Recall from Last Time: Adversarial Games as Search

Convention: first player is called MAX, 2nd player is called MIN
MAX moves first and they take turns until game is over
Winner gets reward, loser gets penalty
Utility values stated from MAX’s perspective
Initial state and legal moves define the game tree
MAX uses game tree to determine next move
Optimal Strategy: Minimax Search

Find the contingent strategy for MAX assuming an infallible MIN opponent

Assumption: Both players play optimally!

Given a game tree, the optimal strategy can be determined by using the minimax value of each node (defined recursively):

\[
\text{MINIMAX-VALUE}(n) = \begin{cases} 
\text{UTILITY}(n) & \text{If } n \text{ is a terminal} \\
\max_{s \in \text{succ}(n)} \text{MINIMAX-VALUE}(s) & \text{If } n \text{ is a MAX node} \\
\min_{s \in \text{succ}(n)} \text{MINIMAX-VALUE}(s) & \text{If } n \text{ is a MIN node}
\end{cases}
\]
Two-Ply Game Tree

Minimax decision = $A_1$

Minimax maximizes the worst-case outcome for max

Is there anyway I could speed up this search?
Pruning trees

Minimax algorithm explores depth-first

Pruning trees
Pruning trees

MAX

MIN

No need to look at or expand these nodes!!
Pruning trees

MAX

MIN

Pruning trees

MAX

MIN
Prune this tree!
Do we need to check this node?
No, because \( \max(-29, -37) = -29 \) and other children of min can only lower min’s value of \(-37\) (because of the min operation).

Another pruning opportunity!
Pruning can eliminate entire subtrees!
This form of tree pruning is known as alpha-beta pruning

alpha = the highest (best) value for MAX along path
beta = the lowest (best) value for MIN along path

Why is it called α-β?

α is the value of the best (i.e., highest-value) choice found so far at any choice point along the path for max

If v is worse than α, max will avoid it → prune that branch

Define β similarly for min
The \( \alpha - \beta \) algorithm
(minimax with four lines of added code)

\[
\text{function } \text{ALPHA-BETA-SEARCH}(\text{state}) \text{ returns an action}
\]
\[
\text{inputs: } \text{state, current state in game}
\]
\[
v \leftarrow \text{MAX-VALUE}(\text{state}, -\infty, +\infty)
\]
\[
\text{return the action in } \text{SUCCESSORS}(\text{state}) \text{ with value } v
\]

\[
\text{function } \text{MAX-VALUE}(\text{state}, \alpha, \beta) \text{ returns a utility value}
\]
\[
\text{inputs: } \text{state, current state in game}
\]
\[
\alpha, \beta, \text{ the value of the best alternative for } \text{MAX along the path to state}
\]
\[
\beta, \text{ the value of the best alternative for } \text{MIN along the path to state}
\]
\[
\text{if } \text{TERMINAL-TEST}(\text{state}) \text{ then return } \text{UTILITY}(\text{state})
\]
\[
v \leftarrow -\infty
\]
\[
\text{for } s, s' \text{ in } \text{SUCCESSORS}(\text{state}) \text{ do}
\]
\[
v \leftarrow \text{MAX}(v, \text{MIN-VALUE}(s, \alpha, \beta))
\]
\[
\text{if } v \geq \beta \text{ then return } v
\]
\[
\alpha \leftarrow \text{MAX}(\alpha, v)
\]
\[
\text{return } v
\]

New

Pruning

The \( \alpha - \beta \) algorithm (cont.)

\[
\text{function } \text{MIN-VALUE}(\text{state}, \alpha, \beta) \text{ returns a utility value}
\]
\[
\text{inputs: } \text{state, current state in game}
\]
\[
\alpha, \beta, \text{ the value of the best alternative for } \text{MAX along the path to state}
\]
\[
\beta, \text{ the value of the best alternative for } \text{MIN along the path to state}
\]
\[
\text{if } \text{TERMINAL-TEST}(\text{state}) \text{ then return } \text{UTILITY}(\text{state})
\]
\[
v \leftarrow +\infty
\]
\[
\text{for } s, s' \text{ in } \text{SUCCESSORS}(\text{state}) \text{ do}
\]
\[
v \leftarrow \text{MIN}(v, \text{MAX-VALUE}(s, \alpha, \beta))
\]
\[
\text{if } v \leq \alpha \text{ then return } v
\]
\[
\beta \leftarrow \text{MIN}(\beta, v)
\]
\[
\text{return } v
\]
Does alpha-beta pruning change the final result? Is it an approximation?

