Scientific Theory in Informatics A1N

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Lecture 8

Paradigms of Cognitive Science

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Topic Overview

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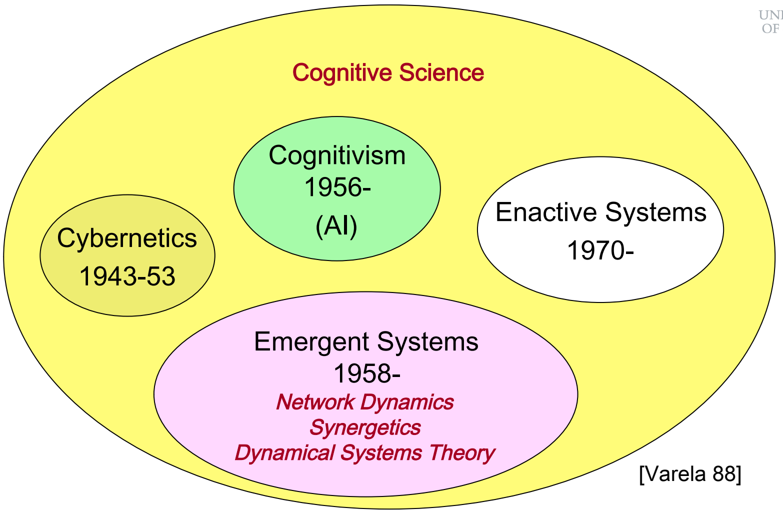
- Introduction
- The cognitivist paradigm of cognitive science
  - An overview of cognitivism
  - Artificial Intelligence and cognitivism
- The emergent paradigm of cognitive science
  - Connectionist systems
  - Dynamical systems
  - Enactive systems
- Hybrid Systems
- A comparison on cognitivist and emergent paradigms
- Which paradigm should we choose?



[Varela 88]

Cybernetics

- The word *cybernetics* has its roots in the Greek word *κυβερνητης* or kybernetes, meaning steersman
- It was defined in Norbert Wiener's book *Cybernetics*, first published in 1948, as "the science of control and communication" (this was the sub-title of the book)
- W. Ross Ashby notes in his book *An Introduction to Cybernetics*, published in 1956 that cybernetics is essentially "the art of steersmanship"
  - co-ordination, regulation, and control.
- The word *governor* derives from *gubernator*, the Latin version of *κυβερνητης*

Cybernetics

- Closed-loop control
- An action by the system causes some change in its environment and that change is fed to the system via feedback that enables the system to change its behaviour
- This "circular causal" relationship is necessary and sufficient for a cybernetic perspective [Wikipedia]

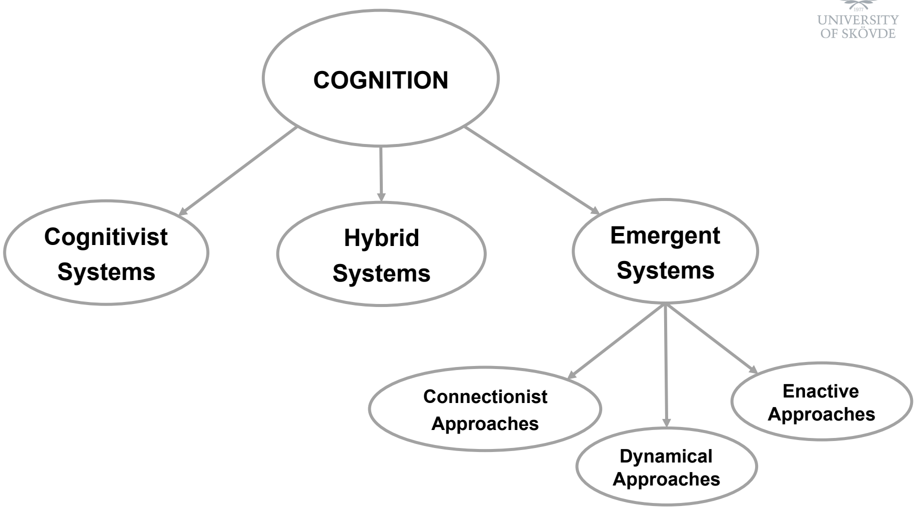
Cybernetics

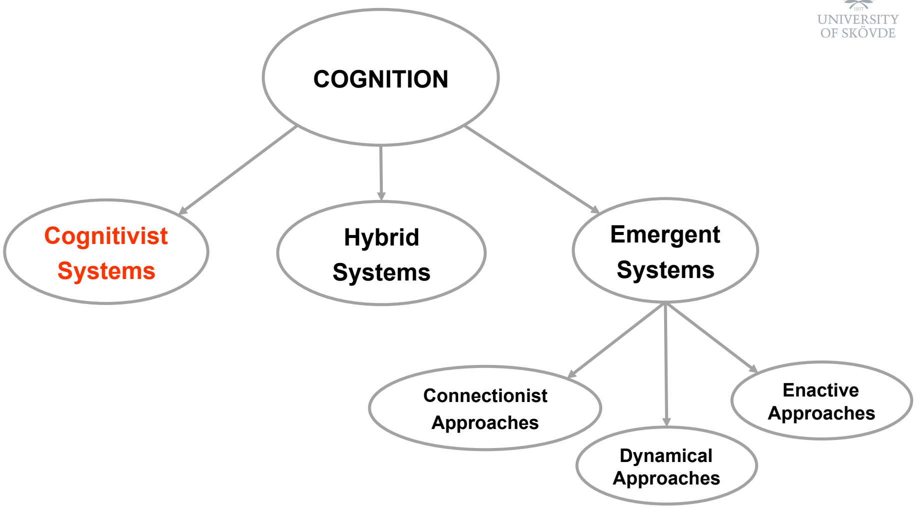
- "The essential goal of cybernetics is to understand and define the functions and processes of systems that have goals and that participate in circular, causal chains that move from action to sensing to comparison with desired goal, and again to action." [Wikipedia]

Cybernetics

- Recent definition proposed by Louis Kauffman, President of the American Society for Cybernetics

  "Cybernetics is the study of systems and processes that interact with themselves and produce themselves from themselves."





