## *Cognitive Systems*

Foundations of Information Processing
in Natural and Artificial Systems

Lecture 3

Levels of Information Processing
and Knowledge Representation

Universität Bremen

## Levels of Information Processing and Knowledge Representation

Overview

- Levels of information processing in cognitive systems
- Symbolic vs. connectionist models of cognition
- Knowledge representation



## Complex Systems

- The problem: understanding cognition
- Cognitive systems are complex systems
- Complex systems (of any kind) cannot be understood by simply extrapolating the properties of their elementary components
- For example ...



## Examples of Complex Systems

- Social / political systems
  - elementary components?
  - higher-level components?
- Thermodynamic systems
  - elementary components?
  - higher-level components?



## Understanding Complex Systems

- Effects in complex systems can be described at several levels
  - each level captures different aspects
- Microscopic and macroscopic descriptions should not be inconsistent
- In theory, all levels of explanation should form a coherent whole; but sometimes they are incommensurable
- Cognitive systems as information processing systems are investigated at three different levels: …



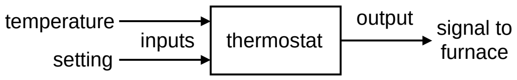
## Marr’s Three Levels (1982)

- Computational theory
  - constraints for mapping input information to output information
- Representation and algorithm
  - definition of information processing operations
- Hardware implementation
  - physical realization of the algorithm within a physical system

## An Example: The Thermostat

(Palmer 1999)

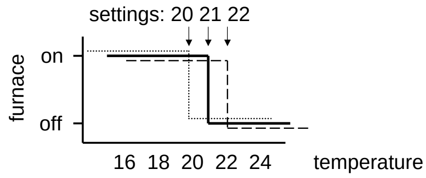
- The computational level






## An Example: The Thermostat

- The computational level (cont'd)

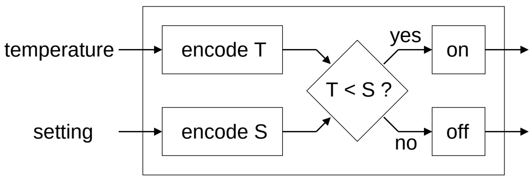



$$O(T, S) = \begin{cases} 1 \text{ iff } T < S \\ 0 \text{ iff } T \geq S \end{cases}$$



## An Example: The Thermostat

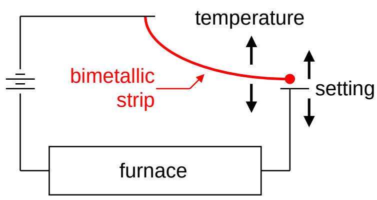
- The algorithmic level






## An Example: The Thermostat

- The implementation level






## In Cognitive Systems?

- The computational level
  - constraints for mapping input information to output information
    - for the overall system (e.g. in small systems)
    - for subsystems within a complex cognitive system (e.g. perceptual subsystems, language processing subsystems)



## In Cognitive Systems?

- The algorithmic level
  - definition of information processing operations
    - description of how the computational level performs its operations (e.g. structural description of memory, algorithmic description of learning processes)

## In Cognitive Systems?

- The implementation level
  - physical realization of the algorithm within a physical system
    - remember: 'cognitive systems' applies to both natural and artificial systems

| natural CSs | artificial CSs |
| --- | --- |
| neurons | program instructions |
| neural structures | methods, functions |
| neural systems | programs |
| brains | computers |
| humans / animals | robots |



## Architectures of Cognition

- Description of cognitive systems as 'architecture' (Simon & Kaplan 1989)
- An architecture identifies components at different levels
  - neurons, brain regions, memory systems
  - design of the architecture depends on what the architecture focuses on



## Levels of the Architecture
(Simon & Kaplan 1989)

symbolic level

connectionist level

basic neural level

!

- these levels and Marr's levels are orthogonal to each other
- each of the architecture's levels can be investigated at each of Marr's levels



## Levels of the Architecture
(Simon & Kaplan 1989)

symbolic level

connectionist level

basic neural level

- computational specification
  - function to be performed
- algorithmic description
  - interaction between components
- implementation
  - realization of the function in neuronal networks



## Levels of the Architecture

- Models of cognitive systems are typically defined as

symbolic level — symbolic models

connectionist level — connectionist models

basic neural level



## Connectionist and Symbolic Models

- Connectionist Models
  - highly simplified and schematized neurons
  - interconnected in a network structure
- Symbolic Models
  - symbols organized in memories
  - symbolic models are abstract higher-level models

## Levels of Information Processing and Knowledge Representation

Overview

- Levels of information processing in cognitive systems
- Symbolic vs. connectionist models of cognition
  - symbolic models
  - connectionist models
- Knowledge representation

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## The Physical Symbol System Hypothesis (PSSH)

Lecture 1

- Fundamental thesis of Cognitive Science:

*A physical symbol system has the necessary and sufficient means for general intelligent action.*

Herbert A. Simon & Alan Newell

- Brains and computers are symbol systems.

