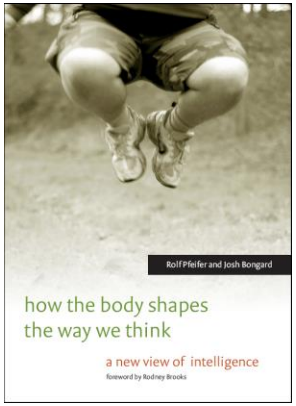
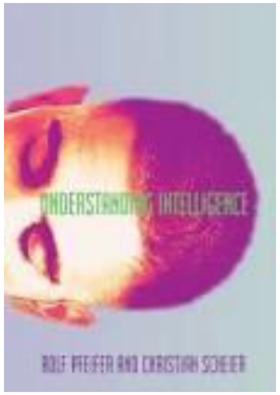
Embodied Artificial Intelligence

Matěj Hoffmann
matej.hoffmann@fel.cvut.cz
https://sites.google.com/site/matejhof

Inspired by and using material from Rolf Pfeifer and:





Outline

- Classical AI – successes and challenges
- Embodied AI
  - Morphology facilitating control
    - Body design simplifying task
    - Behavior emergent from simple sensory-motor loops
  - Morphology facilitating perception
    - Insect eye-morphology
    - Information self-structuring

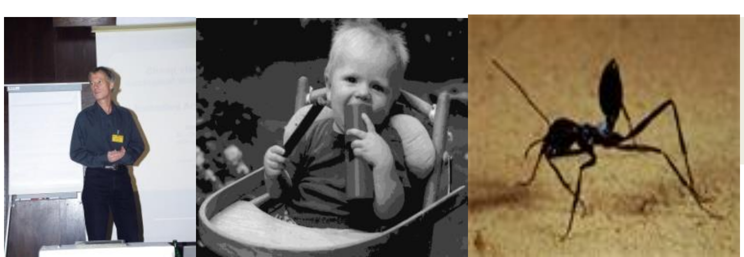
Artificial intelligence as a synthetic science

Goals

understanding biological systems

principles underlying intelligence

useful artifacts

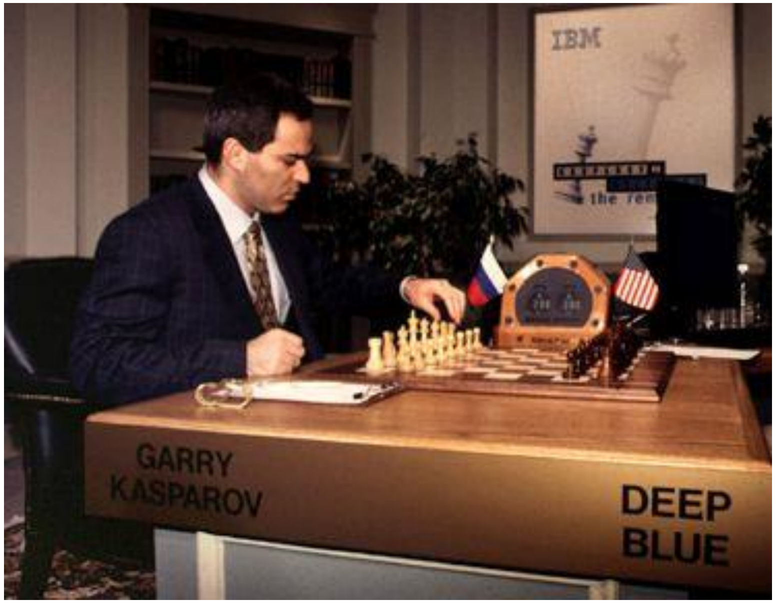


Theory of intelligence

Classical:
“intelligence as computation”

Illustration: Shun Iwasawa, from Pfeifer, R: How the body shapes the way we think, 2007

Where it works nicely… search



IBM Deep Blue chess computer, 1997

Google Deep Mind AlphaGo, 2016

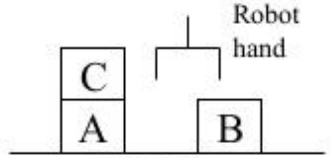
- formally precisely defined discrete state space
- program has access to complete information (fully observable)
- deterministic state evolution
- not real-time (or soft real time)

- Premiere methods – e.g.: **search**, deep reinforcement learning

Where it works nicely… planning

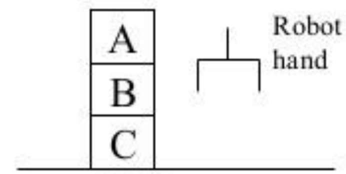
Example : Blocks World

- STRIPS : A planning system – Has rules with precondition deletion list and addition list



START

on(B, table)
on(A, table)
on(C, A)
hand empty
clear(C)
clear(B)



GOAL

on(C, table)
on(B, C)
on(A, B)
hand empty
clear(A)

Classical AI – theoretical positions

- Intelligence ~ abstract symbol processing
- Functionalism
  - Algorithm / software matters
  - Hardware (on which it runs) does not matter
- Physical Symbol Systems Hypothesis (Newell and Simon 1976)
- Digital computer
  - Key tool
  - Metaphor for the mind!
- Nicknamed GOFAI – Good Old-Fashioned Artificial Intelligence (Haugeland 1985)

