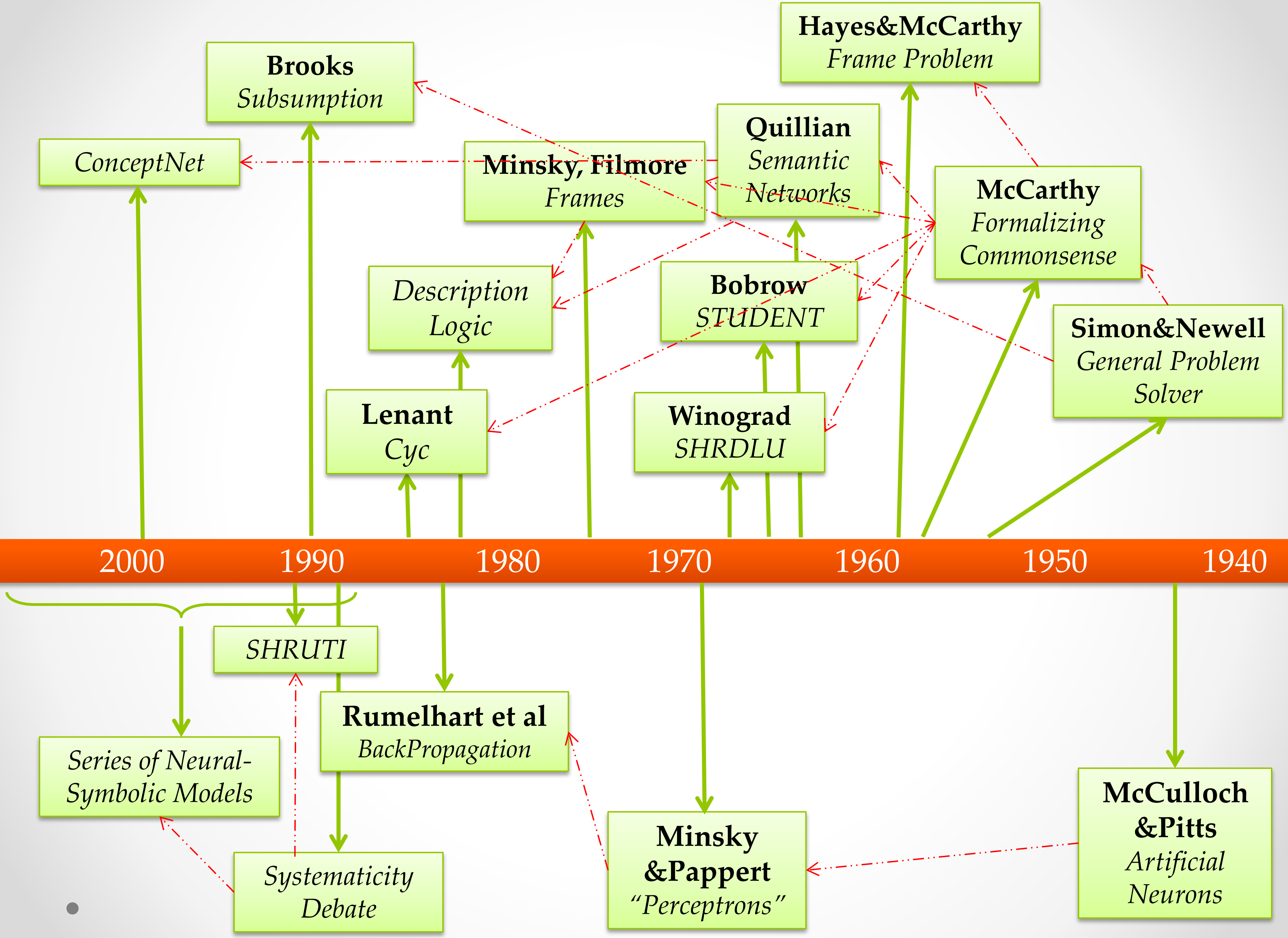
Knowledge Representation: How far we have come?

Daniel Khashabi



Hayes&McCarthy
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AI Goal:
Enabling machines to solve any problems, as good as human

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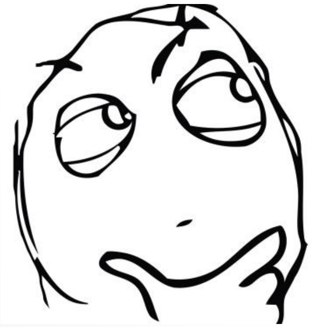

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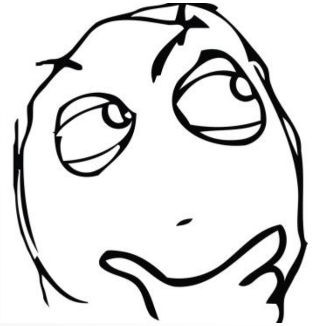

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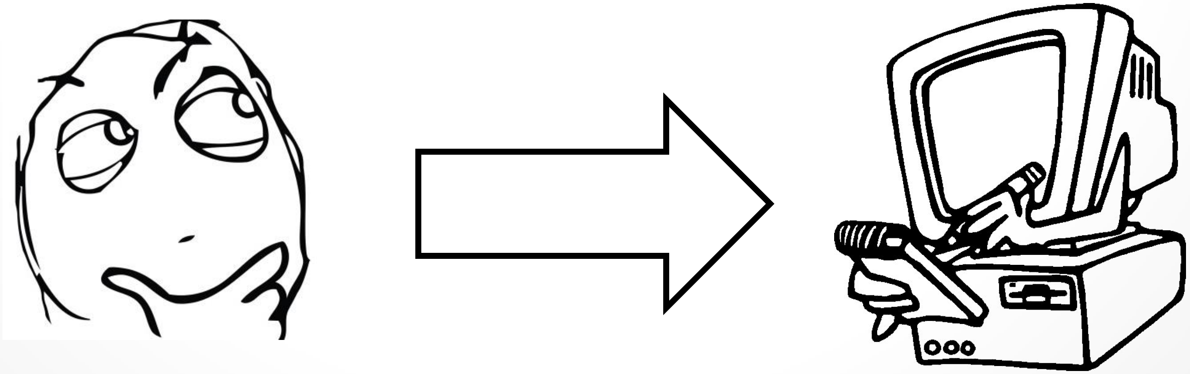

Natural Input

Natural Output

Natural Input

“Yo …what’s up?”

Natural Output

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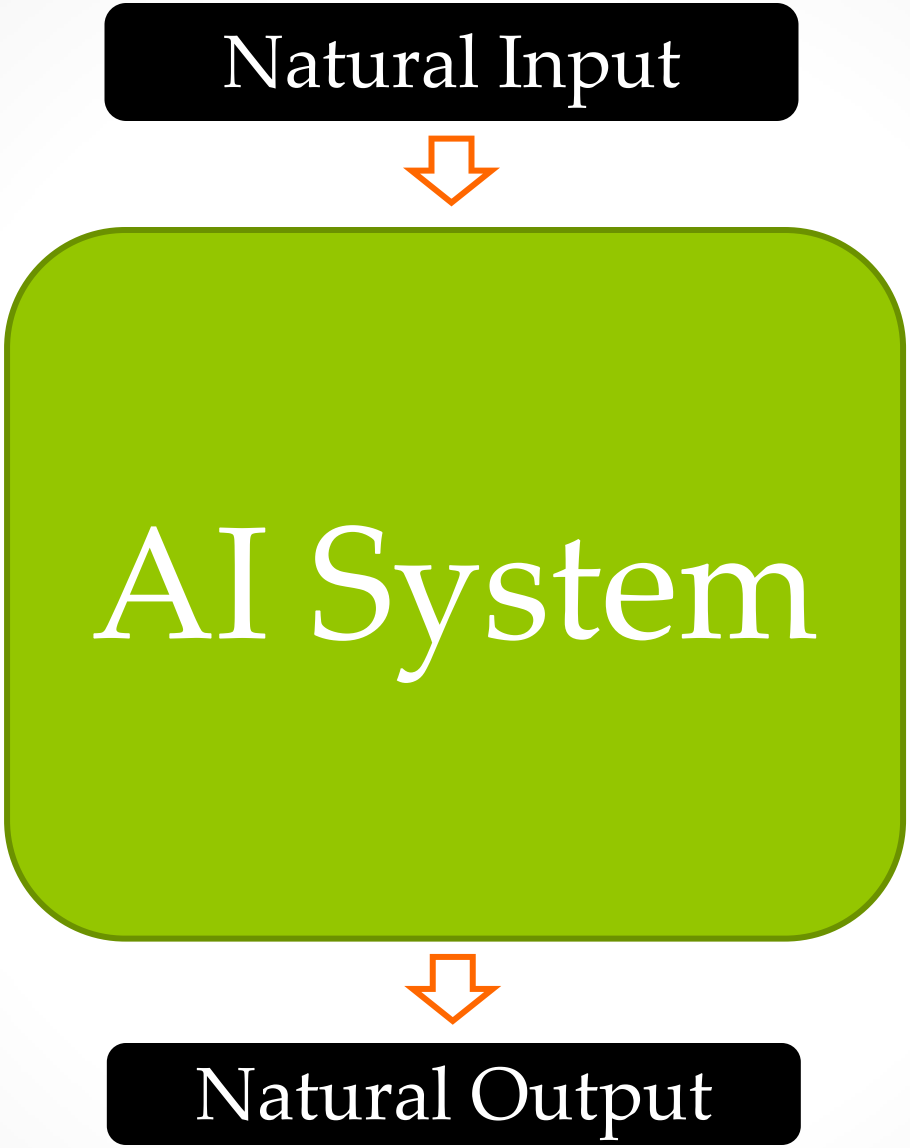
“Yo …what’s up?”

Natural Output

“Yo …not much!
Sup yourself?!”



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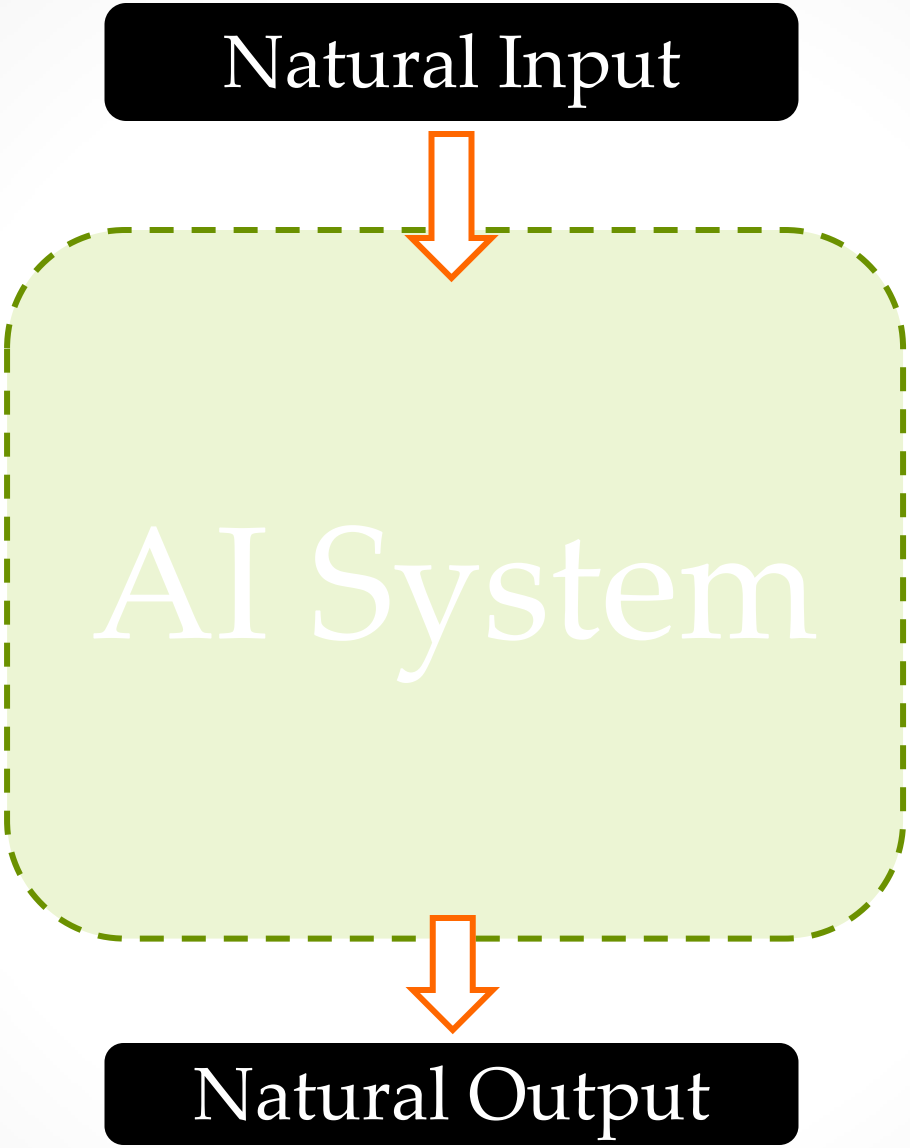

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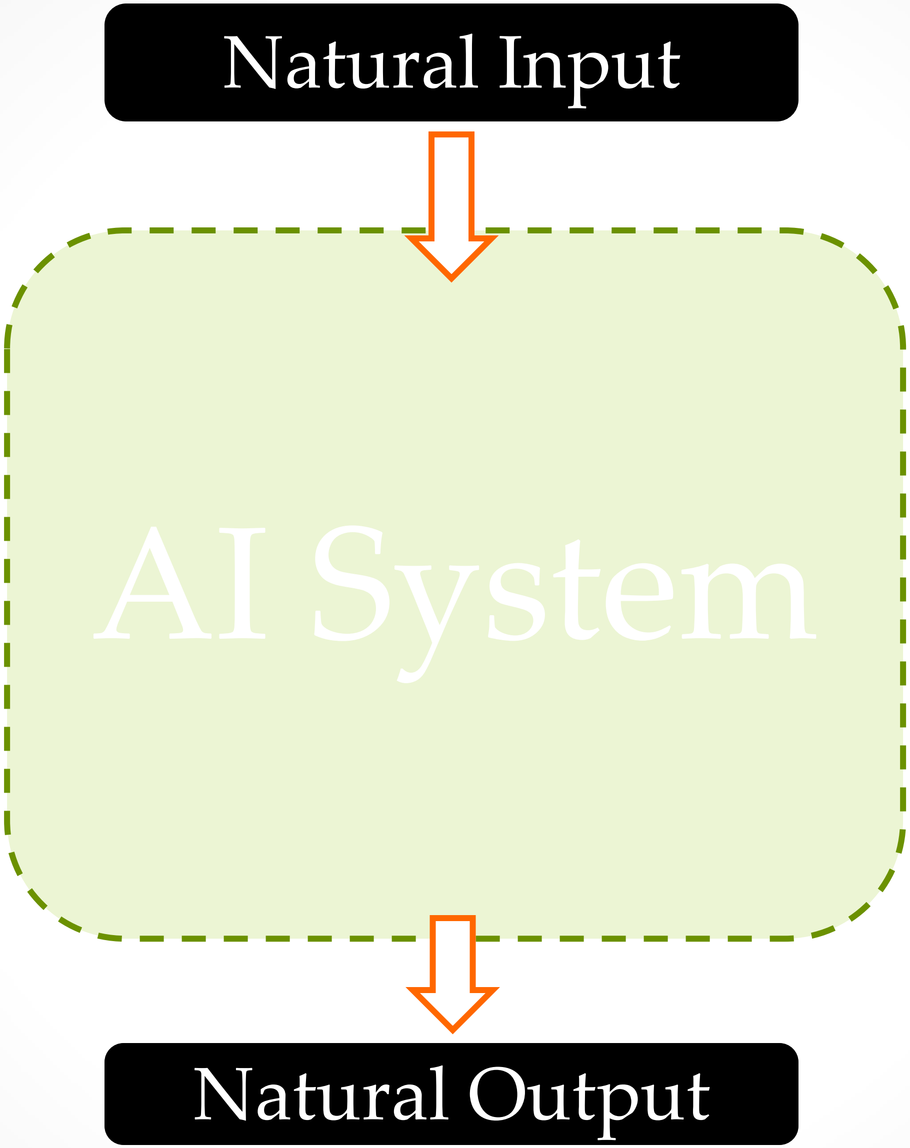


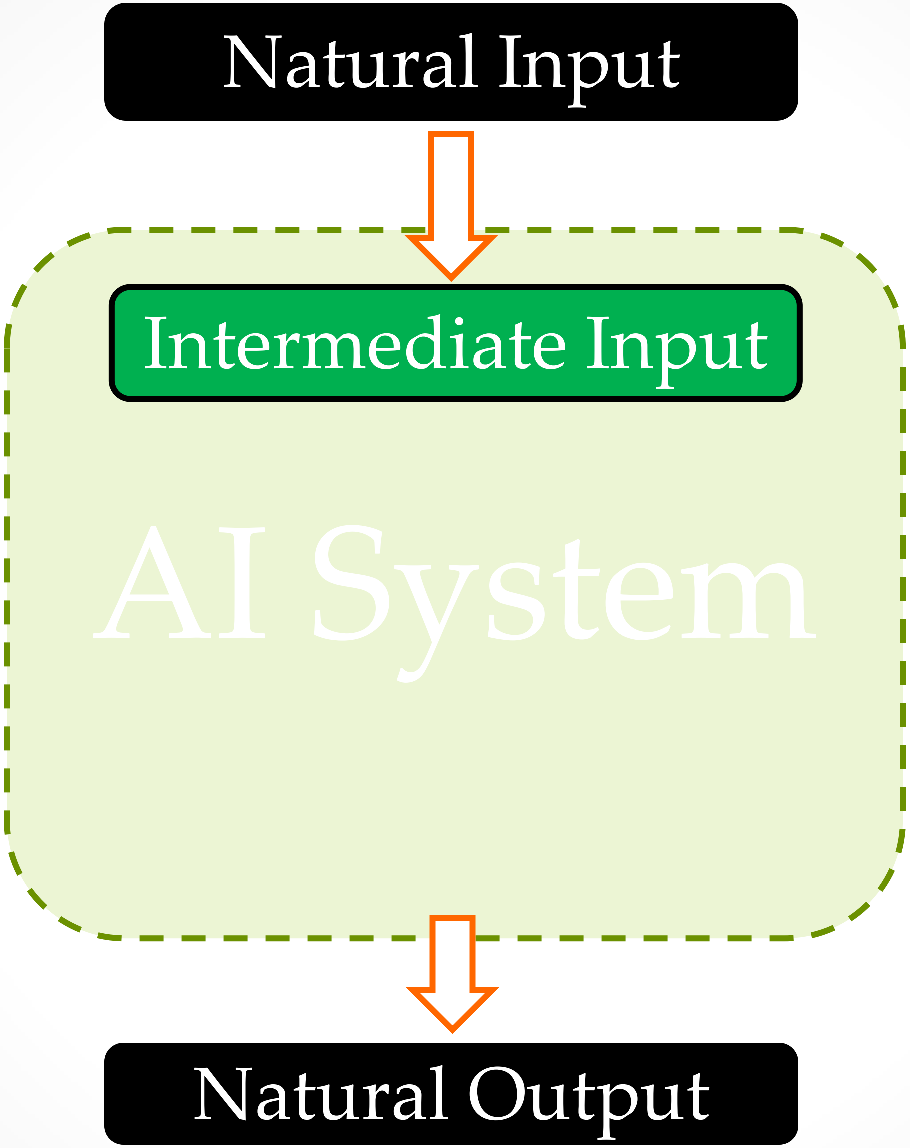
Natural Input

AI System

Natural Output

“What is the sum of five and two?”

