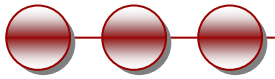

CMSC 671
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Knowledge-Based Agents / Logic
Chapter 7

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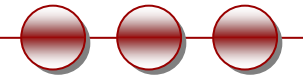
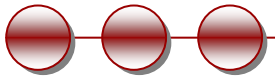
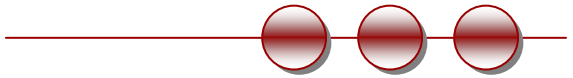
Some material adopted from Hwee Tou Ng's course slides





Knowledge based agents



A knowledge-based agent

- A knowledge-based agent includes a knowledge
- base and an inference system.
- **Knowledge base (KB)**
  - A set of assertions (**sentences**) about the world,
  - expressed in a **knowledge representation language**.
  - Observations can be added as new sentences.
  - Queries about what *follows* from the KB
  - May initially contain some **background knowledge**
- **Inference:** deriving new sentences from old ones.

A knowledge-based agent (2)

- The agent operates as follows:
  - It TELLs the knowledge base what it perceives.
  - It ASKs the knowledge base what action it should
  - perform.
  - It performs the chosen action

Declarative approach

- Knowledge-based agents follow a **declarative approach** to system building
  - Can be built simply by TELLing what it needs to know.
- In contrast a **procedural approach** encodes desired behaviors directly as program code.

Architecture of a knowledge-based agent

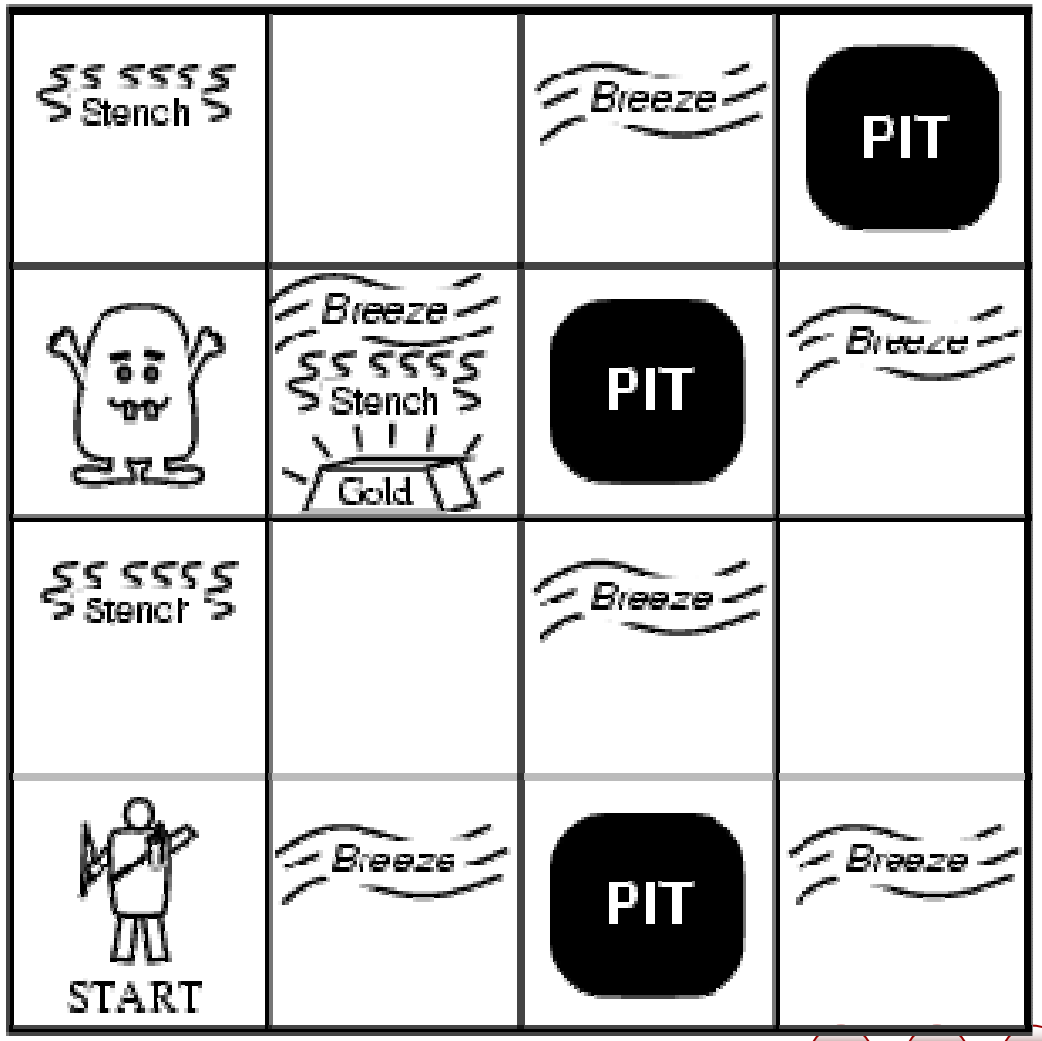
- **Knowledge Level.**
  - The most abstract level: describe agent by saying what it knows.
  - Example: A taxi agent might know that the Golden Gate Bridge connects San Francisco with the Marin County.
- **Logical Level.**
  - The level at which the knowledge is encoded into sentences.
  - Example: Links(GoldenGateBridge, SanFrancisco, MarinCounty).
- **Implementation Level.**
  - The physical representation of the sentences in the logical level.
  - Example: `'(links goldengatebridge sanfrancisco marincounty)`

