Logical Agents

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The world is everything that is the case.

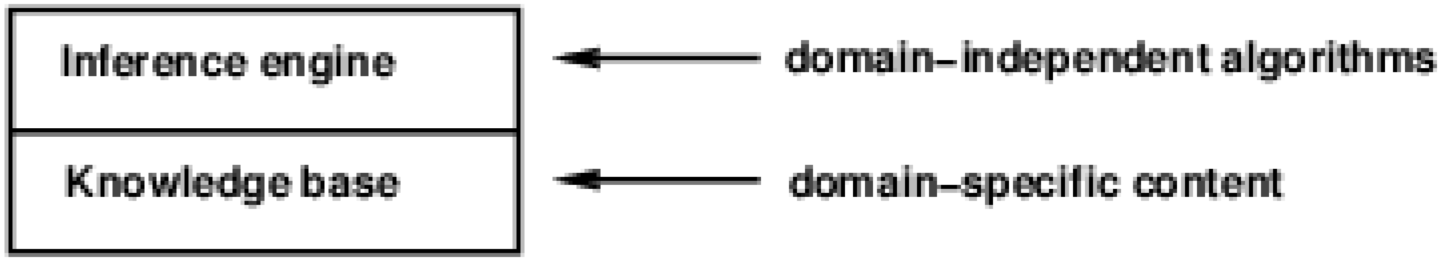
Wittgenstein, Tractatus

Outline

- Knowledge-based agents
- Logic in general—models and entailment
- Propositional (Boolean) logic
- Equivalence, validity, satisfiability
- Inference rules and theorem proving
  - forward chaining
  - backward chaining
  - resolution

knowledge-based agents

Knowledge-Based Agent



- Knowledge base = set of sentences in a **formal** language

- Declarative approach to building an agent (or other system):
  TELL it what it needs to know

- Then it can ASK itself what to do—answers should follow from the KB

- Agents can be viewed at the knowledge level
  i.e., **what they know**, regardless of how implemented

- Or at the implementation level
  i.e., data structures in KB and algorithms that manipulate them

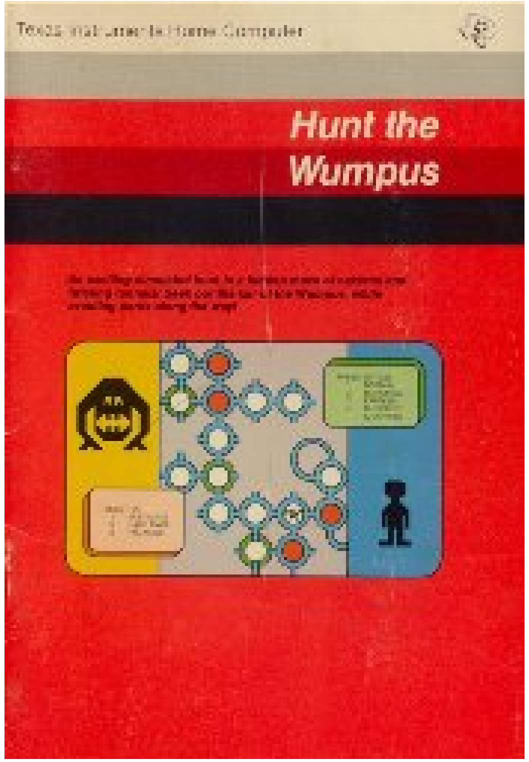
A Simple Knowledge-Based Agent

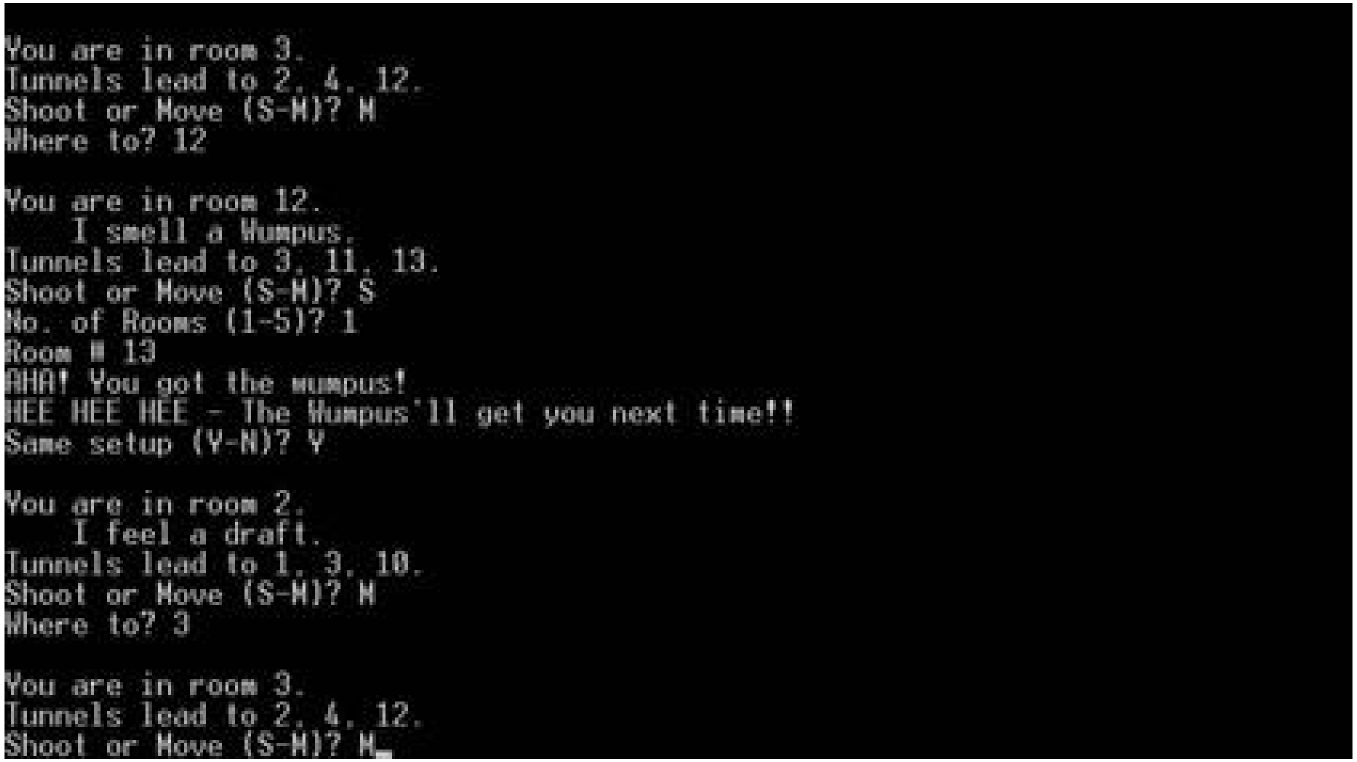

```
function KB-AGENT(percept) returns an action
   static: KB, a knowledge base
           t, a counter, initially 0, indicating time

   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
```

- The agent must be able to
  - represent states, actions, etc.
  - incorporate new percepts
  - update internal representations of the world
  - deduce hidden properties of the world
  - deduce appropriate actions

example

Hunt the Wumpus

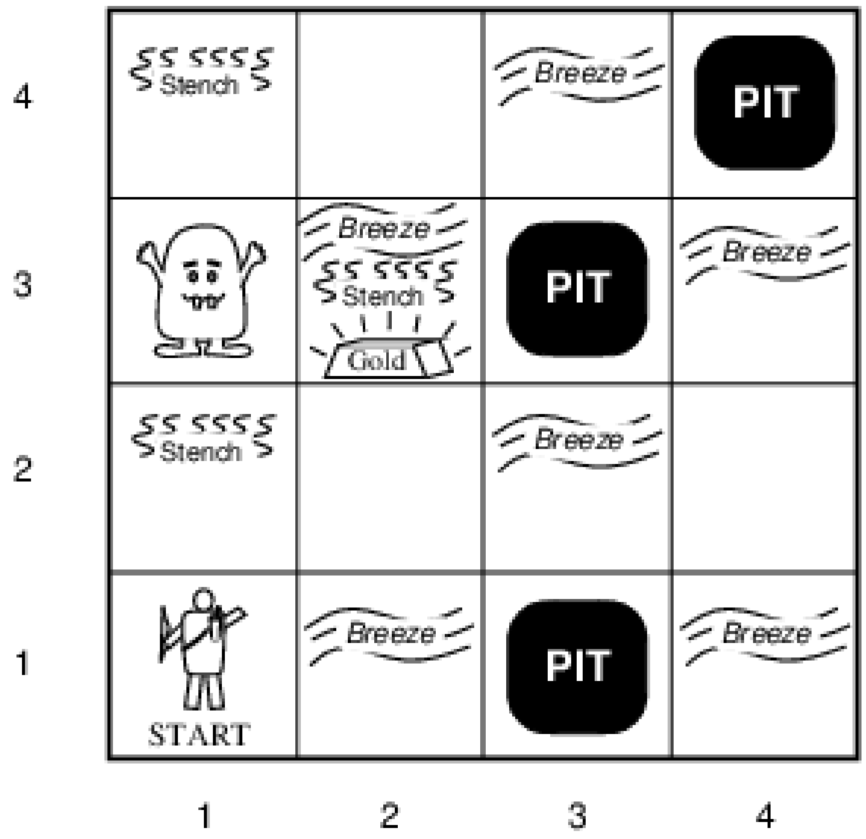




Computer game from 1972

Wumpus World PEAS Description

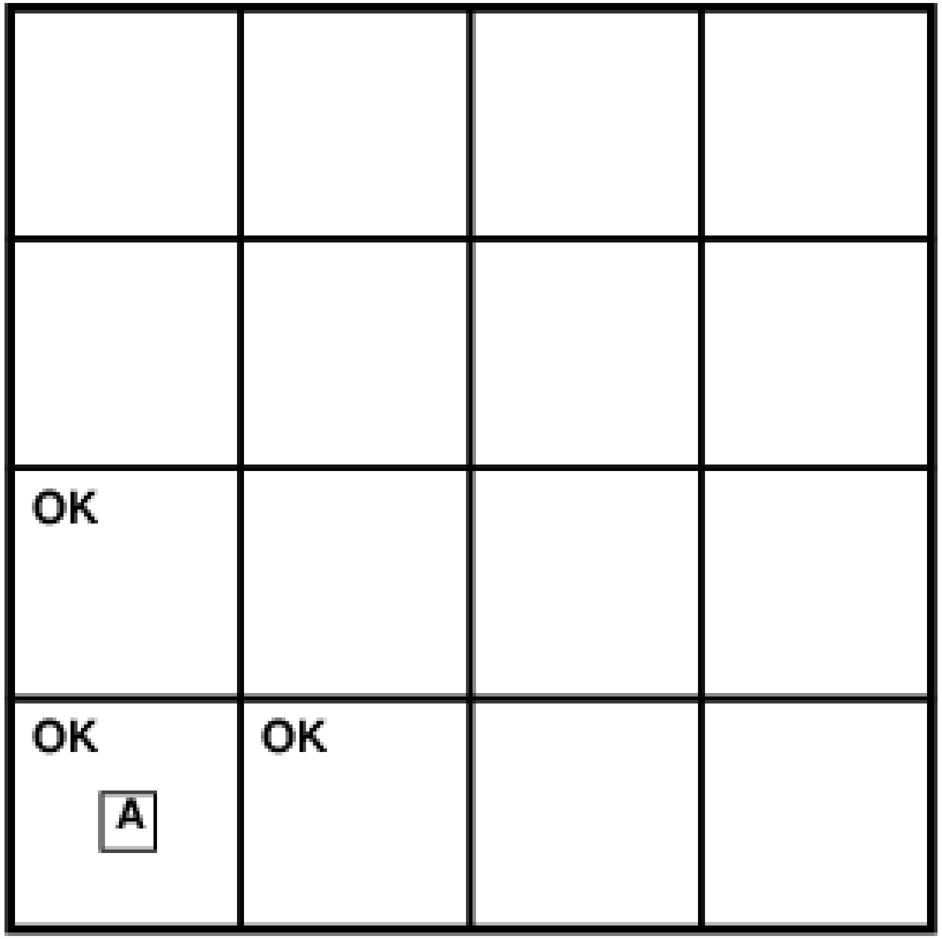
- Performance measure
  - gold +1000, death -1000
  - -1 per step, -10 for using the arrow
- Environment
  - squares adjacent to wumpus are smelly
  - squares adjacent to pit are breezy
  - glitter iff gold is in the same square
  - shooting kills wumpus if you are facing it
  - shooting uses up the only arrow
  - grabbing picks up gold if in same square
  - releasing drops the gold in same square
- Actuators Left turn, Right turn,
  Forward, Grab, Release, Shoot
- Sensors Breeze, Glitter, Smell



Wumpus World Characterization

- Observable? No—only local perception
- Deterministic? Yes—outcomes 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

Exploring a Wumpus World



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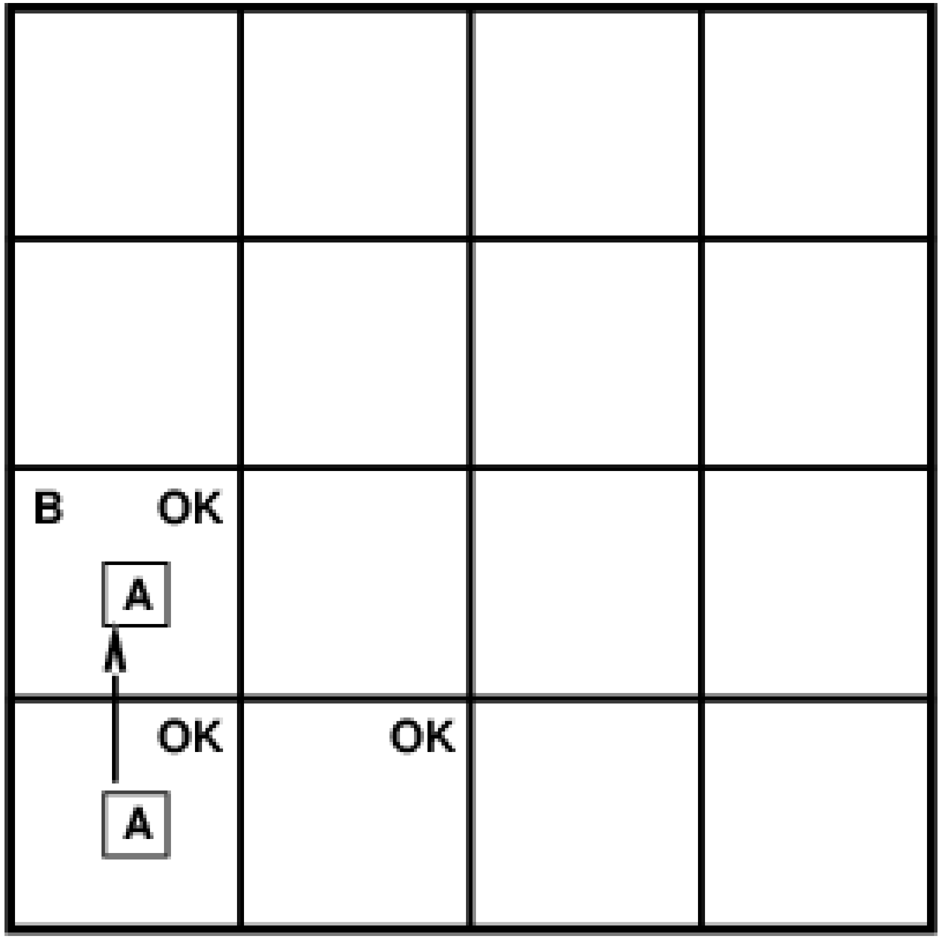