“seven”


Natural Input

Intermediate Input

AI System

Natural Output

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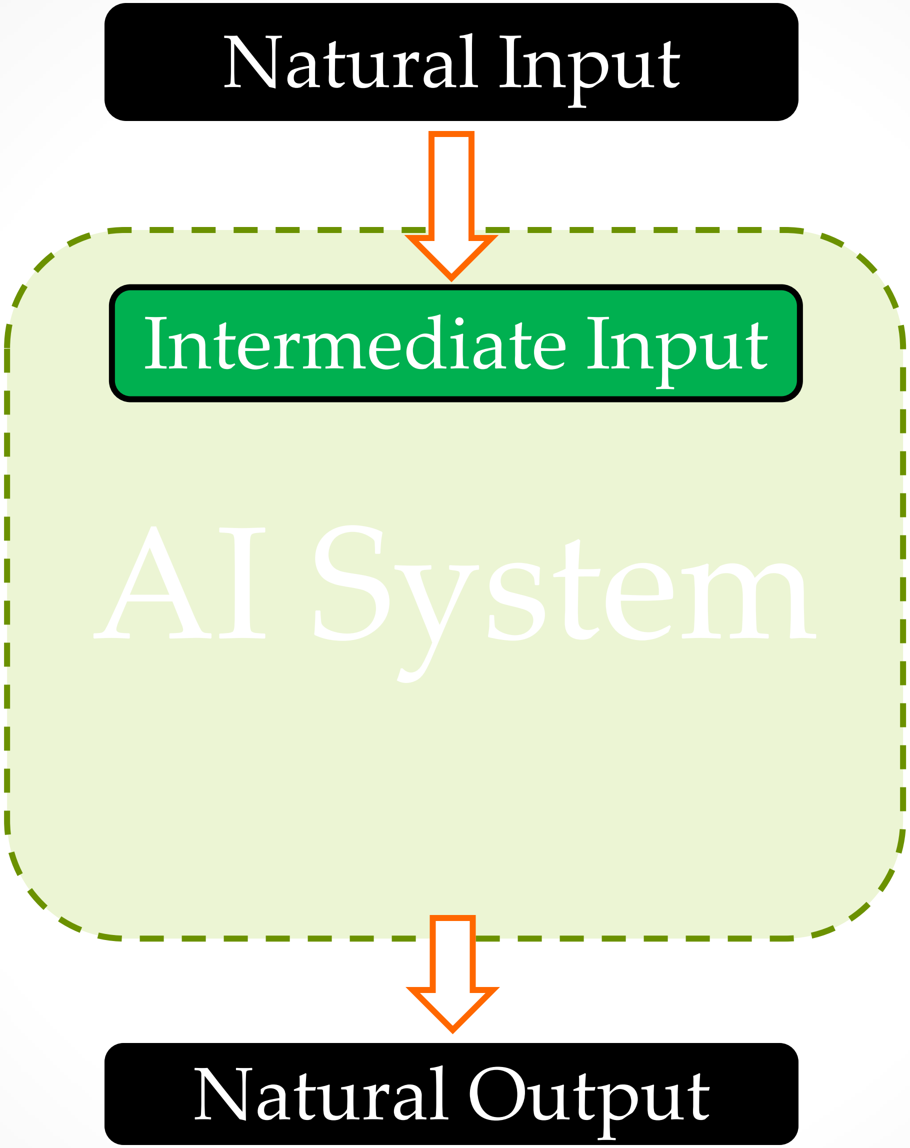


Natural Input

“What is the sum
of five and two?”

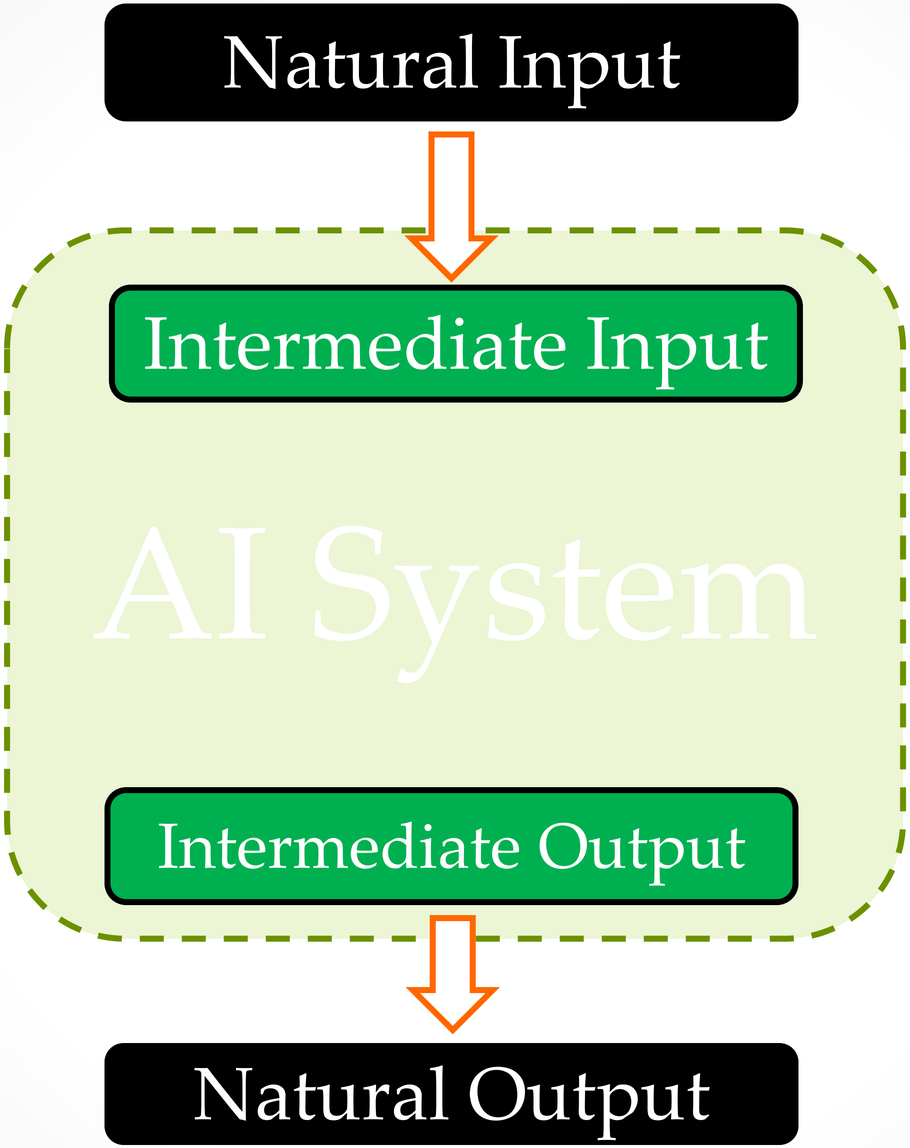
Intermediate Input

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

AI System

Natural Output

“seven”



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AI System

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Intermediate Output

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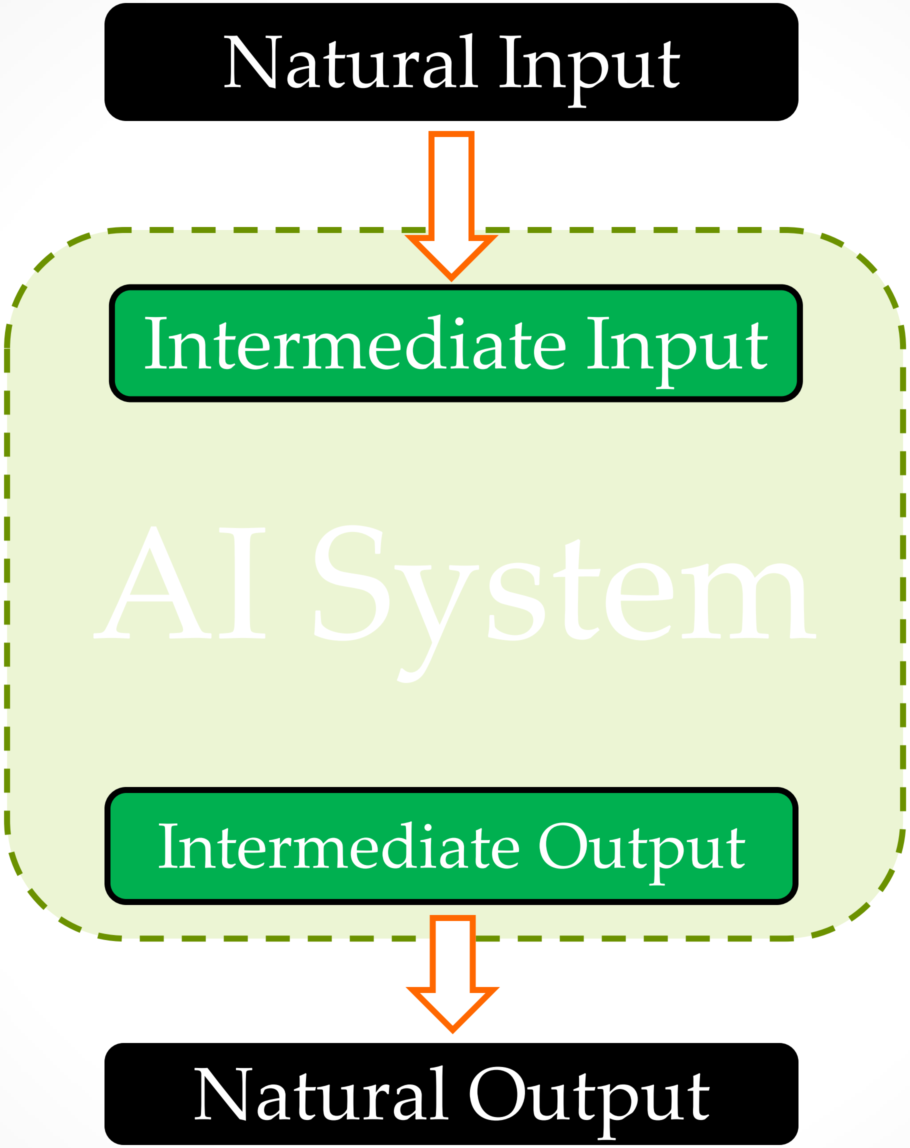
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Goal=7

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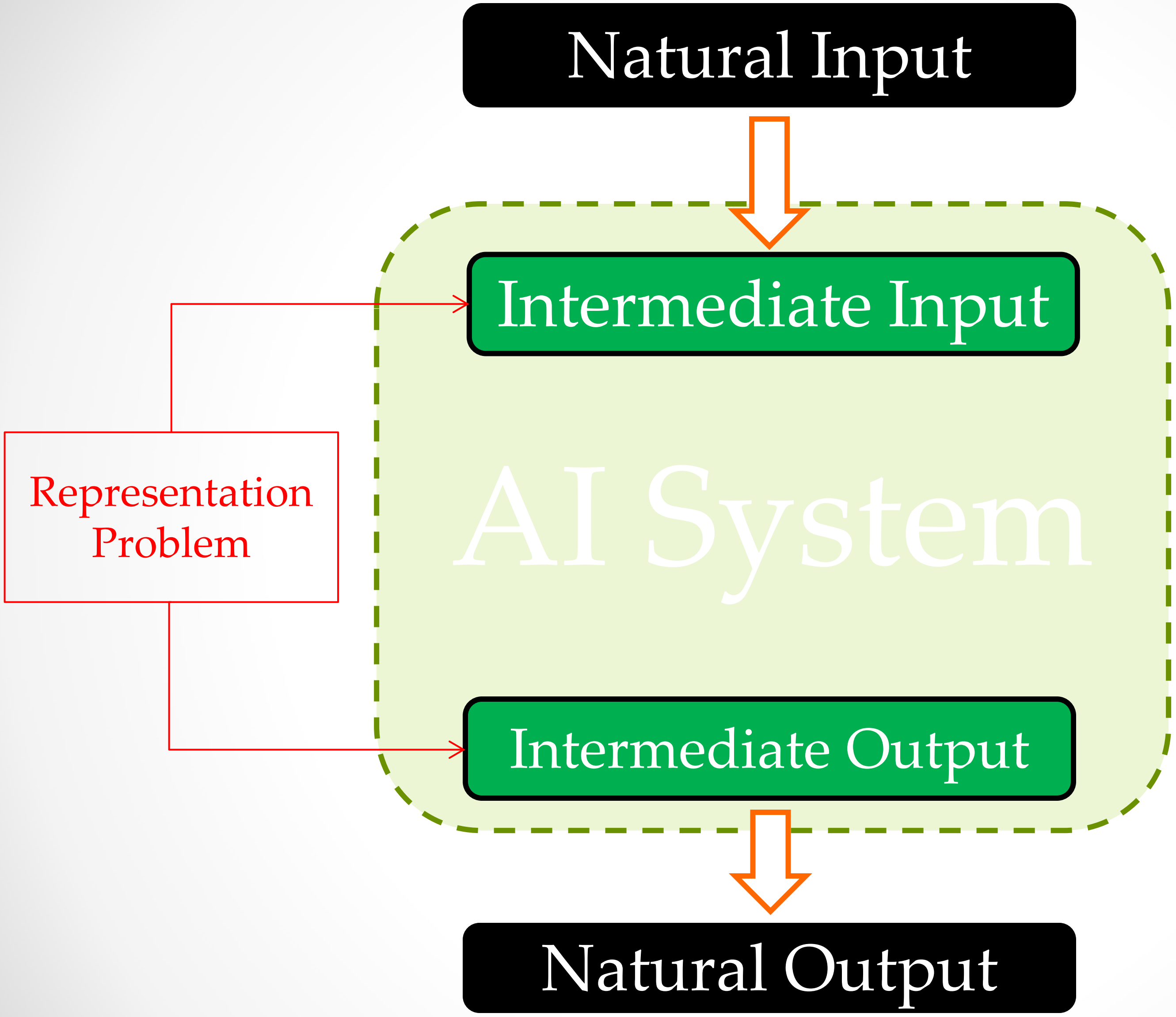

Natural Input

Intermediate Input

AI System

Intermediate Output

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Representation Problem

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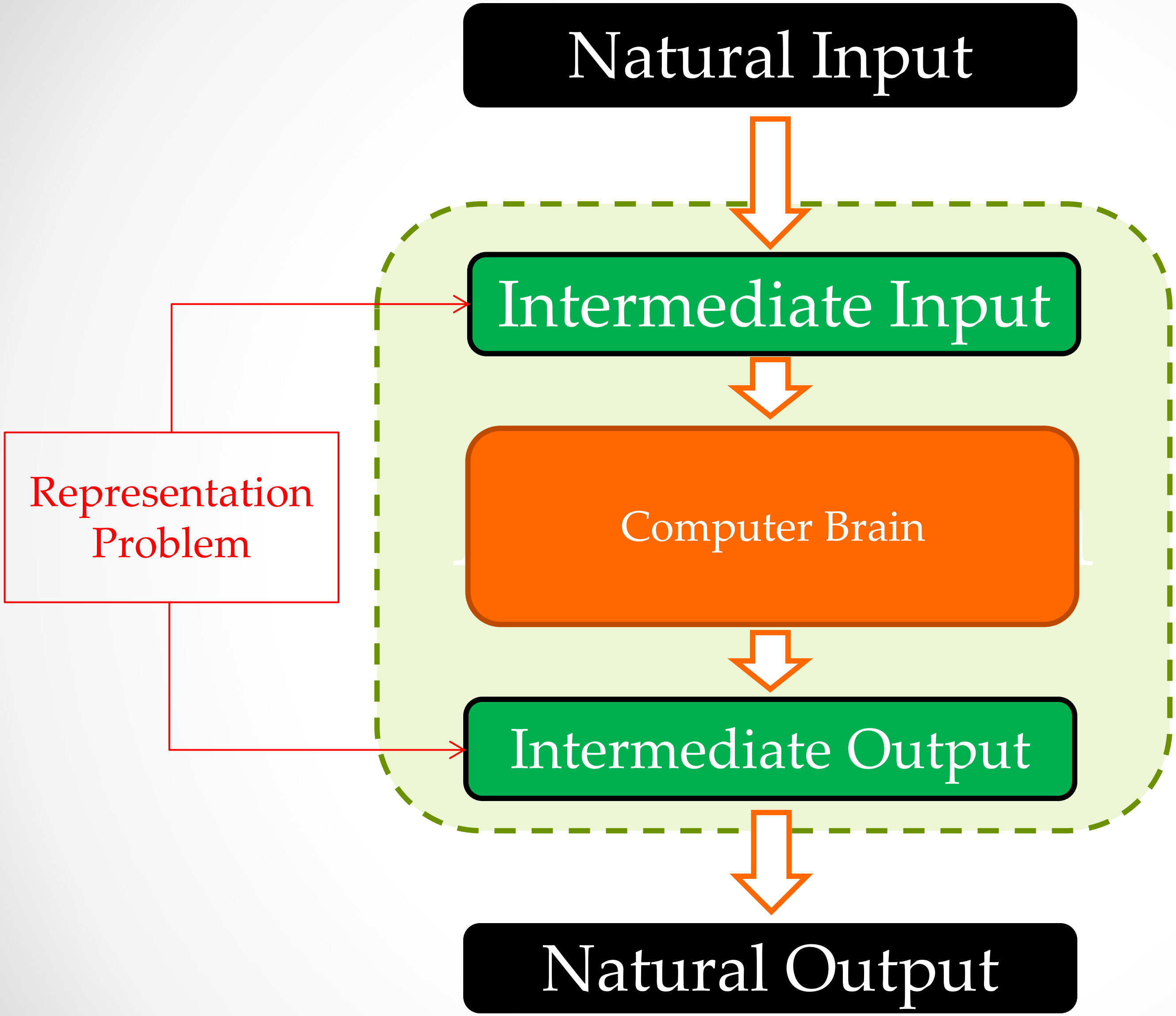

Natural Input

“What is the sum of five and two?”

Intermediate Input

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

Representation Problem

Computer Brain

Intermediate Output

Goal=7

Natural Output

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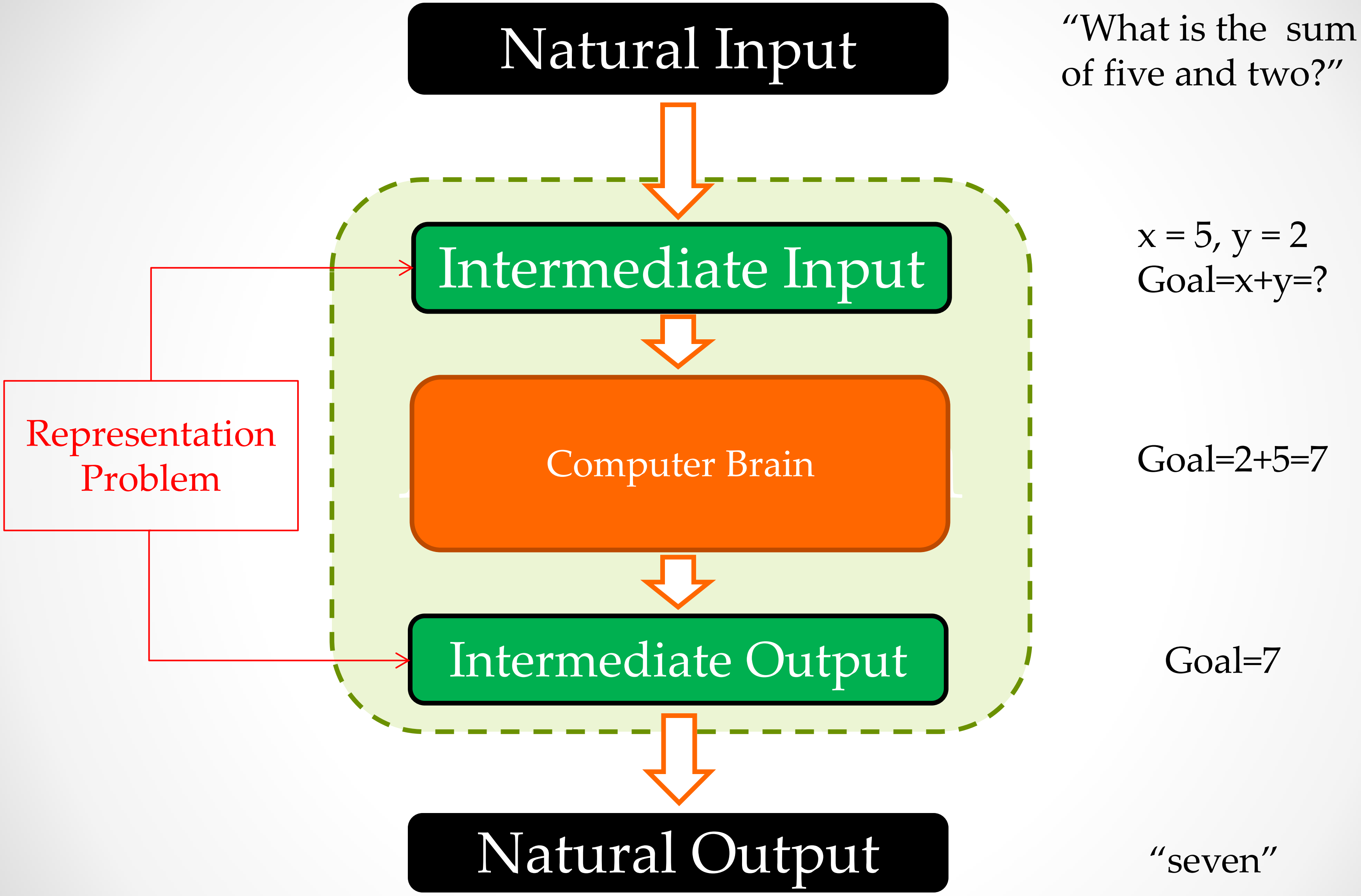

Natural Input

Intermediate Input

Computer Brain

Intermediate Output

Natural Output

Representation Problem

"What is the sum of five and two?"

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

Goal=2+5=7

Goal=7

"seven"

General Problem Solver

(Simon&Newell, 1956)

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Goal: Program for proving theorems !

