Computational Scientific Discovery and Cognitive Science Theories

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KNEW 2014, Kazimierz Dolny, Poland

Summary

- Consider scientific discovery as a heuristic search process
- Represent process-based scientific theories as computer programs
- Apply an evolutionary computational method for evolving computer programs, so as to evolutionarily generate scientific theories
- ‘Fitness’ of a theory depends on fit to data (and may also depend on parsimony)
- The method is applied to generating theories in cognitive science
- Results support the idea that heuristic search using evolutionary computation can generate process-based theories involving several steps

Philosophy of science considerations

- Philosophers of science have taken a strong interest in how existing ideas are assessed, tested and interpreted

- This has included
  - criteria for rejecting (or accepting the falsification of) scientific theories, e.g. Popper 1961, Lakatos 1970
  - the implications of scientific uncertainty for public policy (e.g. Frigg et al. 2013)

- The question of how new theories are generated has received less attention

- But Simon (1973) suggested that normative, logical processes can be applied to some aspects of scientific discovery, e.g. discovery of laws

Scientific discovery

- Science is concerned with explaining observations and phenomena (“data”) by means of underlying principles and processes

- Logical coherence of explanations is necessary; parsimony is desirable

- Such explanations enable a human understanding, in a way which
  - may encompass mental models
  - allows commonalities between phenomena to be established
  - ideally, facilitates predictions

- It is useful to make a distinction between *observational laws* and *theoretical laws* (Holland, Holyoak, Nisbet, Thagard 1986), though the distinction is not absolute (Langley, Simon, Bradshaw, Zytkow 1987)

Scientific discovery as a search process

- When theories are generated, an important consideration is selection of the best theories (e.g. Simonton 1999)
- Langley et al. (1987) consider scientific discovery as selective search
- Naïve participants, given the relevant data, can replicate the discovery of scientific laws (Langley et al. 1987)
- Computer programs using heuristic search methods can replicate some aspects of scientific discovery, such as the discovery of laws
- The search for patterns in data in order to find regularities and laws is akin to dimension reduction methods in data analysis

Some automated discovery systems

- DENDRAL, dating back to the 1960s, was developed to find chemical structures from mass spectrometry data
- The BACON research programme was concerned more generally with the discovery of laws, e.g. Kepler's third law; Boyle's law
- Later versions of BACON went beyond direct data description methods by generating variables representing intrinsic properties of variables such as the refractive index
- King et al (2009) have described the operation of a robot scientist, which collects and analyses data, and generates hypotheses
- None of these methods have the capacity to develop complex theories involving a sequence of processes

Theories in behavioural and cognitive science

- There may be more than one level of explanation for a given phenomenon
- Humans and other animals are purposeful
- This can lead at its simplest to two levels of explanation for a given behaviour
  - in terms of the strategic objectives of the person or animal
  - in terms of underlying processes, cognitive or neural, and how specific functions and mechanisms lead to behaviour
- An example of the second approach is the application of information processing models to cognition
- Our research programme is a development of this approach

A note about models

- A model can be regarded as a *representation* of a real system, to allow “what if” questions to be answered

- A quantitative model can be regarded as an instantiation of a theory

- Models usually involve a deliberate simplification of reality (Weisberg 2007)
  - to make the model computationally tractable
  - to restrict consideration to factors which are causally relevant to the phenomenon being investigated

- The term “fictional model” can be applied to models in which some aspect of physical reality is discarded for explanatory convenience

- The models we are considering could be regarded as fictional

Understanding models of cognition

- Can (or should) models of cognition be regarded as mechanistic?
- The functional view (e.g. Barrett 2014) models cognition as arising from high-level processes known as functions
- A mechanistic view (e.g.) regards functions as being built up from low-level mechanistic processes
- We consider cognitive processes as arising from a mechanistic sequence of functions

A computational system for theory discovery in cognitive science

- The approach combines two ideas
  - First, a scientific theory can be represented as a computer program (e.g. Langley et al. 1987)
  - Second, an evolutionary computation method, genetic programming, allows programs to be improved through a computational trial-and-error process
- Putting the two together leads to a system that can automatically generate and improve scientific theories