Example: The Wumpus World environment

- The Wumpus computer game
  - The agent explores a cave consisting of rooms connected by passageways.
  - Lurking somewhere in the cave is the Wumpus, a beast that eats any agent that enters its room.
  - Some rooms contain bottomless pits that trap any agent that wanders into the room.
  - Occasionally, there is a heap of gold in a room.
  - The goal is to collect the gold and exit the world without being eaten

A typical Wumpus world

- The agent always starts in the field [1,1].
- The task of the agent is to find the gold, return to the field [1,1] and climb out of the cave.



Agent in a Wumpus world: Percepts

- The agent perceives
  - a stench in the square containing the wumpus and in the adjacent squares (not diagonally)
  - a breeze in the squares adjacent to a pit
  - a glitter in the square where the gold is
  - a bump, if it walks into a wall
  - a woeful scream everywhere in the cave, if the wumpus is killed
- The percepts are given as a five-symbol list.
  - Example: [Stench, Breeze, None, None, None]

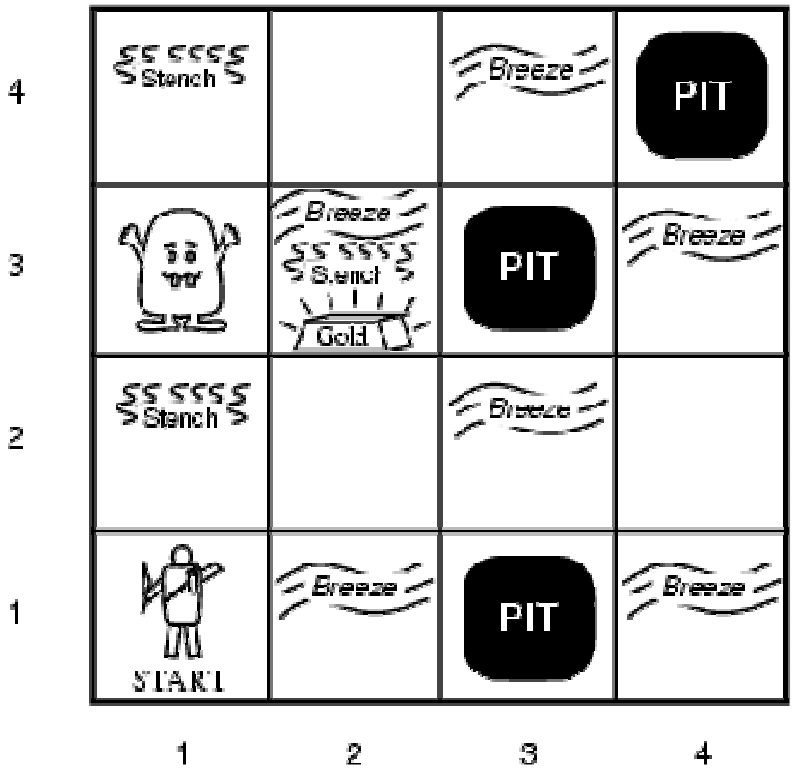
Agent in a Wumpus world: actions

- **go forward**
- **turn right** (90◦)
- **turn left** (90◦)
- **grab**: Pick up an object in same square as the agent
- **shoot**: Fire an arrow in a straight line in the direction the agent is facing (arrow continues until it either hits and kills the wumpus or hits the outer wall). Agent has only 1 arrow, so only the 1st *Shoot* action has any effect.
- **climb** is used to leave the cave (only effective in the start square).
- **die**: This action automatically and irretrievably happens if the agent enters a square with a pit or a live wumpus

