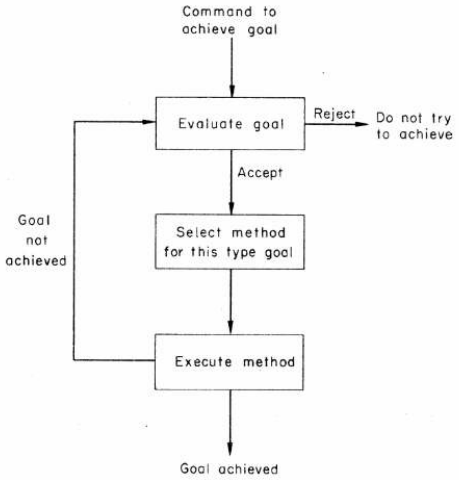


Fig. I — Executive organization of GPS

Newell, Shaw, & Simon, 1959

ACT-R

Anderson, 1983 ; Anderson et al., 2004

How ACT-R Works

A detailed introduction to ACT-R is offered in the ACT-R tutorials. Here we present only the very basic mechanism.

ACT-R's main components are:

- modules,
- buffers,
- pattern matcher.

Modules

There are two types of modules:

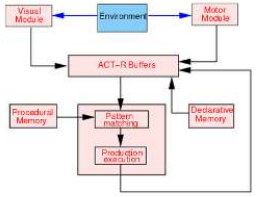
- **perceptual-motor modules**, which take care of the interface with the real world (i.e., with a simulation of the real world). The most well-developed perceptual-motor modules in ACT-R are the visual and the manual modules.
- **memory modules**.

There are two kinds of memory modules in ACT-R:

- **declarative memory**, consisting of facts such as *Washington, D.C. is the capital of United States*, *France is a country in Europe*, or *2+3=5*, and
- **procedural memory**, made of **productions**. Productions represent knowledge about how we do things: for instance, knowledge about how to type the letter "Q" on a keyboard, about how to drive, or about how to perform addition.

Buffers

ACT-R accesses its modules (except for the procedural-memory module) through buffers. For each module, a dedicated buffer serves as the interface with that module. The contents of the buffers at a given moment in time represents the state of ACT-R at that moment.

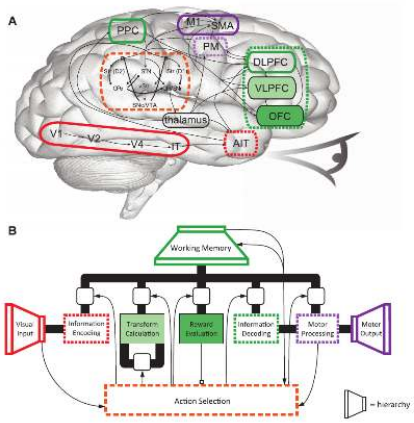


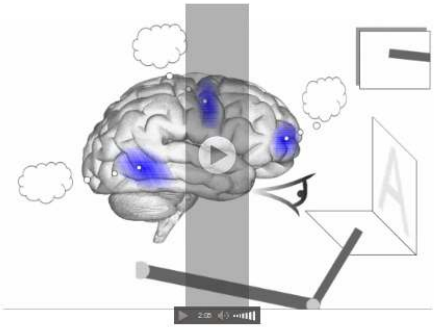
Pattern Matcher

The pattern matcher searches for a production that matches the current state of the buffers. Only one such production can be executed at a given moment. That production, when executed, can modify the buffers and thus change the state of the system. Thus, in ACT-R cognition unfolds as a succession of production firings.

Spaun

Eliasmith et al., 2012





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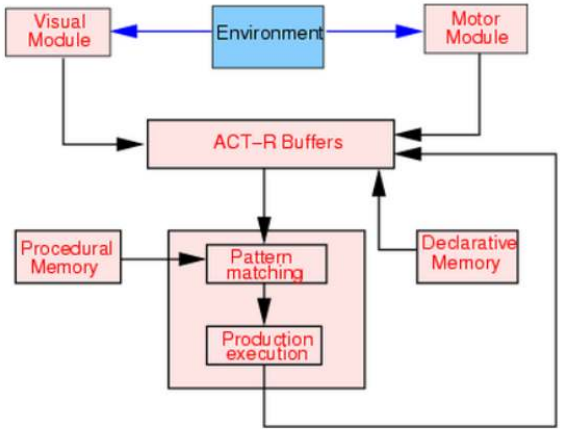

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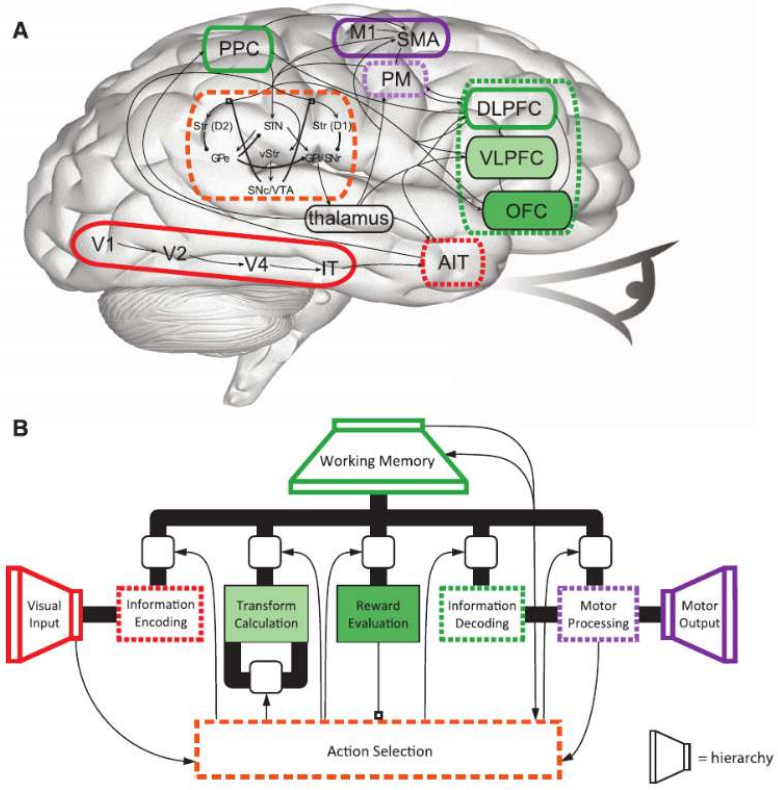

