Embodied computation

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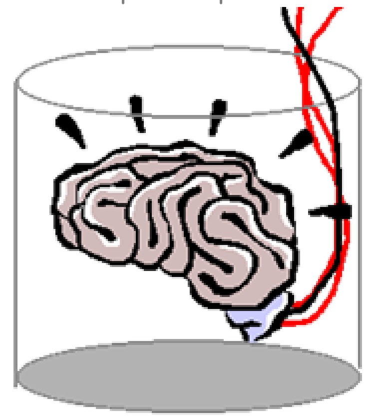
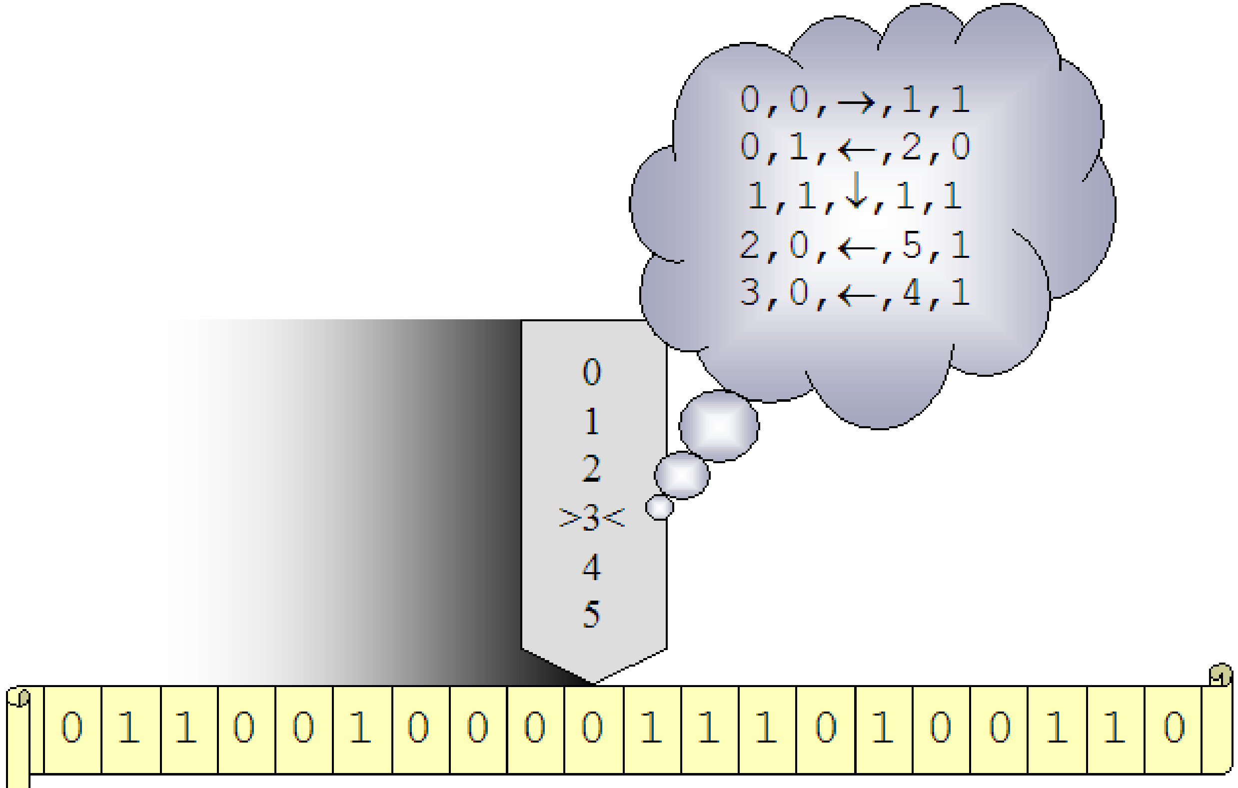
[Susan Stepney. Embodiment. In Darren Flower, Jonathan Timmis, eds. *In Silico Immunology*, Springer, 2006]

disembodied computation

http://users.ox.ac.uk/~ball0888/oxfordopen/scepticism.htm



"brain in a vat"