Wumpus goal

- The agent's goal is to find the gold and bring it back to the start square as quickly as possible, without getting killed

Exercise: make the agent find the gold



- Start at [1,1]
- Move to [2,1]: perceive a breeze (PIT either on [2,2] or [3,1])
- Go back to [1,1]
- ?

The Wumpus agent's first step

(a) (b)

Later

1,4	2,4	3,4	4,4
1,3 W!	2,3	3,3	4,3
1,2 A S OK	2,2 ¬W ¬P OK	3,2	4,2
1,1 V OK	2,1 B V OK	3,1 P! ¬W	4,1

(a)

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

1,4	2,4 P?	3,4	4,4
1,3 W!	2,3 A S G B	3,3 P?	4,3
1,2 S V OK	2,2 ¬W V ¬P OK	3,2	4,2
1,1 V OK	2,1 B V OK	3,1 P! ¬W	4,1

(b)

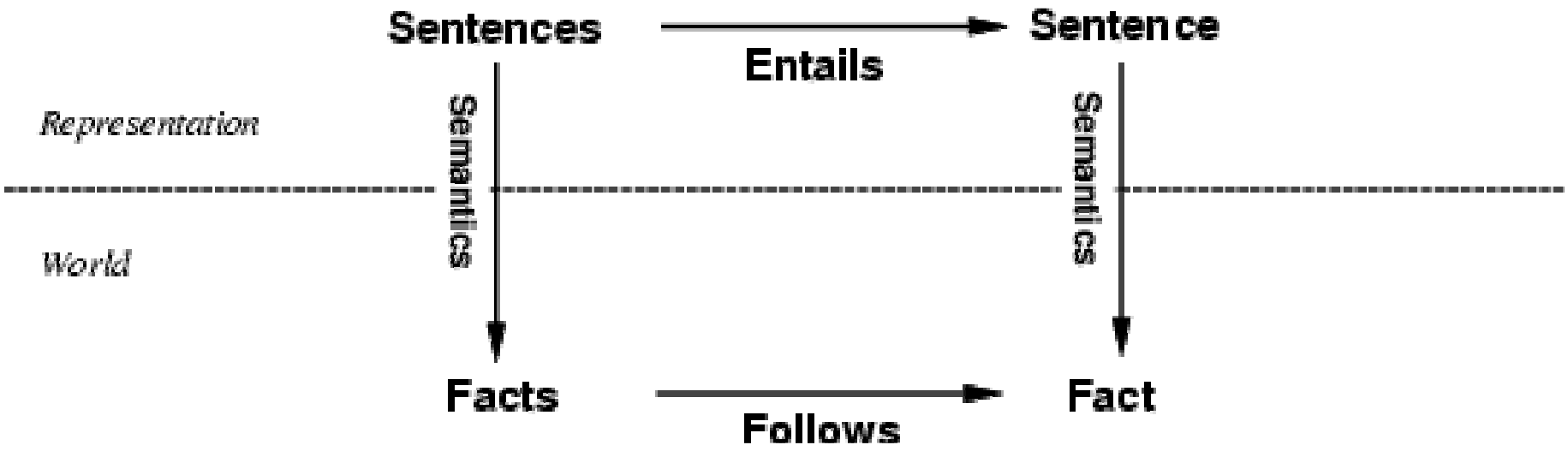
Wumpuses online

- http://www.cs.berkeley.edu/~russell/code/doc/overview-AGENTS.html - Lisp version from Russell & Norvig
- http://www.dreamcodex.com/wumpus.php – Web-based version you can play
- http://codenautics.com/wumpus/ – Downloadable Mac version

Representation, reasoning, and logic

- **Logics** are formal languages for representing information such that conclusions can be drawn
- A knowledge representation language is defined by:
  - its **syntax,** which specifies all valid sentences in the language
  - its **semantics**, which defines the "meaning" or truth of each sentence

The connection between sentences and facts



Semantics maps sentences in logic to facts in the world.
The property of one fact following from another is mirrored by the property of one sentence being entailed by another.