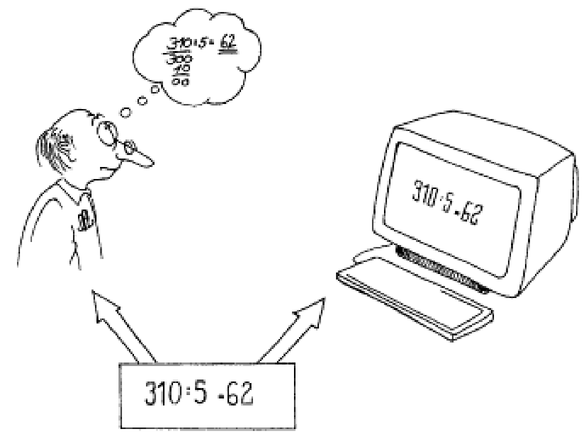


Fig. 2.4 from Pfeifer & Scheier 1999

Connecting to the real world - representation

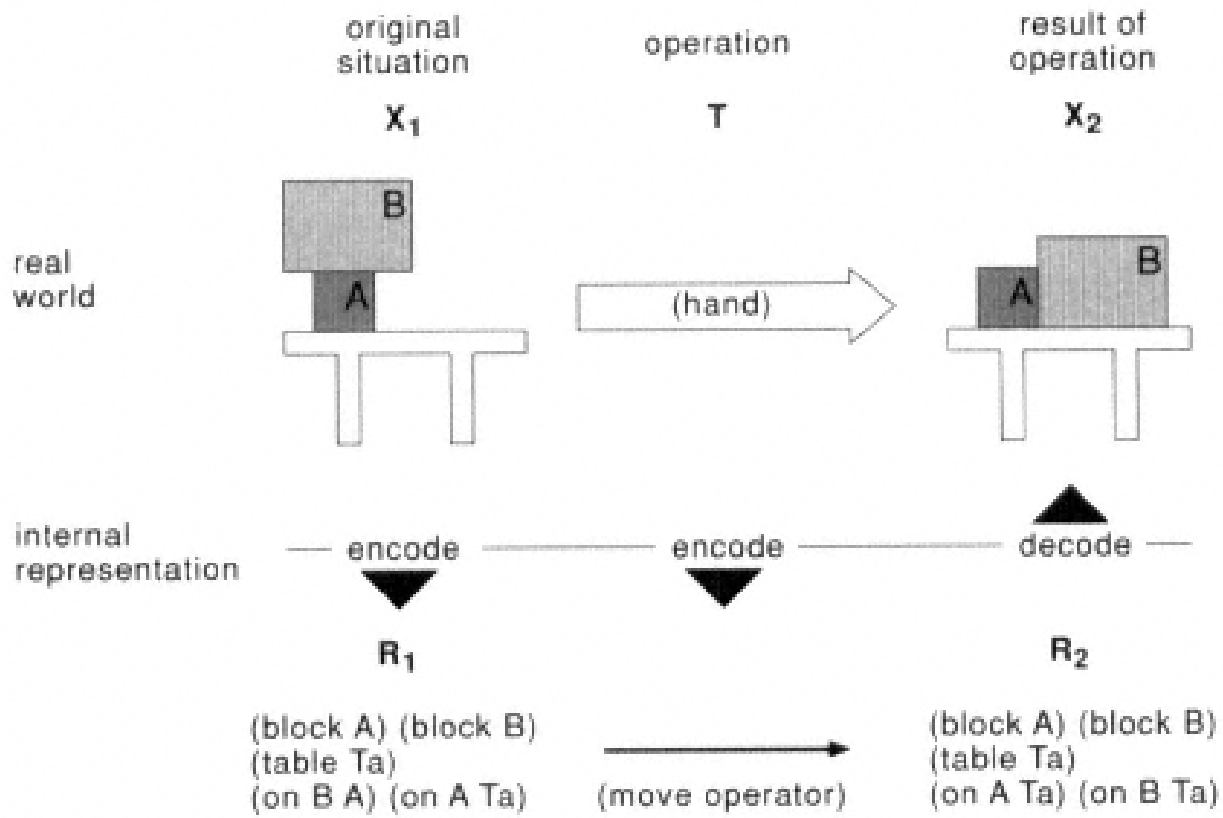
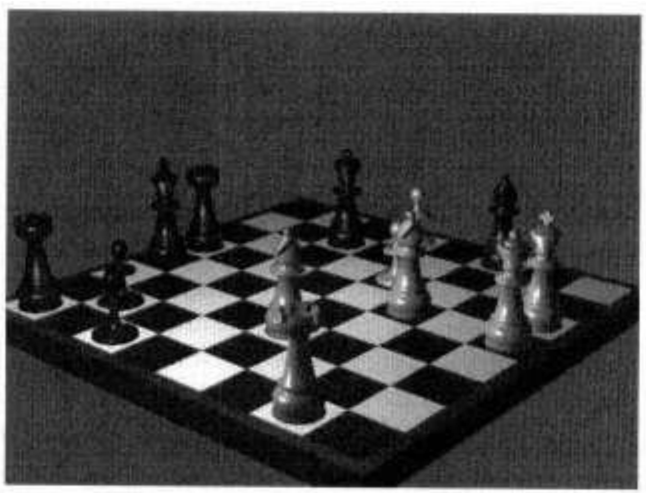


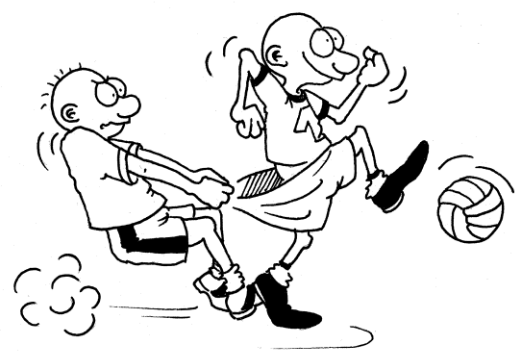
Fig. 2.5 from Pfeifer & Scheier 1999

From formal world to real world

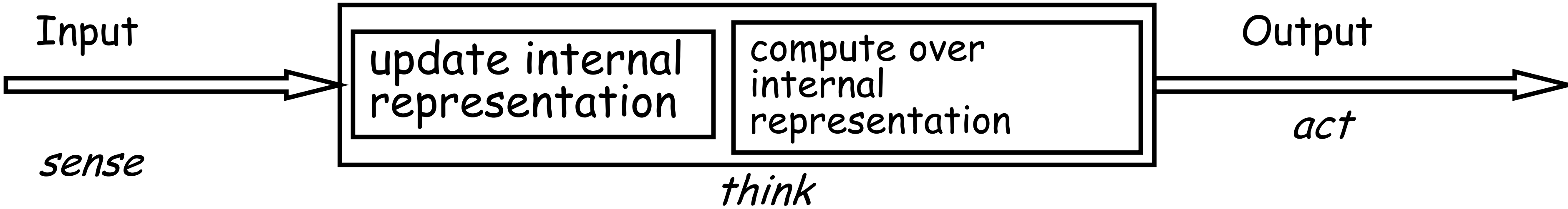
- Chess



- Soccer



From formal world to real world



- Ancient times:

Stanford Cart, 1975

Show video.

GOFAI fundamental problems

- Frame problem
- Symbol grounding problem (Harnad, 1990)
- Frame of reference problem

GOFAI problems viewed today

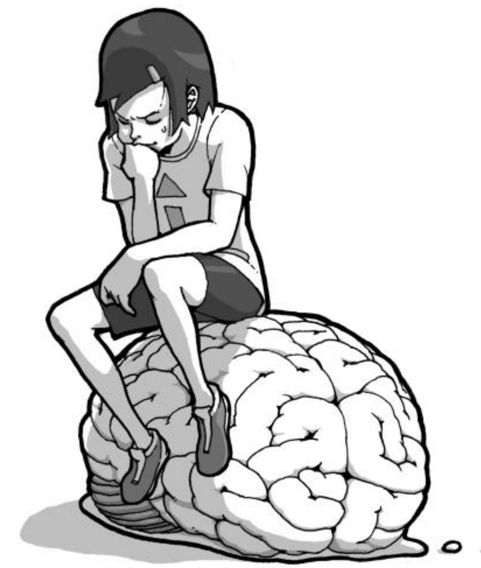
- Some problems have been mitigated through
  - New algorithms
    - Probabilistic reasoning (e.g. Thrun et al. 2005)
    - Learning
      - Reinforcement learning
      - “Deep” neural networks
  - Higher computational power

  => real-time operation in real world is possible

Stanley, 2006

Google self-driving car today

What remains?