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‘The world we perceive is isomorphic with our perceptions of it as a geometric environment’

[Shepard & Hurwitz ‘84]

‘Cognition *is* a type of computation’

‘People “instantiate” … representations physically as cognitive codes and that their behaviour is a causal consequence of operations carried out on these codes’

[Pylyshyn ‘84]

132 THE TREE OF KNOWLEDGE

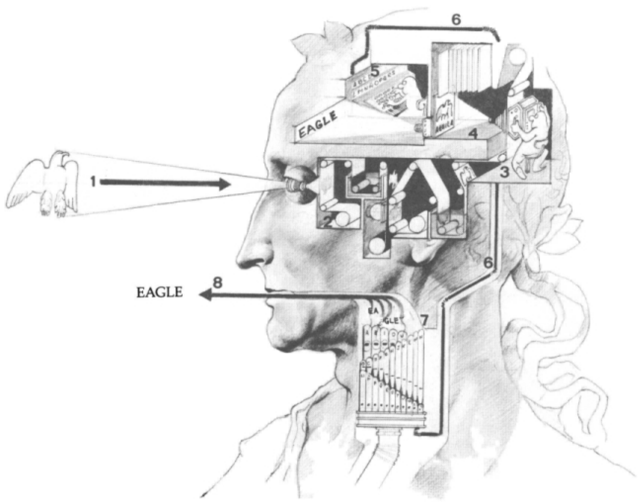

Fig. 34. Caesar according to the representationist metaphor.

From *The Tree of Knowledge – The Biological Roots of Human Understanding*
H. R. Maturana and F. J. Varela, 1988

Cognitivist Systems

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- Strong representations
  - Explicit & symbolic
  - Representations *denote* external objects
  - Isomorphic
  - Projection
  - Implies an absolute and accessible ontology
  - That is consistent with human expression …

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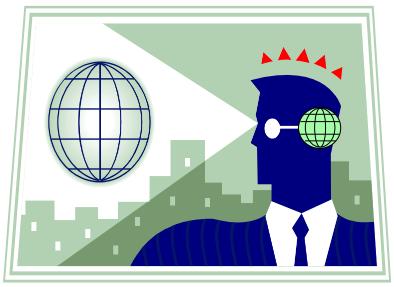

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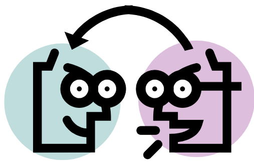
Cognitivist Systems

- Representations
  - Descriptive product of a human designer
  - Can be directly accessed & understood by humans
  - Human knowledge can be directly injected into an artificial cognitive system



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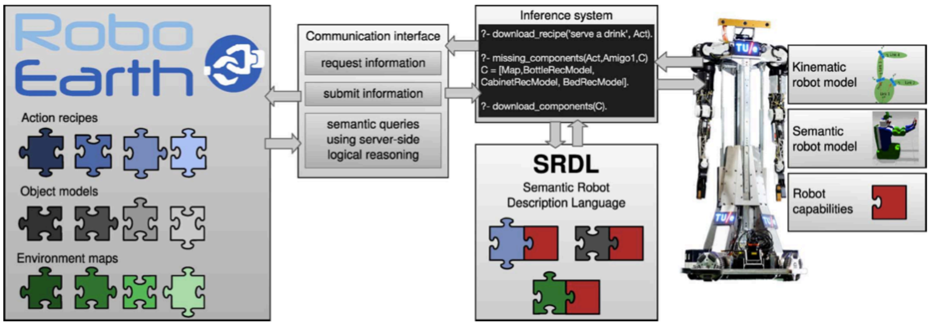

Tenorth et al. 2013

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Actions in a Task
- ehow.com, wikihow.com
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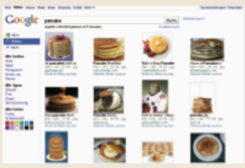

Object Shape
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Tenorth et al. 2011

Cognitivist Systems

- But …

  Programmer-dependent representations bias the system

  'blind' the system (cf. Winograd & Flores)

- … can you anticipate every eventuality in your design?
- The semantic gap … and the Symbol Grounding problem

Cognitivist Systems

- Plugging the gap by …
  - Machine learning
  - Probabilistic modelling
  - Better models
  - Better logics
  - Better reasoning
  - Better everything
  - … and still …

Cognitive science
is involved in an escalating retreat
from the inner symbol:
a kind of inner symbol flight

A. Clark, Mindware

Cognitivism and Artificial Intelligence

Cognitivism & Artificial Intelligence

- Physical symbol system approach to AI
- Intelligence
  - The degree to which a system approximates a knowledge-level system [Unified Theories of Cognition, Newell 90]
  - A knowledge-level system: can bring *all* its knowledge to bear on *every* problem
    - » Perfect knowledge -> complete use of knowledge
    - » Humans aren't there yet!!
  - Principle of maximum rationality [Newell 82]
    - » 'If an agent has knowledge that one of its actions will lead to one of its goals, then the agent will select that action'
  - Rational analysis [Anderson 89]
    - » 'The cognitive system optimizes the adaptation of the behaviour of the organism'.