Entailment and derivation

- **Entailment: KB |= Q**
  - The needle (Q) being in the haystack
  - Q is entailed by KB if and only if the conclusion is true in every logically possible world in which all the premises in KB are true.
- **Derivation: KB |- Q**
  - Finding the needle (Q) in the haystack (KB)
  - We can derive Q from KB if there is a proof consisting of a sequence of valid **inference** steps starting from the premises in KB and resulting in Q

Inference

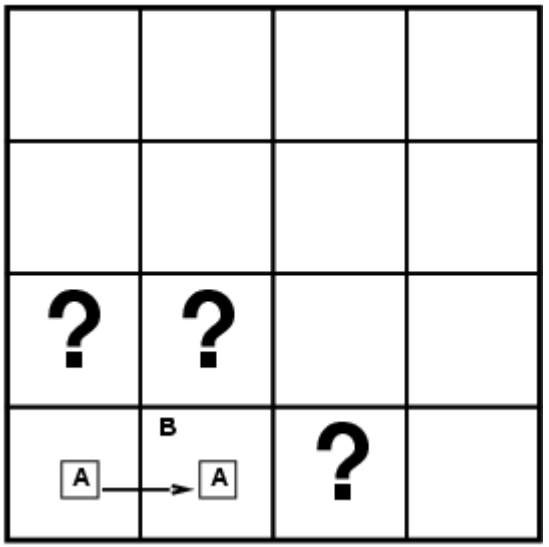
- $KB \vdash_i \alpha$ = sentence α can be derived from KB by procedure i
- Soundness: derivations produce only entailed sentences
- Completeness: derivations can produce all entailed sentences

Entailment in the wumpus world

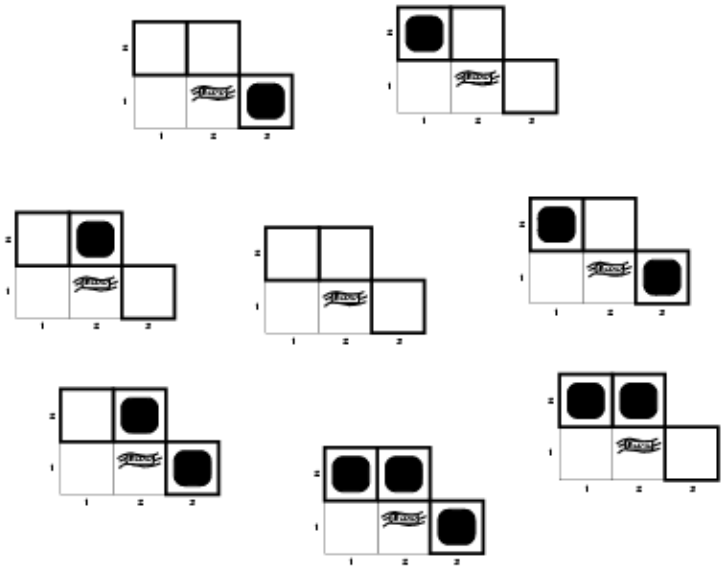
Situation after detecting nothing in [1,1], moving right, breeze in [2,1]

Consider possible models for *KB* assuming only pits

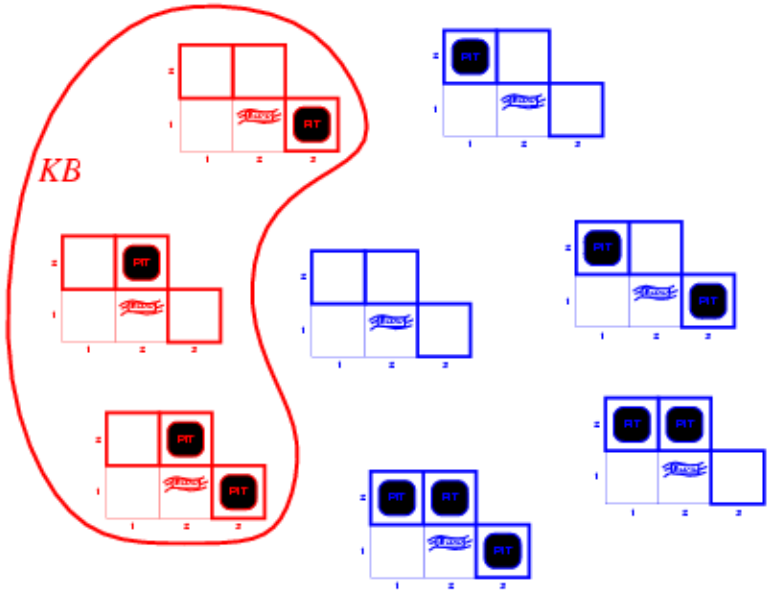
3 Boolean choices $\Rightarrow$ 8 possible models