Properties of $\alpha$-$\beta$

Pruning does not affect final result

Effectiveness of pruning can be improved through good move ordering
(e.g., in chess, captures > threats > forward moves > backward moves)

With "perfect ordering," time complexity $= O(b^{m/2})$
→ allows us to search deeper - doubles depth of search

A simple example of the value of reasoning about which computations are relevant (a form of metareasoning)
**Good enough?**

Chess:
- branching factor $b \approx 35$
- game length $m \approx 100$
- $\alpha$-$\beta$ search space $b^{m/2} \approx 35^{50} \approx 10^{77}$

The Universe:
- number of atoms $\approx 10^{78}$
- age $\approx 10^{21}$ milliseconds

**Can we do better?**

Strategies:
- search to a fixed depth (cut off search)
- iterative deepening search
Evaluation Function

- When search space is too large, create game tree up to a certain depth only.
- Art is to estimate utilities of positions that are not terminal states.
- Example of simple evaluation criteria in chess:
  - Material worth: pawn=1, knight =3, rook=5, queen=9.
  - Other: king safety, good pawn structure
  - Rule of thumb: 3-point advantage = certain victory

\[
\text{eval}(s) = w1 \times \text{material}(s) + w2 \times \text{mobility}(s) + w3 \times \text{king safety}(s) + w4 \times \text{center control}(s) + \ldots
\]
Cutting off search

Does it work in practice?

If \( b^m = 10^6 \) and \( b=35 \) \( \Rightarrow m=4 \)

4-ply lookahead is a hopeless chess player!
- 4-ply \( \approx \) human novice
- 8-ply \( \approx \) typical PC, human master
- 14-ply \( \approx \) Deep Blue, Kasparov
- 18-ply \( \approx \) Hydra (64-node cluster with FPGAs)

What about Games that Include an Element of Chance?

White has just rolled 6-5 and has 4 legal moves.
**Game Tree for Games with an Element of Chance**

- In addition to MIN- and MAX nodes, we include chance nodes (e.g., for rolling dice).

- Search costs increase: Instead of $O(b^d)$, we get $O((bn)^d)$, where $n$ is the number of chance outcomes.

**Expectiminimax Algorithm:**
For chance nodes, compute expected value over successors.

---

**Imperfect Information**

E.g. card games, where opponents’ initial cards are unknown or Scrabble where letters are unknown.

Idea: For all deals consistent with what you can see
- compute the minimax value of available actions for each of possible deals
- compute the expected value over all deals
Game Playing in Practice

- **Chess**: Deep Blue defeated human world champion Gary Kasparov in a 6 game match in 1997. Deep Blue searched 200 million positions per second, used very sophisticated evaluation functions, and undisclosed methods for extending some lines of search up to 40 ply.
- **Checkers**: Chinook ended 40 year reign of human world champion Marion Tinsley in 1994; used an endgame database defining perfect play for all positions involving 8 or fewer pieces on the board, a total of 443,748,401,247 positions (!).
- **Othello**: human champions refuse to play against computers because software is too good.
- **Go**: human champions refuse to play against computers because software is too bad.

