Neurorobotics

Module 2: Neurorobot Design Principles

Lecture 1: Design Principle 1 – Every Action has a Reaction

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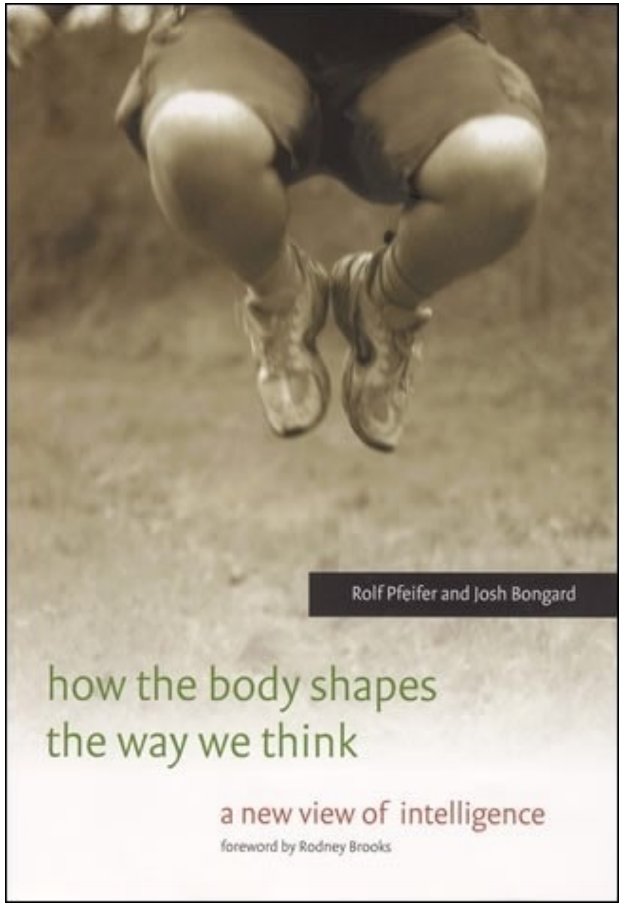
Prologue

- The neurorobot designs principles build on the design principles put forward by Rolf Pfeiffer and Josh Bongard
- Design principle 1 focusses on the processes that respond to events
- Recurring theme: the brain needs a body



TransAIR Workshop on Cognitive Architectures for Robot Agents

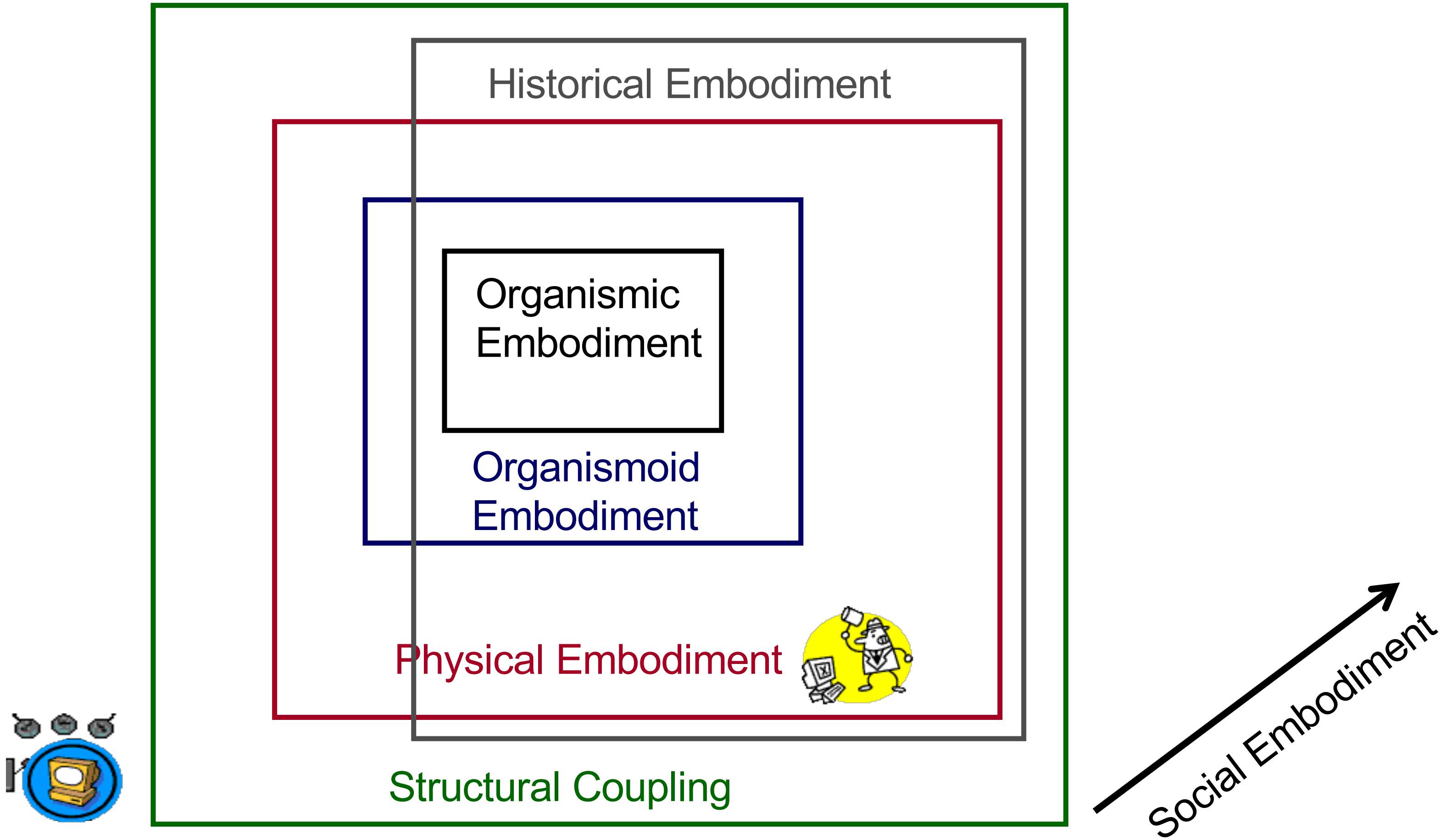
https://transair-bridge.org/workshop-2021/

