

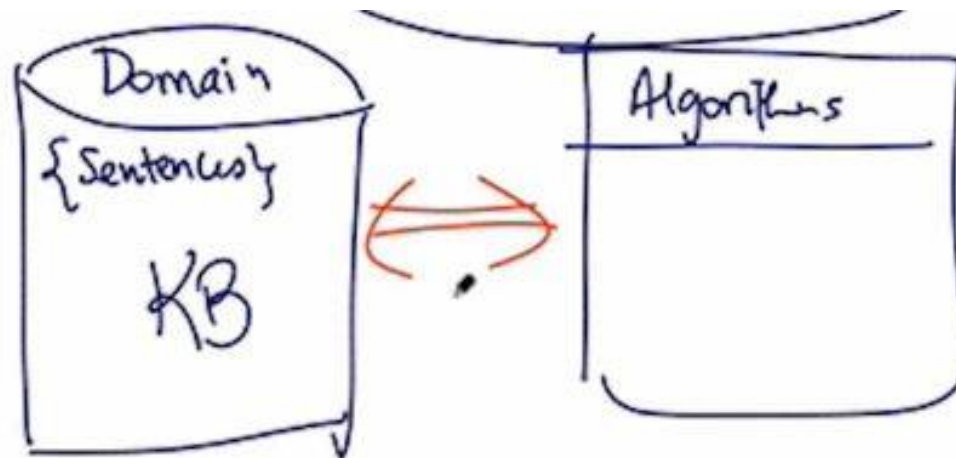
Artificial Intelligence

LOGICAL AGENTS

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Outline

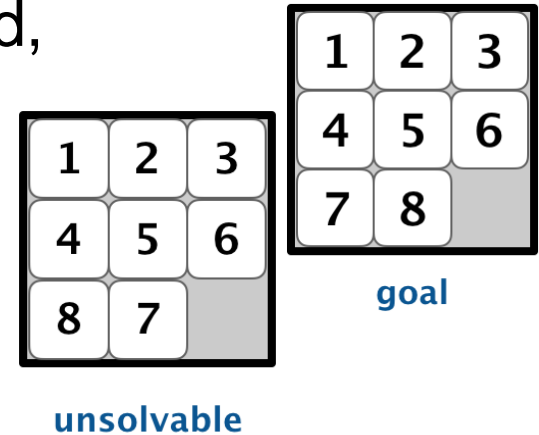
- Knowledge-based agents
- The Wumpus world
- Propositional logic: A very simple logic
- Propositional theorem proving
- Effective propositional model checking



Knowledge-based agents

Problem-solving agents

- These agents know things in a very limited, inflexible sense.
 - E.g., an 8-puzzle agent cannot deduce pairs of unsolvable states from their parities.



Variables: $\{x, y, z\}$

Domains:

x	y	z
1	1	1
2	2	2
3	3	3
4	4	4

Constraints:

x	y
1	2
3	1

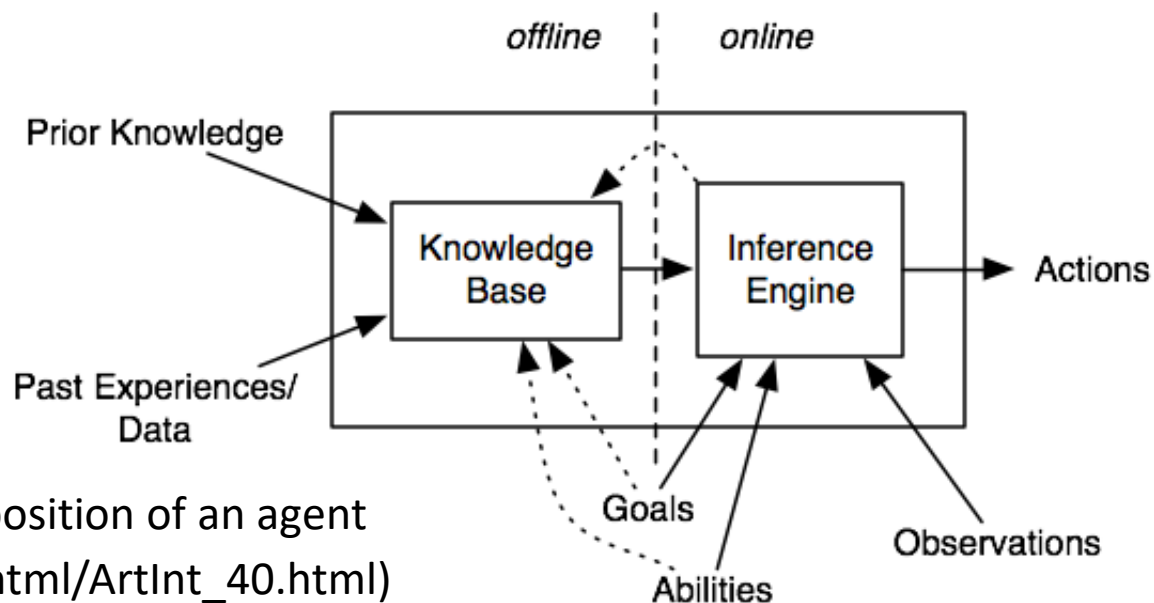
y	z
1	4
2	1

$\{C_1, C_2\}$

- CSP enables some parts of the agent to work domain-independently
 - State = an assignment of values to variables
 - Allow for more efficient algorithms

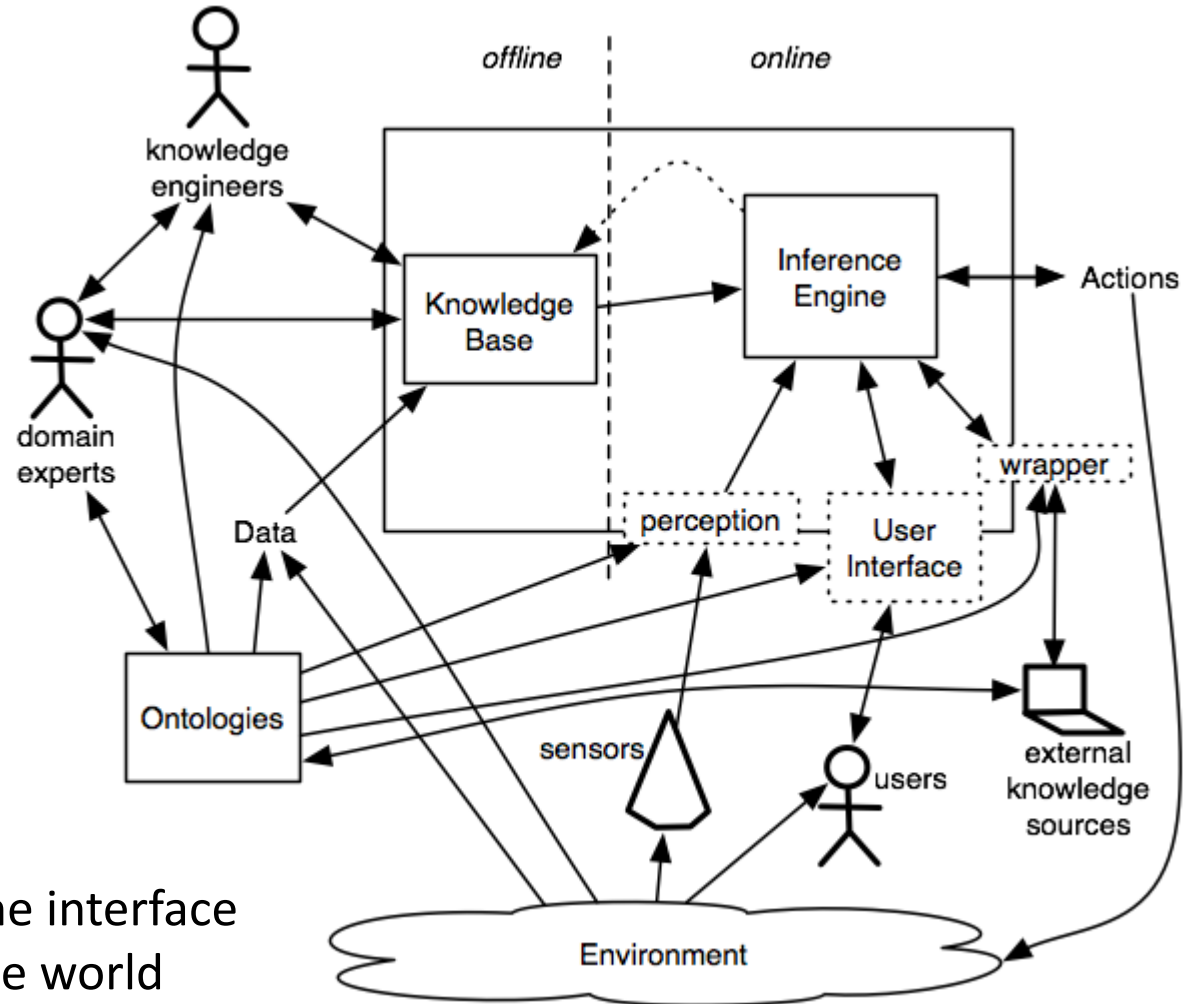
Knowledge-based agents

- Supported by **logic** – a general class of representation
- **Combine and recombine information** to suit myriad purposes
 - **Accept new tasks** in the form of explicitly described goals
 - **Achieve competence** by learning new knowledge of the environment
 - **Adapt to changes** by updating the relevant knowledge



Offline and online decomposition of an agent
(Credit: https://artint.info/html/ArtInt_40.html)

Knowledge-based agents



A detailed description of the interface between the agents and the world

(Credit: https://artint.info/html/ArtInt_40.html)

Knowledge-based agents



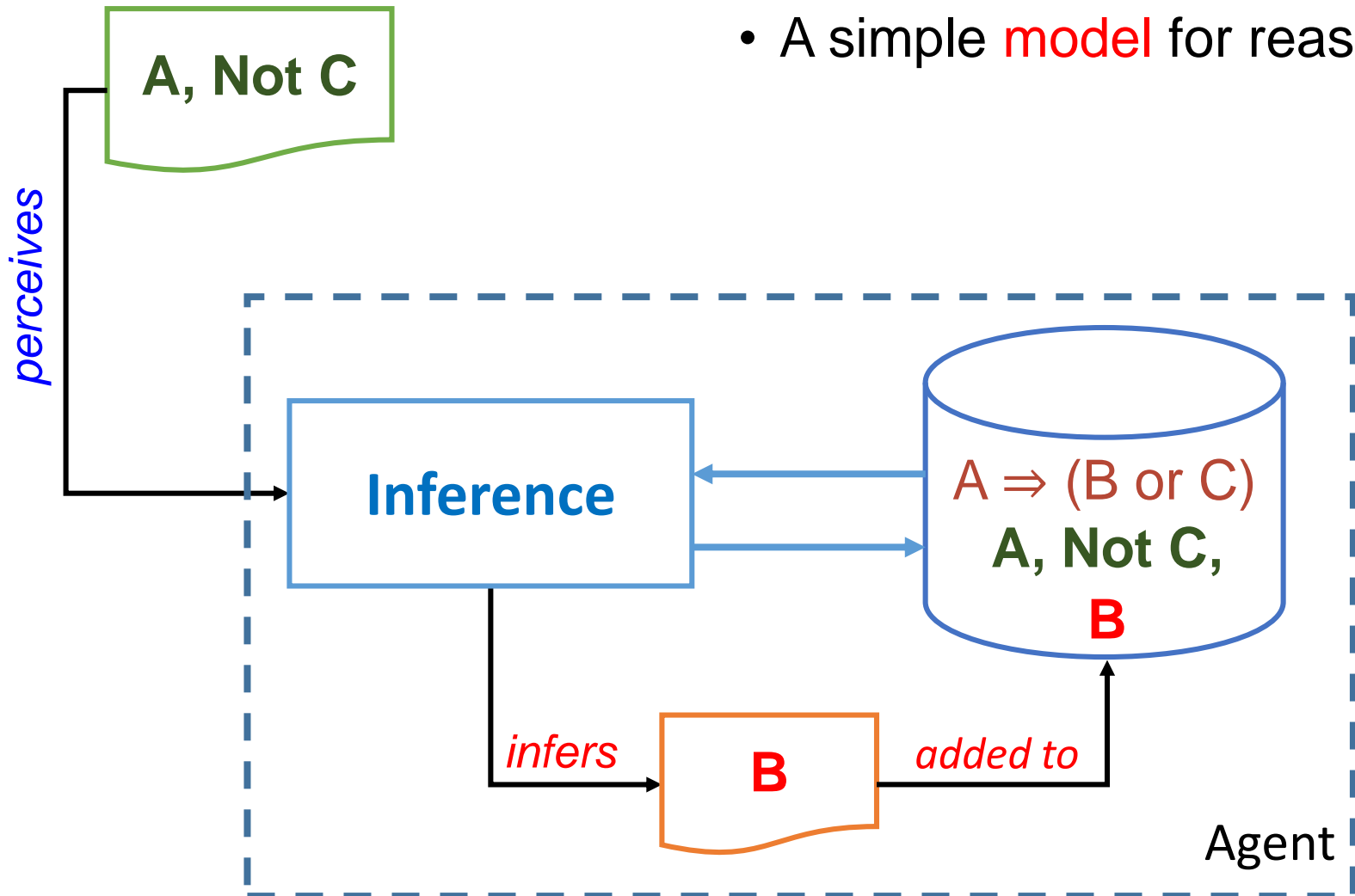
- **Knowledge base (KB):** A set of sentences or facts
 - Each sentence represents some assertion about the world.
 - **Axiom** = sentence that is not derived from other sentences