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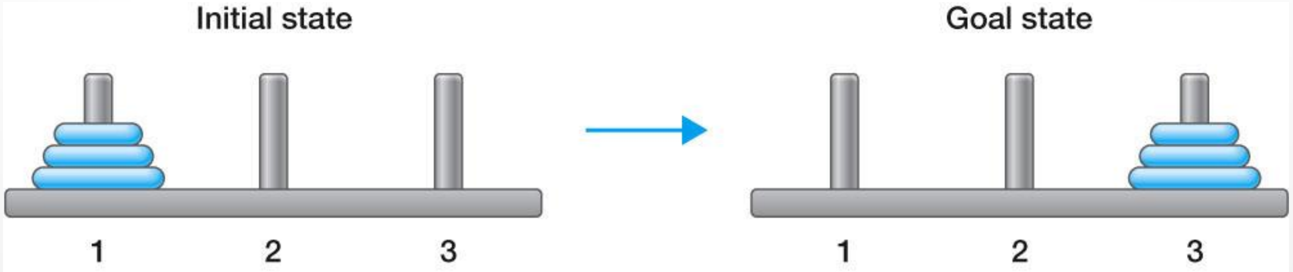

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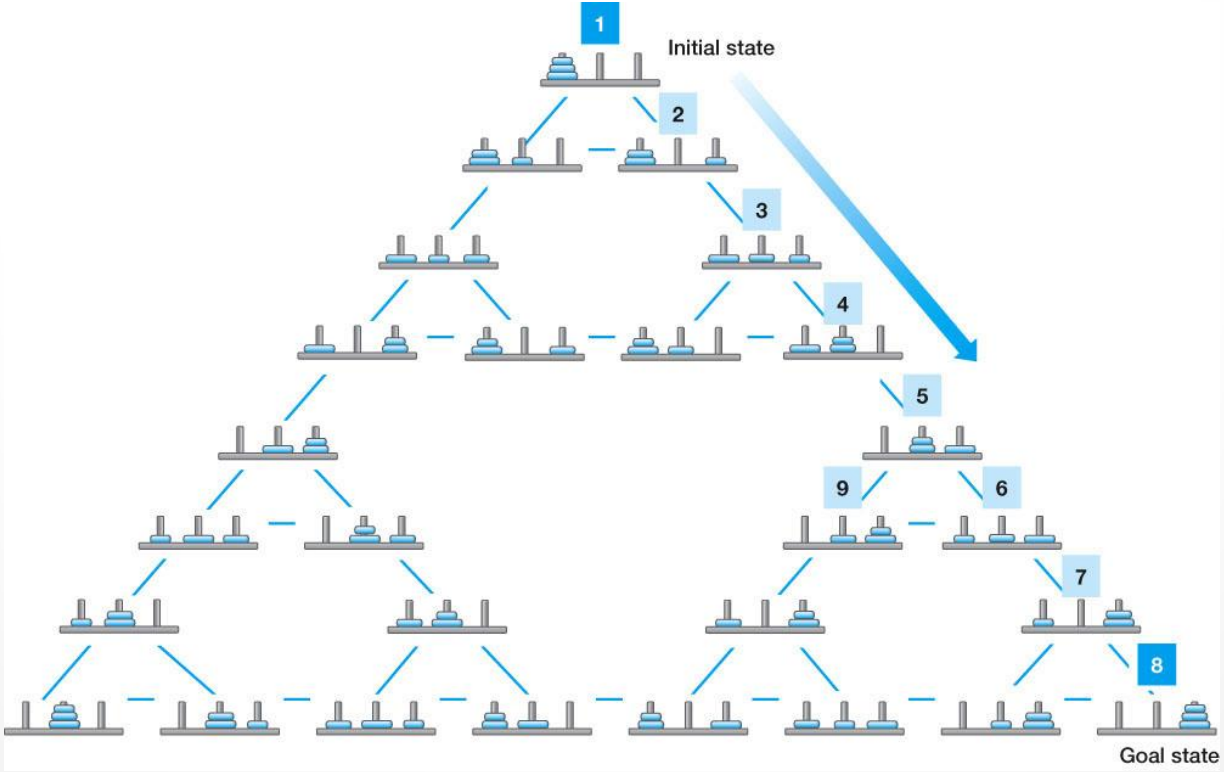

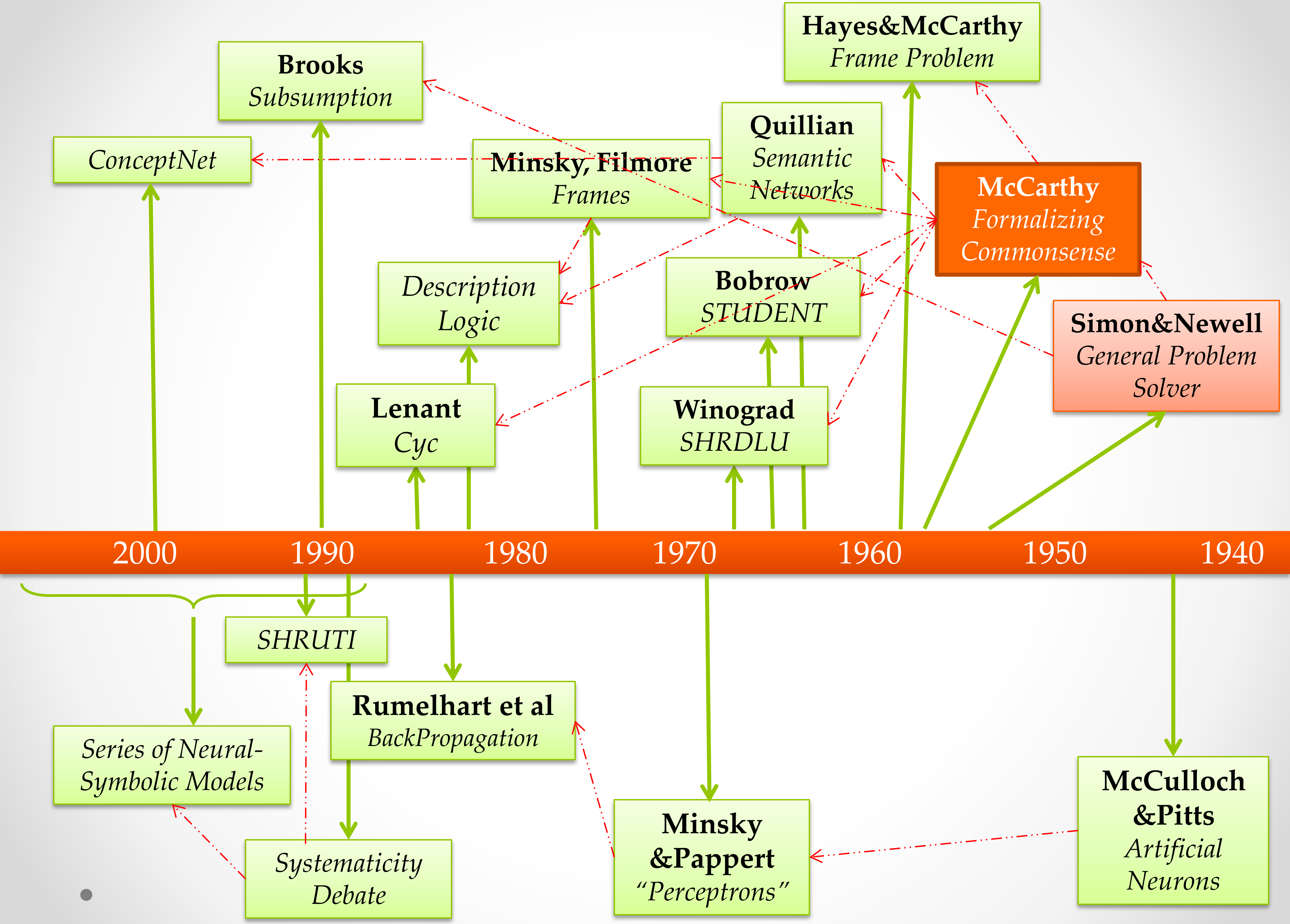

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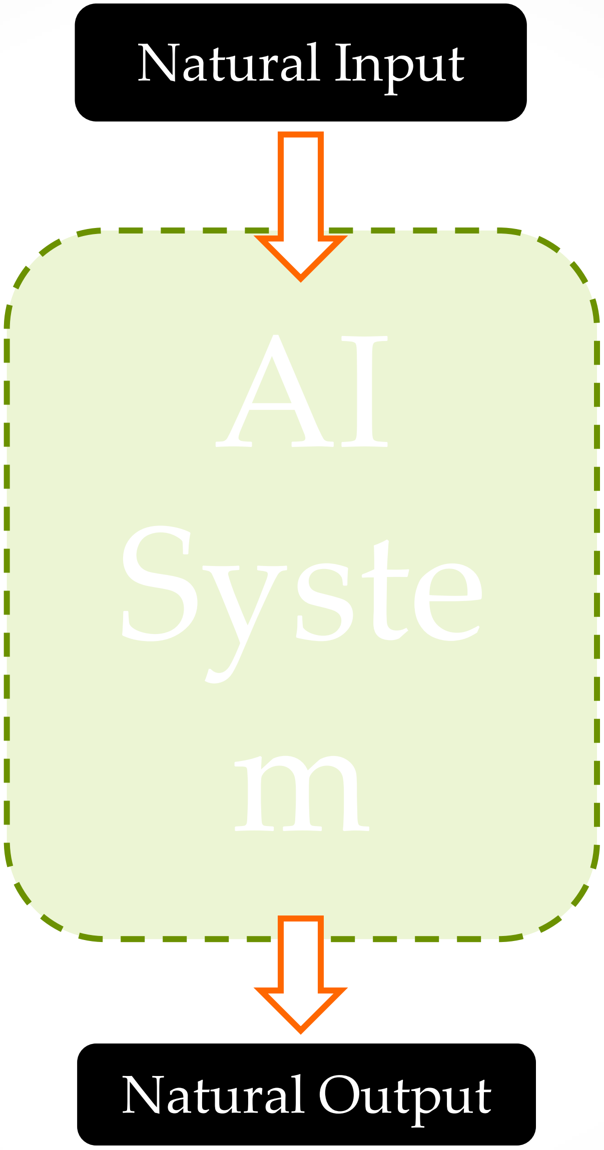
Is he my sibling?"



Natural Input

AI
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“Jack is my brother.
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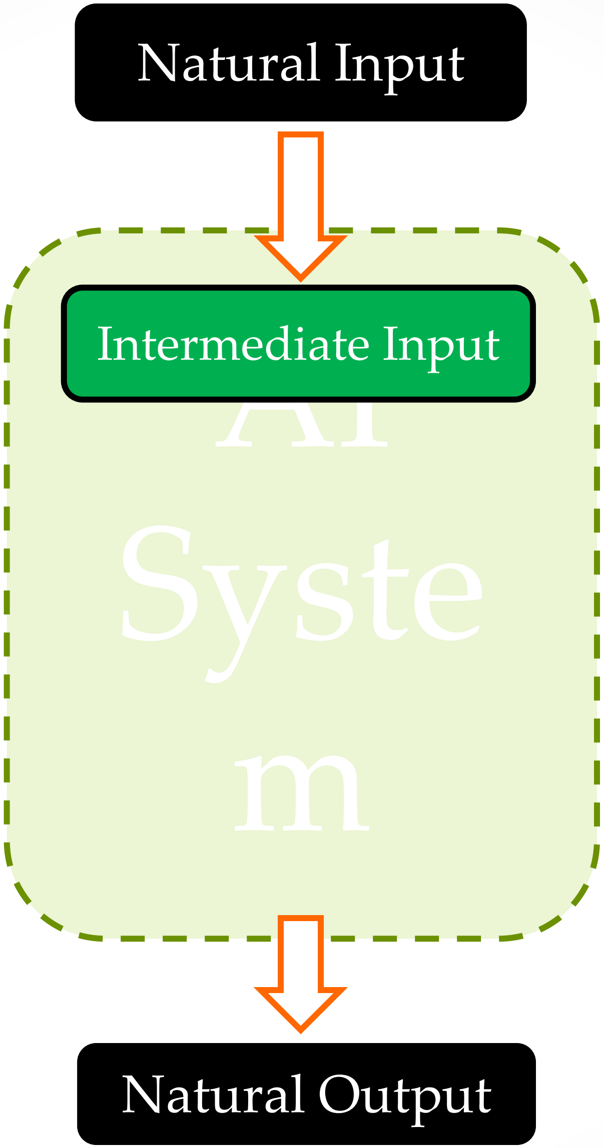

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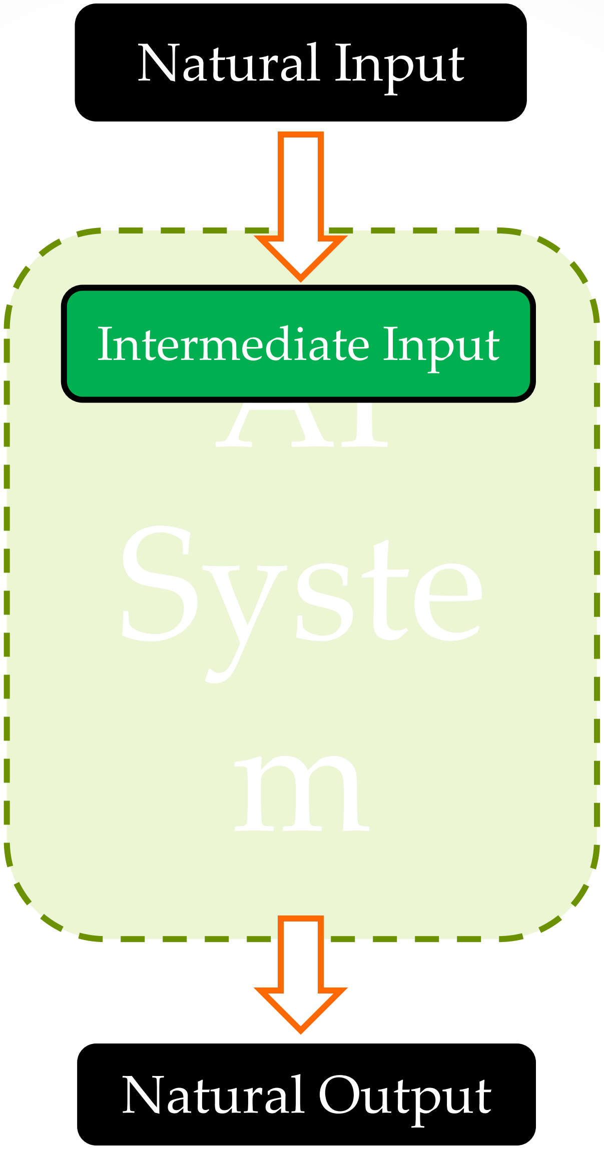


Natural Input

Intermediate Input

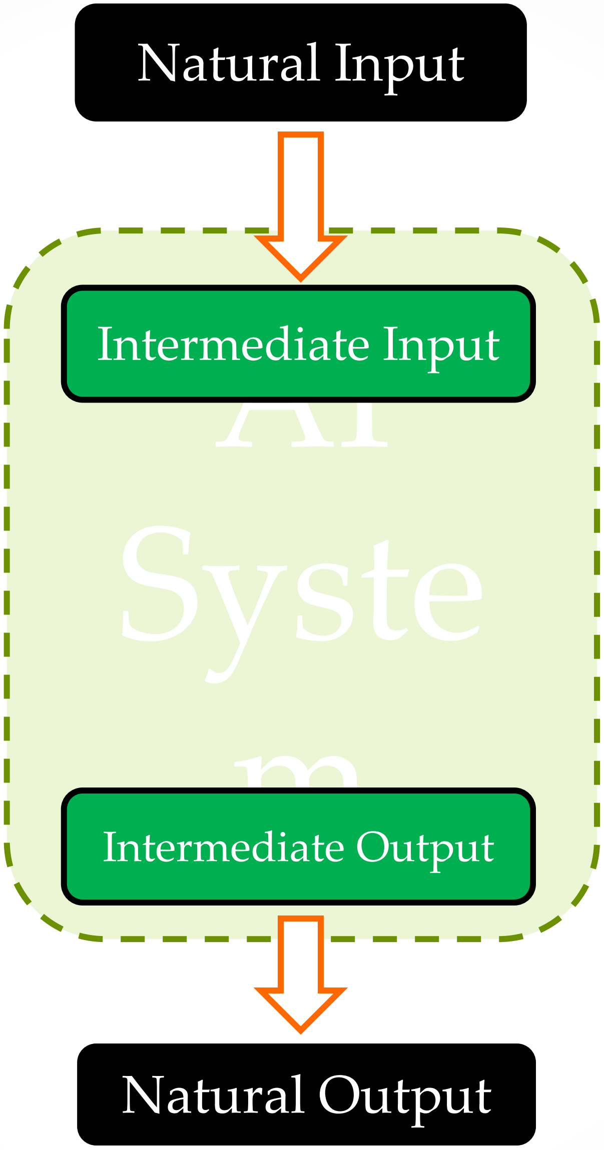
AI System

Natural Output

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

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

“yes”



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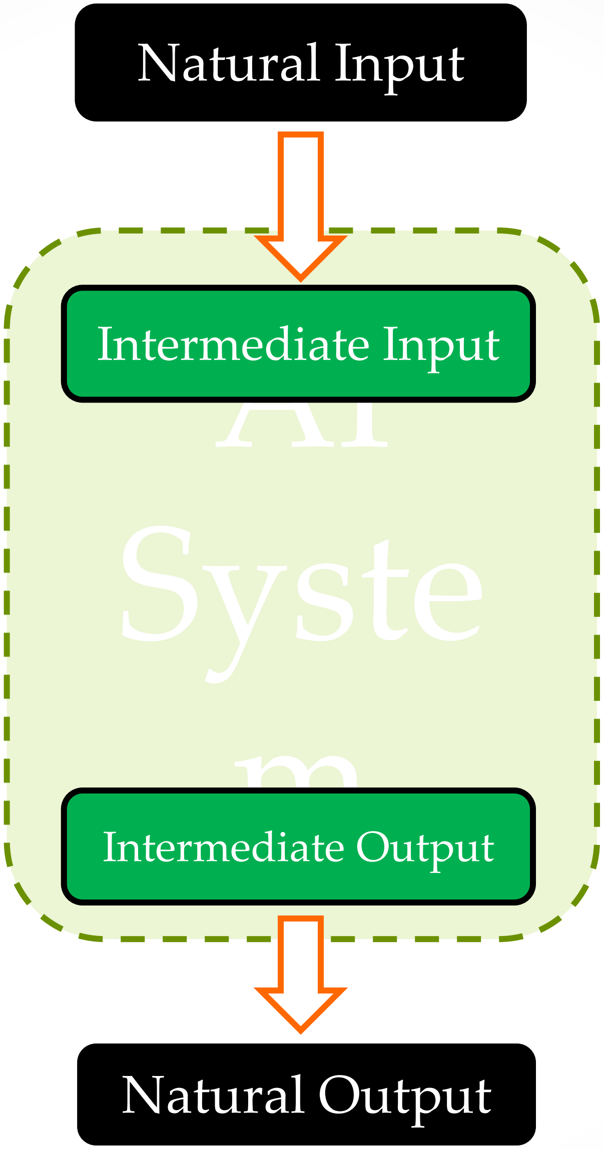

Natural Input

“Jack is my brother.
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Intermediate Input

Premise:
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AI System

Intermediate Output

sibling(“Jack”,“I”): TRUE

Natural Output

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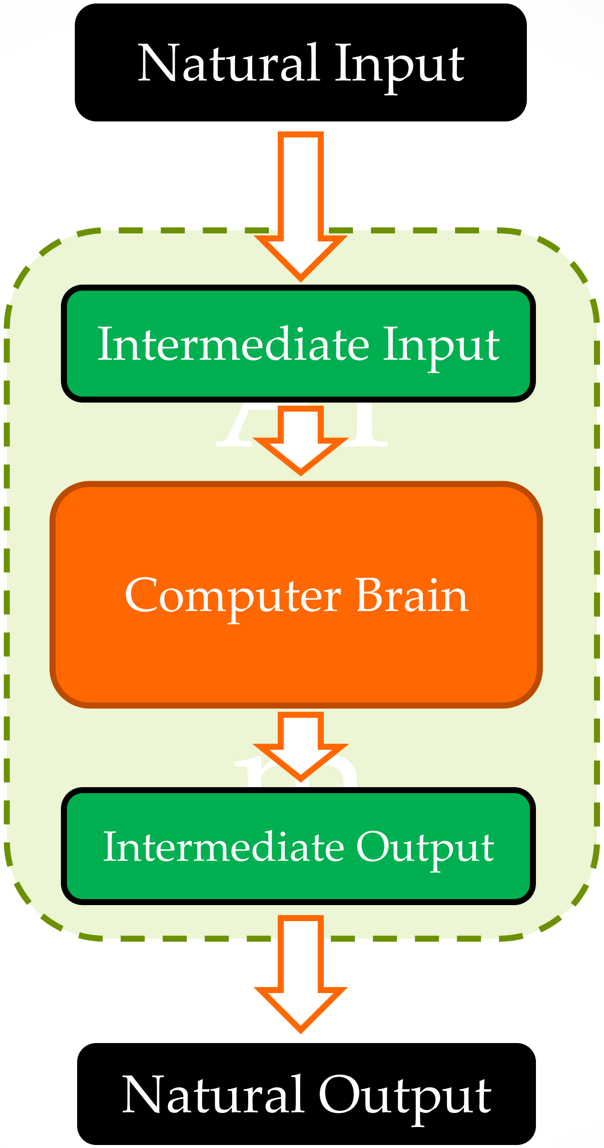