Video

https://youtu.be/rb2OQH7ghW8

Embodiment

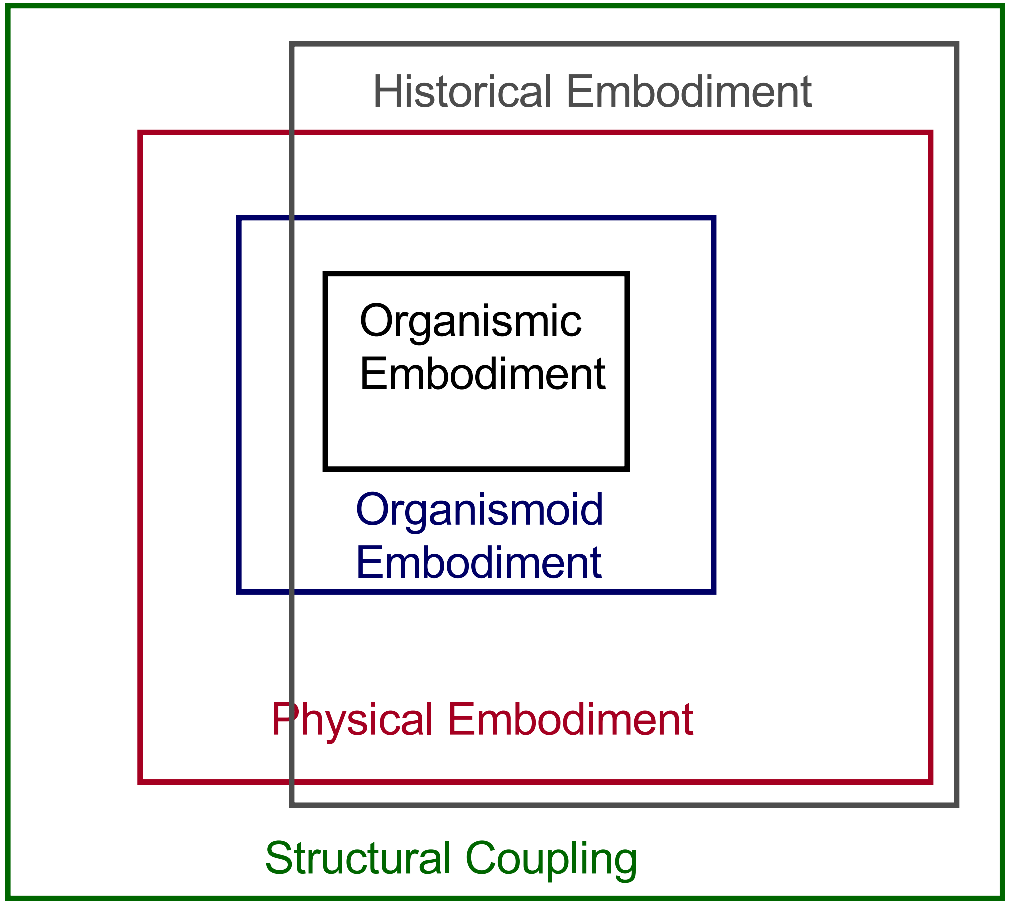
- Brains are closely coupled with the body acting in its environment
  - The brain is embodied
  - The body is embedded in the environment
- Biological organisms perform morphological computation
  - Processes are performed by the body that would otherwise be performed by the brain
  - Moment-to-moment action can be handled
    - At the periphery
    - by the body, sensors, actuators, & (possibly) reflexes at the spinal cord level
  - The (slower) central nervous system can predict, plan, and adapt
    - By comparing its internal models with current information from the body



Ziemke, T. 2001. "Are Robots Embodied?", in Proc. of the First Intl. Workshop on Epigenetic Robotic. Lund University Cognitive Studies, Vol. 85, Lund, Sweden.
Also, see Ziemke, T. 2003. "What's that Thing Called Embodiment?", Proceedings of the Annual Meeting of the Cognitive Science Society.

Embodiment

- Structural coupling
  - System can be perturbed by the environment
  - System can perturb the environment
- Historical embodiment
  - History of structural coupling
  - Adaptation through agent-environment interaction
- Physical embodiment
  - Sensors and actuators for forcible action
  - Layout and range of sensors and actuators shapes behaviour
- Organismoid embodiment
  - Organism-like bodily form (e.g. humanoid) shapes behaviour
- Organismic embodiment
  - Autopoietic living systems



(Ziemke, 2001)

Embodiment

Social embodiment

"Barsalou et al. (in press) have addressed the notion of social embodiment by which they mean that

'... states of the body, such as postures, arm movements, and facial expressions, arise during social interaction and play central roles in social information processing.'" (Ziemke, 2003)

Ziemke, T. (2003). "What's that Thing Called Embodiment?", Proceedings of the Annual Meeting of the Cognitive Science Society.

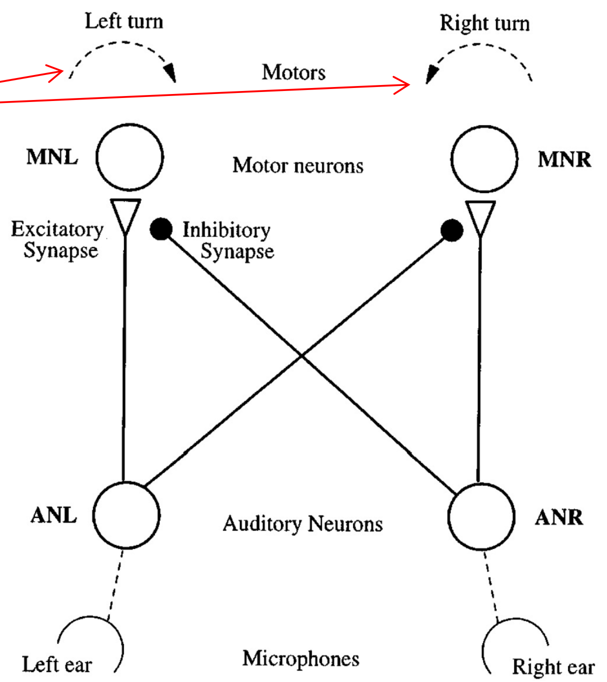
2003

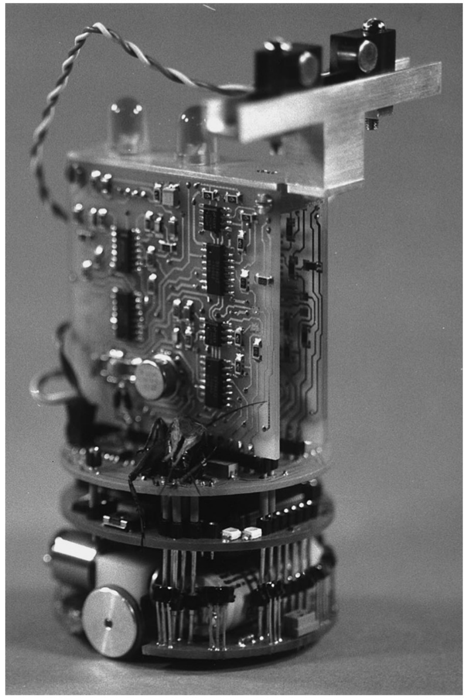
Barsalou, L.; Niedenthal, P, Barbey, A. & Ruppert, J. (in press). Social embodiment. In B. Ross (Ed.), The Psychology of Learning and Motivation, Vol. 43. San Diego, CA: Academic Press.

