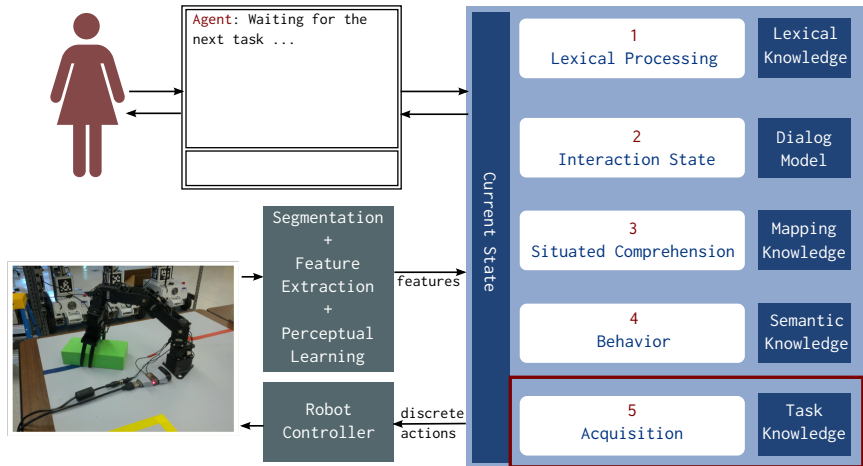


Learning to Ground Verbs in Actions for Agents Embodied in Physical Environments

Shiwali Mohan, John E. Laird

Computer Science and Engineering
University of Michigan

Process Overview

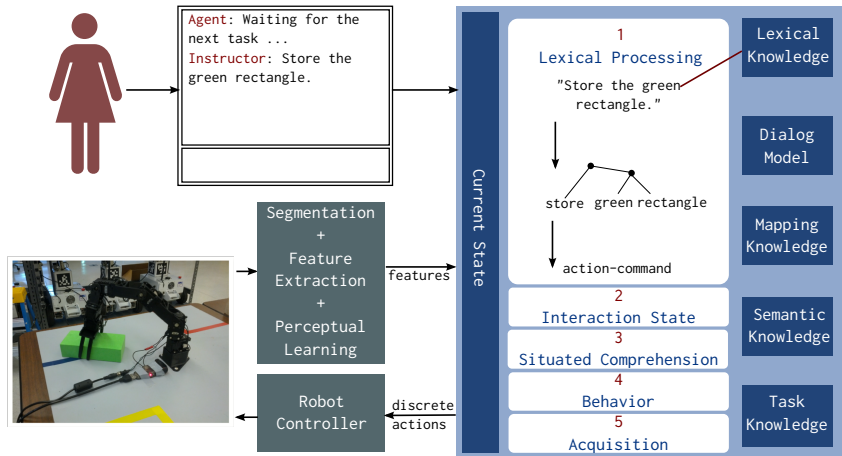


Verb Learning

- Focus on
 - Action verbs: *move, go, store*
 - Perceptible goal: `in(object12, pantry)`
 - Composition of known primitives: `pick-up(object12), put-down(object12, pantry)`
- Goal of verb comprehension
 - Agent be able to *map* the novel verb word to an action
 - Agent be able to instantiate an action with the required objects
 - Agent be able to execute the required action
- Learning Mechanism
 - Interactive instruction
 - Retrospective projection
 - episodic memory of performing the task in an instructed trial
 - generalize from that specific, *situated* experience