Summary of Game Playing using Search

**Basic idea**: Minimax search (but can be slow)

- Alpha-Beta pruning can increase max depth by factor up to 2
- Limited depth search may be necessary
- Static evaluation functions necessary for limited depth search
- Opening and End game databases can help
- Computers can beat humans in some games (checkers, chess, othello) but not in others (Go).
Thinking Rationally

Computational models of human “thought” processes
Computational models of human behavior

\textbf{Computational systems that “think” rationally}

Computational systems that behave rationally
Logical Agents

Chess program calculates legal moves, but doesn’t know that no piece can be on 2 different squares at the same time

Logic (Knowledge-Based) agents combine general knowledge about the world with current percepts to infer hidden aspects of current state prior to selecting actions
  • Crucial in partially observable environments

Outline

Knowledge-based agents
Wumpus world
Logic in general
Propositional logic
  • Inference, validity, equivalence and satisfiability
  • Reasoning
    - Resolution
    - Forward/backward chaining
**Knowledge Base**

*Knowledge Base*: set of sentences represented in a knowledge representation language
- stores assertions about the world

Inference rule: when one ASKS questions of the KB, the answer should *follow* from what has been TELLed to the KB previously.

---

**Generic KB-Based Agent**

```plaintext
function KB-AGENT( percept ) returns an action
static: KB, a knowledge base
       t, a counter, initially 0, indicating time
TELL( KB, MAKE-PERCEPT-SENTENCE( percept, t ) )
action ← ASK( KB, MAKE-ACTION-QUERY( t ) )
TELL( KB, MAKE-ACTION-SENTENCE( action, t ) )
t ← t + 1
return action
```
Abilities of a KB agent

Agent must be able to:
• Represent states and actions
• Incorporate new percepts
• Update internal representation of the world
• Deduce hidden properties of the world
• Deduce appropriate actions

Description level

Agents can be described at different levels
• Knowledge level
  - What they know, regardless of the actual implementation (Declarative description)
• Implementation level
  - Data structures in KB and algorithms that manipulate them, e.g., propositional logic and resolution
A Typical Wumpus World

Wumpus World PEAS Description

Performance measure
- gold +1000, death -1000
- -1 per step, -10 for using the arrow

Environment
- Squares adjacent to wumpus are smelly
- Squares adjacent to pit are breezy
- Glitter iff gold is in the same square
- Shooting kills wumpus if you are facing it
- Shooting uses up the only arrow
- Grabbing picks up gold if in same square
- Climbing in [1,1] gets agent out of the cave

Sensors Stench, Breeze, Glitter, Bump, Scream

Actuators TurnLeft, TurnRight, Forward, Grab, Shoot, Climb
Wumpus World Characterization

Observable?
Deterministic?
Episodic?
Static?
Discrete?
Single-agent?

Observable? No, only local perception
Wumpus World Characterization

Observable? No, only local perception
Deterministic? Yes, outcome exactly specified
Episodic?
Static?
Discrete?
Single-agent?
**Wumpus World Characterization**

Observable? No, only local perception  
Deterministic? Yes, outcome exactly specified  
Episodic? No, sequential at the level of actions  
Static? Yes, Wumpus and pits do not move  
Discrete? Yes  
Single-agent?
Wumpus World Characterization

Observable? No, only local perception
Deterministic? Yes, outcome exactly specified
Episodic? No, sequential at the level of actions
Static? Yes, Wumpus and pits do not move
Discrete? Yes
Single-agent? Yes, Wumpus is essentially a “natural” feature of the environment

Exploring the Wumpus World

[1,1] KB initially contains the rules of the environment. First percept is [none, none, none, none, none], move to safe cell e.g. 2,1
[2,1] Breeze which indicates that there is a pit in [2,2] or [3,1], return to [1,1] to try next safe cell
### Exploring the Wumpus World

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<th>1,1</th>
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</table>

- **A** = Agent
- **B** = Breeze
- **G** = Glitter, Gold
- **OK** = Safe square
- **P** = Pit
- **S** = Stench
- **V** = Visited
- **W** = Wumpus

[1,2] Stench in cell which means that wumpus is in [1,3] or [2,2] but not in [1,1]

**YET** ... wumpus not in [2,2] or stench would have been detected in [2,1]

**THUS** ... wumpus must be in [1,3]

**THUS** [2,2] is safe because of lack of breeze in [1,2]

**THUS** pit in [3,1]

**move to next safe cell [2,2]**

---

### Exploring the Wumpus World

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- **V** = Visited
- **W** = Wumpus

[2,2] **Move to [2,3]**

[2,3] **Detect glitter, smell, breeze**

**Grab gold**

**THUS** pit in [3,3] or [2,4]**
How do we represent rules of the world and percepts encountered so far?

Why not use logic?