Embodiment

Example: cricket phonotaxis, whereby a female cricket locates the mating sound of a male cricket

The directional response depends on the relative timing in neural firing, rather than the firing rate





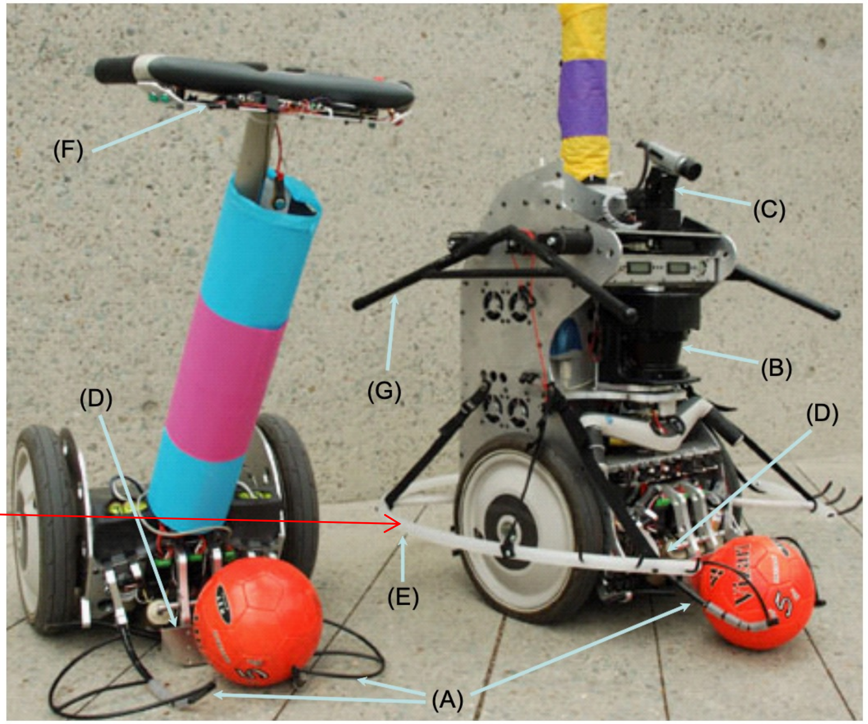
The layout and properties of the ears (microphones), and the properties of the neurons, are all highly tuned to the signature of the cricket sound

(Webb and Scutt, 2000)

Embodiment

Example: trapping a soccer ball

Passive capture ring



(Fleischer et al., 2006)

Efficiency through Cheap Design

- Efficient use of resources

- Using the principle of Occam's Razor:

  "Cheap design means finding the simplest solution to the challenge the robot is facing"

- "*Entia non sunt multiplicanda praeter necessitatem*"

  "Entities should not be multiplied beyond necessity"

  "All things being equal, the simplest solution tends to be the best one"

- Exploit the environment

14th-century English logician
William of Ockham

Efficiency through Cheap Design

The Cornell Walker:

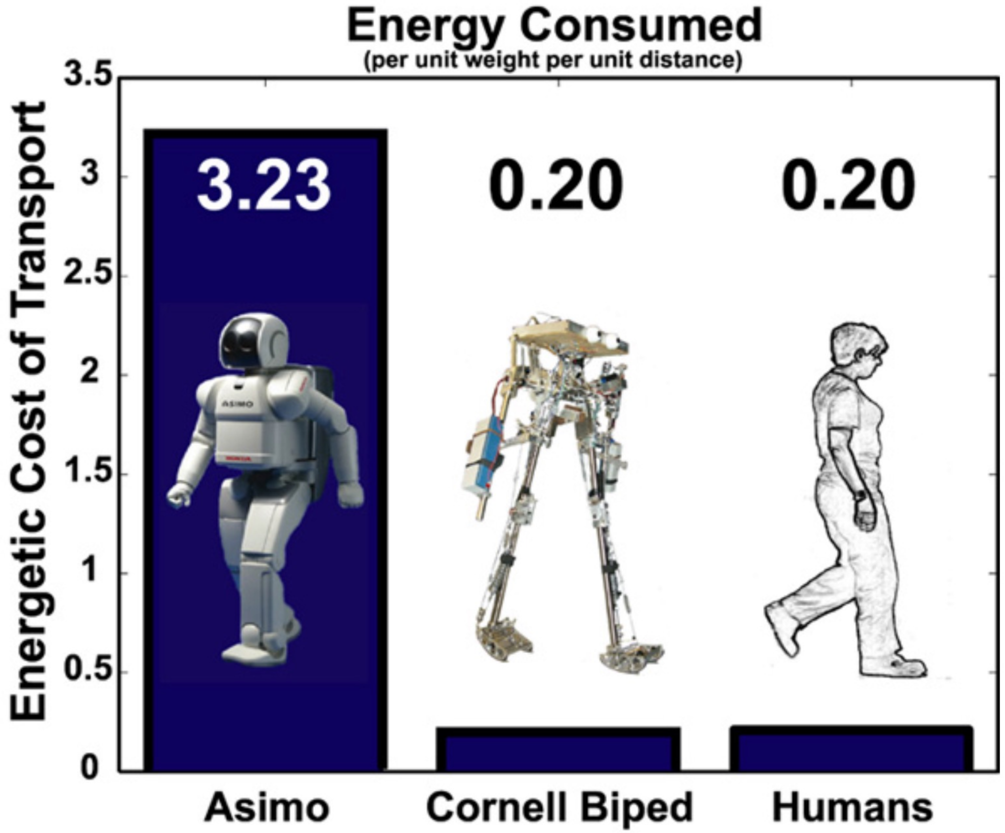
Asimo from Honda

Requires complex control and high-capacity batteries

Passive Dynamic Walker
(Collins and Ruina, 2005)

Exploits gravity, friction, and the forces generated by swinging limbs: require very little energy or control