Cognitivism & Artificial Intelligence

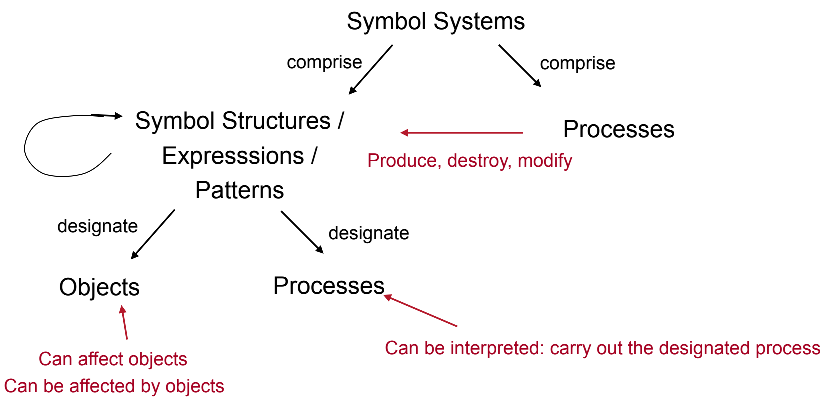
- Physical Symbol Systems
  - Symbols are abstract entities that can be instantiated as tokens
  - A physical symbol system has [Newell 90]:
    - » Memory (to contain the symbolic information)
    - » Symbols (to provide a pattern to match or index other symbols)
    - » Operations (to manipulate symbols)
    - » Interpretations (to allow symbols to specify operations)
    - » Capacities for
      - Composability
      - Interpretability
      - Sufficient memory
  - Symbol systems can be instantiated but … behaviour is independent of the particular form of the instantiation

Cognitivism & Artificial Intelligence

- Physical Symbol Systems [Newell and Simon 1975]
  - The Physical Symbol System Hypothesis
    - » A physical symbol system has the necessary and sufficient means for general intelligent action
    - » Any system that exhibits general intelligence is a physical symbol system
    - » A physical symbol system is ‘a machine that produces through time an evolving collection of symbol structures’

Cognitivism & Artificial Intelligence

- Physical Symbol Systems [Newell and Simon 1975]



Cognitivism & Artificial Intelligence

- Physical Symbol Systems [Newell and Simon 1975]
  - The Heuristic Search Hypothesis
    - » The solutions to problems are represented as symbol structures
    - » A physical symbol system exercises its intelligence in problem-solving by search
      - Generating and progressively modifying symbol structures until ti produces a solution structure
      - Effective and efficient search
    - » 'The task of intelligence is to avert the ever-present threat of the exponential explosion of search'

Cognitivism & Artificial Intelligence

- Physical Symbol Systems
  - The Physical Symbol System Hypothesis

    A physical symbol system has the necessary and sufficient means of general intelligence
  - What are the implications for humans???
  - Natural and artificial intelligence is equivalent (why?)

Cognitivism & Artificial Intelligence

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Newell's four levels

Social

$10^5 – 10^7$ s; behaviours

Requires a symbolic level

Rational

$10^2 – 10^4$ s; tasks requiring reasoning (find way home)

Cognitive

$10^{-1} – 10^1$ s; deliberate acts (reaching),
composed operations (shifting gear)
actions (steering a car into a gate)

Biological

$10^{-4} – 10^{-2}$ s; organelle, neuron, neural circuit

All knowledge is here

Cognitivism & Artificial Intelligence

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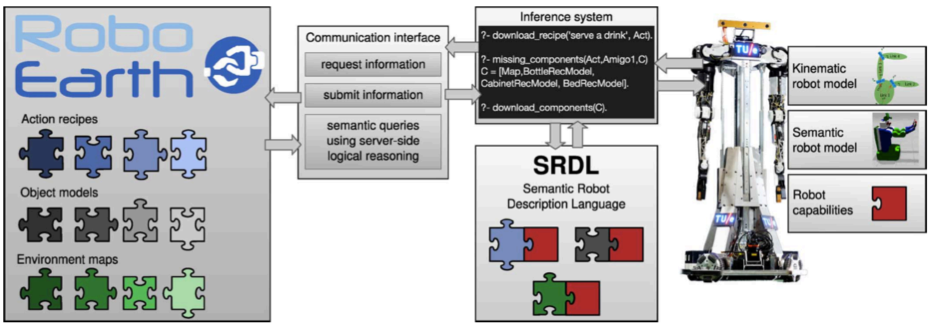
- (Cognitive) Architecture: defines the manner in which a cognitive agent manages the primitive resources at its disposal
- Dictates representations and their deployment
- Dictates properties of cognitive system
  - Organization & control strategies (coordination/cooperation; modular/ hierarchical)
  - Memory, knowledge, representation (world models, delarative representations, procedural representations, associate memory, episodic knowledge, meta-knowledge, represenational structures)
  - Types of learning (deliberative vs reflexive; monotonic vs non-monotonic)
  - Types of planning
  - Behaviour (coherence, saliency, & adequacy: consistency, relevance, sufficiency)

Cognitivism & Artificial Intelligence

- Unified Theories of Cognition
  - Attempts to explain all the mechanisms of all problems in its domain
  - Now plausible (Newell) cf the Soar project
  - Applies to both natural and artificial cognition

Cognitivism & Artificial Intelligence

- Non-functional Attributes of Cognitive Architectures
  - Generality (breadth of tasks)
  - Versatility (ibid)
  - Rationality (cf. consistency and repeatability)
  - Scalability (cf. complexity)
  - Reactivity (cf. unpredictability)
  - Efficiency (cf. time and space constraints)
  - Extendability (cf. reconfigurability)
  - Taskability (cf. external direction)
  - Psychological validity (cf. human models)



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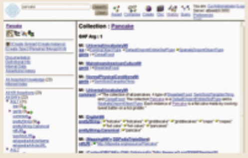