Natural Input

Intermediate Input

Computer Brain

Intermediate Output

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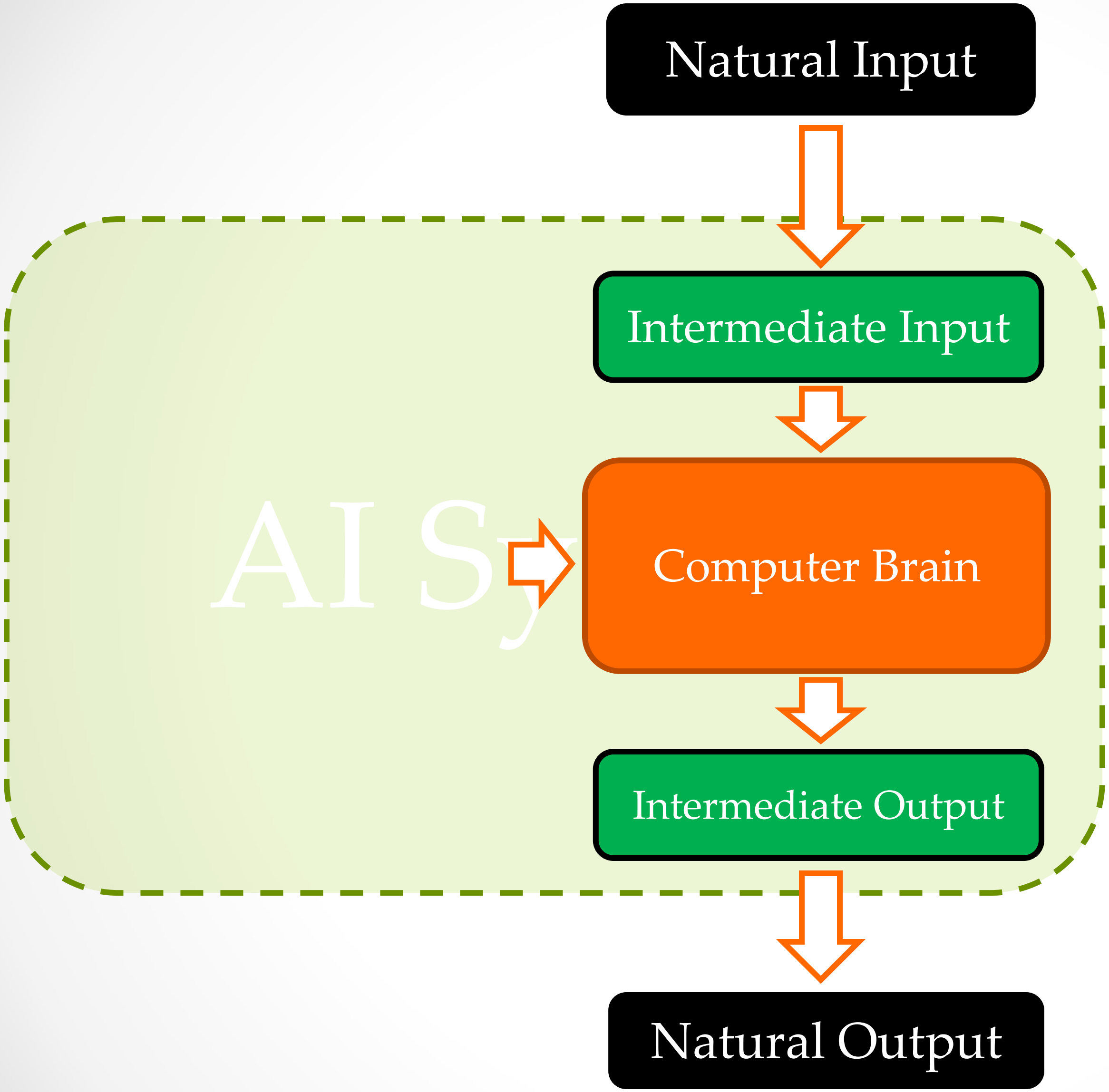

Natural Input

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"Jack is my brother.
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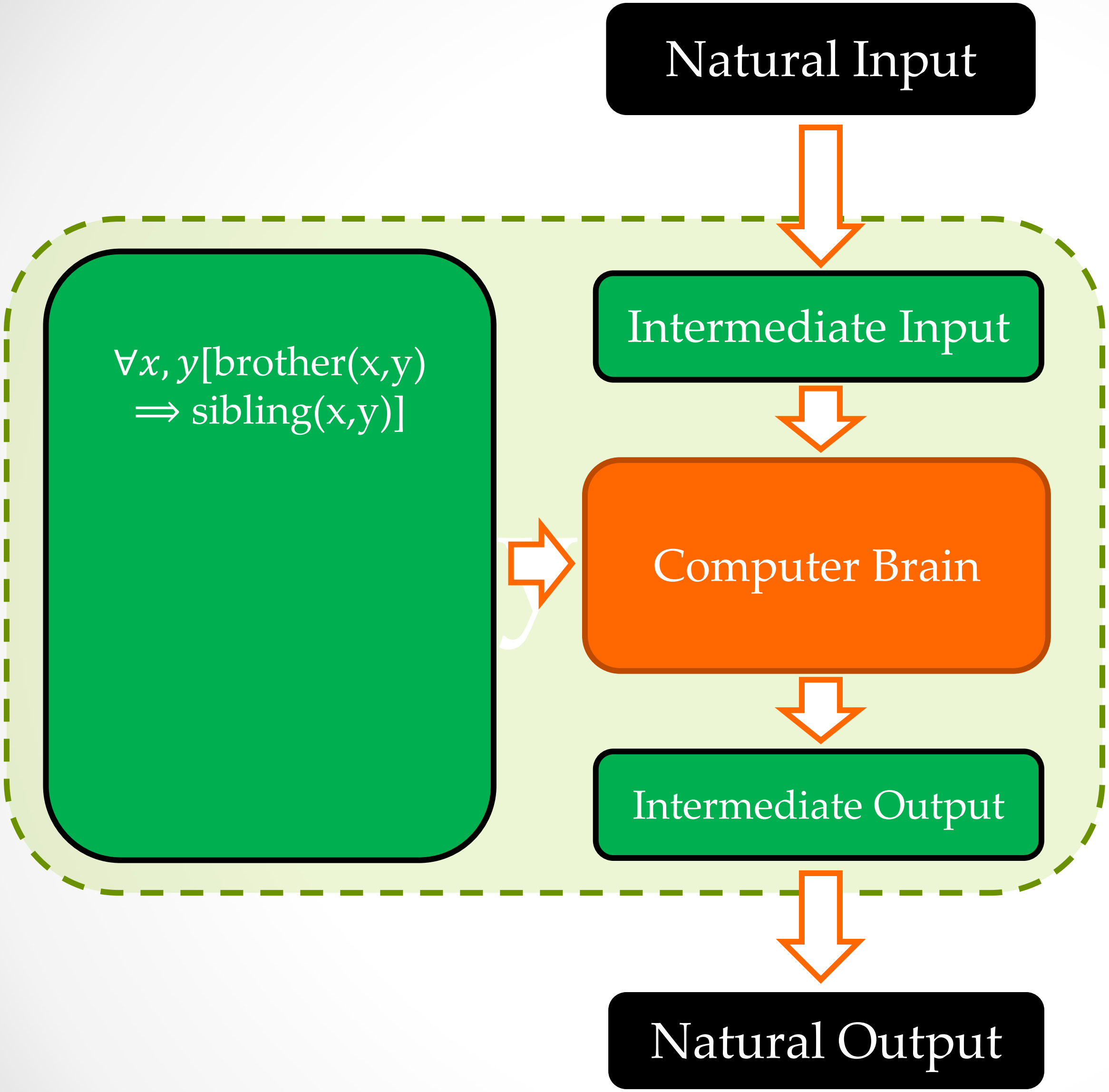

Natural Input

Intermediate Input

$\forall x, y[\text{brother}(x,y) \implies \text{sibling}(x,y)]$

Computer Brain

Intermediate Output

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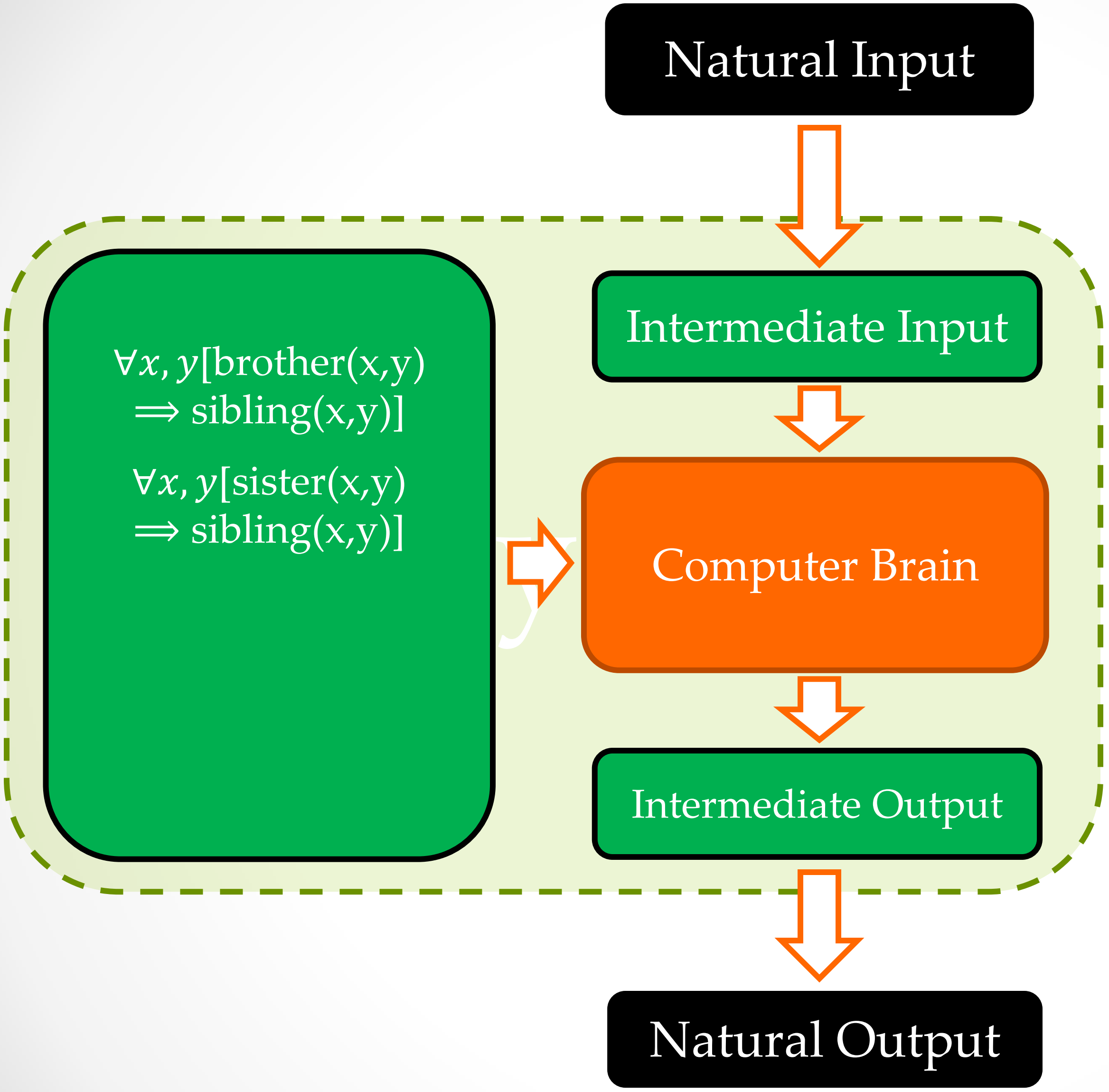

Natural Input

$$\forall x, y[\text{brother}(x,y) \implies \text{sibling}(x,y)]$$

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Intermediate Input

Computer Brain

Intermediate Output

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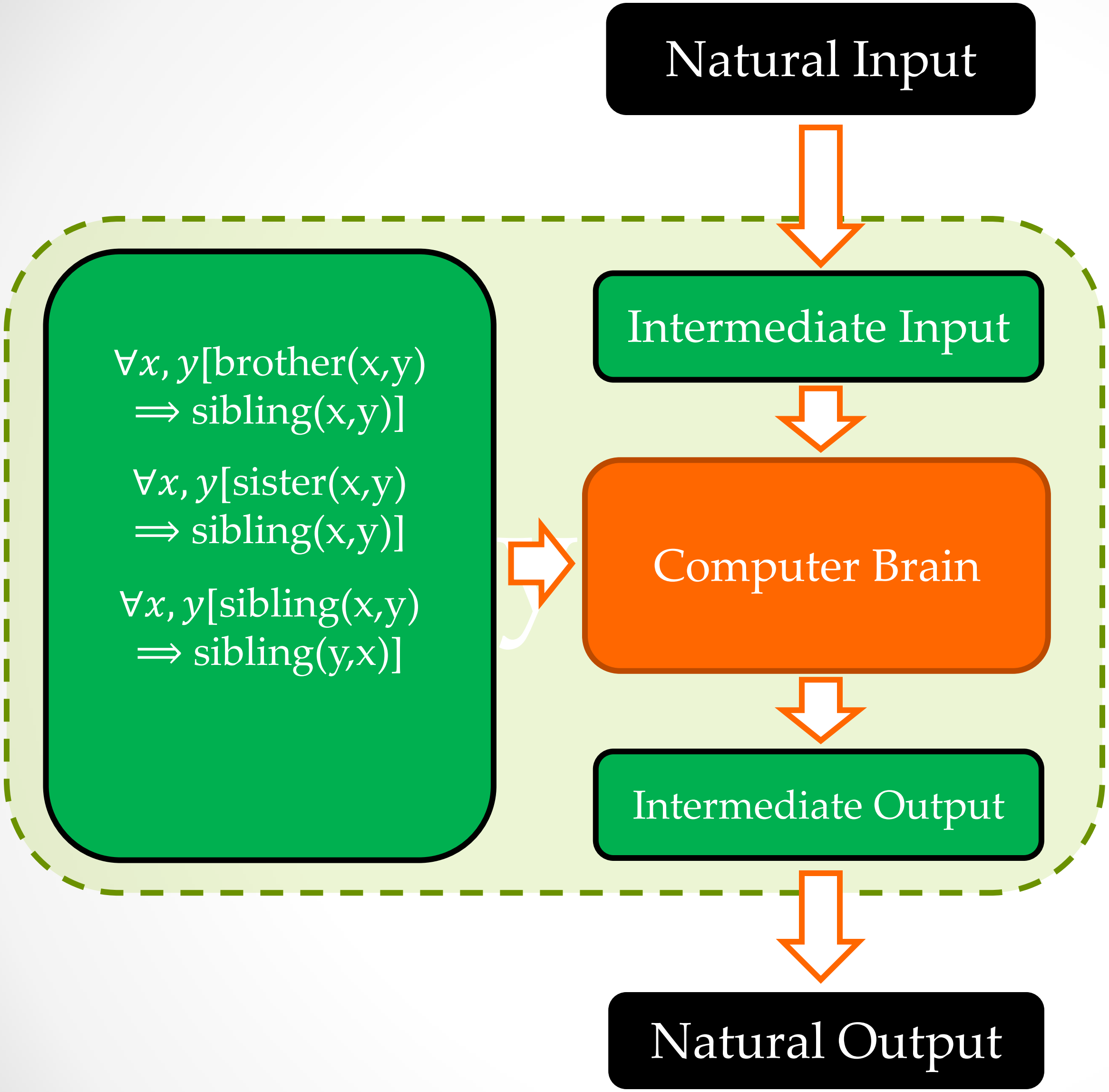

Natural Input

Intermediate Input

$\forall x, y[\text{brother(x,y)} \implies \text{sibling(x,y)}]$

$\forall x, y[\text{sister(x,y)} \implies \text{sibling(x,y)}]$

$\forall x, y[\text{sibling(x,y)} \implies \text{sibling(y,x)}]$

Computer Brain

Intermediate Output

Natural Output

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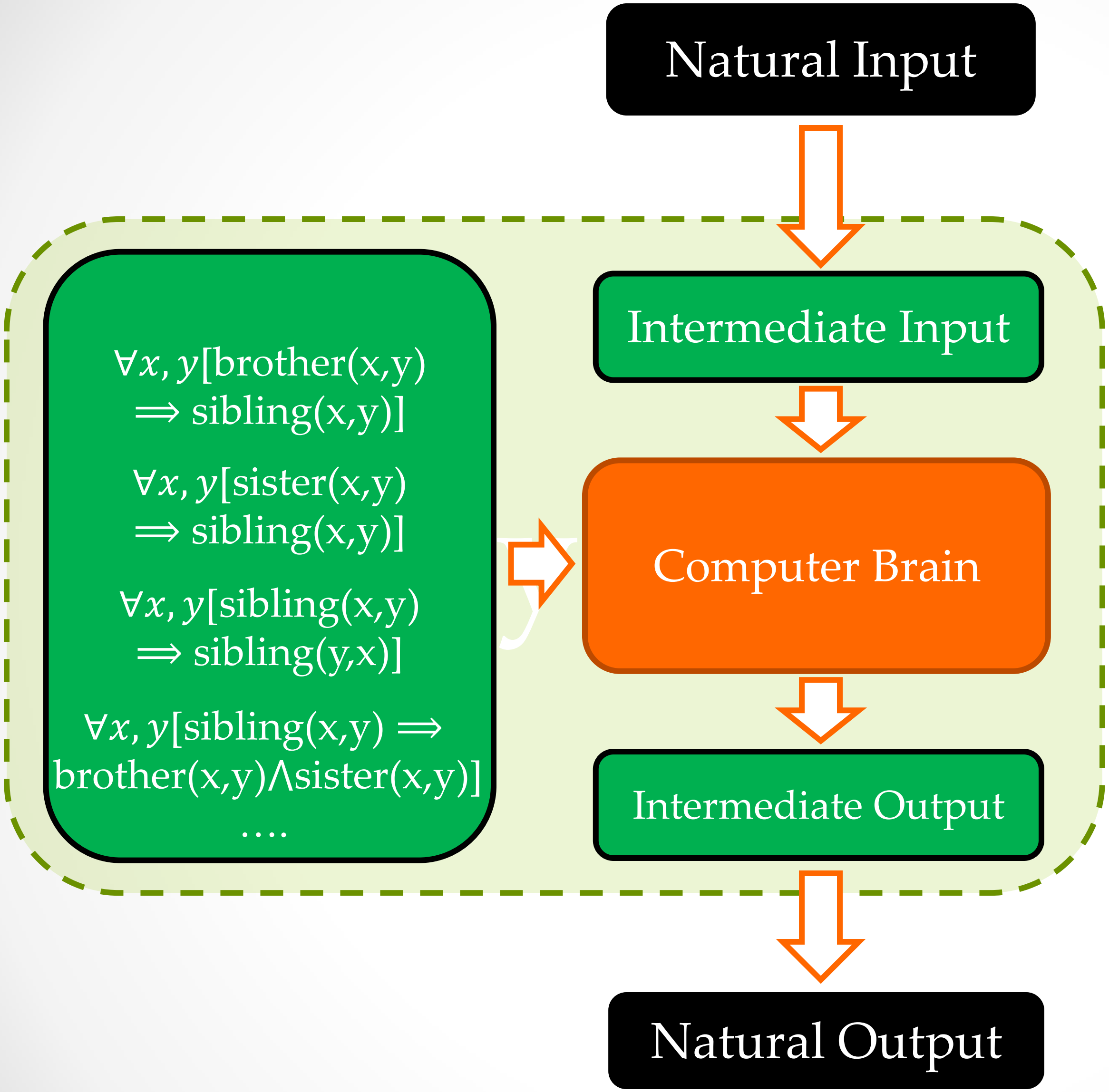

Natural Input

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Computer Brain

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$\forall x, y[\text{brother(x,y)} \Longrightarrow \text{sibling(x,y)}]$