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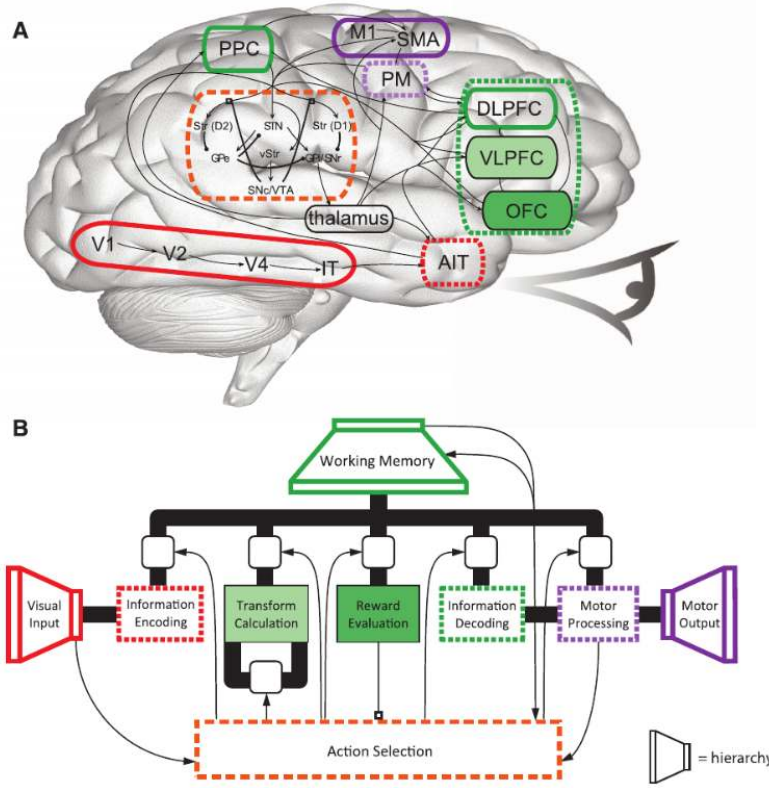

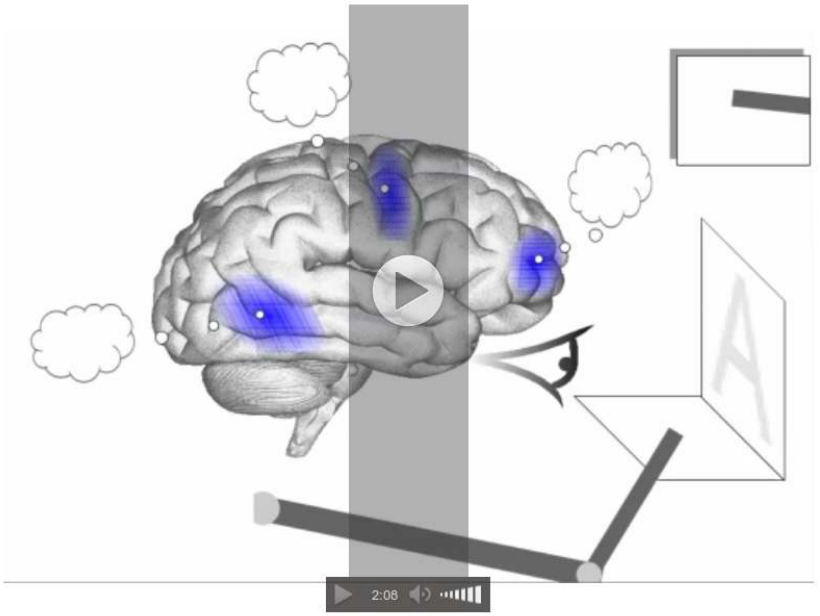

Pros and cons of top-down approaches

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High-level
symbolic reasoning

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https://www.youtube.com/watch?v=NeFkrwagYfc

Pros and cons of top-down approaches

High-level
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Poor embodiement
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Embodiment

Pros and cons of top-down approaches

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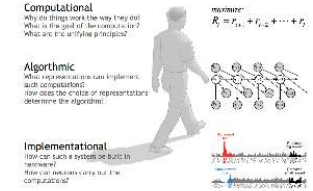
Embodiment is more than connecting symbolic reasoning to a body

Cognitive architectures

A cognitive architecture is a formal theory of how the mind works, which can be implemented computationally.

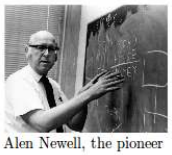
Understanding information processing systems at three levels of analysis (Marr, 1982)



The level of the cognitive architecture is the level at which general cognitive mechanisms can be described irrespective of their implementation (Taatgen & Anderson, 2010), i.e. Marr's algorithmic level.

A single system (mind) produces all aspects of behavior. It is one mind that minds them all. **Even if the mind has parts, modules, components, or whatever, they all mesh together to produce behavior… If a theory covers only one part or component, it flirts with trouble from the start.** It goes without saying that there are dissociations, interdependencies, impenetrabilities, and modularities... But they don't remove the necessity of a theory that provides the total picture and explains the role of the parts and why they exist.

Newell, 1990
Unified theories of cognition



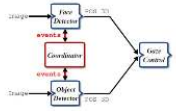
Alen Newell, the pioneer

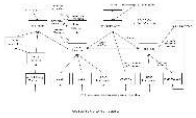
The question for me is how can the human mind occur in the physical universe. We now know that the world is governed by physics. We now understand the way biology nestles comfortably within that. The issue is how will the mind do that as well. The answer must have the details. **I got to know how the gears clank and how the pistons go and all the rest of that detail... My question leads me down to worry about the architecture.**

Newell, 1990

What are the parts of the cognition engine?

- perception
- action
- control
- representation
- attention
- decision making
- learning
- memory
- planning- ...





Top-down, Bottom-up and Modern approaches

Top-down, representation-based approches

A complex internal representation of a task is decomposed into sub-tasks to be executed, recursively

Early days: General Problem Solver

Separating the knowledge
From the strategy of how to solve problems

Newell, Shaw, & Simon, 1959

ACT-R

Anderson, 1983 ; Anderson et al., 2004

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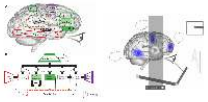
Eliasmith et al., 2012



Pros and cons of top-down approaches

✚ High-level symbolic reasoning

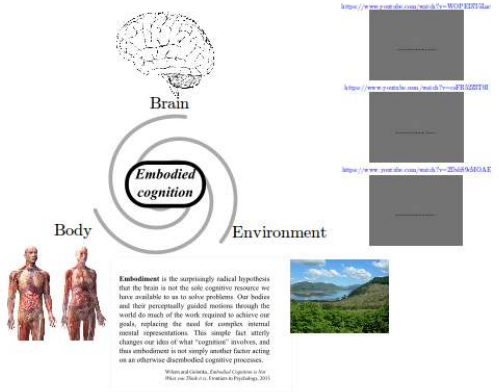
▬ Poor embodiement and autonomy

Embodimentis more than connecting symbolic reasoning to a body

Bottom-up, behavior-based approches

A variety of simple behaviors are built into the robot's repertoire. These behaviors are layered and organized into a hierarchy, with more abstract goals farther up the heirarchy.