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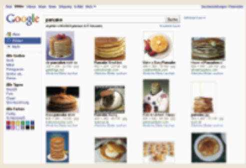

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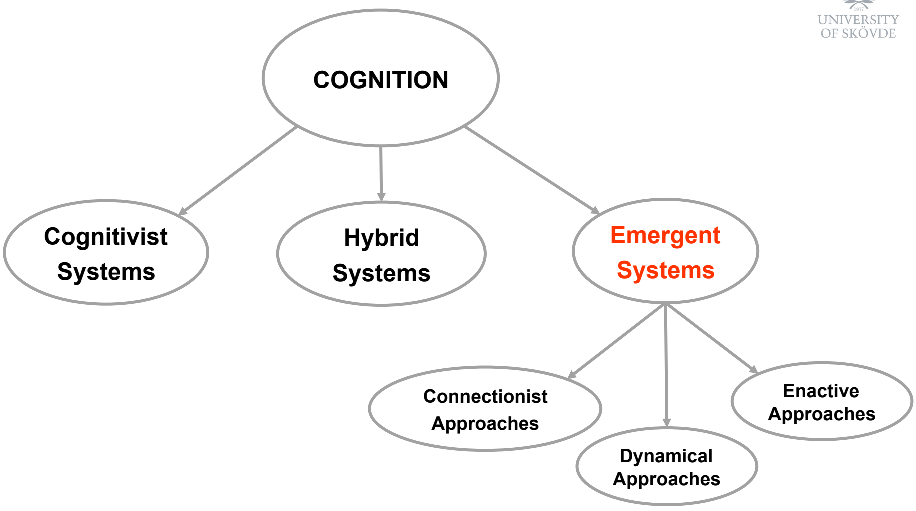
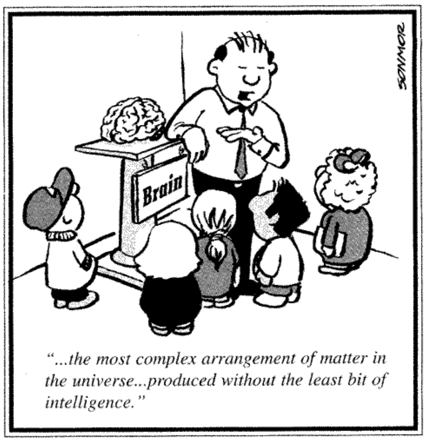




Self-generated AI:
AI by orchestrating the processes that generate it

Luc Steels

Emergent Approaches

- Cognition is the process whereby an autonomous system becomes viable and effective in its environment
- It does so through a process of self-organization
  - System is continually re-constituting itself
  - In real-time
  - To maintain it operational identity
  - Through moderation of mutual system-environment interaction and co-determination

Maturana & Varela 87

Emergent Approaches

- Co-determination
  - Cognitive agent is specified by its environment
  - Cognitive process determines what is real or meaningful for the agent
  - The system constructs its reality (world) as a result of its operation in that world
  - Perception provides sensory data to enable effective action, but as a consequence of the system's actions
  - Cognition and perception are functionally-dependent on the richness of the action interface [Granlund]

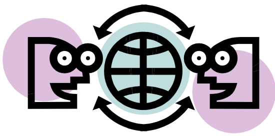
Emergent Approaches

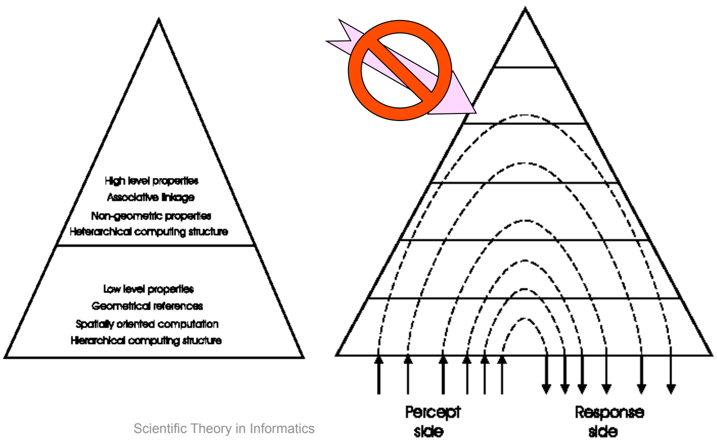
- Cognition is the complement of perception [Sandini]
  - Perception deal with the immediate
  - Cognition deals with longer time frames
- Primary model of cognitive learning is anticipative skill construction (not knowledge acquisition)
- The root of intelligence is to act effectively, anticipate the need to act, and increase the repertoire of actions
- Embodied as physical systems capable of physical interaction with the world

Emergent Approaches

‘Cognitive systems need to acquire information about the external world through learning or association’

[Granlund’02]





Emergent Approaches

- Self-organization
  - “Self-organizing systems are physical and biological systems in which pattern and structure at the global level arises solely from interactions among the lower-level components of the system.”
  - “The rules specifying interactions among the system’s components are executed only using local information, without reference to the global pattern.”
- Emergence
  - A process by which a system of interacting elements acquires qualitatively new pattern and structure that cannot be understood simply as the superposition of the individual contributions.