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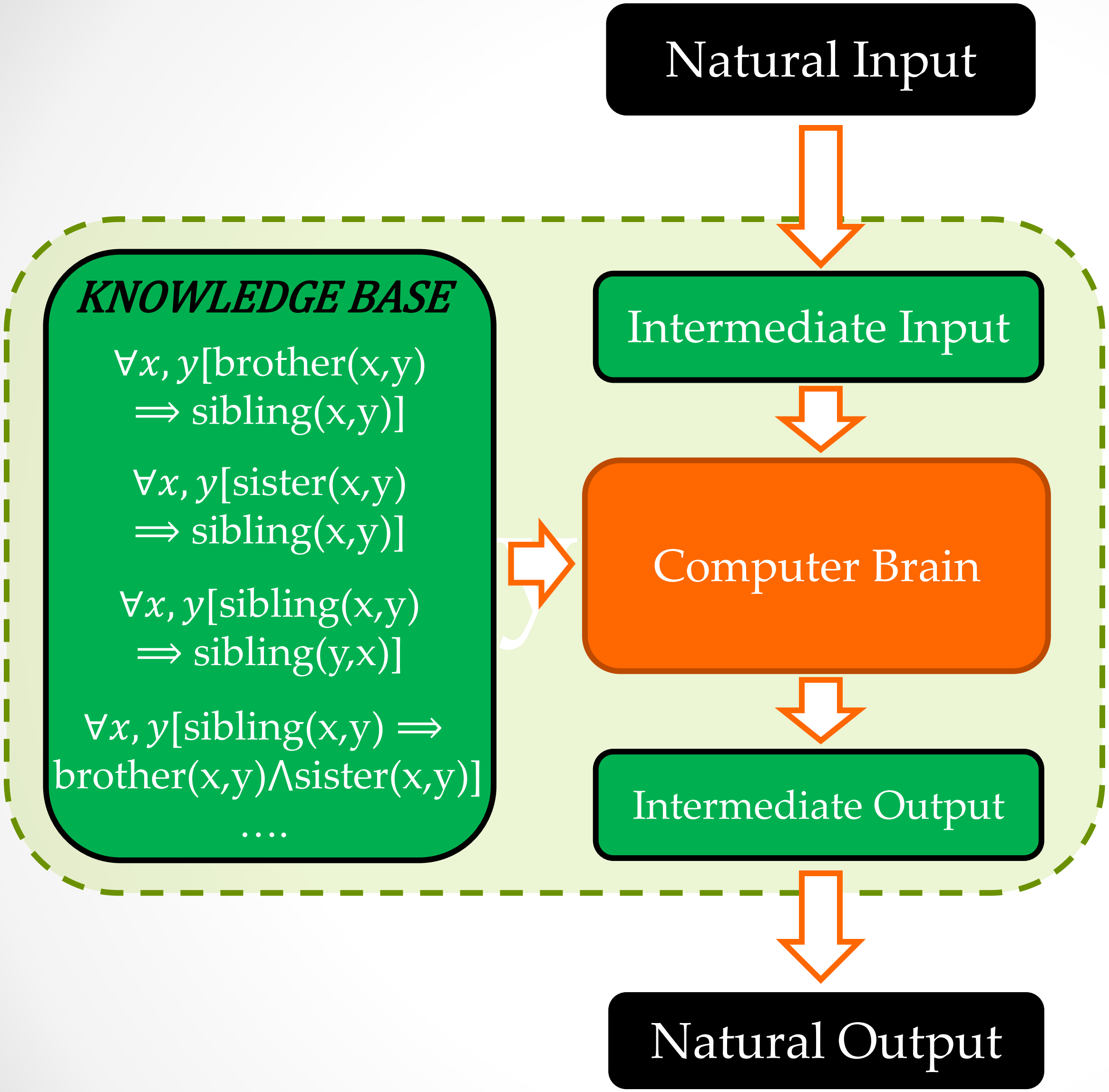

Natural Input

KNOWLEDGE BASE

$\forall x, y[\text{brother}(x,y) \Longrightarrow \text{sibling}(x,y)]$

$\forall x, y[\text{sister}(x,y) \Longrightarrow \text{sibling}(x,y)]$

$\forall x, y[\text{sibling}(x,y) \Longrightarrow \text{sibling}(y,x)]$

$\forall x, y[\text{sibling}(x,y) \Longrightarrow \text{brother}(x,y) \land \text{sister}(x,y)]$

….

Intermediate Input

Computer Brain

Intermediate Output

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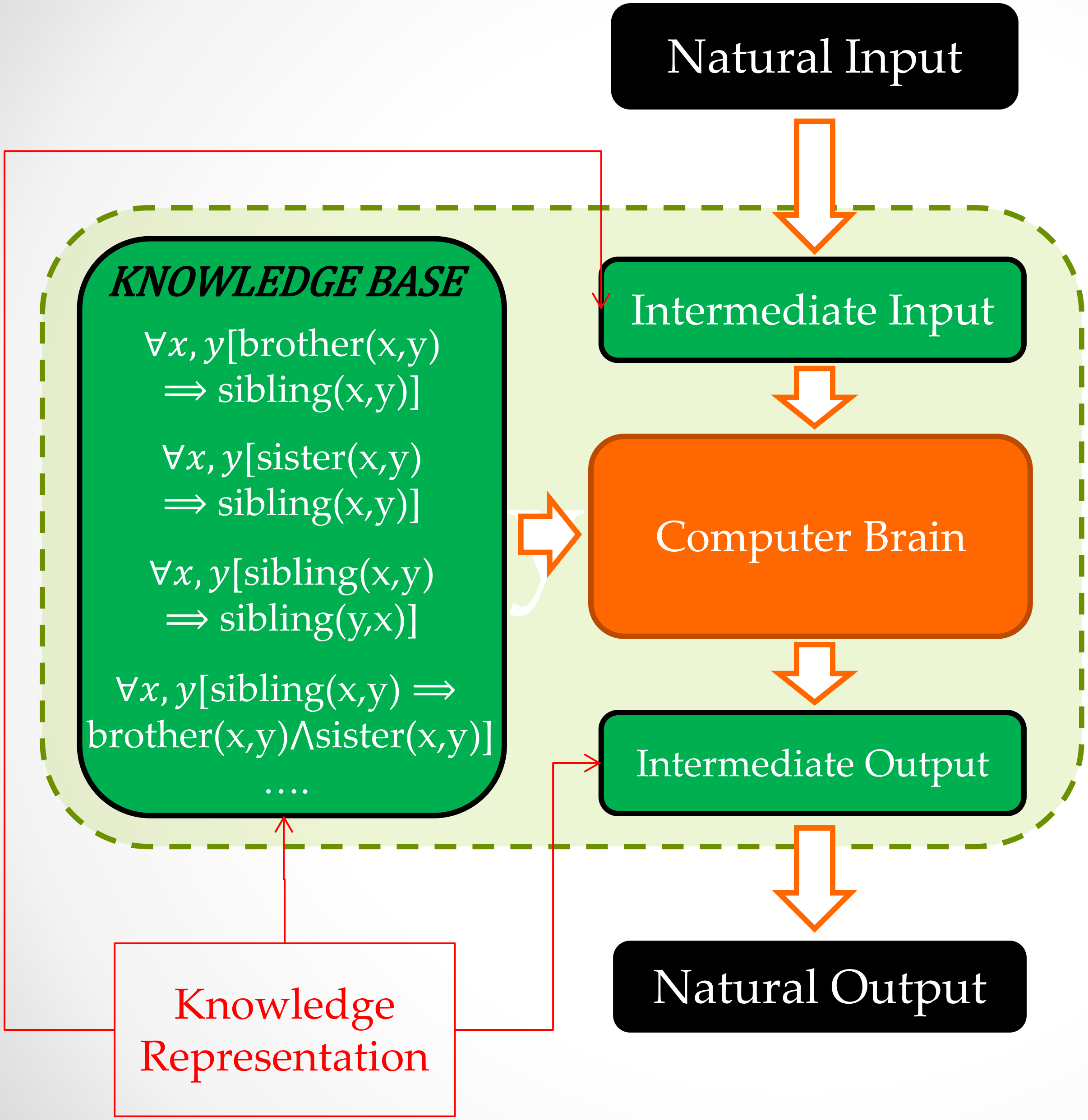

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Knowledge Representation

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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)

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

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)

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:

Logical Reasoning

Deduction: Conclusion from given axioms (facts or observations)

All humans are mortal. *Socrates is a human.*	(axiom) (fact/ premise)
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Induction: Generalization from background knowledge or observations

Socrates is a human *Socrates is mortal*	(background knowledge) (observation/ example)
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Abduction: Simple and mostly likely explanation, given observations

Logical Reasoning

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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

All humans are mortal	(theory)
Socrates is mortal	(observation)
Therefore, Socrates must have been a human	(diagnosis)

Programs With Commonsense

(John McCarthy, 1959)

Formalize world in **logical** form!

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Example:
"My desk is at home" → at(I, desk)
"Desk is at home" → at(desk, home)

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Hypothesis: Commonsense knowledge can be formalized with logic.

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Example Contd.:

$\forall x \forall y \forall z$ at(x,y), at(y,z)→ at(x, z)

∴ at(I, home)

Programs With Commonsense

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Formalize world in **logical** form!

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Do **reasoning** on formal premises!

Example Contd.:
$\forall x \forall y \forall z \; at(x,y), at(y,z) \rightarrow at(x, z)$
$\therefore \; at(I, home)$

Hypothesis: Commonsense problems are solved by logical reasoning

STUDENT

(Daniel G Bobrow, 1964)

Goal: Elementary school algebra problem solver
Input: Natural Language

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

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Example: Bill s father s uncle is twice as old as bills 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.

STUDENT

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Goal: Elementary school algebra problem solver
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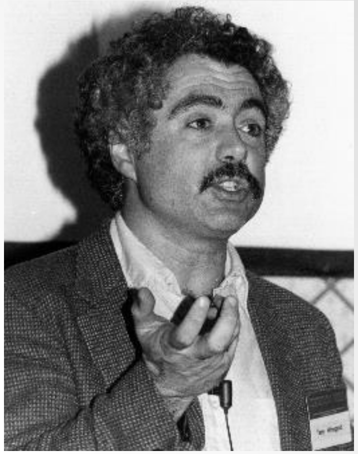
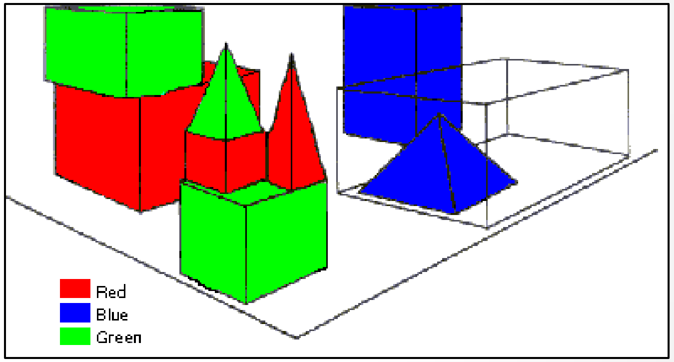
Example: The distance between New York to Los Angeles is 3000 miles. If the average speed of a jet place is 600 miles per hour find the time it takes to travel from New York to Los Angeles by jet.

SHRDLU

(Terry Winograd, 1968)



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



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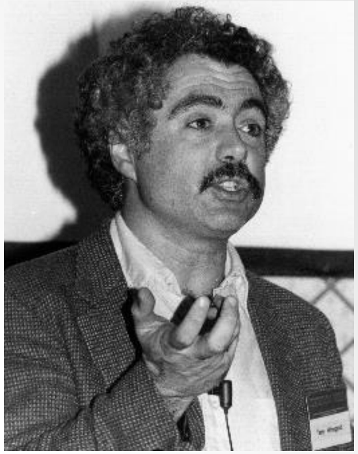
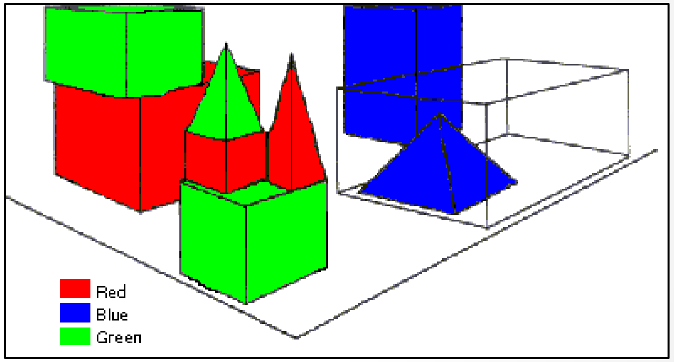
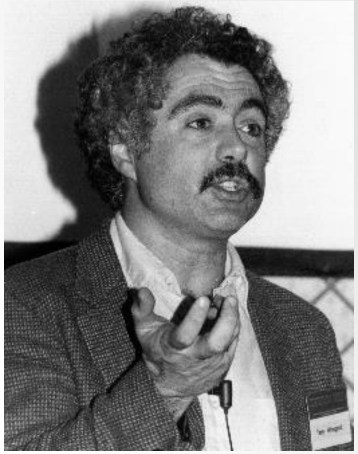


Person: Pick up a big red block.
Computer: OK.
Person: Grasp the pyramid.
Computer: I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.



SHRDLU

(Terry Winograd, 1968)



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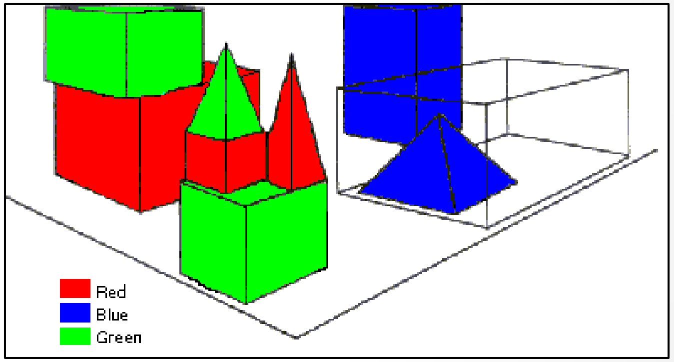

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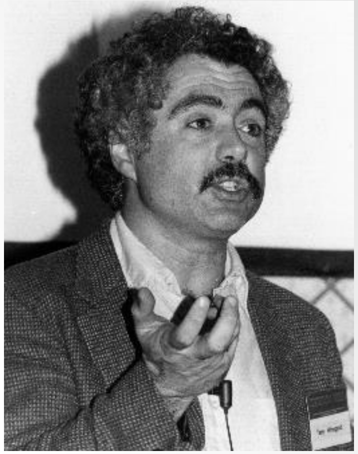

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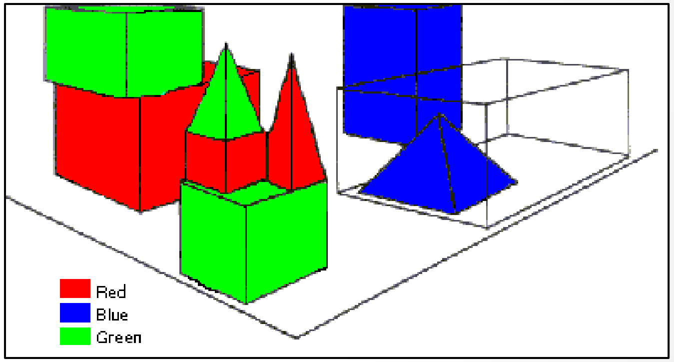
Computer: BY "IT", I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.

Computer: OK.

Person: What does the box contain?



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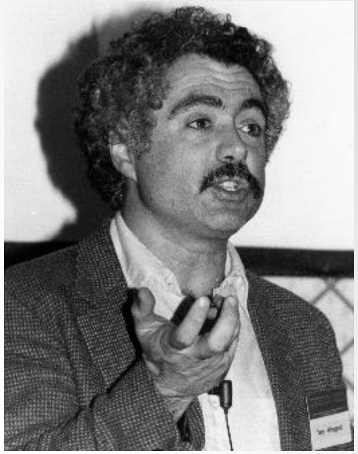

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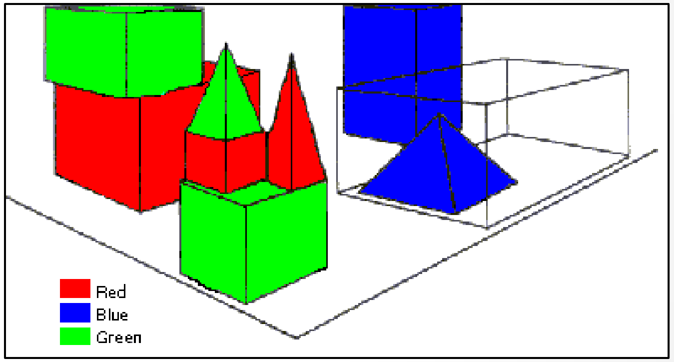

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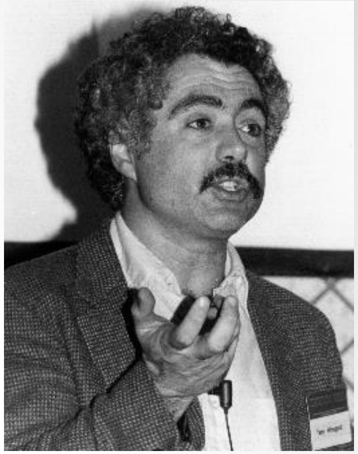

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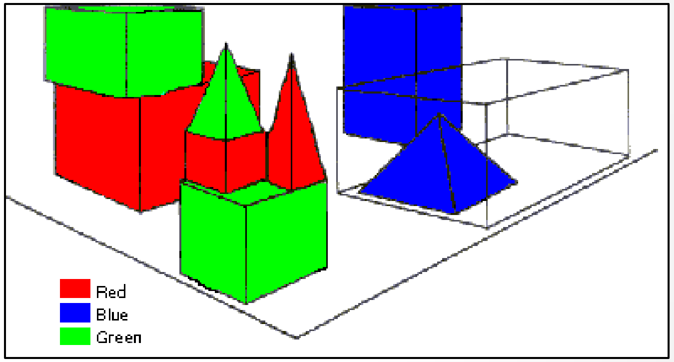
Computer: THE BOX.

Person: How many blocks are not in the box?



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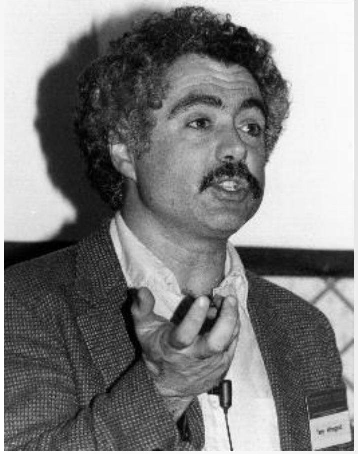

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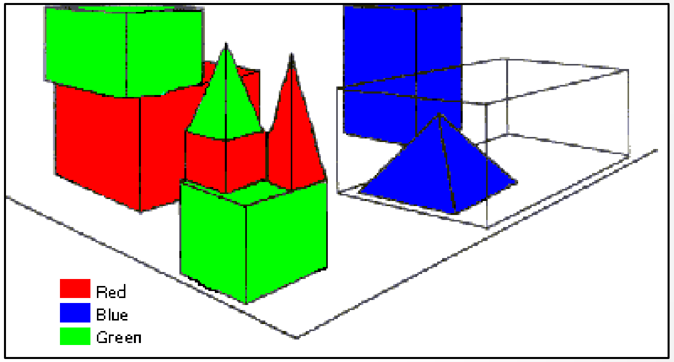

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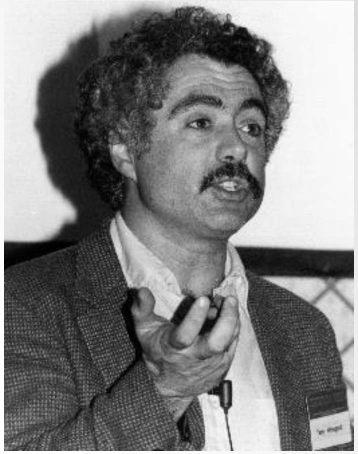

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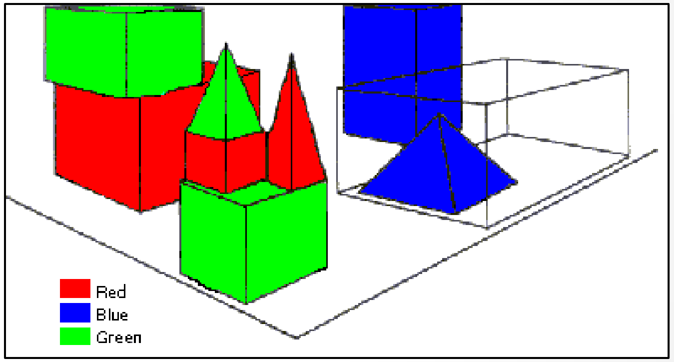

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Computer: YES, THE RED CUBE.