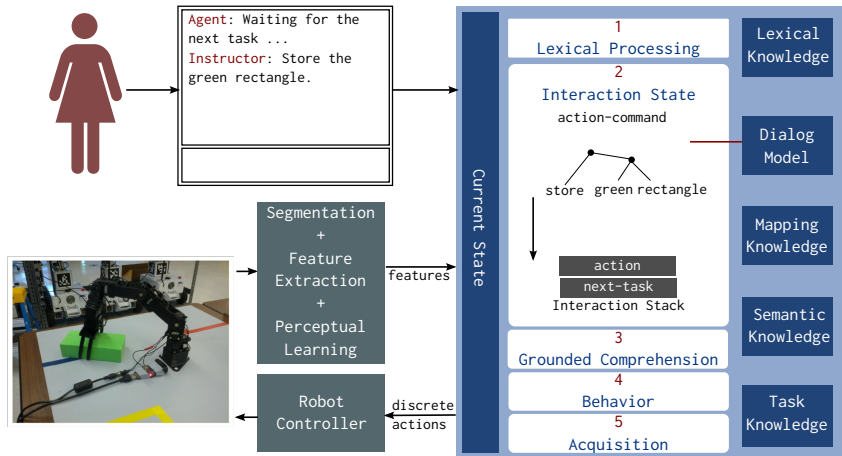
Interaction Cycle

Phase I: Lexical processing



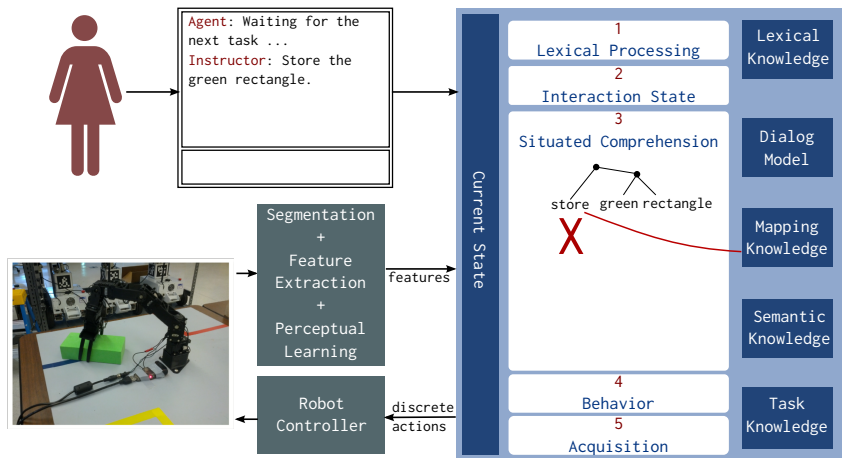
Interaction Cycle

Phase II: Interaction state management



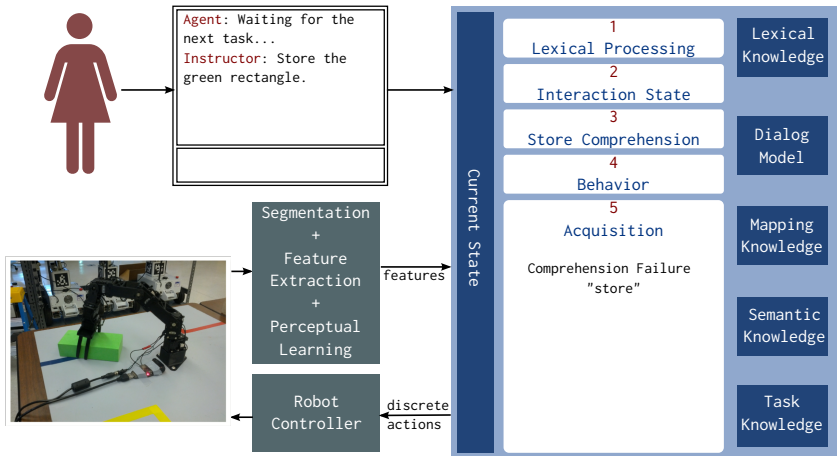
Interaction Cycle

Phase III: Situated comprehension (failure)



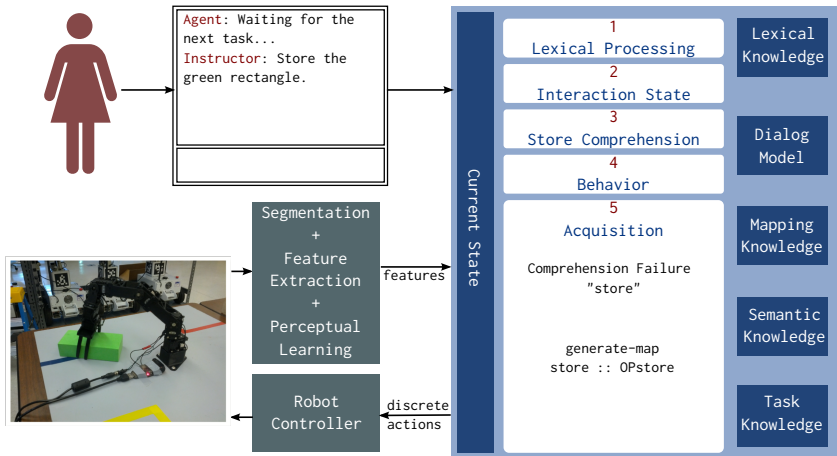
Interaction Cycle

Phase V: Acquisition (map learning)



