Knowledge Representation: How far we have come?

Daniel Khashabi
AI Goal:
Enabling machines to solve any problems, as good as human
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How to measure the progress?
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How to measure the progress?
“Yo ...what’s up?”
Natural Input

“Yo …what’s up?”

Natural Output

“Yo …not much! Sup yourself?!”
“Yo ...what’s up?”

“Yo ...not much! Sup yourself?!”
Natural Input

AI System

Natural Output
“What is the sum of five and two?”

“seven”
“What is the sum of five and two?”

“seven”
Natural Input

“What is the sum of five and two?”

Intermediate Input

x = 5, y = 2
Goal=x+y=?

Natural Output

“seven”
“What is the sum of five and two?”

\[ x = 5, \quad y = 2 \]

Goal: \( x + y = ? \)

“seven”
“What is the sum of five and two?”

x = 5, y = 2
Goal=x+y=?

Goal=7

“seven”
"What is the sum of five and two?"

$x = 5, y = 2$
Goal =$x + y = ?$

Goal = 7

"seven"
“What is the sum of five and two?”

x = 5, y = 2
Goal = x + y = ?

Goal = 7

“seven”
“What is the sum of five and two?”

x = 5, y = 2
Goal = x + y = ?

Goal = 2 + 5 = 7

“seven”
General Problem Solver
(Simon & Newell, 1956)
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**Goal:** Program for proving theorems!
General Problem Solver
(Simon&Newell, 1956)

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**Necessity:** Representation with symbols!
General Problem Solver
(Simon&Newell, 1956)

**Goal:** Program for proving theorems!

**Necessity:** Representation with symbols!

**Hypothesis (physical symbol system hypothesis):**
“A physical symbol system has the necessary and sufficient means for general intelligent action.”
General Problem Solver
(Simon & Newell, 1956)

**Goal:** Program for proving theorems!

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**Hypothesis (physical symbol system hypothesis):**
“A physical symbol system has the necessary and sufficient means for general intelligent action.”

**Reasoning:** Problem solving as Search!
General Problem Solver
(Simon & Newell, 1956)

**Goal:** Program for proving theorems!

**Necessity:** Representation with symbols!

**Hypothesis (physical symbol system hypothesis):**
“A physical symbol system has the necessary and sufficient means for general intelligent action.”

**Reasoning:** Problem solving as Search!

![Diagram of initial and goal states](image)

1  2  3

1  2  3
General Problem Solver
(Simon & Newell, 1956)
"Jack is my brother. Is he my sibling?"
“Jack is my brother. Is he my sibling?”

“yes”
“Jack is my brother. Is he my sibling?”

“yes”
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Premise: brother("Jack", "I")
Proposition: sibling("Jack", "I")

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Premise: brother(“Jack”, “I”)  
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Premise: brother(“Jack”, “I”)
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sibling(“Jack”, “I”): TRUE

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“yes”
Logical Reasoning

Deduction:

Induction:

Abduction:
Logical Reasoning

Deduction: Conclusion from given axioms (facts or observations)

Induction:

Abduction:
Logical Reasoning

**Deduction:** Conclusion from given axioms (facts or observations)

<table>
<thead>
<tr>
<th>All humans are mortal.</th>
<th>(axiom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socrates is a human.</td>
<td>(fact/ premise)</td>
</tr>
<tr>
<td><strong>Therefore, it follows that Socrates is mortal.</strong></td>
<td>(conclusion)</td>
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**Induction:**

**Abduction:**
Logical Reasoning

**Deduction:** Conclusion from given axioms (facts or observations)

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**Induction:** Generalization from background knowledge or observations

**Abduction:**
### Logical Reasoning

**Deduction:** Conclusion from given axioms (facts or observations)

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**Induction:** Generalization from background knowledge or observations

<table>
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<tbody>
<tr>
<td>Socrates is a human</td>
<td>Therefore, I hypothesize that all humans are mortal</td>
</tr>
<tr>
<td>Socrates is mortal</td>
<td>(background knowledge)</td>
</tr>
<tr>
<td></td>
<td>(observation/ example)</td>
</tr>
<tr>
<td></td>
<td>(generalization)</td>
</tr>
</tbody>
</table>

**Abduction:**
**Logical Reasoning**

**Deduction:** Conclusion from given axioms (facts or observations)

| All humans are mortal. (axiom) |
| Socrates is a human. (fact/ premise) |
| **Therefore, it follows that Socrates is mortal.** (conclusion) |

