Levels of analysis and ACT-R

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Sharon Goldwater
School of Informatics
University of Edinburgh
sgwater@inf.ed.ac.uk

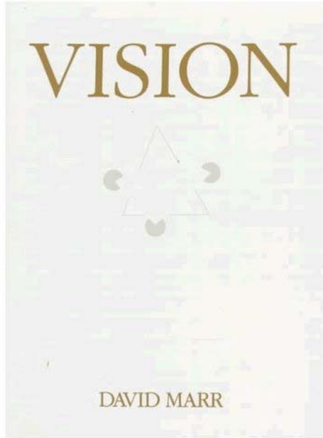
Reading: Marr (1982), pp. 19-29; Anderson (1996)

Outline

Two foundational people in cognitive modeling and their ideas:

- David Marr’s levels of analysis: a way of thinking about cognitive models.
- John R. Anderson’s ACT-R: a unified theory of mind.

David Marr



- Born in Essex, 1945, died of leukemia, age 35.
- Worked in AI Lab and Psychology department at MIT.
- A founder of the field of cognitive neuroscience.
  - First paper (1969) proposed a theory of cerebellar function.
  - “Thirty years later, a significant proportion of researchers working on the cerebellum seem to consider this model as ‘generally correct’ ” (Edelman, 2009).
- Developed influential computational theory of vision.
  - Collected in book, *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information*, published posthumously in 1982.

Image: amazon.co.uk

Marr's *Vision*

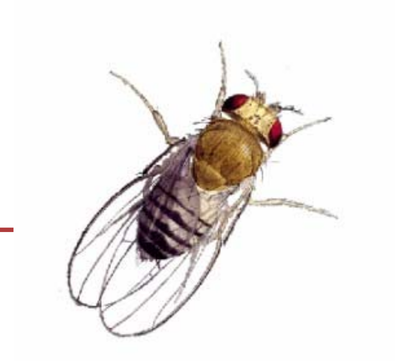
- Proposes a computational theory of vision:
  - Primal sketch, 2.5D sketch, 3D model.
- Describes three levels of analysis for studying information processing systems (dev. w/ T. Poggio):
  - **Computational theory**: what is the goal of the computation and the logical strategy needed to carry it out?
  - **Representation and algorithm**: how can the computation be implemented, and what input/output representations are needed?
  - **Hardware implementation**: what is the physical realization of the algorithm?

Levels of analysis: example

- A cash register:
  - Computational level: what does it do, and why?
    - Computes sum of inputs using theory of addition.
    - Total money owed for goods follows rules of addition.
  - Algorithmic level: what is the representation and algorithm?
    - Arabic numerals.
    - Add least significant digits first, carry remainder, etc.
    - (Unary numerals, counting?)
  - Implementation level: what is the physical realization?
    - Mechanical device, silicon chip, etc.
    - (Matchsticks?)

Image: http://www.tradebit.com/usr/manual/pub/9002/commoncashreg.jpg

Cognitive example



- A fly's visual system:
  - Computational level: what does it do, and why?

Visual input to horizontal flight control system:

$$r(\psi)\dot{\psi} + D(\psi)$$

direction of stimulus → ψ

angular velocity of stimulus → $\dot{\psi}$

  - If objects in visual field "explode", triggers landing behavior.
  - If a small patch appears (e.g., another fly), *ψ* and *ψ'* are delivered to motor system, which is designed to intercept.

Image: http://entoplp.okstate.edu/ddd/IMAGES/fruitfly.jpg

Cognitive example

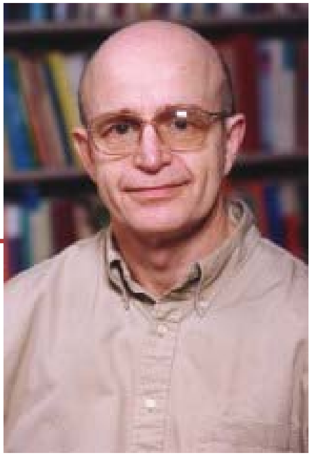
- A fly’s visual system:
  - Algorithmic level: what is the representation and algorithm?
    - Not discussed.
  - Implementation level: what is the physical realization?
    - Visual receptor cells, neurons, etc.

Image: http://entoplp.okstate.edu/ddd/IMAGES/fruitfly.jpg

To consider

- Which level of analysis do other cognitive models address?
  - Chomsky’s generative grammar
  - Associative learning models (e.g., Rescorla-Wagner)
  - Braitenburg’s *Vehicles*
  - Good old-fashioned AI (e.g., Shakey the robot)
- Can all information processing systems be analyzed in this way?
- Is it always easy to separate the three levels?