Can you drive only with a motor engine?



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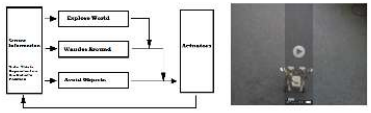
Wilson and Golonka, *Embodied Cognition is Not What you Think it is*, Frontiers in Psychology, 2013

Combining embodied behaviors



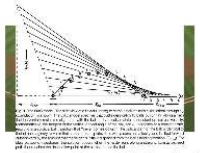
Subsumption architecture (Brooks, 1986)

What is a ball?

Feeling softness

J.K. O'Regan, *Why red doesn't sound like a bell: Understanding the feel of consciousness*, 2011

How to catch a ball?



The world is its own best model (Rodney Brooks)

Pros and cons of bottom-up approaches

✚ Embodiement and autonomy

▬ No high-level symbolic reasoning

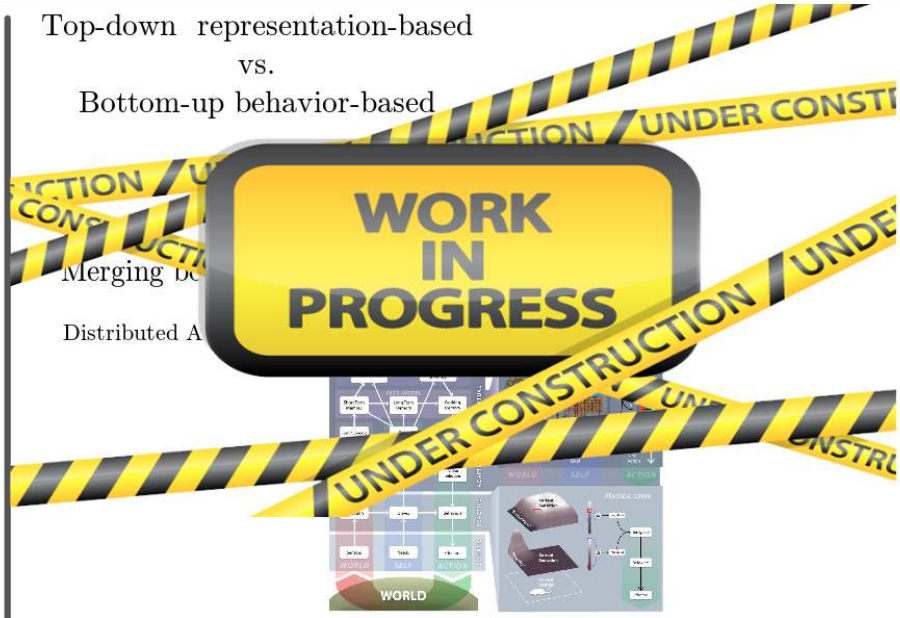
A key challenge is to bridge both approaches, referred as the symbol-grounding problem.

"Symbolic representations must be grounded bottom-up in nonsymbolic" (Harnad, 1990).

Top-down representation-based vs. Bottom-up behavior-based

Merging be

Distributed A



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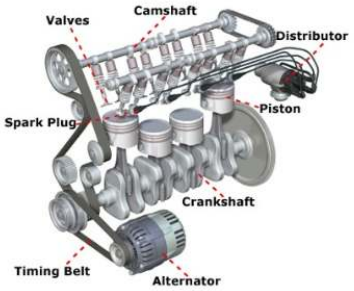

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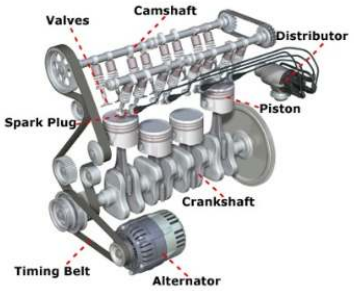

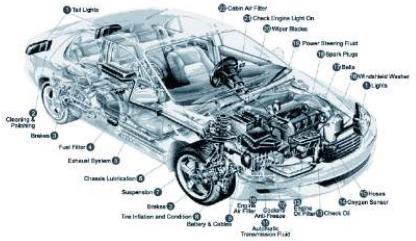

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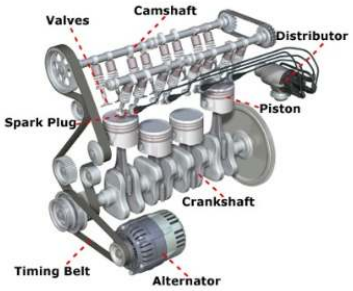

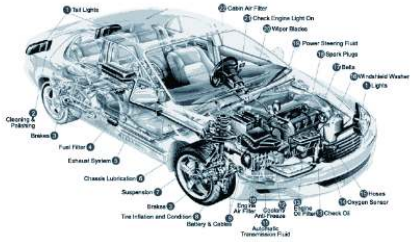

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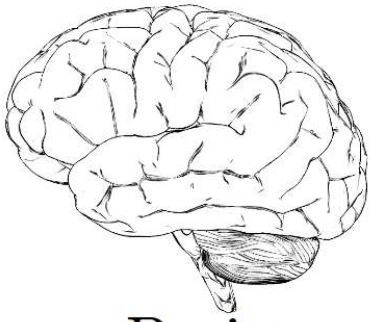
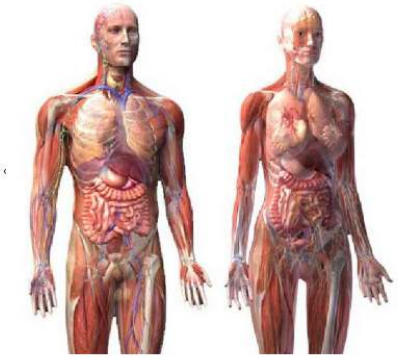


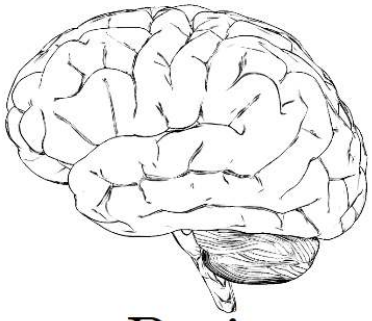
Brain

Body



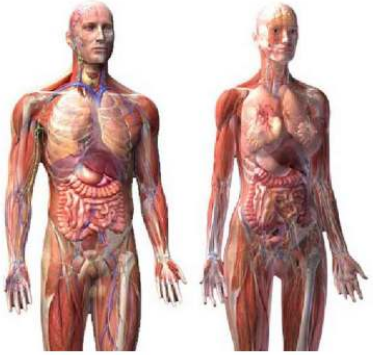
Environment

Can you drive only with a motor engine?