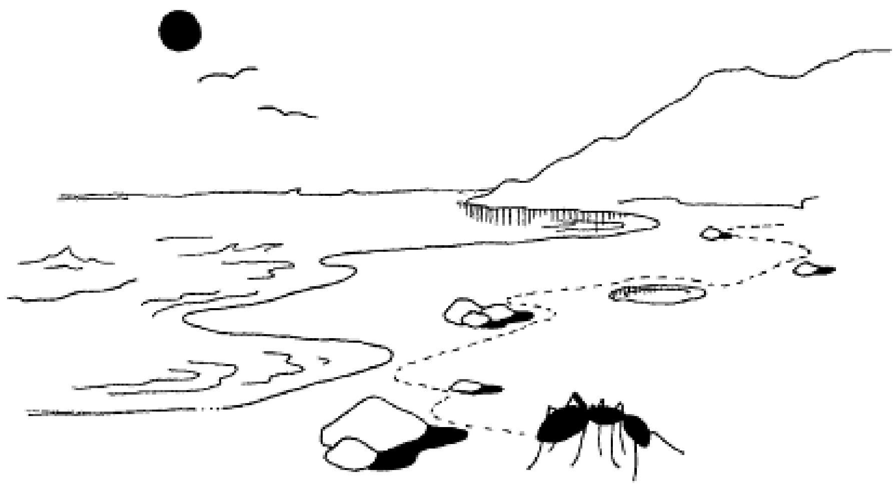


- AI still heavily biased toward representation and computation.

- vs. natural (also human) intelligence:
  - Embodied
  - emergent from sensory-motor and interaction processes

Frame of reference problem

- Simon's ant on the beach



- simple behavioral rules
- Complexity in interaction, not in brain

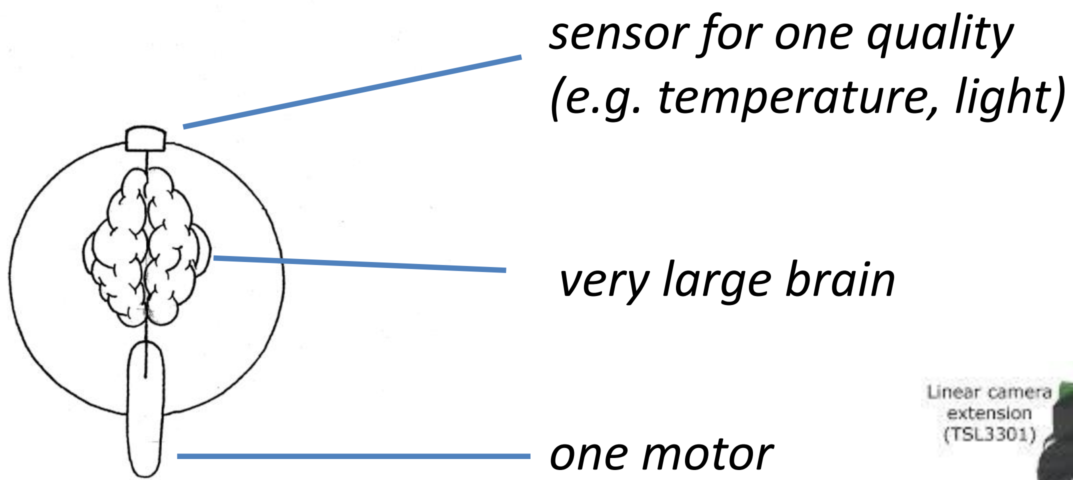
Outline

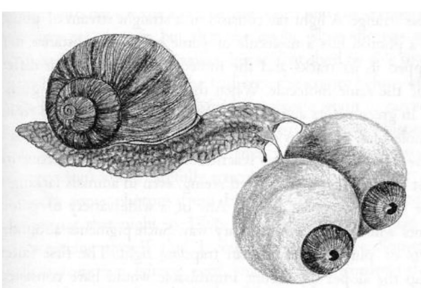
- Classical AI – successes and challenges
- Embodied AI
  - Morphology facilitating control
    - Body design simplifying task
    - Behavior emergent from simple sensory-motor loops
  - Morphology facilitating perception
    - Insect eye-morphology
    - Information self-structuring

Embodiment

- “intelligence requires a body”
- Interplay / task distribution
  – Brain
  – Body (morphology – shape, materials, …)
  – Environment
- Principal of ecological balance
  – match in complexity of sensory, motor, and neural system

Ecologically unbalanced systems





Research questions

- Classical AI
  - Thinking, reasoning, abstract problem solving
- Embodied AI
  - Movement, physical interaction with the real world

"Why do plants not have brains? The answer is actually quite simple: they don't have to move."