Person: Is it supported?

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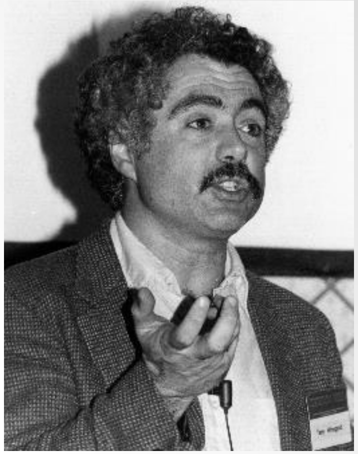

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Computer: FOUR OF THEM.
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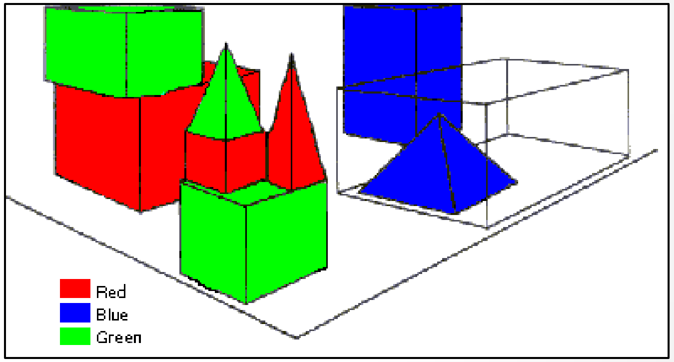
Computer: YES, THE RED CUBE.
Person: Is it supported?
Computer: YES, BY THE TABLE.
Person: Can the table pick up blocks?



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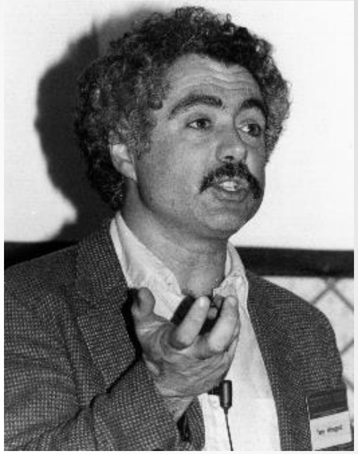

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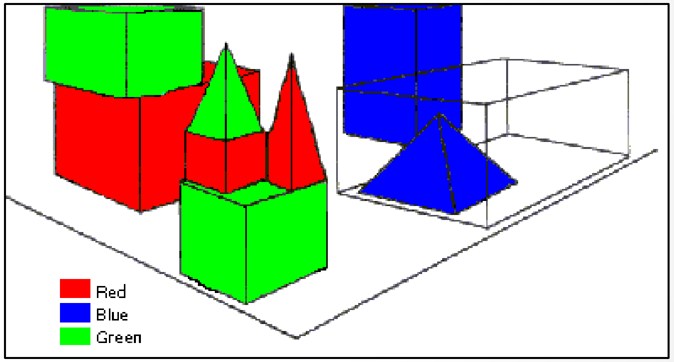

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Computer: YES, THE RED CUBE.

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

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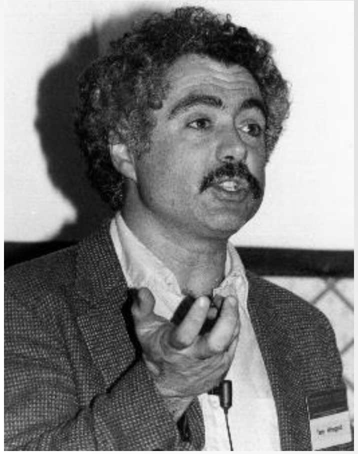

Basic rules:

- Small world
- Memory
- Deduction rule
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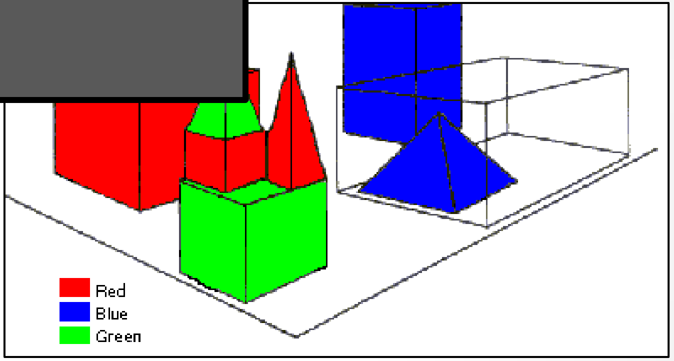

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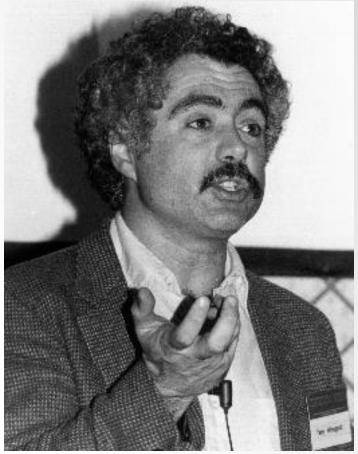

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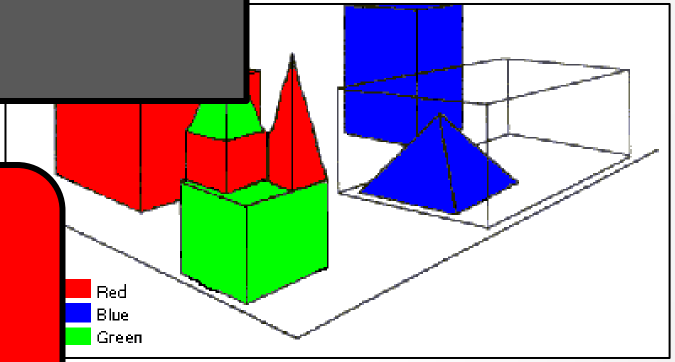

Basic rules:

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Too narrow and brittle!

Frame Problem

(John McCarthy & Patrick J. Hayes, 1959)

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Axioms:

$Paint(x,c,t) \Rightarrow Color(x,c,t)$

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Initial State:

`Color(A,Red,t)`

`Position(A,House,t)`

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Move(x,p,t) ⟹ *Position(x,p,t)*

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Actual State:

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Position(A,Garden,t+1)

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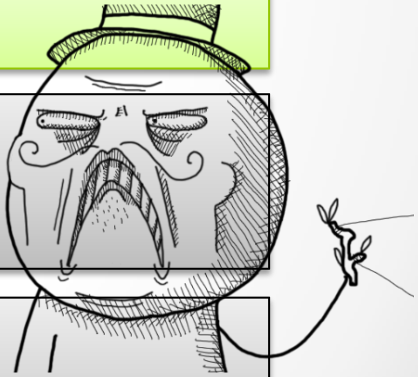
Action:

Move(A,Garden,t+1)



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Action:

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Expected State = Actual State:

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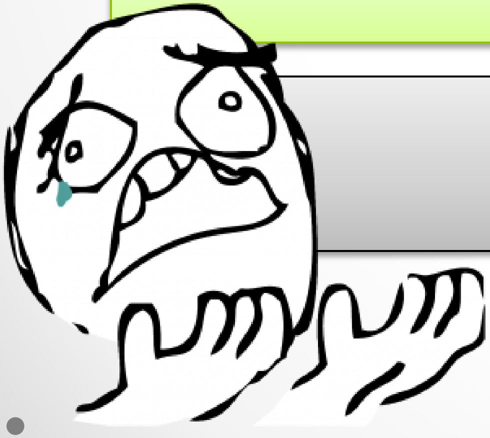

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Problem: Many actions don't change many properties!

$$\begin{cases} M: Actions \\ N: Properties \end{cases} \Rightarrow MN \text{ additional axioms!}$$

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common sense law of inertia

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Example of **non-monotonic** logic (abductive):

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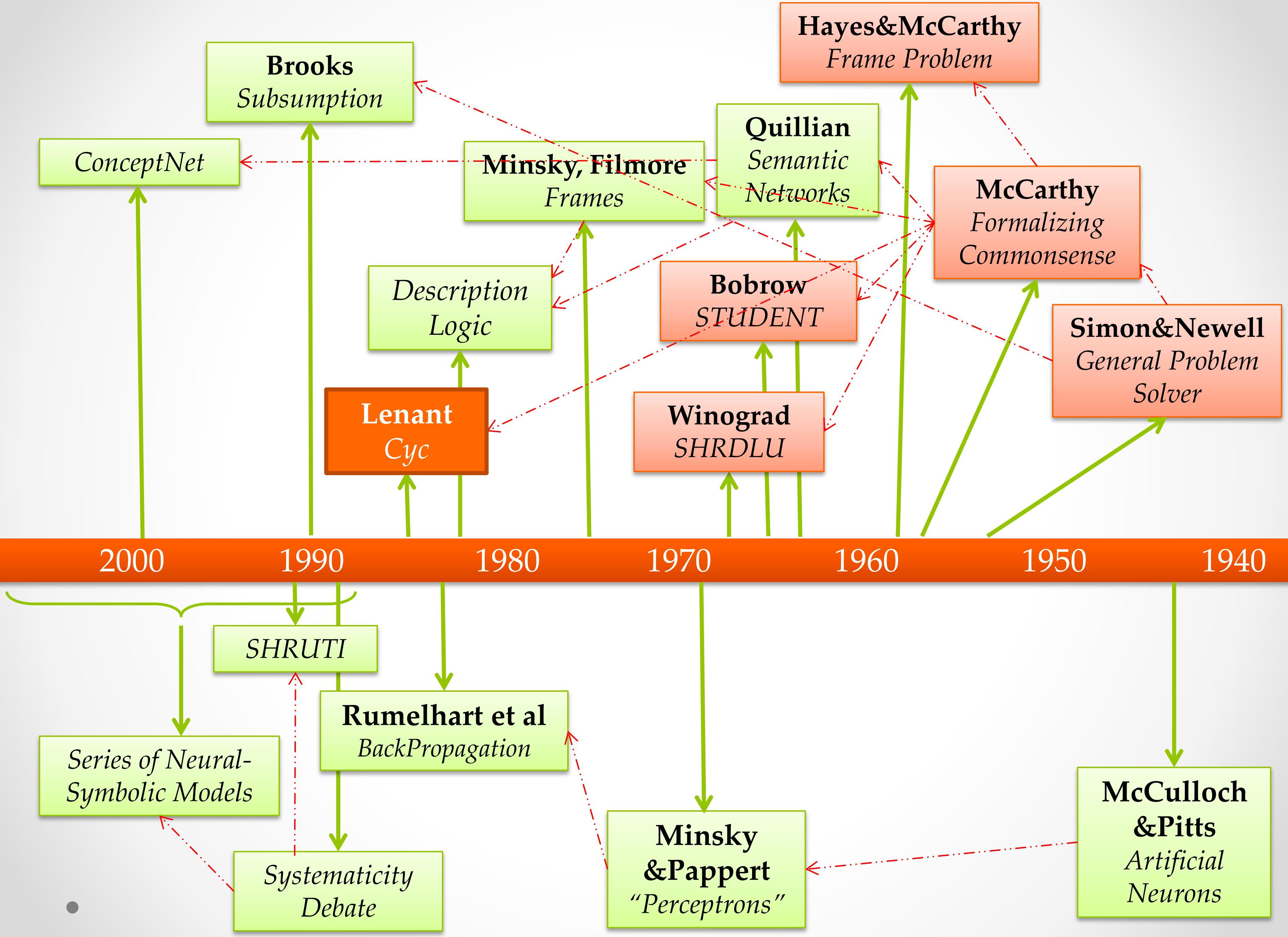
Result: Non-monotonic reasoning

Monotonicity of classical logic: $S \vDash R \;\Rightarrow\; S \cup B \vDash R$

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.



Brooks
Subsumption

ConceptNet

Minsky, Filmore
Frames

Quillian
Semantic Networks

Hayes&McCarthy
Frame Problem

McCarthy
Formalizing Commonsense

Description Logic

Bobrow
STUDENT

Simon&Newell
General Problem Solver

Lenant
Cyc

Winograd
SHRDLU

2000 1990 1980 1970 1960 1950 1940

SHRUTI

Rumelhart et al
BackPropagation

Series of Neural-Symbolic Models

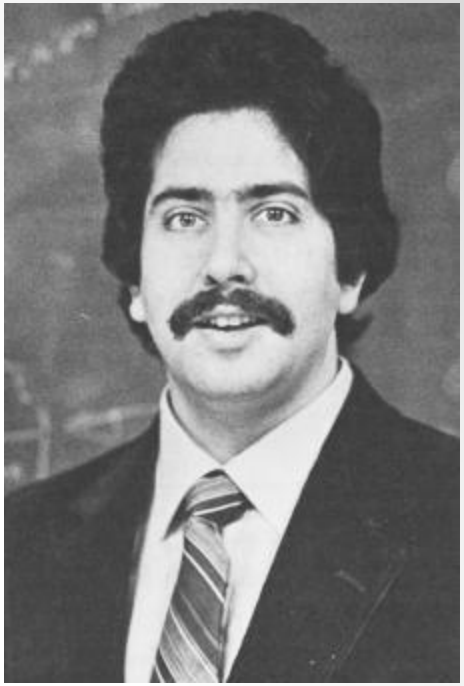
Systematicity Debate

Minsky &Pappert
"Perceptrons"

McCulloch &Pitts
Artificial Neurons

Cyc (1984-present)

(Douglas Lenant, 1984)



Goal:
Knowledge representation schema utilizing first-order relationships.

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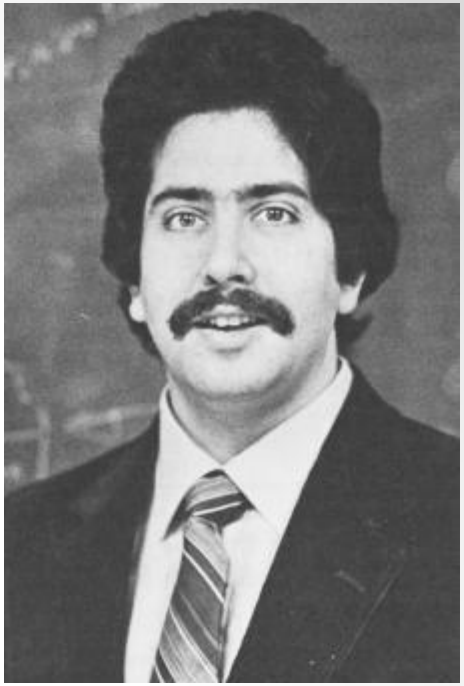

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Example assertions :

"Every tree is a plant"
"Plants die eventually"

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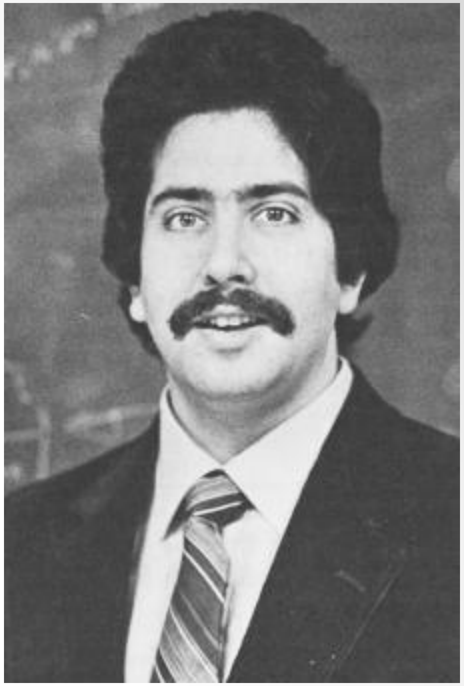

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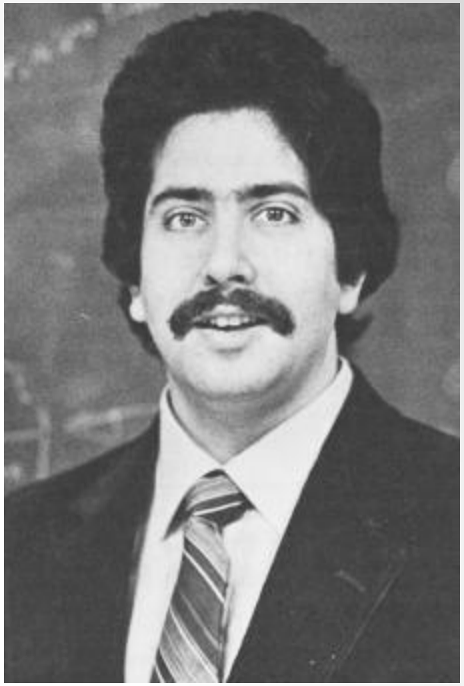
In 1986, Doug Lenat estimated the effort to complete Cyc would be **250,000 rules and 350 man-years of effort**!

500k concepts, 17k relations, ~10M logical facts

Cyc (1984-present)

(Douglas Lenant, 1984)



Example entries:

Constants: `#$OrganicStuff`

Cyc (1984-present)

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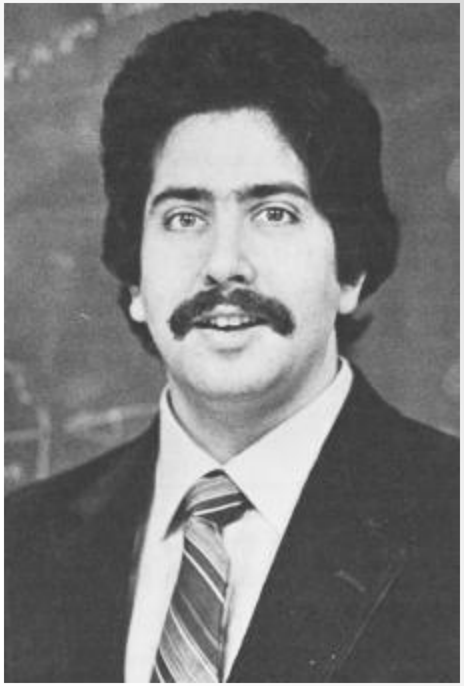


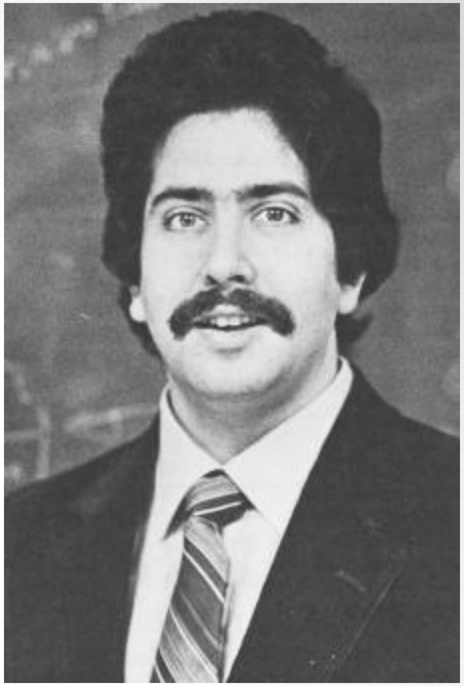
Example entries:

Constants: `#$OrganicStuff`

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

Cyc (1984-present)

(Douglas Lenant, 1984)



Example entries:

Constants: `#$OrganicStuff`

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

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

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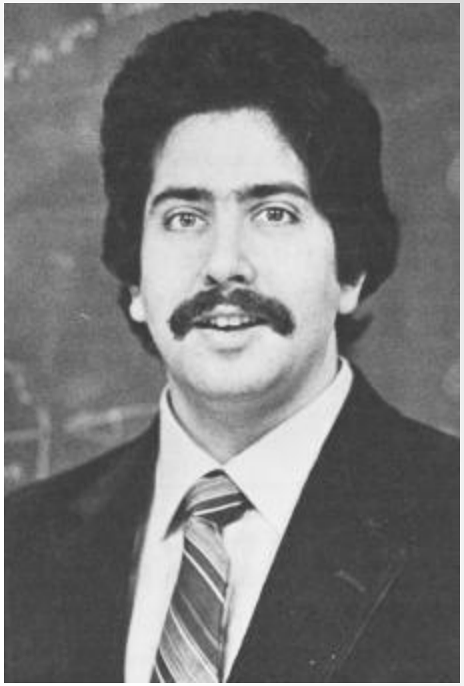

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Expressions: `(#$colorOfObject #$Grass #$Green)`

Assertions: "Animals sleep at home"

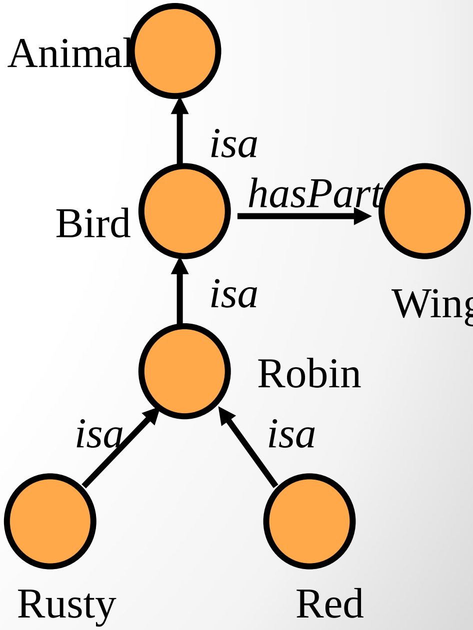
```
(ForAll ?x (ForAll ?S (ForAll ?PLACE
     (implies (and
               (isa ?x Animal)
               (isa ?S SleepingEvent)
               (performer ?S ?x)
               (location ?S ?PLACE))
               (home ?x ?PLACE)))))
```

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.