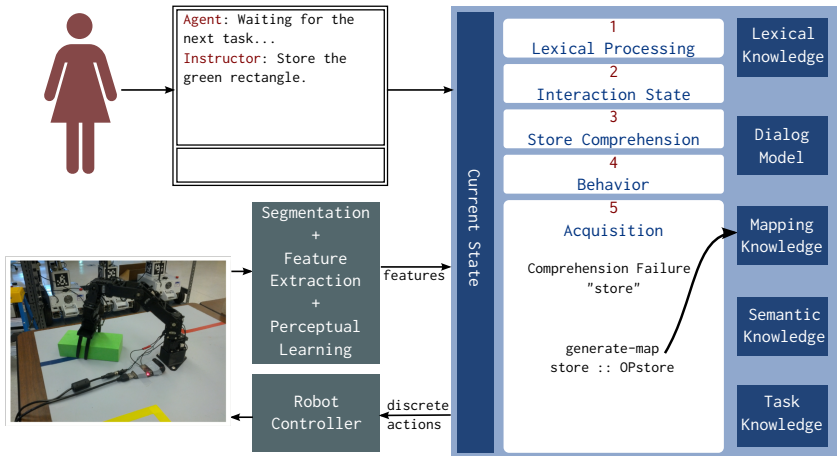
Interaction Cycle

Phase V: Acquisition (map learning)



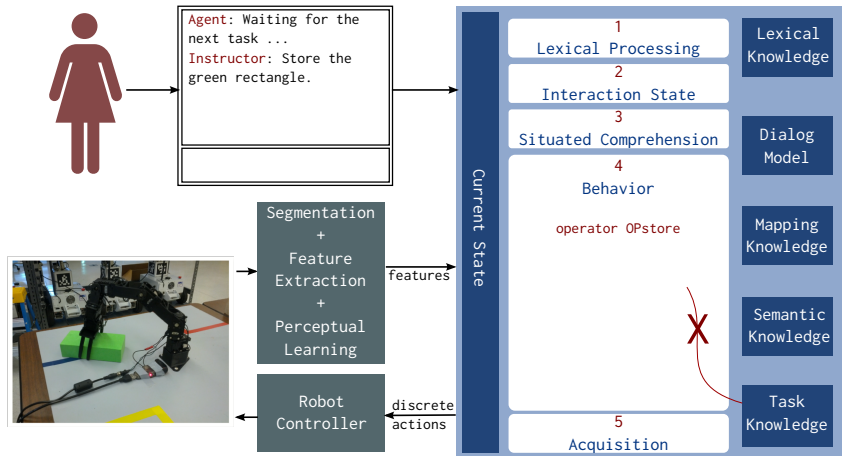
Interaction Cycle

Phase V: Acquisition (map learning)



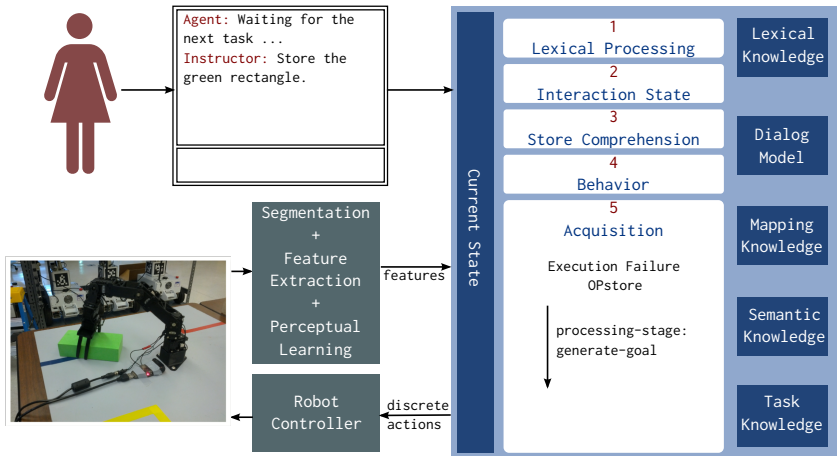
Interaction Cycle

Phase IV: Behavior (failure)