- **Inference:** Derive (infer) new sentences from old ones
 - Add new sentences to the knowledge base and query what is known



Model for reasoning: An example

- A simple **model** for reasoning



A generic knowledge-based agent

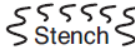


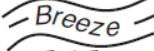
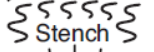
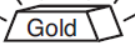
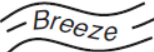
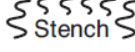


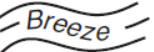

```
function KB-AGENT(percept) returns an action  
  persistent: KB, a knowledge base  
               t, a counter, initially 0, indicating time  
  TELL(KB, MAKE-PERCEPT-SENTENCE(percept, t))  
  action ← ASK(KB, MAKE-ACTION-QUERY(t))  
  TELL(KB, MAKE-ACTION-SENTENCE(action, t))  
  t ← t + 1  
 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

Inference mechanisms are hidden inside TELL and ASK

A generic knowledge-based agent

- Declarative approach
 - Empty KB → TELL the agent the facts, one by one until it knows how to operate in its environment
- Procedural approach
 - Encode desired behaviors directly as program code
- Combined approach → Partially autonomous
- Learning approach (Chapter 18) → Fully autonomous
 - Provide a knowledge-based agent with mechanisms that allow it to learn for itself



4	 Stench		 Breeze	<div>PIT</div>
3		  Stench  Gold	<div>PIT</div>	 Breeze
2	 Stench		 Breeze	
1	 START	 Breeze	<div>PIT</div>	 Breeze
	1	2	3	4



The Wumpus world

PEAS Description

- Environment

- 4×4 grid of rooms, agent starts in the square [1,1], facing to the right
- The locations of Gold and Wumpus are random
- Each square can be a pit, with probability 0.2

- Performance measure

- +1000 for climbing out of the cave with gold, -1000 for death
- -1 per step, -10 for using the arrow
- The game ends when agent dies or climbs out of the cave

- Actuators: *Forward, TurnLeft/TurnRight by 90°, Grab, Shoot, Climb*

- Sensors: *Stench, Breeze, Glitter, Bump, Scream*

- Percept: *[Stench, Breeze, None, None, None]*

Characterize the Wumpus world

- **Fully 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

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

1,4	2,4	3,4	4,4
1,3	2,3	3,3	4,3
1,2 OK	2,2	3,2	4,2
1,1 A OK	2,1 OK	3,1	4,1

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1,4	2,4	3,4	4,4
1,3	2,3	3,3	4,3
1,2 OK	2,2 P?	3,2	4,2
1,1 V OK	2,1 A B OK	3,1 P?	4,1

Exploring a Wumpus world

A = Agent
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W = Wumpus

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

Exploring a Wumpus world

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 V OK	3,2	4,2
1,1 V OK	2,1 B V OK	3,1 P!	4,1



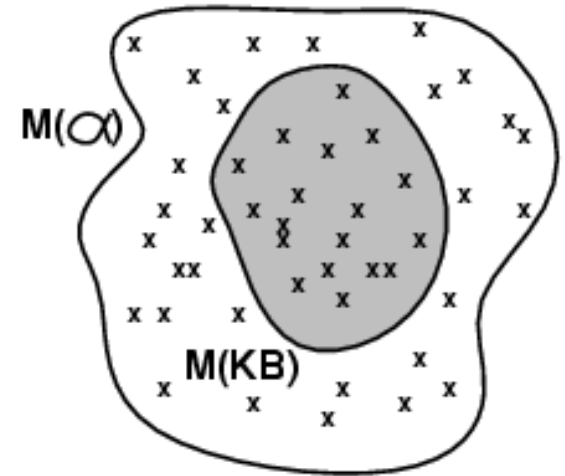
Propositional logic

Logics in general

- **Models** (or possible worlds) are mathematical abstractions that fix the truth or falsehood of every relevant sentence.
 - E.g., all possible assignments of real numbers to x and y
- m **satisfies** (or **is a model of**) α if α is true in model m
- $M(\alpha) =$ the set of all models of α

Entailment in logic

- A sentence **follows logically** from another sentence: $\alpha \models \beta$
- $\alpha \models \beta$ if and only if, in every model in which α is true, β is also true, i.e., $M(\alpha) \subseteq M(\beta)$
- For example,
 - $x = 0$ entails $xy = 0$
 - The KB containing “Apple is red” and “Tomato is red” entails “Either the apple or the tomato is red”
- Entailment is a relationship between sentences (i.e., **syntax**) that is based on **semantics**.

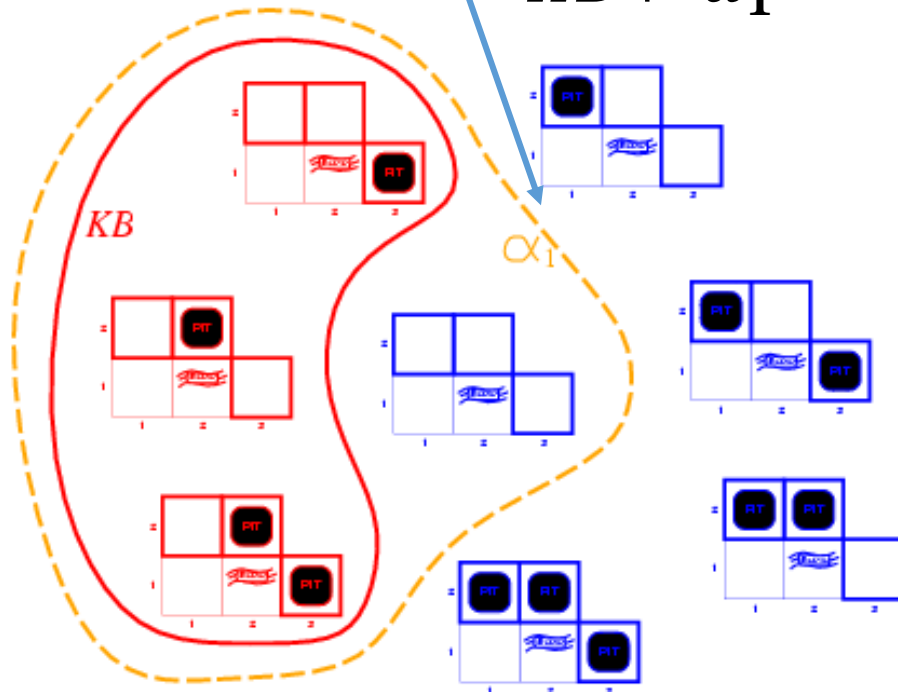


Entailment in logic: Wumpus world

- Consider two possible conclusions α_1 and α_2

“There is no pit in [1,2].”

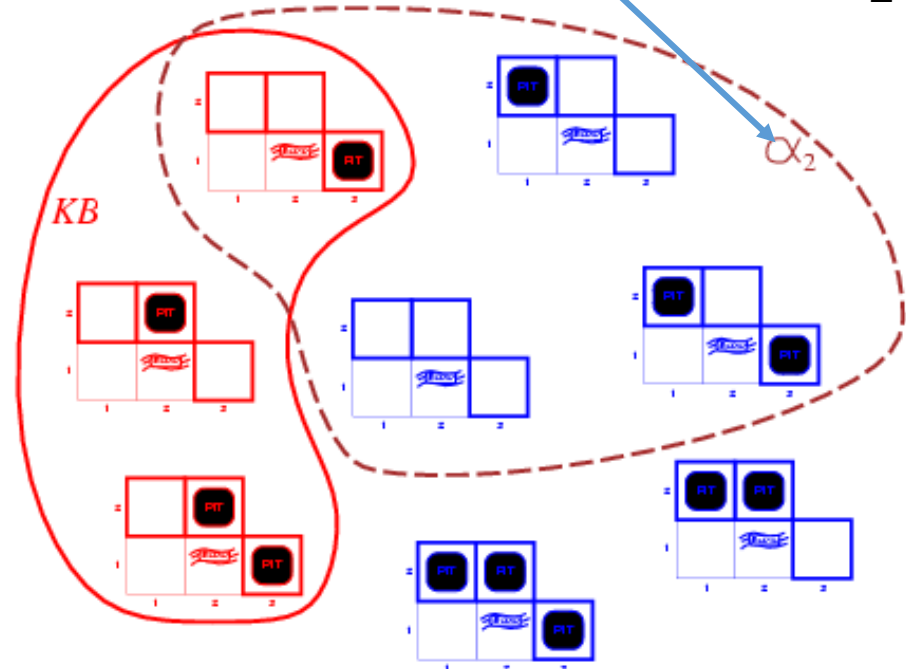
$KB \models \alpha_1$



(a)

“There is no pit in [2,2].”

$KB \not\models \alpha_2$

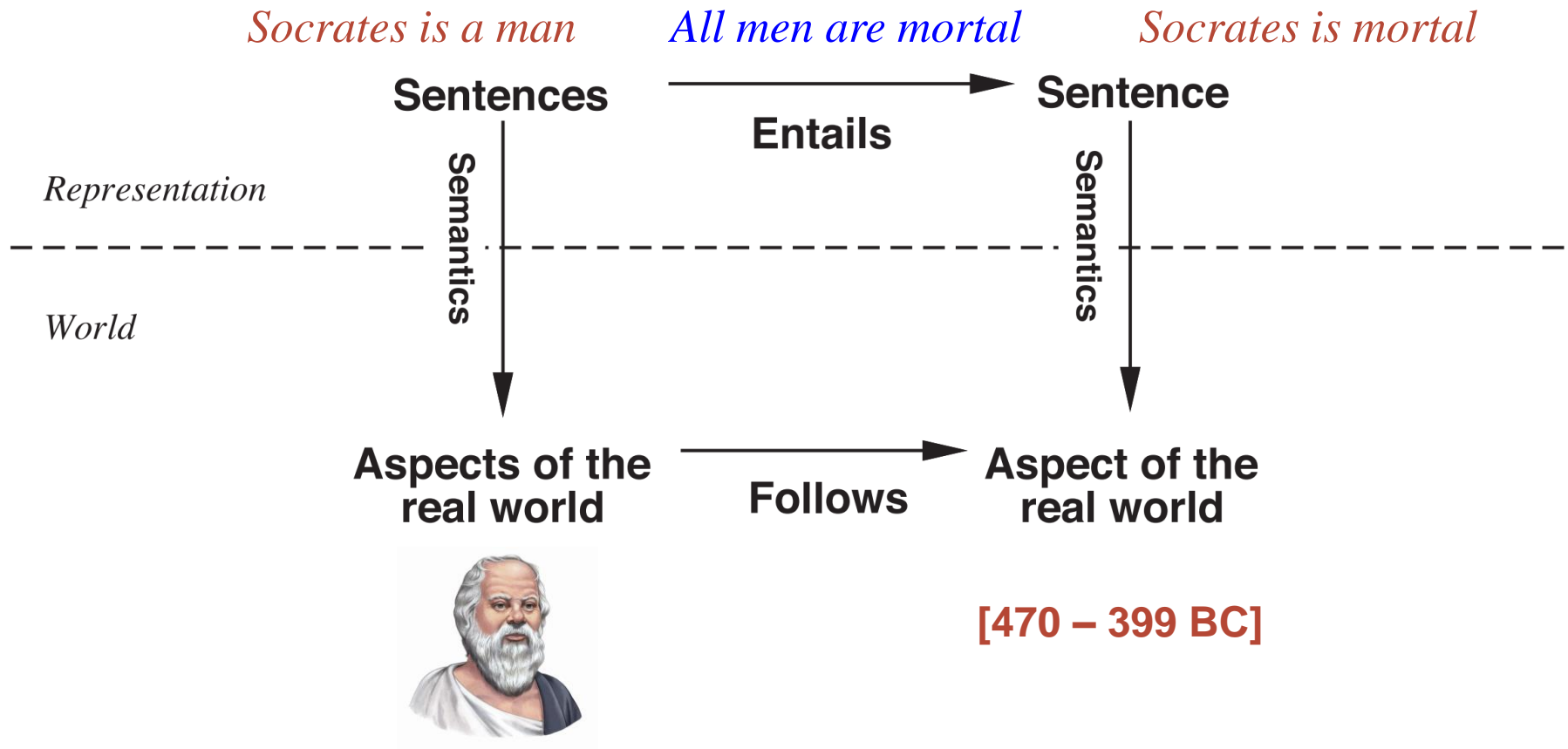


