CSCI 3230

Fundamentals of Artificial Intelligence

Chapter 7

Logical Agents

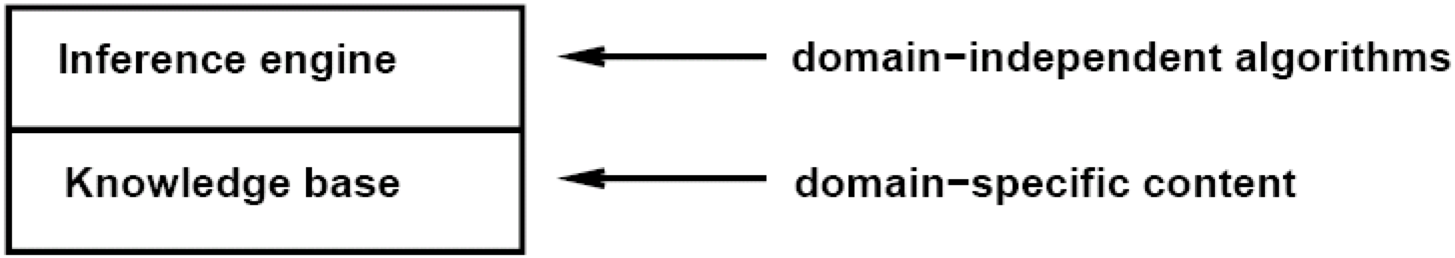
Use of logic and expert systems, power to reason; Inferential knowledge

Fall 2019

Outline

- Knowledge-based agents
- Wumpus World
- Logic in general - models and entailment
- Propositional (Boolean) logic
- Equivalence, validity, satisfiability
- Inference rules and theorem proving
  - Forward chaining
  - Backward chaining
  - Resolution

Knowledge bases



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 infer what to do – answers should follow from the KB

Can describe a knowledge-based agent at 3 levels:

- The knowledge level or epistemological level is the most abstract; can describe the agent by saying what it knows.
- The logical level – at which the knowledge is encoded into sentences.
- The implementation level runs on the agent architecture.

A simple knowledge-based agent

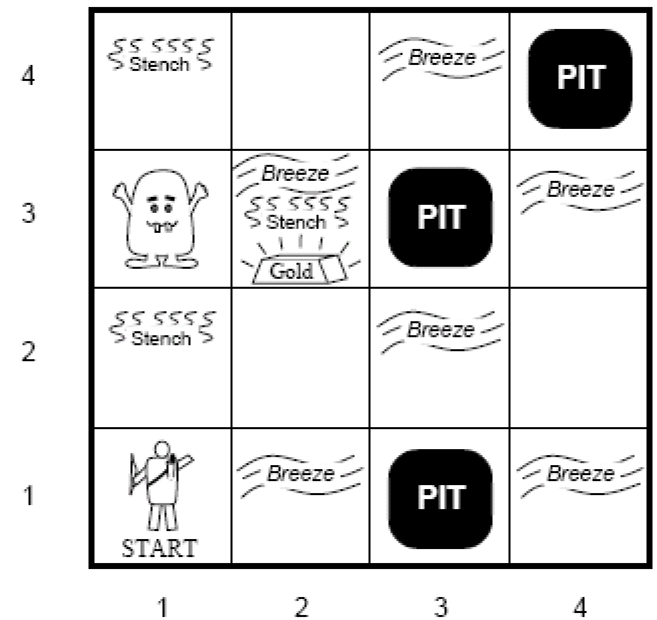
```
function KB-Agent (percept) returns an action
    static: KB, a knowledge base
            t, a counter, initially 0, indicating time
    Tell (KB, Make-Percept-Sentence (percept, t))
    action ← Ask (KB, Make-Action-Query (t))
    Tell (KB, Make-Action-Sentence (action , t))
    t ← t + 1
    return action
```

The agent must be able to:

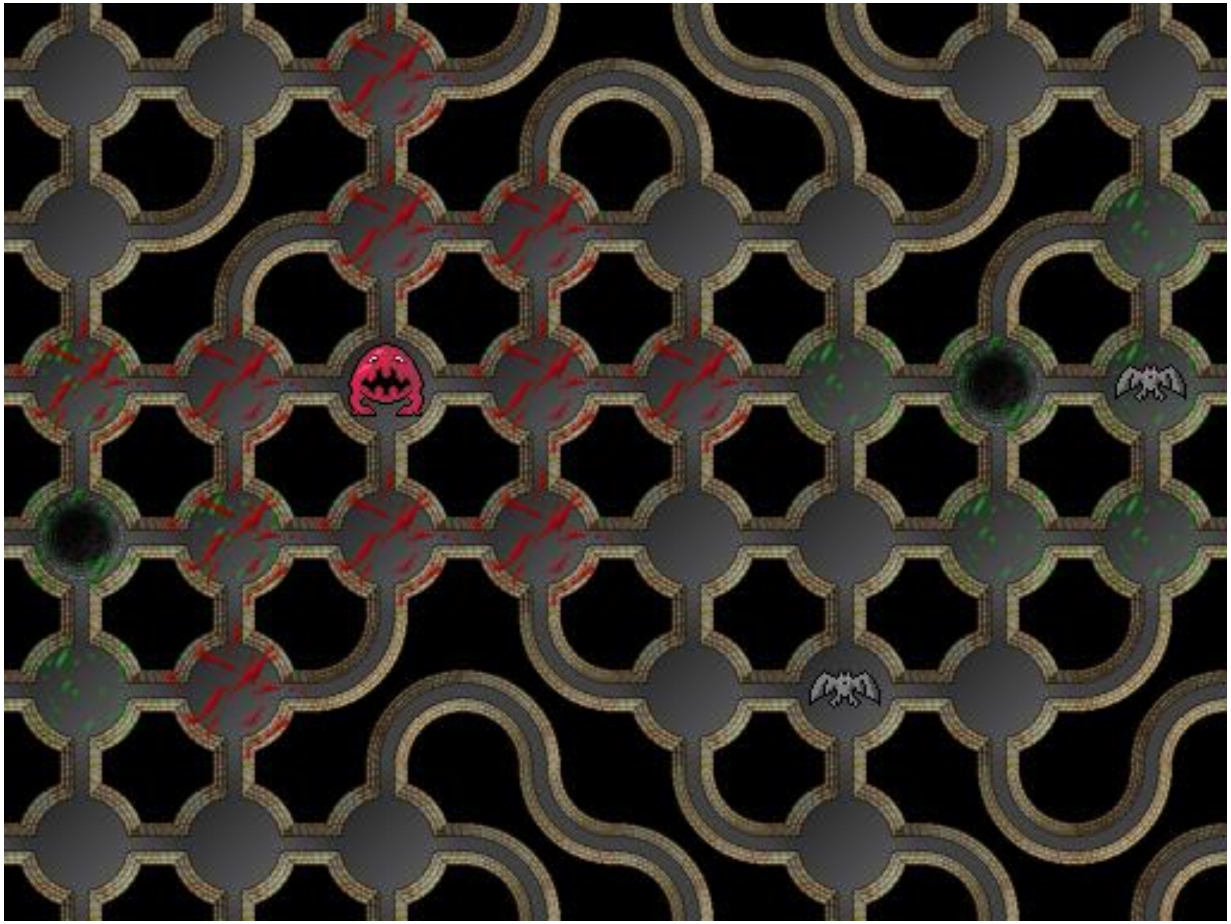
- Represent states, actions, etc.
- Incorporate new percepts
- Update internal representations of the world.
- Deduce hidden properties of the world e.g. diagnose
- Deduce appropriate actions e.g. deduce cure method

Wumpus World PEAS description

- Performance measure (Goal: to pick up the gold & return to start)
  - Gold + 1000, death – 1000
  - −1 per step, −10 for using the arrow
- Environment:
  - Square adjacent to wumpus are smelly
  - Square 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
- Sensors: Breeze, Glitter, Smell
- Actuators:
  - Left turn, Right turn, Forward, Grab, Release, shoot