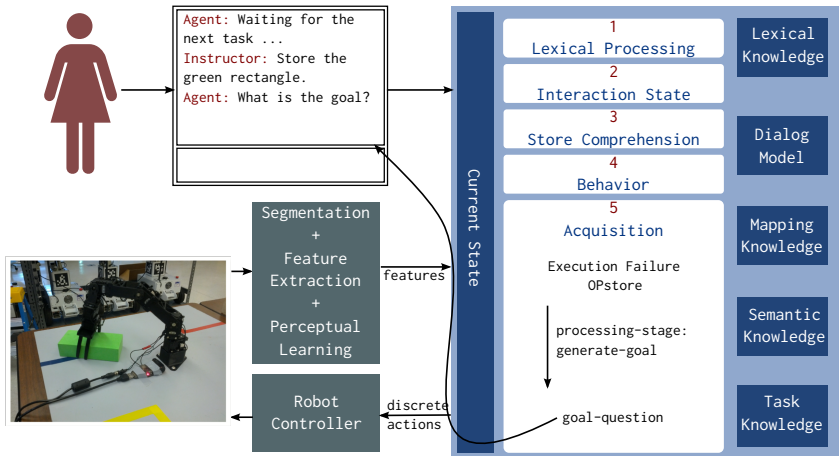
Interaction Cycle

Phase V: Acquisition (goal)



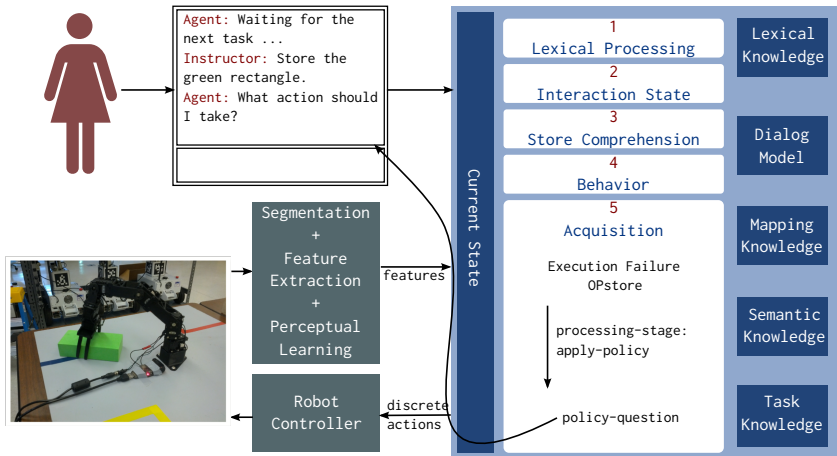
Interaction Cycle

Phase V: Acquisition (goal)



Interaction Cycle

Phase V: Acquisition (policy)



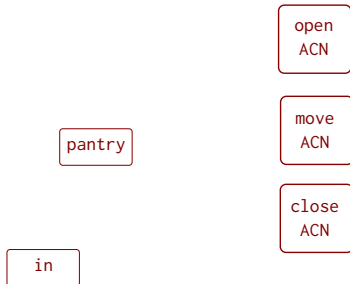
Verb Representation

distributed across three categories

map

Interaction trace

Instructor: Store the green rectangle.



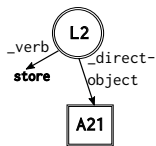
Verb Representation

distributed across three categories

map

Interaction trace

Instructor: Store the green rectangle.



pantry

in

open
ACN

move
ACN

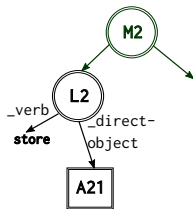
close
ACN

Verb Representation

distributed across three categories
map

Interaction trace

Instructor: Store the green rectangle.



pantry

in

open
ACN

move
ACN

close
ACN

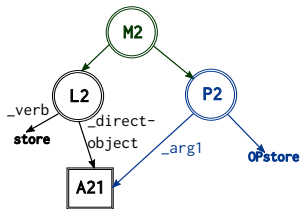
Verb Representation

distributed across three categories

map

Interaction trace

Instructor: Store the green rectangle.



pantry

in

open
ACN

move
ACN

close
ACN

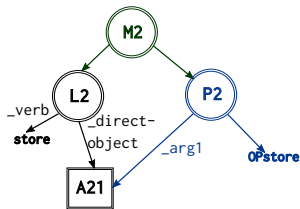
Verb Representation

distributed across three categories
map, action-concept network

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?