Efficiency through Cheap Design



https://www.andrew.cmu.edu/user/shc17/Robot/Robot_photos.htm

Efficiency through Cheap Design

- The brain exhibits the characteristics of cheap design
- It operates under severe metabolic constraints and the need to conserve energy
- It consumes just 20 watts of power even though neural activity is costly
  - Minimize of the number spikes required to encode neural representations
  - Minimize the number of axons between neurons and brain regions: small world network
- Neuromorphic computing architectures use much less power than conventional computers
  - A neuron uses energy when it fires an action potential & when that potential is processed at a synapse
  - Neurons do not fire often: 10 Hz to 100 Hz so the device is in low-power mode most of the time

Generation of an action potential, return to resting state, and synaptic processing

Sensory-Motor Integration

- Sensory and motor systems are tightly coupled in the brain
- Sensory information causes an action, giving rise to a sensory outcome

  Sometimes referred to as a sensory-motor contingency

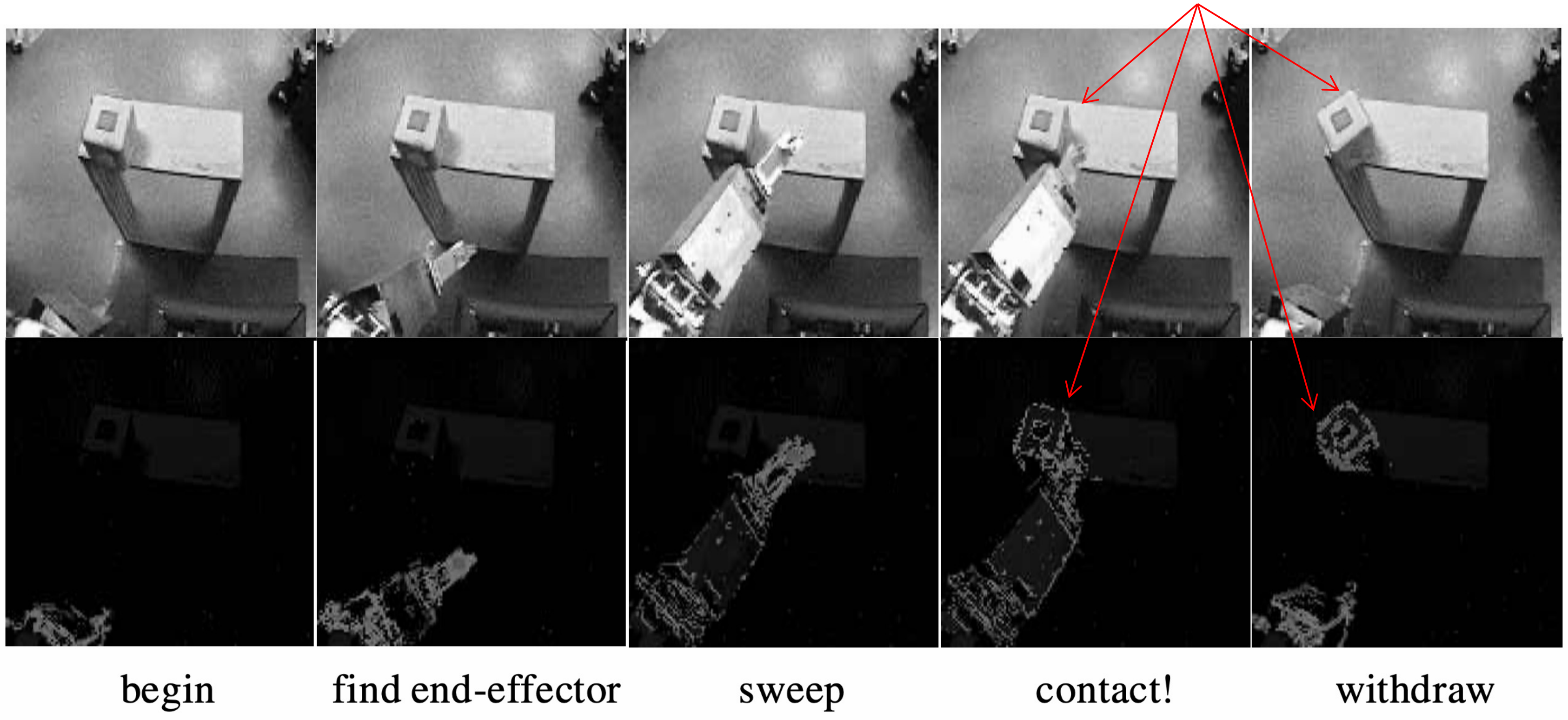
- Neurorobots can take advantage of this tightly coupled loop
  - For example, figure-ground segmentation, separation of foreground objects from their background in static scenes

    The book says "segregration"

  - Facilitated if a hand happens to push an object, resulting in the object moving with respect to its background

Sensory-Motor Integration

The movement of the object, caused by the robot, facilitates the segmentation of the object and separation from the background in the scene

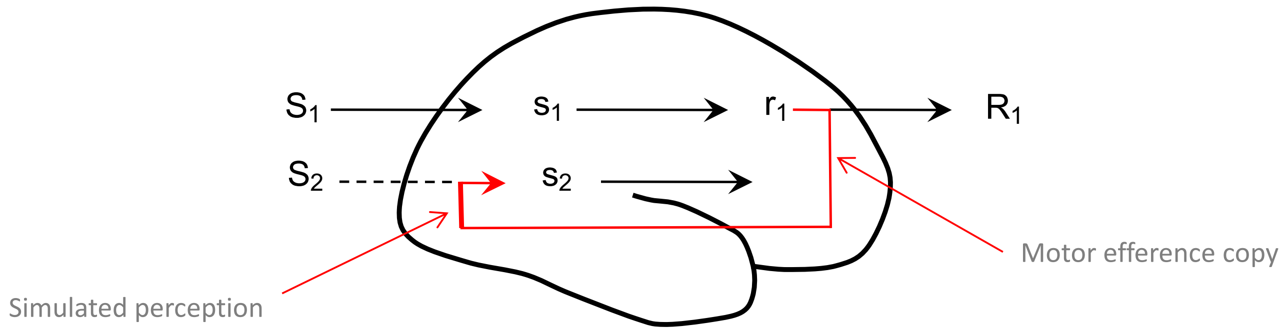


(Fitzpatrick and Metta, 2003)

Sensory-Motor Integration

A copy of the action (or motor command), called a motor efference copy, is fed back to the brain

It creates an expected outcome perception that can be used to evaluate the actual sensory outcome