Demo

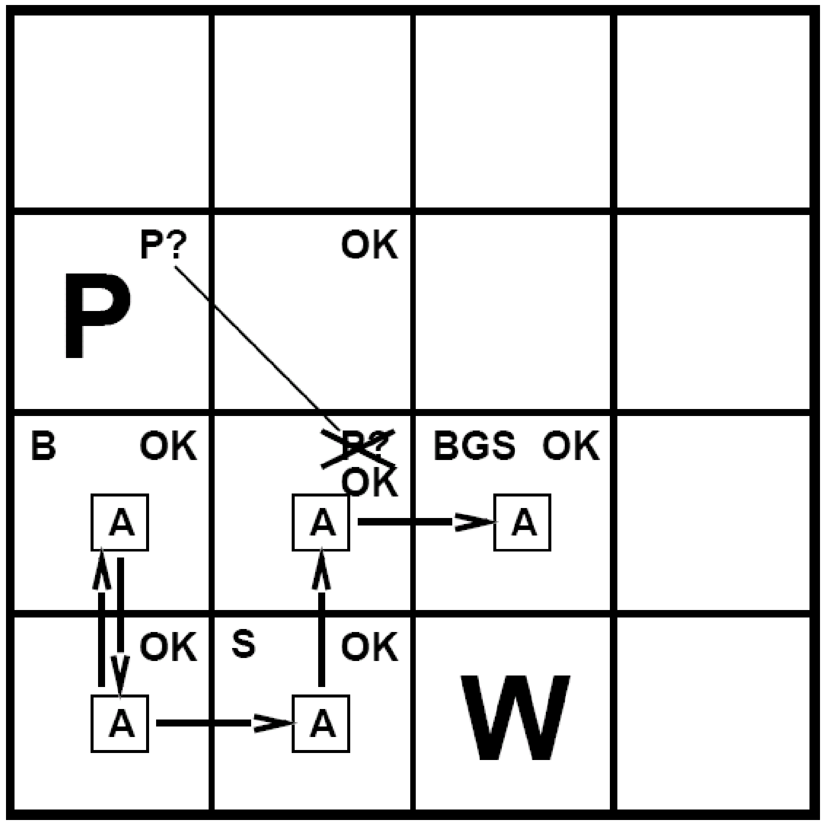


Our goal is to use logic to represent and play it automatically

Wumpus world characterization

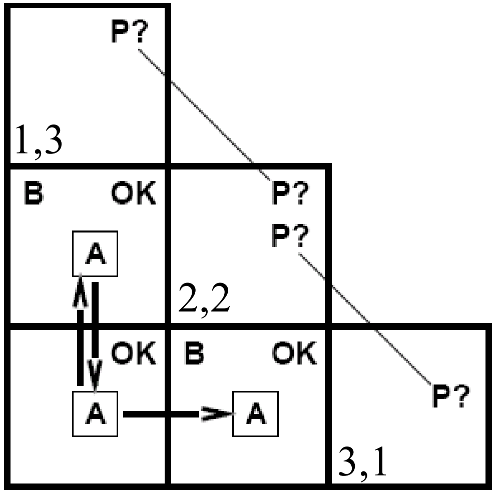
Observable	No, only local perception
Deterministic	Yes, outcomes exactly specified
Episodic	No, sequential at the level of actions
Static	Yes, wumpus and pits do not move
Discrete	Yes
Single-agent	Yes, wumpus is essentially a natural feature

Exploring a wumpus world

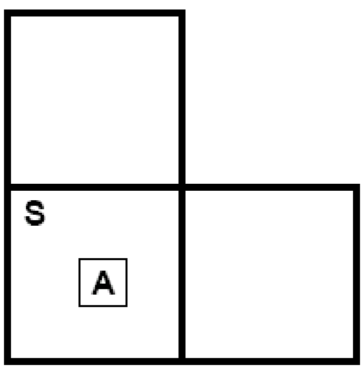


Agent:- Sensor percept -> outside world status -> action

Other tight spots



- Breeze in (1,2) and (2,1)
  ⇒ no safe actions
  - B => (P,0) (0,P) (P,P) 3 possiblilities
- Assuming pits uniformly distributed, (2,2) has pit w/ prob
  0.89 = 1– (1/3)*(1/3) vs.
  2/3=(0.67)=(1/3)+(1/3) for (1,3) and (3,1)