"black box"

http://digitalphysics.org/Publications/Petrov/Pet02a2/Pet02a2.htm

natural embodied computation

continually sensing the ever-changing world, acting based on the current state of the world, and further changing the world

http://home2.vr-web.de/~mycenia/rm-down-under/April/168a_termite_mound.jpg

http://www.dandelion.org/ant/ant_images.htm

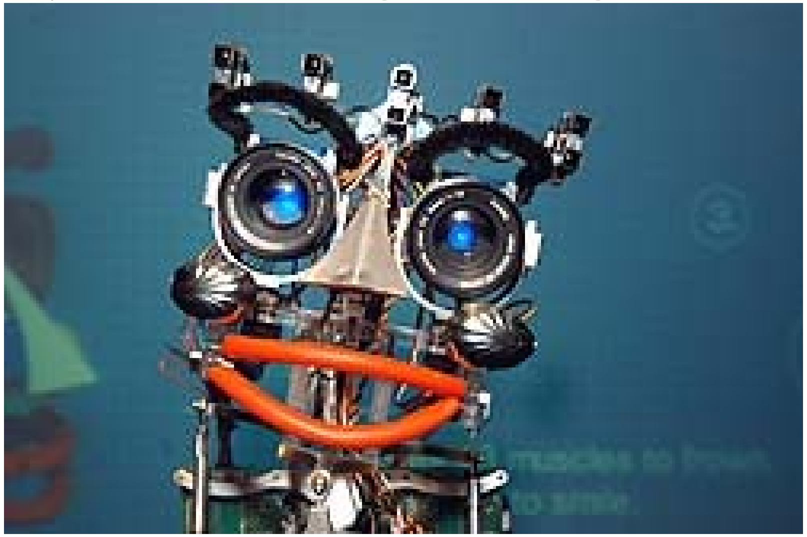
Simon's ant walking on a beach

Viewed as a geometric figure, the ant's path is irregular, complex, hard to describe. But its complexity is really a complexity in the surface of the beach, not a complexity in the ant . . . *The apparent complexity of its behaviour over time is largely a reflection of the complexity of the environment in which it finds itself.*

[Simon, 1996]

embodied : in an environment

http://www.24hourmuseum.org.uk/content/images/2004_0170.JPG



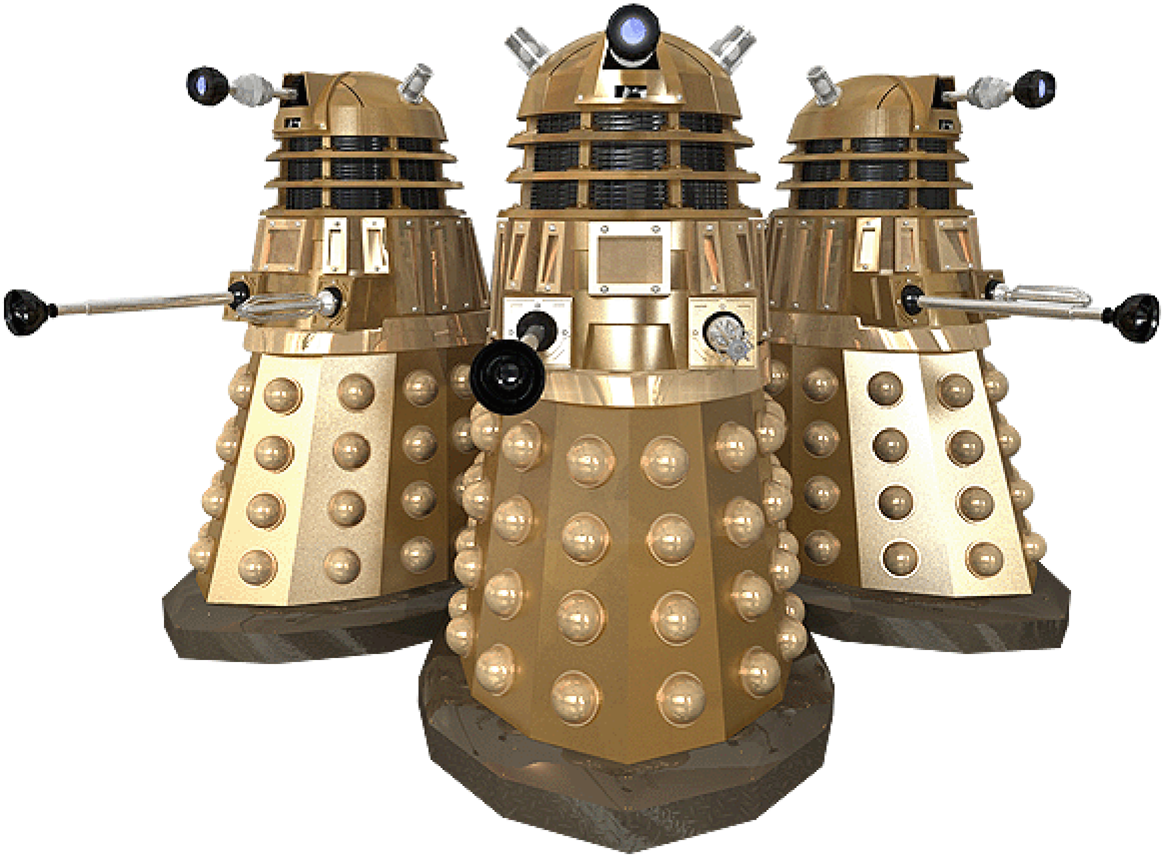
continual rich sensory environmental input