Representing theories as computer programs

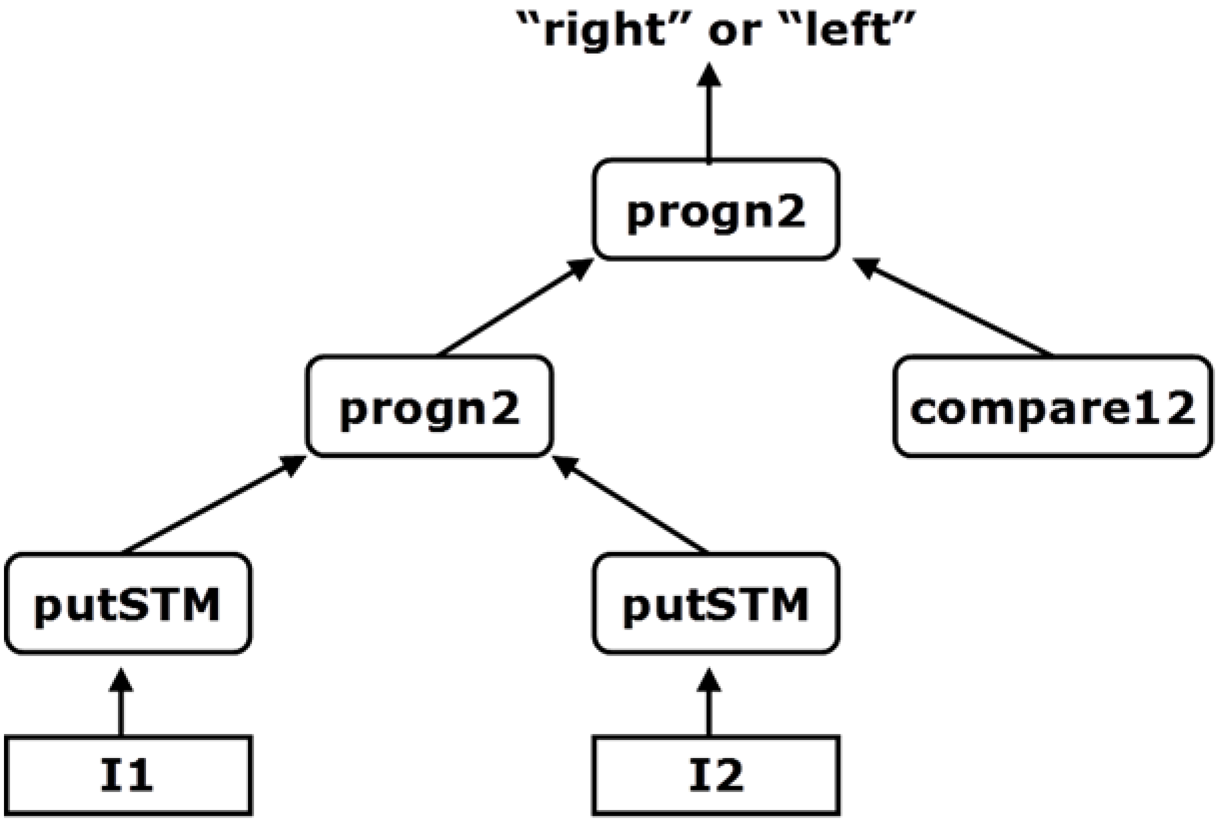
- A program is composed of a set of primitive operators, representing operations such as
  - putting items into short-term memory
  - retrieving items from short-term memory
  - comparing items

- It is represented as a tree: each node holds an operator

- The set of operators is contained in a theory representation language

- Each operator has an associated error rate

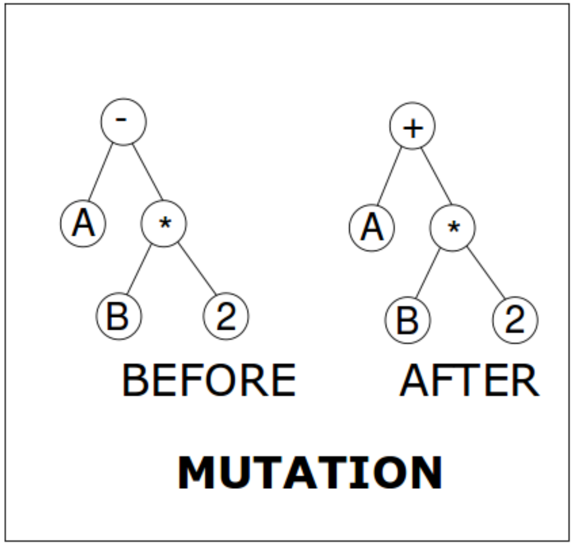
What a cognitive science theory looks like