(b)

Logical inference

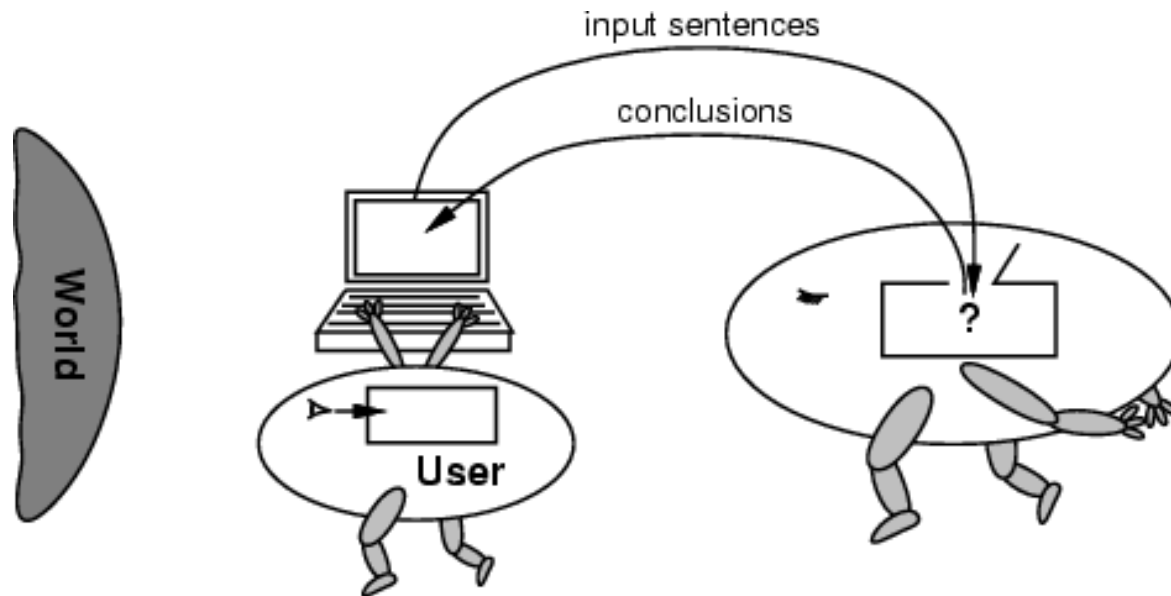
- $KB \models_i \alpha$ means α can be derived from KB by procedure i
- **Soundness**: An inference algorithm that derives only entailed sentences is called **sound**
- **Completeness**: an inference algorithm is complete if it can derive any sentence that is entailed
- If KB is true in the real world, then any sentence α derived from KB by a sound inference procedure is also true in the real world.

World and representation



No independent access to the world

- The reasoning agent gets its knowledge about the facts of the world as a sequence of logical sentences
- Conclusions must be drawn only from those → without agent's independent access to the world
- Thus, it is very important that the agent's reasoning is sound!



Propositional logic: Syntax

- Constants: **TRUE** or **FALSE**
- Symbols stand for **propositions** (sentences): $P, Q, P_1, W_{1,3}, \dots$
- Logical **connectives**

NOT	\neg	Negation
AND	\wedge	Conjunction
OR	\vee	Disjunction
IMPLIES	\Rightarrow	Implication (if..then)
IFF	\Leftrightarrow	Equivalence, biconditional

- **Literal**: atomic sentence (P) or negated atomic sentence ($\neg P$)

Propositional logic: Syntax

$Sentence \rightarrow AtomicSentence \mid ComplexSentence$

$AtomicSentence \rightarrow True \mid False \mid P \mid Q \mid R \mid \dots$

$ComplexSentence \rightarrow (Sentence) \mid [Sentence]$

$\mid \neg Sentence$

$\mid Sentence \wedge Sentence$

$\mid Sentence \vee Sentence$

$\mid Sentence \Rightarrow Sentence$

$\mid Sentence \Leftrightarrow Sentence$

OPERATOR PRECEDENCE : $\neg, \wedge, \vee, \Rightarrow, \Leftrightarrow$

Propositional logic: Semantics

- Each model specifies true/false for each proposition symbol.
 - E.g., $m_1 = \{P_{1,2} = \text{false}, P_{2,2} = \text{false}, P_{3,1} = \text{true}\}$, 8 possible models
- Rules for evaluating truth with respect to a model m

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

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

A simple knowledge base

- Symbols for each position $[i, j]$
 - $P_{i,j}$: there is a pit in $[i, j]$
 - $W_{i,j}$: there is a Wumpus in $[i, j]$
 - $B_{i,j}$: there is a breeze in $[i, j]$
 - $S_{i,j}$: there is a stench in $[i, j]$
- Sentences in Wumpus world's KB

$$R_1: \neg P_{1,1}$$

$$R_2: B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$$

$$R_3: B_{2,1} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{3,1})$$

$$R_4: \neg B_{1,1}$$

$$R_5: B_{2,1}$$

1,4	2,4	3,4	4,4
1,3	2,3	3,3	4,3
1,2 OK	2,2 P?	3,2	4,2
1,1 V OK	2,1 A B OK	3,1 P?	4,1

A simple inference procedure

- **Given:** a set of sentences, **KB** , and sentence **α**
- **Goal:** answer **$KB \models \alpha?$** = “Does **KB** semantically entail **α** ?”
 - In all interpretations in which KB ’s sentences are true, is α also true?
 - E.g., in the Wumpus world, $KB \models P_{1,2}?$ = “Is there a pit in $[1,2]$?”

Model-checking approach (Inference by enumeration)

Inference rules

Conversion to the inverse SAT problem (Resolution refutation)

Model-checking approach

- Check if α is true in every model in which KB is true.
 - E.g., the Wumpus's KB has 7 symbols $\rightarrow 2^7 = 128$ models
- Draw a truth table for checking

No pit in [1,2]

$B_{1,1}$	$B_{2,1}$	$P_{1,1}$	$P_{1,2}$	$P_{2,1}$	$P_{2,2}$	$P_{3,1}$	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	<u>true</u>
false	true	false	false	false	true	false	true	true	true	true	true	<u>true</u>
false	true	false	false	false	true	true	true	true	true	true	true	<u>true</u>
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

Inference by (depth-first) enumeration

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

$symbols \leftarrow$ a list of the proposition symbols in KB and α

return TT-CHECK-ALL($KB, \alpha, symbols, \{ \}$)

function TT-CHECK-ALL($KB, \alpha, symbols, model$) **returns** *true* or *false*