What is a logic?

A formal language
  • Syntax – what expressions are legal (well-formed)
  • Semantics – what legal expressions mean
    - In logic the truth of each sentence evaluated with respect to each possible world

E.g the language of arithmetic
  • x+2 >= y is a sentence, x2y+ is not a sentence
  • x+2 >= y is true in a world where x=7 and y=1
  • x+2 >= y is false in a world where x=0 and y=6
How do we draw conclusions and deduce new facts about the world using logic?

Entailment

Knowledge Base = KB
Sentence \( \alpha \)

\[ KB \models \alpha \] (KB “entails” sentence \( \alpha \))

if and only if \( \alpha \) is true in all worlds (models) where KB is true.

E.g. \( x+y=4 \) entails \( 4=x+y \)
(because \( 4=x+y \) is true for all values of \( x, y \) for which \( x+y=4 \) is true)
**Models and Entailment**

$m$ is a model of a sentence $\alpha$ if $\alpha$ is true in $m$

* e.g. $\alpha$ is “$4=x+y$” and $m = \{ x=2, y=2 \}$

$M(\alpha)$ is the set of all models of $\alpha$

Then $KB \models \alpha$ iff $M(KB) \subseteq M(\alpha)$

* E.g. $KB = CSEP 573$ students are bored and $CSEP 573$ students are sleepy;
  $\alpha = CSEP 573$ students are bored

**Wumpus world model**

Situation after detecting nothing in [1,1], moving right, breeze in [2,1]

Consider possible models for $\alpha$

* assuming only pits

3 Boolean choices $\Rightarrow$ 8 possible models
**Wumpus possible world models**

```
```

**Wumpus world models consistent with observations**

\[ KB = \text{wumpus-world rules} + \text{observations} \]
Example of Entailment

Is [1,2] safe?

$K B = \text{wumpus-world rules + observations}$

$M(KB) \subseteq M(\alpha_1)$

$\alpha_1 = \text{"[1,2] is safe"}, \ K B \models \alpha_1$, proved by model checking
Another Example

Is [2,2] safe?

$KB = \text{wumpus-world rules + observations}$

Another Example

$KB = \text{wumpus-world rules + observations}$

$\alpha_2 = \text{"[2,2] is safe"}$, $KB \not\models \alpha_2 \quad M(KB) \not\models M(\alpha_2)$
Soundness and Completeness

If an inference algorithm only derives entailed sentences, it is called sound (or truth preserving).

- Otherwise it just makes things up
- Algorithm i is sound if whenever $KB \models \alpha$ (i.e. $\alpha$ is derived by i from KB) it is also true that $KB \models \alpha$

Completeness: An algorithm is complete if it can derive any sentence that is entailed.

\[ i \text{ is complete if whenever } KB \models \alpha \text{ it is also true that } KB \vdash \alpha \]

Relating to the Real World

If $KB$ is true in the real world, then any sentence $\alpha$ derived from $KB$ by a sound inference procedure is also true in the real world.
Propositional Logic: Syntax

Propositional logic is the simplest logic - illustrates basic ideas

Atomic sentences = proposition symbols = A, B, P_{1,2}, P_{2,2} etc. used to denote properties of the world

• Can be either True or False

E.g. P_{1,2} = “There’s a pit in location [1,2]” is either true or false in the wumpus world