Brain

Body



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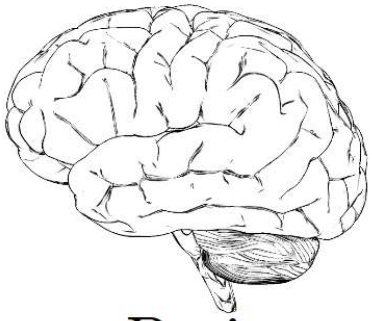

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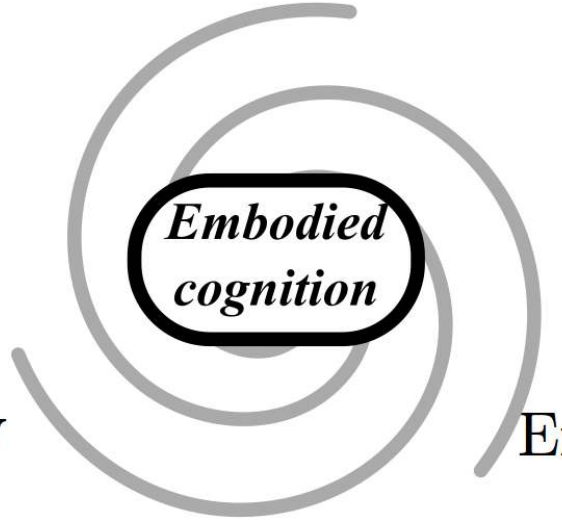

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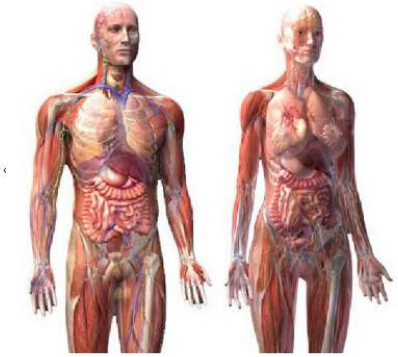


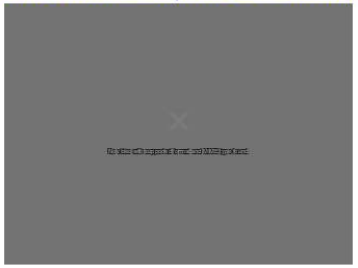
Environment

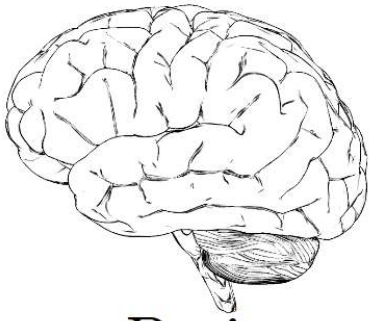
Can you drive only with a motor engine?

https://www.youtube.com/watch?v=WOPED7I5Lac

https://www.youtube.com/watch?v=csFR52Z3T0I

https://www.youtube.com/watch?v=2DsbS9cMOAE

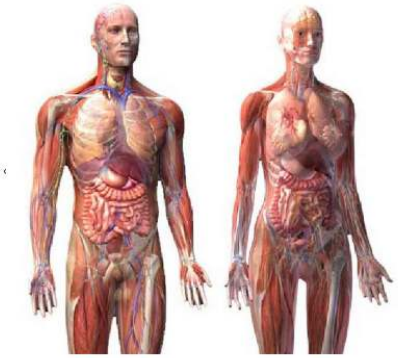




Brain

Embodied cognition

Body



Environment

Brain

https://www.youtube.com/watch?v=WOPED7I5Lac

Embodied

No video with supported format and MIME type found.

cognition

Body

Environment

https://www.youtube.com/watch?v=csFR52Z3T0I

Brain

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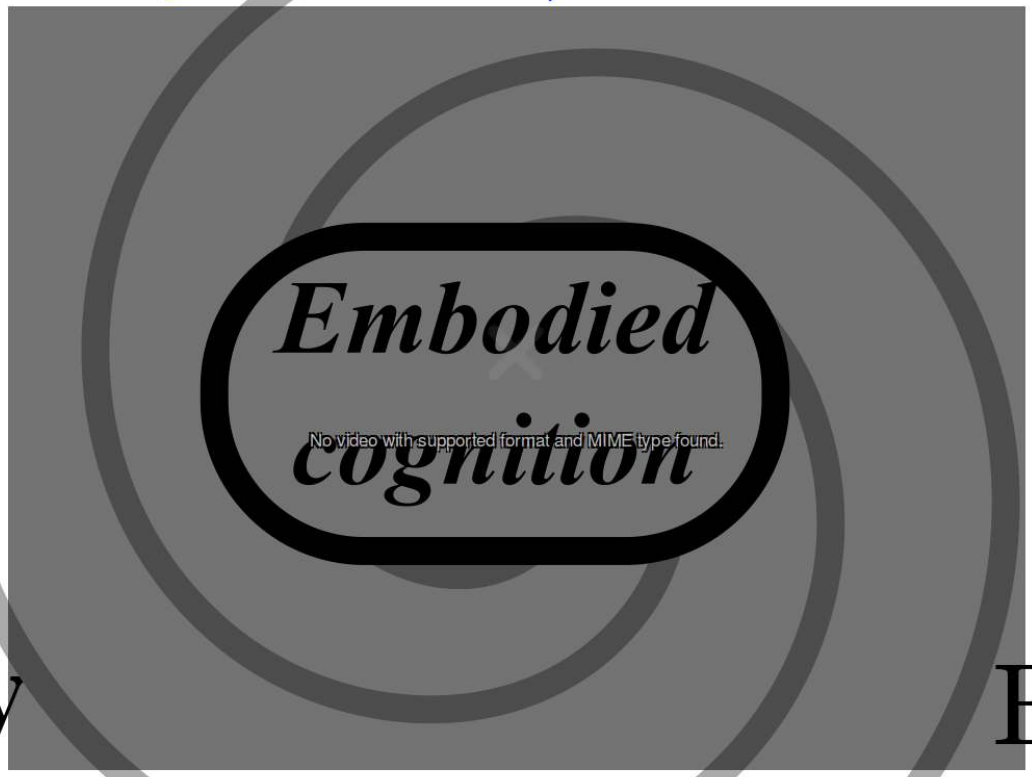