John R. Anderson



- Born 1947, Vancouver.
- Professor of psychology at CMU since 1978.
- Early pioneer of work on intelligent tutoring.
- Influential work on cognitive architectures (ACT, ACT*)
- Introduced framework for rational analysis (Anderson, 1990)
- Now works with ACT-R, a hybrid approach.

Image: http://act-r.psy.cmu.edu/people/ja/

ACT-R

- Provides “important new insights into the integration of cognition” (Anderson, 1996).
  - Unified theory of cognition realized as a production system.
  - Designed to predict human behavior by processing information and generating intelligent behavior.
  - Integrates theories of cognition, visual attention, and motor control.
  - Successfully models a variety of high-level phenomena, e.g., working memory, scientific reasoning, skill acquisition, HCI.

A unified theory of mind

- ACT-R intended to be a single model to capture all aspects of cognitive processing.
  - Good for tackling applied problems.
  - Many other models address only isolated research questions.
- Ex: learning mathematics involves
  - Understanding mathematical expressions
  - Reading (visual and language processing)
  - Problem solving
  - Reasoning and skill acquisition

Example application (Salvucci and Macuga, 2001)

What is the effect of mobile phone use on driving?

- Develop two separate ACT-R models for driving and dialing mobile phone.
- Put them together to predict effects of driving on phone use and vice versa.
  - Compared four ways of dialing.
  - Predicted that only full manual dialing has significant impact on steering abilities.
  - Predictions borne out through later experiments.

Other domains

- **Perception and attention**: visual search, eye movements, task switching, driving behavior, situational awareness.
- **Learning and memory**: list memory, implicit learning, skill acquisition, category learning, arithmetic, learning by exploration and example.
- **Problem-solving and decision-making**: use and design of artifacts, spatial reasoning, game playing, insight and scientific discovery.
- **Language processing**: parsing, analogy and metaphor, learning, sentence memory, communication and negotiation.
- **Other**: cognitive development, emotion, individual differences.

Basic theory

Cognition emerges from the interaction between very many small bits of procedural and declarative knowledge.

- Declarative knowledge: facts.
- Procedural knowledge: encodes processes and skills, represented as production rules.

Declarative knowledge

- Units of declarative knowledge are called chunks.
- Chunks encode things remembered or perceived, as well as current goals:
  - 2+2 = 4
  - Edinburgh is the capital of Scotland.
  - There is a car to my right.
  - I’m trying to get to class.