if EMPTY?($symbols$) **then**

if PL-TRUE?($KB, model$) **then return** PL-TRUE?($\alpha, model$)

else return *true* // when KB is false, always return *true*

else do

$P \leftarrow$ FIRST($symbols$)

$rest \leftarrow$ REST($symbols$)

return (TT-CHECK-ALL($KB, \alpha, rest, model \cup \{P = true\}$)

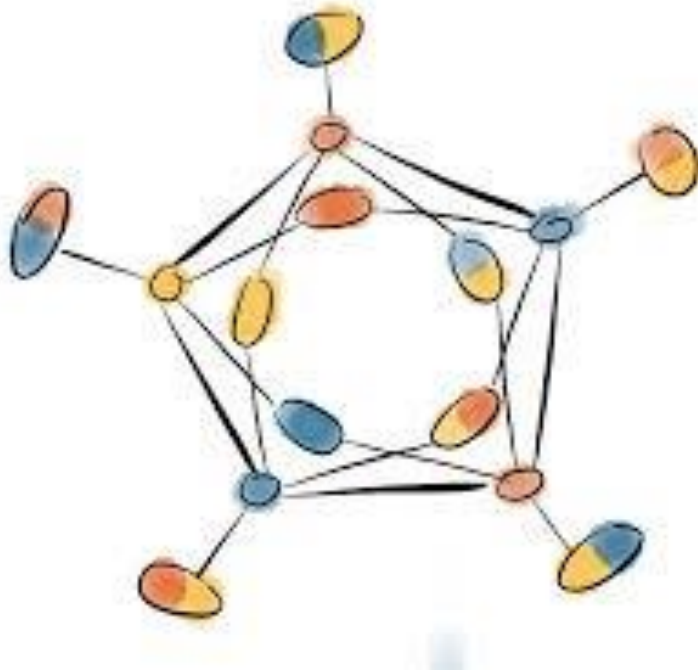
and TT-CHECK-ALL($KB, \alpha, rest, model \cup \{P = false\}$))

sound and **complete**

Time complexity $O(2^n)$, space complexity $O(n)$

Quiz 01: Model-checking approach

- Given a KB containing the following rules and facts
 - R_1 : IF hot AND smoky THEN fire
 - R_2 : IF alarm_beeps THEN smoky
 - R_3 : IF fire THEN sprinklers_on
 - F_1 : alarm_beeps
 - F_2 : hot
- Represent the KB in propositional logic with given symbols
 - H = hot, S = smoky, F = fire, A = alarms_beeps, R = sprinklers_on
- Answer the question “Sprinklers_on?” by using the model-checking approach.

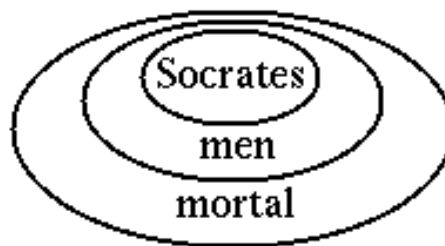


Propositional theorem proving

- *Proof by Resolution*
- *Forward and Backward Chaining*

Inference rules approach

- **Theorem proving:** Apply **rules of inference directly** to the sentences in KB to construct a **proof of the desired sentence without consulting models**
- More efficient than model checking when the number of models is large, yet the length of the proof is short



men \rightarrow mortal
Socrates \rightarrow man
Socrates \rightarrow mortal



Logical equivalence

- Two sentences, α and β , are **logically equivalent** if they are true in the same set of models.

$$\alpha \equiv \beta \text{ iff } \alpha \models \beta \text{ and } \beta \models \alpha$$

$(\alpha \wedge \beta) \equiv (\beta \wedge \alpha)$	commutativity of \wedge
$(\alpha \vee \beta) \equiv (\beta \vee \alpha)$	commutativity of \vee
$((\alpha \wedge \beta) \wedge \gamma) \equiv (\alpha \wedge (\beta \wedge \gamma))$	associativity of \wedge
$((\alpha \vee \beta) \vee \gamma) \equiv (\alpha \vee (\beta \vee \gamma))$	associativity of \vee
$\neg(\neg\alpha) \equiv \alpha$	double-negation elimination
$(\alpha \Rightarrow \beta) \equiv (\neg\beta \Rightarrow \neg\alpha)$	contraposition
$(\alpha \Rightarrow \beta) \equiv (\neg\alpha \vee \beta)$	implication elimination
$(\alpha \Leftrightarrow \beta) \equiv ((\alpha \Rightarrow \beta) \wedge (\beta \Rightarrow \alpha))$	biconditional elimination
$\neg(\alpha \wedge \beta) \equiv (\neg\alpha \vee \neg\beta)$	De Morgan
$\neg(\alpha \vee \beta) \equiv (\neg\alpha \wedge \neg\beta)$	De Morgan
$(\alpha \wedge (\beta \vee \gamma)) \equiv ((\alpha \wedge \beta) \vee (\alpha \wedge \gamma))$	distributivity of \wedge over \vee
$(\alpha \vee (\beta \wedge \gamma)) \equiv ((\alpha \vee \beta) \wedge (\alpha \vee \gamma))$	distributivity of \vee over \wedge

Validity

- A sentence is **valid** if it is true in all models.
 - E.g., $P \vee \neg P$, $P \Rightarrow \neg P$, $(P \wedge (P \Rightarrow Q)) \Rightarrow Q$
- Valid sentences are also known as **tautologies**.
- Validity is connected to inference via the **Deduction Theorem**
 $\alpha \models \beta$ iff $\alpha \Rightarrow \beta$ is valid

Satisfiability

- A sentence is **satisfiable** if it is true in **some** model.
 - E.g., $P \vee Q$, P
- A sentence is **unsatisfiable** if it is true in **no** models.
 - E.g., $P \wedge \neg P$
- Satisfiability is connected to inference via the following
$$\alpha \models \beta \text{ iff } \alpha \wedge \neg \beta \text{ is unsatisfiable}$$

→ **Refutation** or **proof by contradiction**
- The **SAT problem** determines the satisfiability of sentences in propositional logic (NP-complete)
 - E.g., in CSPs, the constraints are satisfiable by some assignment.

Quiz 02: Validity and Satisfiability

- Check the validity and satisfiability of the below sentences using the truth table

1. $A \vee B \Rightarrow A \wedge C$

