

Artificial Intelligence Programming
Intro to Knowledge Representation

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10-2: Introduction

- So far, we've talked about search, which is a means of considering alternative possibilities.
 - The way in which problem states were represented was typically pretty straightforward.
- The other aspect of many AI problems involves representing possible states.
- Our choice of representation influences:
 - The problems our agent is able to solve.
 - The sorts of environments an agent can deal with.
 - The complexity of search
 - The sophistication of our agent.

10-3: Knowledge Representation

- Choices we'll look at include:
 - Logic-based approaches
 - Propositional logic
 - First-order logic
 - Ontologies
 - Logic is a flexible, well-understood, powerful, versatile way to represent knowledge.
 - Often fits with the way human experts describe their world
 - Facts are either true or false
 - Has a hard time dealing with uncer tainty.

10-4: Knowledge Representation

- Choices we'll look at include:
 - Probabilistic approaches
 - Bayesian reasoning
 - Bayesian networks
 - Decision theory
 - Probabilistic reasoning works well in domains with uncertainty.
 - Inference can be more complex
 - Requires more prior knowledge to use effectively.
 - Representational power typically more limited.

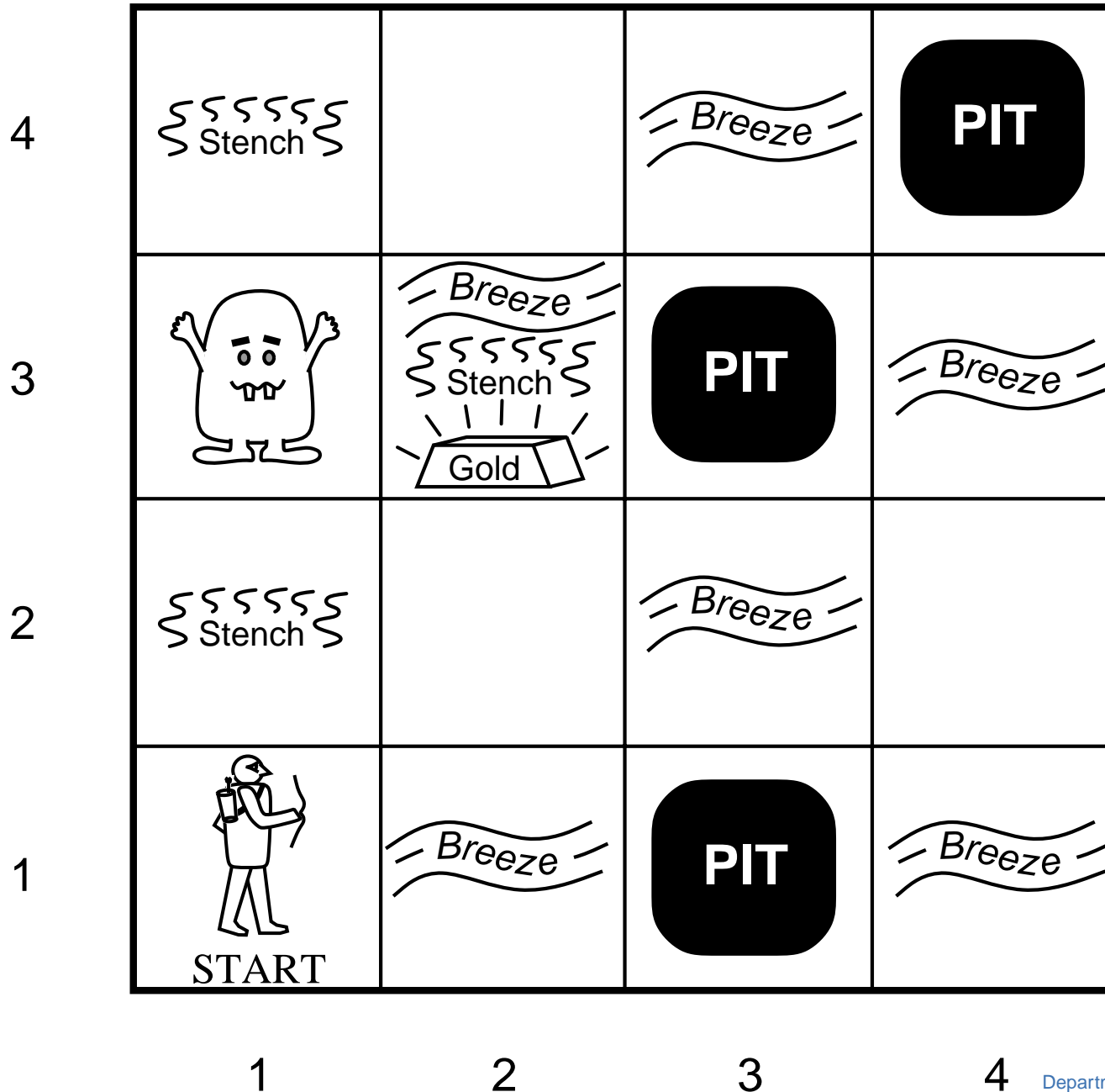
10-5: Declarative vs. Procedural

- Knowledge representation entails a shift from a procedural way of thinking about agents to a declarative way.
- Procedural: Behavior is encoded directly in agent program. Focus is on algorithms.
- Declarative: Agent knowledge is represented as sentences. Focus is on data.
- Agents maintain a knowledge base that allows them to reason about a problem.
- Knowledge is represented as facts and relations
- Inference is typically performed automatically.
- This is sometimes called programming at the knowledge level.
- Specify facts known by an agent, along with goals.
- Programming focus is on encoding knowledge

10-6: Wumpus World

- R & N use the Wumpus World as an example domain.
- Environment: 4x4 grid of rooms.
 - Gold in one room, wumpus in another
 - Pits in some rooms
- Actions: Move forward, turn left, turn right, shoot arrow, grab gold.
- Sensors: Perceive stench, perceive breeze, perceive gold, sense wall, hear wumpus death.
- Goal: maximize performance, which means finding gold quickly without encountering the wumpus or falling into a pit.

10-7: Wumpus World



10-8: Knowledge base

- A knowledge base is composed of *sentences* that assert facts about the world.