**Induction:** Generalization from background knowledge or observations

| Socrates is a human (background knowledge) |
| Socrates is mortal (observation/ example) |
| **Therefore, I hypothesize that all humans are mortal** (generalization) |

**Abduction:** Simple and mostly likely explanation, given observations
**Logical Reasoning**

**Deduction:** Conclusion from given axioms (facts or observations)

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Therefore, it follows that Socrates is mortal. (conclusion)

**Induction:** Generalization from background knowledge or observations

<table>
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Therefore, I hypothesize that all humans are mortal (generalization)

**Abduction:** Simple and mostly likely explanation, given observations

<table>
<thead>
<tr>
<th>All humans are mortal</th>
<th>(theory)</th>
</tr>
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<tbody>
<tr>
<td>Socrates is mortal</td>
<td>(observation)</td>
</tr>
</tbody>
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Therefore, Socrates must have been a human (diagnosis)
Programs With Commonsense
(John McCarthy, 1959)

Formalize world in *logical* form!
Programs With Commonsense
(John McCarthy, 1959)

Formalize world in **logical** form!

**Example:**
“My desk is at home” → at(I, desk)
“Desk is at home” → at(desk, home)
Programs With Commonsense

(John McCarthy, 1959)

Formalize world in **logical** form!

**Example:**
“My desk is at home” → at(I, desk)
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**Hypothesis:** Commonsense knowledge can be formalized with logic.
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Do **reasoning** on formal premises!
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Do **reasoning** on formal premises!

**Example Contd.:**
\[
\forall x \forall y \forall z \text{ at}(x,y), \text{ at}(y,z) \rightarrow \text{ at}(x, z) \\
\therefore \text{ at}(I, \text{home})
\]
Programs With Commonsense
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Formalize world in **logical** form!

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**Example Contd.:**
\[ \forall x \forall y \forall z \; \text{at}(x, y), \text{at}(y, z) \rightarrow \text{at}(x, z) \]
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**Hypothesis:** Commonsense problems are solved by logical reasoning
STUDENT
(Daniel G Bobrow, 1964)

**Goal:** Elementary school algebra problem solver
**Input:** Natural Language
STUDENT
(Daniel G Bobrow, 1964)

**Goal:** Elementary school algebra problem solver

**Input:** Natural Language

**Example:** The sum of two numbers is 111. One of the numbers is consecutive to the other number. Find the two numbers.
Goal: Elementary school algebra problem solver
Input: Natural Language

Example: The sum of two numbers is 111. One of the numbers is consecutive to the other number. Find the two numbers.

Example: Bill's father's uncle is twice as old as Bill's father. 2 years from now Bill's father will be 3 times as old as Bill. The sum of their ages is 92. Find Bill's age.
Goal: Elementary school algebra problem solver
Input: Natural Language

Example: The sum of two numbers is 111. One of the numbers is consecutive to the other number. Find the two numbers.

Example: Bill's father's uncle is twice as old as Bill's father. 2 years from now Bill's father will be 3 times as old as Bill. The sum of their ages is 92. Find Bill's age.

Example: The distance between New York to Los Angeles is 3000 miles. If the average speed of a jet plane is 600 miles per hour find the time it takes to travel from New York to Los Angeles by jet.
Person: Pick up a big red block.
Computer: OK.
SHRDLU
(Terry Winograd, 1968)

**Person:** Pick up a big red block.
**Computer:** OK.
**Person:** Grasp the pyramid.
**Computer:** I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.
**SHRDLU**
(Terry Winograd, 1968)

*Person:* Pick up a big red block.
*Computer:* OK.
*Person:* Grasp the pyramid.
*Computer:* I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.
*Person:* Find a block which is taller than the one you are holding and put it into the box.
*Computer:* BY "IT", I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.
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**Computer:** BY "IT", I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.  
**Computer:** OK.  
**Person:** What does the box contain?
**SHRDLU**  
*(Terry Winograd, 1968)*

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**Computer:** BY "IT", I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.  
**Computer:** OK.  
**Person:** What does the box contain?  
**Computer:** THE BLUE PYRAMID AND THE BLUE BLOCK.  
**Person:** What is the pyramid supported by?
**SHRDLU**  
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**Person:** What does the box contain?  
**Computer:** THE BLUE PYRAMID AND THE BLUE BLOCK.  
**Person:** What is the pyramid supported by?  
**Computer:** THE BOX.  
**Person:** How many blocks are not in the box?
Person: Pick up a big red block.
Computer: OK.
Person: Grasp the pyramid.
Computer: I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.
Person: Find a block which is taller than the one you are holding and put it into the box.
Computer: BY "IT", I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.
Computer: OK.
Person: What does the box contain?
Computer: THE BLUE PYRAMID AND THE BLUE BLOCK.
Person: What is the pyramid supported by?
Computer: THE BOX.
Person: How many blocks are not in the box?
Computer: FOUR OF THEM.
Person: Is at least one of them narrower than the one which i told you to pick up?
**Person:** Pick up a big red block.
**Computer:** OK.