2. $A \wedge B \Rightarrow A \vee C$

3. $(A \vee B) \wedge (\neg B \vee C) \Rightarrow A \vee C$

4. $(A \vee \neg B) \Rightarrow A \wedge B$

Inference and Proofs

- **Proof:** A chain of conclusions leads to the desired goal
- Example sound rules of inference

$$\frac{\alpha \Rightarrow \beta \quad \alpha}{\therefore \beta}$$

Modus Ponens

$$\frac{\alpha \Rightarrow \beta \quad \neg \beta}{\therefore \neg \alpha}$$

Modus Tollens

$$\frac{\alpha \quad \beta}{\therefore \alpha \wedge \beta}$$

AND-Introduction

$$\frac{\alpha \wedge \beta}{\therefore \alpha}$$

AND-Elimination

Inference rules: An example

KB	No.	Sentences	Explanation
$P \wedge Q$	1	$P \wedge Q$	From KB
$P \Rightarrow R$	2	$P \Rightarrow R$	From KB
$Q \wedge R \Rightarrow S$	3	$Q \wedge R \Rightarrow S$	From KB
$S?$	4	P	1 And-Elim
	5	R	4,2 Modus Ponens
	6	Q	1 And-Elim
	7	$Q \wedge R$	5,6 And-Intro
	8	S	3,7 Modus Ponens

Inference rules in Wumpus world

$R_1: \neg P_{1,1}$

$R_2: B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$

$R_3: B_{2,1} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{3,1})$

$R_4: \neg B_{1,1}$

$R_5: B_{2,1}$

Proof: $\neg P_{1,2}$

- Bi-conditional elimination to $R_2: R_6: (B_{1,1} \Rightarrow (P_{1,2} \vee P_{2,1})) \wedge ((P_{1,2} \vee P_{2,1}) \Rightarrow B_{1,1})$
- And-Elimination to $R_6: R_7: (P_{1,2} \vee P_{2,1}) \Rightarrow B_{1,1}$
- Logical equivalence for contrapositives: $R_8: \neg B_{1,1} \Rightarrow \neg(P_{1,2} \vee P_{2,1})$
- Modus Ponens with R_8 and the percept $R_4: R_9: \neg(P_{1,2} \vee P_{2,1})$
- De Morgan's rule: $R_{10}: \neg P_{1,2} \wedge \neg P_{2,1}$

Proving by search

- Search algorithms can be applied to find a sequence of steps that constitutes a proof.
 - INITIAL STATE: the initial knowledge base
 - ACTIONS: apply all inference rules to all the sentences that match the top half of the inference rule
 - RESULT: add the sentence in the bottom half of the inference rule
 - GOAL: a state that contains the sentence need to be proved
- The proof can ignore irrelevant propositions, no matter how many of them there are → more efficient
 - E.g., in the Wumpus world, $B_{2,1}$, $P_{1,1}$, $P_{2,2}$ and $P_{3,1}$ are not mentioned.

Monotonicity

- The set of entailed sentences only increases as information is added to the knowledge base.

$$\textit{if } KB \models \alpha \textit{ then } KB \wedge \beta \models \alpha$$

- Additional conclusions can be drawn without invalidating any conclusion α already inferred.

Proof by Resolution

- Proof by Inference Rules: **sound but not complete**
 - If the rules are inadequate, then the goal is not reachable.
- **Resolution: sound and complete**, a single inference rule
 - A **complete** inference algorithm when coupled with any complete search algorithm

- Unit resolution inference rule

where l_i and m are **complementary literals**

$$\frac{l_1 \vee \cdots \vee l_k \quad m}{l_1 \vee \cdots \vee l_{i-1} \vee l_{i+1} \vee \cdots \vee l_k}$$

- Full resolution rule

$$\frac{l_1 \vee \cdots \vee l_k \quad m_1 \vee \cdots \vee m_n}{l_1 \vee \cdots \vee l_{i-1} \vee l_{i+1} \vee \cdots \vee l_k \vee m_1 \vee \cdots \vee m_{j-1} \vee m_{j+1} \vee \cdots \vee m_n}$$

where l_i and m_j are complementary literals

Inference rules in Wumpus world

$$R_1: \neg P_{1,1}$$

$$R_2: B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$$

$$R_3: B_{2,1} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{3,1})$$

$$R_4: \neg B_{1,1}$$

$$R_5: B_{2,1}$$

$$R_6: \left(B_{1,1} \Rightarrow (P_{1,2} \vee P_{2,1}) \right) \wedge \left((P_{1,2} \vee P_{2,1}) \Rightarrow B_{1,1} \right)$$

$$R_7: \neg P_{1,2} \wedge \neg P_{2,1} \Rightarrow B_{1,1}$$

$$R_8: \neg B_{1,1} \Rightarrow \neg(P_{1,2} \vee P_{2,1})$$

$$R_9: \neg(P_{1,2} \vee P_{2,1})$$

$$R_{10}: \neg P_{1,2} \wedge \neg P_{2,1}$$

1,4	2,4	3,4	4,4
1,3	2,3	3,3	4,3
1,2 OK	2,2 P?	3,2	4,2
1,1 V OK	2,1 A B OK	3,1 P?	4,1