Wumpus models

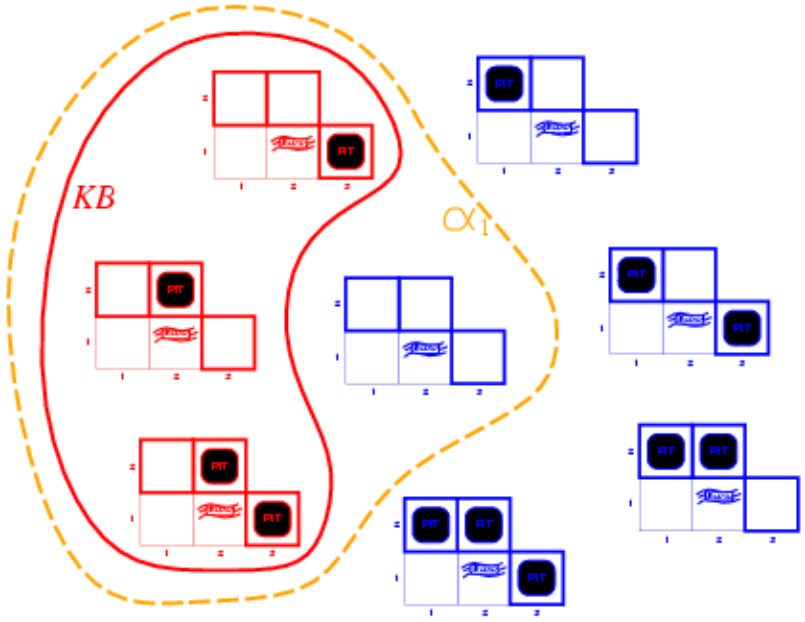


Wumpus models



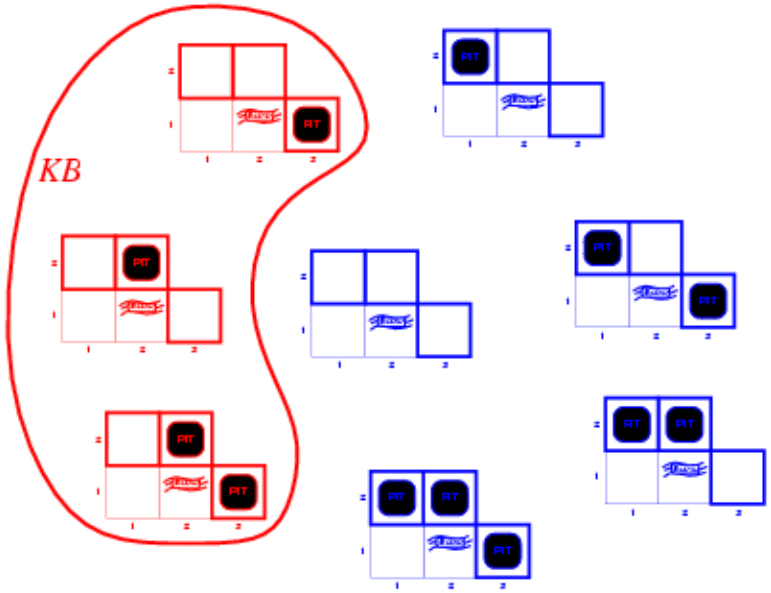
- *KB* = wumpus-world rules + observations