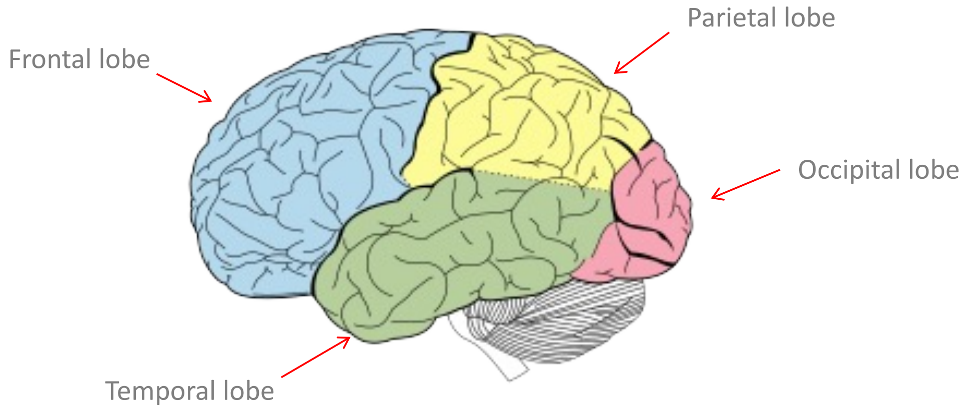


Internal Simulation Hypothesis
(Hesslow, 2002, 2012)

A motor response to an input stimulus causes the internal simulation of an associated perception

Sensory-Motor Integration

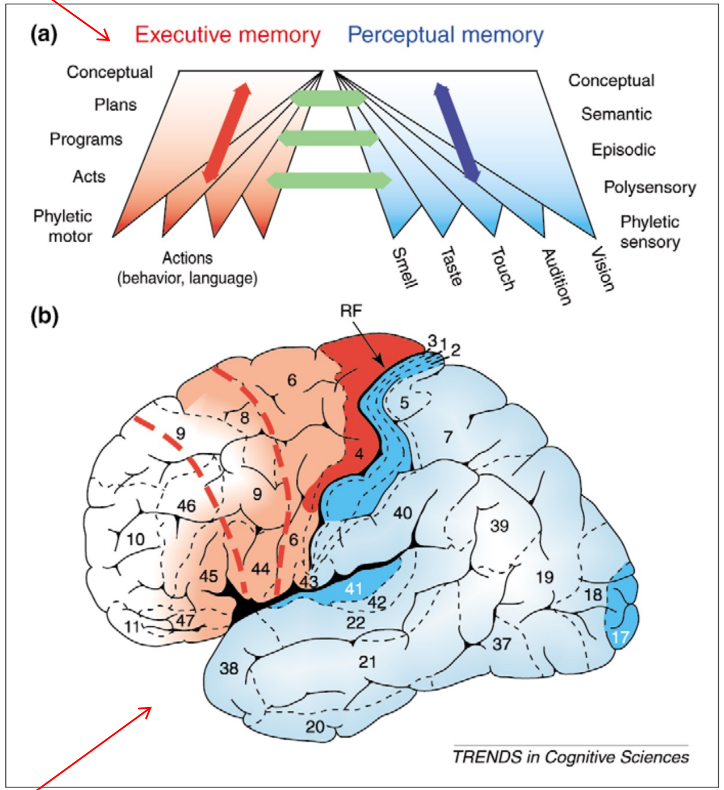
- Most of the cortex is associational
- Does not comprise exclusively sensory or motor systems
- The pareital cortex (lobe) gets multimodal sensory inputs and is important for planning movements
- The frontal cortex (lobe) gets multimodal sensory inputs and is important for decisions, control of actions, and action selection

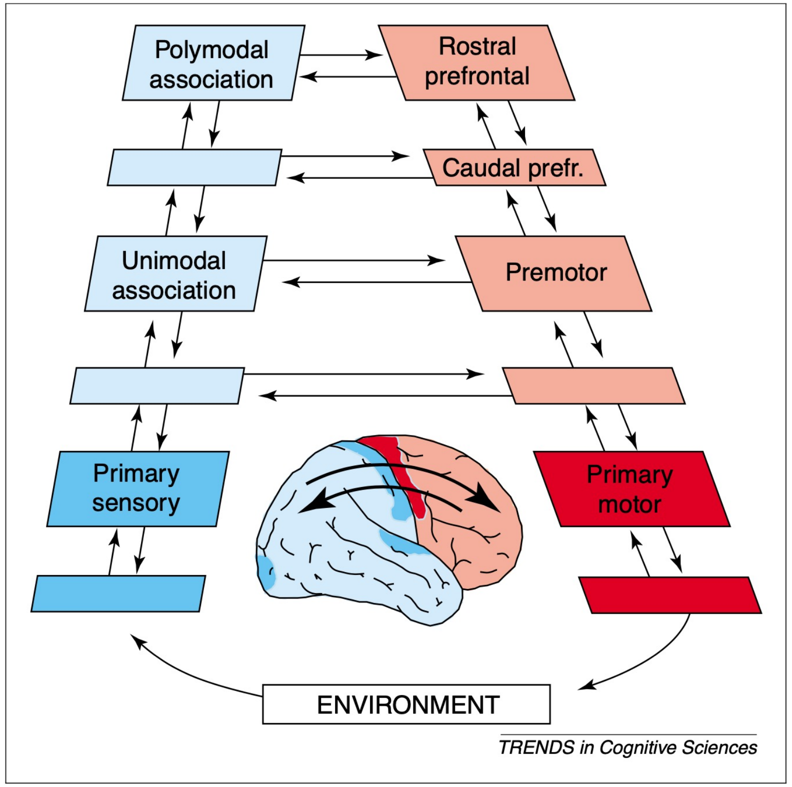


https://en.wikipedia.org/wiki/Parietal_lobe

Sensory-Motor Integration

Schema of the hierarchical organization of memory and knowledge





Approximate topographic distribution of memory networks; same color-code as (a)

(Fuster, 2004)