 - What's the difference between a knowledge base and a database?
 - In principle, expressiveness and usage.
 - In practice, a knowledge base might be implemented using a database.
- Sentences describe:
 - Objects of interest in the world (wumpuses, gold, pits, rooms, agent)
 - Relationships between objects (agent is holding arrow)

10-9: Syntax and Semantics

- Syntax: Defines whether a sentence is properly constructed.
 - In arithmetic, $x + 2 = 5$ is syntactically correct, whereas $x + = 3$ is not.
 - In a Python program, `timeElapsed = 3` is syntactically correct, while `3 = timeElapsed` is not.
- Semantics: Defines when a sentence is true or false.
 - The semantics of $x + 2 = 5$ are that this sentence is true in worlds where $x = 3$ and false otherwise.
 - Logical sentences must be true or false; no “degree of truth”.

10-10: Models

- Model: A model is an assignment of values to a subset of the variables of interest in our problem.
 - A model for the U2 problem might indicate where each band member is.
 - In the Wumpus World, a model would indicate the location of the pits, gold, agent, arrow, and wumpus.
- A model provides an agent with a *possible world*; one guess at how things might be.
- We'll often be interested in finding models that make a sentence true or false, or all the models that could be true for a given set of sentences.
- Models are very much like states.

10-11: Logic

- Entailment: Entailment is the idea that one sentence follows logically from another.
 - Written as: $a \models b$
 - Technically, this says: for all models where a is true, b is also true.
 - (think if-then)
 - $a + 2 = 5 \models a = 3$
- Note that entailment is a property of a set of sentences, and not an instruction to an agent.

10-12: Inference

- A knowledge base plus a model allows us to perform inference.
 - For a given set of sentences, plus some assignment of values to variables, what can we conclude?
- Entailment tells us that a sentence can be derived.
- Inference tells us *how* it is derived.
- An algorithm that only derives entailed sentences is said to be *sound*.
 - Doesn't make mistakes or conclude incorrect sentences.

10-13: Inference

- An inference algorithm that can derive all entailed sentences is *complete*.
 - If a sentence is entailed, a complete algorithm will eventually infer it.
 - If entailed sentences are goals, this is the same definition of complete we used for search.
 - That means we can think of inference as search, and use the algorithms we've already learned about.