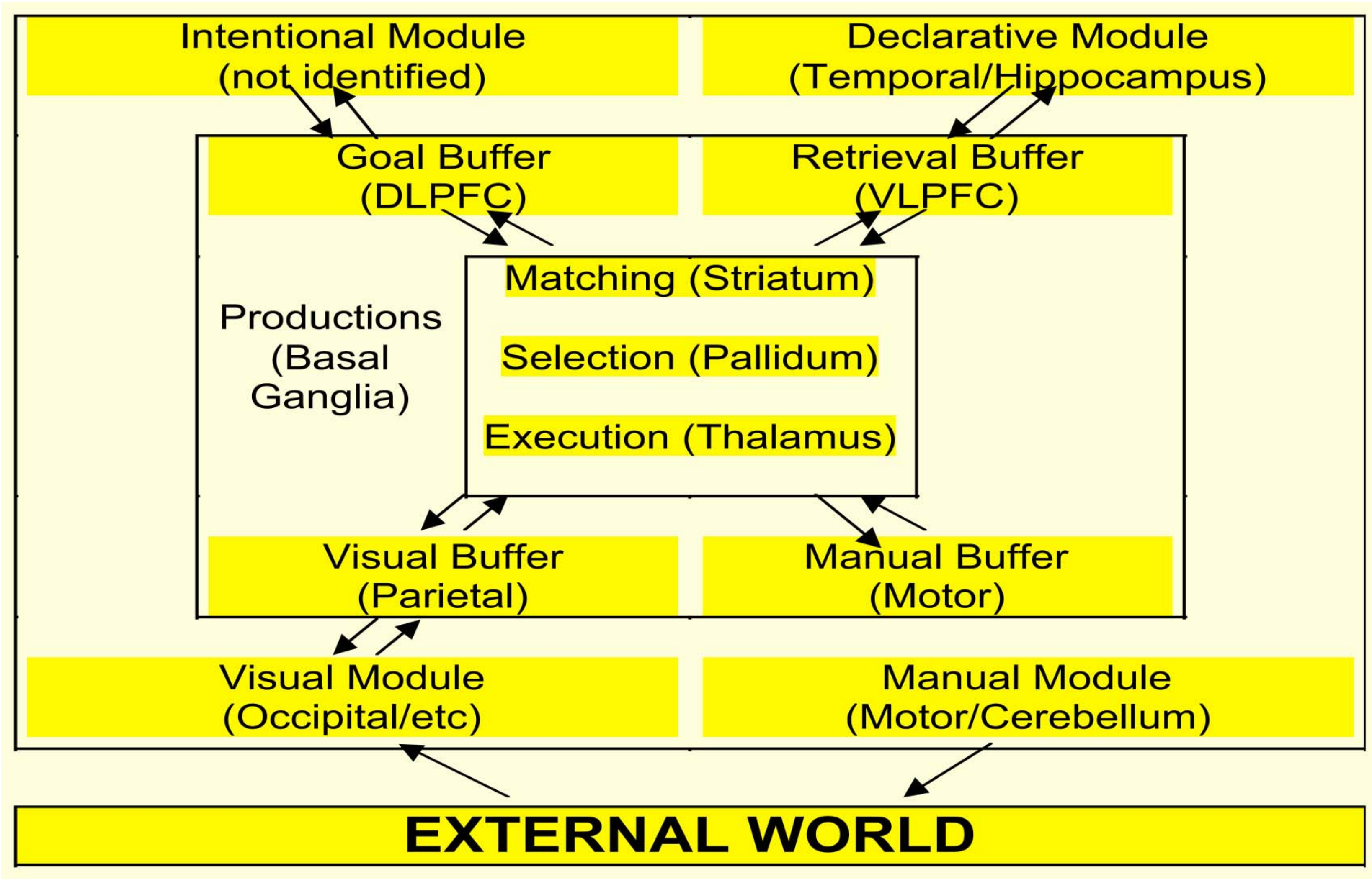
Procedural knowledge

- Encoded as production rules, consisting of conditions and actions.

IF goal is to add two digits d_1 and d_2 in a column and $d_1+d_2=d_3$
THEN set a subgoal to write d_3 in the column.

- Conditions: may depend on declarative knowledge, buffer contents, and/or sensory input.
- Actions: can change declarative knowledge, goals, or buffer contents, or initiate motor actions.

Modular organization



(Anderson et al., 2004)

Modular organization

- Modules: store and process long-term information, which is deposited in buffers.
  - Goal buffer: tracks state in solving problems.
  - Retrieval buffer: holds information retrieved from long-term declarative memory.
  - Visual buffer: tracks visual objects and their identities.
  - Manual buffer: control and sensation of hands.
- Central production system: executive control and coordination of modules.
  - Not sensitive to activity in modules, only to buffer contents.

Timing and coordination

- Within modules, processing is in parallel.
  - Ex: visual system processes entire visual field at once.
- Overall timing determined by serial processing in central production system. In one critical cycle:
  - Patterns in buffers are recognized and a production fires.
  - Buffers are updated for the next cycle.
- Assumptions:
  - Each buffer may contain only one chunk.
  - Only a single production fires each cycle.
  - Cycle takes about 50 ms (based on experimental data).

Hybrid architecture

- Behavior determined by interaction between symbolic and sub-symbolic (statistical) systems.
  - Symbolic: production system.
  - Sub-symbolic: massively parallel processes summarized by mathematical equations.
- Each symbol (production/chunk) has sub-symbolic parameters that reflect past use and determine probability of current use.

Ex: declarative memory module

- Purpose: retrieve chunks formed previously.
- Each chunk has a sub-symbolic activation level, the sum of
  - Base level activation, reflecting general usefulness in past.
  - Associative activation, reflecting relevance to current context.
- Total activation determines probability of being retrieved and speed of retrieval.

Ex: procedural memory

- Many production rules may match at once, but only one can fire.
- Each rule has a sub-symbolic utility function combining
  - The probability that the current goal will be achieved if this rule is chosen (based on past experience).
  - The relative cost (time/effort) and benefit of achieving the current goal.
- The rule with the highest utility is executed.

ACT-R summary

- Complex cognition emerges as the result of (procedural) production rules operating on (declarative) chunks.
- Independent modules encapsulate parallel processing functions, place single chunks in buffers.
- Central production system accesses buffers, detects when rule triggers are satisfied, fires one rule at a time.
- Chunks and rules are symbolic, but sub-symbolic activation levels determine which ones get used.
- Learning involves either acquiring new chunks and productions, or tuning their sub-symbolic parameters.

ACT-R features

- Can predict time-sharing between different tasks.
- Bridges short time-scale processes (retrieval, single productions) with long time-scale processes (e.g., learning to solve algebraic equations), with implications for education.
- Some evidence that modular structure corresponds to different brain regions.

Questionnaire

- Name, degree, and course/specialism.
- For MSc: undergraduate course.
- Background with machine learning, programming, probability theory, cognitive psychology.
- Are there any particular areas of interest to you, things you're hoping to learn about, or reasons for taking this course?

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