**Person:** Grasp the pyramid.
**Computer:** I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.

**Person:** Find a block which is taller than the one you are holding and put it into the box.
**Computer:** BY "IT", I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.
**Computer:** OK.

**Person:** What does the box contain?
**Computer:** THE BLUE PYRAMID AND THE BLUE BLOCK.

**Person:** What is the pyramid supported by?
**Computer:** THE BOX.

**Person:** How many blocks are not in the box?
**Computer:** FOUR OF THEM.

**Person:** Is at least one of them narrower than the one which i told you to pick up?
**Computer:** YES, THE RED CUBE.

**Person:** Is it supported?
Person: Pick up a big red block.
Computer: OK.
Person: Grasp the pyramid.
Computer: I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.
Person: Find a block which is taller than the one you are holding and put it into the box.
Computer: BY "IT", I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.
Computer: OK.
Person: What does the box contain?
Computer: THE BLUE PYRAMID AND THE BLUE BLOCK.
Person: What is the pyramid supported by?
Computer: THE BOX.
Person: How many blocks are not in the box?
Computer: FOUR OF THEM.
Person: Is at least one of them narrower than the one which i told you to pick up?
Computer: YES, THE RED CUBE.
Person: Is it supported?
Computer: YES, BY THE TABLE.
Person: Can the table pick up blocks?
**SHRDLU**
(Terry Winograd, 1968)

**Person:** Pick up a big red block.
**Computer:** OK.

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**Computer:** I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.

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**Person:** What is the pyramid supported by?
**Computer:** THE BOX.

**Person:** How many blocks are not in the box?
**Computer:** FOUR OF THEM.

**Person:** Is at least one of them narrower than the one which i told you to pick up?
**Computer:** YES, THE RED CUBE.

**Person:** Is it supported?
**Computer:** YES, BY THE TABLE.

**Person:** Can the table pick up blocks?
**Computer:** NO.

**Person:** Can a pyramid be supported by a block?
**Computer:** YES.
SHRDLU
(Terry Winograd, 1968)

Basic rules:
- Small world
- Memory
- Deduction rule
- Learn new names

Person: Pick up a big red block.
Computer: OK.
Person: Grasp the pyramid.
Computer: I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.
Person: Find a block which is taller than the one you are holding and put it into the box.
Computer: BY "IT", I ASK WHICH IS THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.
Computer: OK.
Person: What does the box contain?
Computer: THE BLUE PYRAMID AND THE BLUE BLOCK.
Person: What is the pyramid supported by?
Computer: THE BOX.
Person: How many blocks are not in the box?
Computer: FOUR OF THEM.
Person: Is at least one of them narrower than the one which I told you to pick up?
Computer: YES, THE RED CUBE.
Person: Is it supported?
Computer: YES, BY THE TABLE.
Person: Can the table pick up blocks?
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Basic rules:
- Small world
- Memory
- Deduction rule
- Learn new names

Too narrow and brittle!
Frame Problem

(John McCarthy & Patrick J. Hayes, 1959)
Frame Problem
(John McCarthy & Patrick J. Hayes, 1959)

Axioms:

\[ \text{Paint}(x,c,t) \implies \text{Color}(x,c,t) \]
\[ \text{Move}(x,p,t) \implies \text{Position}(x,p,t) \]
Frame Problem
(John McCarthy & Patrick J. Hayes, 1959)

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\text{Paint}(x, c, t) \implies \text{Color}(x, c, t) \\
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\]

Initial State:
\[
\text{Color}(A, \text{Red}, t) \\
\text{Position}(A, \text{House}, t)
\]
Frame Problem
(John McCarthy & Patrick J. Hayes, 1959)

**Axioms:**

\[
\begin{align*}
\text{Paint}(x, c, t) &\Rightarrow \text{Color}(x, c, t) \\
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\end{align*}
\]

**Initial State:**

\[
\begin{align*}
\text{Color}(A, \text{Red}, t) \\
\text{Position}(A, \text{House}, t)
\end{align*}
\]