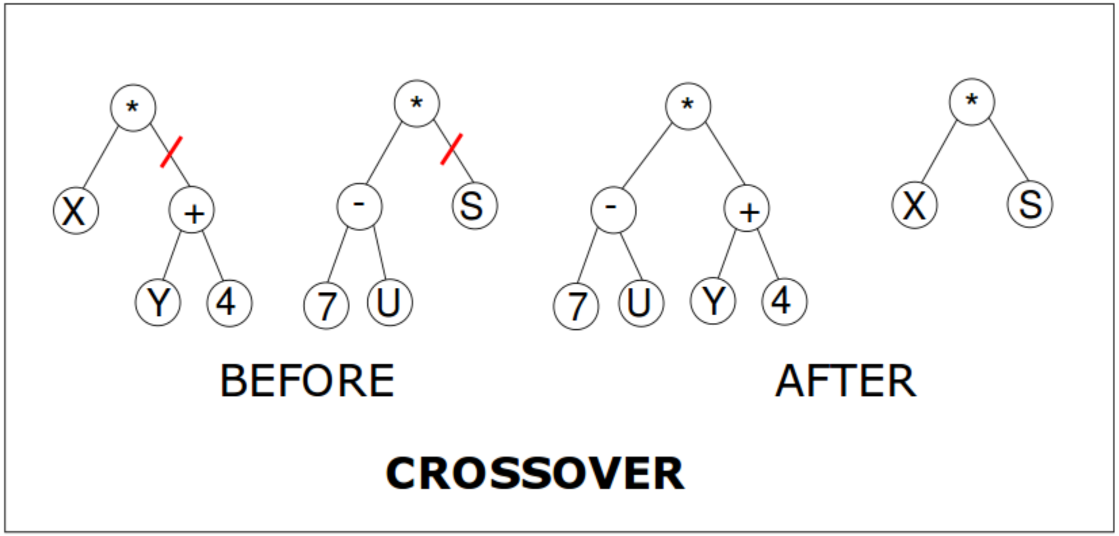


How theories are treated

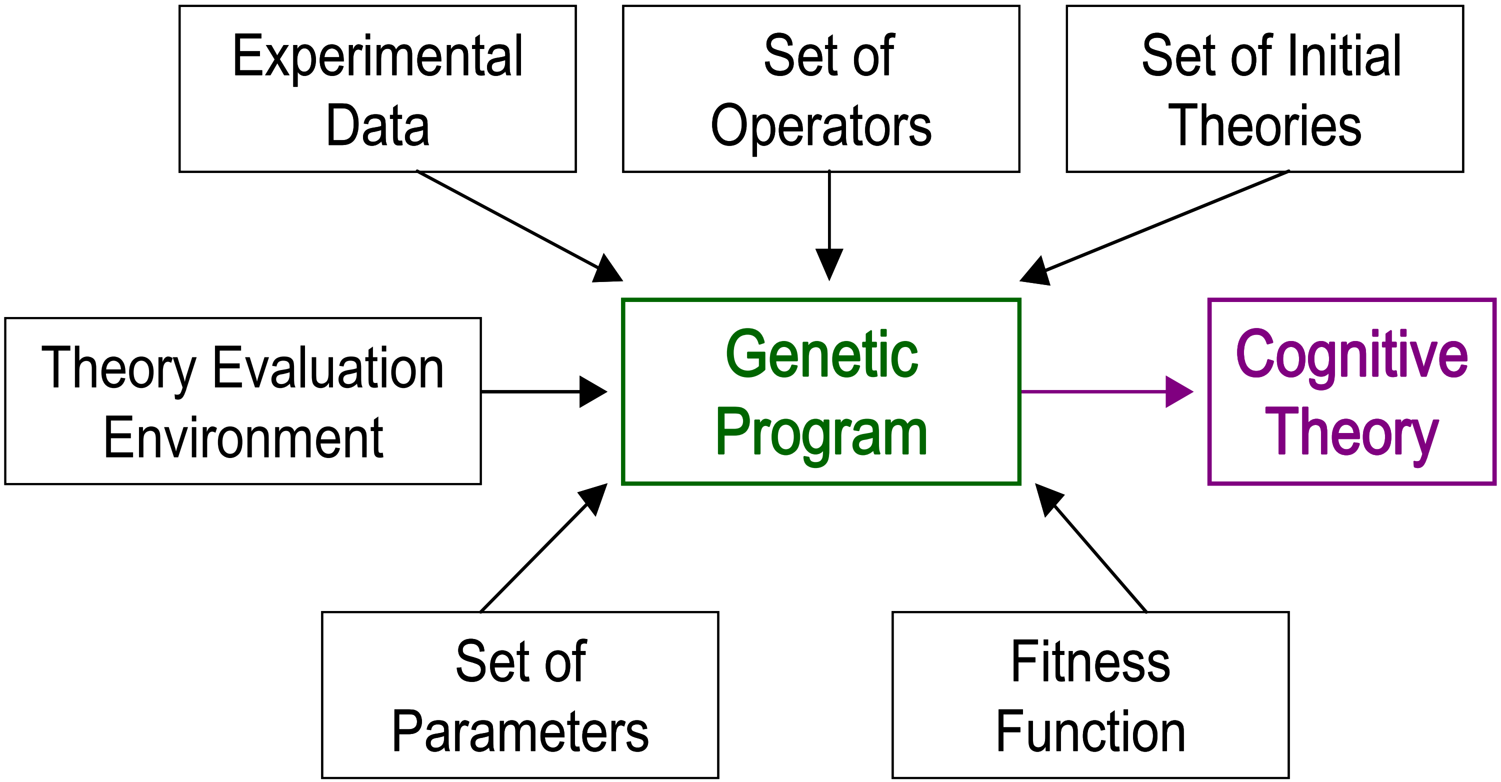
- Simulation of computer program representing a theory yields predictions about how subjects will behave
- A theory which yields predictions closer to the experimental data is a better theory
- It is also possible to apply a penalty for program size so that more parsimonious theories are preferred
- For a theory, we can compute its fitness
- Apply genetic programming to evolve fitter programs (theories) by an evolutionary trial and error process