pantry

in

open
ACN

move
ACN

close
ACN

Verb Representation

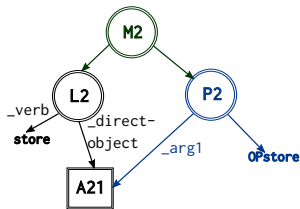
distributed across three categories
map, action-concept network

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.



pantry

in

open
ACN

move
ACN

close
ACN

Verb Representation

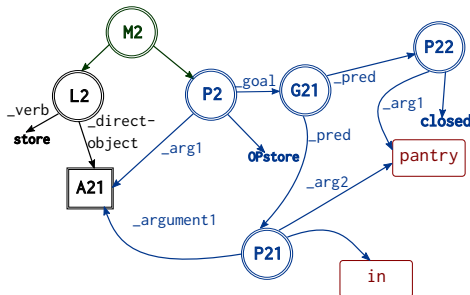
distributed across three categories
map, action-concept network

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.



open
ACN

move
ACN

close
ACN

Verb Representation

distributed across three categories
map, action-concept network

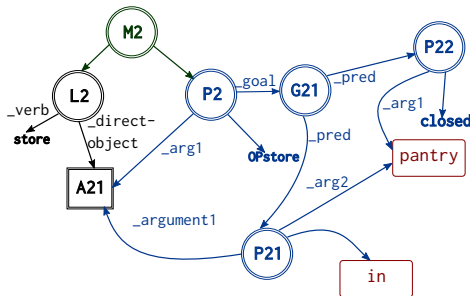
Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

Agent: Which action should I take?



open
ACN

move
ACN

close
ACN

Verb Representation

distributed across three categories
map, action-concept network

Interaction trace

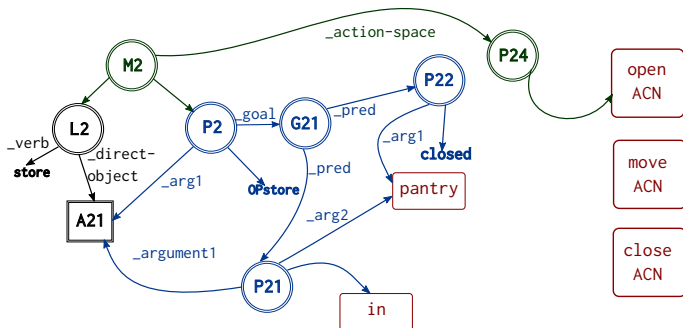
Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

Agent: Which action should I take?

Instructor: Open the pantry.



Verb Representation

distributed across three categories
map, action-concept network

Interaction trace

Instructor: Store the green rectangle.

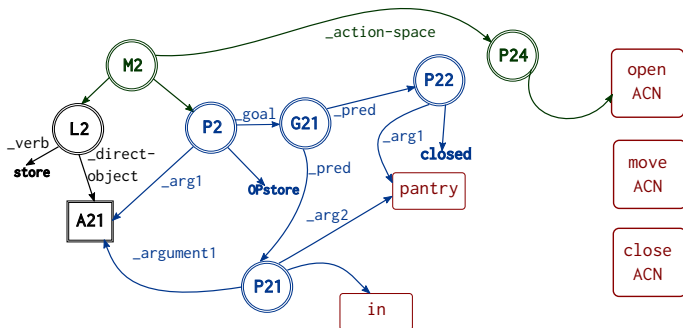
Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

Agent: Which action should I take?

Instructor: Open the pantry.

Agent: Which action should I take?



Verb Representation

distributed across three categories
map, action-concept network

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

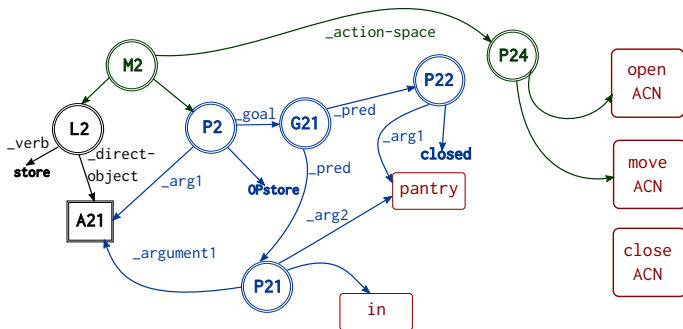
Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

Agent: Which action should I take?