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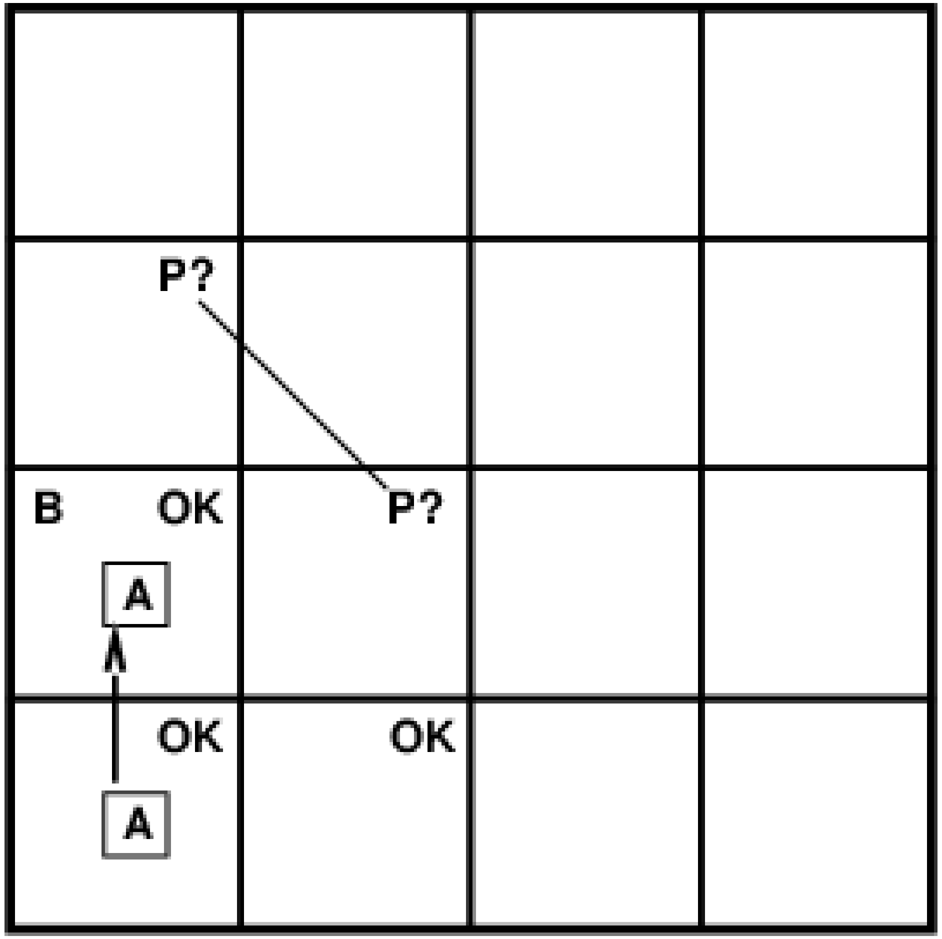

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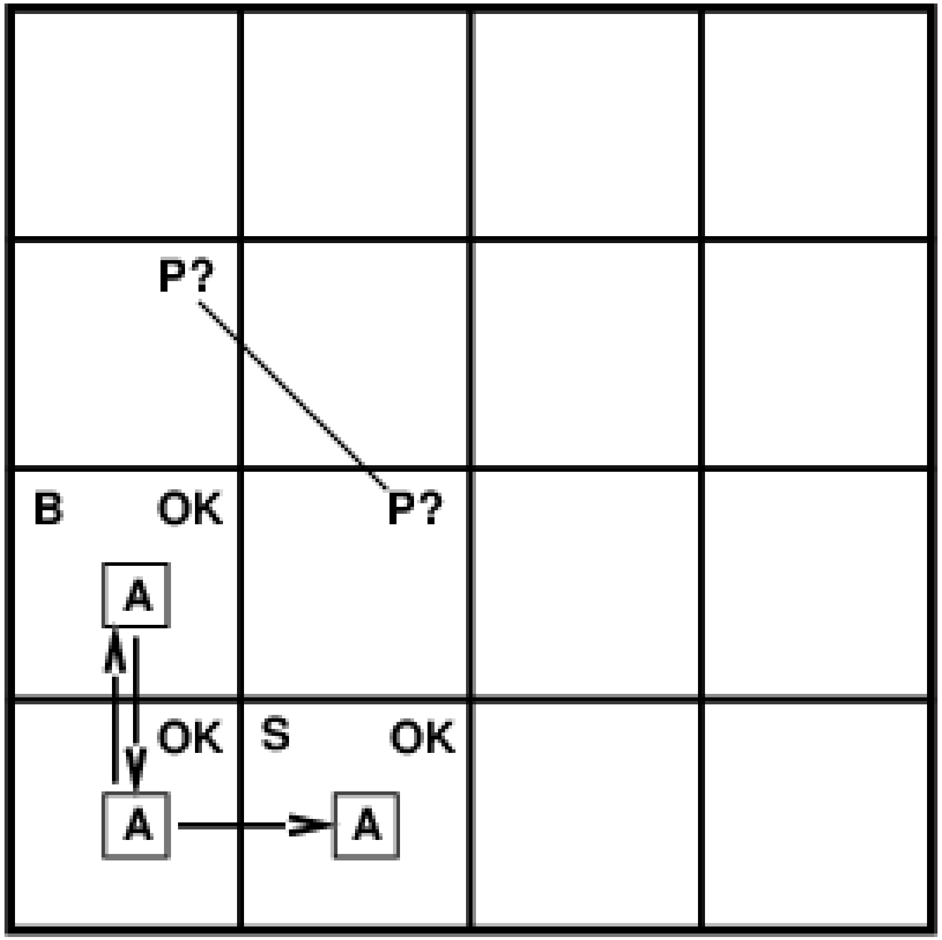

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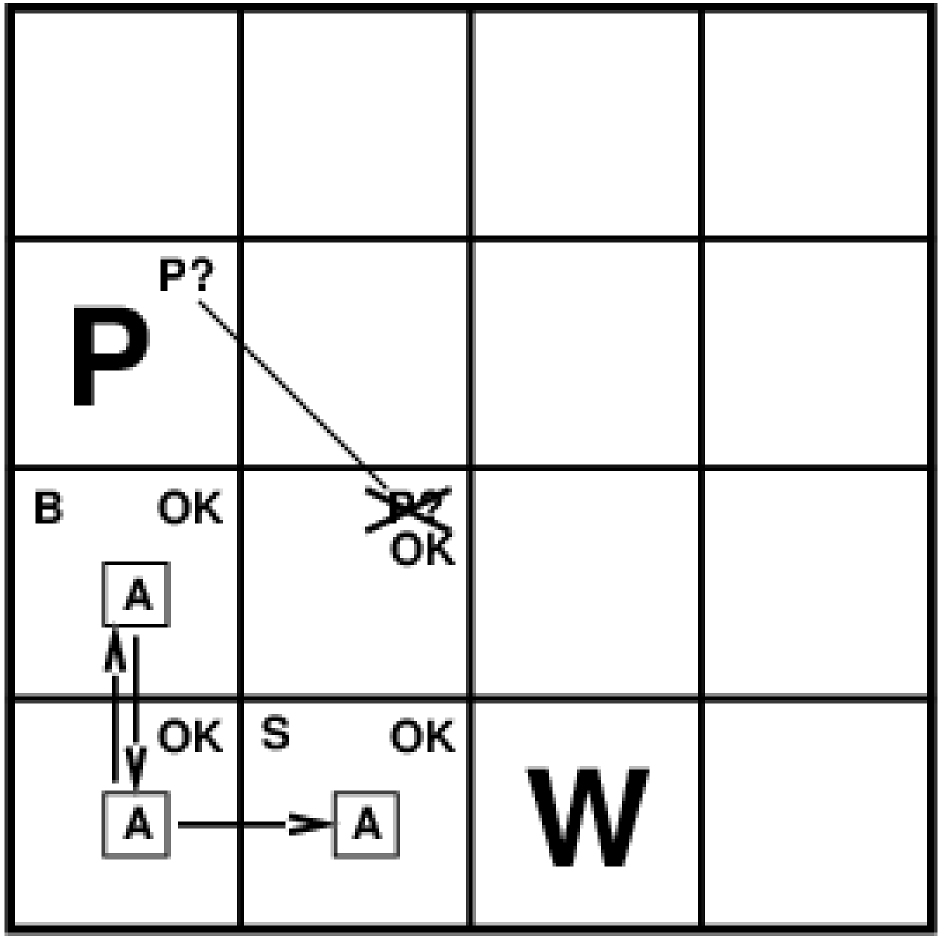

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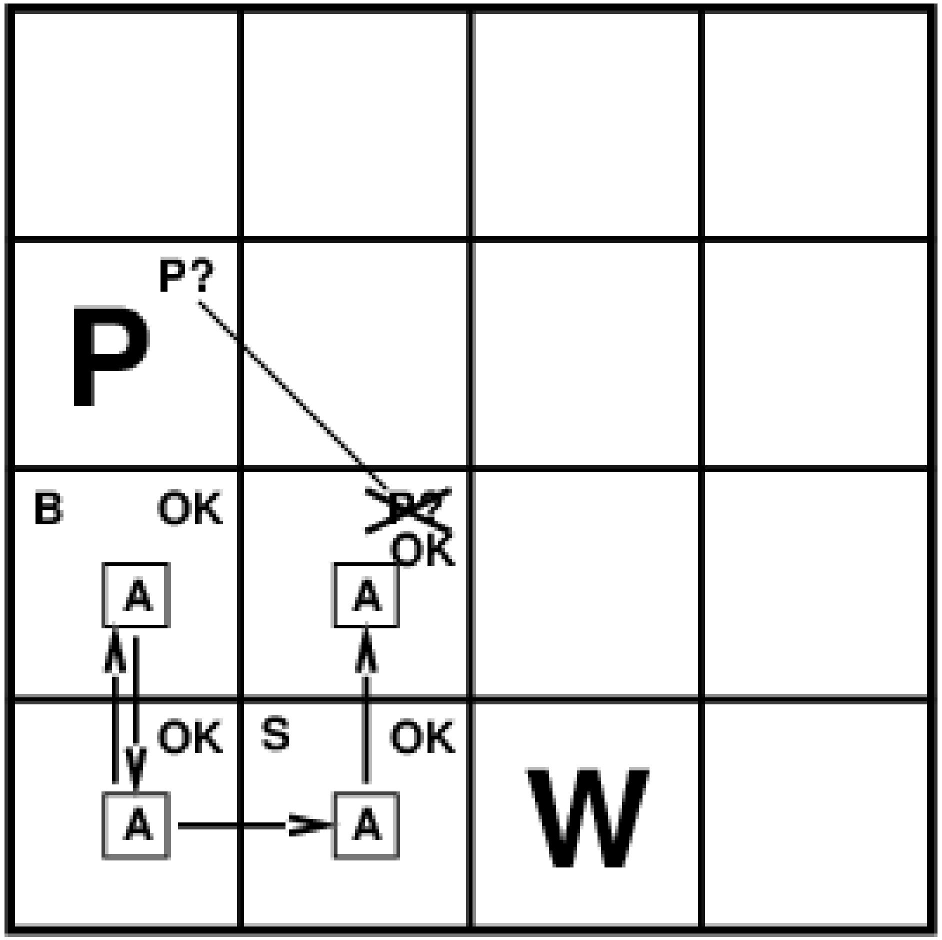

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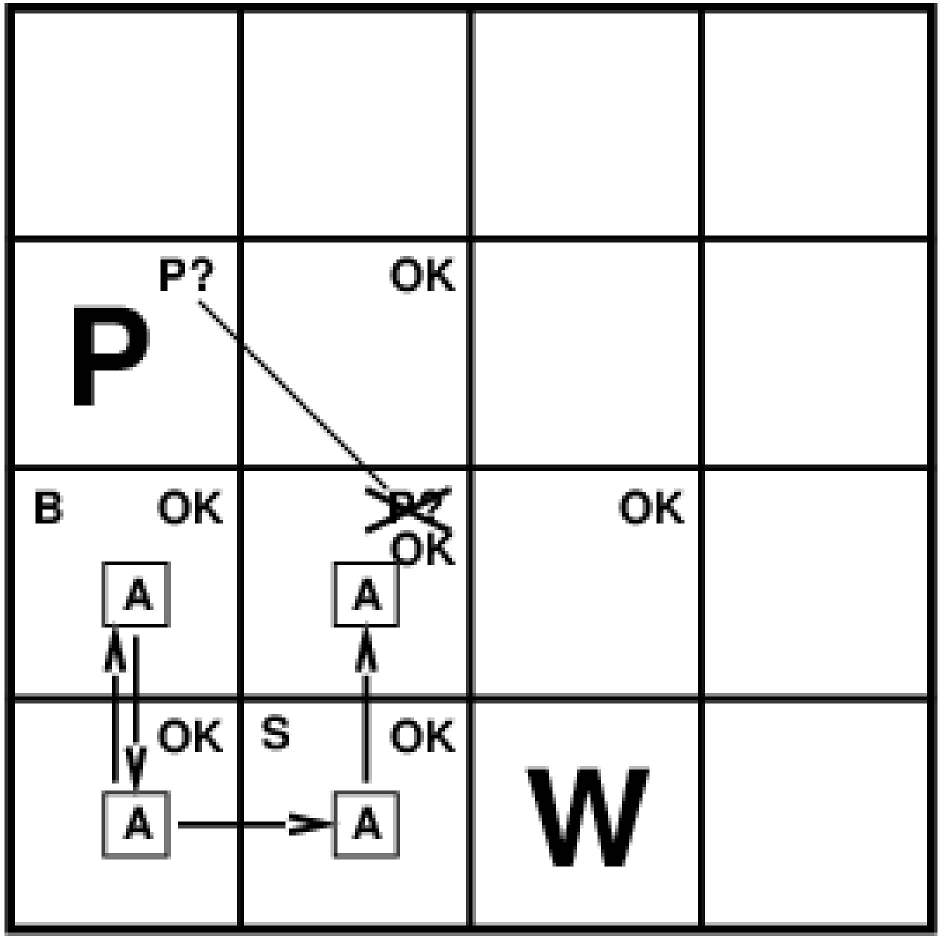