Body

Environment

https://www.youtube.com/watch?v=2DsbS9cMOAE

Brain

https://www.youtube.com/watch?v=2DsbS9cMOAE

Embodied cognition

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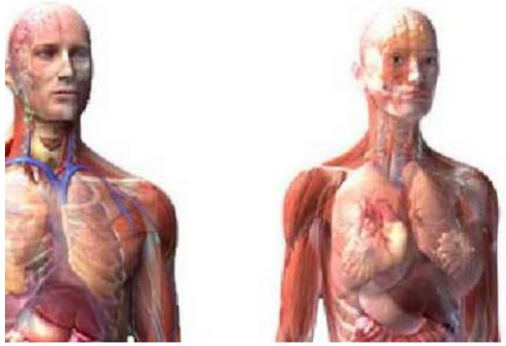
Body

Environment



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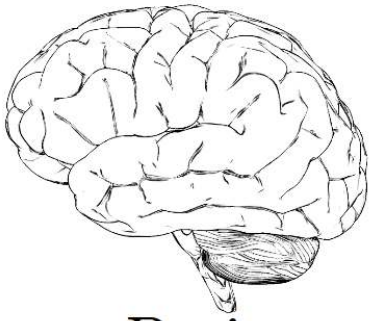
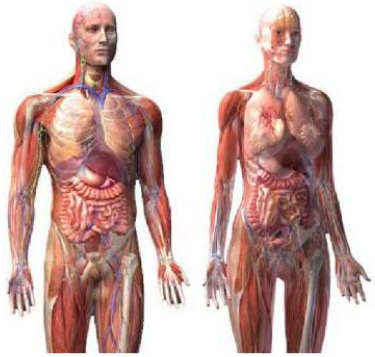
Wilson and Golonka, *Embodied Cognition is Not What you Think it is*, Frontiers in Psychology, 2013



Brain

Embodied cognition

Body



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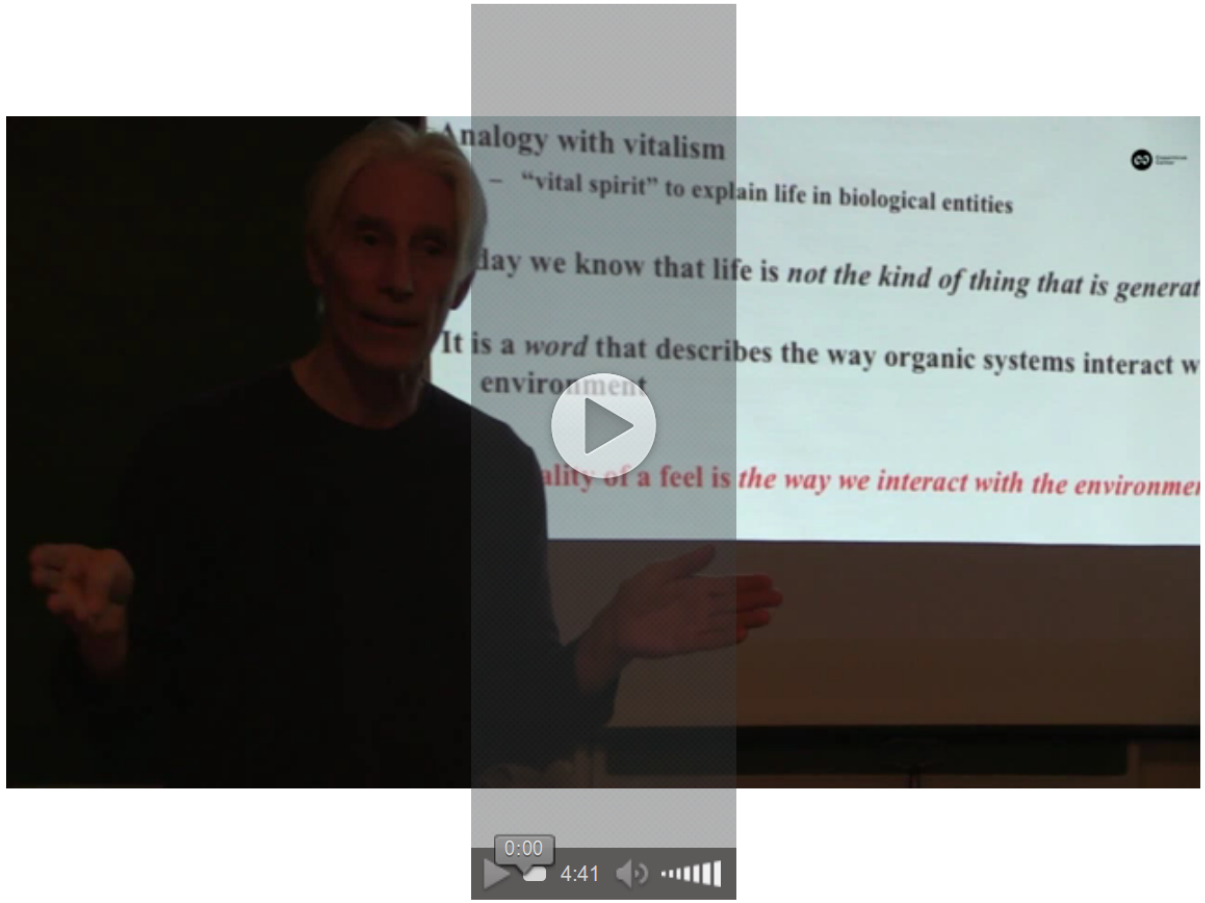
What is a ball?

What is a ball?

Feeling softness

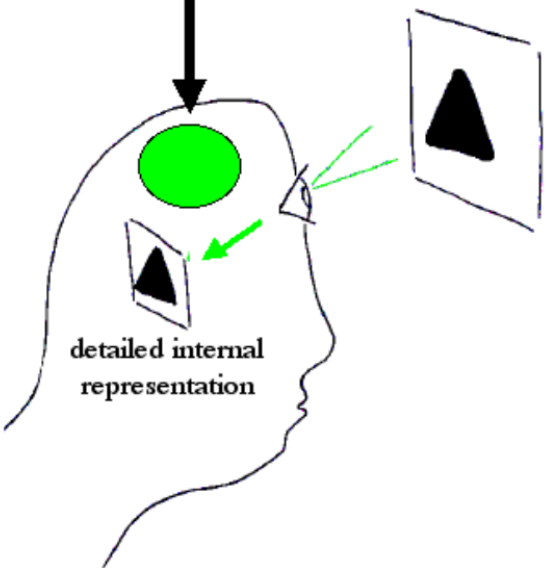
https://www.youtube.com/watch?v=8c-qbGgEAEI (from 16:06)