Instructor: Open the pantry.

Agent: Which action should I take?

Instructor: Move the object to the pantry.



Verb Representation

distributed across three categories
map, action-concept network

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

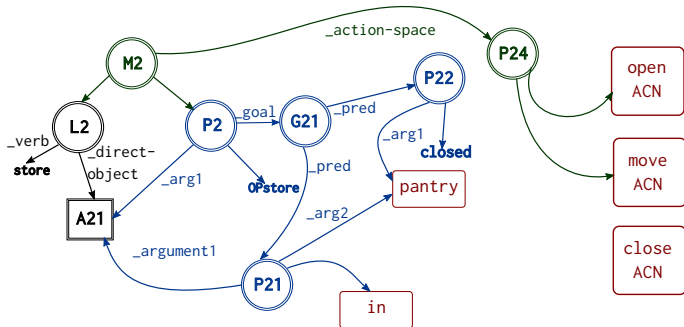
Agent: Which action should I take?

Instructor: Open the pantry.

Agent: Which action should I take?

Instructor: Move the object to the pantry.

Agent: Which action should I take?



Verb Representation

distributed across three categories
map, action-concept network

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

Agent: Which action should I take?

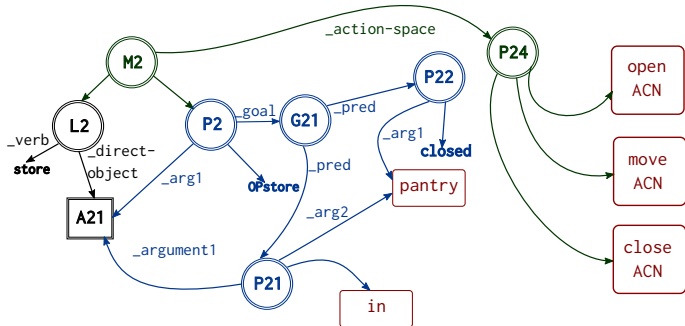
Instructor: Open the pantry.

Agent: Which action should I take?

Instructor: Move the object to the pantry.

Agent: Which action should I take?

Instructor: Close the pantry.



Verb Representation

distributed across three categories
map, action-concept network

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

Agent: Which action should I take?

Instructor: Open the pantry.

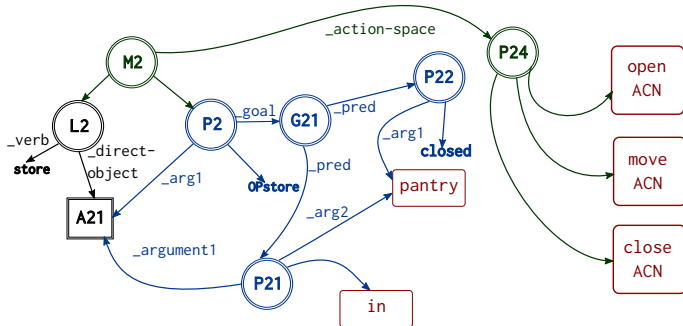
Agent: Which action should I take?

Instructor: Move the object to the pantry.

Agent: Which action should I take?

Instructor: Close the pantry.

Agent: Which action should I take?



Verb Representation

distributed across three categories
map, action-concept network

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

Agent: Which action should I take?

Instructor: Open the pantry.

Agent: Which action should I take?

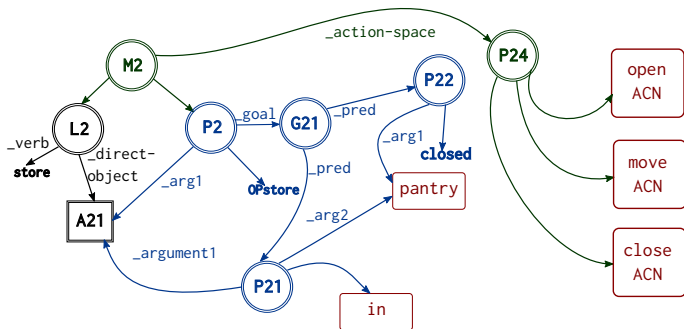
Instructor: Move the object to the pantry.

Agent: Which action should I take?

Instructor: Close the pantry.

Agent: Which action should I take?

Instructor: You are done.



Verb Representation

distributed across three categories
map, action-concept network, procedural policy

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

Agent: Which action should I take?