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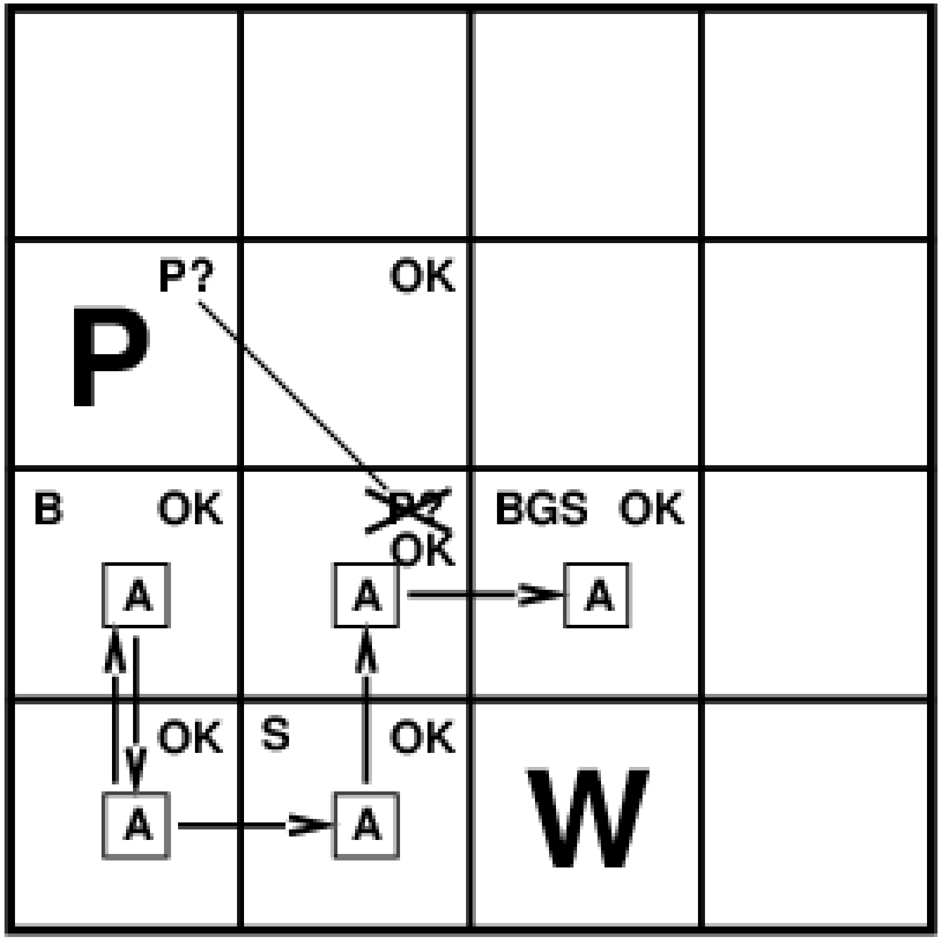
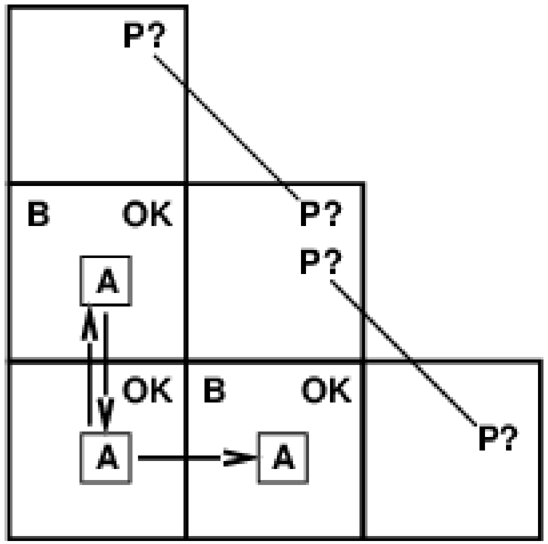


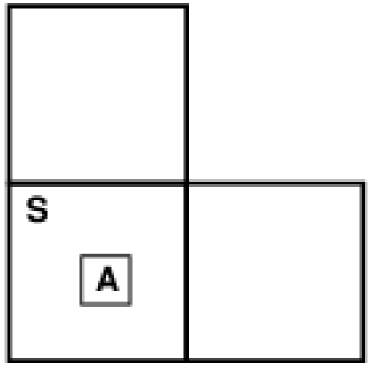
Tight Spot



- Breeze in (1,2) and (2,1)
  $\implies$ no safe actions

- Assuming pits uniformly distributed,
  (2,2) has pit w/ prob 0.86, vs. 0.31

Tight Spot



- Smell in (1,1)
  $\implies$ cannot move

- Can use a strategy of coercion: shoot straight ahead
  - wumpus was there $\implies$ dead $\implies$ safe
  - wumpus wasn't there $\implies$ safe

logic in general

Logic in General

- Logics are formal languages for representing information
  such that conclusions can be drawn

- Syntax defines the sentences in the language

- Semantics define the "meaning" of sentences;
  i.e., define truth of a sentence in a world

- E.g., the language of arithmetic
  - $x + 2 \geq y$ is a sentence; $x2 + y >$ is not a sentence
  - $x + 2 \geq y$ is true iff the number $x + 2$ is no less than the number y
  - $x + 2 \geq y$ is true in a world where $x = 7,\ y = 1$
    $x + 2 \geq y$ is false in a world where $x = 0,\ y = 6$

Entailment

- Entailment means that one thing **follows from** another:

$$KB \models \alpha$$

- Knowledge base KB entails sentence α
  if and only if
  α is true in all worlds where KB is true

- E.g., the KB containing “the Ravens won” and “the Jays won” entails “the Ravens won or the Jays won”

- E.g., $x + y = 4$ entails $4 = x + y$

- Entailment is a relationship between sentences (i.e., **syntax**) that is based on **semantics**

- Note: brains process **syntax** (of some sort)

Models

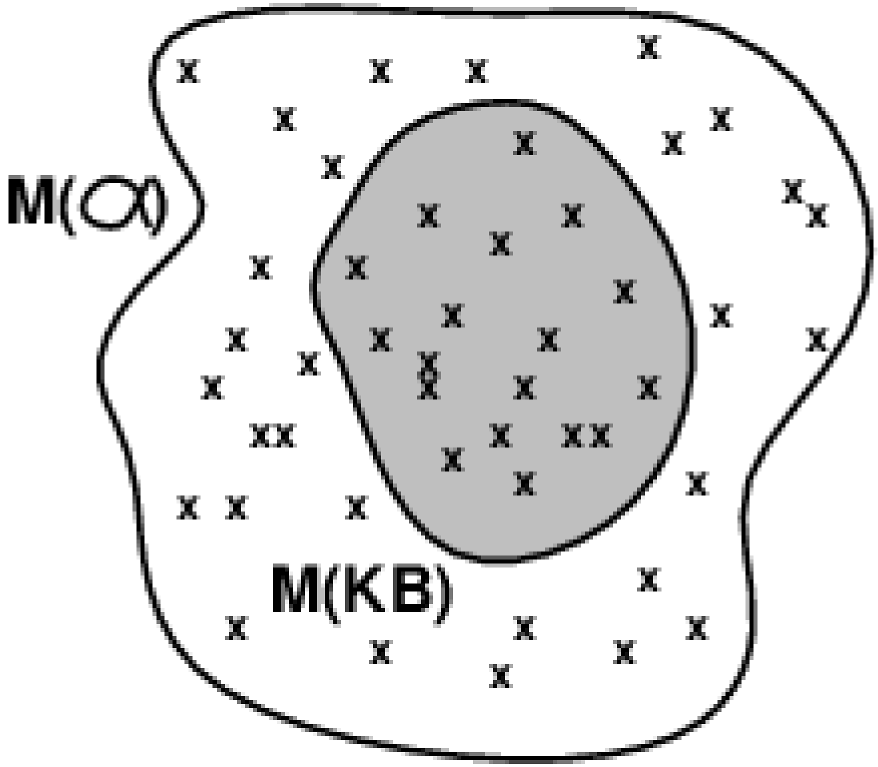
- Logicians typically think in terms of models, which are formally structured worlds with respect to which truth can be evaluated

- We say m is a model of a sentence α if α is true in m

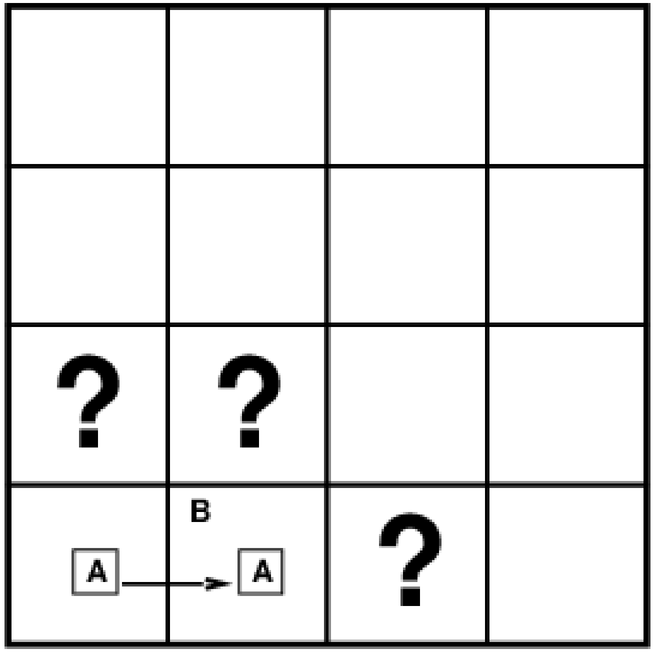
- $M(\alpha)$ is the set of all models of α

⇒ $KB \models \alpha$ if and only if $M(KB) \subseteq M(\alpha)$

- E.g. KB = Ravens won and Jays won
  α = Ravens won

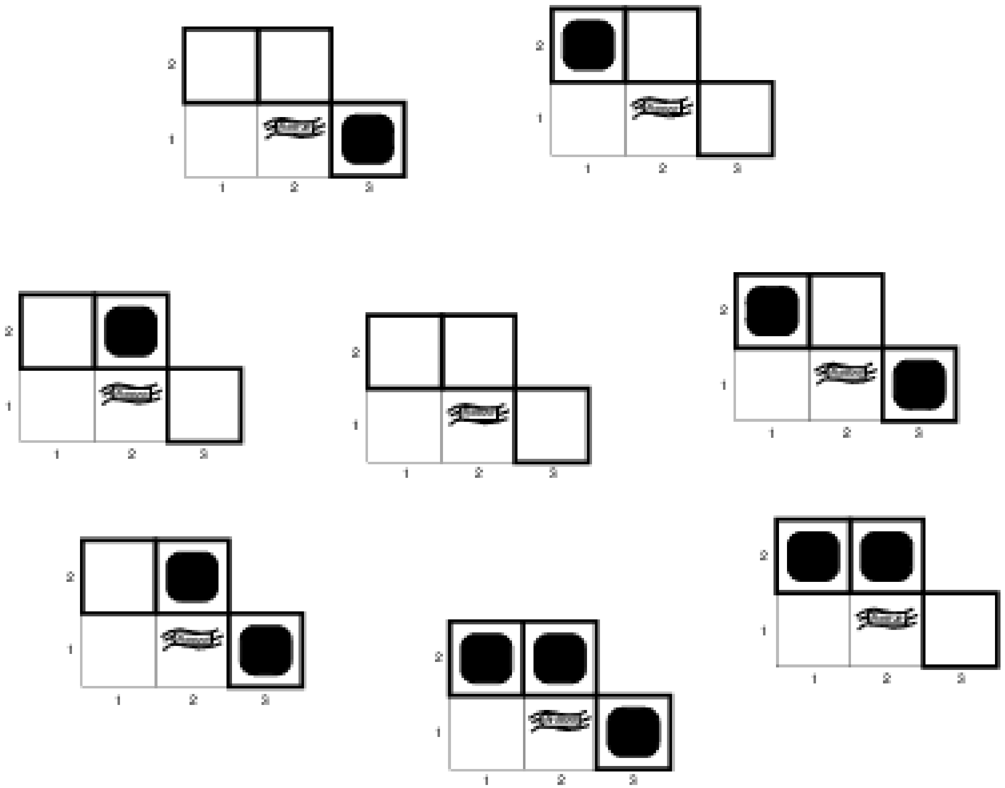


Entailment in the Wumpus World

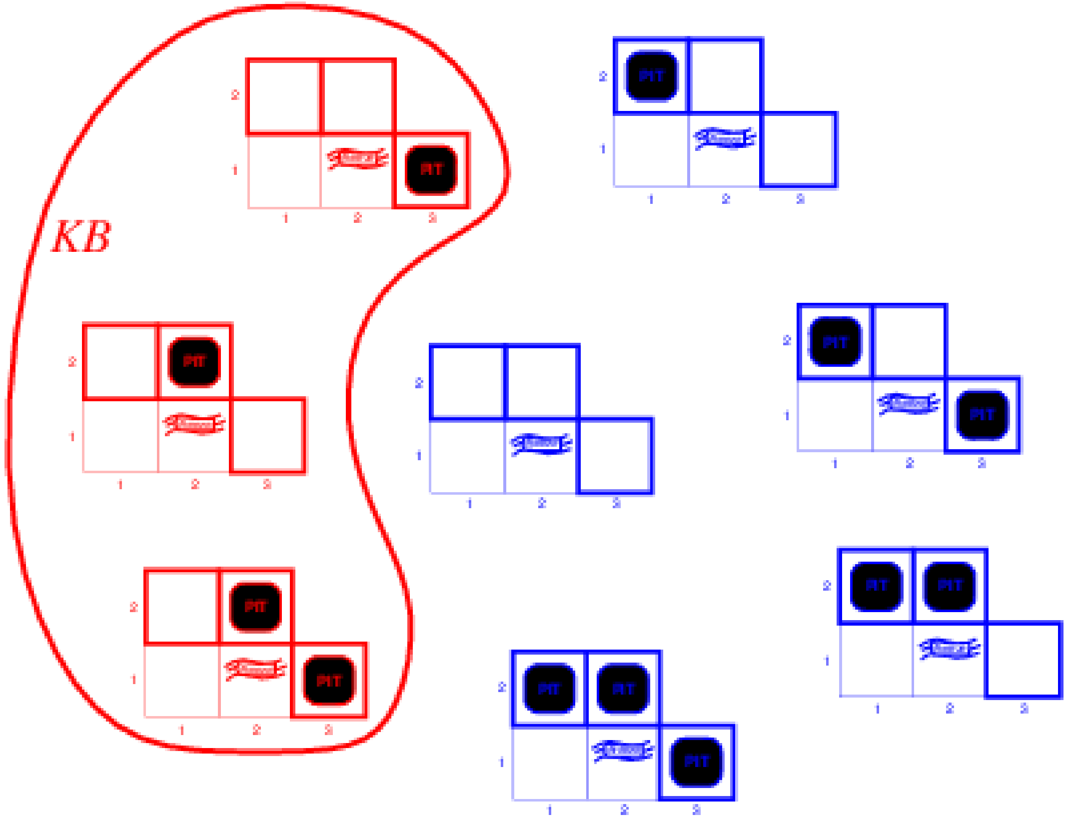


- Situation after detecting nothing in [1,1], moving right, breeze in [2,1]
- Consider possible models for all **?**, assuming only pits
- 3 Boolean choices $\Longrightarrow$ 8 possible models