Lewis Wolpert, UCL

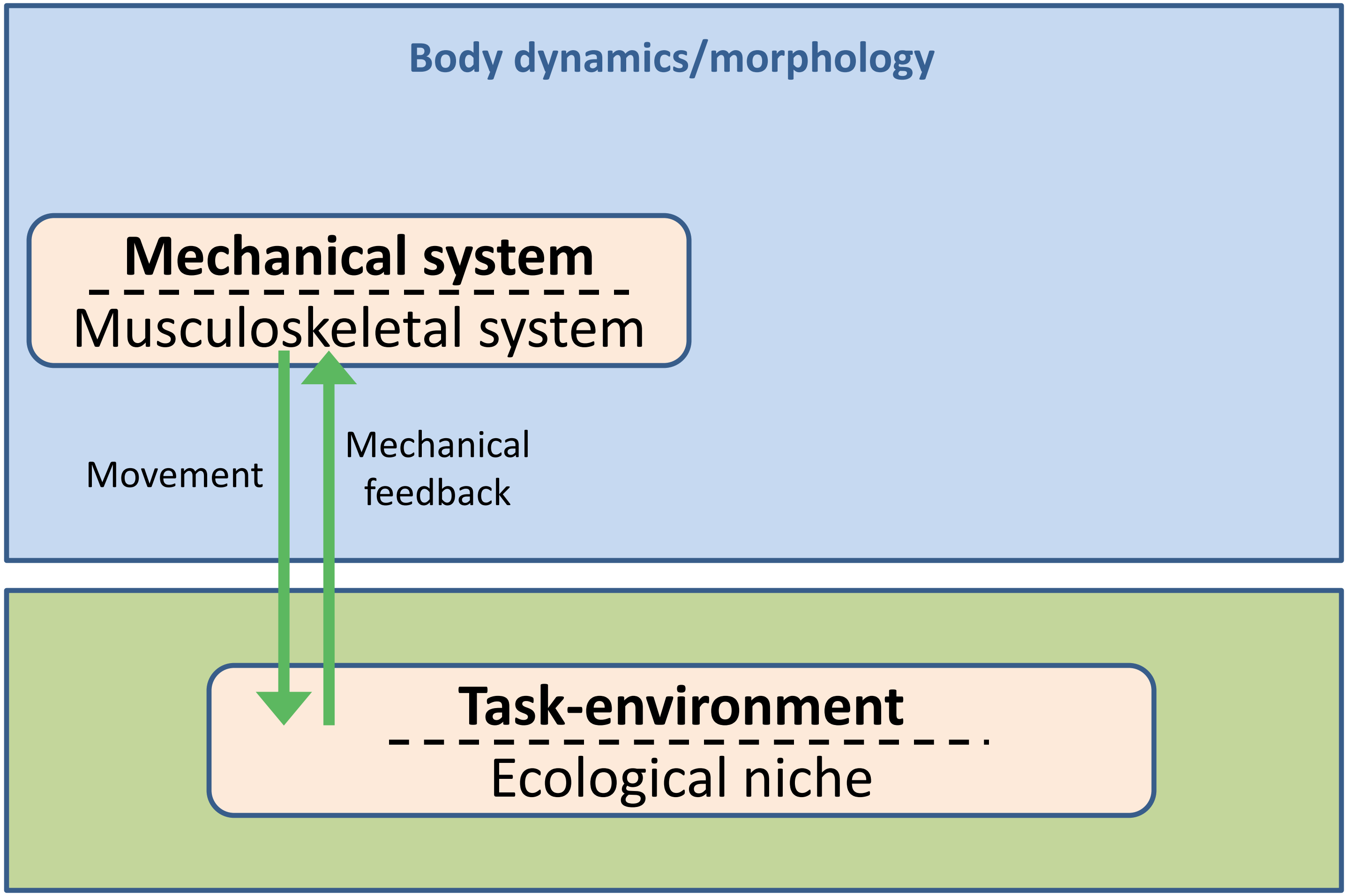
Physical implications of embodiment

~ morphology facilitating control

- Is brain/computation needed for walking?
- Passive dynamic walkers (McGeer 1990)
  - “pure physics walking”
  - No computer
  - No motors
  - No sensors

Morphology:
- shape of feet
- counterswing of arms
- friction on bottom of feet

Cornell PDW with arms,
Collins et al. 2001



Schematics based on Pfeifer et al., Science 2007

Self-stabilization

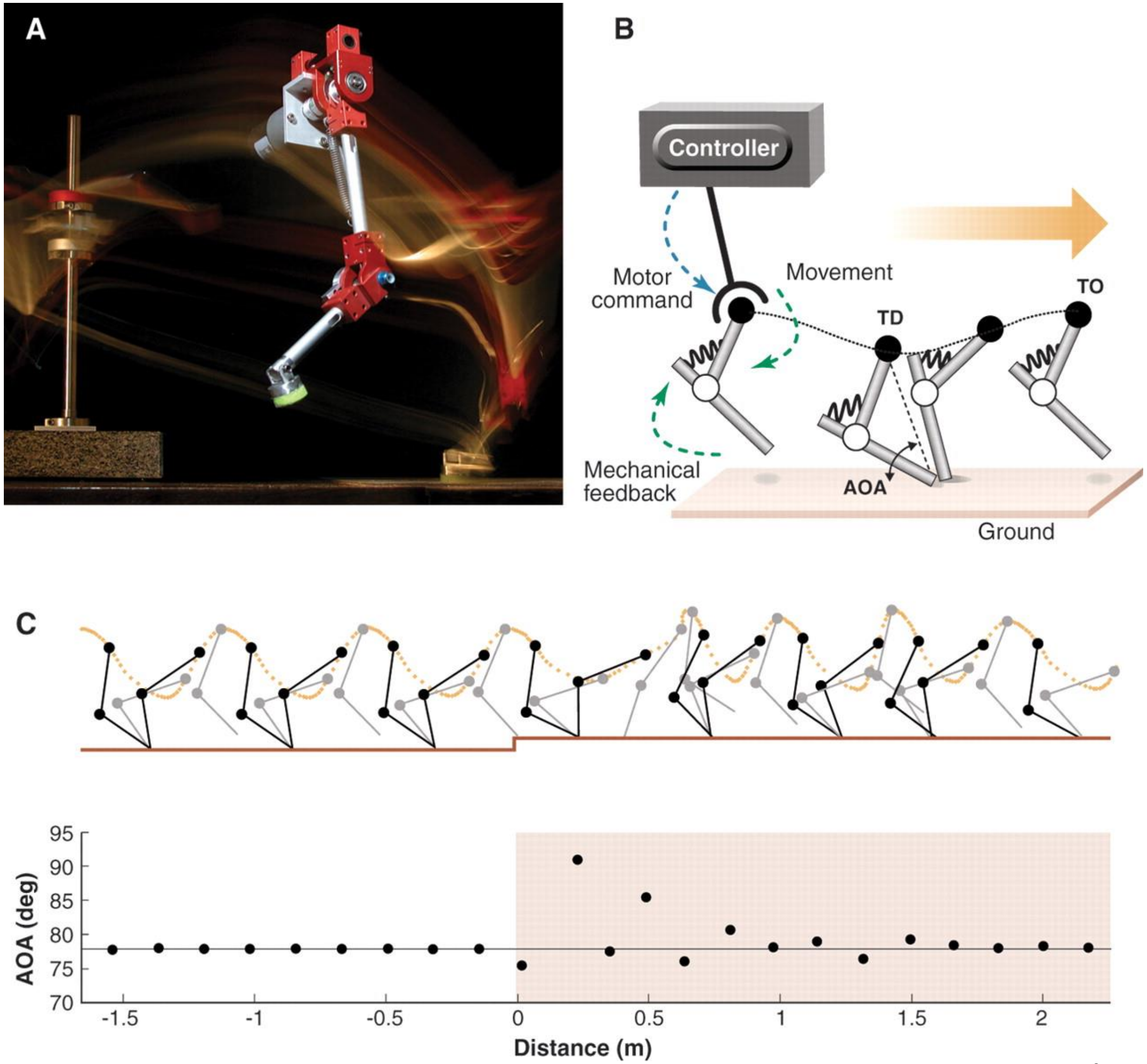
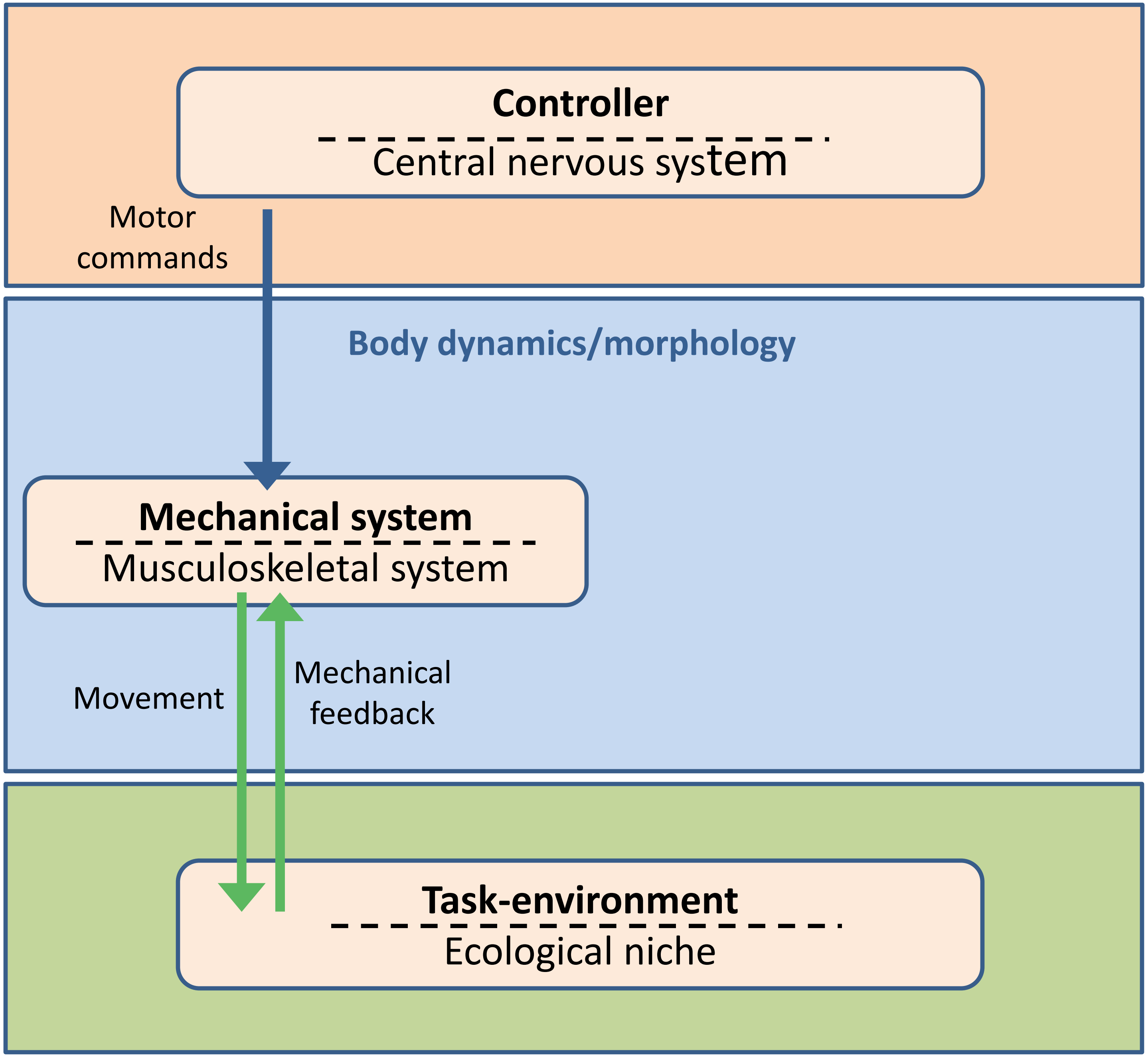