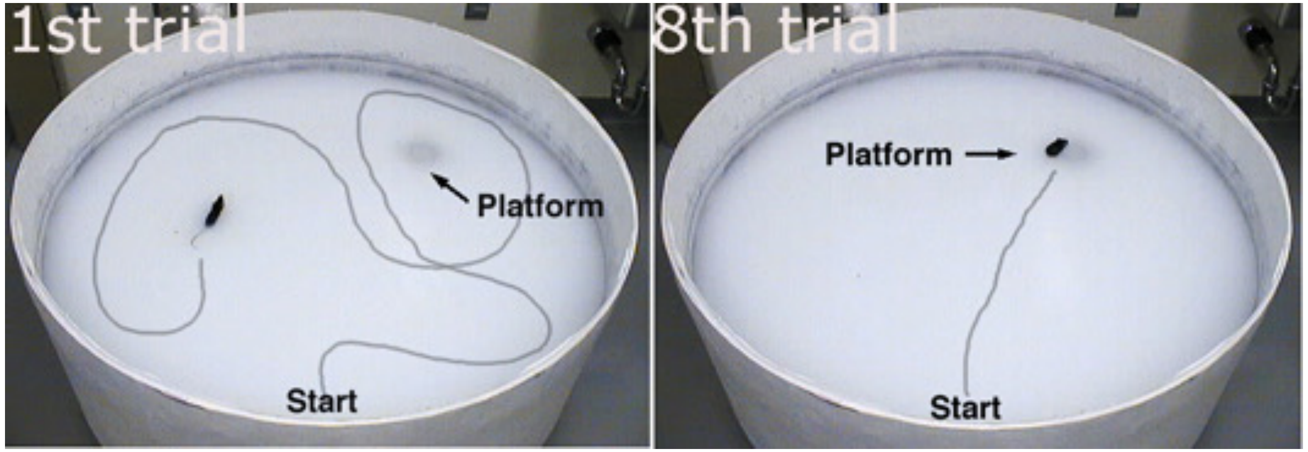
Cortical substrate of the perception-action cycle

Blue: perception
Red: action

Degeneracy

- Degeneracy is the ability of elements that are structurally different
  - To perform the same function or
  - To yield the same output
- A fault-tolerant flexible system should have an architecture that has
  - Different subsystems with different functional processes
  - An overlap of functionality between subsystems
- If any subsystem fails, the overall system can still function
- Not the same thing as redundancy (identical copies of a subsystem)

Sensory-Motor Integration



(https://brainstuff.org/blog/morris-water-maze-learning-memory)

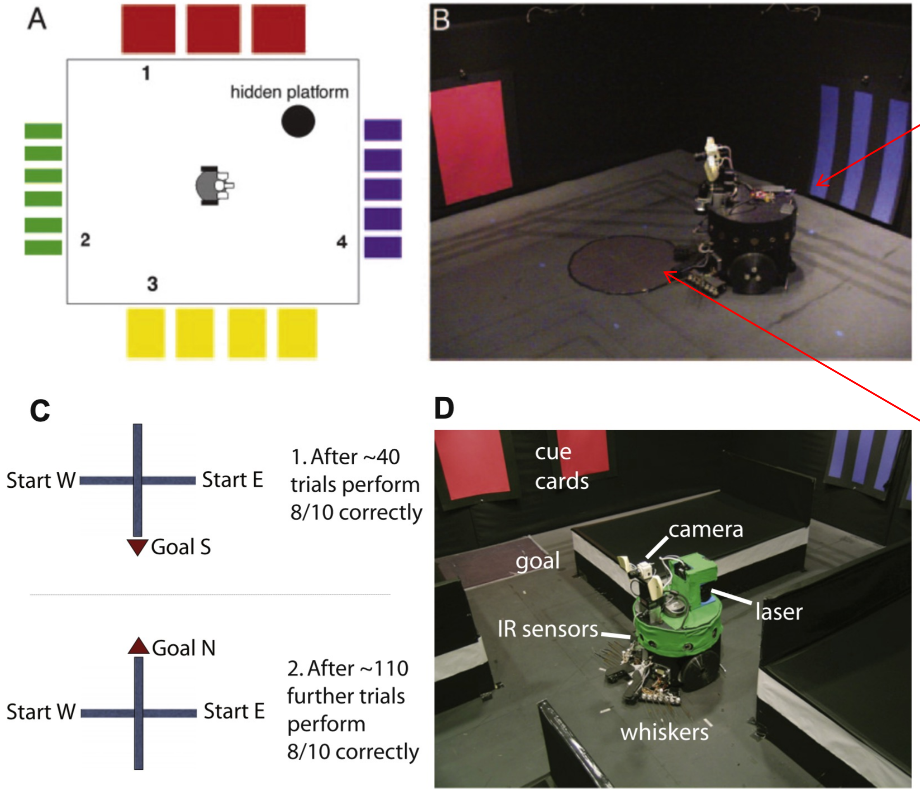
The rat creates a map of the water maze in its hippocampus

See https://www.nobelprize.org/prizes/medicine/2014/advanced-information/ for the scientific background to the award of the Nobel Prize in Physiology or Medicine to J. O'Keefe and M-.B. Moser, and E. Moser for their work on the brain's navigational place and grid cell systems in the hippocampus and entorhinal cortex

Sensory-Motor Integration

- Darwin X has a model of the hippocampus
  and surrounding cortical areas

- As Darwin X explores the maze, hippocampal place cells emerge
  - A place cell is active in a specific location



Darwin X in a dry version of the Morris water maze

Reflective paper is a proxy for the platform:

invisible to the camera but is detected by light sensor when Darwin is on the platform

Sensory-Motor Integration

Several levels of degeneracy

- Neuronal level

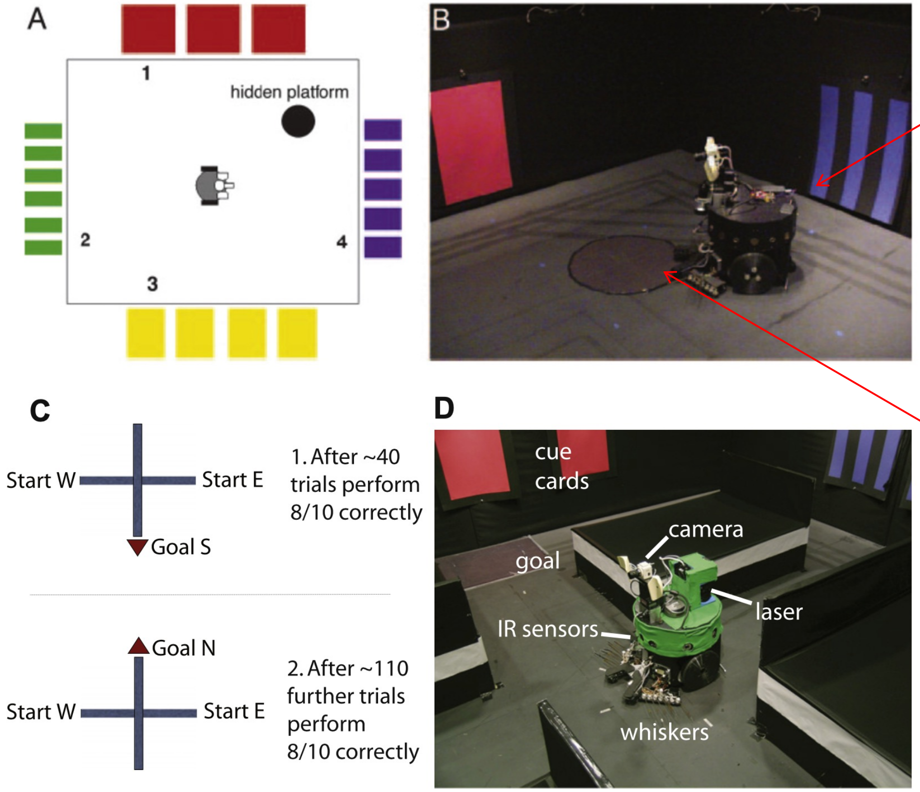
  Different neural activation patterns led to the same hippocampal place cell outcome