Possible Wumpus Models

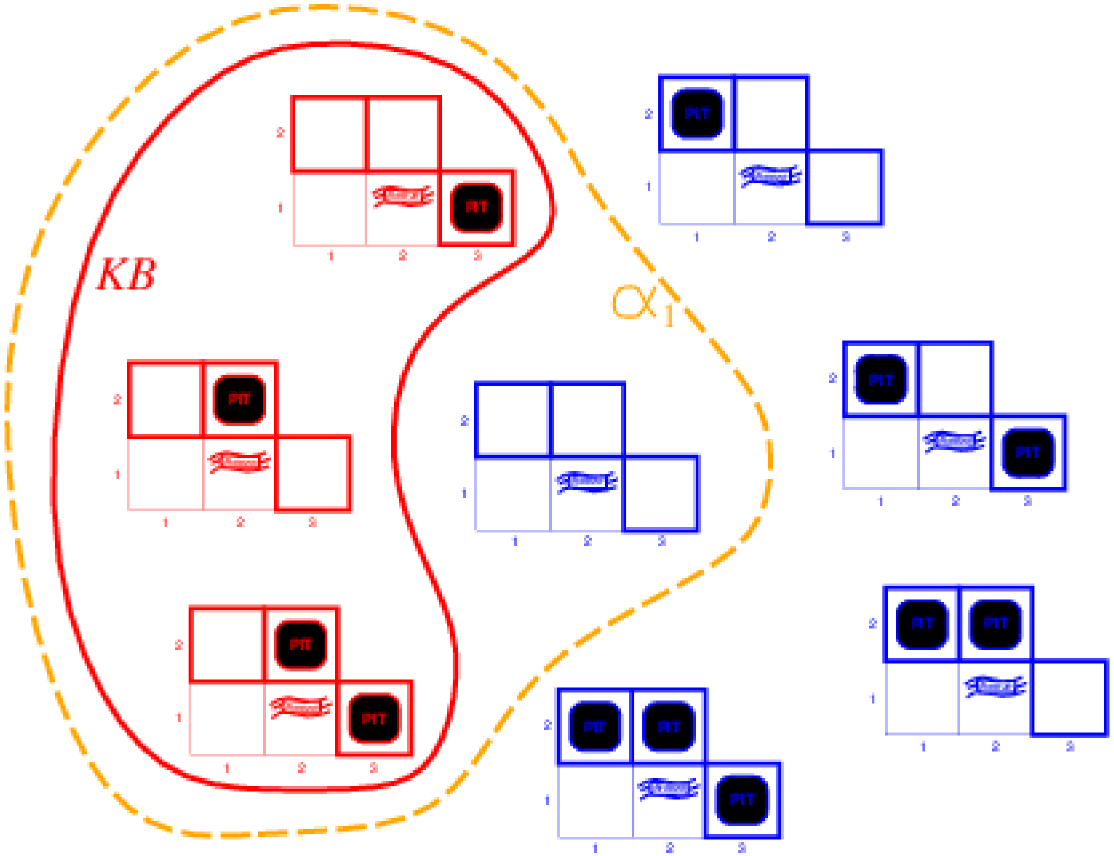


Valid Wumpus Models



KB = wumpus-world rules + observations

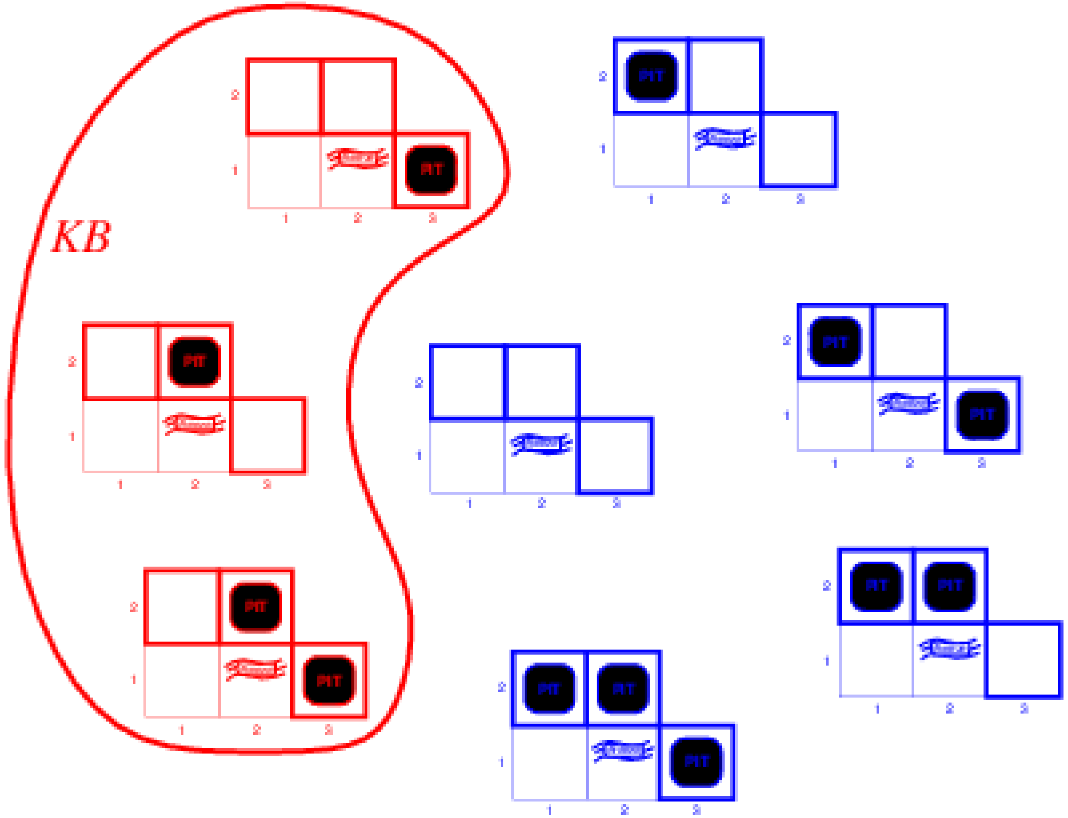
Entailment



KB = wumpus-world rules + observations

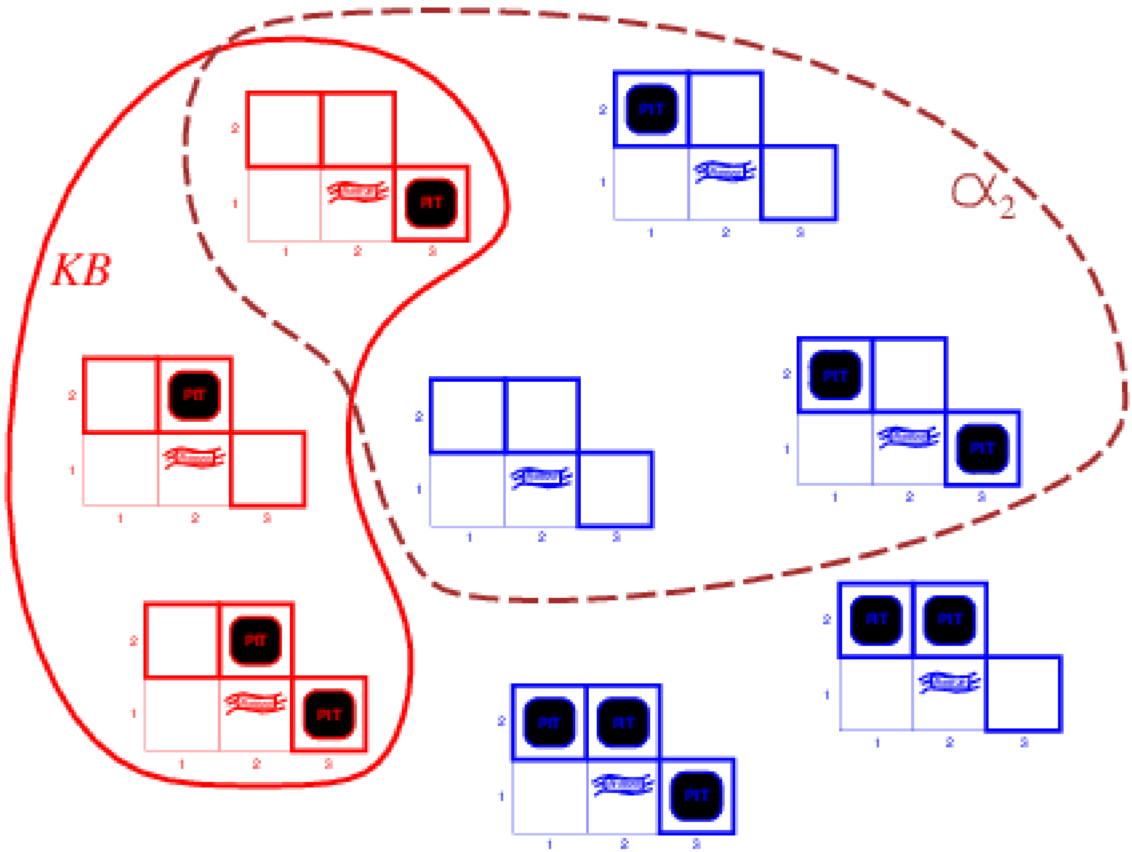
α_1 = "[1,2] is safe", $KB \models \alpha_1$, proved by model checking

Valid Wumpus Models



KB = wumpus-world rules + observations

Not Entailed



KB = wumpus-world rules + observations

α_2 = "[2,2] is safe", $KB \not\models \alpha_2$

Inference

- $KB \vdash_i \alpha$ = sentence α can be derived from KB by procedure i
- Consequences of KB are a haystack; α is a needle.
  Entailment = needle in haystack; inference = finding it
- Soundness: i is sound if
  whenever $KB \vdash_i \alpha$, it is also true that $KB \vDash \alpha$
- Completeness: i is complete if
  whenever $KB \vDash \alpha$, it is also true that $KB \vdash_i \alpha$
- Preview: we will define a logic (first-order logic) which is expressive enough to say almost anything of interest, and for which there exists a sound and complete inference procedure.
- That is, the procedure will answer any question whose answer follows from what is known by the KB.

propositional logic

Propositional Logic: Syntax

- Propositional logic is the simplest logic—illustrates basic ideas
- The proposition symbols P_1, P_2 etc are sentences
- If P is a sentence, $\neg P$ is a sentence (negation)
- If P_1 and P_2 are sentences, $P_1 \wedge P_2$ is a sentence (conjunction)
- If P_1 and P_2 are sentences, $P_1 \vee P_2$ is a sentence (disjunction)
- If P_1 and P_2 are sentences, $P_1 \implies P_2$ is a sentence (implication)
- If P_1 and P_2 are sentences, $P_1 \Leftrightarrow P_2$ is a sentence (biconditional)

Propositional Logic: Semantics

- Each model specifies true/false for each proposition symbol

E.g. $\begin{array}{ccc} P_{1,2} & P_{2,2} & P_{3,1} \\ false & true & false \end{array}$

(with these symbols, 8 possible models, can be enumerated automatically)

- Rules for evaluating truth with respect to a model m:

$\neg P$	is true iff	P	is false		
$P_1 \wedge P_2$	is true iff	P_1	is true **and**	P_2	is true
$P_1 \vee P_2$	is true iff	P_1	is true **or**	P_2	is true
$P_1 \implies P_2$	is true iff	P_1	is false **or**	P_2	is true
i.e.,	is false iff	P_1	is true **and**	P_2	is false
$P_1 \Leftrightarrow P_2$	is true iff	$P_1 \implies P_2$	is true **and**	$P_2 \implies P_1$	is true

- Simple recursive process evaluates an arbitrary sentence, e.g.,
$\neg P_{1,2} \wedge (P_{2,2} \vee P_{3,1}) = true \wedge (false \vee true) = true \wedge true = true$

Truth Tables for Connectives

P	Q	$\neg P$	$P \wedge Q$	$P \vee Q$	$P \Rightarrow Q$	$P \Leftrightarrow Q$
false	*false*	*true*	*false*	*false*	*true*	*true*
false	*true*	*true*	*false*	*true*	*true*	*false*
true	*false*	*false*	*false*	*true*	*false*	*false*
true	*true*	*false*	*true*	*true*	*true*	*true*

Wumpus World Sentences

- Let $P_{i,j}$ be true if there is a pit in $[i,j]$
  - observation $R_1 : \neg P_{1,1}$

- Let $B_{i,j}$ be true if there is a breeze in $[i,j]$.

- "Pits cause breezes in adjacent squares"
  - rule $R_2 : B_{1,1} \;\Leftrightarrow\; (P_{1,2} \vee P_{2,1})$
  - rule $R_3 : B_{2,1} \;\Leftrightarrow\; (P_{1,1} \vee P_{2,2} \vee P_{3,1})$
  - observation $R_4 : \neg B_{1,1}$
  - observation $R_5 : B_{2,1}$

- What can we infer about $P_{1,2}$, $P_{2,1}$, $P_{2,2}$, etc.?

Truth Tables for Inference

$B_{1,1}$	$B_{2,1}$	$P_{1,1}$	$P_{1,2}$	$P_{2,1}$	$P_{2,2}$	$P_{3,1}$	R_1	R_2	R_3	R_4	R_5	KB
false	*false*	*false*	*false*	*false*	*false*	*false*	*true*	*true*	*true*	*true*	*false*	*false*
false	*false*	*false*	*false*	*false*	*false*	*true*	*true*	*true*	*false*	*true*	*false*	*false*
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
false	*true*	*false*	*false*	*false*	*false*	*false*	*true*	*true*	*false*	*true*	*true*	*false*
false	*true*	*false*	*false*	*false*	*false*	*true*	*true*	*true*	*true*	*true*	*true*	*true*
false	*true*	*false*	*false*	*false*	*true*	*false*	*true*	*true*	*true*	*true*	*true*	*true*
false	*true*	*false*	*false*	*false*	*true*	*true*	*true*	*true*	*true*	*true*	*true*	*true*
false	*true*	*false*	*false*	*true*	*false*	*false*	*true*	*false*	*false*	*true*	*true*	*false*
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
true	*true*	*true*	*true*	*true*	*true*	*true*	*false*	*true*	*true*	*false*	*true*	*false*

- Enumerate rows (different assignments to symbols $P_{i,j}$)
- Check if rules are satisfied (R_i)
- Valid model (KB) if all rules satisfied

Inference by Enumeration

- Depth-first enumeration of all models is sound and complete

```
function TT-ENTAILS?(KB, α) returns true or false
   inputs: KB, the knowledge base, a sentence in propositional logic
           α, the query, a sentence in propositional logic

   symbols ← a list of the proposition symbols in KB and α
   return TT-CHECK-ALL(KB, α, symbols, [ ])
--------------------------------------------------------------------------
function TT-CHECK-ALL(KB, α, symbols, model) returns true or false
   if EMPTY?(symbols) then
      if PL-TRUE?(KB, model) then return PL-TRUE?(α, model)
      else return true
   else do
      P ← FIRST(symbols); rest ← REST(symbols)
      return TT-CHECK-ALL(KB, α, rest, EXTEND(P, true, model)) and
             TT-CHECK-ALL(KB, α, rest, EXTEND(P, false, model))
```

- $O(2^n)$ for n symbols; problem is **co-NP-complete**

equivalence, validity, satisfiability

Logical Equivalence

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

$$
\begin{array}{rcll}
(\alpha \land \beta) & \equiv & (\beta \land \alpha) & \text{commutativity of } \land \\
(\alpha \lor \beta) & \equiv & (\beta \lor \alpha) & \text{commutativity of } \lor \\
((\alpha \land \beta) \land \gamma) & \equiv & (\alpha \land (\beta \land \gamma)) & \text{associativity of } \land \\
((\alpha \lor \beta) \lor \gamma) & \equiv & (\alpha \lor (\beta \lor \gamma)) & \text{associativity of } \lor \\
\neg(\neg\alpha) & \equiv & \alpha & \text{double-negation elimination} \\
(\alpha \implies \beta) & \equiv & (\neg\beta \implies \neg\alpha) & \text{contraposition} \\
(\alpha \implies \beta) & \equiv & (\neg\alpha \lor \beta) & \text{implication elimination} \\
(\alpha \Leftrightarrow \beta) & \equiv & ((\alpha \implies \beta) \land (\beta \implies \alpha)) & \text{biconditional elimination} \\
\neg(\alpha \land \beta) & \equiv & (\neg\alpha \lor \neg\beta) & \text{De Morgan} \\
\neg(\alpha \lor \beta) & \equiv & (\neg\alpha \land \neg\beta) & \text{De Morgan} \\
(\alpha \land (\beta \lor \gamma)) & \equiv & ((\alpha \land \beta) \lor (\alpha \land \gamma)) & \text{distributivity of } \land \text{ over } \lor \\
(\alpha \lor (\beta \land \gamma)) & \equiv & ((\alpha \lor \beta) \land (\alpha \lor \gamma)) & \text{distributivity of } \lor \text{ over } \land
\end{array}
$$

