THE STUFF OF LONG TERM MEMORY: Concepts & Categories

- Concepts and Categories: Early Research
- Concepts and Categories: Modern Agenda
- Concepts and Categories, Connectionist Models and Neuroimaging
Concept & Categories I: Classical view –2000 years ago!

ARISTOTLE’S VIEW (384-322 B.C.)

Book 1, Chapter 31: "CATEGORIES"

These dimensions are jointly exhaustive and mutually exclusive:

(1) Substance (or being)
(2) Quantity
(3) Qualification
(4) Relation
(5) Where
(6) When
(7) Being in a position
(8) Having
(9) Doing
(10) Being Affected

There are necessary & sufficient values for category inclusion. This is referred to hereafter as the "Classical View" or "Aristotelian View"
Why Categorize?

Classification: A concept can be defined as mental representation that includes information about critical properties or features of a class of collection of objects: This allows us to stay in contact with world or defines our reality. Concrete vs Abstract... Hospital (appendicitus) vs Truth (politics)
Concepts & Categories

- Why Categorize?
- Explanation: Categorization allows organization of old information to understand and explain new information. The world would mostly be incoherent without such context. People get up and leave a restaurant...without prior concepts for restaurant, eating out, paying for food etc.. the event has no explanation. Is this somehow similar to the end of the class—will the instructors be paid?!
Concepts & Categories

- Why Categorize?
- Prediction: Categories allows us to generalize from past experience. We can predict in restaurant that we will get a menu, order food and then pay. Violations of these predictions in another episode will require updating of the concept information in order to improve future predictions.
Concepts & Categories

- Why Categorize?
- Reasoning: Abstraction from a category supports deduction. From the knowledge that cats are animals and they breathe air, one can infer (before meeting it) that the Komodo Dragon in Indonesia also breathes. One can abstract and infer from categories based on the scope or coverage of the category over its members.
Concepts & Categories

• Why Categorize?
• Communication: To the extent that people share knowledge about the world, it is most efficient to communicate through categories. Hence learning about dangerous situations: “Road ahead has steep curves”, indicates to the extent that we have a concept of steep curves and the difficulties involved in driving on them—that there is danger ahead and care must be taken.
Concepts & Categories: I

• Representation is fundamental to human knowledge representation more generally: How do we represent or learn common categories ("cat", "square", "chair", "color"..)

• Historically there are roughly THREE periods of Categorization Research:
  – I  Classical Period/boolean n&s: 1950s-1970s
  – III Rococo Period: DOMAIN KNOWLEDGE /Exemplar-based theories 1980s-Present
Concepts & Categories

Some Definitions

- Some Definitions:
- Concept -intension of a category—representation
- Category-extension of a concept—actual members and measures
- Variables—properties or dimensions of a category
- Features—properties of a concept
- Exemplars—individual members of a category
- Samples—collections of exemplars
- Rules—booleans that describe the category
- Supervised Learning, Feedback
- Unsupervised Learning: Identification task or Sorting Task
CUPS?
Cats?
Generalization Error?

- The Universe: Cats
The Generalization problem is so hard, it is known:
(1) in unsupervised learning, there are two many possible consistent hypotheses with any particular sample
(2^N-1; 20 exemplars= 1M possible categories)
(2) some BIAS is required for learning some assumptions about features, potential concepts or distribution of exemplars.
(3) the AMOUNT of BIAS per Concept is UNKNOWN
The Classical Period

• The Classical View assumes that concepts have defining features that act as criteria for category membership:

• E.G., A triangle is a closed geometric form with three sides with the sum of the interior angles equal to 180 degrees.

• A bird is an animal with feathers, that flys, breaths air and lays eggs.

• These properties are seen to be necessary and sufficient for category membership which is also an EQUIVALENCE CLASS.
Rules Define Categories

\[ \psi_{\text{circle}}(X) = \begin{cases} 1 & \text{if the figure } X \text{ is a circle;} \\ 0 & \text{if the figure is not a circle;} \end{cases} \]

\[ \psi_{\text{convex}}(X) = \begin{cases} 1 & \text{if } X \text{ is a convex figure;} \\ 0 & \text{if } X \text{ is not a convex figure;} \end{cases} \]

\[ \psi_{\text{connected}}(X) = \begin{cases} 1 & \text{if } X \text{ is a connected figure;} \\ 0 & \text{otherwise.} \end{cases} \]
Early Concept Learning: Hull 1920