Instructor: Open the pantry.

Agent: Which action should I take?

Instructor: Move the object to the pantry.

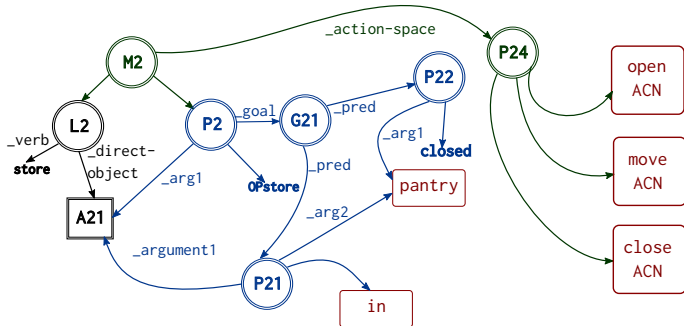
Agent: Which action should I take?

Instructor: Close the pantry.

Agent: Which action should I take?

Instructor: You are done.

Agent: forward projection
EBG



Verb Representation

distributed across three categories
map, action-concept network, procedural policy

Interaction trace

Instructor: Store the green rectangle.

Agent: What is the goal of the action?

Instructor: The goal is the green rectangle in the pantry and the pantry is closed.

Agent: Which action should I take?

Instructor: Open the pantry.

Agent: Which action should I take?

Instructor: Move the object to the pantry.

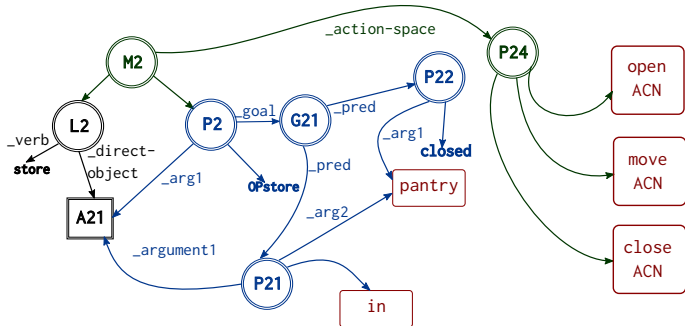
Agent: Which action should I take?

Instructor: Close the pantry.

Agent: Which action should I take?

Instructor: You are done.

Agent: forward projection
EBG



rule-1

If operator is OPstore and CLOSED(pantry)

--> execute open(pantry)

rule-2

If operator is OPstore and arg1 is [A21] and OPEN(pantry)

--> execute move([A21], pantry)

rule-3

If operator is OPstore and arg is [A21], and IN([A21], pantry) and OPEN(pantry)

--> execute CLOSE(pantry)

Acquisition Model

Generality of instruction

Reasons about and removes instructions (actions) that do not occur in the causal link

Move the red block to the pantry.

The goal is red block in the pantry.

Pick up the red block.

Put the block in the garbage.

Pick up the red block.

Put the block in the pantry.

Acquisition Model

Generality of instruction

Reasons about and removes instructions (actions) that do not occur in the causal link

Move the red block to the pantry.

The goal is red block in the pantry.

Pick up the red block.

~~Put the block in the garbage.~~

~~Pick up the red block.~~

Put the block in the pantry.

Acquisition Model

Generality of situation

Reasons about the situation, rather than memorizing steps

Scenario 1

State: -Holding

Command: *Move the red block to the pantry.*

Actions: Pick up the red block, Put the block in the pantry.

Scenario 2

State: Holding(red block)

Command: *Move the red block to the pantry.*

Actions: Put the red block in the pantry.

Verb Representation

| Template | Goal | Policy | I |
|----------------------------------|----------------------------------|--|----------|
| move [obj] to [loc] | in(obj, loc) | pick-up(obj), put-down(in, obj, loc) | 9 |
| move [obj] to the left of [loc] | in(obj, loc) | pick-up(obj), put-down(left, obj, loc) | 9 |
| move [obj] to the right of [loc] | in(obj, loc) | pick-up(obj), put-down(right, obj, loc) | 9 |
| shift [obj] to [loc] | in(obj, loc), closed (loc) | 1. open(loc), pick-up(obj), put-down(in, obj, loc), close(loc) 2. open(loc), move(in, obj, loc), close(loc) | 13 11 |
| store [obj] | in(obj, pantry), closed (pantry) | open(pantry), move(in, obj, pantry), close(pantry) | 11 |
| discard [obj] | in(obj, garbage) | move(obj, in, garbage) | 7 |