10-14: Propositional Logic

- Propositional logic is a very simple logic.
 - Nice for examples
 - Computationally feasible.
 - Limited in representational power.
- Terms (R & N call these atomic sentences) consist of a single symbol that has a truth value.
 - *BonoOnLeft, FlashlightOnLeft*

10-15: Propositional Logic

- a complex sentence is a set of terms conjoined with \vee , \neg , *wedge*, \Rightarrow , \Leftrightarrow .
 - $BonoOnLeft \wedge (EdgeOnLeft \vee EdgeOnRight \vee AdamOnLeft \vee AdamOnRight \vee LarryOnLeft \vee LarryOnRight)$
 - $Breeze_{1,1} \Rightarrow (Pit_{1,2} \vee Pit_{2,1})$

10-16: Propositional Logic

- This is the sort of representation you are using in your project.
- A document is represented as a series of words that are either present (true) or absent (false).
- The TFIDFScorer extends this to map words to numbers, but the representational power is the same.
- Note that there's no way to indicate relationships between words
 - Occur near each other
 - Synonyms
 - Antonyms
 - General/specific
 - Author, subject, date, etc

10-17: Propositional Logic

- Notice that propositional logic does not have any way to deal with classes of objects.
 - We can't concisely say "For any room, if there is a breeze, then there is a pit in the next room."
 - To say "The time needed for two people to cross is the time needed for the slower person" requires us to list all possibilities.
 - We don't have functions or predicates.
 - There's a computational tradeoff involved; if we're careful about how we use propositions, we can do fast (polynomial-time) inference.
 - But, we're limited in what our agent can reason about.
 - Propositional logic is the logic underlying hardware design (Boolean logic)

10-18: More on predicates

- Often, people will replace atomic terms with simple predicates.
 - Replace *BonoOnLeft* with *On(Bono, Left)*.
 - As it is, this is fine.
 - What we're missing is a way to talk about all people who are on the left without explicitly enumerating them.
 - We don't have *variables*
 - To do that, we need *first-order logic* (next week)

10-19: Notation

- $A \wedge B$ - AND. sentence is true if both A and B are true.
- $A \vee B$ OR. Sentence is true if either A or B (or both) are true.
- $\neg A$ NOT. Sentence is true if A is false.
- $A \Rightarrow B$ Implies. Sentence is true if A is false or B is true.
- $A \Leftrightarrow B$ Equivalence. Sentence is true if A and B have the same truth value.

10-20: Propositional Logic - implication

- Implication is a particularly useful logical construct.
- The *sentence* $A \Rightarrow B$ is true if:
 - A is true and B is true.
 - A is false.
- Example: If it is raining right now, then it is cloudy right now.
- $A \Rightarrow B$ is equivalent to $\neg A \vee B$.
- Implication will allow us to perform inference.

10-21: Propositional Logic - Still more definitions

- Logical equivalence: Two sentences are logically equivalent if they are true for the same set of models.
 - $P \wedge Q$ is logically equivalent to $\neg(\neg P \vee \neg Q)$
- Validity (tautology): A sentence is valid if it is true for all models.
 - $A \vee \neg A$
- Contradiction: A sentence that is false in all models.
 - $A \wedge \neg A$

10-22: Propositional Logic - Still more definitions

- Satisfiability: A sentence is satisfiable if it is true for some model.
 - $EdgeOnLeft \vee BonoOnLeft$ is true in some worlds.
 - Often our problem will be to find a model that makes a sentence true (or false).
 - A model that satisfies all the sentences we're interested in will be the goal or solution to our search.

10-23: Logical reasoning

- Logical reasoning proceeds by using existing sentences in an agent's KB to *deduce* new sentences.
- Deduction is guaranteed to produce true sentences, assuming a sound mechanism is used.
- Rules of inference.
 - Modus Ponens
 - $A, A \Rightarrow B$, conclude B
 - And-Elimination
 - $A \wedge B$, conclude A .
 - Or-introduction
 - A , conclude $A \vee B$