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## Symbol Manipulation = Information Processing

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- Information is processed by syntactic operations on formal symbols
- Synthesis of syntactic operations allows forming more abstract symbols (concepts)
- Meaning emerges from syntactic operations

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## Requirements on Symbolic Architectures (Newell et al. 1989)

1. Flexible behavior as function of the environment
2. Adaptive, rational, and goal-oriented behavior
3. Real-time operation
4. Operation in rich, complex, and detailed environment
   - perception of changing details
   - use of stored knowledge
   - control of complex motoric systems
5. Use of symbols and abstractions

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## Requirements on Symbolic Architectures (2)

6. Use of language
7. Learning from environment and from experience
8. Acquisition of capabilities through the environment
9. Live autonomously within a society of other cognitive systems
10. Self-awareness and sense of self

(list not claimed to be complete)

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## Symbolic Models of Cognition

- Symbolic models explain cognition on the computational (or functional) level, rather than on the basis of neural structures and mechanisms
  - radical difference on the implementation level in neural and symbolic cognitive systems

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## Components of Symbolic Architectures

- Memory
- Symbols
- Operations
- Interpretations

the first four components form the symbol system

- Interaction facilities with external world

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## Memory

- Consists of symbol structures that contain symbol tokens
- Independently modifiable
- Sufficient memory available

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## Symbols

- Symbol tokens form patterns in structures
- Symbol tokens provide access to other symbol structures in memory
- Sufficiently many symbols available

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## Operations

- Processes that take symbol structures as input and produce symbol structures as output

Symbol systems are considered to be universal computers (like Turing machines)

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## Interpretations

- Processes that take symbol structures as input and produce behavior by executing operations

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## Interaction with External World

- Perceptual and motor interfaces
  - symbol system embedded in a ‘body’ acting in the real world
- Buffering and interrupts
  - to interface between the symbol system and perception / motor subsystems
- Real-time demands for action
- Continuous acquisition of knowledge

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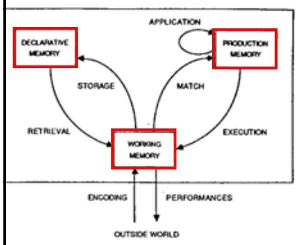
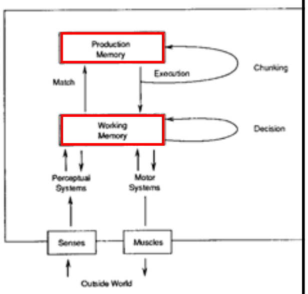
## Two Examples

memories




ACT* (Anderson 1983)




Soar (Laird et al. 1987)

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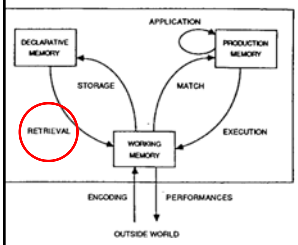
## Two Examples

symbols

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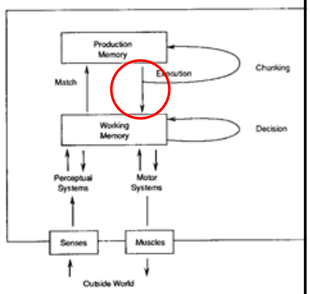


Soar (Laird et al. 1987)

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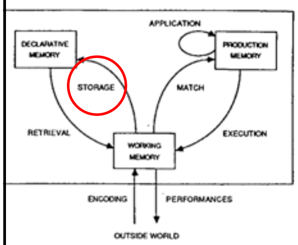
## Two Examples

operations

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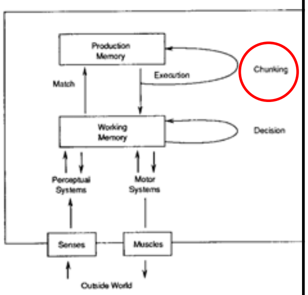


Soar (Laird et al. 1987)

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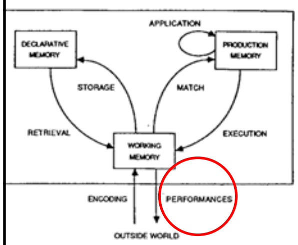
## Two Examples

interpretations

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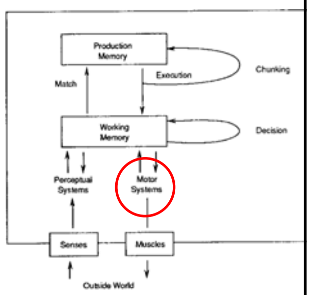


Soar (Laird et al. 1987)

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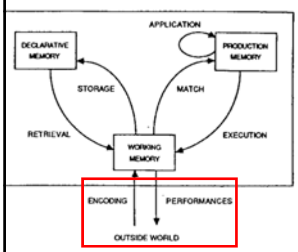
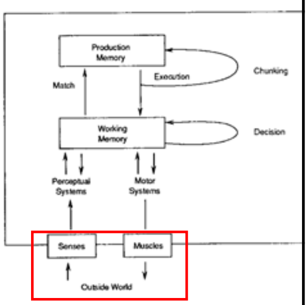
## Two Examples

interaction with external world




ACT* (Anderson 1983)




Soar (Laird et al. 1987)

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## Levels of Information Processing and Knowledge Representation