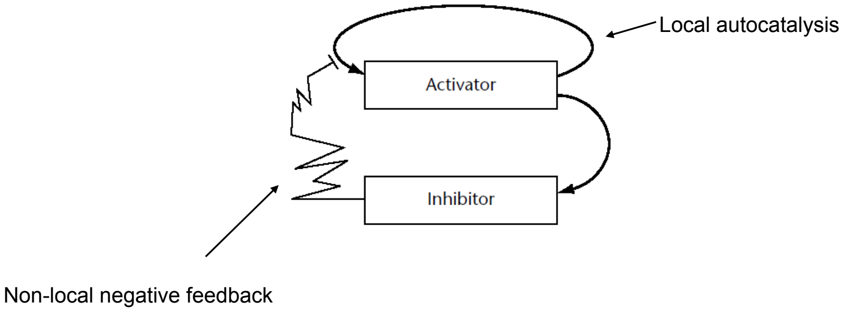
[Camazine 2006]

Emergent Approaches

- Self-organization
  - Short-range Activator
    - » autocatalysis: promote its own productions
    - » Increase the production of an inhibitor (antagonist)
  - Inhibitor
    - » Diffuses rapidly
  - Result:
    - » Local increase in activation
    - » Long-range antagonistic inhibition which keeps the self-enhancing reaction localized

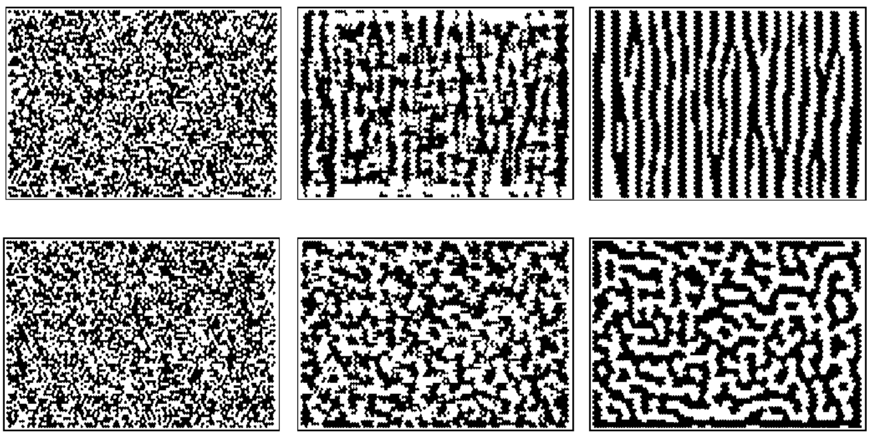
[Camazine 2006]

Emergent Approaches



[Meinhardt 95]

Emergent Approaches



[Camazine 2006]

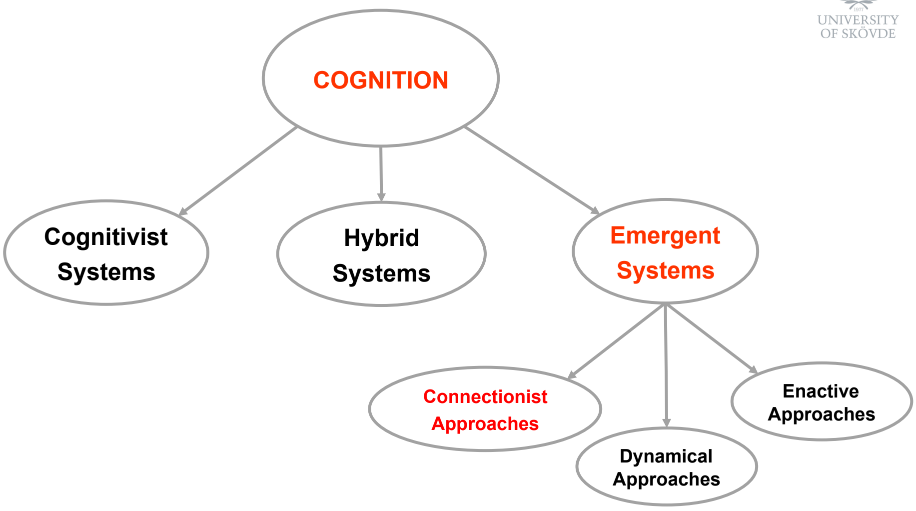
Caveat

Harry gasped for breath, “but *what* is going *on?*”

“Magic,” said Professor McGonagall. She shrugged.

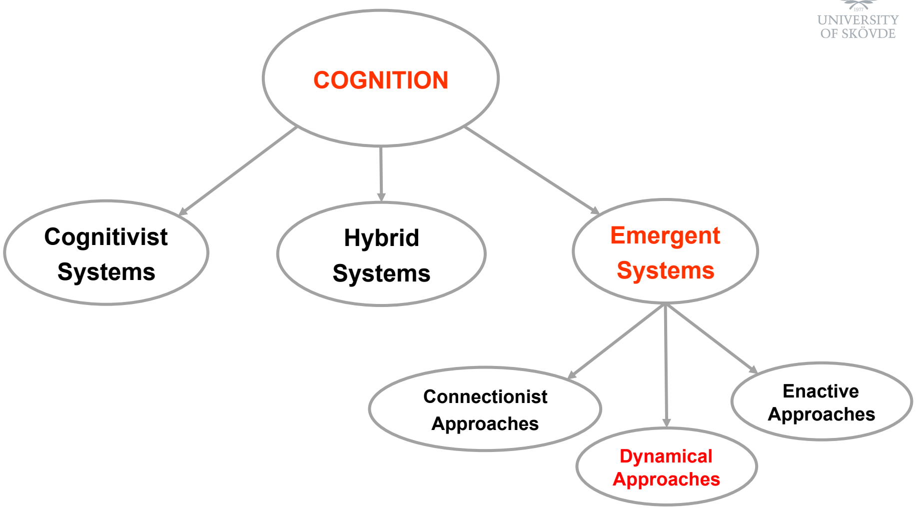
“That’s just a *word!* Even after you tell me that, I can’t make any new predictions! It’s exactly like saying ‘phlogiston’ or ‘elan vital’ or ‘emergence’ or ‘complexity’!”