Verb Representation

Implicit and Explicit Argumentation

| Template | Goal | Policy | I |
|----------------------------------|----------------------------------|--|----------|
| move [obj] to [loc] | in(obj, loc) | pick-up(obj), put-down(in, obj, loc) | 9 |
| move [obj] to the left of [loc] | in(obj, loc) | pick-up(obj), put-down(left, obj, loc) | 9 |
| move [obj] to the right of [loc] | in(obj, loc) | pick-up(obj), put-down(right, obj, loc) | 9 |
| shift [obj] to [loc] | in(obj, loc), closed (loc) | 1. open(loc), pick-up(obj), put-down(in, obj, loc), close(loc) 2. open(loc), move(in, obj, loc), close(loc) | 13 11 |
| store [obj] | in(obj, pantry), closed (pantry) | open(pantry), move(in, obj, pantry), close(pantry) | 11 |
| discard [obj] | in(obj, garbage) | move(obj, in, garbage) | 7 |

Verb Representation

Goal Predicates

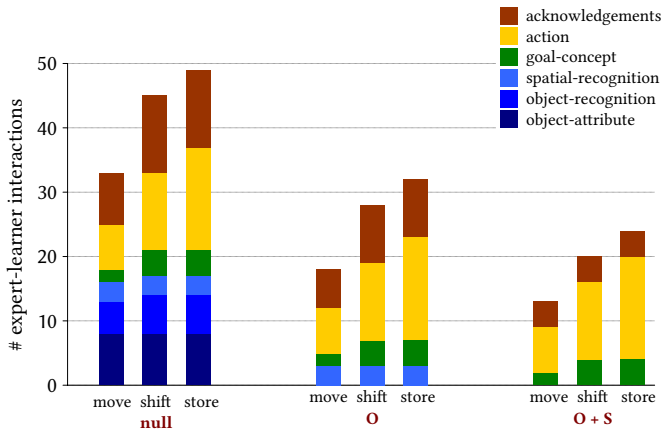
| Template | Goal | Policy | I |
|----------------------------------|----------------------------------|--|----------|
| move [obj] to [loc] | in(obj, loc) | pick-up(obj), put-down(in, obj, loc) | 9 |
| move [obj] to the left of [loc] | in(obj, loc) | pick-up(obj), put-down(left, obj, loc) | 9 |
| move [obj] to the right of [loc] | in(obj, loc) | pick-up(obj), put-down(right, obj, loc) | 9 |
| shift [obj] to [loc] | in(obj, loc), closed (loc) | 1. open(loc), pick-up(obj), put-down(in, obj, loc), close(loc) 2. open(loc), move(in, obj, loc), close(loc) | 13 11 |
| store [obj] | in(obj, pantry), closed (pantry) | open(pantry), move(in, obj, pantry), close(pantry) | 11 |
| discard [obj] | in(obj, garbage) | move(obj, in, garbage) | 7 |

Verb Representation

Hierarchical Policy

| Template | Goal | Policy | I |
|----------------------------------|----------------------------------|--|----------|
| move [obj] to [loc] | in(obj, loc) | pick-up(obj), put-down(in, obj, loc) | 9 |
| move [obj] to the left of [loc] | in(obj, loc) | pick-up(obj), put-down(left, obj, loc) | 9 |
| move [obj] to the right of [loc] | in(obj, loc) | pick-up(obj), put-down(right, obj, loc) | 9 |
| shift [obj] to [loc] | in(obj, loc), closed (loc) | 1. open(loc), pick-up(obj), put-down(in, obj, loc), close(loc) 2. open(loc), move(in, obj, loc), close(loc) | 13 11 |
| store [obj] | in(obj, pantry), closed (pantry) | open(pantry), move(in, obj, pantry), close(pantry) | 11 |
| discard [obj] | in(obj, garbage) | move(obj, in, garbage) | 7 |

Flexible Instruction



Nuggets and Coal

- Nuggets
 - a representation that encodes diverse knowledge
 - flexible, agent-driven learning paradigm
 - integrated with comprehension and dialog processing
- Coal
 - not complete, currently only represents and learns conjunctive goals and *achievement* policies
 - not rigorously evaluated in HRI contexts