Wumpus models



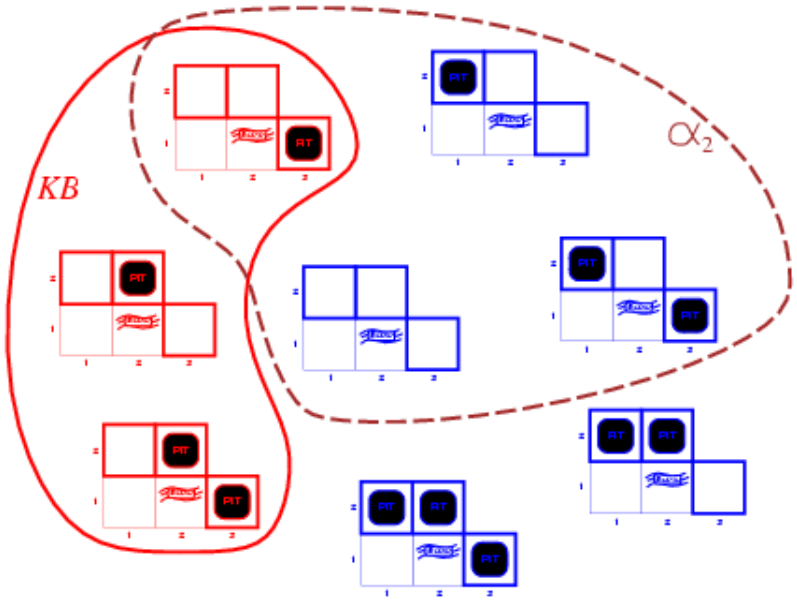
- *KB* = wumpus-world rules + observations
- α_1 = "[1,2] is safe", $KB \models \alpha_1$, proved by model checking

Wumpus models

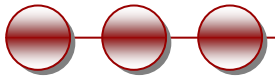


- *KB* = wumpus-world rules + observations

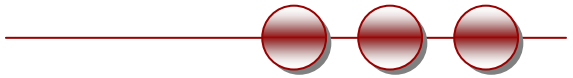
Wumpus models



- *KB* = wumpus-world rules + observations
- α_2 = "[2,2] is safe", $KB \not\models \alpha_2$



Propositional Logic



Propositional logic

- Propositional logic is the simplest logic – illustrates basic ideas
- Syntax - the proposition symbols P_1, P_2 are sentences
  - $\neg S$ (negation), $S_1 \wedge S_2$ (conjunction), $S_1 \vee S_2$ (disjunction), $S_1 \Rightarrow S_2$ (implication), $S_1 \Leftrightarrow S_2$ (biconditional)
- Semantics

$\neg S$	is true iff	S is false		
$S_1 \wedge S_2$	is true iff	S_1 is true and		S_2 is true
$S_1 \vee S_2$	is true iff	$S_1$is true or		S_2 is true
$S_1 \Rightarrow S_2$	is true iff		S_1 is false or	S_2 is true
i.e.,	is false iff		S_1 is true and	S_2 is false
$S_1 \Leftrightarrow S_2$	is true iff		$S_1 \Rightarrow S_2$ is true and	$S_2 \Rightarrow S_1$ is true

- Wumpus world sentences
  - $P_{i,j}$ true if pit in [i, j]; $B_{i,j}$ true if breeze in [i, j]
    $\neg P_{1,1}; \neg B_{1,1}; B_{2,1}$
  - "Pits cause breezes in adjacent squares"
    $B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$
    $B_{2,1} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{3,1})$

Propositional logic: inference

- $KB \models \alpha$
- Different approaches:
  - Model checking – enumerate all models and check that α=T when KB=T
    - Truth table enumeration (always exponential in *n*)
    - improved backtracking, e.g., Davis--Putnam-Logemann-Loveland (DPLL)
    - Local heuristic search in model space (sound but incomplete) e.g., min-conflicts-like hill-climbing
  - Application of inference rules to the sentences in KB to construct a *proof* of the desired sentence.

Truth tables for inference

$B_{1,1}$	$B_{2,1}$	$P_{1,1}$	$P_{1,2}$	$P_{2,1}$	$P_{2,2}$	$P_{3,1}$	KB	α_1
$false$	$false$	$false$	$false$	$false$	$false$	$false$	$false$	$true$
$false$	$false$	$false$	$false$	$false$	$false$	$true$	$false$	$true$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
$false$	$true$	$false$	$false$	$false$	$false$	$false$	$false$	$true$
$false$	$true$	$false$	$false$	$false$	$false$	$true$	$\underline{true}$	$\underline{true}$
$false$	$true$	$false$	$false$	$false$	$true$	$false$	$\underline{true}$	$\underline{true}$
$false$	$true$	$false$	$false$	$false$	$true$	$true$	$\underline{true}$	$\underline{true}$
$false$	$true$	$false$	$false$	$true$	$false$	$false$	$false$	$true$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
$true$	$true$	$true$	$true$	$true$	$true$	$true$	$false$	$false$