Inference rules in Wumpus world

$R_1: \neg P_{1,1}$

...

$R_{11}: \neg B_{1,2}$

$R_{12}: B_{1,2} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{1,3})$

$R_{13}: \neg P_{2,2}$

$R_{14}: \neg P_{1,3}$

$R_{15}: P_{1,1} \vee P_{2,2} \vee P_{3,1}$

$R_{16}: P_{1,1} \vee P_{3,1}$

$R_{17}: P_{3,1}$

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

$\neg P_{2,2}$ resolves with $P_{2,2}$

$\neg P_{1,1}$ resolves with $P_{1,1}$

Proof by Resolution

- **Factoring:** the resulting clause should contain only one copy of each literal.
 - E.g., resolving $(A \vee B)$ with $(A \vee \neg B)$ obtains $(A \vee A) \rightarrow$ reduced to A
- For *any pair of sentences, α and β , in propositional logic, a resolution-based theorem prover can decide whether $\alpha \models \beta$.*

Conjunctive Normal Form (CNF)

- Resolution applies only to clauses, i.e., disjunctions of literals
→ Convert all sentences in KB into clauses (CNF form)
- For example, convert $B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$ into CNF
$$(\neg B_{1,1} \vee P_{1,2} \vee P_{2,1}) \wedge (\neg P_{1,2} \vee B_{1,1}) \wedge (\neg P_{2,1} \vee B_{1,1})$$

→ A conjunction of 3 clauses

Conversion to CNF

1. Eliminate \Leftrightarrow : $\alpha \Leftrightarrow \beta \equiv (\alpha \Rightarrow \beta) \wedge (\beta \Rightarrow \alpha)$
2. Eliminate \Rightarrow : $\alpha \Rightarrow \beta \equiv \neg\alpha \vee \beta$
3. The operator \neg appears only in literals: “move \neg inwards”
 - $\neg\neg\alpha \equiv \alpha$ (double-negation elimination)
 - $\neg(\alpha \wedge \beta) \equiv \neg\alpha \vee \neg\beta$ (De Morgan)
 - $\neg(\alpha \vee \beta) \equiv \neg\alpha \wedge \neg\beta$ (De Morgan)
4. Apply the distributivity law to distribute \vee over \wedge
 - $(\alpha \wedge \beta) \vee \gamma \equiv (\alpha \vee \gamma) \wedge (\beta \vee \gamma)$

Quiz 03: Conversion to CNF

- Convert the following sentences into CNF

1. $(A \wedge B) \Rightarrow (C \Rightarrow D)$

2. $P \vee Q \Leftrightarrow R \wedge \neg Q \Rightarrow P$

The resolution algorithm

- **Proof by contradiction** (resolution refutation): To show that $KB \models \alpha$, prove $KB \wedge \neg\alpha$ is **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

$clauses \leftarrow$ the set of clauses in the CNF representation of $KB \wedge \neg\alpha$

$new \leftarrow \{ \}$

loop do

for each pair of clauses C_i, C_j **in** $clauses$ **do**

$resolvents \leftarrow$ PL-RESOLVE(C_i, C_j)

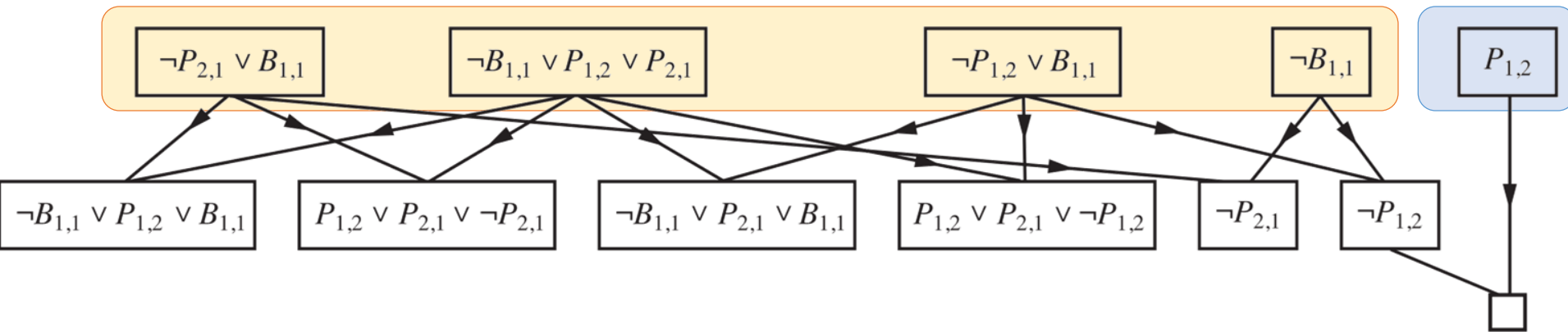
if $resolvents$ contains the empty clause **then return** *true*

$new \leftarrow new \cup resolvents$

if $new \subseteq clauses$ **then return** *false*

$clauses \leftarrow clauses \cup new$

The resolution algorithm



- Many resolution steps are pointless.
- Clauses with two complementary literals can be discarded.
 - E.g., $B_{1,1} \vee \neg B_{1,1} \vee P_{2,1} \equiv \text{True} \vee P_{2,1} \equiv \text{True}$

Quiz 04: The resolution algorithm

- Given the following hypotheses
 - If it rains, Joe brings his umbrella.
 - If Joe brings his umbrella, Joe does not get wet.
 - If it does not rain, Joe does not get wet.
- Prove that Joe does not get wet.

Quiz 04: The resolution algorithm

- The KB contains facts and hypotheses

KB

$$R \Rightarrow U$$

$$U \Rightarrow \neg W$$

$$\neg R \Rightarrow \neg W$$

- Check if the sentence
 $\neg W$ is entailed by KB?

Horn clauses and Definite clauses

- **Definite clause:** a disjunction of literals of which **exactly one is positive**.
 - E.g., $\neg P \vee \neg Q \vee R$ is a definite clause, whereas $\neg P \vee Q \vee R$ is not.
- **Horn clause:** a disjunction of literals of which **at most one is positive**.
 - All definite clauses are Horn clauses
- **Goal clause:** clauses with **no positive literals**
- Horn clauses are closed under resolution
 - Resolving two Horn clauses will get back a Horn clause.