Validity and Satisfiability

- A sentence is valid if it is true in **all** models,
  e.g., $True$, $A \lor \neg A$, $A \implies A$, $(A \land (A \implies B)) \implies B$

- 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:
  $KB \vDash \alpha$ if and only if $(KB \land \neg\alpha)$ is unsatisfiable
  i.e., prove α by *reductio ad absurdum*

inference

Proof Methods

- Proof methods divide into (roughly) two kinds

- Application of inference rules
  - Legitimate (sound) generation of new sentences from old
  - Proof = a sequence of inference rule applications
    Can use inference rules as operators in a standard search alg.
  - Typically require translation of sentences into a normal form

- Model checking
  - truth table enumeration (always exponential in n)
  - improved backtracking
  - heuristic search in model space (sound but incomplete)
    e.g., min-conflicts-like hill-climbing algorithms

Forward and Backward Chaining

- Horn Form (restricted)
  KB = **conjunction** of **Horn clauses**

- Horn clause =
  - proposition symbol; or
  - (conjunction of symbols) $\implies$ symbol

  e.g., C, $\quad B \implies A$, $\quad C \wedge D \implies B$

- Modus Ponens (for Horn Form): complete for Horn KBs

$$\frac{\alpha_1, \ldots, \alpha_n, \qquad \alpha_1 \wedge \cdots \wedge \alpha_n \implies \beta}{\beta}$$

- Can be used with forward chaining or backward chaining

- These algorithms are very natural and run in **linear** time

Example

- Idea: fire any rule whose premises are satisfied in the KB,
  add its conclusion to the KB, until query is found

$P \implies Q$

$L \wedge M \implies P$

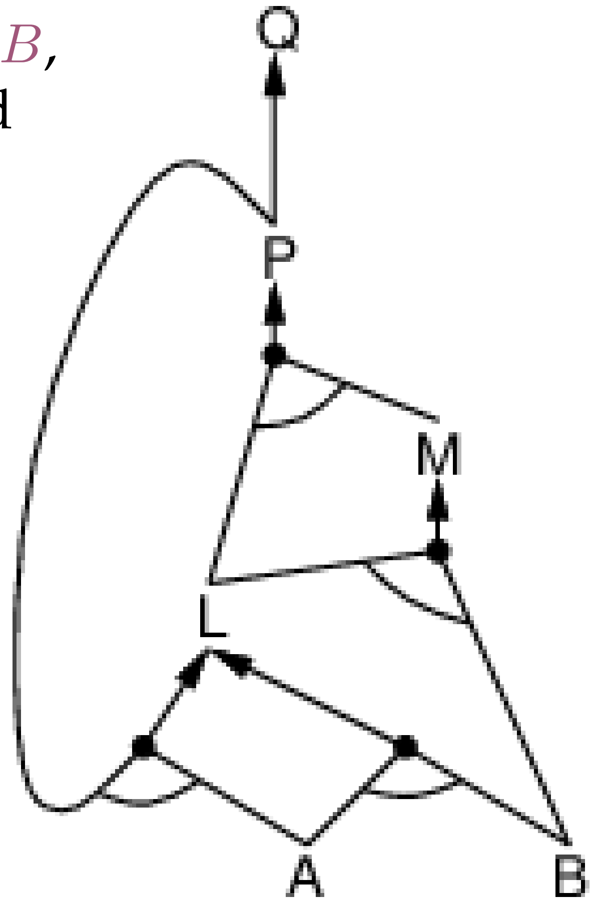
$B \wedge L \implies M$

$A \wedge P \implies L$

$A \wedge B \implies L$

A

B



forward chaining

Forward Chaining

- Start with given proposition symbols (atomic sentence)
  e.g., A and B

- Iteratively try to infer truth of additional proposition symbols
  e.g., $A \land B \implies C$, therefor we establish C is true

- Continue until
  - no more inference can be carried out, or
  - goal is reached

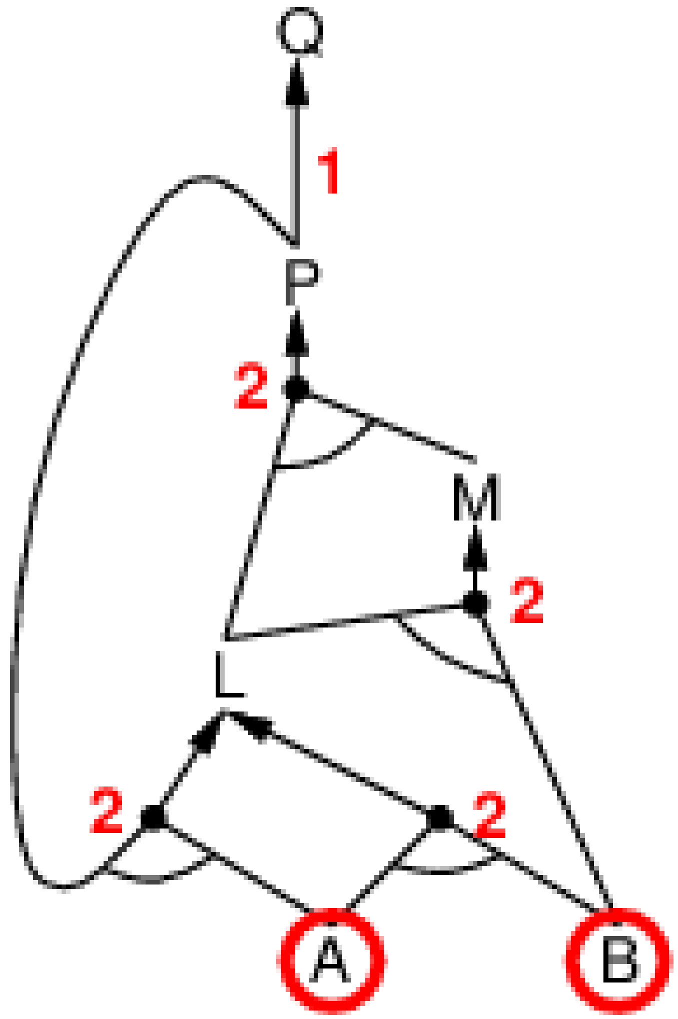
Forward Chaining Example

- Given

$$P \implies Q$$
$$L \wedge M \implies P$$
$$B \wedge L \implies M$$
$$A \wedge P \implies L$$
$$A \wedge B \implies L$$
$$A$$
$$B$$

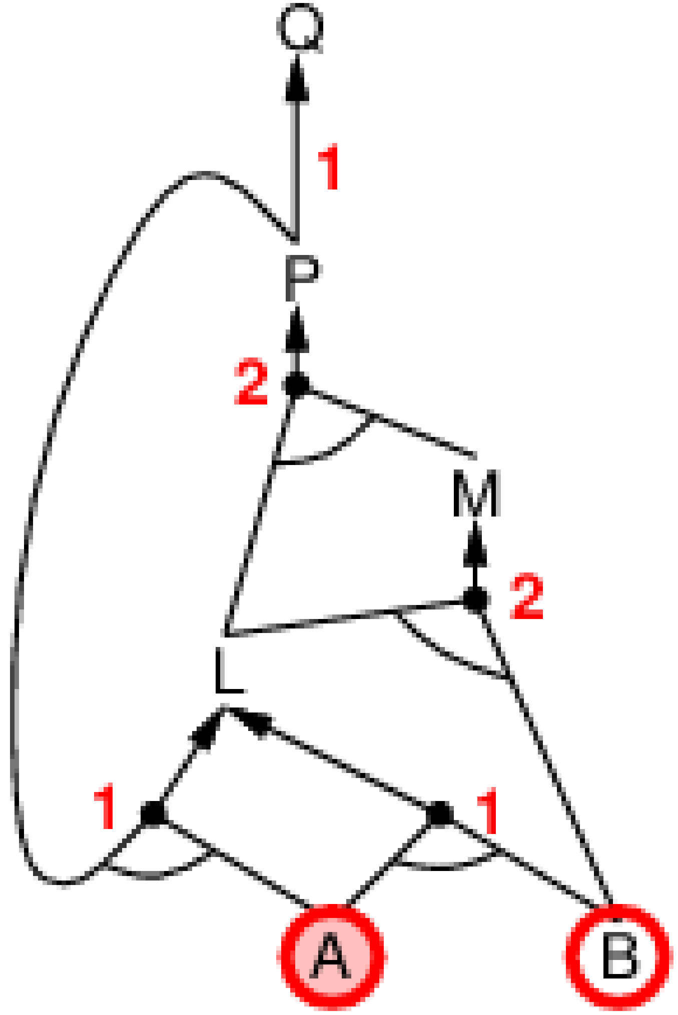
- Agenda: A, B

- Annotate horn clauses with number of premises



Forward Chaining Example

- Process agenda item A
- Decrease count for horn clauses in which A is premise



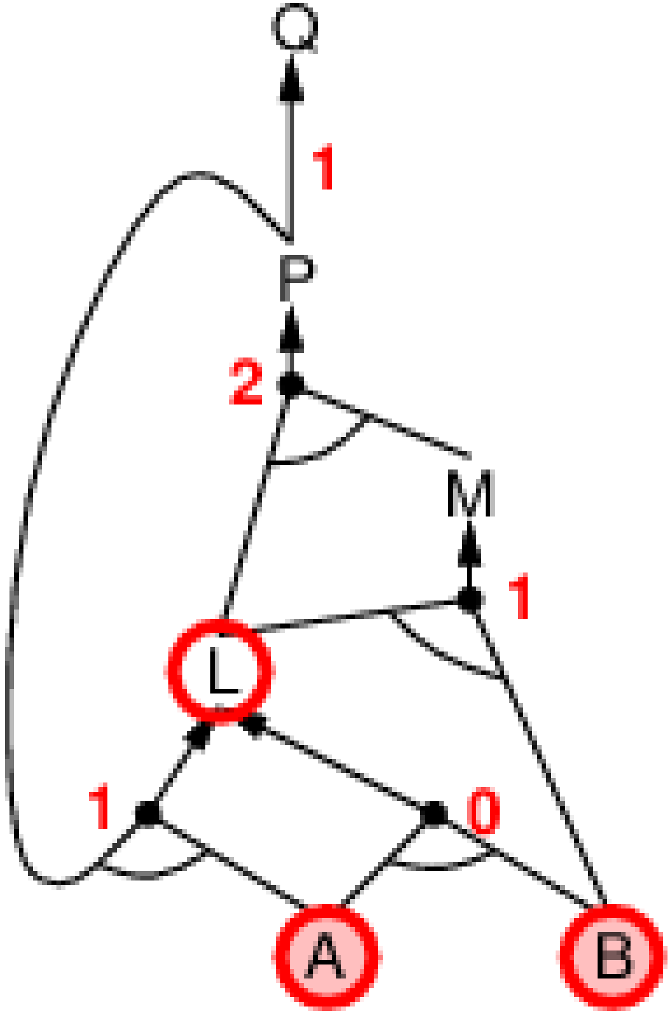
Forward Chaining Example

- Process agenda item B

- Decrease count for horn clauses in which B is premise

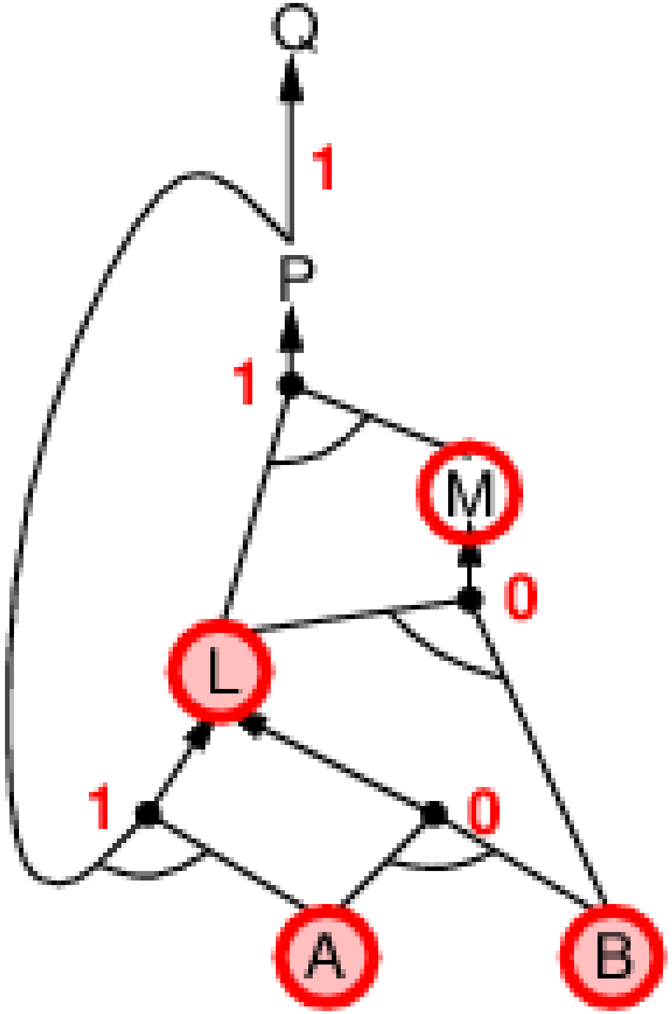
- $A \wedge B \implies L$ has now fulfilled premise

- Add L to agenda



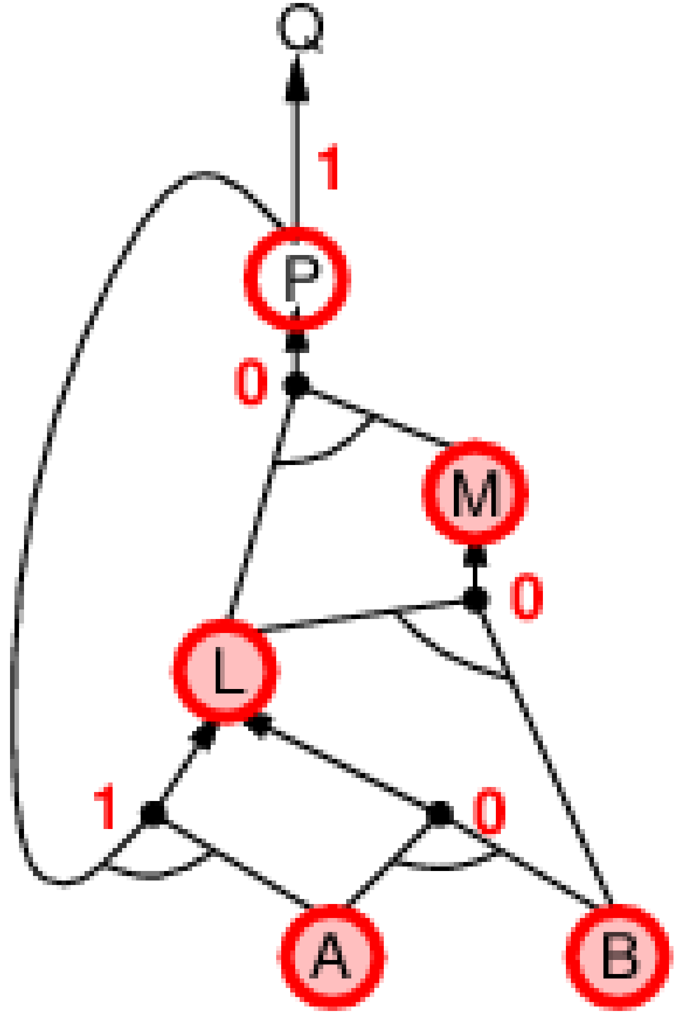
Forward Chaining Example

- Process agenda item L
- Decrease count for horn clauses in which L is premise
- $B \land L \implies M$ has now fulfilled premise
- Add M to agenda