10-24: Logical Reasoning

- Rules of inference.
 - Contraposition: $A \Rightarrow B$ can be rewritten as $\neg B \Rightarrow \neg A$
 - Double negative: $\neg(\neg A) = A$
 - Distribution
 - $A \vee (B \wedge C) = (A \vee B) \wedge (A \vee C)$
 - $A \wedge (B \vee C) = (A \wedge B) \vee (A \wedge C)$
 - DeMorgan's theorem
 - $A \vee B$, rewrite as $\neg(\neg A \wedge \neg B)$
 - or $A \wedge B \Leftrightarrow \neg(\neg A \vee \neg B)$

10-25: Inference as Search

- We can then use good old breadth-first search (or any other search) to perform inference and determine whether a sentence is entailed by a knowledge base.
- Basic idea: Begin with statements in our KB.
- Actions are applications of implication.
 - For example, say we know 1) $A \Rightarrow B$, 2) $B \Rightarrow C$, and 3) A .
 - One possible action is to apply Modus Ponens to 1 and 3 to conclude B .
 - We can then apply Modus Ponens again to conclude C .

10-26: Inference as Search

- Our search can proceed in a breadth-first manner (what are all the possible conclusions from the original KB), depth-first (take one inference, then use it to make further inferences, and so on) or somewhere in-between.
- Successor function defines all applicable rules for a given knowledge base.
- The result of this search is called a *proof*.

10-27: Example

- Begin with:
 - There is no pit in (1,1): $R_1 : \neg P_{1,1}$
 - A square has a breeze iff there is a pit in the neighboring square
 - $R_2 : B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$
 - $R_3 : B_{2,1} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{3,1})$ (and so on for all other squares)
- Assume the agent visits 1,1 and senses no breeze, but does sense a breeze in 2,1. Add:
 - $R_4 : \neg B_{1,1}$
 - $R_5 : B_{2,1}$

10-28: Example

- We can use biconditional elimination to rewrite R_2 as:
 - $R_6 : (B_{1,1} \Rightarrow (P_{1,2} \vee P_{2,1})) \wedge ((P_{1,2} \vee P_{2,1}) \Rightarrow B_{1,1})$
- And-elimination on R_6 produces $R_7 : ((P_{1,2} \vee P_{2,1}) \Rightarrow B_{1,1})$
- Contraposition on R_7 gives us: $R_8 : \neg B_{1,1} \Rightarrow \neg(P_{1,2} \vee P_{2,1})$
- Modus Ponens with R_8 and R_4 produces $R_9 : \neg(P_{1,2} \vee P_{2,1})$
- DeMorgan's then gives us $R_{10} : \neg P_{1,2} \wedge \neg P_{2,1}$

10-29: Resolution

- The preceding rules are sound, but not necessarily complete.
- Also, search can be inefficient: there might be many operators that can be applied in a particular state.
- Luckily, there is a complete rule for inference (when coupled with a complete search algorithm) that uses a single operator.
- This is called *resolution*.
 - $A \vee B$ and $\neg A \vee C$ allows us to conclude $B \vee C$.
 - A is either true or not true. If A is true, then C must be true.
 - if A is false, then B must be true.
 - This can be generalized to clauses of any length.

10-30: Conjunctive Normal Form

- Resolution works with disjunctions.
- This means that our knowledge base needs to be in this form.
- Conjunctive Normal Form is a conjunction of clauses that are disjunctions.
- $(A \vee B \vee C) \wedge (D \vee E \vee F) \wedge (G \vee H \vee I) \wedge \dots$
- Every propositional logic sentence can be converted to CNF.