**Action:**

\[
\text{Move}(A, \text{Garden}, t+1)
\]
Frame Problem

(John McCarthy & Patrick J. Hayes, 1959)

**Axioms:**

- \( \text{Paint}(x, c, t) \Rightarrow \text{Color}(x, c, t) \)
- \( \text{Move}(x, p, t) \Rightarrow \text{Position}(x, p, t) \)

**Initial State:**

- \( \text{Color}(A, \text{Red}, t) \)
- \( \text{Position}(A, \text{House}, t) \)

**Action:**

- \( \text{Move}(A, \text{Garden}, t+1) \)

**Expected State:**

- \( \text{Color}(A, \text{Red}, t+1) \)
- \( \text{Position}(A, \text{Garden}, t+1) \)
Frame Problem
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- $\text{Paint}(x,c,t) \Rightarrow \text{Color}(x,c,t)$
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**Initial State:**
- $\text{Color}(A,\text{Red},t)$
- $\text{Position}(A,\text{House},t)$

**Action:**
- $\text{Move}(A,\text{Garden},t+1)$

**Expected State:**
- $\text{Color}(A,\text{Red},t+1)$
- $\text{Position}(A,\text{Garden},t+1)$

**Actual State:**
- $\text{Color}(A,\text{Red},t+1) / \text{Color}(A,\text{Blue},t+1)$
- $\text{Position}(A,\text{Garden},t+1)$
Frame Problem
(John McCarthy & Patrick J. Hayes, 1959)

Axioms:
\[ \text{Paint}(x,c,t) \implies \text{Color}(x,c,t) \]
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\[ \text{Color}(A, \text{Red}, t) \]
\[ \text{Position}(A, \text{House}, t) \]

Action:
\[ \text{Move}(A, \text{Garden}, t+1) \]

Expected State:
\[ \text{Color}(A, \text{Red}, t+1) \]
\[ \text{Position}(A, \text{Garden}, t+1) \]

Actual State:
\[ \text{Color}(A, \text{Red}, t+1) / \text{Color}(A, \text{Blue}, t+1) \]
\[ \text{Position}(A, \text{Garden}, t+1) \]
Frame Problem

(John McCarthy & Patrick J. Hayes, 1959)
Frame Problem

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**Axioms:**

- \( \text{Paint}(x,c,t) \implies \text{Color}(x,c,t) \)
- \( \text{Move}(x,p,t) \implies \text{Position}(x,p,t) \)
- \( \text{Color}(x,c,t) \land \text{Move}(x,p,t) \implies \text{Color}(x,c,t+1) \)
- \( \text{Position}(x,p,t) \land \text{Paint}(x,c,t) \implies \text{Position}(x,p,t+1) \)
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- \( \text{Paint}(x, c, t) \Rightarrow \text{Color}(x, c, t) \)
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- \( \text{Color}(x, c, t) \land \text{Move}(x, p, t) \Rightarrow \text{Color}(x, c, t+1) \)
- \( \text{Position}(x, p, t) \land \text{Paint}(x, c, t) \Rightarrow \text{Position}(x, p, t+1) \)

**Initial State:**

- \( \text{Color}(A, \text{Red}, t) \)
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Frame Problem
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- \( \text{Color}(x, c, t) \land \text{Move}(x, p, t) \Rightarrow \text{Color}(x, c, t+1) \)
- \( \text{Position}(x, p, t) \land \text{Paint}(x, c, t) \Rightarrow \text{Position}(x, p, t+1) \)

**Initial State:**

- \( \text{Color}(A, \text{Red}, t) \)
- \( \text{Position}(A, \text{House}, t) \)

**Action:**

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**Axioms:**
\[
\begin{align*}
\text{Paint}(x,c,t) \implies & \text{Color}(x,c,t) \\
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\text{Color}(x,c,t) \land & \text{Move}(x,p,t) \implies \text{Color}(x,c,t+1) \\
\text{Position}(x,p,t) \land & \text{Paint}(x,c,t) \implies \text{Position}(x,p,t+1)
\end{align*}
\]

**Initial State:**
- Color(A,Red,t)
- Position(A,House,t)

**Action:**
- Move(A,Garden,t)

**Expected State = Actual State:**
- Color(A,Red,t+1)
- Position(A,Garden,t+1)
Frame Problem
(John McCarthy & Patrick J. Hayes, 1959)