[Less Wrong, *Harry Potter and the Methods of Rationality*, 2015]



Connectionist Systems

- Rely on
  - Parallel processing
  - Non-symbolic distributed activation patterns in networks
  - Not logical rules
- Neural networks are the most common instantiations
  - Dynamical systems that capture statistical regularities or associations



Dynamical Systems

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- Dynamical Systems
  - A dynamical system is an open dissipative non-linear non-equilibrium system
  - System: large number of interacting components & large number of degrees of freedom
  - Dissipative: diffuse energy – phase space decreased in volume with time (⇨ preferential sub-spaces)
  - Non-equilibrium: unable to maintain structure or function without external sources of energy, material, information (hence, open)
  - Non-linearity: dissipation is not uniform – small number of system's degrees of freedom contribute to behaviour

    … order parameters / collective variables

Kelso '95: Dynamic Pattern – The Self-Organization of Brain and Behaviour

Dynamical System

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$$\dot{\mathbf{q}} = \mathrm{N}(\mathbf{q}, \mathbf{p}, n)$$

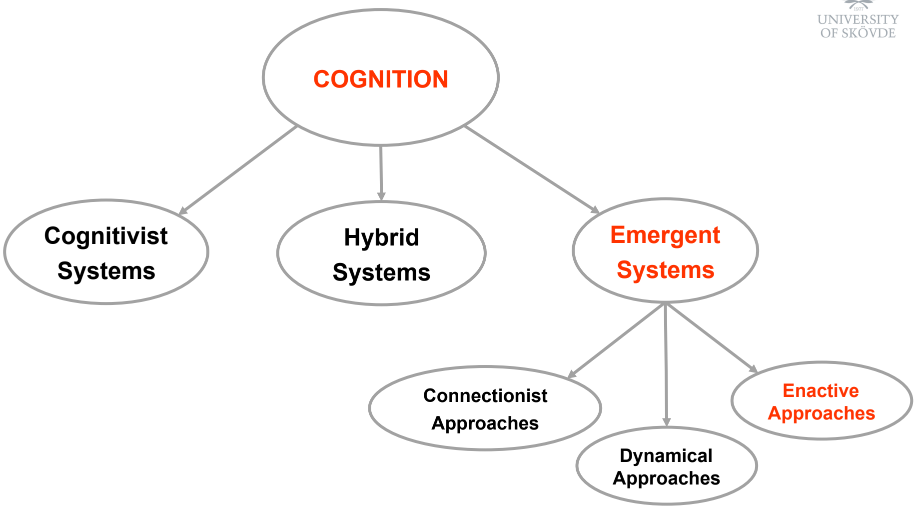
noise

time derivative

control parameters

state vector

From [Shoner Kelso 88]



Enaction

- Orthodoxy (cognitivist)
  - World as the system experiences it is independent of the cognitive system (knower)
- Enactive view
  - Known and knower ‘stand in relation to each other as mutual specification: they arise together’

Enaction

- Five key elements to enactive systems
  - Autonomy
  - Embodiment
  - Emergence
  - Experience
  - Sense-making

Enaction

- Autonomy
  - Self-maintenance
  - Homeostasis
  - Not controlled by outside agencies
  - Stands apart from its environment

Enaction

- Embodiment
  - Exists as a physical entity
  - Directly interacts with its environment
    - » Structural coupling
    - » Mutual perturbation
  - Constitutive part of the cognitive process

Enaction

- Emergence
  - Cognitive behaviour arises from dynamic interplay between component parts
  - Internal dynamics
    - » Maintains autonomy
    - » Condition the system's experiences through their embodiment in a specific structure

Enaction

- Experience
  - History of interaction with the world
  - Interactions don’t control
  - Interaction do trigger changes in system state
  - Changes are structurally-determined
    - » Phylogeny
    - » Structural coupling

Enaction

- Sense-making
  - Knowledge is generated by the system itself
  - Captures some regularity or lawfulness in the interactions
  - The ‘sense’ is dependent on the way interaction can take place
    - » Perception & Action
  - Modify its own state (CNS) to enhance
    - » Predictive capacity
    - » Action capabilities
  - Development: generative autonomous self-modification

Development

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Progressive ontogenetic acquisition of anticipatory capabilities

- Cognition cannot short-circuit ontogeny
- Necessarily the product of a process of embodied development
- Initially dealing with immediate events $\longmapsto t$
- Increasingly acquiring a predictive capability $\longmapsto\!\!\!\longrightarrow t$

Cognition and perception are functionally-dependent
on the richness of the action interface

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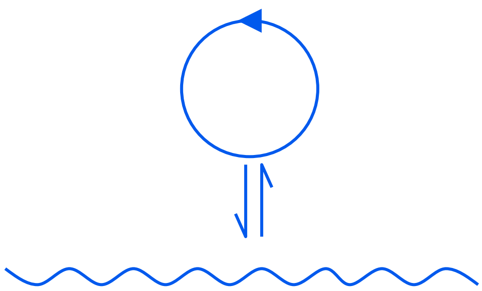
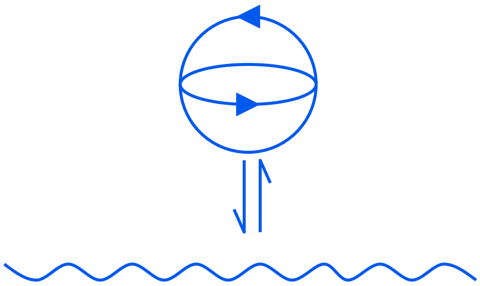


Co-determination / Structural Coupling

Autonomomy-preserving mutual interaction

Perturbation of the system is only effected by the environment

[Note: this ideogram and similar ones to follow were introduced in Maturana and Varela 1987]



Cognitive system: operationally-closed system with a nervous system

Nervous system facilitates a highly-plastic mapping between sensor and motor surfaces