10-31: Conjunctive Normal Form Recipe

1. Eliminate equivalence

- $A \Leftrightarrow B$ becomes $A \Rightarrow B \wedge B \Rightarrow A$

2. Eliminate implication

- $A \Rightarrow B$ becomes $\neg A \vee B$

3. Move \neg inwards using double negation and DeMorgan's

- $\neg(\neg A)$ becomes A
- $\neg(A \wedge B)$ becomes $(\neg A \vee \neg B)$

4. Distribute nested clauses

- $(A \vee (B \wedge C))$ becomes $(A \vee B) \wedge (A \vee C)$

10-32: Example

- $B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$
- Eliminating equivalence produces:
 - $(B_{1,1} \Rightarrow (P_{1,2} \vee P_{2,1})) \wedge ((P_{1,2} \vee P_{2,1}) \Rightarrow B_{1,1})$
- Removing implication gives us:
 - $(\neg B_{1,1} \vee (P_{1,2} \vee P_{2,1})) \wedge (\neg(P_{1,2} \vee P_{2,1}) \vee B_{1,1})$
- We then use DeMorgan's rule to move negation inwards:
 - $(\neg B_{1,1} \vee P_{1,2} \vee P_{2,1}) \wedge ((\neg P_{1,2} \wedge \neg P_{2,1}) \vee B_{1,1})$
- Finally, we distribute OR over AND:
 - $(\neg B_{1,1} \vee P_{1,2} \vee P_{2,1}) \wedge (\neg P_{1,2} \vee B_{1,1}) \wedge (\neg P_{2,1}) \vee B_{1,1})$
- Now we have clauses that can be plugged into a resolution theorem prover. (can break ANDs into separate sentences)
- They're less readable by a human, but more computationally useful.

10-33: Proof By Refutation

- Once your KB is in CNF, you can do resolution by refutation.
 - In math, this is called proof by contradiction
- Basic idea: we want to show that sentence A is true.
- Insert $\neg A$ into the KB and try to derive a contradiction.

10-34: Example

- Prove that there is not a pit in (1,2). $\neg P_{1,2}$
- Relevant Facts:
 - $R_{2a} : (\neg B_{1,1} \vee P_{1,2} \vee P_{2,1})$
 - $R_{2b} : (\neg P_{1,2} \vee B_{1,1})$
 - $R_{2c} : (\neg P_{2,1} \vee B_{1,1})$
 - $R_4 : \neg B_{1,1}$
- Insert $R_n : P_{1,2}$ into the KB

10-35: Example

- Resolve R_n with R_{2b} to get: $R_6 : B_{1,1}$
- We already have a contradiction, since $R_4 : \neg B_{1,1}$
- Therefore, the sentence we inserted into the KB must be false.
- Most proofs take more than one step to get to a contradiction ...

10-36: Horn clauses

- Standard resolution theorem proving (and propositional inference in general) is exponentially hard.
- However, if we're willing to restrict ourselves a bit, the problem becomes (computationally) easy.
- A *Horn* clause is a disjunction with at most one positive literal.
 - $\neg A \vee \neg B \vee \neg C \vee D$
 - $\neg A \vee \neg B$
- These can be rewritten as implications with one consequent.
 - $A \wedge B \wedge C \Rightarrow D$
 - $A \wedge B \Rightarrow \text{False}$
- Horn clauses are the basis of logic programming (sometimes called rule-based programming)

10-37: How to use a KB: Forward Chaining

- Forward chaining involves starting with a KB and continually applying Modus Ponens to derive all possible facts.
- This is sometimes called data-driven reasoning
- Start with domain knowledge and see what that knowledge tells you.
- This is very useful for discovering new facts or rules
- Less helpful for proving a specific sentence true or false
 - Search is not directed towards a goal

10-38: How to Use A KB: Backward Chaining

- Backward chaining starts with the goal and “works backward” to the start.
- Example: If we want to show that A is entailed, find a sentence whose consequent is A .
- Then try to prove that sentence’s antecedents.
- This is sometimes called query-driven reasoning.
- More effective at proving a particular query, since search is focused on a goal.
- Less likely to discover new and unknown information.
- Means-ends analysis is a similar sort of reasoning.
- Prolog uses backward chaining.

10-39: Strengths of Propositional Logic

- Declarative - knowledge can be separated from inference.
- Can handle partial information
- Can compose more complex sentences out of simpler ones.
- Sound and complete inference mechanisms (efficient for Horn clauses)

10-40: Weaknesses of Propositional logic

- Exponential increase in number of literals
- No way to describe relations between objects
- No way to quantify over objects.
- First-order logic is a mechanism for dealing with these problems.
- As always, there will be tradeoffs.
 - There's no free lunch!

10-41: Applications

- Propositional logic can work nicely in bounded domains
 - All objects of interest can be enumerated.
- Fast algorithms exist for solving SAT problems via model checking.
 - Search all models to find one that satisfies a sentence.
 - Can be used for some scheduling and planning problems
- Constraint satisfaction problems can be expressed in propositional logic.
 - Often, we'll use a predicate-ish notation as syntactic sugar.