Smell in (1,1) ⇒ cannot move
Can use a strategy of coercion:
  shoot straight ahead
  wumpus was there ⇒ dead ⇒safe
  wumpus wasn't there ⇒ safe

no pit in (2,2)= 1/3*1/3

Logic in general

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

knowledge

inference

Syntax語法 defines the sentences in the language. grammar

Semantics語義 define the “meaning” of sentences.

i.e. define truth of sentences in a world.

E.g. the language of *arithmetic*

- $x + 2 \geq y$ is sentence; $x2 + y >$ is not a sentence syntax error
- $x + 2 \geq y$ is true iff the number $x + 2$ is not 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 (iff) α is true in all worlds where KB is true
- E.g. the KB containing "HKU won" and "CUHK won" entails "Either HKU won or CUHK 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 & semantics (of some sort) function based on grammar. Fuzzy logic?

Models

Logicians typically think in terms of models: Formal structured worlds in which truth can be evaluated.

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

Model: a world state represented

by a logic sentence (with truth values)

– a Truth Table row

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

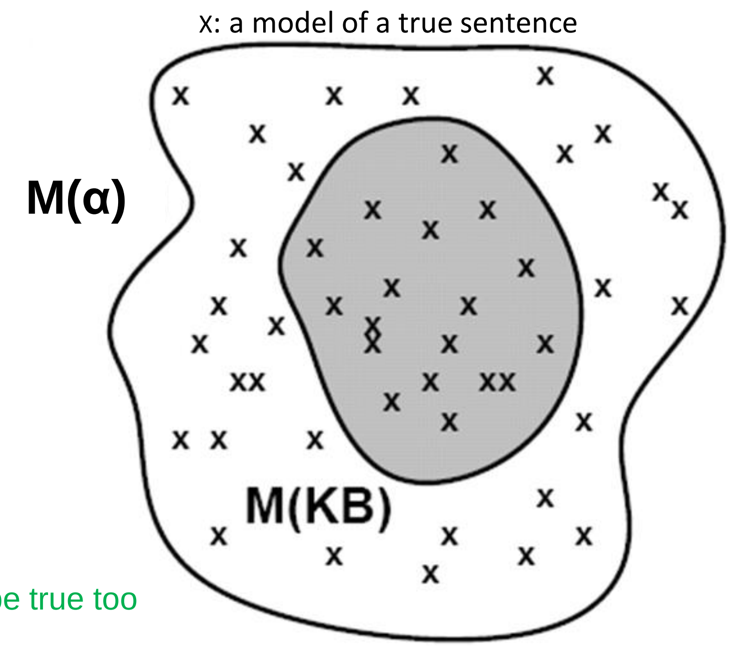
Then $KB \models \alpha$ iff $M(KB) \subseteq M(\alpha)$

E.g. World: CUHK, HKU won or not?

4 possible models (TT, TF, FT, FF)

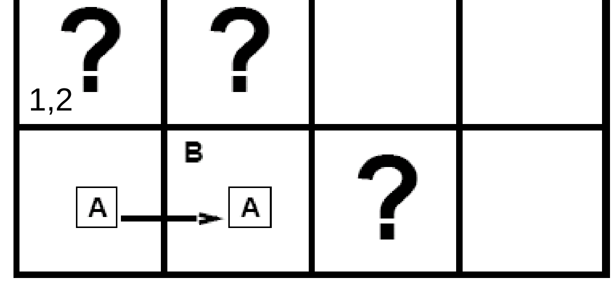
KB = CUHK won and HKU won (TT)

α = CUHK won $M(\alpha)$=(TT, TF)



$M(KB) \subseteq M(\alpha)$ => whenever KB is T, α must be true too

Models Examples



3 Models of KB

$B_{1,1}$	$B_{2,1}$	$P_{1,1}$	$P_{1,2}$	$P_{2,1}$	$P_{2,2}$	$P_{3,1}$	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	true	true
false	true	false	false	false	true	false	true	true
false	true	false	false	false	true	true	true	true
false	true	false	false	true	false	false	false	true
...	...	...	...	...	...	...	...	...
true	true	true	true	true	true	true	false	false

$\alpha_1 = \neg P_{1,2}$?