Genetic programming: modifiers

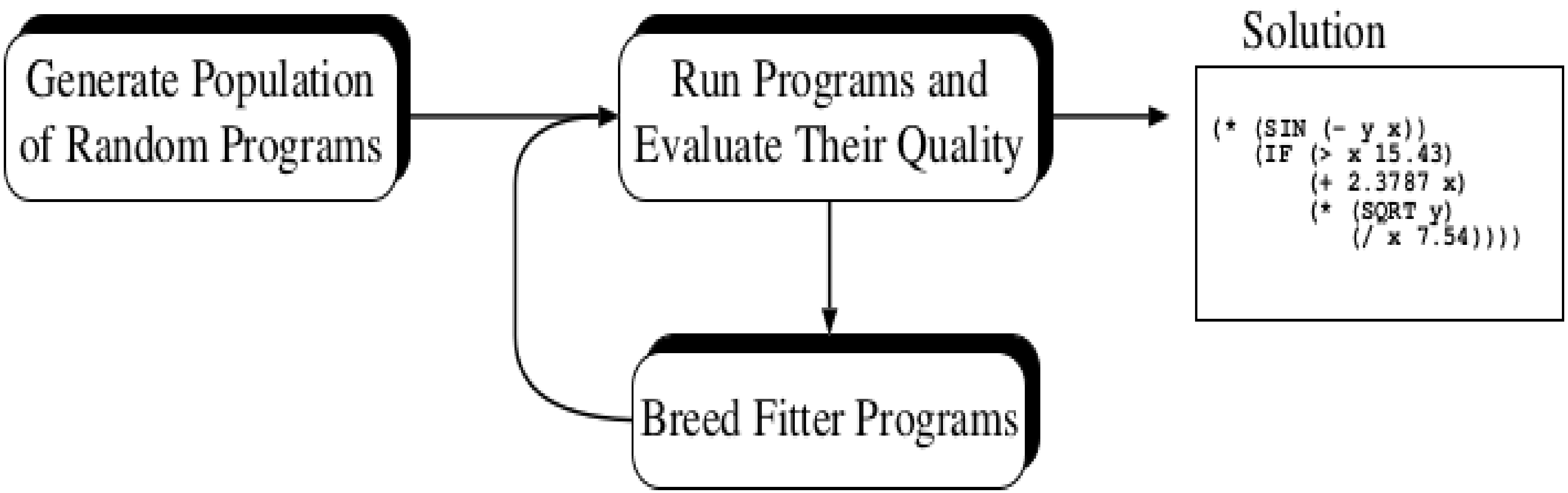




Theory Discovery System



Search process: genetic programming

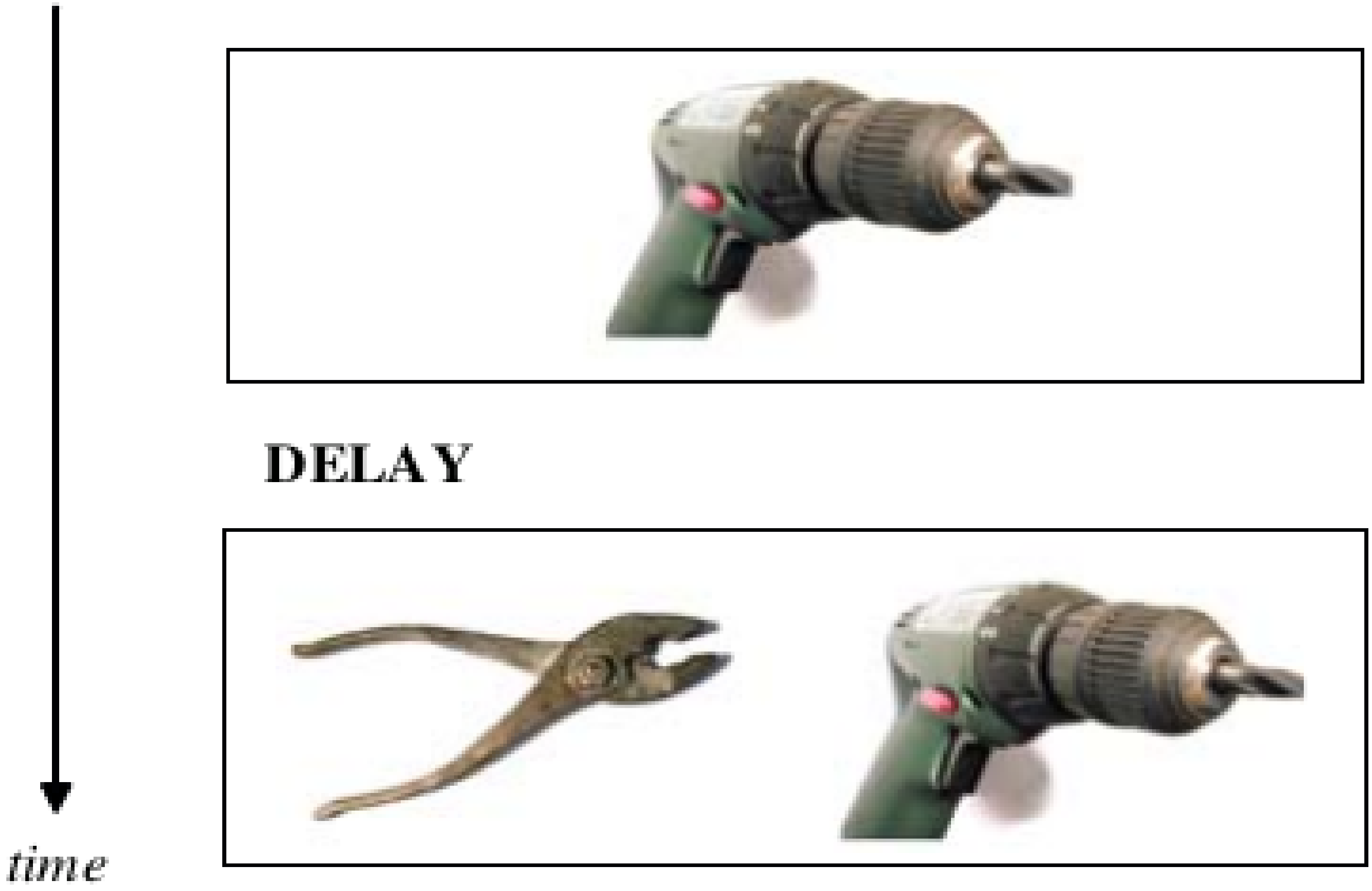


From Poli et al (2008), Field Guide to Genetic Programming

Example: delayed-match-to-sample

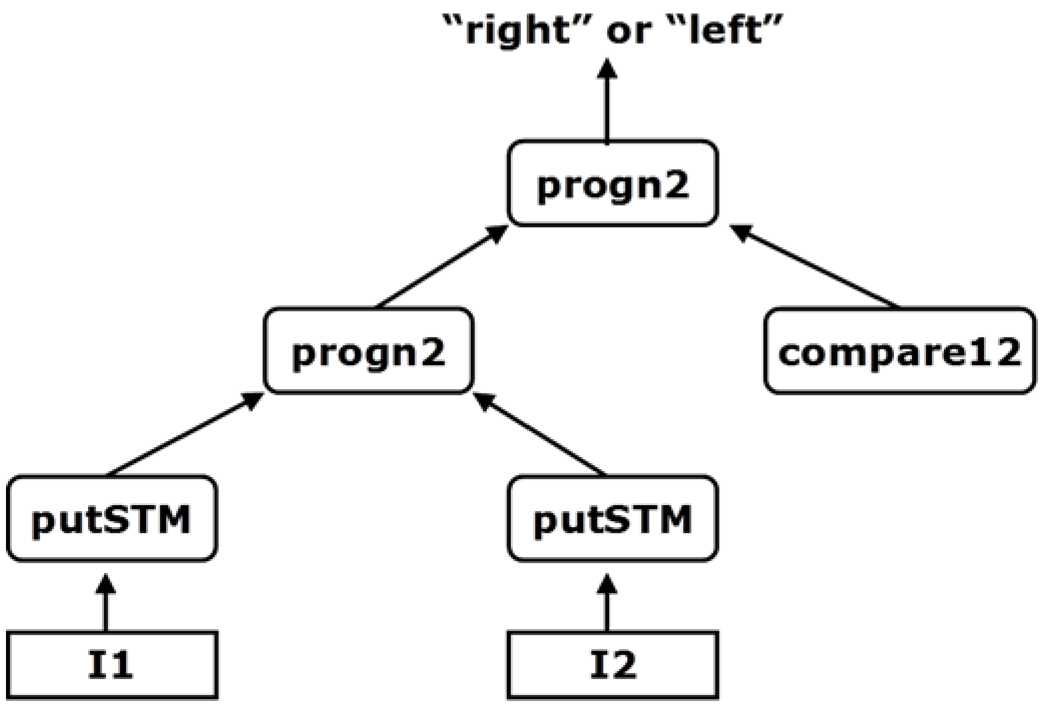
- A subject is shown an image. Then, after a delay, two new images, one of which is the same as the one originally shown
- Subject must identify which of the new images matches the original one
- Outcome variables: accuracy and response time
- For images of tools, subjects achieved a mean accuracy of 95%, with a mean response time of 767ms (Chao et al. 1999)

Psychological Task: DMTS



From Frias-Martinez and Gobet, 2007 – images from www.freeimages.co.uk

Delayed match-to-sample: theory



- From Frias-Martinez & Gobet (1987), matching only accuracy

Delayed match-to-sample: operators

Operator	Description