http://www.piaggio.ccii.unipi.it/robotics/images/hand.jpg

sophisticated outputs; environmental manipulation (stigmergy)

the environment [is] a rich and active resource—a partner in the production of adaptive behavior. [Clark, 1997]

embodiment yesterday …

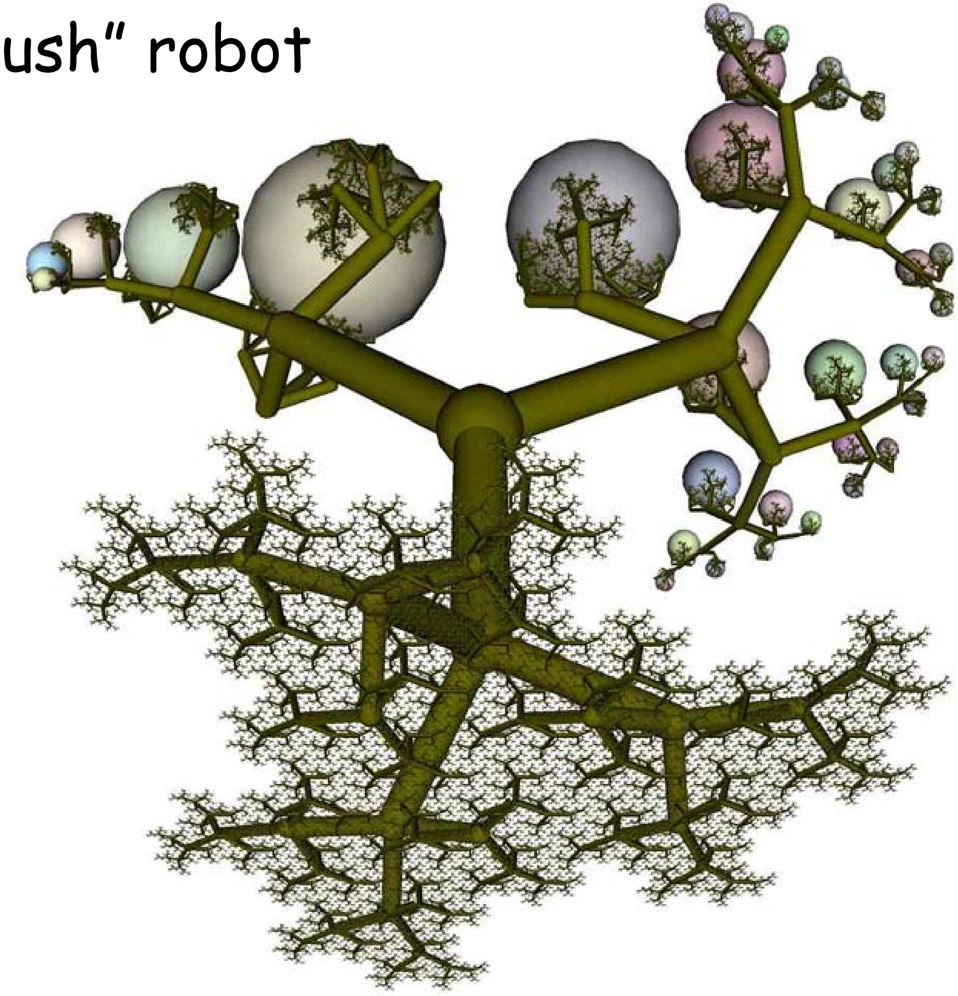


“What are you going to do? *Sucker* me to death?”

… today …

… tomorrow ?