Backus normal form (BNF)

$$CNFSentence \rightarrow Clause_1 \wedge \dots \wedge Clause_n$$
$$Clause \rightarrow Literal_1 \vee \dots \vee Literal_m$$
$$Literal \rightarrow Symbol \mid \neg Symbol$$
$$Symbol \rightarrow P \mid Q \mid R \mid \dots$$
$$HornClauseForm \rightarrow DefiniteClauseForm \mid GoalClauseForm$$
$$DefiniteClauseForm \rightarrow (Symbol_1 \wedge \dots \wedge Symbol_l) \Rightarrow Symbol$$
$$GoalClauseForm \rightarrow (Symbol_1 \wedge \dots \wedge Symbol_l) \Rightarrow False$$

KB of definite clauses

- KB containing only definite clauses are interesting.
- Every definite clause can be written as an implication.
 - Premise (**body**) is a conjunction of positive literals and Conclusion (**head**) is a single positive literal (**fact**) → easier to understand
 - E.g., $\neg P \vee \neg Q \vee R \equiv (P \wedge Q) \Rightarrow R$
- Inference can be done with forward-chaining and backward-chaining algorithms
 - This type of inference is the basis for **logic programming**.
- Deciding entailment can be done in linear time.

KB: Horn clauses vs. CNF clauses

Disjunctions of literals
($l_1 \vee l_2 \vee \dots \vee l_m$)

CNF clauses

Clause 1

\wedge

Clause 2

$\wedge \dots \wedge$

Clause n

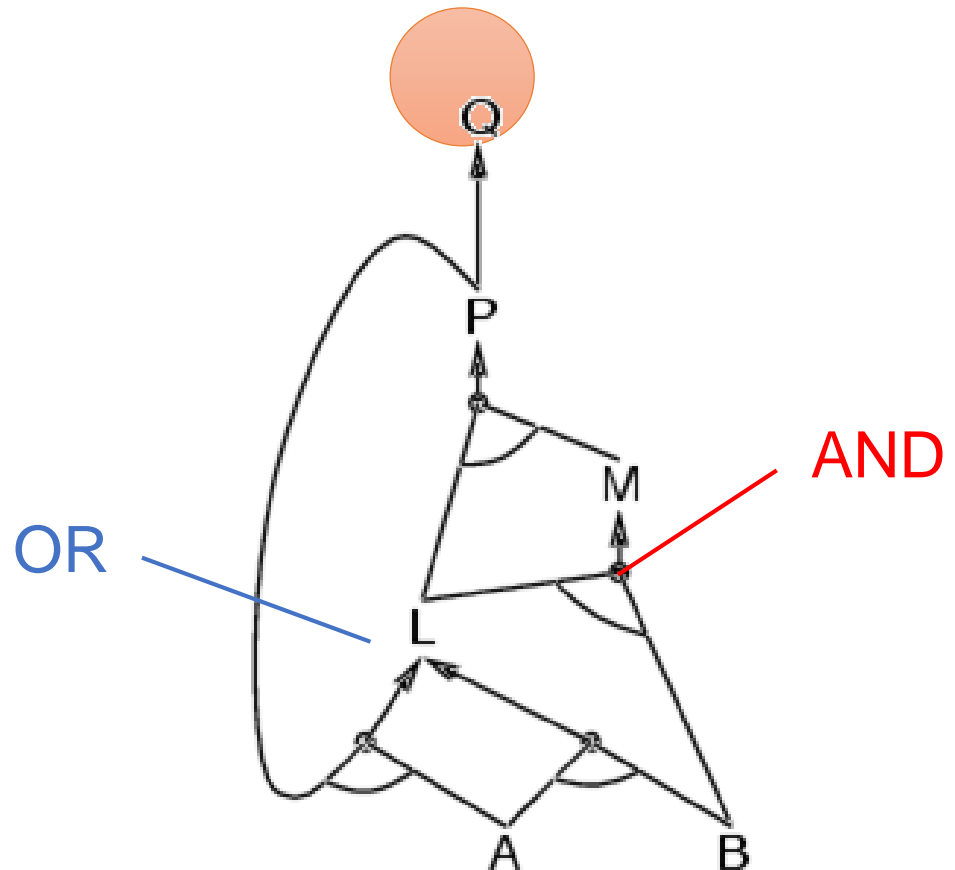
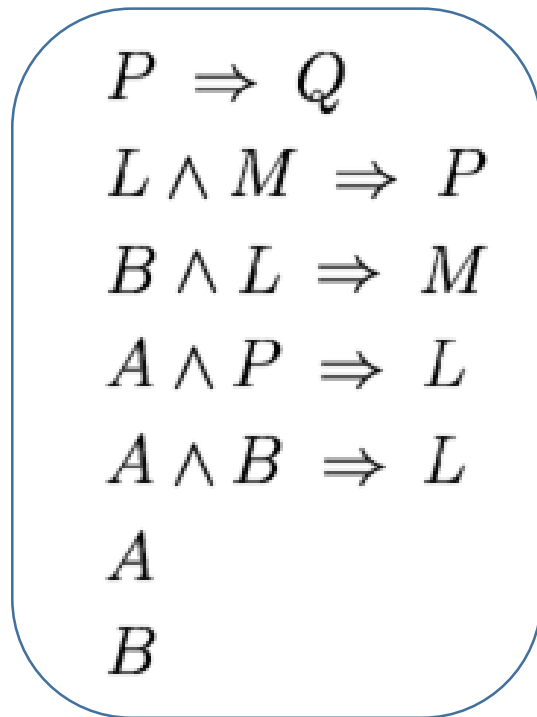
Disjunctions of literals of which **at most one is positive**
($\neg l_1 \vee \neg l_2 \vee \dots \vee l_m$)

Horn clauses

Restricted form

Forward chaining

- **Key idea:** Fire any rule whose premises are satisfied in the KB, add its conclusion to the KB, until the query is found.



The forward chaining algorithm

function PL-FC-ENTAILS?(KB, q) **returns** *true* or *false*

inputs: KB , the knowledge base, a set of propositional definite clauses

q , the query, a proposition symbol

$count \leftarrow$ a table, where $count[c]$ is the number of symbols in c 's premise

$inferred \leftarrow$ a table, where $inferred[s]$ is initially false for all symbols

$agenda \leftarrow$ a queue of symbols, initially symbols known to be *true* in KB

while $agenda$ is not empty **do**

$p \leftarrow \text{POP}(agenda)$

if $p = q$ **then return** *true*

if $inferred[p] = \text{false}$ **then**

$inferred[p] \leftarrow \text{true}$

for each clause c in KB where p is in $c.PREMISE$ **do**

decrement $count[c]$

if $count[c] = 0$ **then** add $c.CONCLUSION$ to $agenda$

return *false*

Sound and complete

Forward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

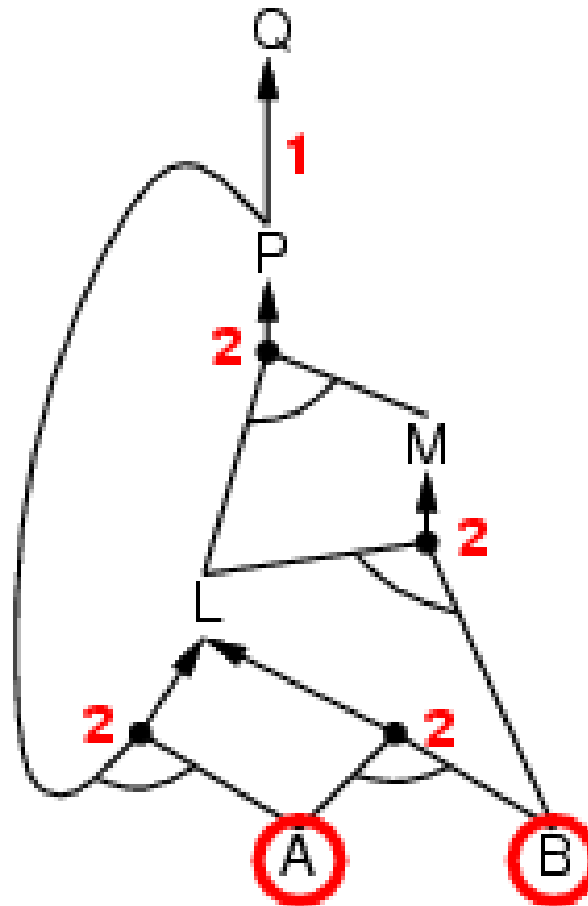
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Forward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

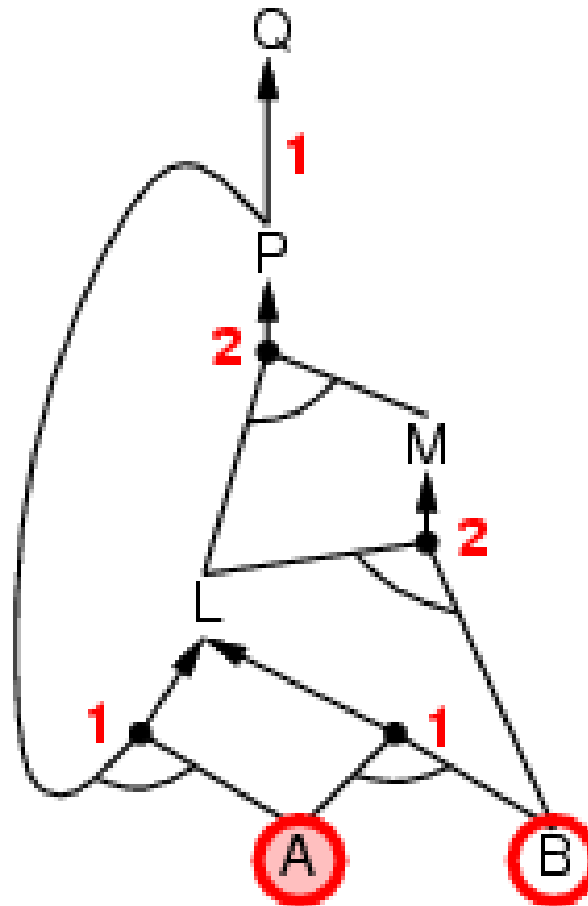
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Forward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

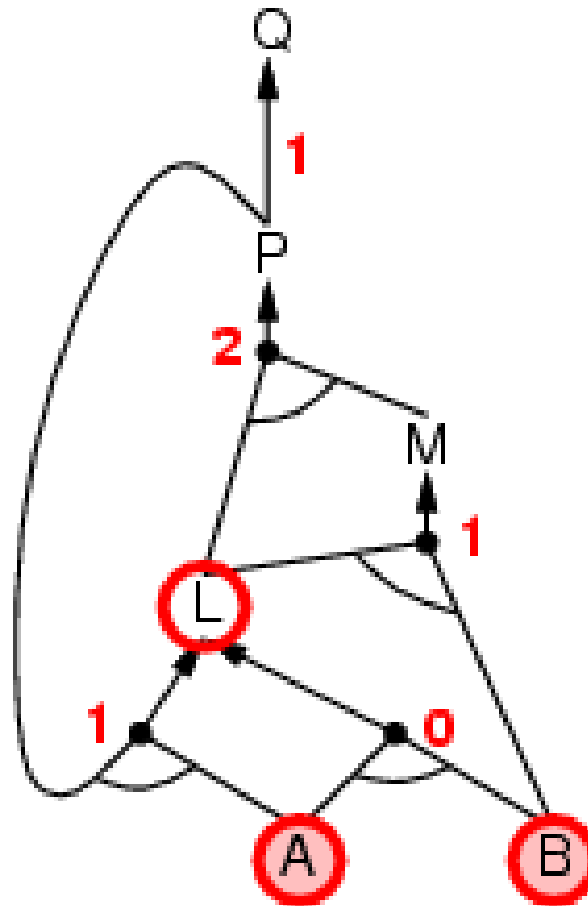
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Forward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

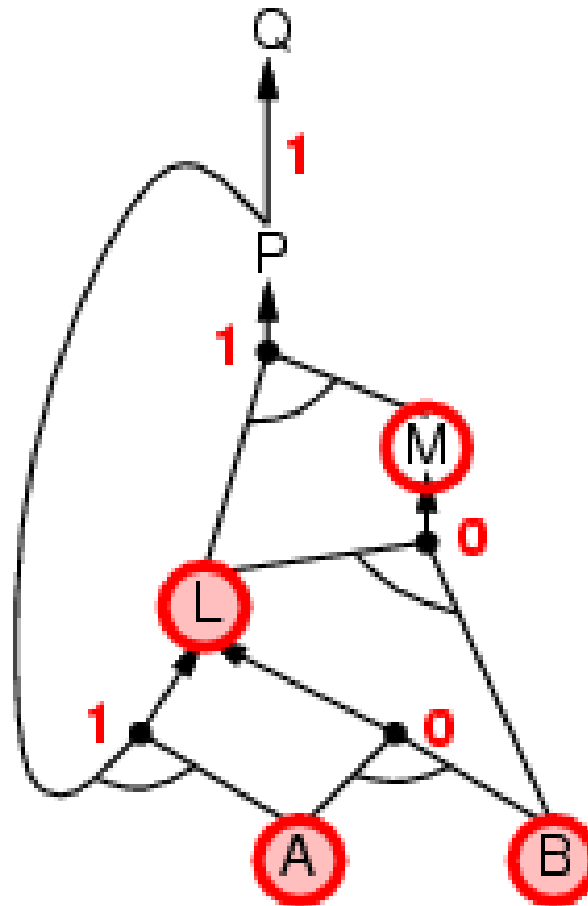
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Forward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

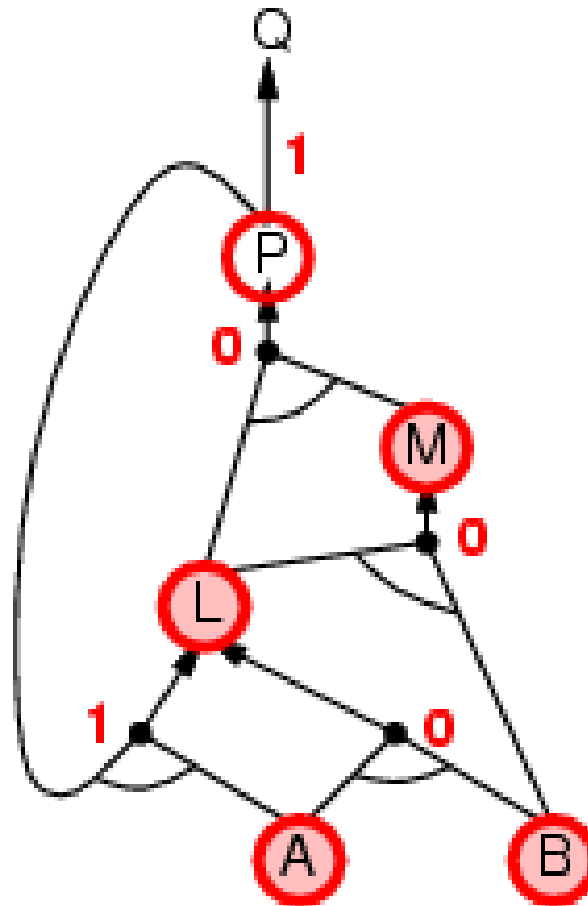
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Forward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

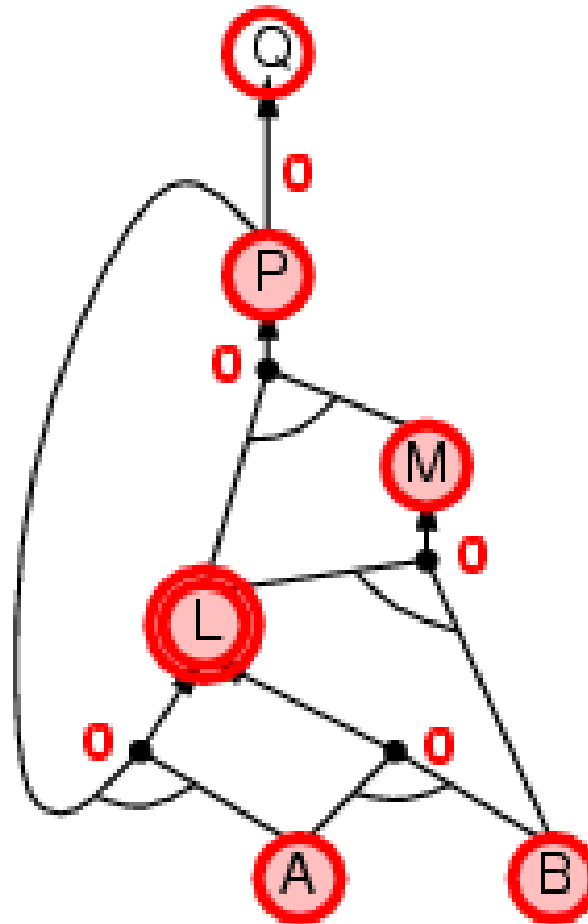
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Forward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

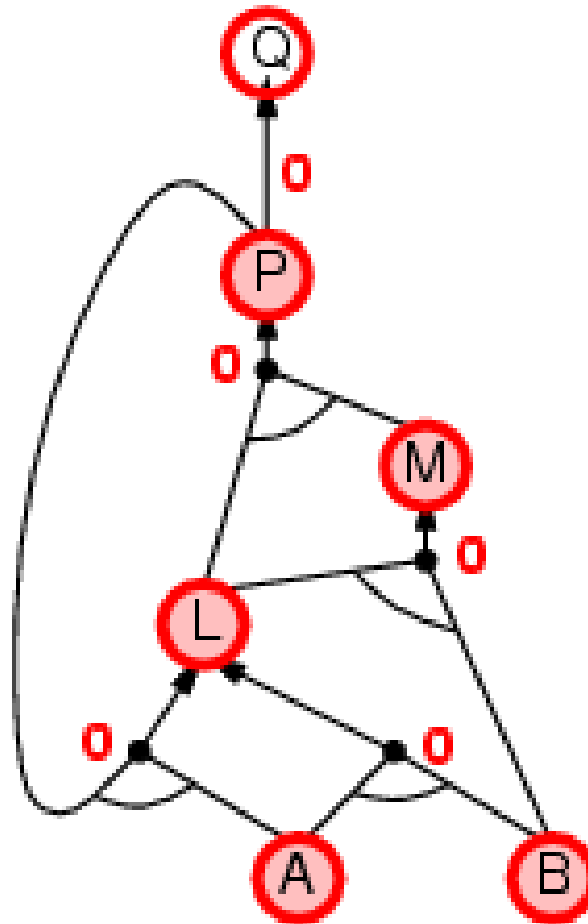
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Forward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

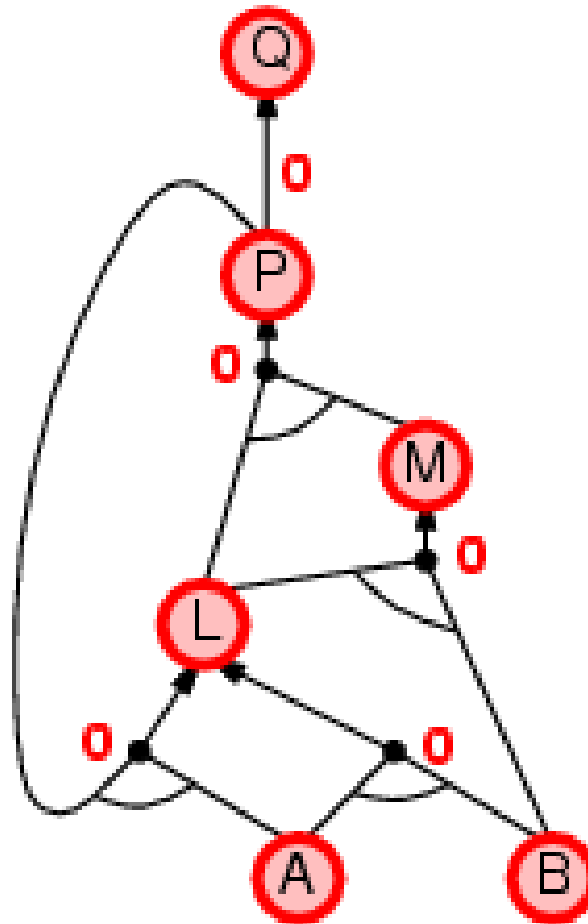
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Forward chaining: Another example

KB	No.	Sentences	Explanation
$A \wedge B \Rightarrow C$	1	$A \wedge B \Rightarrow C$	From KB
$C \wedge D \Rightarrow E$	2	$C \wedge D \Rightarrow E$	From KB