J.K. O'Regan, *Why red doesn't sound like a bell: Understanding the feel of consciousness*, 2011

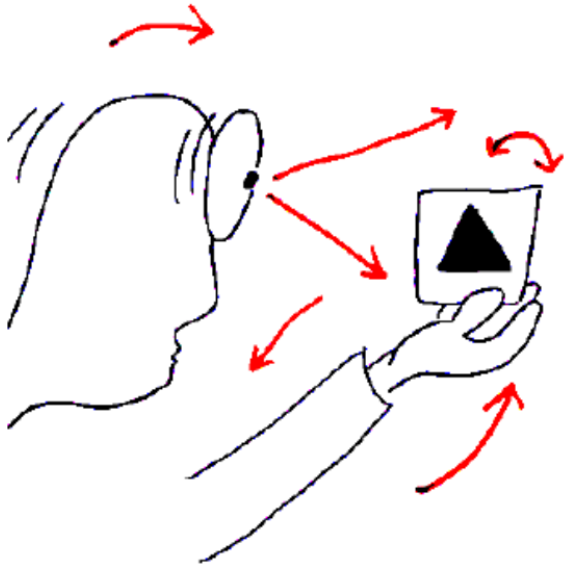
standard view

Brain creates experience

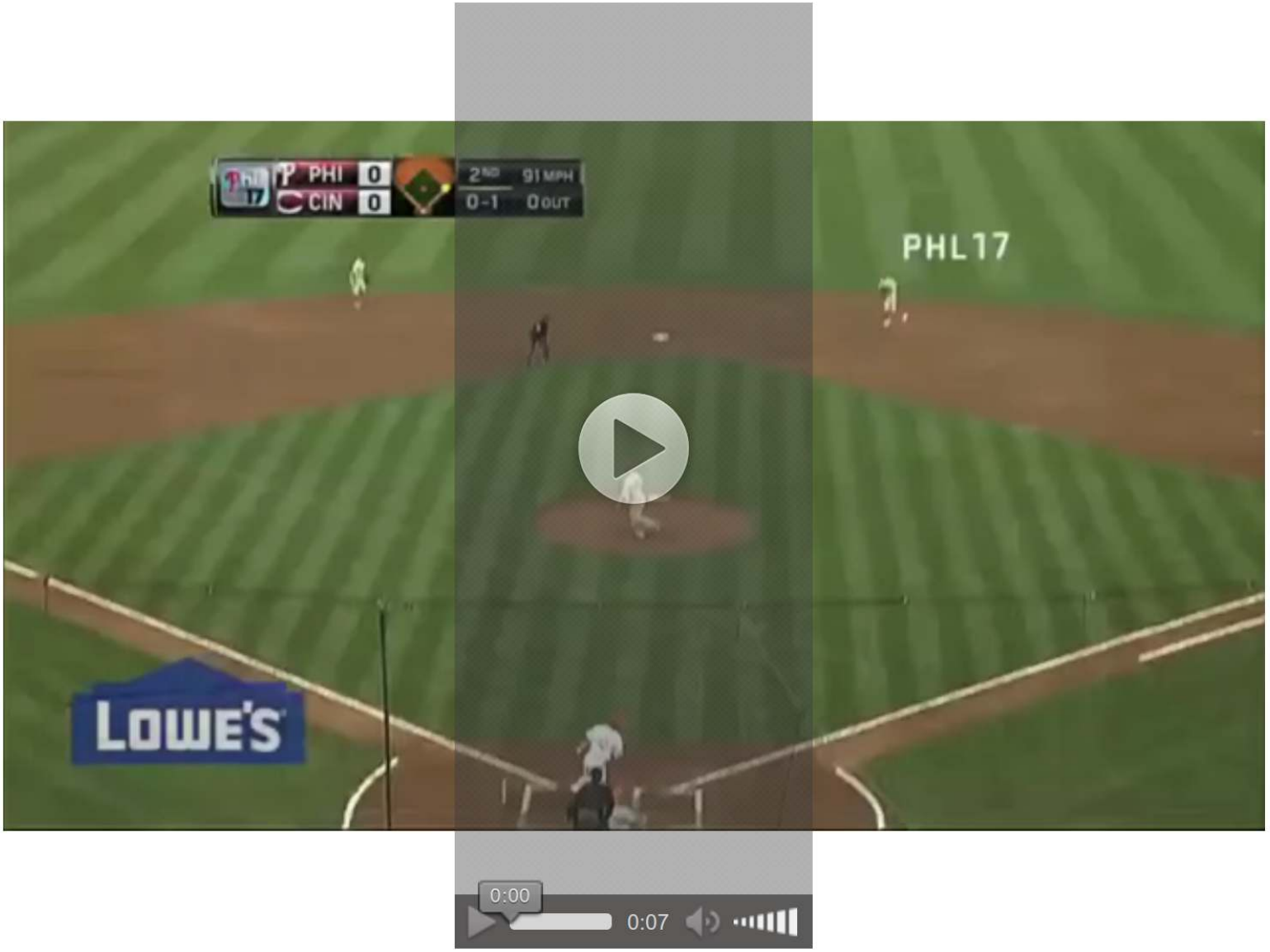


new view

Brain creates actions and has knowledge



How to catch a ball?