Fig. adapted from Blickhan et al. 2007

Grasping with coffee balloon grippers

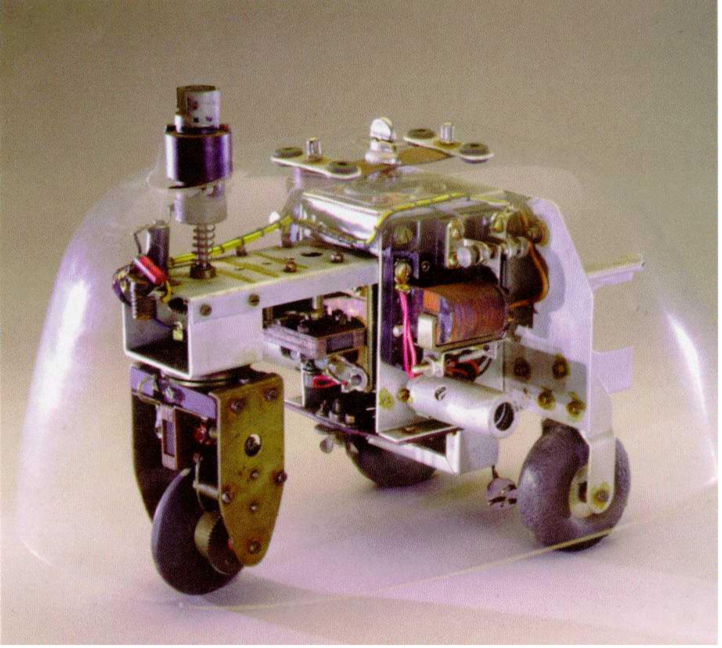
Image: John Amend (jra224@cornell.edu)

Brown et al. 2010


Controller
Central nervous system
Motor commands
Body dynamics/morphology
Mechanical system
Musculoskeletal system
Movement
Mechanical feedback
Task-environment
Ecological niche

Outline

- Classical AI – successes and challenges
- Embodied AI
  - Morphology facilitating control
    - Body design simplifying task
    - Behavior emergent from simple sensory-motor loops
  - Morphology facilitating perception
    - Insect eye-morphology
    - Information self-structuring