- System level

  Different sensory pathways led to the same outcome

- Individual level

  Nine individual Darwin X robots solved the navigation problem in different ways



Darwin X in a dry version of the Morris water maze

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Multitasking and Event-driven Processing

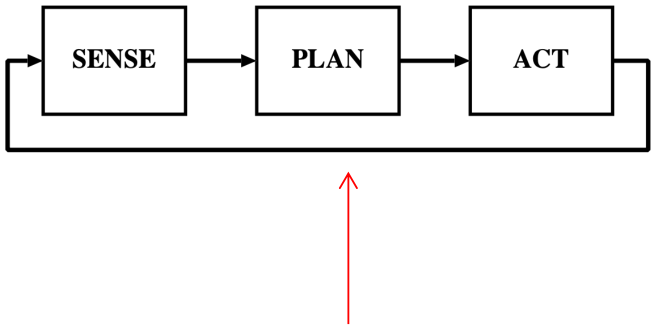
Intelligence emerges from many processes operating in parallel and driven by events

- Neurorobots should have a multitask design
  - That responds in a timely manner
  - To multiple asynchronous events
- Sense-plan-act architecture vs. behavior-based architecture

Also referred to as sense-think-act

Software Architecture Models

- Sense-plan-act / Deliberative / Hierarchical
- Reactive
- Behaviour-based



Input sensory data

Processed into abstract representations

Analyzed to plan the next action

Output the action motor commands

Software Architecture Models

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- Reactive
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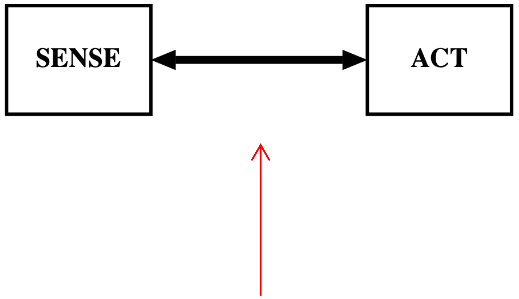


Act first; think later

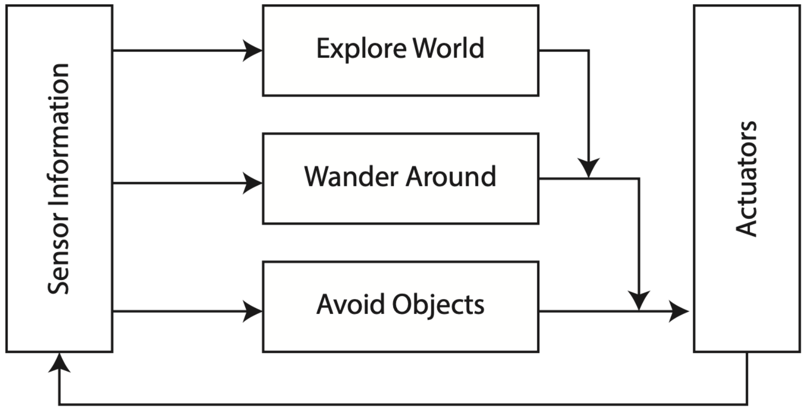
Multiple instances of Sense-Act couplings called sensorimotor contingencies or behaviors

Each behavior operates in parallel

Advantage: immediately respond to an external event

Software Architecture Models

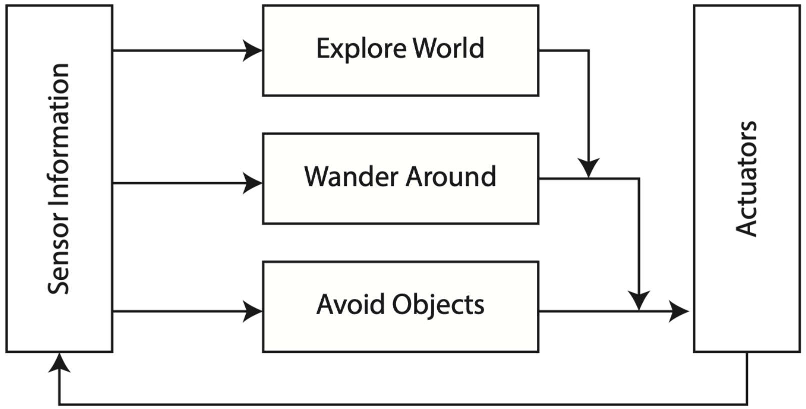
- Sense-plan-act / Deliberative / Hierarchical
- Reactive
- Behaviour-based
  - Rodney Brooks (1986) and Ron Arkin (1988)
  - Invoke mechanisms to mediate between which behaviors are active and which are not
  - For example, the subsumption architecture which organizes behaviors into hierarchies



Software Architecture Models

Subsumption Architecture

- Introduced by Rodney Brooks (1991)
- While not having an explicit representation of the world, it can still behave in an "apparently" intelligent way
- Cleaning robot: two behaviors in parallel
    1. Avoid walls
    2. Steer slightly to the right
        - The resulting, emergent, behavior is "wall-following"
        - The iRobot Roomba was developed with this in mind



Software Architecture Models

Subsumption Architecture

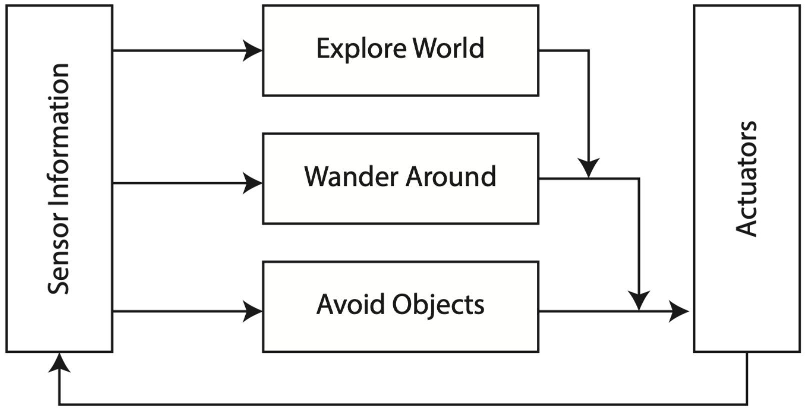
Brooks emphasized four principles

1. Situatedness: to have a close relationship with the environment, relying more by responding to current environmental situations rather than long-term, top-down planning

2. Embodiment is the robust instantiation of an agent in an actual environment, as opposed to a simulation or abstract computational framework.