- Core Concepts, associative learning

<table>
<thead>
<tr>
<th>Name</th>
<th>Concept</th>
<th>Pack I</th>
<th>Pack II</th>
<th>Pack III</th>
<th>Pack IV</th>
<th>Pack V</th>
<th>Pack VI</th>
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Concepts & Categories

Hull's Observations

- Behaviorist view of Concepts: reinforcement for concept inclusion.
- No reference to Mental representation.
- Hull focused on creating efficient learning by showing how more complex ideograms that were composed from simpler (he would highlight the common syllable and the fade it out and test for generalization to unseen combinations).
Bruner Goodnow & Austin 1956: Modern Classical Age

- First Order Features: “surface”
  - Color
  - Shape
  - Size
  - Number
  - etc..
- But could be hidden requiring discovery:
- Black beans, chick peas, soy sauce, peanuts ...etc..

No COMMON 1\textsuperscript{st} order FEATURE--

- second order effects!  Allergies-- a single protein!
Bruner Goodnow & Austin (1956)

From Bruner, Goodnow, and Austin (1956)
If striped must be square; if ~striped then any
If striped must be square; if square must be striped
Figure 8.5. Average number of trials to solution for four different logical rules. (From “Knowing and Using Concepts,” by L. E. Bourne, Jr. In Psychological Review, 1970, 77, 546–556. Copyright 1970 by the American Psychological Association. Reprinted by permission.)
Bruner Goodnow & Austin (1956)
Observations: Strategies

1. Minimal effects of early trials on categorization: random to very good performance, non-efficacy of changing rule during learning phase.

2. Different people use different strategies to try to identify the correct concepts. These strategies are specific task related. Reception strategies (e.g., "Wholist"--select intersection of hits; and "partist"--test hypotheses ) and Selection strategies (e.g., "scanning"--test hypotheses; and "focusing"--use positive instance as anchor).

3. Strategy: Confirmation bias : There is a tendency for people to focus on confirmation of hypotheses and to pay attention to confirmatory rather than disconfirmatory evidence, although they can learn make use of information of all types.
Artificial Intelligence: Michalski and AQ (1980)

- In the 1970s and 1980s AI researchers began to build systems that could induce concept representation using Boolean rules—basically inspired by the BGA and the idea that FORMAL LOGIC underlay Concept representation.

  1. Pick a positive example e
  2. Generalize feature description of e (drop terms)
  3. Update this version space for all the negative examples in the data. Each description in G now covers e—but no negative examples.
  4. Choose some element of G to be the next
  5. Remove all examples of g from the data.
  6. Repeat 1-5 until there are no positive examples left in the data. NB The selection of the The resulting disjunctive description is more like the "G" of a concept than its "S" (i.e. it is a very general concept that excludes all the negative examples, rather than a very specific concept that includes all the examples). This is basically a "greedy" hill-climbing algorithm.
Learning the Trains

AQ solves Problems like this in milliseconds

Can you?
Implicit vs Explicit:
sequence
temporal structure
vs static

Figure 10. A “road map” representing a regular grammar. Any string of letters that is produced along a path starting in state 0 and finishing in state 4 is said to be grammatical.

us still in state 3, but S takes us on to state 2, etc. A list of all the paths from start to finish, ordered from shortest to longest, would begin

NG  
SSG  
NNSG  
SSXG  
SXSG  
NNSXG  
NNXSG  
SXSSG  
SXXXG  

and it would go on forever, because there is no longest path. Seen in this way, a grammar is a set of rules for producing grammatical sequences.

A grammar can also be viewed as a set of rules for selecting
Shepard Hovland & Jenkins (1961)

Selective Attention

- In a landmark study of category learning and complexity, Shepard Hovland and Jenkins at Bell Labs ran 100s of Housewifes around Berkeley Heights NJ in a series of category learning tasks.
- SHJ were interested in two aspects of category learning
  - (1) Concept Complexity (defined again Boolean form)
  - (2) Selective Attention (do subjects ignore irrelevant features?)
Fig. 1. Six different classifications of the same set of eight stimuli. (Within each box the four stimuli on the left belong in one class and the four stimuli on the right in the other class.)
Logical Structure of SHJ Stimuli

- **I:** Linearly Necessary & Sufficient Conjunction
  - One Dimension

- **II:** Non-Linearly Polymorphism
  - Two Dimensions
  - XOR

- **III:** Non-Linearly Polymorphism
  - Three Dimensions
  - 2-term 2-DNF

- **IV:** Linearly M/N Polymorphism
  - Three Dimensions
  - 3-term 2-DNF

- **V:** Non-Linearly Polymorphism
  - Three Dimensions
  - 2-term 2-DNF + 3-DNF

- **VI:** Non-Linearly Polymorphism
  - Three Dimensions
  - 3-bit Parity
Boolean Complexity