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- Levels of information processing in cognitive systems
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  - symbolic models
  - connectionist models
- Knowledge representation

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## Connectionist Models of Cognition

- Symbolic models ignore the physical realization of intelligence in brains
- Physical structure influences the algorithms that may be used
- Connectionist models are neurally inspired
- "Brain-style" computation
- Artificial neuron as basic computing unit
- Computation through interaction of 'neurons'

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## Neurons …

- Neurons are slow
  - $10^6$ times slower than microprocessors
  - "100-step program" (Feldman 1985)
- But there are many of them
  - in the human brain about $10^{11}$
- Neurons operate in parallel
- "Knowledge" is encoded in the neural connections
  - one neuron connects to up to $10^5$ other neurons
- no explicit states, but implicit representation in the neural structure

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## Seven Components of connectionist models

1. Set of processing units
2. State of activation
   - defined over processing units
3. Output function
   - maps state of activation to output
4. Pattern of connectivity among units

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## Seven Components (cont'd)

5. Activation rule
   - computes new level of activation from inputs and current state
6. Learning rule
   - modifies patterns of connectivity based on experience
7. Environment in which the system operates

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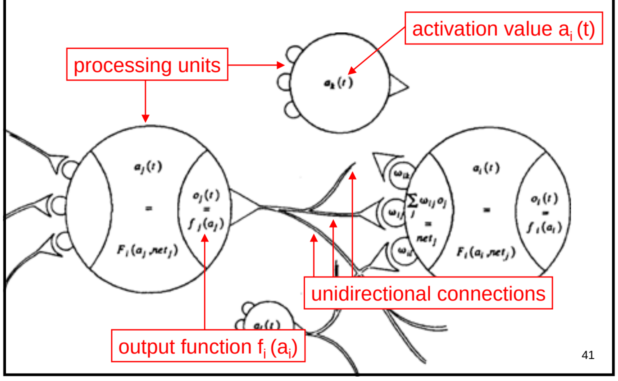
## Connectionist Model

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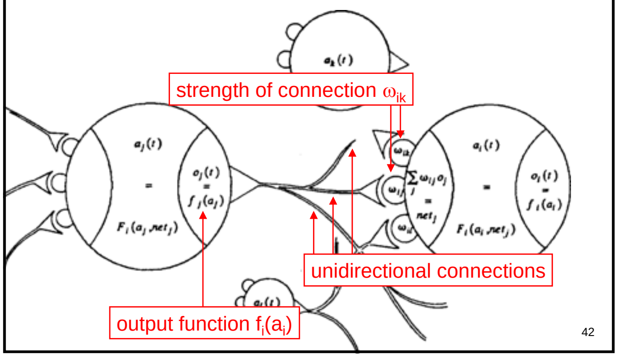
## Connectionist Model

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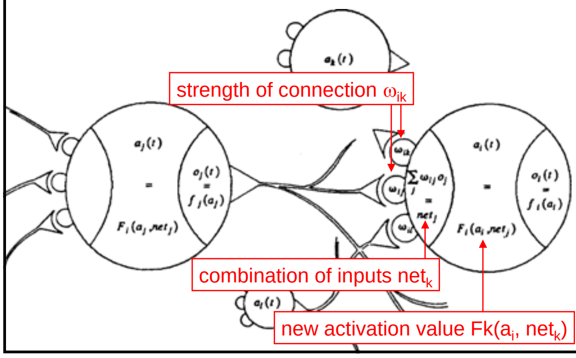
## Connectionist Model

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## Remarks on Connectionist Models

- Connectionist systems represent knowledge in a distributed manner
  - "micro features"
  - no one-unit to one-concept matching (i.e. no localism)
- Types of units
  - input units, hidden units, output units
- Strength of connection represents the connectivity among units
  - excitatory connection, inhibitory connection, no connection

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## Learning in Connectionist Systems

- Learning through modification of patterns of connectivity
  - development of new connections
  - loss of existing connections
  - modification of strengths of existing connections
- Hebb's (1949) learning rule:

If a unit $u_i$ receives an input from another unit $u_k$, then, if both are highly active, the weight $\omega_{ik}$ from $u_k$ to $u_i$ should be strengthened.

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## Levels of Information Processing and Knowledge Representation

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## Internal Representations

Lecture 1

- Environmental information is transformed into neurological structures and meaningful symbols (internal representation)
- This representation is processed in connection with other internally available information about the world (knowledge)
- The result is transformed into actions on the environment

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## Knowledge Representation

- How can a symbol system represent the external world?
- Symbols are not themselves representations of the external world
  - symbols provide internal representation function
- Representation of the external world is a function of the entire cognitive system

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## Knowledge Representation

- A representation is a formal system for making something explicit in the system, together with the specification of how the system does this
- A description of something in a representation uses the representation to describe a specific entity in the world
- An example: …

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## Knowledge Representation: An Example

- Numeral systems are formal systems for representing numbers; a specific number encoded in a numeral system is a description of that number
- Description of the number ‘12’ in different representations

  12    XII    1100    C    dz.

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## Next week

Foundations of visual perception:

retina, receptors, and visual cortex

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