Psychology 354
Multiple Levels Of Investigation

Logicism
Mechanizing Thought
Four Levels Of Investigation

18th Century Animism

- The Renaissance was an age of animism; people were fascinated and the Church was challenged by clockwork automata
- If machines were life-like, might man too be a kind of machine?
- In 1727, androids of Vaucanson's that served dinner and cleared tables were deemed profane, and his workshop was ordered destroyed
- Pierre Jaquet-Droz was imprisoned by the Spanish Inquisition -- along with his writing automaton!
- "The Renaissance conception of an animistic universe, operated by magic, prepared the way for a conception of a mechanical universe, operated by mathematics" (Yates, 1966, p. 224)


Vaucanson's duck


Frances Yates

Man As Machine

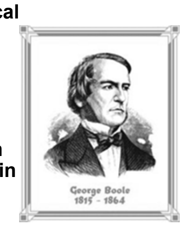
- "For seeing life is but a motion of limbs, the beginning whereof is in some principal part within; why may we not say, that all Automata (Engines that move themselves by means of springs and wheeles as doth a watch) have an artificial life? For what is the Heart, but a Spring; and the Nerves, but so many Springs; and the Joynts, but so many Wheeles, giving motion to the whole Body, such as was intended by the Artificer?" (p. 3).
- Descartes claimed that man was a machine with a soul


Thomas Hobbes


Rene Descartes

Logicism

- A first step towards the mechanization of thought was the view that thinking was identical to mathematical or logical manipulations
- A key 19th century proponent of such logicism was George Boole, who invented modern mathematical logic
- "There is not only a close analogy between the operations of the mind in general reasoning and its operations in the particular science of Algebra, but there is to a considerable extent an exact agreement in the laws by which the two classes of operations are conducted" (Boole, 1854/2003, p. 6).



The Laws Of Thought

- Boole did not invent binary logic, he instead developed an algebra of sets
- X, Y, Z are classes of entities
- 1 is universal set, 0 is empty set
- Operations 'elect' subsets of entities
- X + Y is exclusive or of X, Y
- XY is the intersection of X, Y
- Fundamental law of thought: XX = X
- Purely formal manipulations:
  - $x^2 = x$
  - $0 = x - x^2 = x(1-x)$
  - Intersection of a set with its negation is the empty set

Mechanical Logic

- Jevons revised Boole's logic to define addition as 'or', instead of 'exclusive or'
- It was at this time that logic seemed to be precise enough to be implemented by a machine
- Many different mechanical devices for performing logic began to appear in the late 19th century


William Stanley Jevons

Early Logic Machines

- The development of logic machines then led to the development of a two-valued logic
- In this logic, propositions could either be true or false
- Charles Sanders Peirce and his students (such as Christine Ladd) developed binary arithmetic, two-valued logic, and machines for performing such operations


Marquand Logic Machine


Jevons Logic Piano


Charles Sanders Peirce


Christine Ladd

Truth Tables

- By the 1920s, the two-valued logic had led to the invention and the wide use of truth tables
- These tables represent what we would now call Boolean logic, and launched modern computing science

p	q	$p \cdot q$	$p + q$	$p \cdot (p + q)$
1	1	1	1	1
1	0	0	1	0
0	1	0	1	0
0	0	0	0	0

Table 2-1. Examples of the truth-value system for two elementary propositions and some of their combinations. The possible values of *p* and *q* are given in the first two columns. The resulting values of different functions of these propositions are provided in the remaining columns.

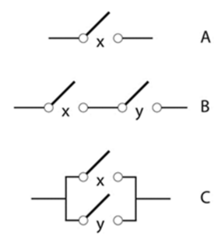
From Formal To Physical

- Claude Elwood Shannon was trained in both electrical engineering and philosophy
- He recognized a equivalence between two-valued logic and electrical switches in the most important masters thesis ever, published in 1938
- This permitted Boolean algebra to be used to design complex electric circuits


Claude Elwood Shannon

Shannon's Logic

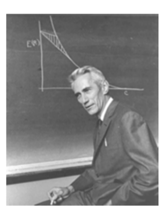
- Shannon viewed as switch as being either true or false
- Two switches in serial defined AND, and in parallel defined OR
- "It's not so much that a thing is 'open' or 'closed,' the 'yes' or 'no' that you mentioned. The real point is that two things in series are described by the word 'and' in logic, so you would say this 'and' this, while two things in parallel are described by the word 'or'" (Liversidge, 1993).



A) A switch. B) Two switches in serial. C) Two switches in parallel

Two Levels

- Shannon's insight shows that an electrical circuit can be described at two completely different levels, physical and logical
- One did not have to design a complex circuit by hand
- Instead, one could create it mathematically, and then convert the equations into a working electrical system
- Amazingly, Charles Sander Peirce had the same realization, in 1866!