Exclusive OR

Example 1

Feature 1 = 0
Feature 2 = 0

Example 2

Feature 1 = 0
Feature 2 = 1

Example 3

Feature 1 = 1
Feature 2 = 0

Example 4

Feature 1 = 1
Feature 2 = 1

Abstracting away from surface features combine features to get new features

Example 1: $0 + 0 = 0$ "EVEN NUMBER"
Example 2: $0 + 1 = 1$ "ODD NUMBER"
Example 3: $1 + 0 = 1$ "ODD NUMBER"
Example 4: $1 + 1 = 2$ "EVEN NUMBER"
### Linearly and Nonlinearly Separable Complexity of Categorization

<table>
<thead>
<tr>
<th>TYPES OF DECISION REGIONS</th>
<th>EXCLUSIVE OR PROBLEM</th>
<th>CLASSES WITH MESHED REGIONS</th>
<th>MOST GENERAL REGION SHAPES</th>
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</thead>
<tbody>
<tr>
<td>HALF PLANE BOUNDED BY HYPERPLANE</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>CONVEX OPEN OR CLOSED REGIONS</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>ARBITRARY (Complexity Limited By Number of Nodes)</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
</tbody>
</table>
Data from Nosofsky (unpublished). Plotted are the total number of errors per block.
DIFFICULTY (STANDARD UNITS)

ERRORS

TIME

ERRORS

TIME

ERRORS
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<thead>
<tr>
<th>3[2]</th>
<th>Concept</th>
<th>Raw formula</th>
<th>Minimal formula</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td>$a'b'c + a'bc$</td>
<td>$a'bc' + abc$</td>
<td>5</td>
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<tr>
<td>II</td>
<td><img src="image2.png" alt="Diagram" /></td>
<td>$a'bc' + abc$</td>
<td>$a'bc' + abc$</td>
<td>6</td>
</tr>
<tr>
<td>III</td>
<td><img src="image3.png" alt="Diagram" /></td>
<td>$a'bc' + abc$</td>
<td>$a'bc' + abc$</td>
<td>6</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>3[3]</th>
<th>Concept</th>
<th>Raw formula</th>
<th>Minimal formula</th>
<th>Complexity</th>
</tr>
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<tr>
<td>I</td>
<td><img src="image4.png" alt="Diagram" /></td>
<td>$a'b'c + ab'c \quad a'bc' \quad a'bc'$</td>
<td>$a'bc' + abc$</td>
<td>3</td>
</tr>
<tr>
<td>II</td>
<td><img src="image5.png" alt="Diagram" /></td>
<td>$a'bc' + ab'c - abc'$</td>
<td>$a'b - abc'$</td>
<td>5</td>
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<tr>
<td>III</td>
<td><img src="image6.png" alt="Diagram" /></td>
<td>$a'bc' + ab'c + abc'$</td>
<td>$a'bc' + abc$</td>
<td>8</td>
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</table>

<table>
<thead>
<tr>
<th>3[4]</th>
<th>Concept</th>
<th>Raw formula</th>
<th>Minimal formula</th>
<th>Complexity</th>
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<tr>
<td>I</td>
<td><img src="image7.png" alt="Diagram" /></td>
<td>$a'b'c' + a'b'c - a'bc' + ab'c$</td>
<td>$a'$</td>
<td>7</td>
</tr>
<tr>
<td>II</td>
<td><img src="image8.png" alt="Diagram" /></td>
<td>$a'b'c' + ab'c - abc + abc$</td>
<td>$ab + a'bc$</td>
<td>4</td>
</tr>
<tr>
<td>III</td>
<td><img src="image9.png" alt="Diagram" /></td>
<td>$a'b'c' + ab'c - a'bc' + ab'c'$</td>
<td>$a'(bc)' - ab'c$</td>
<td>6</td>
</tr>
<tr>
<td>IV</td>
<td><img src="image10.png" alt="Diagram" /></td>
<td>$a'b'c' + ab'c - a'bc' + ab'c'$</td>
<td>$a'(bc)' - ab'c$</td>
<td>6</td>
</tr>
<tr>
<td>V</td>
<td><img src="image11.png" alt="Diagram" /></td>
<td>$a'b'c' + ab'c - a'bc' + abc'$</td>
<td>$a'(bc)' abc$</td>
<td>6</td>
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<tr>
<td>VI</td>
<td><img src="image12.png" alt="Diagram" /></td>
<td>$a'b'c' + ab'c + abc + abc'$</td>
<td>$a(b'c + bc)' = a'(b'c + bc)$</td>
<td>10</td>
</tr>
</tbody>
</table>

*Figure 4.* Concepts from three of the families tested (3[2], 3[3], and 3[4]), showing the “raw” (uncompressed) formula, minimal formula, and Boolean complexity (length of the minimal formula in literals).
Boolean Complexity?

