Levels of Analysis and ACT-R
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[based on slides by Sharon Goldwater & Frank Keller]
David Marr: levels of analysis
   Background
   Levels of Analysis

John R. Anderson: ACT-R
   Background
   ACT-R: a cognitive architecture

Two foundational people in cognitive modeling and their ideas:

- **David Marr** (1945–1980), who introduced the idea of different levels of analysis for information processing systems. These levels provide a framework for thinking about cognitive models.

- **John R. Anderson** (1947–), who developed the widely known cognitive architecture, ACT-R. We will compare its high-level commitments with those of Cogent, and we’ll return to a different idea of Anderson’s, rational analysis, later on.
David Marr (1945-1980)

- Worked in MIT’s AI Lab and Department of Psychology
- A founder of Cognitive Neuroscience.
  - First paper (1969) proposed theory of cerebellar function which is still relevant today (Strata, 2009).
- Developed influential computational theory of vision, treating computational results on par with neurobiological findings.
Marr suggested that the solution to a complex information processing (IP) problem often divides naturally into three parts:

- A characterization of the problem as a particular type of computation based in the physical world — i.e., an abstract formulation of what is being computed and why.
- A choice of algorithms for implementing the computation, including necessary I/O and internal representations — i.e., an abstract formulation of how the computation is carried out.
- A commitment to particular hardware in which the algorithm is implemented and physically realized — i.e., a concrete formulation of how the computation is carried out.

Problems that decompose this way have, in Marr’s terms, a Type 1 theory.
Non-cognitive example: Cash Register

Figure: http://www.springdaleark.org/shiloh/image_archive/cash_register.jpg
Non-cognitive example: Cash Register

- **Computational level**: what does it do, and why?
  - Computes sum of inputs using theory of addition;
  - Need correct total of money owed for goods.

- **Algorithmic level**: what is the representation and algorithm?
  - Arabic numerals
  - Add least significant digits first, carry remainder to more significant digit, add, carry, etc.

- **Implementation level**: what is the physical realization?
  - 1880’s: Mechanical device using a crank and rotary wheels
  - Later: Electromechanical, electricity replacing manually-operated crank
  - Modern adding machine: Electronic
Cognitive Example: Bats hunting for prey

Figure: http://askabiologist.asu.edu/sites/default/files/echolocation.jpg
Cognitive Example: Bats hunting for prey

Bats use **echolocation** to find food (insects, fruit, nectar).

- **Computational level:** what does it do, and why?
  - Computes distance, motion, and location of objects. (Could be more specific using mathematical equations).
  - Bats hunt at night, so can’t rely on vision.

- **Algorithmic level:** what is the representation and algorithm?
  - I/O: delay and Doppler shift between bat calls and returning echo.
  - Algorithm for object recognition?? Active area of research; robots use Kalman filters, artificial neural networks, etc.

- **Implementation level:** what is the physical realization?
  - Bats: neural mechanisms
  - Other: silicon chips; mechanical device??
But...

Biological-based IP problems (such as those posed by cognition) need not have a decomposable (Type 1) theory. Instead, when a problem is solved by the simultaneous interaction of multiple processes, the interaction may be its own simplest description. Marr refers to this as a Type 2 theory.

www.math.uwaterloo.ca/AM_Dept/prospective/media/p_fold.jpg
Even an Information Processing problem which has a Type 1 theory may be tied to an IP problem where only a Type 2 suffices.  

**Example:** Language processing may be Type 1 for grammar but Type 2 for word meaning.  

Main challenge: determine which problems have Type 1 theories, in part by trying to discover computational-level descriptions of them.  

- Marr argues that computational level yields greater insight.  
- Some researchers disagree, preferring to work at algorithmic level (either because models are more satisfying, or more practical).
John R Anderson (1947–)

- Professor of Psychology at CMU since 1978
- Early pioneer of work on intelligent tutoring
- Influential work on Cognitive Architectures – *Adaptive Control of Thought* (ACT, ACT*)
- Introduced framework for rational analysis (Anderson, 1990)
- Incorporated into ACT-R (*Adaptive Control of Thought – Rational*), a hybrid Cognitive Architecture in widespread use.
ACT-R Overview

- Unified theory of cognition realized as a production system (a type of cognitive architecture model; similar to Cogent).
- Intended as single model to capture all aspects of cognitive processing.
- Originally implemented in LISP; a Python reimplementation available here: https://sites.google.com/site/site/pythonactr/
- Example: Learning mathematics involves
  - Reading (both visual processing and language processing)
  - Understanding mathematical expressions
  - Problem solving
  - Reasoning and skill acquisition
- All would be modelled in ACT-R.
Want to predict effects of dialing mobile phone while driving.

- Develop two separate ACT-R models for driving and dialing mobile phone.
- Put them together to predict effects of driving on phone dialling 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.

N.B. Real distraction is talking on mobile phone!
Other domains

Hundreds of papers on ACT-R site (http://act-r.psy.cmu.edu/):

- 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, individual differences
Cognition emerges from the interaction between very many small bits of two different types of knowledge (procedural and declarative), stored in corresponding parts of memory.

- **Declarative knowledge**: facts, things remembered or perceived, goals; represented in ACT-R as chunks (really: feature structures / AVMs)
  - $2+2 = 4$
  - Edinburgh is the capital of Scotland.
  - There is a car to my right.
  - I’m trying to get to class.

- **Procedural knowledge**: processes and skills (represented in ACT-R as production rules)
Procedural Knowledge

- Production rule consists of conditions and actions:
  \[ \text{IF goal is to add two digits } d_1 \text{ and } d_2 \text{ in a column and } d_1 + d_2 = d_3 \]
  \[ \text{THEN set a subgoal to write } d_3 \text{ in the column} \]

- In ACT-R, 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 then 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.
- Inclusion of sub-symbolic activation levels is a major difference to Cogent.
Example 1: 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.
Example 2: 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.