KB is true when all the 5 sentences in KB is true

KB $\models \alpha_1$?

$\neg P_{1,1}$; $\neg B_{1,1}$; $B_{2,1}$;
$B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$;
$B_{2,1} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{3,1})$

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

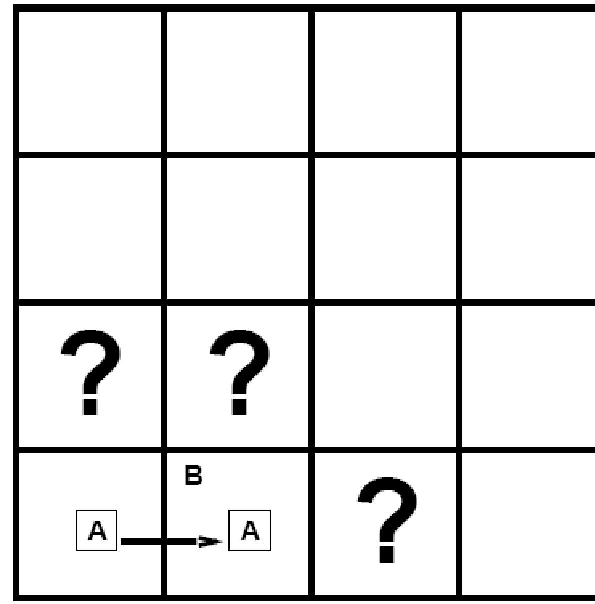
Inference by Truth Table Enumeration

Entailment in the wumpus world

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

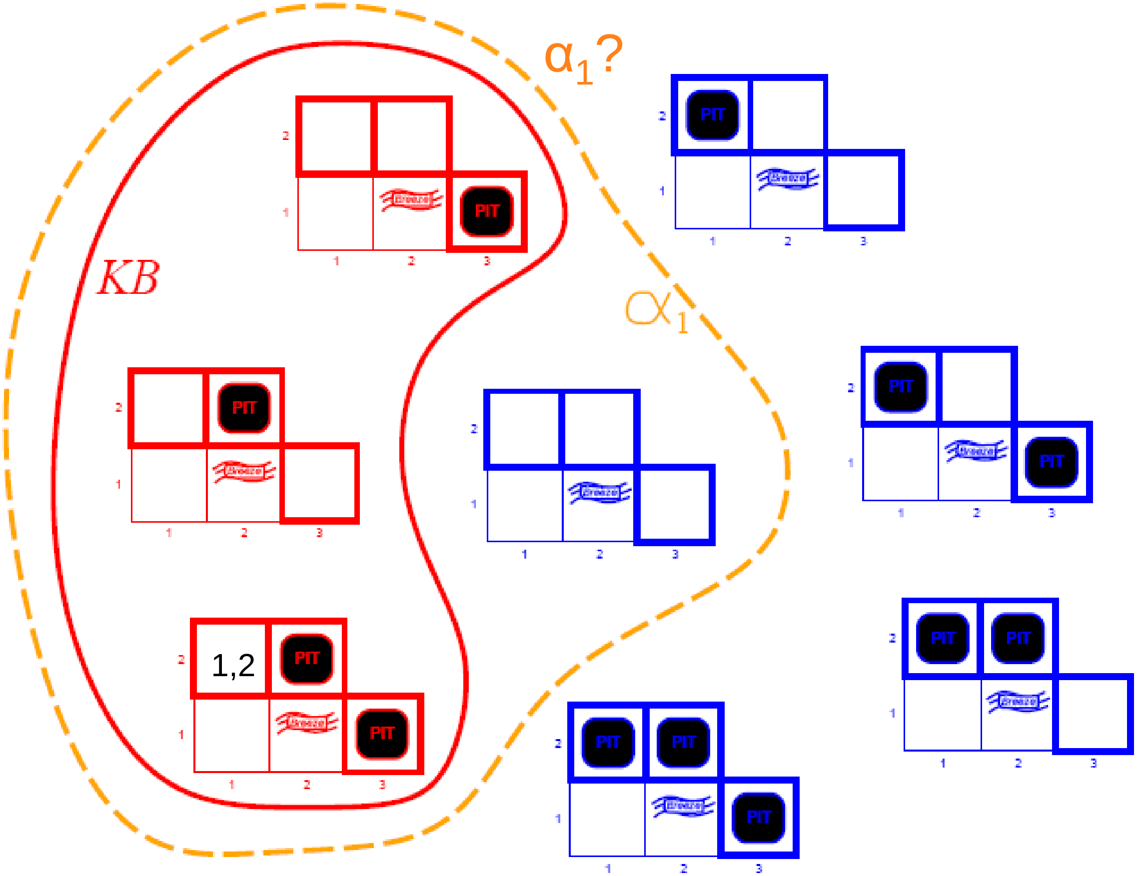
Consider possible models for ?s (3 Sqs) assuming only pits