3. Intelligence is defined as the ability to perceive and move about in the world

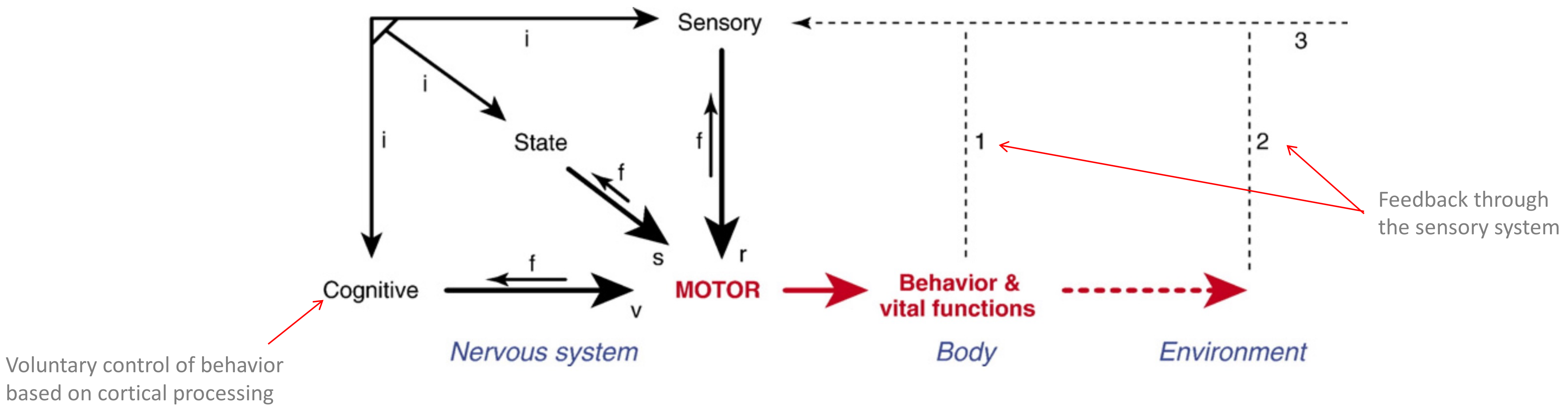
4. Emergence occurs when seemingly intelligent and unexpected behaviors arise out of simpler behaviors



Multitasking and Event-driven Processing

Layered hierarchical control in the nervous system

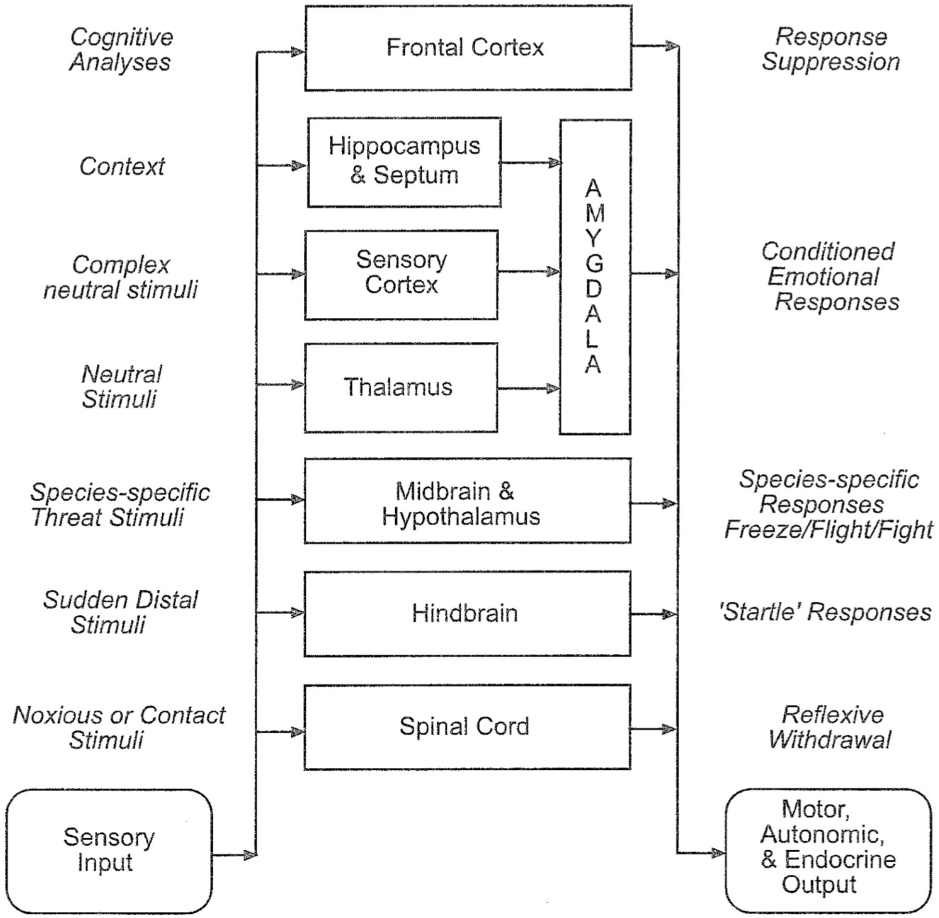
1. Four component global model of vertebrate nervous system organization (Swanson, 2007)



Multitasking and Event-driven Processing

Layered hierarchical control in the nervous system

2. Subsumption architecture for controlling defense behavior
   (Prescott et al., 2007)



Reading

Hwu, T. and Krichmar, J. (2022). Neurorobotics: Connecting the Brain, Body and Environment, MIT Press.

Chapter 5, Sections 5.1 - 5.5, pp. 82 – 98.