Propositional Logic: Syntax

Complex sentences constructed from simpler ones recursively

If S is a sentence, \neg S is a sentence (negation)
If S_1 and S_2 are sentences, S_1 \land S_2 is a sentence (conjunction)
If S_1 and S_2 are sentences, S_1 \lor S_2 is a sentence (disjunction)
If S_1 and S_2 are sentences, S_1 \Rightarrow S_2 is a sentence (implication)
If S_1 and S_2 are sentences, S_1 \Leftrightarrow S_2 is a sentence (biconditional)
Propositional Logic: Semantics

A model specifies true/false for each proposition symbol

E.g. \( P_{1,2} \quad P_{2,2} \quad P_{3,1} \)

false  true  false

Rules for evaluating truth w.r.t. a model \( m \):

\[ \neg S \text{ is true iff } S \text{ is false} \]
\[ S_1 \land S_2 \text{ is true iff } S_1 \text{ is true and } S_2 \text{ is true} \]
\[ S_1 \lor S_2 \text{ is true iff } S_1 \text{ is true or } S_2 \text{ is true} \]
\[ S_1 \Rightarrow S_2 \text{ is true iff } S_1 \text{ is false or } S_2 \text{ is true} \]
\[ S_1 \Leftrightarrow S_2 \text{ is true iff both } S_1 \Rightarrow S_2 \text{ and } S_2 \Rightarrow S_1 \text{ are true} \]

Truth Tables for Connectives

<table>
<thead>
<tr>
<th>( P )</th>
<th>( Q )</th>
<th>( \neg P )</th>
<th>( P \land Q )</th>
<th>( P \lor Q )</th>
<th>( P \Rightarrow Q )</th>
<th>( P \Leftrightarrow Q )</th>
</tr>
</thead>
<tbody>
<tr>
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</table>
**Propositional Logic: Semantics**

Simple recursive process can be used to evaluate an arbitrary sentence.

E.g., Model: \( P_{1,2} \quad P_{2,2} \quad P_{3,1} \)

<table>
<thead>
<tr>
<th>( P_{1,2} )</th>
<th>( P_{2,2} )</th>
<th>( P_{3,1} )</th>
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<tbody>
<tr>
<td>false</td>
<td>true</td>
<td>false</td>
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</tbody>
</table>

\[
\neg P_{1,2} \land (P_{2,2} \lor P_{3,1})
= true \land (true \lor false)
= true \land true
= true
\]

**Example: Wumpus World**

Proposition Symbols and Semantics:
Let \( P_{i,j} \) be true if there is a pit in \([i, j]\).
Let \( B_{i,j} \) be true if there is a breeze in \([i, j]\).
### Wumpus KB

Knowledge Base (KB) includes the following sentences:

**Statements currently known to be true:**

- \( \neg P_{1,1} \)
- \( \neg B_{1,1} \)
- \( B_{2,1} \)

**Properties of the world:** E.g., "Pits cause breezes in adjacent squares"

- \( B_{1,1} \leftrightarrow (P_{1,2} \lor P_{2,1}) \)
- \( B_{2,1} \leftrightarrow (P_{1,1} \lor P_{2,2} \lor P_{3,1}) \)

(and so on for all squares)

<table>
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<tr>
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<th>1,4</th>
<th>2,4</th>
<th>3,4</th>
<th>4,4</th>
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**Can a Wumpus-Agent use this logical representation and KB to avoid pits and the wumpus, and find the gold?**

- Is there no pit in [1,2]?
- Does KB \( \models \neg P_{1,2} \)?
### Inference by Truth Table Enumeration

<table>
<thead>
<tr>
<th>$B_{1,1}$</th>
<th>$B_{2,1}$</th>
<th>$P_{1,1}$</th>
<th>$P_{1,2}$</th>
<th>$P_{2,1}$</th>
<th>$P_{2,2}$</th>
<th>$P_{3,1}$</th>
<th>$KB$</th>
<th>$\neg P_{1,2}$</th>
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</tr>
</tbody>
</table>