- J. Feldman: Compression == Comprehension
SHJ: Data & Observations

- Response time and Errors increased with increasing complexity
- Subjects were able to selectively attend to features that were relevant to categorization task and ignore features that were irrelevant
- Do features or Perceptual Channels INTERACT?
Garner & Stimulus Channels

- Helmholtz (1890) argued that Stimulus Dimensions interacted while Herring (1890) disagreed. Garner (1974) revived this debate and characterized stimulus types as either integral or separable as Wholistic or analytic or interacting or independent.
- He suggested two types of experiments based on an Information theory analogy:
  - Filtration: Can the subject filter irrelevant dimensions and therefore be more efficient?
  - Condensation: Can the subject condense/compress dimensions and therefore be more efficient?
Which figure has a different shape?

Height of rectangle and Width are not separable while AREA and SHAPE are separable.
Krushke's Integral Stimuli
Figure 4.10. Stimuli used in Kruschke’s (1993) filtration/condensation experiment. Left-hand panel: the stimuli (as before) were boxes with internal lines, and the height of the box and the position of the internal line varied as shown. These co-ordinates are from an MDS analysis based on subjects’ pairwise similarity judgments. Right-hand panel: category partitions in filtration and condensation problems for this set of stimuli. In the filtration problems, only one dimension is relevant to the classification, whereas in the condensation problems both dimensions are relevant. (From Kruschke, 1993, reprinted with permission.)
**Category tasks diagnostic**

**FIG. 5.** Filtration and condensation category structures are shown on the left. The axes indicate the two dimensions of psychological space, and the circles indicate particular stimuli within that space. The color of the circle, blank vs filled, indicates which of the two categories was the correct category. On the right is human learning data for the two structures. (Figure adapted from Kruschke, 1993.)
**Concept Complexity Limit?**

- Subjects sensitive to feature complexity
- Can compress stimulus dimensions and process composite dimensions as efficiently as 1\(^{st}\) order dimensions.
- What is complexity limit on concept comprehensibility?
Case III vs IV:
Medin & Schwanafugel (1978)
(A) LINEARLY SEPARABLE TASK

<table>
<thead>
<tr>
<th>Comparison Type</th>
<th>Hamming Distance</th>
<th>Average</th>
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<tr>
<td></td>
<td>1</td>
<td>2</td>
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<tr>
<td>between category</td>
<td>0</td>
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<td>within category</td>
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(B) NON-LINEARLY SEPARABLE TASK

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<td>within category</td>
<td>1</td>
<td>0</td>
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Subjects take 10 time longer to learn then simple disjunction and never seem to be able to articulate a RULE—instead discuss family resemblance, similarity etc.. Concept appears Implicit.
Biological Complexity
Threshold Logic
(family resemblance?)
THE ANATOMY of A MODEL NEURON

Firing RATE to other Cells
Pre synaptic EPSPs

activation approximation

Decision Capacity

Memory of Network

Transform to internal “arousal” to RATE or Frequency of Spikes; Probably Nonlinear including threshold

\[ a_i = \sum w_{ij} x_i \]

\[ f(a_i, \theta) \]

\[ x_1 \quad x_2 \quad x_3 \] (sensory input)

THE WORLD

Synaptic weights are represented by real valued numbers and can be changed by a learning rule

Represents what the Dendrites compute from EPSPs and IPSPs
Wittgenstein introduces family resemblances and Polymorphy to help us understand how some concepts actually work, how they function in language. Take the classic example of a game.

“What is a game? How do we decide if this is or isn't a game? Why is this a game but that not? And so on. In short, how do we define "game"? Solitaire is a game, so is basketball, chess, bingo, poker, pick-up-sticks, Parcheesi, .... If these are all games, we want to say that they MUST have something in common, something in virtue of which they are games. But what would that be?

66. ...--For if you look at them you will not see something that is common to all, but similarities, relationships, and a whole series of them at that. To repeat: don't think, but look!

What emerges is the picture of overlapping sets of features which come together to form an interlinked array.”
Concepts & Categories

• Eleanor Rosch revives Wittengenstein's concerns about necessary and sufficient features; Family resemblance, Prototypes, and Natural Categories come under scrutiny

• To be continued....