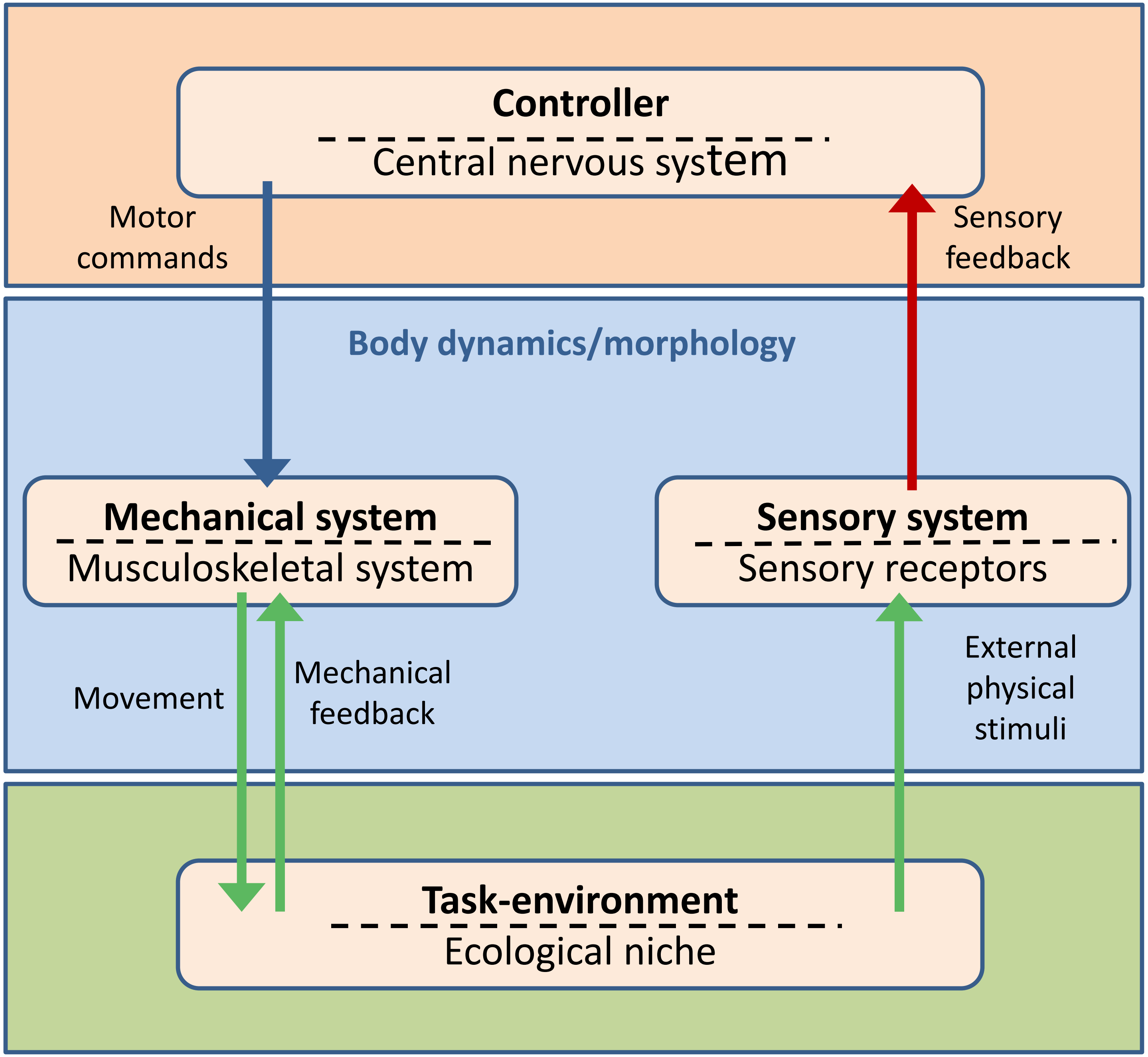


Grey Walter
Turtle, 1940s

V. Breitenberg, 1980s

R. Brooks, 1980s
subsumpční architektura

Braitenberg vehicle – avoid light


Controller
Central nervous system
Motor commands
Sensory feedback
Body dynamics/morphology
Mechanical system
Musculoskeletal system
Sensory system
Sensory receptors
Movement
Mechanical feedback
External physical stimuli
Task-environment
Ecological niche

Behavior-based robotics manifestos

Intelligence without representation*

Rodney A. Brooks

MIT Artificial Intelligence Laboratory, 545 Technology Square, Rm. 836, Cambridge, MA 02139, USA

Received September 1987

Brooks, R.A., Intelligence without representation, Artificial Intelligence 47 (1991), 139–159.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ARTIFICIAL INTELLIGENCE LABORATORY

A.I. Memo No. 1293 April, 1991

Intelligence Without Reason

Rodney A. Brooks
Prepared for *Computers and Thought*, IJCAI-91

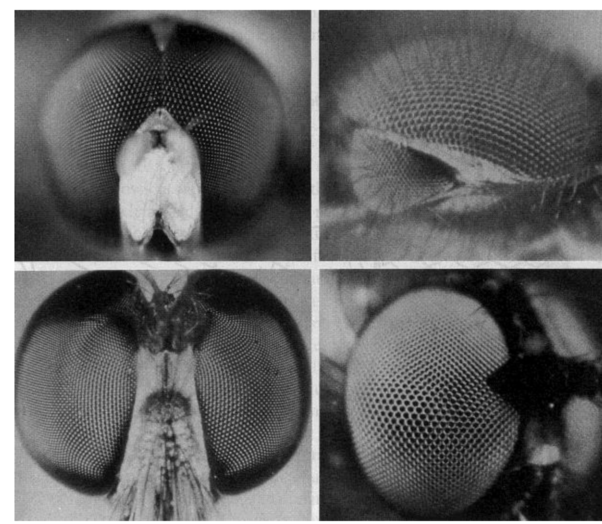
Outline

- Classical AI – successes and challenges
- Embodied AI
  - Morphology facilitating control
    - Body design simplifying task
    - Behavior emergent from simple sensory-motor loops
  - Morphology facilitating perception
    - Insect eye-morphology
    - Information self-structuring

Insect eye morphology

- Different species of insects have evolved different non-homogeneous arrangements of the light-sensitive cells in their eyes, providing an advantageous nonlinear transformation of the input for a particular task

horsefly

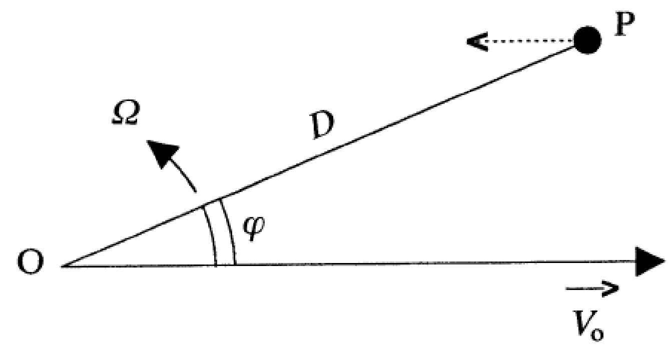


honeybee

Obstacle avoidance

- exploiting ego-motion together with motion parallax

Franceschini et al. 1992



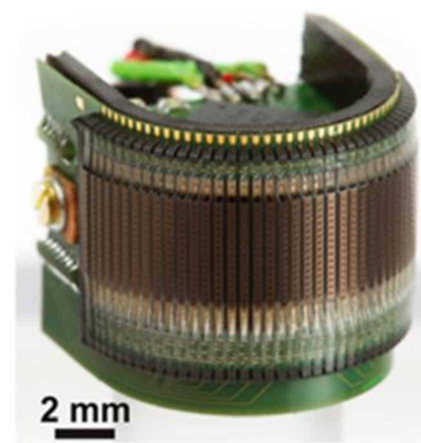
$$\Omega = \frac{V_o}{D} \cdot \sin\varphi$$

Figure 6. Principle of motion parallax. Any agent (fly, human, robot, etc.) translating at speed V_0 can gauge the distance to a contrast point P located at azimuth φ if it is equipped with a passive sensor able to measure the angular speed Ω of P when this point crosses its visual field due to the agent's own movement.