$C \wedge F \Rightarrow G$	3	$C \wedge F \Rightarrow G$	From KB
A	4	A	From KB
B	5	B	From KB
D	6	D	From KB
$E?$	7	C	1, 4 and 5
	8	E	2, 6, and 7

Backward chaining

- **Key idea:** Work backwards from the query q
 - Check if q is known already, or
 - Recursively prove by BC all premises of some rule concluding q
- **Avoid loops:** A new subgoal is already on the goal stack?
- **Avoid repeated work:** A new subgoal has already been proved true, or has already failed?

Backward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

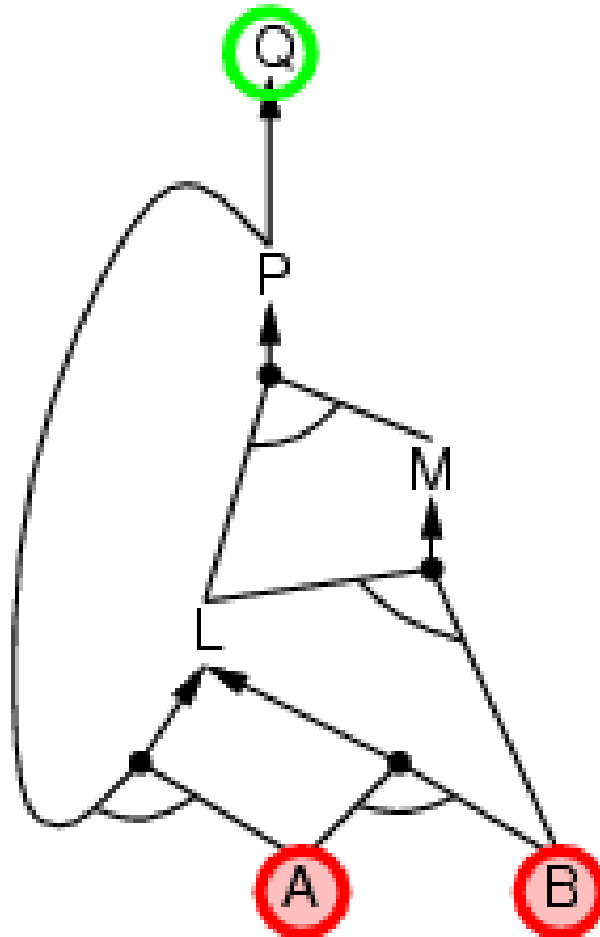
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Backward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

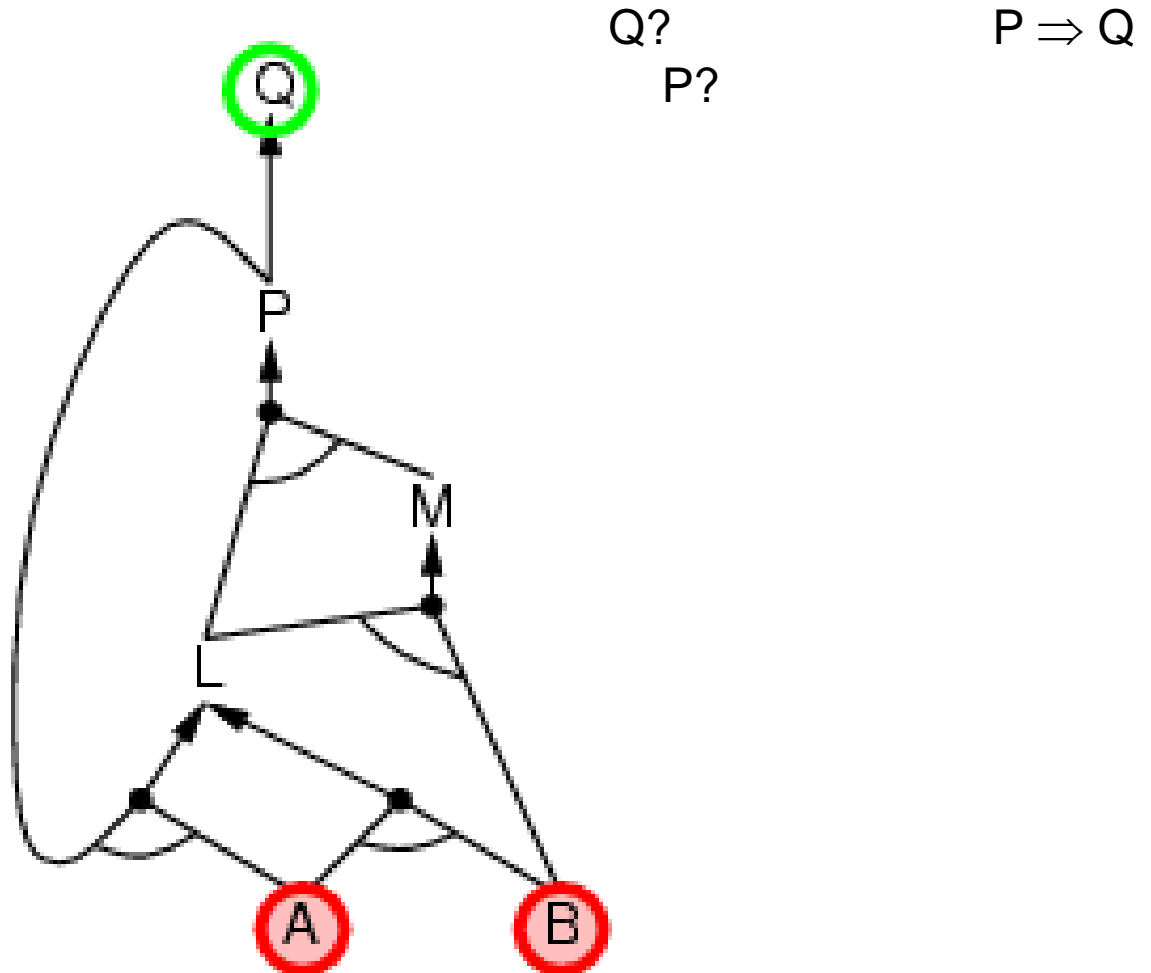
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Backward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

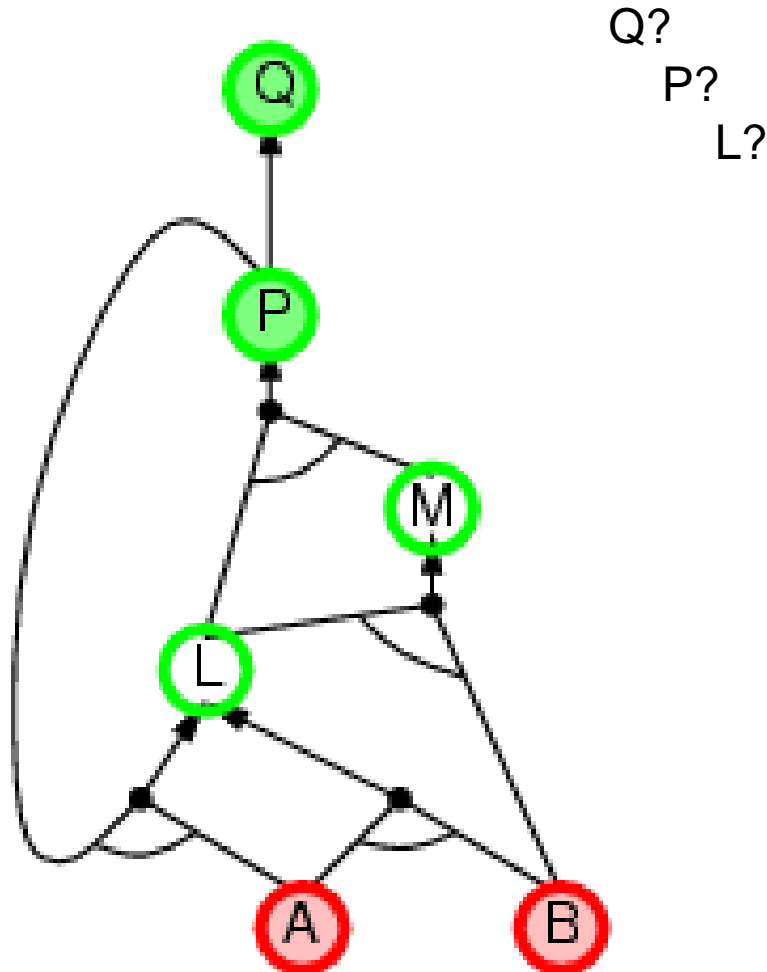
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



$$P \Rightarrow Q$$
$$L \wedge M \Rightarrow P$$

Backward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

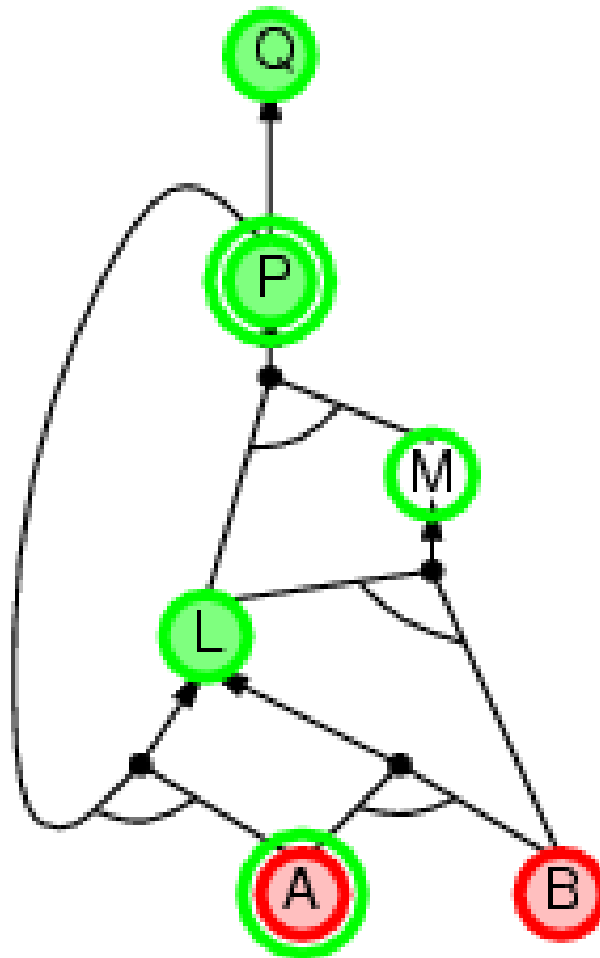
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Q?

P?

L?

A?

$P \Rightarrow Q$

$L \wedge M \Rightarrow P$

$A \wedge B \Rightarrow L$

✓

Backward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

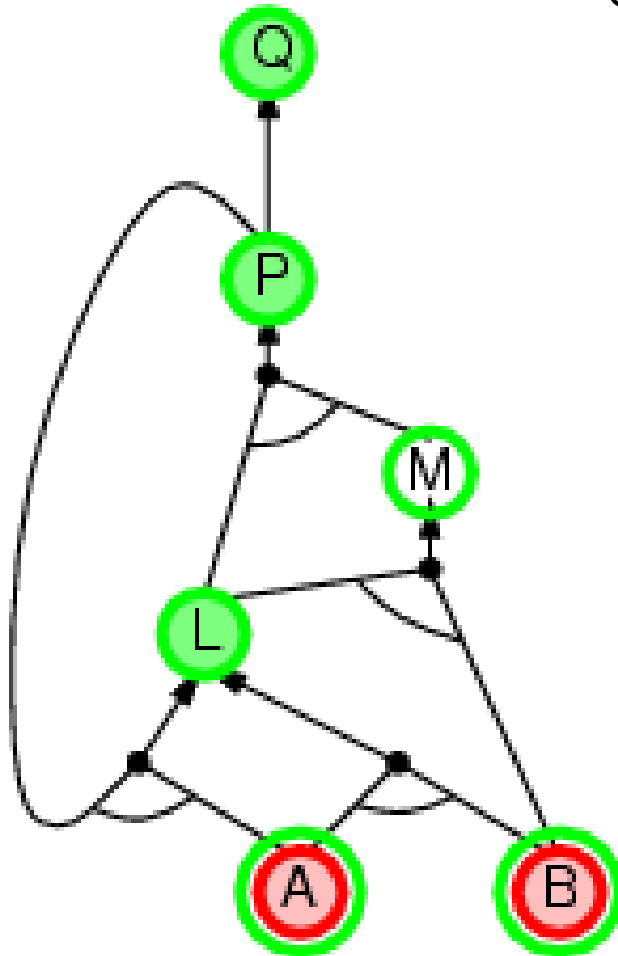
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Q?

P?

L?

A?

B?

$P \Rightarrow Q$

$L \wedge M \Rightarrow P$

$A \wedge B \Rightarrow L$

✓

✓

Backward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

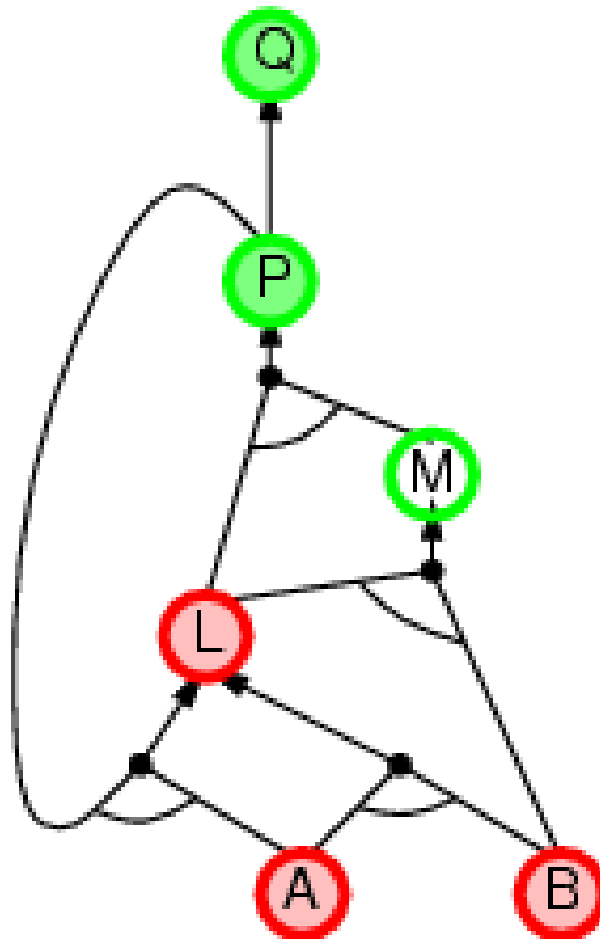
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Q?

P?

L? ✓

A?

B?

$P \Rightarrow Q$

$L \wedge M \Rightarrow P$

✓

✓

Backward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

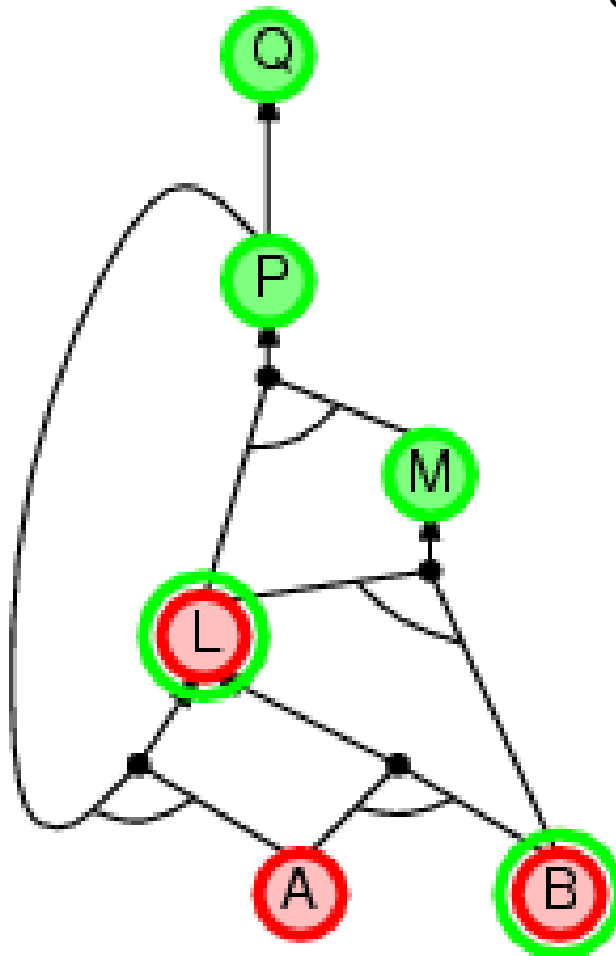
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Q?

P?

L? ✓

A?

B?

M?

L?

B?

$P \Rightarrow Q$

$L \wedge M \Rightarrow P$

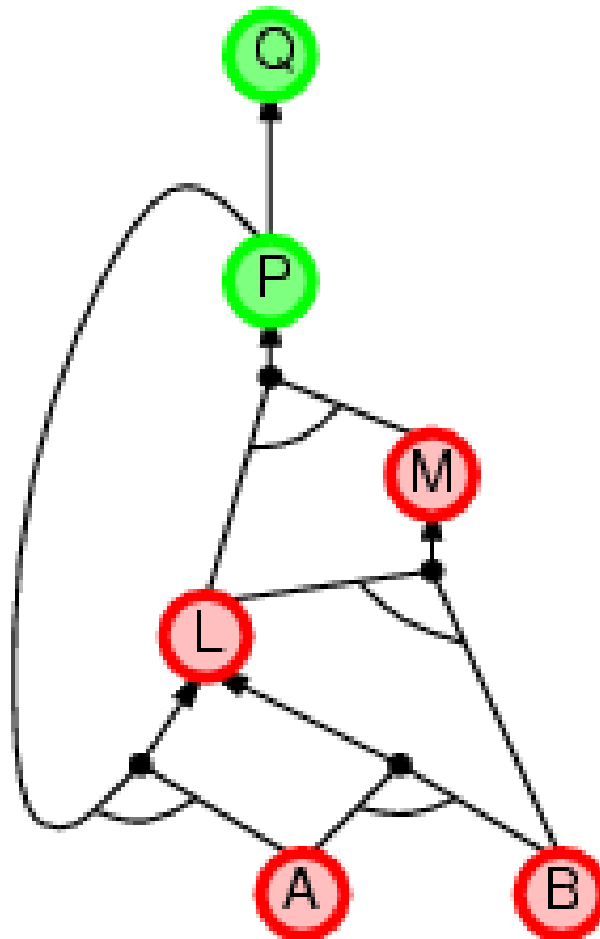
✓

✓

$L \wedge B \Rightarrow M$

Backward chaining: An example

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



Q?
 P?
 L? ✓
 A?
 B?
 M? ✓
 L?
 B?

$P \Rightarrow Q$
 $L \wedge M \Rightarrow P$
 ✓
 ✓
 ✓
 ✓

Backward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

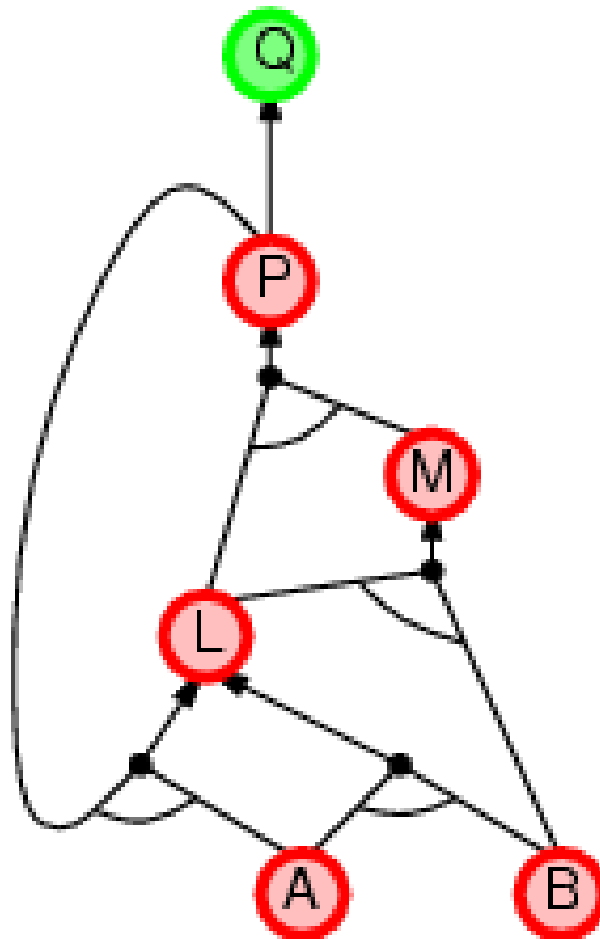
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Q?

✓

P?

✓

L? ✓

A?

✓

B?

✓

M? ✓

L?

✓

B?

✓

Backward chaining: An example

$$P \Rightarrow Q$$

$$L \wedge M \Rightarrow P$$

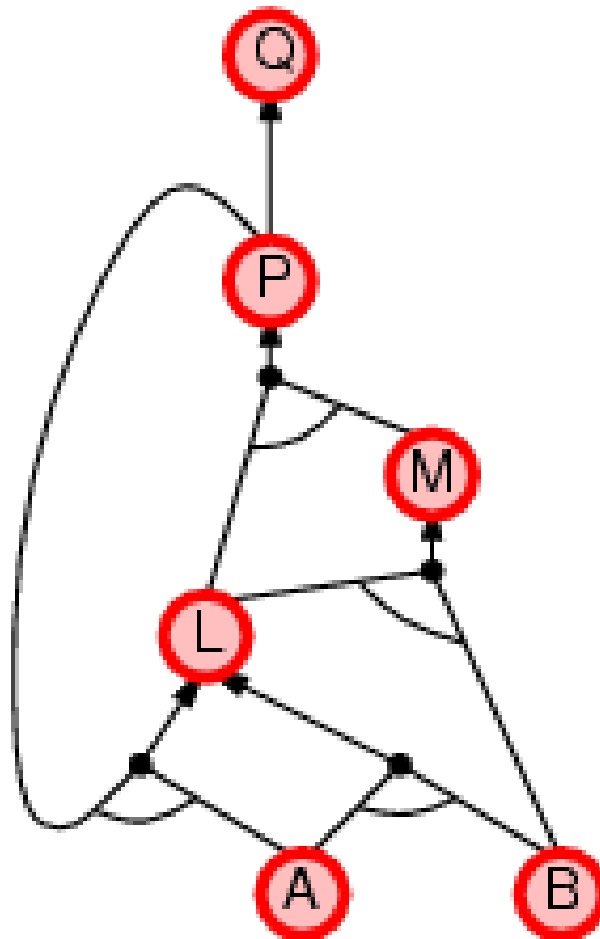
$$B \wedge L \Rightarrow M$$

$$A \wedge P \Rightarrow L$$

$$A \wedge B \Rightarrow L$$

A

B



Q?

✓

P?

✓

L? ✓

A?

✓

B?

✓

M? ✓

L?

✓

B?

✓

Backward chaining: Another example

KB

$A \wedge B \Rightarrow C$

$C \wedge D \Rightarrow E$

$C \wedge F \Rightarrow G$

A

B

D

$E?$

- $E?$

$C \wedge D \Rightarrow E$

- $C?$

$A \wedge B \Rightarrow C$

- $A?$

- $B?$

- $D?$

- A, B and D are given \rightarrow All needed rules are satisfied \rightarrow The goal is proven.

Forward vs. Backward chaining

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

Quiz 05: Forward vs. Backward chaining

- Given a KB containing the following rules and facts
 - R_1 : IF hot AND smoky THEN fire
 - R_2 : IF alarm_beeps THEN smoky
 - R_3 : IF fire THEN sprinklers_on
 - F_1 : alarm_beeps
 - F_2 : hot
- Represent the KB in propositional logic with given symbols
 - H = hot, S = smoky, F = fire, A = alarms_beeps, R = sprinklers_on
- Answer the question “Sprinklers_on?” by using the forward chaining and backward chaining approaches

Quiz 06: DPLL and DP

- Given a KB as shown aside

KB

$$A \Rightarrow B \vee C$$

$$A \Rightarrow D$$

$$C \wedge D \Rightarrow \neg F$$

$$B \Rightarrow F$$

$$A$$

- Using either DPLL or DP to check whether KB entails each of the following sentences
 - C
 - $B \Rightarrow \neg C$



THE END