$\neg P_{1,2}$ true in all models in which $KB$ is true

Therefore, $KB \vdash \neg P_{1,2}$

### Another Example

Is there a pit in [2,2]?
Inference by Truth Table Enumeration

Algorithm: Depth-first enumeration of all models (see Fig. 7.10 in text for pseudocode)
- Algorithm is sound & complete

For $n$ symbols:
- time complexity $= O(2^n)$, space $= O(n)$
Concepts for Other Techniques: Logical Equivalence

Two sentences are logically equivalent iff they are true in the same models: $\alpha \equiv \beta$ iff $\alpha \vdash \beta$ and $\beta \vdash \alpha$

- $(\alpha \land \beta) \equiv (\beta \land \alpha)$ commutativity of $\land$
- $(\alpha \lor \beta) \equiv (\beta \lor \alpha)$ commutativity of $\lor$
- $((\alpha \land \beta) \land \gamma) \equiv (\alpha \land (\beta \land \gamma))$ associativity of $\land$
- $((\alpha \lor \beta) \lor \gamma) \equiv (\alpha \lor (\beta \lor \gamma))$ associativity of $\lor$
- $\neg(\neg \alpha) \equiv \alpha$ double-negation elimination
- $(\alpha \Rightarrow \beta) \equiv (\neg \beta \Rightarrow \neg \alpha)$ contraposition
- $(\alpha \Rightarrow \beta) \equiv (\neg \alpha \lor \beta)$ implication elimination
- $(\alpha \iff \beta) \equiv ((\alpha \Rightarrow \beta) \land (\beta \Rightarrow \alpha))$ biconditional elimination
- $\neg(\alpha \land \beta) \equiv (\neg \alpha \lor \neg \beta)$ de Morgan
- $\neg(\alpha \lor \beta) \equiv (\neg \alpha \land \neg \beta)$ de Morgan
- $(\alpha \land (\beta \lor \gamma)) \equiv ((\alpha \land \beta) \lor (\alpha \land \gamma))$ distributivity of $\land$ over $\lor$
- $(\alpha \lor (\beta \land \gamma)) \equiv ((\alpha \lor \beta) \land (\alpha \lor \gamma))$ distributivity of $\lor$ over $\land$

Concepts for Other Techniques: Validity and Satisfiability

A sentence is valid if it is true in all models (a tautology)
- e.g., $\text{True}$, $A \lor \neg A$, $A \Rightarrow A$, $(A \land (A \Rightarrow B)) \Rightarrow B$

Validity is connected to inference via the Deduction Theorem:

$KB \vdash a$ if and only if $(KB \Rightarrow a)$ is valid

A sentence is satisfiable if it is true in some model
- e.g., $A \lor B$, $C$

A sentence is unsatisfiable if it is true in no models
- e.g., $A \land \neg A$

Satisfiability is connected to inference via the following: $KB \vdash a$ if and only if $(KB \land \neg a)$ is unsatisfiable (proof by contradiction)
Inference Techniques for Logical Reasoning

Two kinds (roughly):
- Model checking
  - Truth table enumeration (always exponential in \( n \))
  - Efficient backtracking algorithms
    - e.g., Davis-Putnam-Logemann-Loveland (DPLL)
  - Local search algorithms (sound but incomplete)
    - e.g., randomized hill-climbing (WalkSAT)

Successive application of inference rules
- Generate new sentences from old in a sound way
- Proof = a sequence of inference rule applications
- Use inference rules as successor function in a standard search algorithm
Inference Technique I: Resolution

Terminology:

Literal = proposition symbol or its negation
E.g., A, ¬A, B, ¬B, etc.