Claude Shannon

Simple To Complex

- Logical operations can be combined into complex expressions
- Therefore a small set of primitive operations can be used to build more complex logic circuits, like Shannon's (1938) combination lock

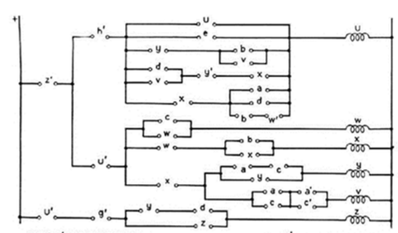


Figure 34. Combination-lock circuit

Many To One

- Many different circuits can be created to perform the same function
- There is a "many-to-one" relation between circuits and a particular input-output function
- Shannon (1938) showed how Boole's logic could be used to take a complex circuit and convert it into a much simpler circuit that would perform the same task

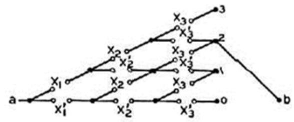


Figure 23. Circuit for realizing $S_3(X_1, X_2, X_3)$

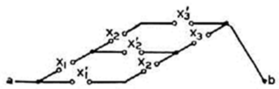


Figure 24. Simplification of figure 23

A Third Level

- The many to one relationship between circuits and functions illustrates a third level of inquiry, called the algorithmic level
- What sequence of steps – what particular circuit – is being used to compute a particular function?
- What algorithm is being used to generate an input-output relation?
- Marr (1982) called this the algorithmic level of analysis

David Marr

Universal Building Blocks

- An algorithm is built on a foundation of primitive operations
- One can use a small set of primitive logical operations to define other logical operations
- The operators NOT, AND and OR are universal building blocks
- These three building blocks can be used to create circuits for performing any of the other 16 logical operations in Boole's algebra
- "This idea of a universal set of blocks is important: it means that the set is general enough to build anything" (Hillis, 1998, p. 22)

Daniel Hillis

The Architecture

- A set of primitive building blocks is called an architecture, after Brooks (1962)
- Pylyshyn (1984, p. 30) defined the architecture as "the basic operations for storing and retrieving symbols, comparing them, treating them differently as a function of how they are stored (hence, as a function of whether they represent beliefs or goals), and so on, as well as such basic resources and constraints of the system, as a limited memory. It also includes what computer scientists refer to as the 'control structure', which selects which rules to apply at various times" (p. 30).

Frederick P. Brooks

Zenon Pylyshyn

Three Levels So Far

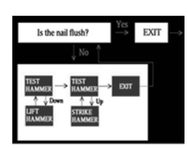
We have already seen that one information processing system can be described in many different ways

- What information processing problem is it solving?
- What steps are being used to solve this problem?
- What architecture is used?

Functional Analysis

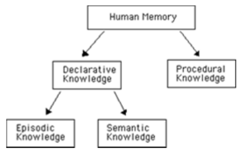
- Method for understanding complex systems, and the most typical approach adopted by cognitive psychologists
- Take a complicated system and decompose it into an organized system of simpler subsystems
- The decomposition is supported by experimental evidence
- TOTE units from Miller, Galanter & Pribram's (1960) *Plans and the structure of behavior*

Eugene Galanter



Psychological Example

- Much of cognitive psychology's work on human memory can be viewed as being an example of functional analysis
  - Memory
  - Primary memory, Secondary memory
  - Working memory, Semantic memory, Episodic memory, Sensory memory
  - Central executive, visuospatial scratchpad, rehearsal buffer



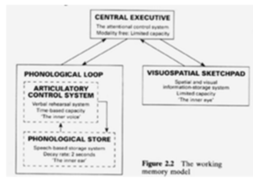
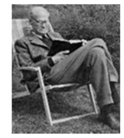


Figure 2.2 The working memory model

Ryle's Regress

- Functional analysis is a fundamental tool in cognitive science
- Functional analysis is also the Cognitivist's Achilles heel
- In doing functional analysis, we take one functional term and decompose it into a set of other functional terms
- Philosopher Gilbert Ryle argued that this approach was doomed to fail, because it leads to an infinite proliferation of unexplained terms.
- This is known as "Ryle's regress", or sometimes as "the homunculus problem


Gilbert Ryle
1900-1976


Dawson's mental imagery system trapped in the homunculus problem

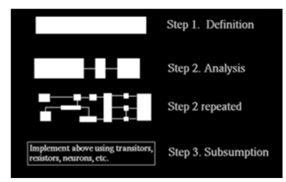
Escaping Ryle's Regress

- How does a cognitive scientist, committed to functional analysis, extract himself or herself from Ryle's infinite regress?
- *There must be some level of analysis which does not permit any further decomposition into mental state terms!*
- Philosopher Robert Cummins has provided a detailed account of functional analysis which aims to escape Ryle's regress
  - Define the function
  - Analyze the function
  - Subsume the function


Robert Cummins

Cummins' Program

- Define the function being computed by the system
- Decompose this function into a system of subfunctions. Repeat as necessary to the subfunctions.
- Stop the decomposition when the subfunctions are so simple that they can be carried out by simple machines
- These functions define the architecture!