Moravec: fractal “bush” robot



http://www.frc.ri.cmu.edu/~hpm/project.archive/robot.papers/1999/NASA.report.99/9901.NASA.S3.html

the power of embodiment

- rich interaction allows the system to transfer some of its computational burden (memory / state / processing) *to the environment*

- may allow *new classes* of problems to be solved
  - exploiting vastly more computational power

- both richness *and* constraints of environment contribute to this power
  - richness gives environment vast computational power
  - constraints give some solutions "for free" (or much cheaper)
    - constraining the space to a smaller region
    - constraining the computation to particular trajectories

virtual embodiment

- embodiment offers advantages (to the embodied)
  - can we engineer these, including *software* systems in *software* environments?
    - *embodied* software agents on the Web?
    - *embodied* AIS on a network?

- "having some (physical) body interacting with some (physical) environment" [many authors…]
  - says both too little, and too much!
    - little insight into nature of interactions, etc: no design help
    - assumes a ***material situatedness*** : seems to rule out software/virtual embodiment

"ontologically neutral" definitions

- "structural coupling" [Maturana & Varela, 1980]
- "continuous reciprocal causation" [Clark, 1997]
- "non-destructive perturbations between a system and its environment, each having an effect on the dynamical trajectory of the other, and this in turn effecting the generation of and responses to subsequent perturbations." [Quick and Dautenhahn, 1999]

embodiment model

sensors

computational system

"suitably rich"
complex internal dynamics

rich dynamical perturbatory **interactions**

environment
---
complex dynamics (assumed?)

analogue / digital
open / predefined

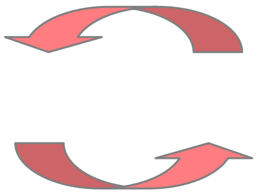
actuators

material / virtual
open

embodied via rich complex feedback

rich feedback

- actuators change the environment …
- … thereby changing what the system senses



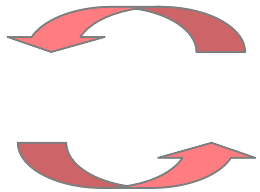
- minimal interaction:
  move the system (position, orientation)
  - change the part of the environment that is sensed
    - environment may *react* to changed location
- rich stigmergic interaction :
  alter the environment
  - mark, erase, build, dismantle, …
  - sense these alterations, and act accordingly
    - communication with *other* embodied systems

physical and virtual constraints

- physical/material constraints
  - fundamental physical laws
    - speed of light; conservation of energy/matter; entropy; …
  - specific laws
    - material composition: strength; resistance; …
  - may give some solutions "for free"

- virtual/logical constraints
  - computability
    - maybe also a physical constraint? [philosophical arguments]
  - feasibility (not NP-complete, or worse)
    - theoretical constraint of a class of problems
      - approximations, particular instances, may be feasible

interaction constraints : timescales

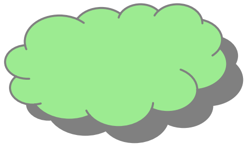


- interaction timescales need to be comparable to environmental changes
  - not too fast : environment cannot react in time
  - not too slow : environment has "moved on"
    - (part of) the solution to Searle's "Chinese Room" fallacy

- real time constraints *essential*
  - high bandwidth interactions *on relevant timescales*
    - animals and plants are both embodied
      - animals have vision: fast interaction (motion)
      - plants do not: much longer interaction timescales

My vegetable love should grow
Vaster than empires and more slow. [Marvell]

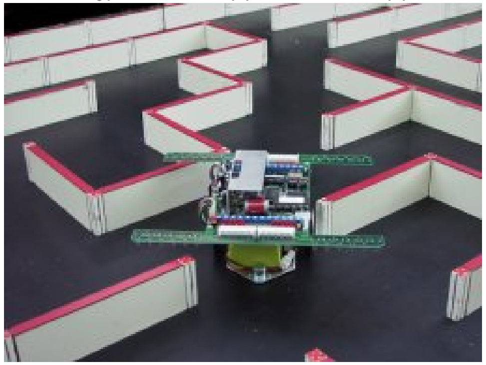
rich physical environment



- "complex dynamics (assumed?)"
  - of sufficient complexity that it is possible to transfer some of the computational burden to it
- "open", exhibit continual novelty
  - which can be exploited by the computational system
  - can exploit *any* feature of the environment
    - not just those in our abstract models
  - evolve to exploit "extra-logical properties"
    - Adrian Thompson's FPGA experiments
    - cryptanalysis side channels
    - analogue properties
- hence "the world is its own best model" [Brooks]