3 Boolean choices $\Rightarrow$ 8 possible models



Wumpus models

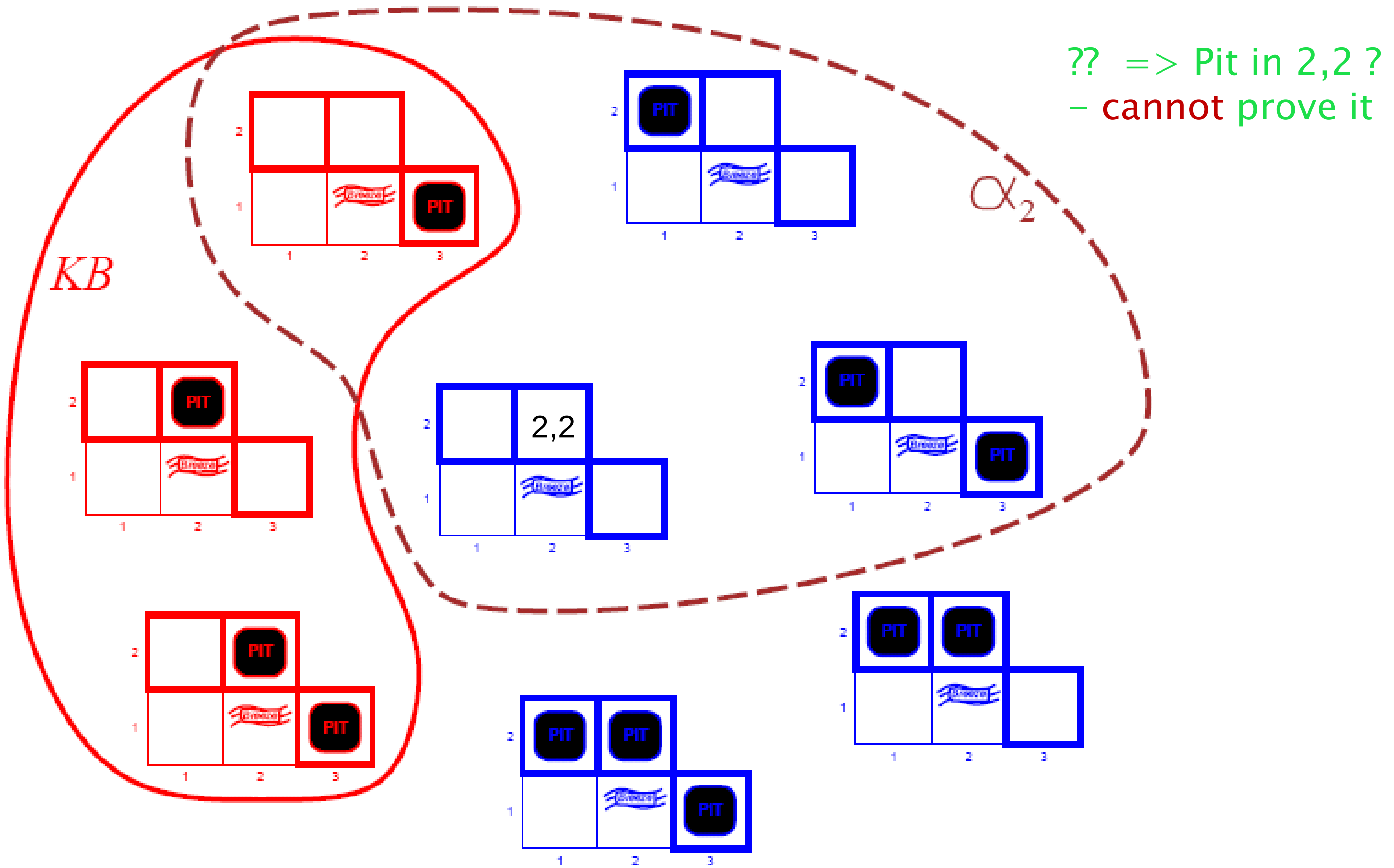
8 possible models



KB = wumpus-world rules + observations

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

Wumpus models



KB = wumpus-world rules + observations