Clause = disjunction of literals
E.g., (B ∨ ¬C ∨ ¬D)

Resolution assumes sentences are in Conjunctive Normal Form (CNF):

sentence = conjunction of clauses
E.g., (A ∨ ¬B) ∧ (B ∨ ¬C ∨ ¬D)

Conversion to CNF

E.g., B₁,₁ ⇔ (P₁,₂ ∨ P₂,₁)

1. Eliminate ⇔, replacing α ⇔ β with (α ⇒ β) ∧ (β ⇒ α).
   (B₁,₁ ⇒ (P₁,₂ ∨ P₂,₁)) ∧ ((P₁,₂ ∨ P₂,₁) ⇒ B₁,₁)

2. Eliminate ⇒, replacing α ⇒ β with ¬α ∨ β.
   (¬B₁,₁ ∨ P₁,₂ ∨ P₂,₁) ∧ (¬(P₁,₂ ∨ P₂,₁) ∨ B₁,₁)

3. Move ¬ inwards using de Morgan’s rules and double-negation:
   (¬B₁,₁ ∨ P₁,₂ ∨ P₂,₁) ∧ ((¬P₁,₂ ∧ ¬P₂,₁) ∨ B₁,₁)

4. Apply distributivity law (∧ over ∨) and flatten:
   (¬B₁,₁ ∨ P₁,₂ ∨ P₂,₁) ∧ (¬P₁,₂ ∨ B₁,₁) ∧ (¬P₂,₁ ∨ B₁,₁)

   This is in CNF – Done!
Resolution motivation

There is a pit in [1,3] or There is a pit in [2,2] There is no pit in [2,2]

There is a pit in [1,3]

More generally,

\[ l_1 \lor \ldots \lor l_k \quad \neg l_i \]
\[ l_1 \lor \ldots \lor l_{i-1} \lor l_{i+1} \lor \ldots \lor l_k \]

Inference Technique: Resolution

General Resolution inference rule (for CNF):

\[ l_1 \lor \ldots \lor l_k \quad m_1 \lor \ldots \lor m_n \]
\[ l_1 \lor \ldots \lor l_{i-1} \lor l_{i+1} \lor \ldots \lor l_k \lor m_1 \lor \ldots \lor m_{j-1} \lor m_{j+1} \ldots \lor m_n \]

where \( l_i \) and \( m_j \) are complementary literals (\( l_i = \neg m_j \))

E.g., \( p_{1,3} \lor p_{2,2} \quad \neg p_{2,2} \)

Resolution is sound and complete for propositional logic
**Soundness**

Proof of soundness of resolution inference rule:

\[ \neg (l_1 \lor \ldots \lor l_{i-1} \lor l_{i+1} \lor \ldots \lor l_k) \Rightarrow l_i \]

\[ \neg m_j \Rightarrow (m_1 \lor \ldots \lor m_{j-1} \lor m_{j+1} \lor \ldots \lor m_n) \]

\[ \neg (l_1 \lor \ldots \lor l_{i-1} \lor l_{i+1} \lor \ldots \lor l_k) \Rightarrow (m_1 \lor \ldots \lor m_{j-1} \lor m_{j+1} \lor \ldots \lor m_n) \]

(since \( l_i = \neg m_j \))

**Resolution algorithm**

To show \( KB \models \alpha \), use proof by contradiction, i.e., show \( KB \land \neg \alpha \) unsatisfiable

function PL-RESOLUTION(\( KB, \alpha \)) returns true or false

\[ \text{clauses} \leftarrow \text{the set of clauses in the CNF representation of } KB \land \neg \alpha \]

\[ \text{new} \leftarrow \{ \} \]

loop do

for each \( C_i, C_j \) in \( \text{clauses} \) do

\[ \text{resolvents} \leftarrow \text{PL-RESOLVE}(C_i, C_j) \]

if resolvents contains the empty clause then return true

\[ \text{new} \leftarrow \text{new} \cup \text{resolvents} \]

if \( \text{new} \subseteq \text{clauses} \) then return false

\[ \text{clauses} \leftarrow \text{clauses} \cup \text{new} \]

end loop

PL-RESOLUTION can be shown to be complete (see text)
Resolution example

Given no breeze in [1,1], prove there's no pit in [1,2]

\[ KB = (B_{1,1} \iff (P_{1,2} \lor P_{2,1})) \land \neg B_{1,1} \text{ and } \alpha = \neg P_{1,2} \]