Logical equivalence

- Two sentences are logically equivalent} iff true in same models: $\alpha \equiv$ ß iff $\alpha \models \beta$ and $\beta \models \alpha$

$$
\begin{aligned}
(\alpha \wedge \beta) &\equiv (\beta \wedge \alpha) && \text{commutativity of } \wedge \\
(\alpha \vee \beta) &\equiv (\beta \vee \alpha) && \text{commutativity of } \vee \\
((\alpha \wedge \beta) \wedge \gamma) &\equiv (\alpha \wedge (\beta \wedge \gamma)) && \text{associativity of } \wedge \\
((\alpha \vee \beta) \vee \gamma) &\equiv (\alpha \vee (\beta \vee \gamma)) && \text{associativity of } \vee \\
\neg(\neg\alpha) &\equiv \alpha && \text{double-negation elimination} \\
(\alpha \Rightarrow \beta) &\equiv (\neg\beta \Rightarrow \neg\alpha) && \text{contraposition} \\
(\alpha \Rightarrow \beta) &\equiv (\neg\alpha \vee \beta) && \text{implication elimination} \\
(\alpha \Leftrightarrow \beta) &\equiv ((\alpha \Rightarrow \beta) \wedge (\beta \Rightarrow \alpha)) && \text{biconditional elimination} \\
\neg(\alpha \wedge \beta) &\equiv (\neg\alpha \vee \neg\beta) && \text{de Morgan} \\
\neg(\alpha \vee \beta) &\equiv (\neg\alpha \wedge \neg\beta) && \text{de Morgan} \\
(\alpha \wedge (\beta \vee \gamma)) &\equiv ((\alpha \wedge \beta) \vee (\alpha \wedge \gamma)) && \text{distributivity of } \wedge \text{ over } \vee \\
(\alpha \vee (\beta \wedge \gamma)) &\equiv ((\alpha \vee \beta) \wedge (\alpha \vee \gamma)) && \text{distributivity of } \vee \text{ over } \wedge
\end{aligned}
$$

Resolution

Conjunctive Normal Form (CNF)

conjunction of disjunctions of literals

clauses

E.g., $(A \vee \neg B) \wedge (B \vee \neg C \vee \neg D)$

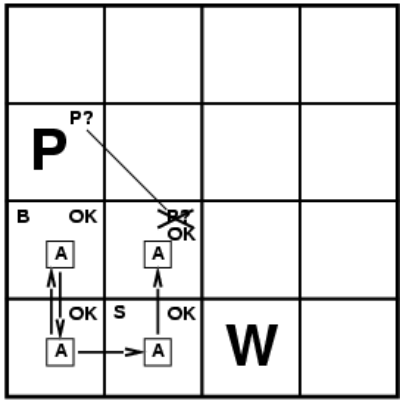
- Resolution inference rule (for CNF):

$$\frac{\ell_i \vee \ldots \vee \ell_k, \qquad m_1 \vee \ldots \vee m_n}{\ell_i \vee \ldots \vee \ell_{i-1} \vee \ell_{i+1} \vee \ldots \vee \ell_k \vee m_1 \vee \ldots \vee m_{j-1} \vee m_{j+1} \vee \ldots \vee m_n}$$

where ℓ_i and m_j are complementary literals.