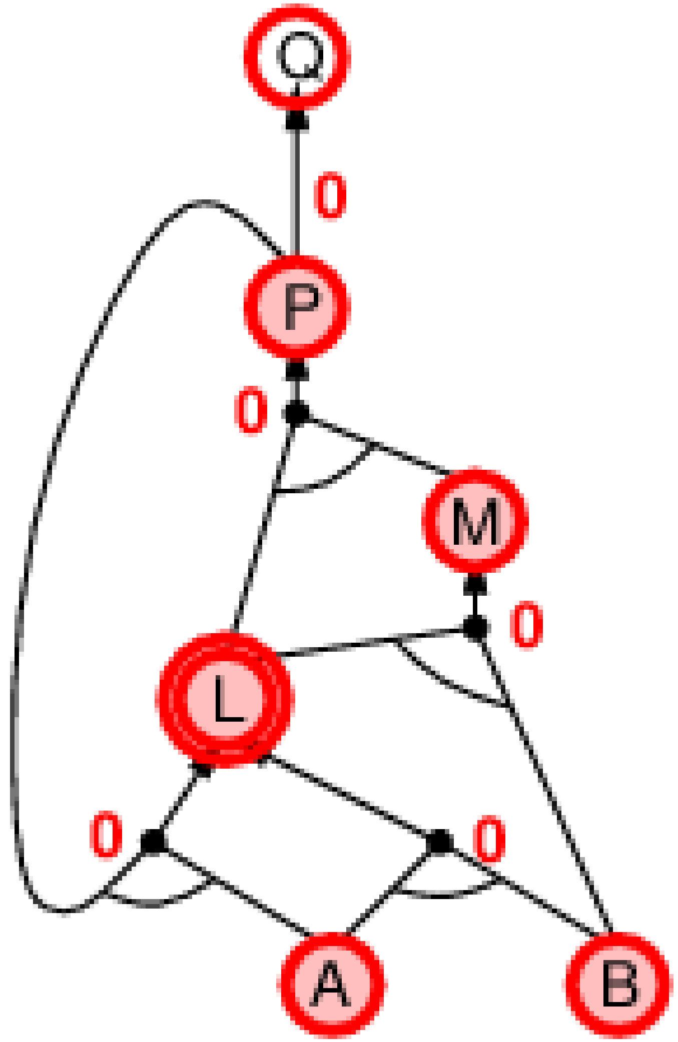
Forward Chaining Example

- Process agenda item M
- Decrease count for horn clauses in which M is premise
- $L \wedge M \implies P$ has now fulfilled premise
- Add P to agenda



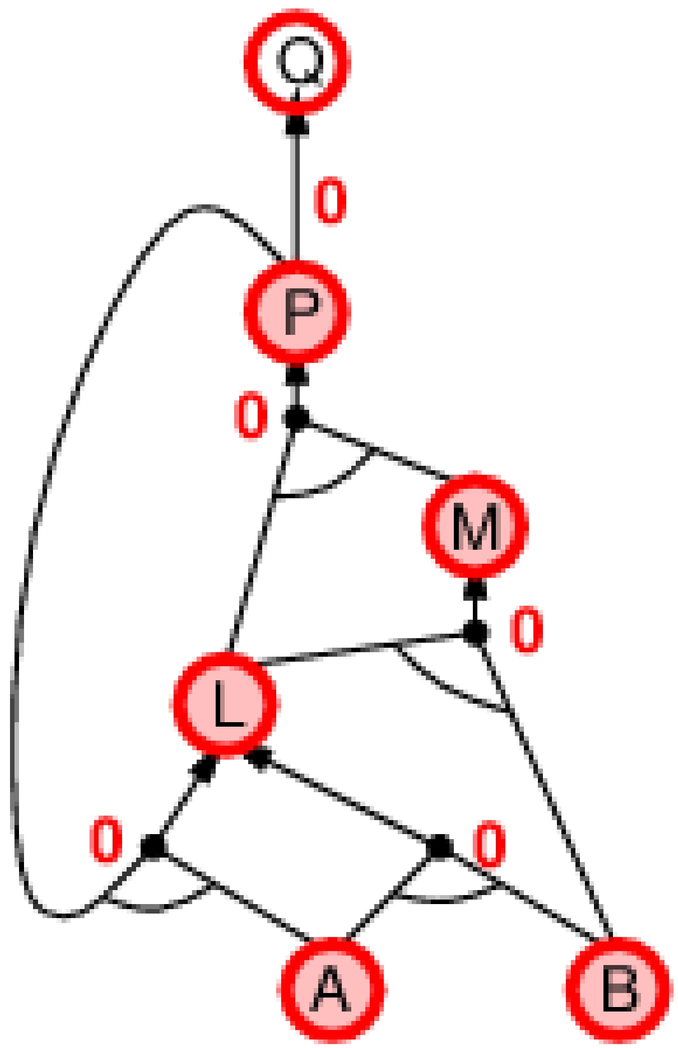
Forward Chaining Example

- Process agenda item P
- Decrease count for horn clauses in which P is premise
- $P \implies Q$ has now fulfilled premise
- Add Q to agenda
- $A \wedge P \implies L$ has now fulfilled premise



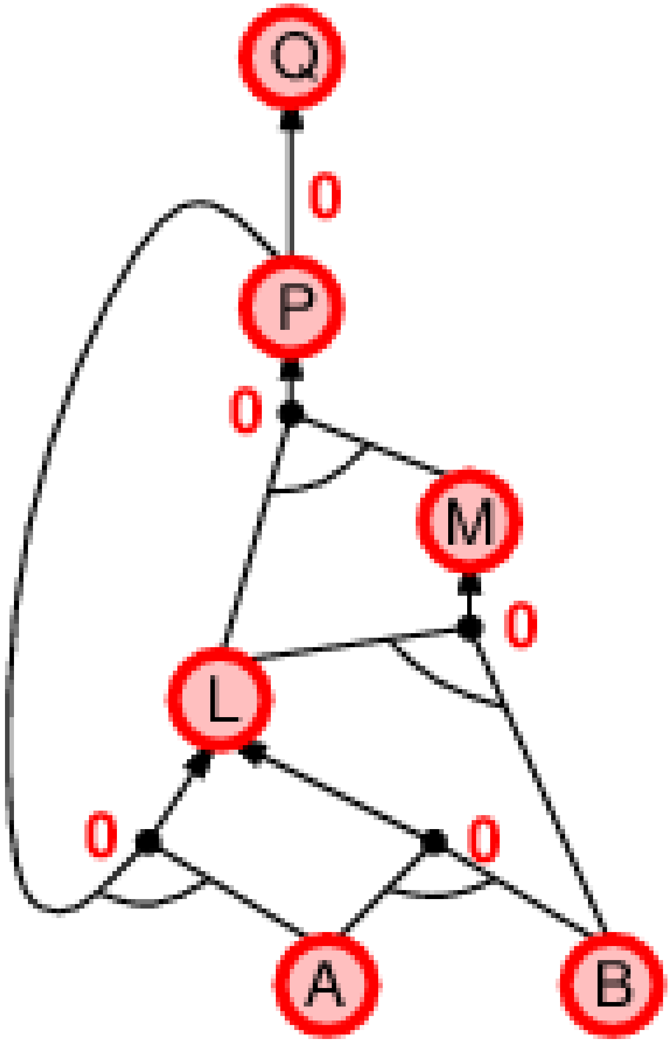
Forward Chaining Example

- Process agenda item P
- Decrease count for horn clauses in which P is premise
- $P \implies Q$ has now fulfilled premise
- Add Q to agenda
- $A \wedge P \implies L$ has now fulfilled premise
- But L is already inferred



Forward Chaining Example

- Process agenda item Q
- Q is inferred
- Done



Forward Chaining Algorithm


```
function PL-FC-ENTAILS?(KB, q) returns true or false
   inputs: KB, the knowledge base, a set of propositional Horn clauses
           q, the query, a proposition symbol
   local variables: count, a table, indexed by clause, init. number of premises
                    inferred, a table, indexed by symbol, each entry initially false
                    agenda, a list of symbols, initially the symbols known in KB

   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]
               if count[c] = 0 then do
                   if HEAD[c] = q then return true
                   PUSH(HEAD[c], agenda)
   return false
```

backward chaining

Backward Chaining

- Idea: work backwards from the query Q:
  to prove Q by BC,
  check if Q is known already, or
  prove by BC all premises of some rule concluding q

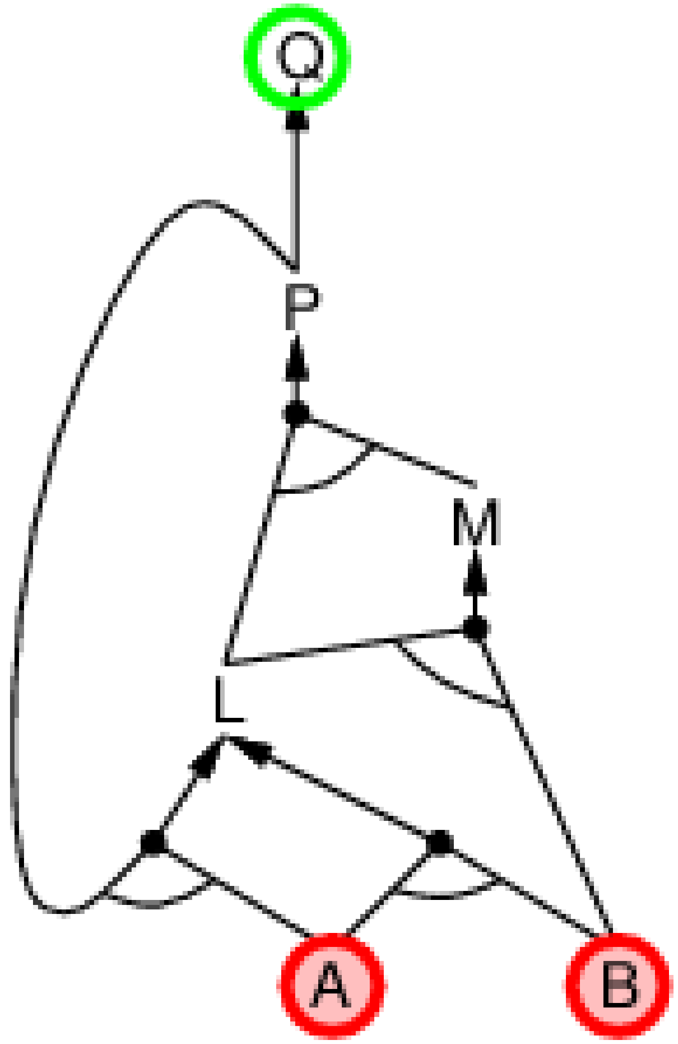
- Avoid loops: check if new subgoal is already on the goal stack