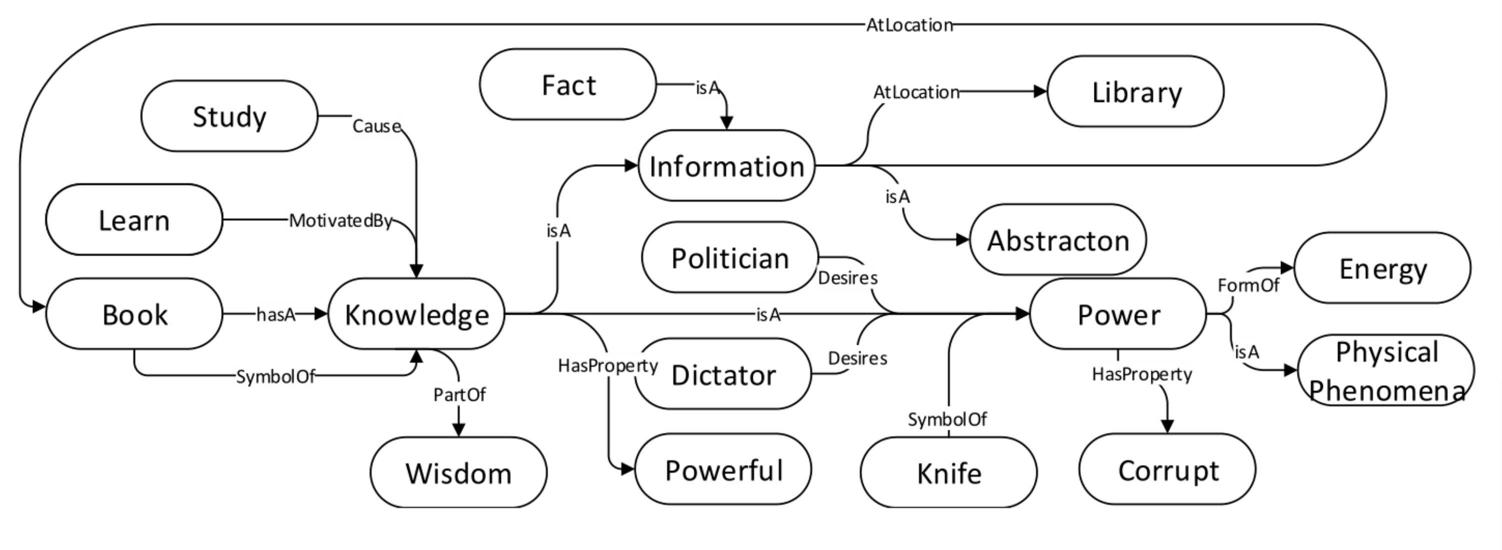
Link Type	Semantic s	Example
$A \xrightarrow{Subset} B$	$A \subset B$	$Cats \subset Mammals$
$A \xrightarrow{Member} B$	$A \in B$	$Bill \in Cats$
$A \xrightarrow{R} B$	$R(A, B)$	$Bill \xrightarrow{Age} 12$
$A \xrightarrow{\boxed{R}} B$	$\forall x, x \in A \Rightarrow R(x, B)$	$Bird \xrightarrow{\boxed{legs}} 12$
$A \xrightarrow{\boxed{\boxed{R}}} B$	$\forall x\ \exists y, x \in A \Rightarrow y \in B \wedge\ R(x, B)$	$Birds \xrightarrow{\boxed{\boxed{Parent}}} Birds$



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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SELLER:
PREDICATE:
GOODS:
BUYER:

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Cynthia	sold	a car	to Bob
SELLER	**PREDICATE**	**GOODS**	**BUYER**

SELLER:
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Premise: Meaning is based on prototypical abstract scenes

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SELLER: Cynthia
PREDICATE: sold
GOODS: a car
BUYER: to Bob

Frames

(Minsky, 1974; Fillmore, 1977)

Premise: Meaning is based on prototypical abstract scenes

Cynthia	sold	a car	to Bob
SELLER	**PREDICATE**	**GOODS**	**BUYER**
Bob	bought	a car	from Cynthia.

SELLER: Cynthia
PREDICATE: sold
GOODS: a car
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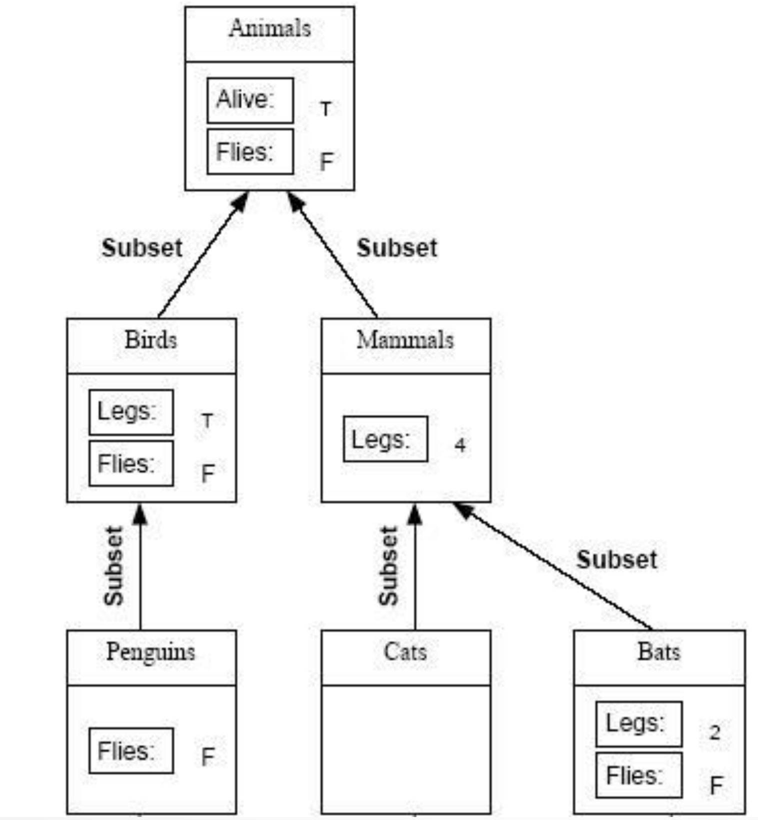
Frames

(Minsky, 1974; Fillmore, 1977)

Hierarchical Representation with Frames



Rel(Alive,Animals,T)
Rel(Flies,Animals,T)

Birds ⊂ Animals
Mammals ⊂ Animals

Rel(Flies,Birds,T)
Rel(Legs,Birds,2)
Rel(Legs,Mammals,4)

Penguins ⊂ Birds
Cats ⊂ Mammals
Bats ⊂ Mammals

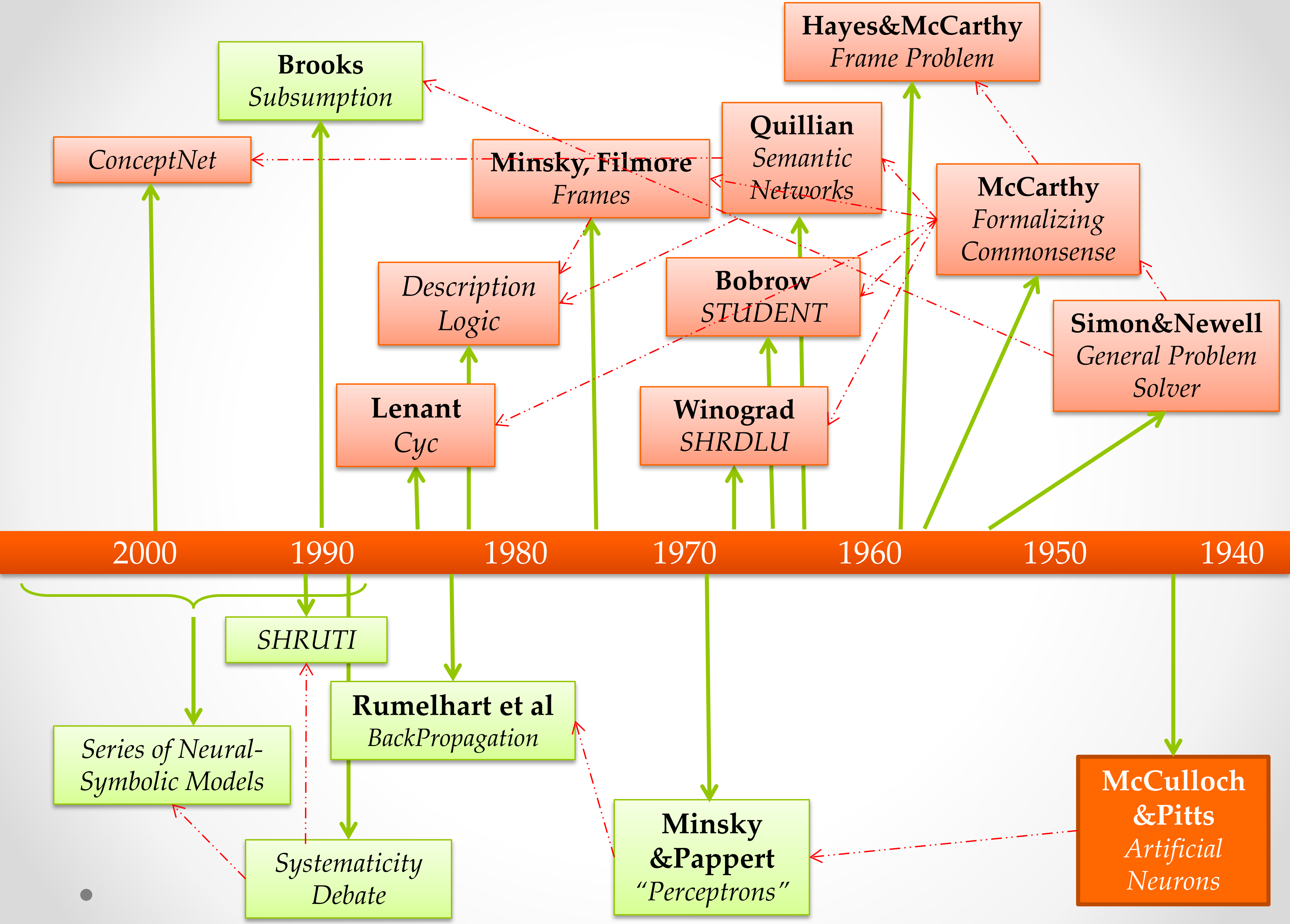
Rel(Flies,Penguins,F)
Rel(Legs,Bats,2)
Rel(Flies,Bats,T)

ThoughtTreasure (1994-2000)

(Erik Mueller, 2000)