Resolution: Convert to CNF and show KB \land \neg \alpha is unsatisfiable
Resolution example

\[ \neg P_1 \lor B_{1,1} \quad \neg B_{1,1} \lor P_{1,2} \lor P_{1,3} \quad \neg P_{1,4} \lor B_{1,1} \quad \neg B_{1,1} \quad P_{1,2} \]

Empty clause
(i.e., \( KB \land \neg \alpha \) unsatisfiable)

Inference Technique II: Forward/Backward Chaining

Require sentences to be in Horn Form:

- \( KB = \) conjunction of Horn clauses

  - Horn clause =
    - proposition symbol or
    - “(conjunction of symbols) \( \Rightarrow \) symbol”
      (i.e. clause with at most 1 positive literal)
  
  - E.g., \( KB = C \land (B \Rightarrow A) \land ((C \land D) \Rightarrow B) \)

F/B chaining is based on “Modus Ponens” rule:

\[
\begin{array}{c}
\alpha_1, \ldots, \alpha_n \\
\alpha_1 \land \ldots \land \alpha_n \Rightarrow \beta
\end{array}
\]

\[
\beta
\]

- Complete for Horn clauses

Very natural and linear time complexity in size of KB
**Forward chaining**

Idea: fire any rule whose premises are satisfied in \( KB \) add its conclusion to \( KB \), until query \( q \) is found

\[
\begin{align*}
\text{KB:} & \\
& P \Rightarrow Q \\
& L \land M \Rightarrow P \\
& B \land L \Rightarrow M \\
& A \land P \Rightarrow L \\
& A \land B \Rightarrow L \\
& A \\
& B \\
\end{align*}
\]

Query: “Is \( Q \) true?”

**AND-OR Graph for KB**

---

**Forward chaining algorithm**

```plaintext
function PL-FC-ENTAILS?(KB, q) returns true or false
local variables: count, a table, indexed by clause, initially the number of premises
inferred, a table, indexed by symbol, each entry initially false
agenda, a list of symbols, initially the symbols known to be true

while agenda is not empty do
    p ← POP(agenda)
    unless inferred[p] do
        inferred[p] ← true
        for each Horn clause \( c \) in whose premise \( p \) appears do
            decrement count[c]  // Decrement # premises
            if count[c] = 0 then do  // All premises satisfied
                if HEAD[c] = q then return true
            PUSH(HEAD[c], agenda)

return false
```

Forward chaining is sound & complete for Horn KB
Query = Q
(i.e. “Is Q true?”)

Forward chaining example

A is known to be true
Forward chaining example

B is also known to be true

count = 0; therefore, L is true

Forward chaining example

count = 0; therefore, M is true
Forward chaining example

count = 0; therefore, P is true

Query = Q (i.e. “Is Q true?”)

count = 0; therefore, Q is true
Backward chaining

Idea: work backwards from the query \( q \)

to prove \( q \):
check if \( q \) is known already, OR
prove by backward chaining all premises of
some rule concluding \( q \)

Avoid loops: check if new subgoal is already on goal stack

Avoid repeated work: check if new subgoal
1. has already been proved true, or
2. has already failed

Backward chaining example
Backward chaining example
Backward chaining example
Backward chaining example

Backward chaining example
Backward chaining example

Backward chaining example
**Forward vs. backward chaining**

FC is data-driven, automatic, unconscious processing  
 e.g., object recognition, routine decisions

FC may do lots of work that is irrelevant to the goal

BC is goal-driven, appropriate for problem-solving  
 e.g., How do I get an A in this class?  
 e.g., What is my best exit strategy out of the classroom?  
 e.g., How can I impress my date tonight?

Complexity of BC can be much less than linear in size of KB

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**Next Class: More logic & Uncertainty**

Note: No homework this week, HW #2 will be assigned next week