- Avoid repeated work: check if new subgoal

  1. has already been proved true, or
  2. has already failed

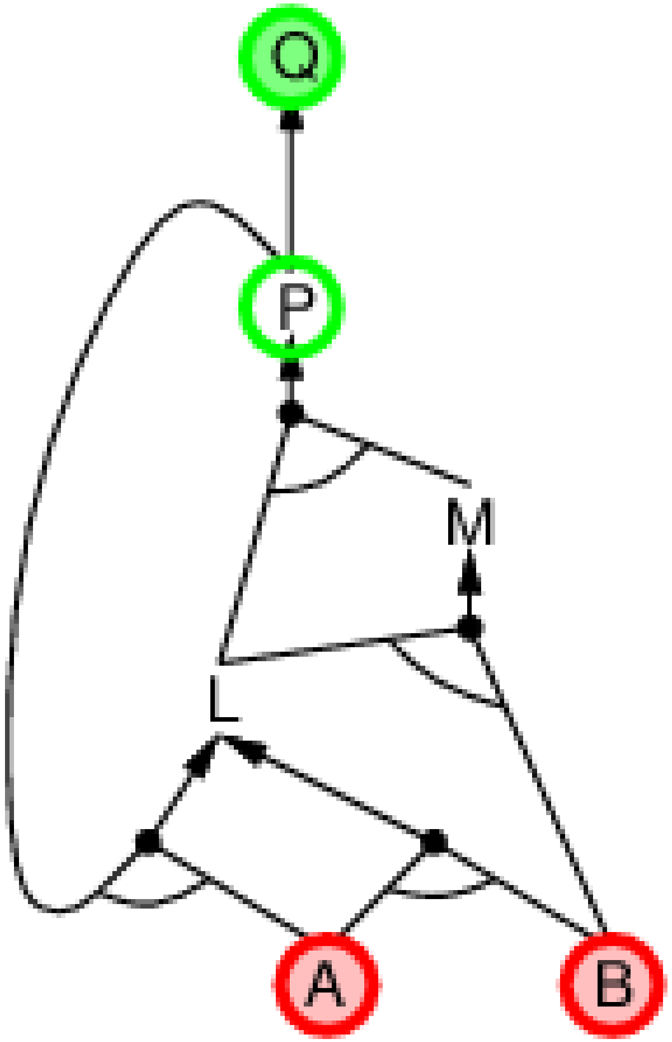
Backward Chaining Example

- A and B are known to be true
- Q needs to be proven



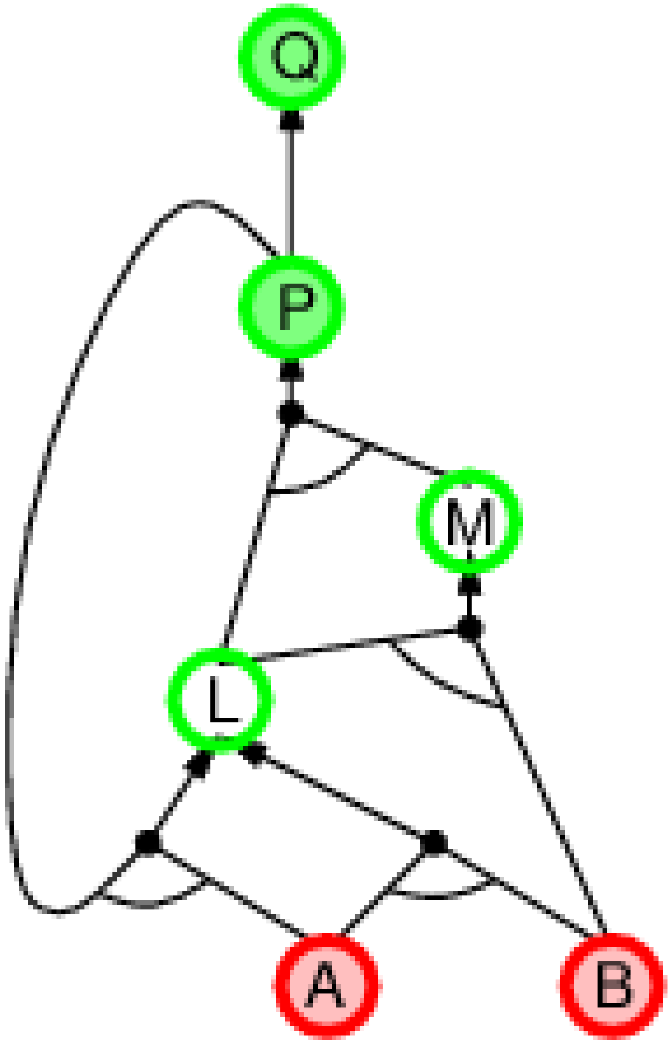
Backward Chaining Example

- Current goal: Q
- Q can be inferred by $P \implies Q$
- P needs to be proven



Backward Chaining Example

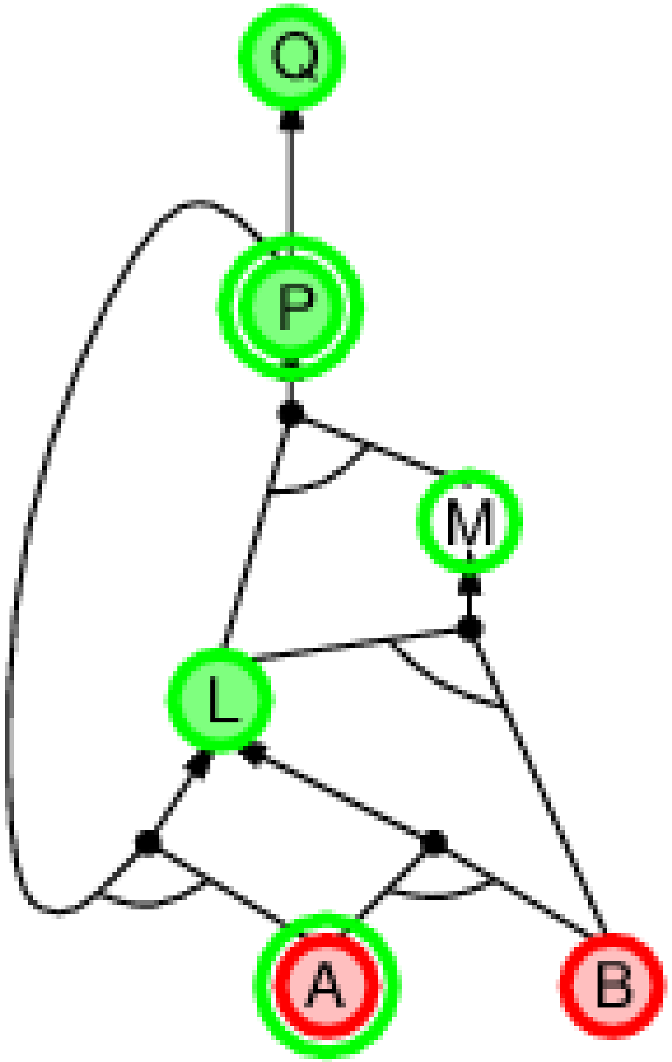
- Current goal: P
- P can be inferred by $L \wedge M \implies P$
- L and M need to be proven



Backward Chaining Example

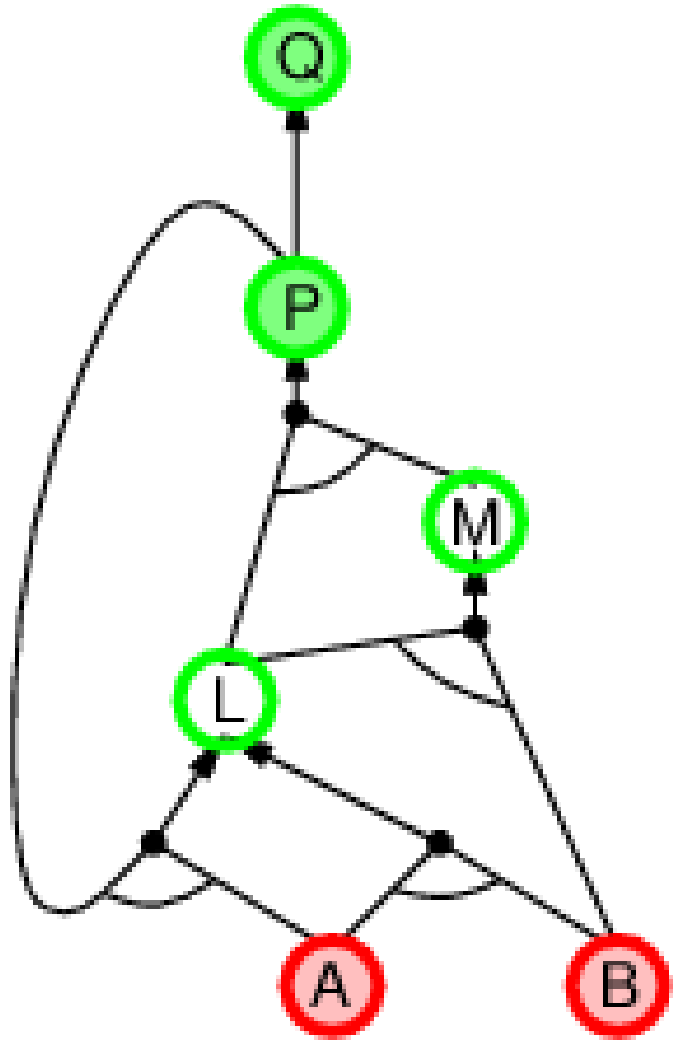
- Current goal: L
- L can be inferred by $A \wedge P \implies L$
- A is already true
- P is already a goal

$\Rightarrow$ repeated subgoal



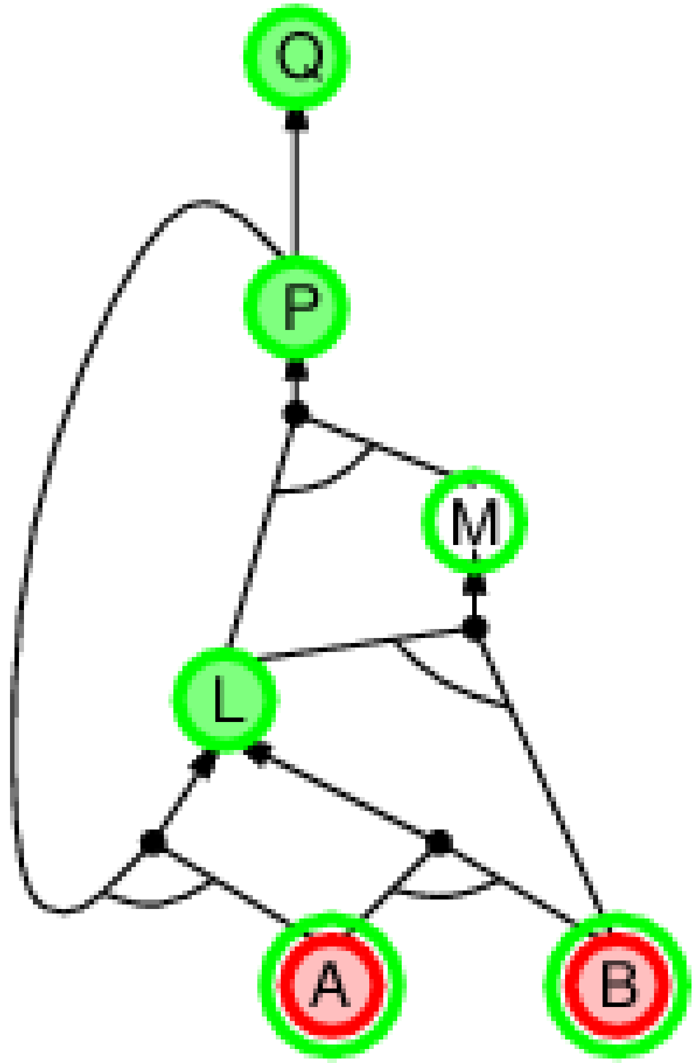
Backward Chaining Example

- Current goal: L



Backward Chaining Example

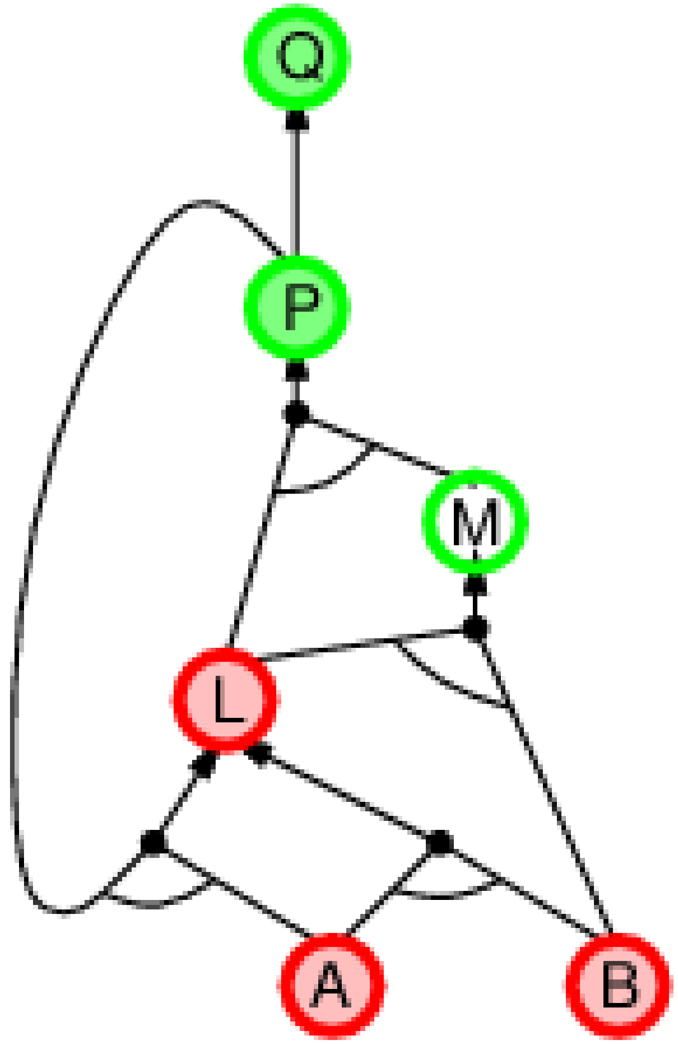
- Current goal: L
- L can be inferred by $A \wedge B \implies L$
- Both are true



Backward Chaining Example

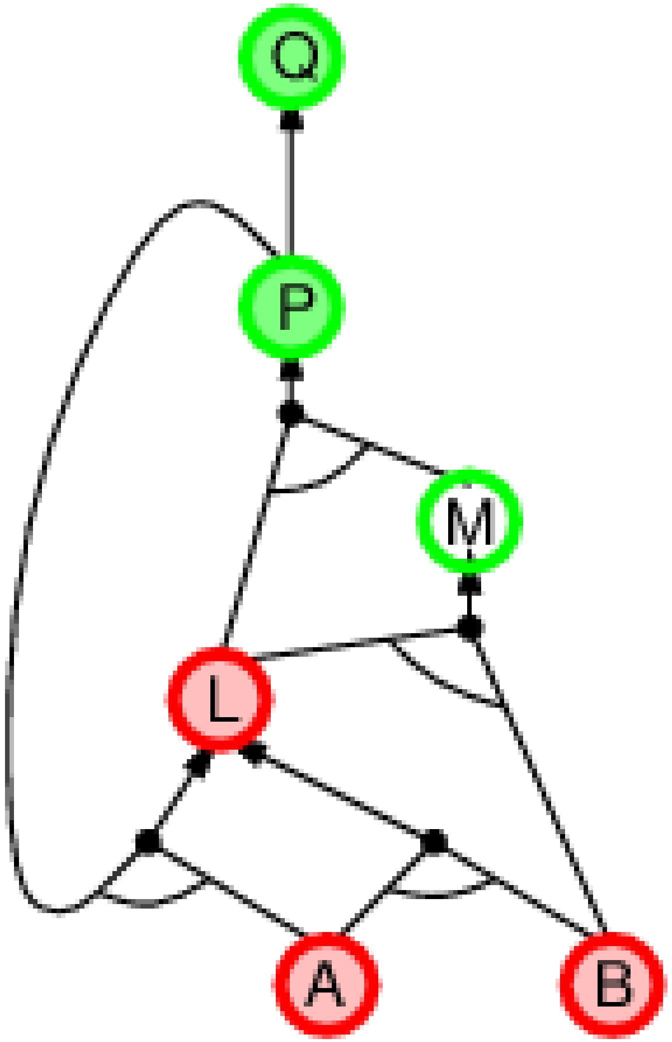
- Current goal: L
- L can be inferred by $A \wedge B \implies L$
- Both are true