Nonuniform distribution & elementary motion detectors

The distribution of the cells is nonuniform and follows a sine gradient in the interommatidial angle, such that sampling of the visual space is finer towards the front than laterally. This effectively compensates for the sine relationship in the formula and allows uniform motion detection circuitry to be used everywhere.

(a)



(b)

CurvACE – artificial compound eye
- image courtesy of Dario Floreano

The principle of sensory-motor coordination / information self-structuring

- self-structuring of sensory data through – physical – interaction with environment
- reduction of complexity – induction of correlations
- *physical process – not „computational“*

The principle of sensory-motor coordination / information self-structuring

- self-structuring of sensory data through interaction with environment
- reduction of complexity – induction of correlations
- information-theoretic reason for sensory-motor coordination

prerequisite for learning

inspiration
— John Dewey, 1896 (!)
— Merleau-Ponty, 1963
— Bajcsy 1963; Aloimonos, 1990; Ballard, 1991
— Edelman, Sporns, and co-workers
— developmental studies; Thelen and Smith

Active perception

“We begin not with a sensory stimulus, but with a sensory-motor coordination […] In a certain sense it is the movement which is primary, and the sensation which is secondary, the movement of the body, head, and eye muscles determining the quality of what is experienced. In other words, the real beginning is with the act of seeing; it is looking, and not a sensation of light.” (“The reflex arc in psychology,” John Dewey, 1896)

“Since all the stimulations which the organism receives have in turn been possible only by its preceding movements which have culminated in exposing the receptor organ to external influences, one could also say that behavior is the first cause of all the stimulations.” (“The structure of Behavior,” Maurice Merleau-Ponty, 1963)

“Problems that are ill-posed, nonlinear, or unstable for a passive observer become well-posed, linear, or stable for an active observer.” (Ruzena Bajcsy, 1988) (similar points: Aloimonos, 1990; Ballard, 1991)

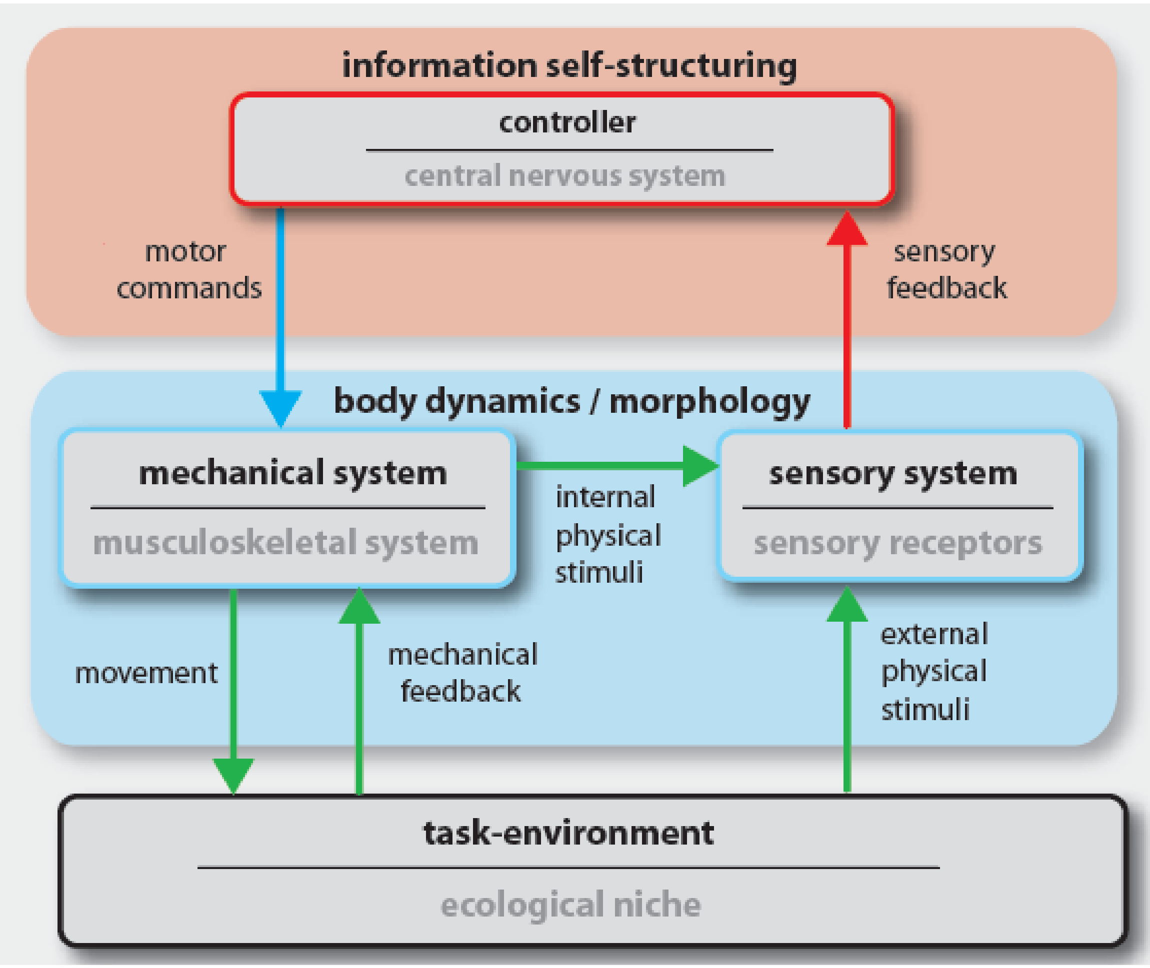
quotations courtesy Olaf Sporns

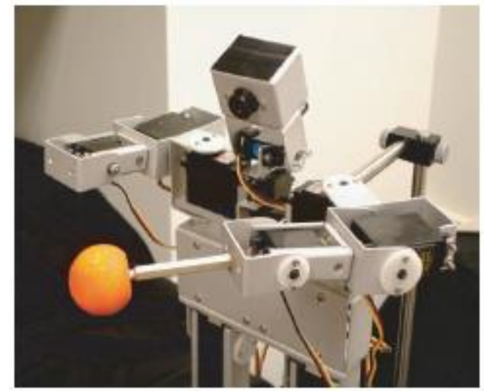
Quantification of information structure induced?