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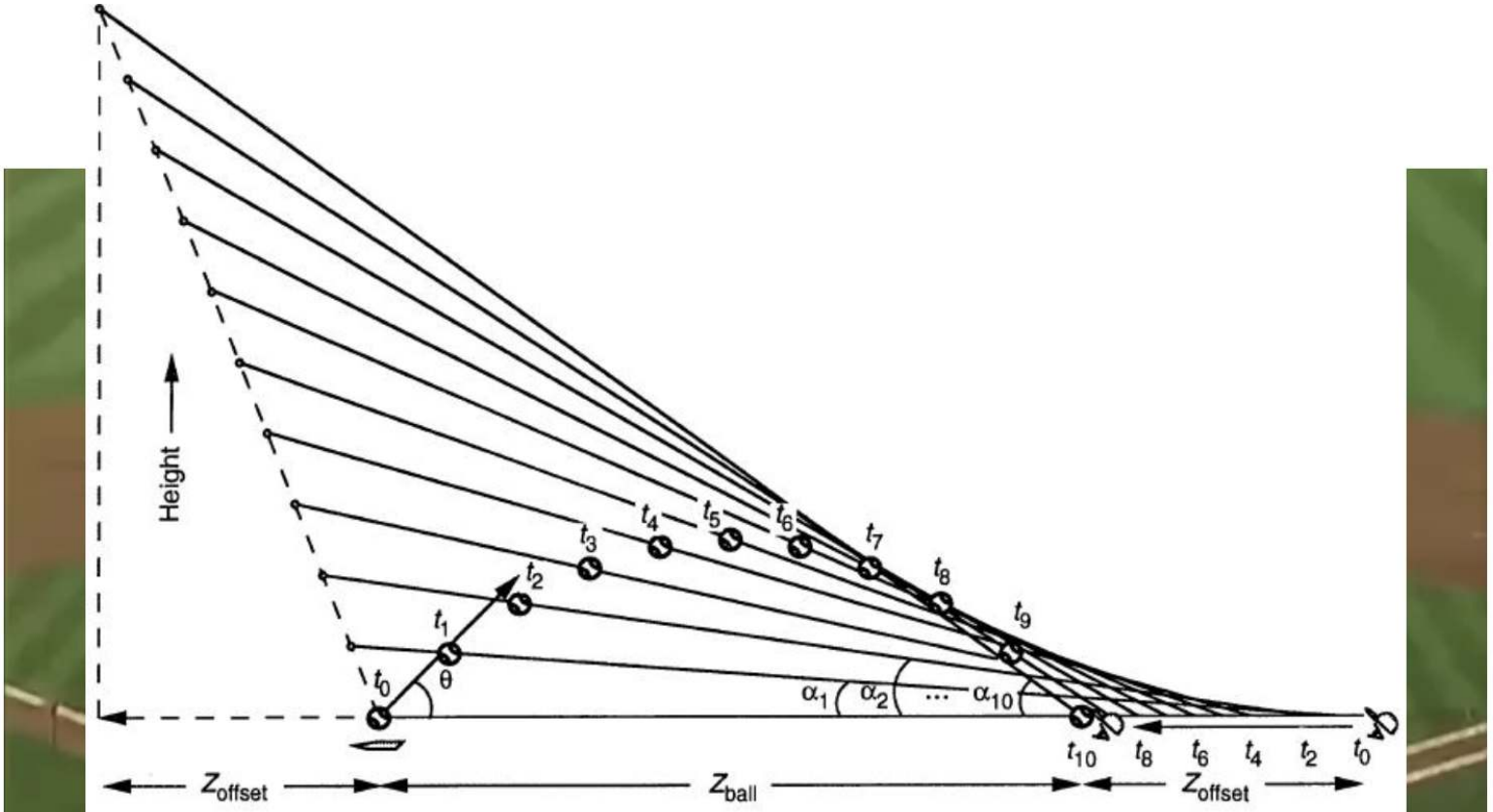
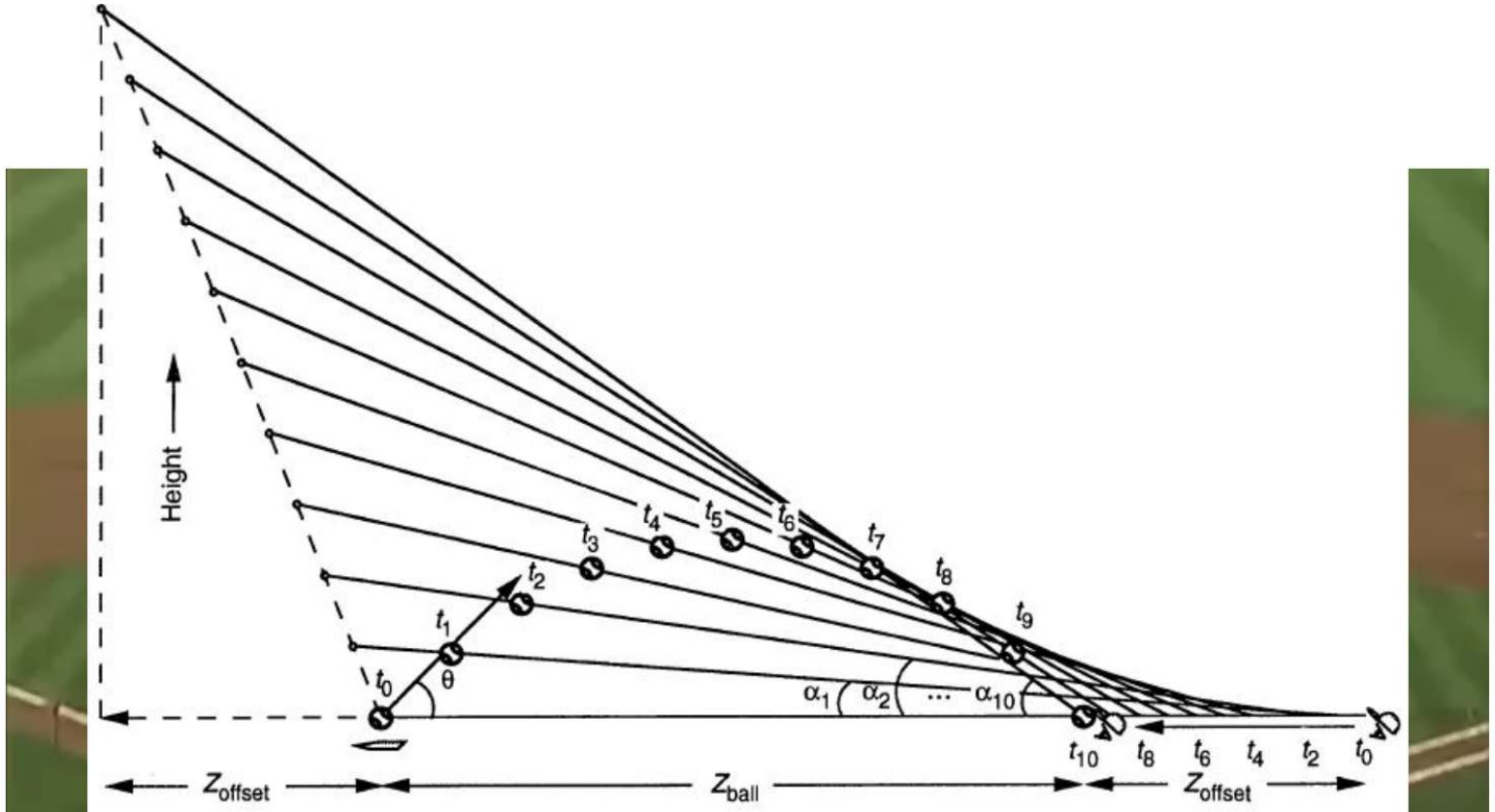


Fig. 1. The OAC model. The side view of a fielder running to catch a ball at times t_0 (initiation) through t_{10} (completion) is shown. The OAC model specifies that outfielders catch fly balls by running along a path that horizontally maintains alignment with the ball and vertically maintains constant optical ball velocity. Mathematically, the tangent of the vertical optical angle of the ball, tan α, increases at a constant rate, resulting in an optical ball trajectory that "never comes down." The optical path of the ball is identical to that of an imaginary elevator that starts at home plate, rises with a constant velocity, and is tilted forward or backward by the amount that the fielder is initially displaced from the ball's landing location (Z_{offset}). For ideal parabolic trajectories, the solution occurs when the fielder runs along a straight, constant-speed path that reaches the destination point at the same time as the ball.