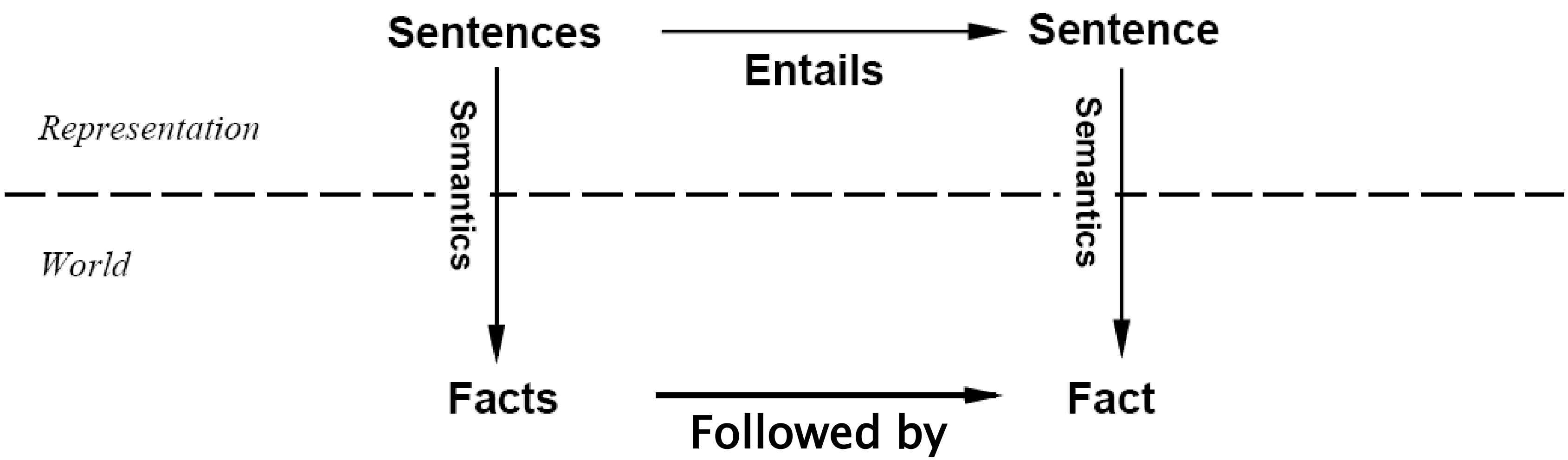
α_2 = "[2,2] is safe", KB $\not\models$ α_2 ??

Logic

- The syntax of a language describes the possible configurations of legal sentences.
- The semantics determines the facts in the world to which the sentences refer.