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}
...
```



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2000 1990 1980 1970 1960 1950 1940

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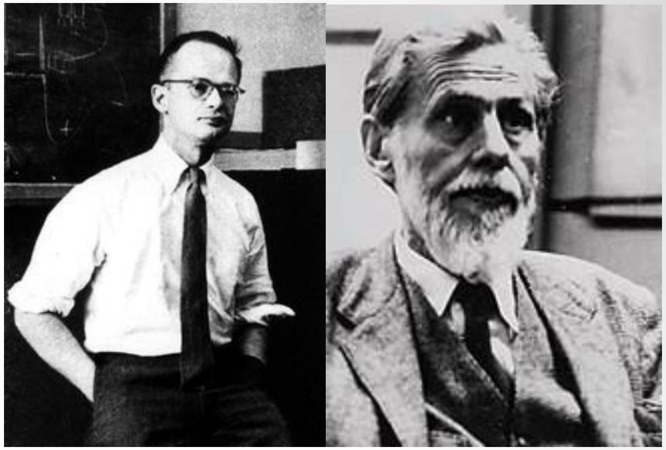
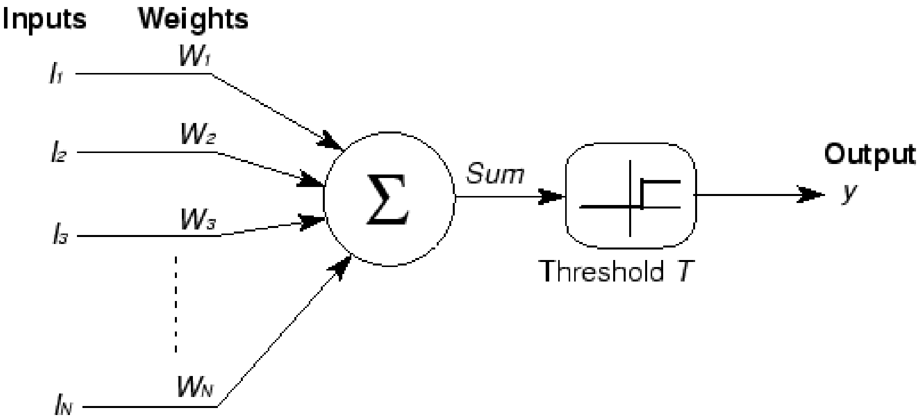
Neuron

- (McCulloch,Pitts, 1943)





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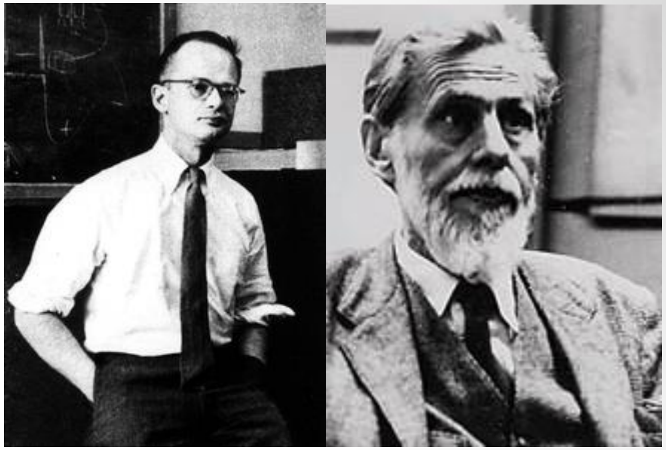

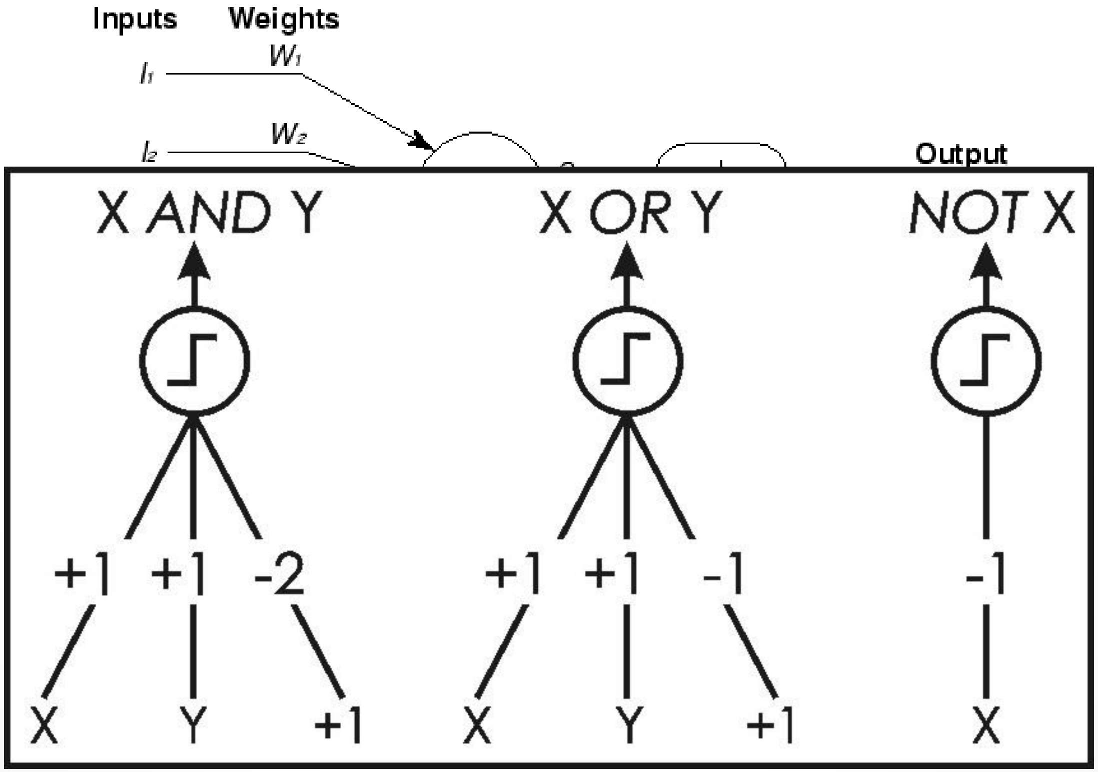

Connectionism

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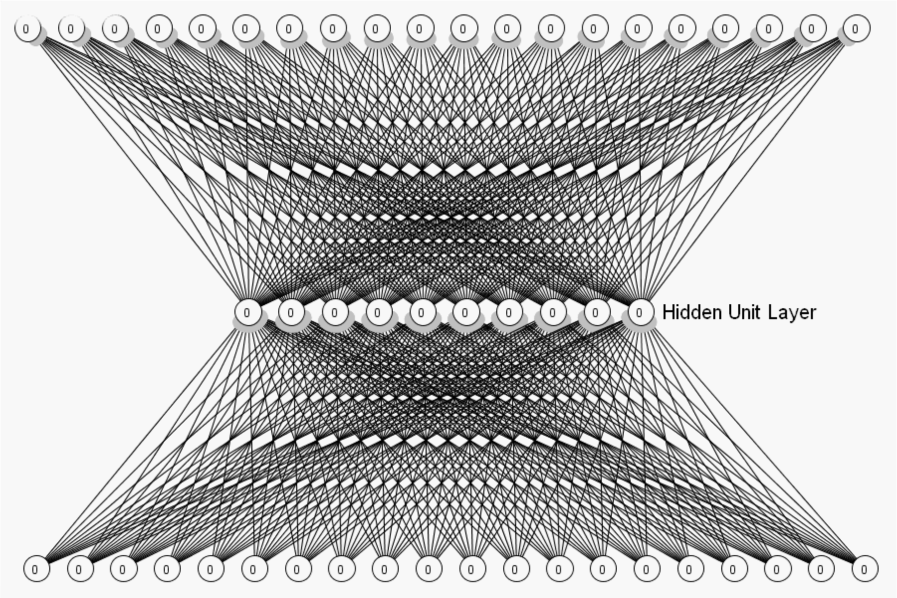

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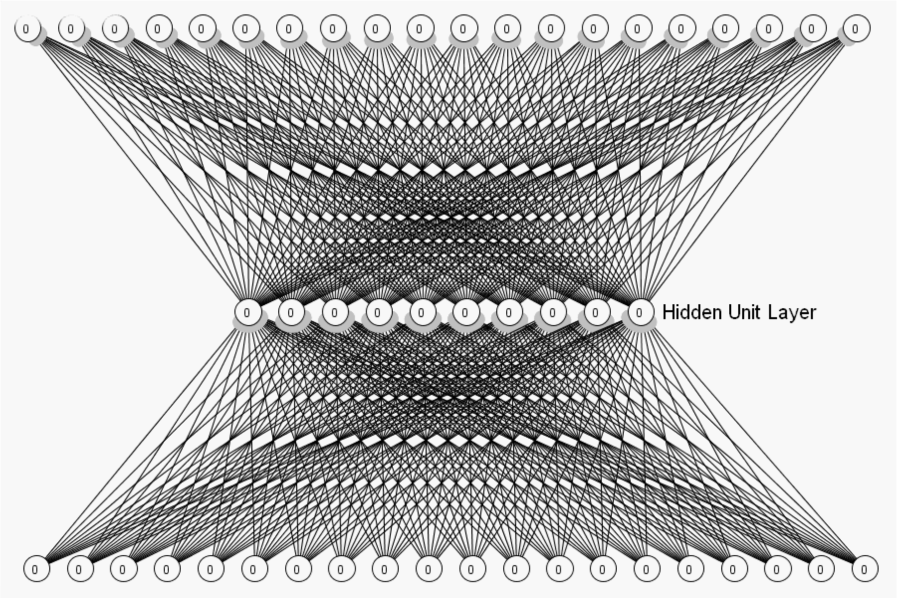
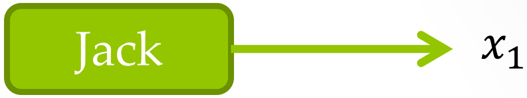
  80s: popularization of “parallel distributed models” aka “Connectionism”



Distributed vs. Classical Representation

Classical representations:



Jack $\rightarrow$ x_1

Distributed vs. Classical Representation

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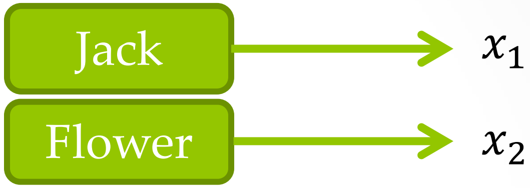

Jack → x_1

Flower → x_2

Distributed vs. Classical Representation

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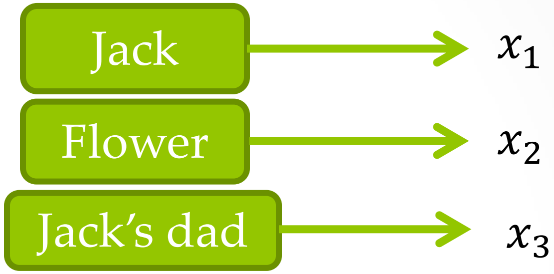


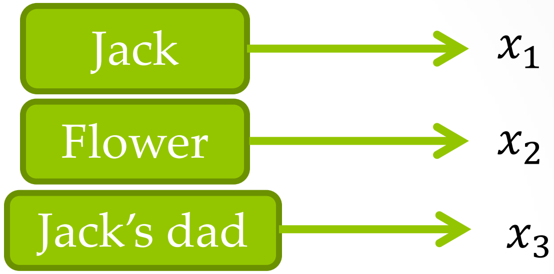
Jack → x_1

Flower → x_2

Jack's dad → x_3

Distributed vs. Classical Representation

Classical representations:



Distributed representation:

- a symbol is encoded across all elements of the representation
  each element the representation takes part in representing the symbol.

Distributed vs. Classical Representation

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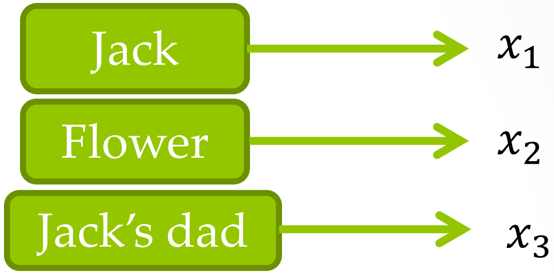
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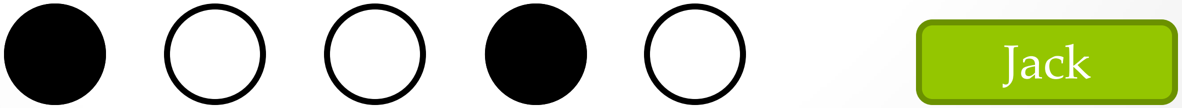

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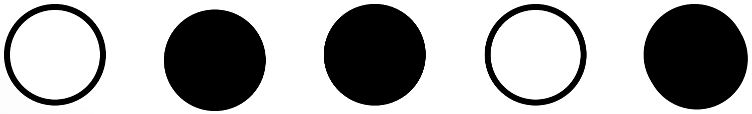

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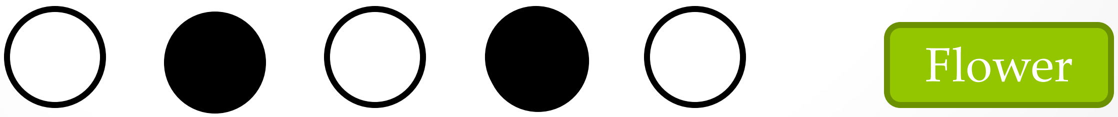

Distributed vs. Classical Representation

Activity	Connectionist	Classical Symbolic Systems
Knowledge base And computation elements	Connections, network architecture Nodes, Weights, Thresholds	Rules, Premises, conclusions, rule strengths
Processing	Continuous activation	Discrete symbols

Distributed vs. Classical Representation

	Connectionist	Classical Symbolic Systems
Pro	Robust	Given rules, the reasoning can formally be done.
Con	Need a lot of training data No (logical) reasoning, just mapping from input to output	Brittle and crisp Need for many rules

Distributed vs. Classical Representation

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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.

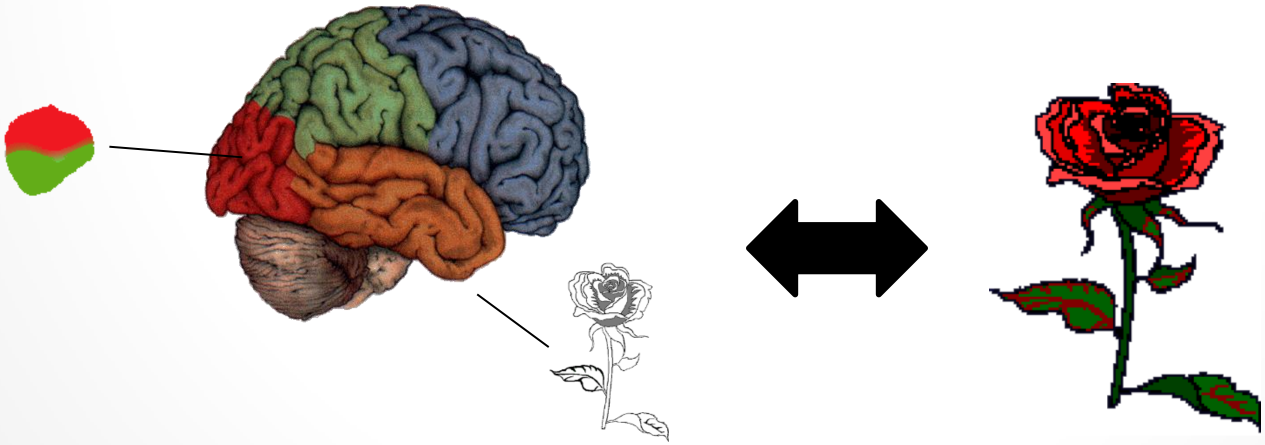
SHRUTI

- (Shastri, 1989)

Variable binding:

- conjunctive of elements and properties
- Variables of logical forms

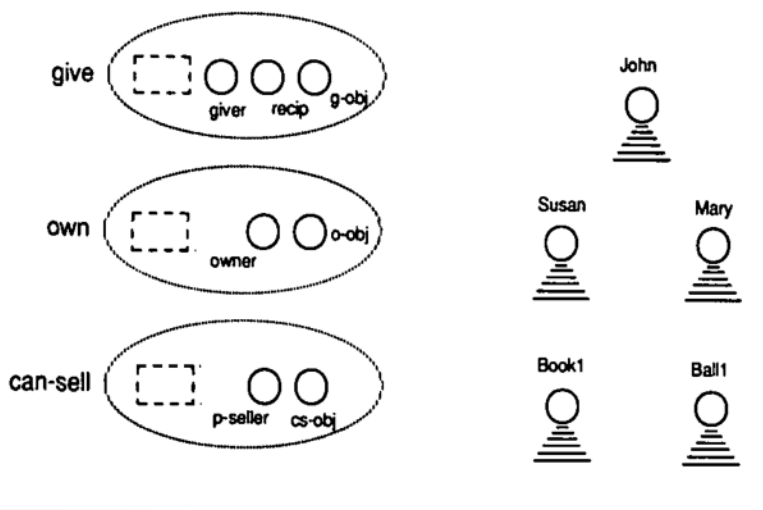
	Red	Blue	Green
Circle			■
Rectangle	■		
Triangle	■		

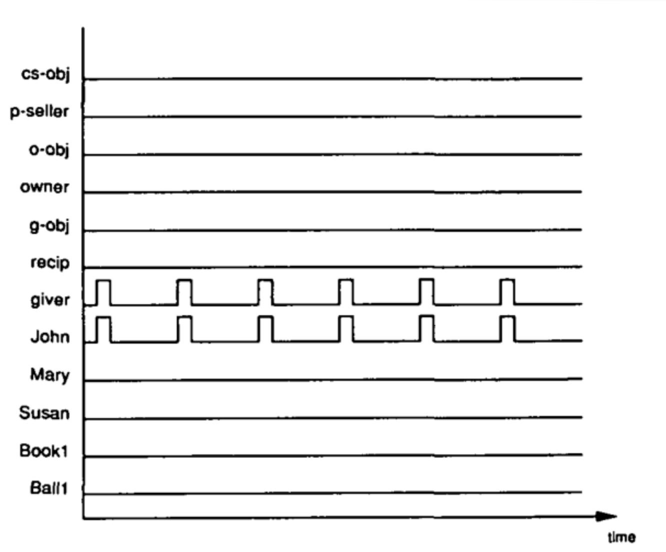


SHRUTI

- (Shastri, 1989)

Variable binding by **synchronization of neurons**.





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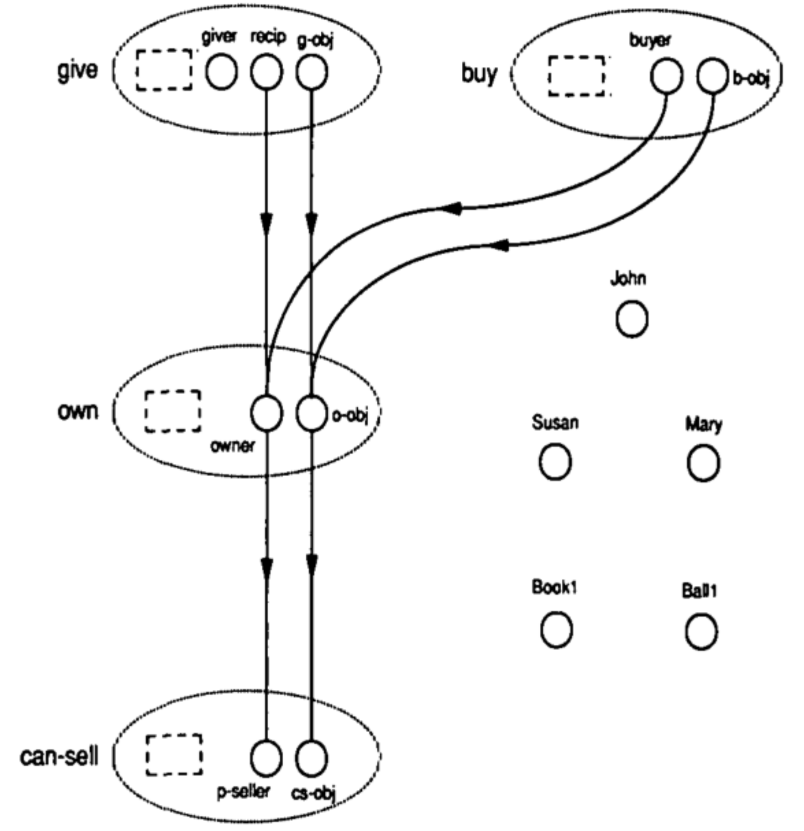
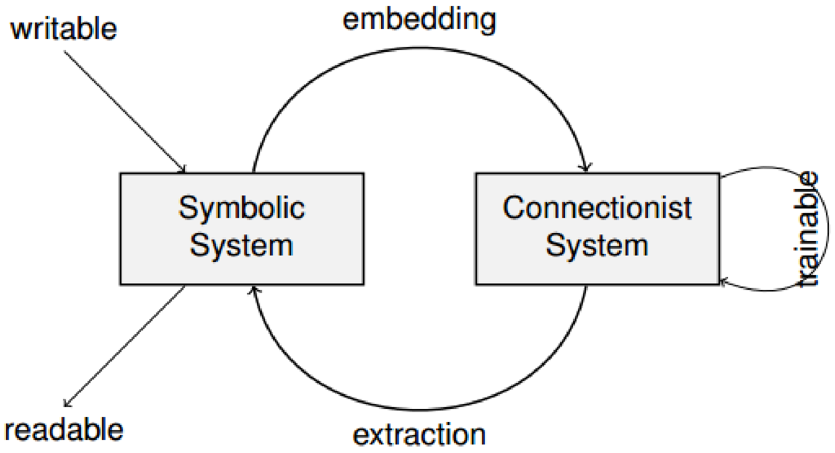
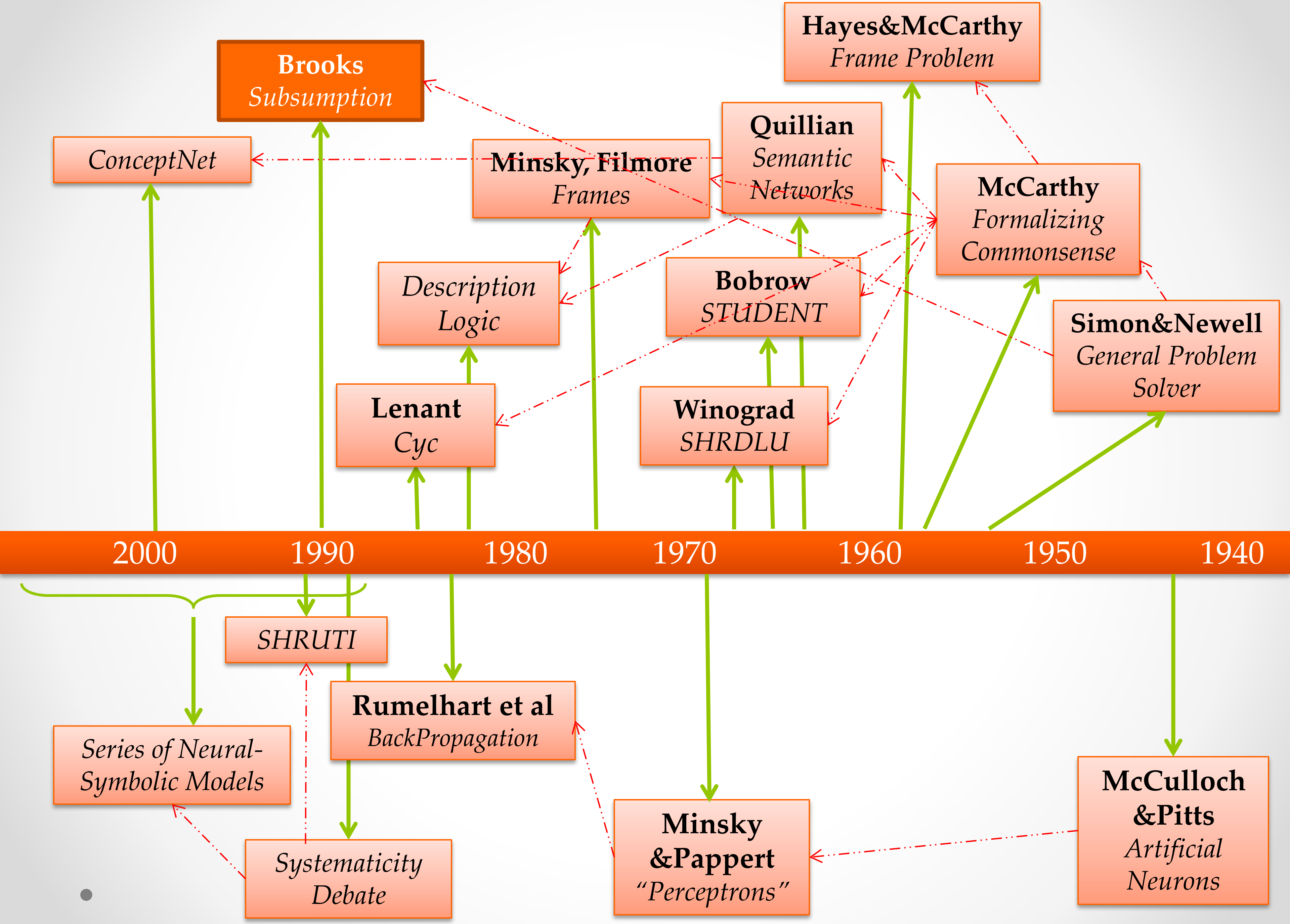
Dynamic binding for First order logic!



Neural-Symbolic models

- (90s-now)





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Allen:

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- Distance sensors, and 3 layers of control

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- Like combination of Finite State Machines
- No symbolic representation
  - implicit and distribution inside FSMs.

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(Rodney Brooks, 1991)

Subsumption Architecture

Representation Necessary?

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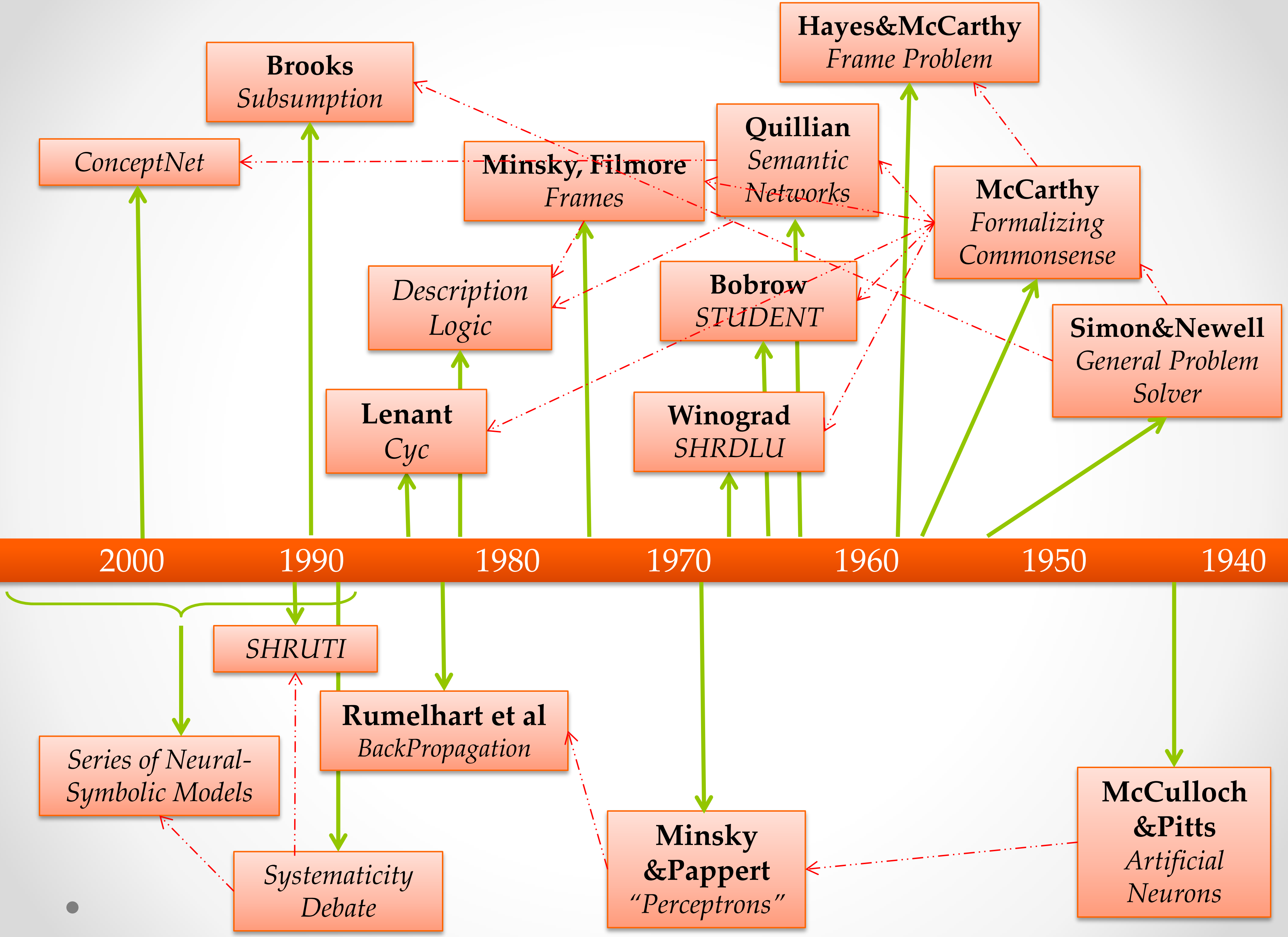
Critiques:

- Scaling?
- How does it solve our AI problem?!



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Cyc

Winograd
SHRDLU

2000 1990 1980 1970 1960 1950 1940

SHRUTI

Rumelhart et al
BackPropagation

Series of Neural-Symbolic Models

McCulloch &Pitts
Artificial Neurons

Minsky &Pappert
"Perceptrons"

Systematicity Debate

So what now?!

Questions left to answer

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  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.)
```

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