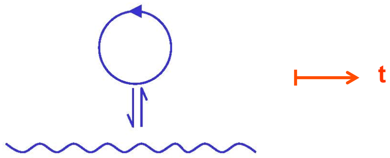
Perturbation by both environment and system (of receptors & NS)

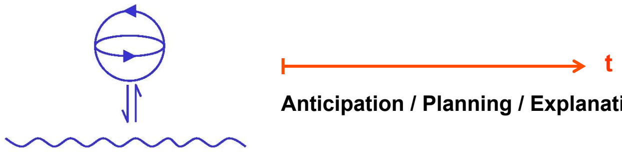
Enaction

NERVOUS SYSTEM

(a) Facilitates huge increase in the number of possible sensor-motor patterns (that result from structural coupling with the environment)

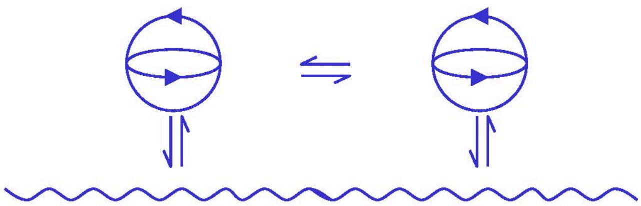
(b) Creates new dimensions (degrees of freedom) of structural coupling by facilitating association of internal states with the system interactions





Anticipation / Planning / Explanation / Prediction

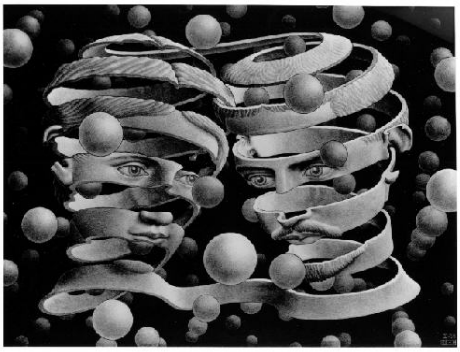
INTERACTION



A shared activity in which the actions of each agent influences the actions of the other agents

Resulting in a mutually-constructed pattern of shared behaviour

Meaning emerges through shared consensual experience mediated by interaction



Bond of Union
M. C. Escher, 1956

"Interaction is a shared activity in which the actions of each agent influence the actions of the other agents engaged in the same interaction, resulting in a mutually-constructed patterns of shared behaviour"

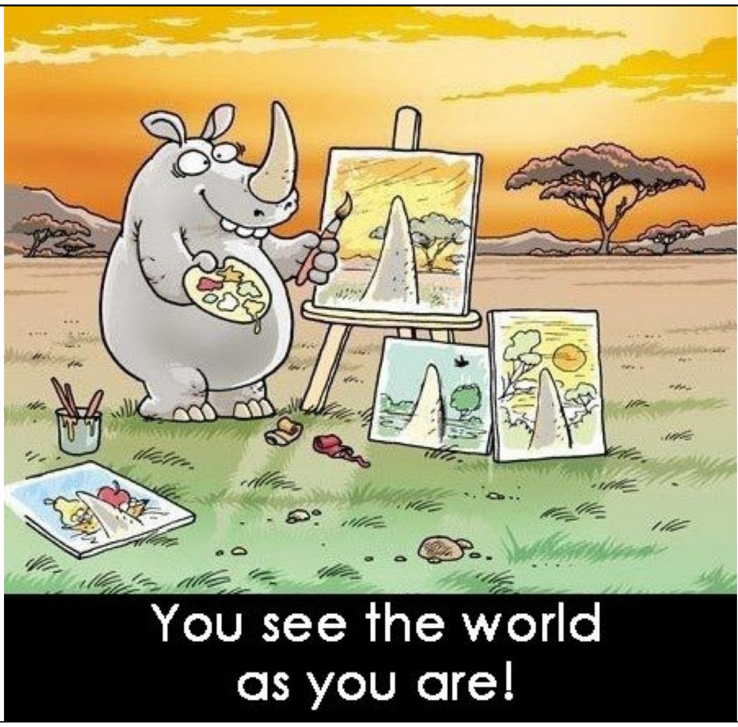
Ogden, Dautenhahn, Stribling 2002

COGNITION & SENSE-MAKING

Cognition is a process whereby the issues that are important for the continued existence of the cognitive entity are brought forth …

co-determined by the entity as it interacts with the environment

- THE SPACE OF PERCEPTUAL POSSIBILITIES
- Is predicated not on an objective environment,
- but on the space of possible actions
- that the system can engage
- … Cognition involves seeing as if, rather than seeing as is



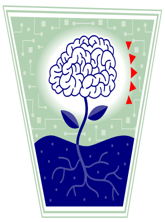
Enactive Cognition

MEANING

Emerges through shared consensual experience
mediated by interaction

Enactive Cognition

- Structural coupling
  - Necessarily embodied
  - Operating in synchronous real-time



Machine representations reflect the machine's epistemology

Enactive Cognition

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Avoid falling back into using cognitivist preconceptions basing the 'design' on representations derived by external observers (us)

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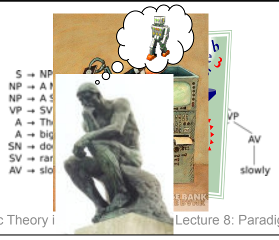
Differences between Cognitivist & Emergent Paradigms

1. Computational operation
2. Representational framework
3. Semantic grounding
4. Temporal constraints
5. Inter-agent epistemology
6. Embodiment
7. Perception
8. Action
9. Anticipation
10. Adaptation
11. Motivation
12. Autonomy
13. Cognition
14. Philosophical foundation

[Vernon, Von Hofsten, Fadiga 2010]