How to catch a ball?



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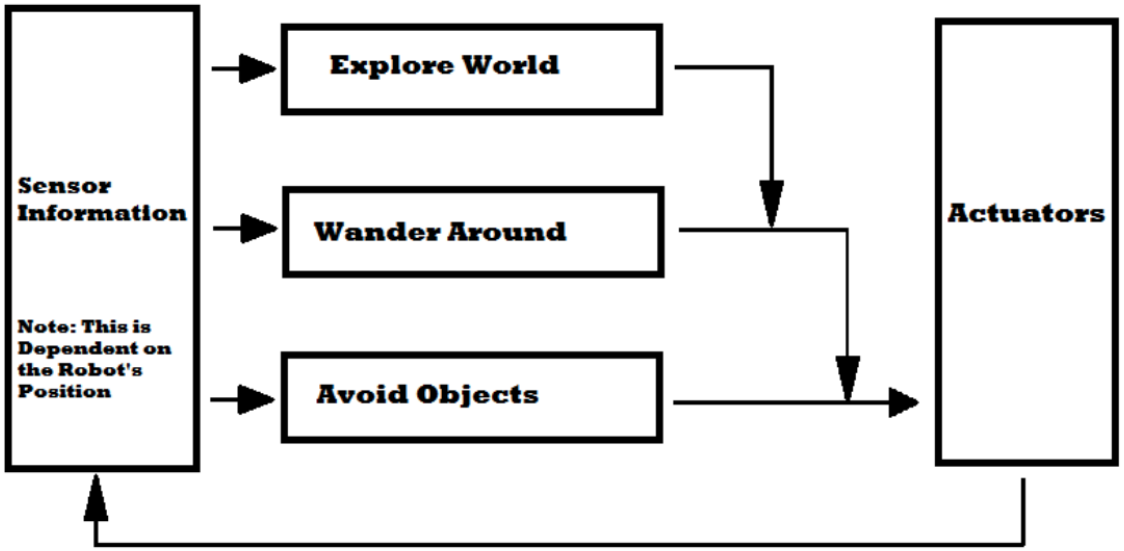
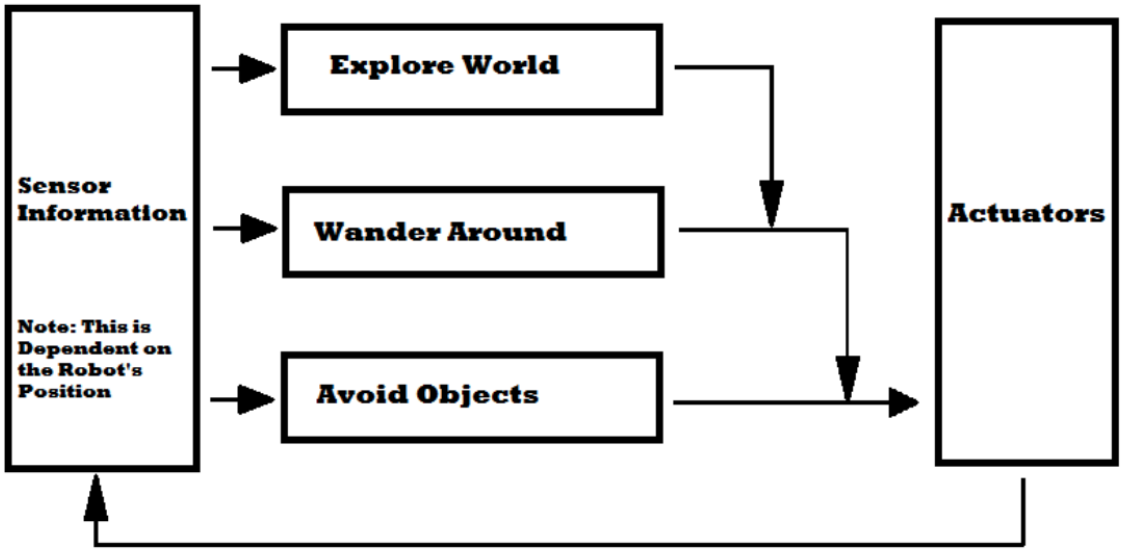
The world is its own best model (Rodney Brooks)

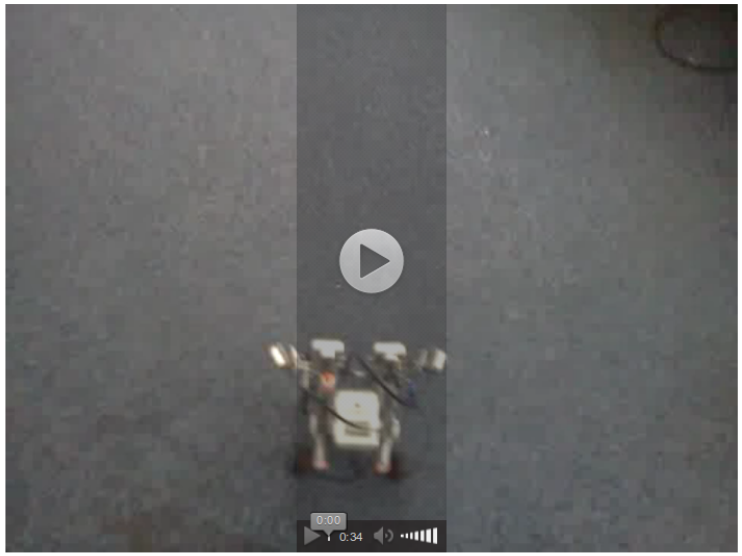
Combining embodied behaviors



Subsumption architecture (Brooks, 1986)

Combining embodied behaviors





Subsumption architecture (Brooks, 1986)

Pros and cons of bottom-up approaches

Embodiement and autonomy

No high-level symbolic reasoning

A key challenge is to bridge both approaches, referred as the symbol-grounding problem.

"Symbolic representations must be grounded bottom-up in nonsymbolic" (Harnad, 1990).