$\Rightarrow$ L is true



Backward Chaining Example

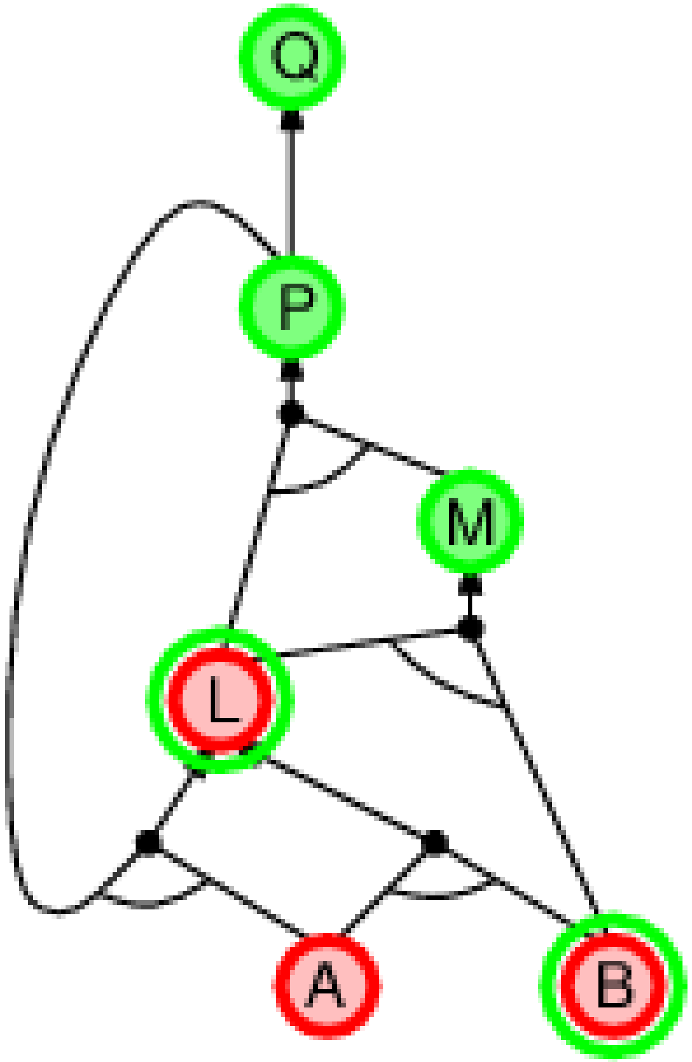
- Current goal: M



Backward Chaining Example

- Current goal: M

- M can be inferred by $B \wedge L \implies M$



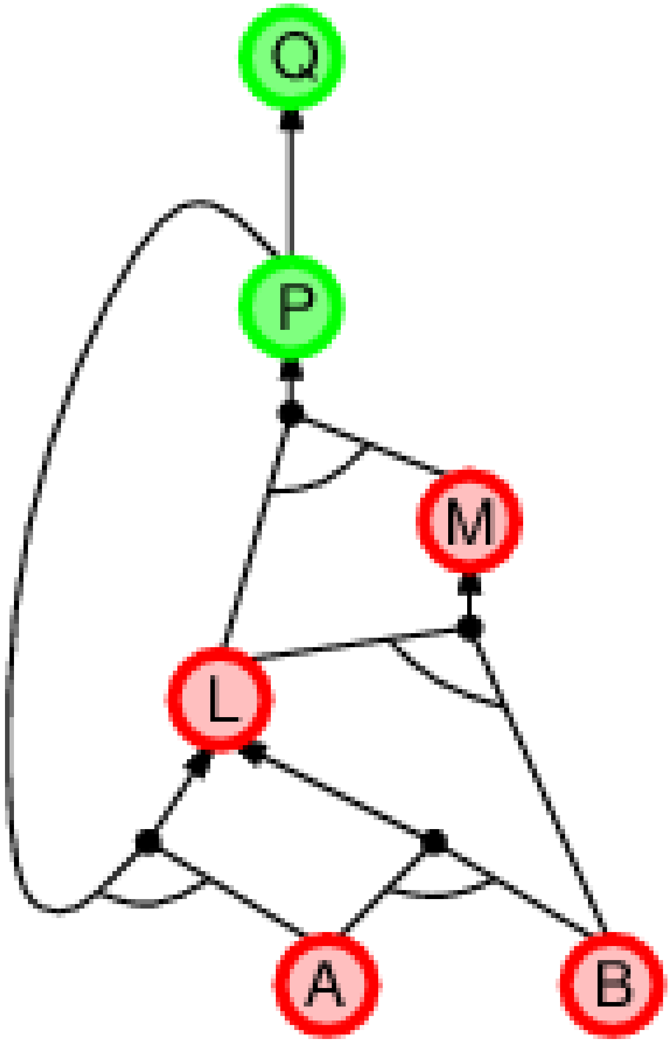
Backward Chaining Example

- Current goal: M

- M can be inferred by $B \wedge L \implies M$

- Both are true

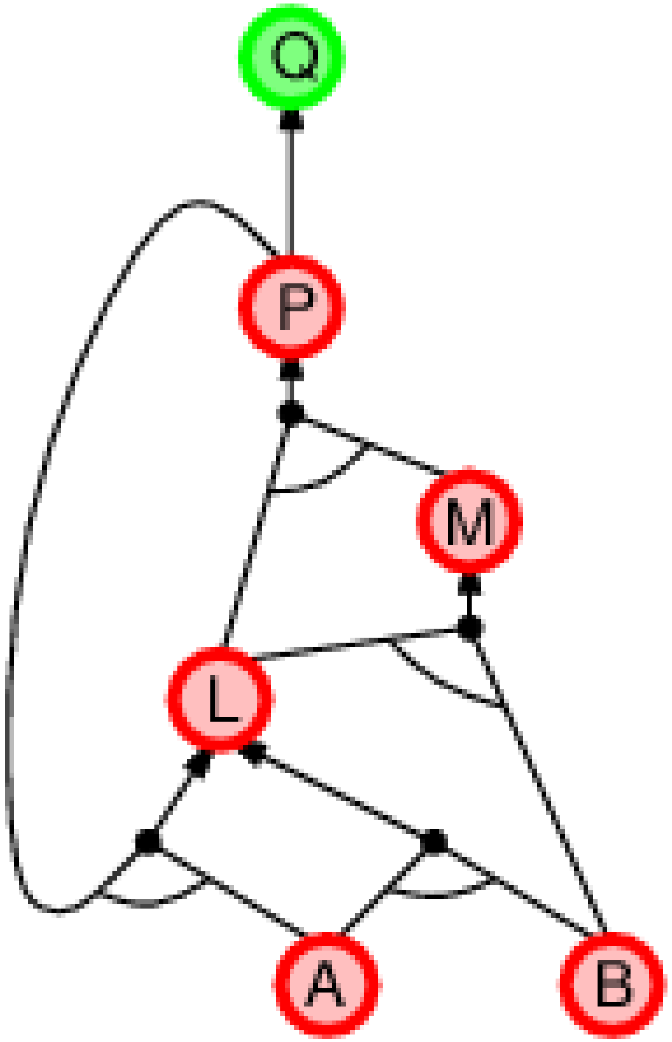
$\Rightarrow$ M is true



Backward Chaining Example

- Current goal: P
- P can be inferred by $L \wedge M \implies P$
- Both are true

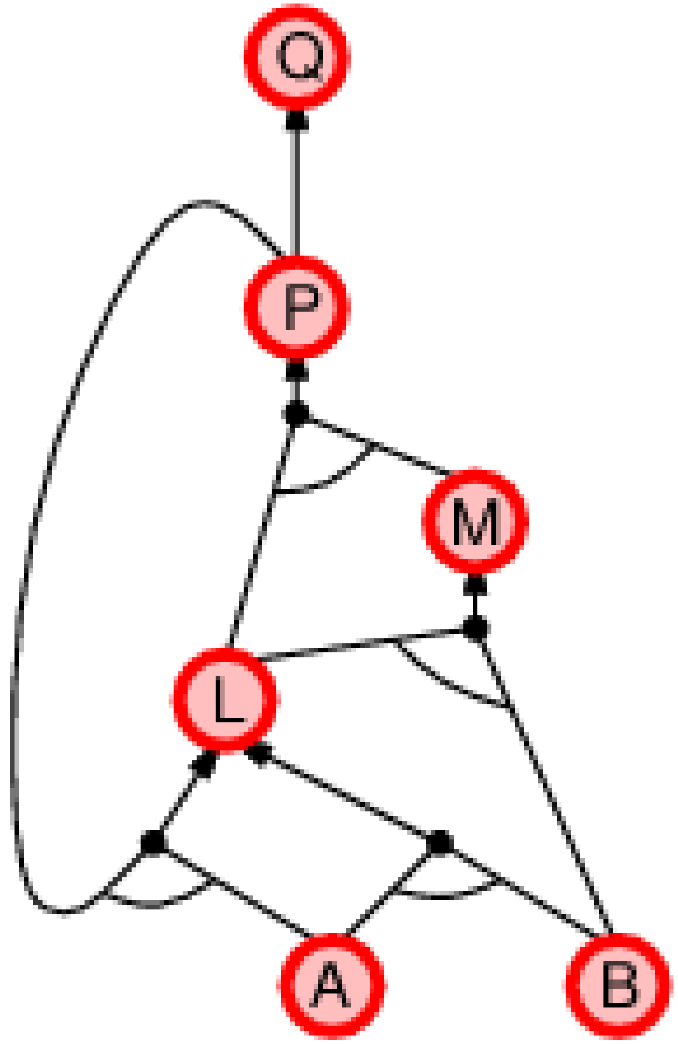
$\Rightarrow$ P is true



Backward Chaining Example

- Current goal: Q
- Q can be inferred by $P \implies Q$
- P is true

$\Rightarrow$ Q is true



Forward vs. Backward Chaining

- FC is data-driven, cf. 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

resolution

Resolution

- Conjunctive Normal Form (CNF—universal)

  $\textbf{conjunction}$ of $\underbrace{\textbf{disjunctions} \text{ of } \textbf{literals}}_{\textbf{clauses}}$

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

- Resolution inference rule (for CNF): complete for propositional logic

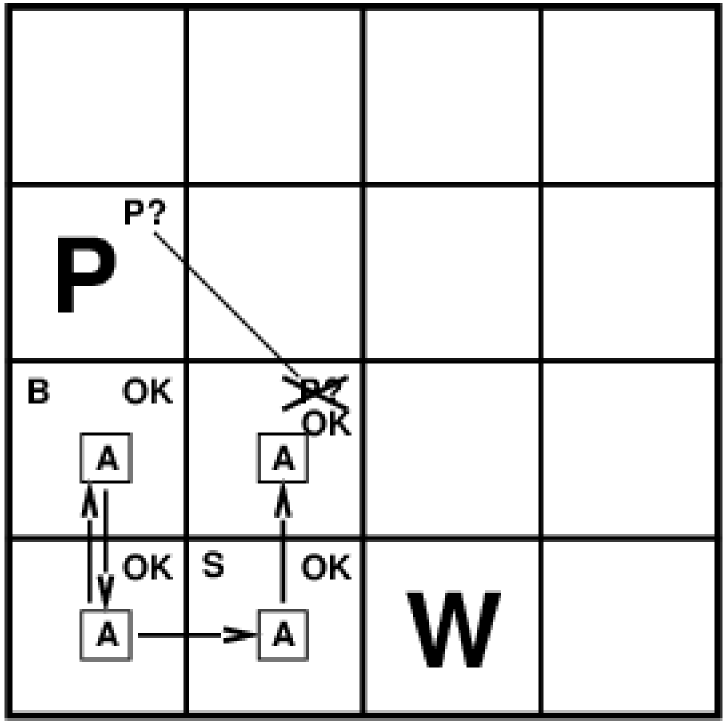
$$\frac{\ell_1 \vee \cdots \vee \ell_k, \qquad m_1 \vee \cdots \vee m_n}{\ell_1 \vee \cdots \vee \ell_{i-1} \vee \ell_{i+1} \vee \cdots \vee \ell_k \vee m_1 \vee \cdots \vee m_{j-1} \vee m_{j+1} \vee \cdots \vee m_n}$$

  where ℓ_i and m_j are complementary literals. E.g.,

$$\frac{P_{1,3} \vee P_{2,2}, \qquad \neg P_{2,2}}{P_{1,3}}$$

- Resolution is sound and complete for propositional logic

Wampus World



- Rules such as: “If breeze, then a pit adjacent.“

$$B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$$

Conversion to CNF

$$B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$$

1. Eliminate $\Leftrightarrow$, replacing $\alpha \Leftrightarrow \beta$ with $(\alpha \implies \beta) \wedge (\beta \implies \alpha)$.

$$(B_{1,1} \implies (P_{1,2} \vee P_{2,1})) \wedge ((P_{1,2} \vee P_{2,1}) \implies B_{1,1})$$

2. Eliminate $\Rightarrow$, replacing $\alpha \Rightarrow \beta$ with $\neg\alpha \vee \beta$.

$$(\neg B_{1,1} \vee P_{1,2} \vee P_{2,1}) \wedge (\neg(P_{1,2} \vee P_{2,1}) \vee B_{1,1})$$

3. Move $\neg$ inwards using de Morgan's rules and double-negation:

$$(\neg B_{1,1} \vee P_{1,2} \vee P_{2,1}) \wedge ((\neg P_{1,2} \wedge \neg P_{2,1}) \vee B_{1,1})$$

4. Apply distributivity law ($\vee$ over $\wedge$) and flatten:

$$(\neg B_{1,1} \vee P_{1,2} \vee P_{2,1}) \wedge (\neg P_{1,2} \vee B_{1,1}) \wedge (\neg P_{2,1} \vee B_{1,1})$$

Resolution Example

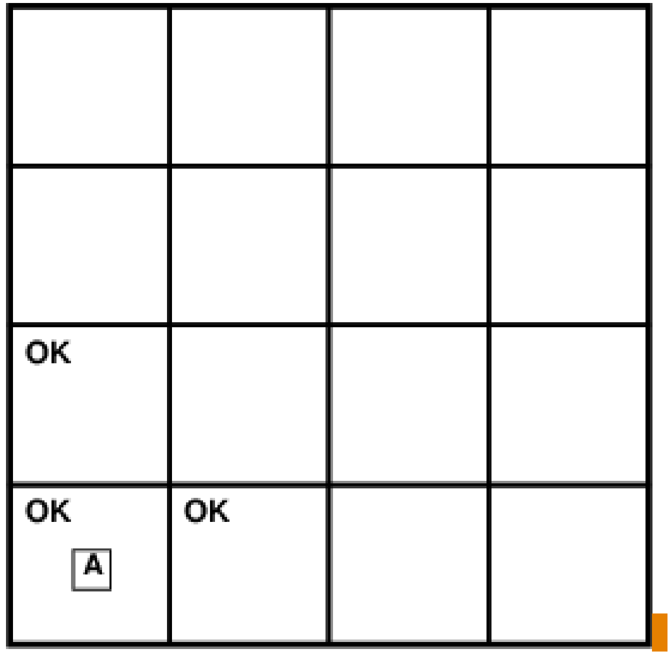
- $KB = (B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1}))$

  reformulated as:

  $(\neg B_{1,1} \vee P_{1,2} \vee P_{2,1}) \wedge (\neg P_{1,2} \vee B_{1,1}) \wedge (\neg P_{2,1} \vee B_{1,1})$

- Observation: $\neg B_{1,1}$

- Goal: disprove: $\alpha = \neg P_{1,2}$
  (we add $P_{1,2}$ to the KB and check for contraction)



- Resolution

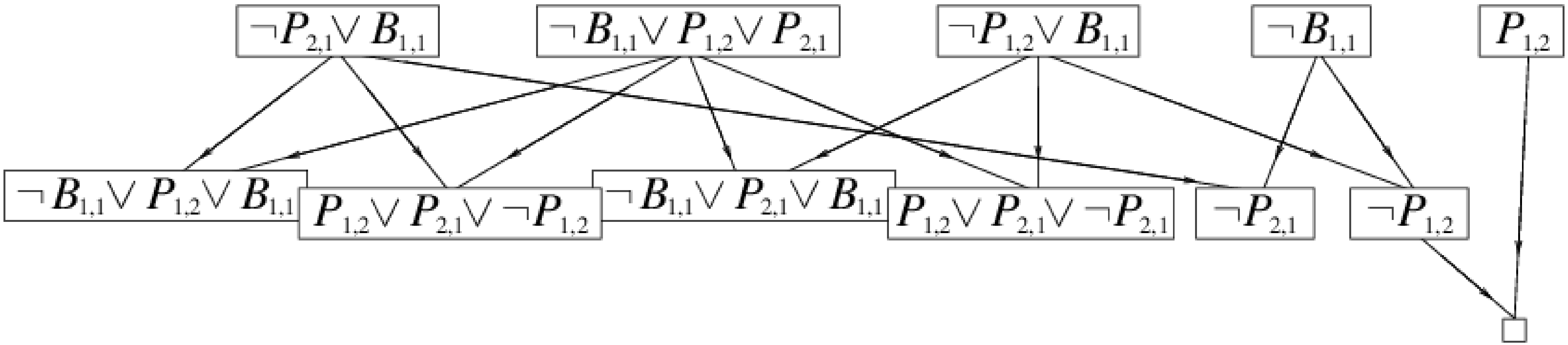
$$\frac{\neg P_{1,2} \vee B_{1,1} \qquad \neg B_{1,1}}{\neg P_{1,2}}$$

- Resolution

$$\frac{\neg P_{1,2} \qquad P_{1,2}}{\mathit{false}}$$

Resolution Example

- In practice: all resolvable pairs of clauses are combined



Resolution Algorithm

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

```
function PL-RESOLUTION(KB, α) returns true or false
   inputs: KB, the knowledge base, a sentence in propositional logic
           α, the query, a sentence in propositional logic
   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
```

Logical Agent

- Logical agent for Wumpus world explores actions
  - observe glitter → done
  - unexplored safe spot → plan route to it
  - if Wampus in possible spot → shoot arrow
  - take a risk to go possibly risky spot
- Propositional logic to infer state of the world
- Heuristic search to decide which action to take

Summary

- Logical agents apply inference to a knowledge base
  to derive new information and make decisions

- Basic concepts of logic:
  - syntax: formal structure of sentences
  - semantics: truth of sentences wrt models
  - entailment: necessary truth of one sentence given another
  - inference: deriving sentences from other sentences
  - soundess: derivations produce only entailed sentences
  - completeness: derivations can produce all entailed sentences

- Wumpus world requires the ability to represent partial and negated information, inference to determine state of the world, etc.

- Forward, backward chaining are linear-time, complete for Horn clauses

- Resolution is complete for propositional logic