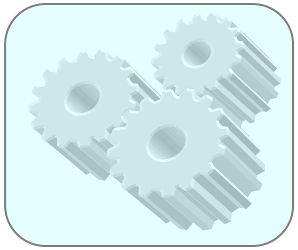
impoverished environments

http://www.ftech-net.co.jp/robot/appli/robot_app.html



- physical environments
  - robot mazes : sterile white-walled corridors
    - no rich structure to couple to
    - could *you* navigate in such an environment?
    - remember Simon's ant: *The apparent complexity of its behaviour … is … a reflection of the complexity of the environment …*
- (most) virtual environments
  - closed, pre-determined, finite, discrete representations
  - no "rich" dynamics
    - fragile, brittle, impoverished
      - true of most computational systems, too
  - no rich structure to couple to!
  - contrast the Internet/Web
    - open, constantly changing and growing

rich virtual dynamics



- sufficiently complex dynamics,
  at the "edge of chaos"
  - random noise is not "rich"; it is unstructured
- stable, persistent, yet "poised", emergent patterns
  - sufficient stability for memory; sufficient changeability for adaptation
- fractal proteins [Bentley]
  - exploit non-linear properties of Mandelbrot set to simulate complex non-linear, rich behaviours
- artificial "gene regulatory networks"
  - with suitable complex non-linear, rich behaviours

co-evolution of sensors/actuators

- "rich dynamical perturbatory interactions"
  - coupling rich dynamics of computational system and environment
- cannot design in isolation
  - codesign/coevolve system and its sensors and actuators
    - in the context of the environment
      - embodied systems cannot be "transplanted" to very different environments
    - completely opposed to "well-defined interface" design philosophy
- adaptive system and environment will each learn to exploit the others' inputs/outputs
    - depend on both, and both are changing!
  - adaptive system needs to change/adapt sensors and actuators
    - modalities, number, position, bandwidths, …

developmental embodied systems

- simple designed system
  - static, non-adaptive, unchanging
- adaptive system
  - initially designed, then changes and adapts with environment
- developmental system
  - mature system "grows" from a "seed"
    - the seed itself may be designed
  - embodied: grows and adapts in an environment
    - same seed grows differently in different environments
  - environment shapes *and is shaped by* that growth
  - developmental systems cannot be "transplanted" to very different environments

http://www.artificialplants.co.uk/page2.htm

design principles I

1. design the system with sufficiently complex dynamics, that can execute this dynamics on the relevant timescale(s) of the environment
   - there may be several relevant timescales: immediate reaction; slower adaptation/learning; even slower evolution

2. design a sufficiently high interaction bandwidth on the relevant interaction timescale(s)
   - physical environments naturally offer high bandwidth
   - virtual environments need to be designed to offer sufficiently rich information

design principles II

3. ensure that input from the environment is constantly available and up to date
   - continually sensing/filtering relevant data
     - not requesting or polling it
   - data needs limited spatial/temporal extent to be "up-to-date"

4. ensure that the system perturbs the environment, rather than being merely a passive observer
   - actuators as well as sensors
   - must change/affect the "data stream"

design principles III

5. ensure that the environment has sufficiently complex dynamics
   - a "given" for a physical environment
     - but beware those sterile artificial mazes!
   - add "edge of chaos", or similar, to a virtual environment

6. allow the system to exploit structure and constraints in the environment in order to simplify its tasks
   - physical environment naturally has structure and constraints
   - virtual environment needs suitable structure and constraints designed in
     - "structure and constraints" $\Rightarrow$ randomness not suitable "richness"

design principles IV

7. Apply embodied systems only in "softer" problem domains where approximate solutions are appropriate and acceptable
   - approximation is natural in the physical, analogue world
     - determine the acceptable degree of approximation
   - crisp digital problems are not appropriate
     - removes many classical computing applications!
       - including integer arithmetic, and the ubiquitous "2-bit adder" case study

design principles V

8. co-design the system and its interface (sensor and actuator numbers, positions, data formats, etc)

9. design the system to develop, “grow”, in the relevant environment
   - the system should start as small as possible (“embryo”), and develop in the context of its environment
   - continual online learning
     - not offline learning followed by a frozen state deployment

where next?

- "BiGBIE" : immuno-engineering principles (EPSRC proposal)
  - three diverse case studies, with different styles of embodiment
- YCCSA pump priming
  - embodied robot experiments