Progn2	Function: executes two inputs sequentially Input: Input1, Input2 Output: the output produced by Input2
PutSTM	Function: writes the input into STM Input: Input1 Output: the element written in STM (Input 1)
Compare12	Function: compares positions 1 and 2 of STM and returns NIL if they are not equal or the element if they are equal Input: none Output: NIL or the element being compared

Delayed-match-to-sample: further work

- Lane, Sozou, Addis and Gobet (presented at AISB, 2014) considered getting a good fit to data for both accuracy and reaction time
- Each operator has an associated execution time: they are added to obtain response time
- Best theories differ from experimental data by less than 0.2% in accuracy and less than 0.025ms in reaction time
- In this example, theory discovery process successful at locating theories which fit target data

Conclusion

- The theories generated by this theory discovery process have certain characteristics:
  - they involve clearly defined processes, and are explanatory
  - they can be tested (they have been tested on the experimental data)
  - they make clear predictions
  - as they involve simple processes, they can be easily understood by humans
  - they are flexible and can easily be modified by a human theorist
  - if parsimony is desired, this can be incorporated into the fitness function

- They compare in complexity with theories published in psychology and neuroscience journals

Conclusion (cont)

- The main conclusion is that heuristic search using evolutionary computation as a search tool can generate process-based theories involving a sequence of steps
- This does not eliminate need for human input:
  - reasonable prior assumptions about operators must be made
  - the human scientist is important for interpretation and providing context
- Therefore, the human scientist is not about to be made redundant