**Axioms:**
- \( \text{Paint}(x,c,t) \implies \text{Color}(x,c,t) \)
- \( \text{Move}(x,p,t) \implies \text{Position}(x,p,t) \)
- \( \text{Color}(x,c,t) \land \text{Move}(x,p,t) \implies \text{Color}(x,c,t+1) \)
- \( \text{Position}(x,p,t) \land \text{Paint}(x,c,t) \implies \text{Position}(x,p,t+1) \)

**Initial State:**
- \( \text{Color}(A,\text{Red},t) \)
- \( \text{Position}(A,\text{House},t) \)

**Action:**
- \( \text{Move}(A,\text{Garden},t) \)

**Expected State = Actual State:**
- \( \text{Color}(A,\text{Red},t+1) \)
- \( \text{Position}(A,\text{Garden},t+1) \)
Frame Problem
(John McCarthy & Patrick J. Hayes, 1959)

**Problem:** Many actions don’t change many properties!

\[
\{ M: Actions \}
\{ N: Properties \} \Rightarrow MN \text{ additional axioms!}
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**Solution:** An action does not change any property *unless* there is evidence to the contrary

*common sense law of inertia*
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(John McCarthy & Patrick J. Hayes, 1959)

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Example of non-monotonic logic (abductive):
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Monotonicity of classical logic: \( S \models R \Rightarrow S \cup B \not\models R \)

Example of non-monotonic logic (abductive):

**Observation 1:** Your daughter’s messy room
**Conclusion 1:** She has school problem, or relationship problem, etc.

**Observation 2:** Bookshelf has broken.
**Conclusion 2:** The heavy weight of things on the shelf has broken it.
Cyc (1984-present)
(Douglas Lenant, 1984)

Goal:
Knowledge representation schema utilizing first-order relationships.
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Knowledge representation schema utilizing first-order relationships.

**Example assertions:**
“Every tree is a plant”
“Plants die eventually”
**Cyc** (1984-present)

(Douglas Lenant, 1984)

**Goal:**
Knowledge representation schema utilizing first-order relationships.

**Example assertions:**

“Every tree is a plant”

“Plants die eventually”

In 1986, Doug Lenat estimated the effort to complete Cyc would be **250,000 rules and 350 man-years of effort**!

500k concepts, 17k relations, ~10M logical facts
Cyc (1984-present)
(Douglas Lenant, 1984)

Example entries:

Constants:  #$OrganicStuff
Cyc (1984-present)
(Douglas Lenant, 1984)

Example entries:

Constants: #$OrganicStuff

Variable: (#$colorOfObject #$Grass ?someColor)
Cyc (1984-present)
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Example entries:

Constants:  #$OrganicStuff

Variable:  (#$colorOfObject #$Grass ?someColor)

Expressions:  (#$colorOfObject #$Grass #$Green)
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Example entries:

Constants:  #$OrganicStuff

Variable:  (#$colorOfObject #$Grass ?someColor)

Expressions:  (#$colorOfObject #$Grass #$Green)

Assertions:  “Animals sleep at home”
(ForAll ?x (ForAll ?S (ForAll ?PLACE
  (implies (and
    (isa ?x Animal)
    (isa ?S SleepingEvent)
    (performer ?S ?x)
    (location ?S ?PLACE))
    (home ?x ?PLACE)))))
Semantic Networks

(Ross Quillian, 1963)

A graph of labeled nodes and labeled, directed arcs
Arcs define binary relationships that hold between objects denoted by the nodes.

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Semantics</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subset</td>
<td>$A \subset B$</td>
<td>Cats $\subset$ Mammals</td>
</tr>
<tr>
<td>Member</td>
<td>$A \in B$</td>
<td>Bill $\in$ Cats</td>
</tr>
<tr>
<td>$A \rightarrow B$</td>
<td>$R(A,B)$</td>
<td>Bill $\stackrel{Age}{\rightarrow} 12$</td>
</tr>
<tr>
<td>$A \rightarrow B$</td>
<td>$\forall x, x \in A \Rightarrow R(x,B)$</td>
<td>Bird $\stackrel{legs}{\rightarrow} 12$</td>
</tr>
<tr>
<td>$A \rightarrow B$</td>
<td>$\forall x \exists y, x \in A \Rightarrow y \in B \land R(x,B)$</td>
<td>Birds $\stackrel{Parent}{\rightarrow}$ Birds</td>
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</table>

Diagram: Semantic network with nodes labeled as follows:
- Animal
- Bird
- Robin
- Rusty
- Red

Links:
- isa
- hasPart
- legs
- Parent
ConceptNet (2000-present)

- Based on Open Mind Common Sense (OMCS)
  - goal was to build a large commonsense knowledge base
  - from the contributions of many people across the Web.