The Cognitivist Paradigm vs. the Emergent Paradigm		
Characteristic	**Cognitivist**	**Emergent**
Computational Operation	Syntactic manipulation of symbols	Concurrent self-organization of a network
Representational Framework	Patterns of symbol tokens	Global system states
Semantic Grounding	Percept-symbol association	Skill construction
Temporal Constraints	Atemporal	Synchronous real-time entrainment
Inter-agent epistemology	Agent-independent	Agent-dependent
Embodiment	No role implied: functionalist	Direct constitutive role: non-functionalist
Perception	Abstract symbolic representations	Perturbation by the environment
Action	Causal consequence of symbol manipulation	Perturbation by the system
Anticipation	Procedural or probabilistic reasoning	Traverse of perception-action state space
Adaptation	Learn new knowledge	Develop new dynamics
Motivation	Criteria for goal selection	Increase space of interaction
Autonomy	Not entailed	Cognition entails autonomy
Cognition	Rational goal-achievement	Self-maintenance and self-development
Philosophical Foundation	Positivism	Phenomenology



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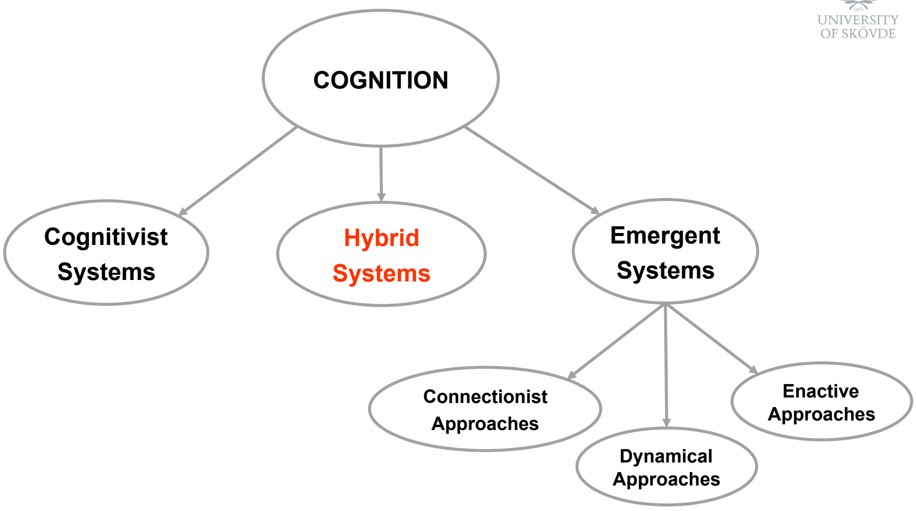

Hybrid Models

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- Combination of cognitivist & emergent approaches
- Don’t use explicit programmer based knowledge
- Can use symbolic representations (& representational invariances) but these are populated by the system itself as it learns
- Still emphasize perception-action coupling
- Often with action-dependent perception

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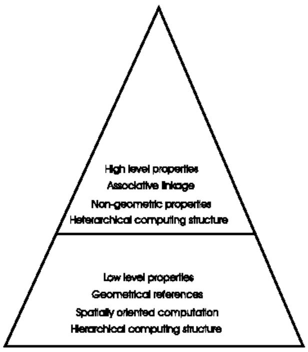
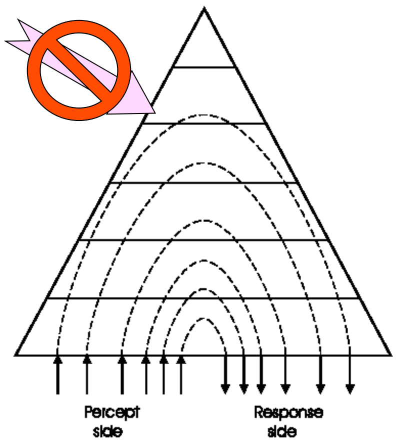
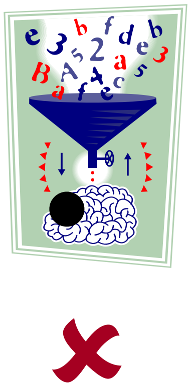
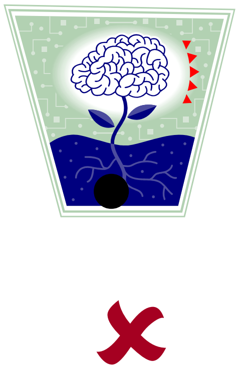




Hybrid Models





Which Paradigm is Correct?

- Paradigms are not equally mature
- Dynamical systems
  - Arguments are compelling BUT ..
  - Not yet clear how to get higher-level cognition
- Cognitivist systems
  - More advanced
  - Not many achievements in generalization
  - More brittle (in principle)
- Enactive (& Dynamical)
  - SHOULD be much less brittle (mutual specification through co-development)
  - But limited cognition at present
- Hybrid systems
  - Best of both worlds?
  - But unclear how one can really combine antagonistic philosophies

Which Paradigm is Correct?

- No on one has actually designed a complete cognitive system
- Still lots of disagreement on the right approach to take

Recommended Reading

Vernon, D. *Artificial Cognitive Systems – A Primer*, MIT Press, (2014); Chapter 2.

Vernon, D., Metta. G., and Sandini, G. "A Survey of Artificial Cognitive Systems: Implications for the Autonomous Development of Mental Capabilities in Computational Agents", IEEE Transactions on Evolutionary Computation, special issue on Autonomous Mental Development, Vol. 11, No. 2, pp. 151-180 (2007).

Vernon, D., von Hofsten, C., and Fadiga, L. A Roadmap for Cognitive Development in Humanoid Robots, Cognitive Systems Monographs (COSMOS), Springer, ISBN 978-3-642-16903-8 (2010); Chapter 5.