E.g., $\dfrac{P_{1,3} \vee P_{2,2}, \qquad \neg P_{2,2}}{P_{1,3}}$

- Resolution is sound and complete for propositional logic



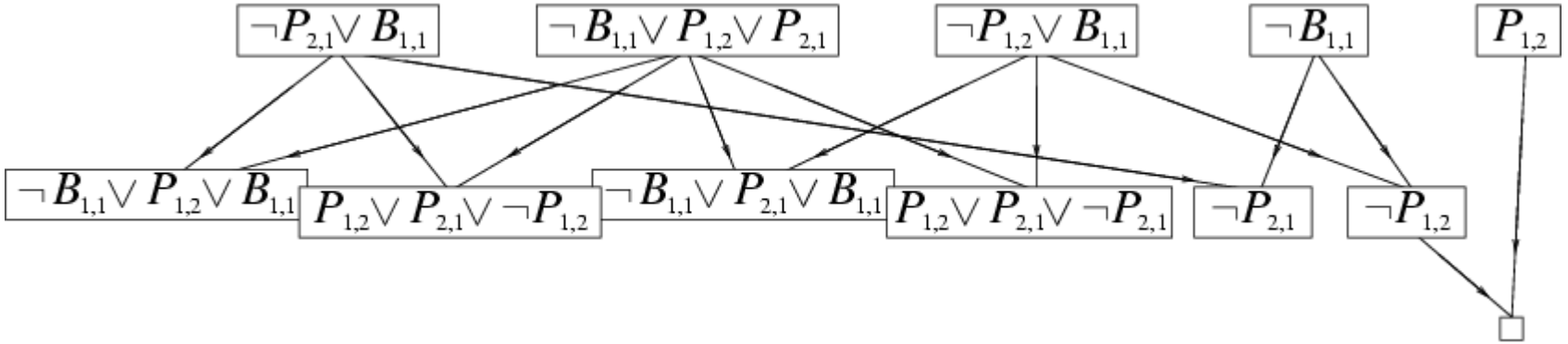
Resolution algorithm

- Proof by contradiction, i.e., show $KB \wedge \neg\alpha$ unsatisfiable

```
function PL-RESOLUTION(KB, α) returns true or false
    clauses ← the set of clauses in the CNF representation of KB ∧ ¬α
    new ← { }
    loop do
        for each C_i, C_j in clauses do
            resolvents ← PL-RESOLVE(C_i, C_j)
            if resolvents contains the empty clause then return true
            new ← new ∪ resolvents
        if new ⊆ clauses then return false
        clauses ← clauses ∪ new
```

Resolution example

- $KB = (B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})) \wedge \neg B_{1,1}$ $\alpha = \neg P_{1,2}$



Forward and backward chaining

- Inference with Horn Clauses (KB = conjunction of Horn clauses)
  - Body, Head, and Fact
  - $C \wedge (B \Rightarrow A) \wedge (C \wedge D \Rightarrow B)$
- Forward Chaining
  - Fire any rule whose premises are satisfied in the *KB*
  - Add its conclusion to the *KB*, until query is found
- Backward Chaining
  - Work backwards from the query *q*
    - Check if *q* is known already, or
    - Prove by BC all premises of some rule concluding *q*
- These algorithms are very natural and run in linear time (in the size of the KB)

Forward vs. backward chaining

- FC is data-driven, automatic, unconscious processing,
  - e.g., object recognition, routine decisions
- May do lots of work that is irrelevant to the goal
- BC is goal-driven, appropriate for problem-solving,
  - e.g., Where are my keys? How do I get into a PhD program?
- Complexity of BC can be much less than linear in size of KB

Efficient propositional inference

Two families of efficient algorithms for propositional inference:

- Complete backtracking search algorithms
  - DPLL algorithm (Davis, Putnam, Logemann, Loveland)
- Incomplete local search algorithms
  - `WalkSAT` algorithm

The DPLL algorithm

- Recursive depth first enumeration of possible models with 3 improvements

1. Early termination
   A clause is true if any literal is true.
   A sentence is false if any clause is false.

2. Pure symbol heuristic
   Pure symbol: always appears with the same "sign" in all clauses.
   e.g., In the three clauses $(A \vee \neg B)$, $(\neg B \vee \neg C)$, $(C \vee A)$
   A and B are pure, C is impure.
   Make a pure symbol literal true.

3. Unit clause heuristic
   Unit clause: only one literal in the clause
   The only literal in a unit clause must be true.

The `WalkSAT` algorithm

- Incomplete, local search algorithm
- Evaluation function: The min-conflict heuristic of minimizing the number of unsatisfied clauses
- Balance between greediness and randomness

Summary

- Intelligent agents need knowledge about the world for making good decisions.
- The knowledge of an agent is stored in a knowledge base in the form of **sentences** in a knowledge representation language.
- A knowledge-based agent needs a **knowledge base** and an **inference mechanism**. It operates by storing sentences in its knowledge base, inferring new sentences with the inference mechanism, and using them to deduce which actions to take.
- A **representation language** is defined by its syntax and semantics, which specify the structure of sentences and how they relate to the facts of the world.
- The **interpretation** of a sentence is the fact to which it refers. If this fact is part of the actual world, then the sentence is true.