A network represents semantic relation between concepts.
Frames
(Minsky, 1974; Fillmore, 1977)

Premise: Meaning is based on prototypical abstract scenes
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Cynthia sold a car to Bob
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Bob bought a car from Cynthia.
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Bob bought a car from Cynthia.
Frames
(Minsky, 1974; Fillmore, 1977)

Hierarchical Representation with Frames
Procedural knowledge: For typical actions, like inter-personal relations, sleeping, attending events, sending a message

work-box-office(B, F) :-
    dress(B, work-box-office),
    near-reachable(B, F),
    TKTBOX = FINDO(ticket-box);
    near-reachable(B, FINDO(employee-side-of-counter)),
    /* HANDLE NEXT CUSTOMER */
100: WAIT FOR attend(A = human, B) OR
    pre-sequence(A = human, B), may-I-help-you(B, A),
    /* HANDLE NEXT REQUEST OF CUSTOMER */
103: WAIT FOR request(A, B, R)
    AND GOTO 104 OR WAIT FOR post-sequence(A, B)
    AND GOTO 110,
104: IF R ISA tod
    { current-time-sentence(B, A) ON COMPLETION GOTO 103 }
ELSE IF R ISA performance
    { GOTO 105 }
ELSE
    { interjection-of-noncomprehension(B, A) ON COMPLETION GOTO 103}
Neuron

- (McCulloch, Pitts, 1943)
Neuron

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Connectionism

- **1949-69**: Basic forms for updates for perceptron
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- **1969**: Negative results on approximating ability of perceptron
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- **1986**: Advent of backpropagation and training multi-layer networks
- **80s**: Popularization of “parallel distributed models” aka “Connectionism”
Distributed vs. Classical Representation

Classical representations:

Jack $\rightarrow x_1$
Distributed vs. Classical Representation

Classical representations:

- Jack \( x_1 \)
- Flower \( x_2 \)
Distributed vs. Classical Representation

Classical representations:

- Jack → $x_1$
- Flower → $x_2$
- Jack’s dad → $x_3$
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Distributed representation:
- a symbol is encoded across all elements of the representation
- each element the representation takes part in representing the symbol.
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## Distributed vs. Classical Representation

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<td>Rules, premises, conclusions, rule strengths</td>
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**Systematicity debate:** (Fodor and Pylyshyn)

“John loves Mary”
“Mary loves John”

Connectionists do not account for systematicity, although it can be trained to.

**Responses:** Elman (1990), Smolensky (1990), Pollak (1990), etc.
Variable binding:
- conjunctive of elements and properties
- Variables of logical forms
Variable binding by synchronization of neurons.
SHRUTI

- (Shastri, 1989)

Dynamic binding for First order logic!
Neural-Symbolic models

- (90s-now)
Representation Necessary?
(Rodney Brooks, 1991)

- MIT CSAIL, Roboticist
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Allen:
• Can approach goal, while avoiding obstacles – without plan or map of environment
• Distance sensors, and 3 layers of control
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- Like combination of Finite State Machines
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  - implicit and distribution inside FSMs.
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Subsumption Architecture
Representation Necessary?
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• No central model of world
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Critiques:
- Scaling?
- How does it solve our AI problem?!
So what now?!

Questions left to answer

• "symbolic" representation necessary?
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  Unify reasoning with representation?
  Separate knowledge base?
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Represent uncertainty better than “probability theory”?
Unify distributed and logic-based representation?
  Or do logical reasoning with statistical models?
• Or make more robust logical systems?
So what now?!

**Questions left to answer**

- "symbolic" representation necessary?
  - Unify reasoning with representation?
    - Separate knowledge base?
  - Represent uncertainty better than “probability theory”?
- Unify distributed and logic-based representation?
  - Or do logical reasoning with statistical models?
- Or make more robust logical systems?
- How knowledge should be accessed?
  - How this can be made dynamics in the case when there are multiple types of information?
Thanks for coming!
ThoughtTreasure (1994-2000)
(Erik Mueller, 2000)

Minsky (1988): there is no single “right” representation for everything,

Facts: 27,000 concepts and 51,000 assertions

[isa soda drink]
(Soda is a drink.)

[is the-sky blue]
(The sky is blue.)

@19770120:19810120|[President-of country-USA Jimmy-Carter]
(Jimmy Carter was the President of the USA from January 20, 1977 to January 20, 1981.)