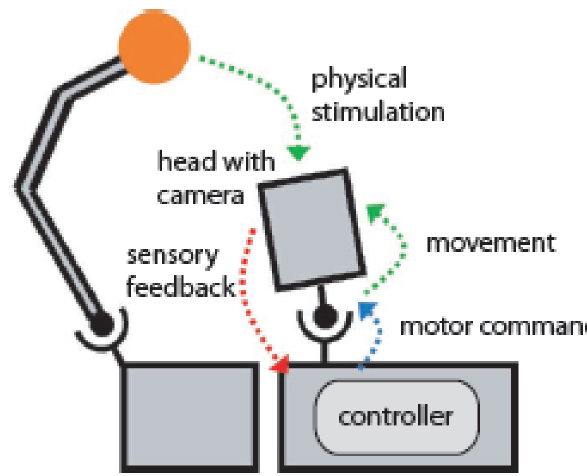
Olaf Sporns (Indiana)

Max Lungarella (AI Lab, Univ. of Zurich)

Information self-structuring







Experiments by Lungarella and Sporns, 2006

Quantitative measures

entropy: order, disorder, information

$$H(X) = -\sum_i p(x_i) \log p(x_i)$$

mutual information: statistical dependency

$$MI(X,Y) = H(X) + H(Y) - H(XY) = -\sum_i \sum_j p(x_i, y_j) \log \frac{p(x_i)p(y_j)}{p(x_i, y_j)}$$

integration: global statistical dependence

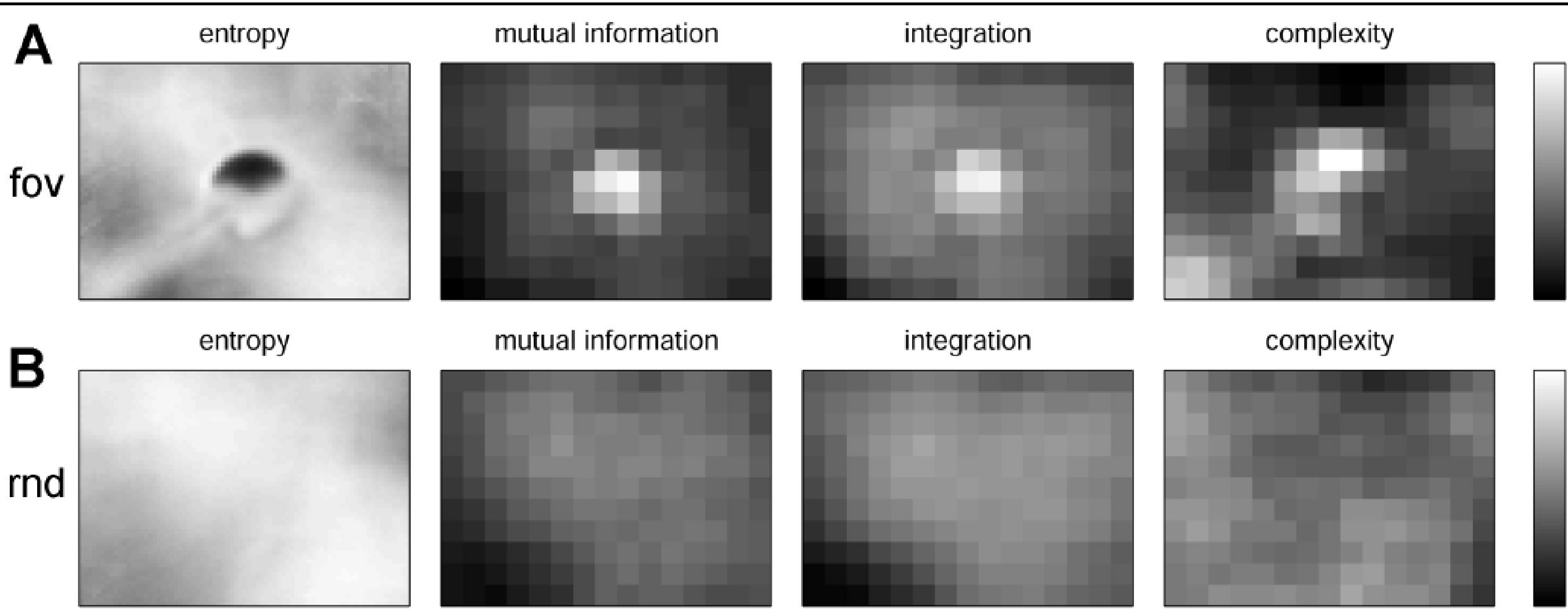
$$I(X) = \sum_i H(x_i) - H(X)$$

complexity: co-existence of local and global structure

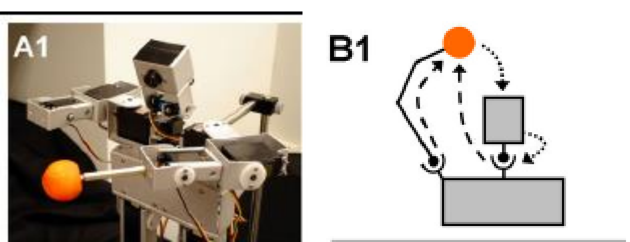
$$C(X) = H(X) - \sum_i H(x_i | X - x_i).$$

Tononi, Sporns, Edelman, PNAS, 1994, 1996

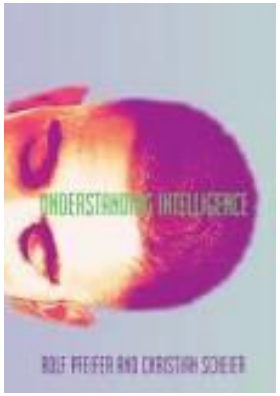
Results
(foveation vs. random)

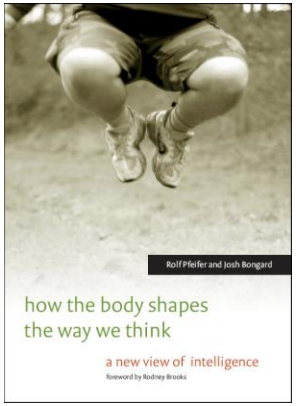


entropy | mutual information | integration (over patch) | complexity (over patch)



Resources





- Pfeifer, R. & Scheier, C. (2001), *Understanding intelligence, MIT Press Cambridge, MA, USA.*
- Pfeifer, R. & Bongard, J. C. (2007), *How the body shapes the way we think: a new view of intelligence, MIT Press, Cambridge, MA.*
- *ShanghAI lectures repository: http://shanghailectures.org/lectures*
- Hoffmann M., Assaf D., Pfeifer R.: Tutorial on embodiment http://www.eucognition.org/index.php?page=tutorial-on-embodiment
- Hoffmann, M. & Pfeifer, R. (2011), The implications of embodiment for behavior and cognition: animal and robotic case studies, in W. Tschacher & C. Bergomi, ed., 'The Implications of Embodiment: Cognition and Communication', Exeter: Imprint Academic, pp. 31-58.