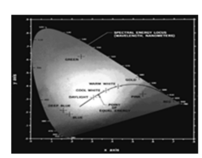


Functional Architecture

- When subfunctions are subsumed, they are said to be primitive
- They cannot be decomposed (functionally) any further
- These primitive subfunctions define a "mental programming language"
- This is called the functional architecture of cognition
  - The special level at which functional decomposition stops
  - The set of primitive processing operations
  - The biologically fixed part of cognition
  - The bridge between algorithm and implementation
  - The set of functions for which behaviorism is true

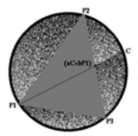
An Example

- One example of a successfully subsumed functional analysis in psychology comes from the study of color perception



Maxwell's Proof

- Maxwell used Newton's barocentric circle to prove that any color could be expressed as the sum of three other colors
- This was a computational analysis of color vision

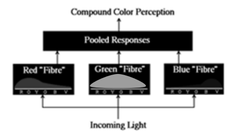


Maxwell's proof

James Clerk Maxwell (1831-1879)

Trichromatic Theory

- Helmholtz used the results of psychophysical experiments to come up with an algorithm for color vision
- This trichromatic theory was predictive, but was functional, not physical
  - "It must be confessed that both in men and in quadrupeds we have at present no anatomical basis for this theory of colors" (1873)

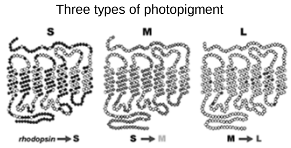


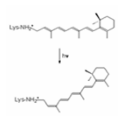
Hermann von Helmholtz (1821-1894)

Subsumption

- The trichromatic theory was not subsumed until the 1960s
- Retinal pigments were isolated at this time, with different pigments corresponding to the different "fibres"
- Photons caused the pigments to change shape, resulting in the transduction of color signals

Three types of photopigment





Photons cause pigments to change shape

Intelligent Machines Are Possible

- We will explore in this course the general assumptions used in cognitive science
- They lead researchers to accept the inevitability of machine intelligence
- "To be consistent with the assumptions already made, we must suppose (and the author accepts) that a real solution of our problem will enable an artificial system to be made that will be able, like the living brain, to develop adaptation in its behavior" (Ashby, 1960, p.10).
- These assumptions developed as a progression of important 20th century ideas – let us briefly look at this history:

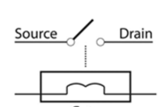
W. Ross Ashby

Multiple Realization

- Why is Cummins' kind of analysis 'functional'?
- Because it decomposes systems in terms of what its components do, and not in terms of what they are made of
- Why?
- Because different physical systems can be used to create the same function
- For example, the function 'switch' can be implemented by a relay, by a vacuum tube, or by a transistor

A Fourth Level

- Multiple realization means that there is a fourth level of an information processing system to investigate
- What physical mechanisms or principles are used to bring a particular function in the architecture to life?
- It also means that one can use computer simulation – silicon hardware can implement the same architecture as can the brain
- "For most purposes, we can forget about technology [physical realization]. This is wonderful, because it means that almost everything that we say about computers will be true even when transistors and silicon chips become obsolete" (Hillis, 1998, p. 19)



Four Questions To Answer

Clearly, explaining information processors requires us to answer four different kinds of questions; there are four levels of investigation:

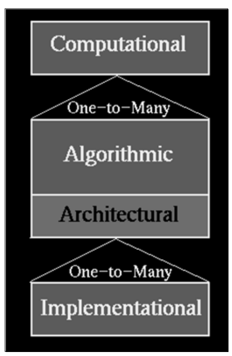
- What information processing problem is being solved? (Computational Level)
- What steps are being carried out to solve this problem? (Algorithmic Level)
- What architecture is being used as the basis of the algorithm? (Architectural Level)
- What physical properties are actually used to instantiate the architecture? (Implementational Level)

Implications

- Marr made a theoretical argument for the need to perform computational, algorithmic, and implementational analyses
- Marr gained further support for his tri-level hypothesis by collecting hard evidence relating the three levels for a number of different phenomena

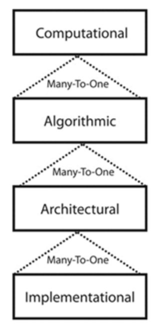
Dawson's Tri-Level Hypothesis

- Dawson (1998) used Marr's tri-level hypothesis as the theoretical glue to hold cognitive science together
- In his formulation, the architecture belonged to the algorithmic level, and served as a bridge to the implementational



Multiple Levels Of Investigation

- We are going to modernize Dawson's (1998) approach by recognizing that the architecture is a distinct level, although it is obviously related to the implementational level below and the algorithmic level above



Many Disciplines Required!

- Cognitive science must explore all four levels of investigation, and must find links between them
- Each level has its own vocabulary and its own methodology
- Few researchers would be trained in all of the required methods
- As a result, cognitive science is interdisciplinary, and requires researchers from many different disciplines to collaborate on common problems!

Theme of Course

- The main theme of this course is that the four multiple levels of investigation provide the unifying structure for cognitive science, as well as a means for understanding the methods used in this discipline.
- Even though we will explore three different schools of thought within cognitive science, the differences between them can be managed within the theoretical perspective that we have sketched out this week