A logic language defines the syntax and semantics precisely. From the syntax and semantics, we can derive an inference mechanism for an agent to use the language.

Logic



- The combination between sentences and facts is provided by the semantics of the language.

mapping

- The property of one fact following from some other facts is mirrored by the property of one sentence being entailed by some other sentences.
- Logical inference generates new sentences that are entailed by existing sentences. ⇔ reasoning in real world

Inference

$KB \vdash_i \alpha$ ⇨ sentence α can be derived (inferred) 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 $KB \models \alpha$

Completeness: i is complete if
whenever $KB \models \alpha$, it is also true that $KB \vdash_i \alpha$

Preview: first-order logic is expressive enough to say almost anything of interest with a sound and complete inference procedure.

That is, the procedure will answer any question whose answer entailed by the KB.

Propositional logic: Syntax

- Propositional logic is the simplest logic – illustrates basic ideas
- The proposition symbol P_1, P_2 etc… are sentences
- If S is a sentences, $\neg S$ is a sentence (negation)
- If S_1 and S_2 are sentences, $S_1 \wedge S_2$ is a sentence (conjunction)
- If S_1 and S_2 are sentences, $S_1 \vee S_2$ 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)
- More complicated sentences can be made using above rules recursively

Many rule-based Expert systems!

Propositional logic: Semantics

Each model specifies true/ false for each proposition symbol

	Pit in 1,2		
E.g.	$P_{1,2}$	$P_{2,2}$	$P_{3,1}$
	true	true	false

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

Rules for evaluating truth with respect to a model m:

$\neg S$	is true iff	S	is false		
$S_1 \land S_2$	is true iff	S_1	is true and	S_2	is true
$S_1 \lor S_2$	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

Simple recursive process evaluates an arbitrary sentence, e.g.

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

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

rule base systems

$F \Rightarrow F$??

SARS $\Rightarrow$ Die

No SARS $\Rightarrow$ Won't die X

Wumpus world sentences

KB:

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]

$\neg P_{1,1}$

$\neg B_{1,1}$

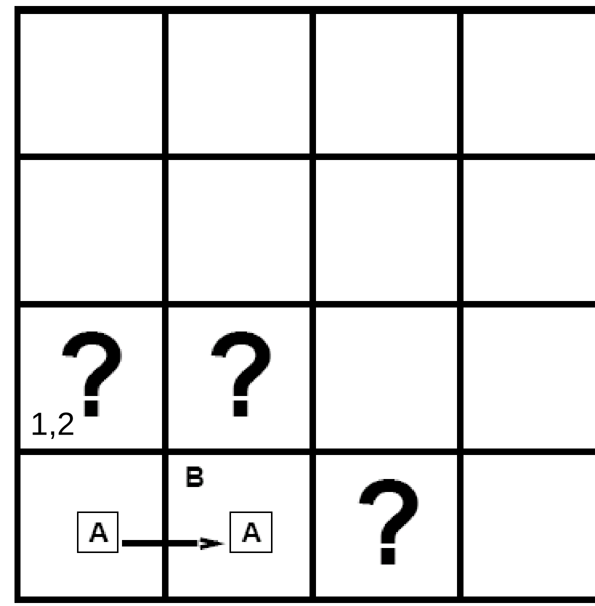
$B_{2,1}$

"Pits cause breeze in adjacent squares"

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

$B_{2,1} \Leftrightarrow (P_{1,1} \lor P_{2,2} \lor P_{3,1})$

"A square is breezy iff there is an adjacent pit"



Question: $\alpha_1 = \neg P_{1,2}$; $KB \vDash \alpha_1$?

Truth tables for inference (Inference by model enumeration)

	$B_{1,1}$	$B_{2,1}$	$P_{1,1}$	$P_{1,2}$	$P_{2,1}$	$P_{2,2}$	$P_{3,1}$	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
3 Models of KB	false	true	false	false	false	false	true	true	true
	false	true	false	false	false	true	false	true	true
	false	true	false	false	false	true	true	true	true
	false	true	false	false	true	false	false	false	true
	…	…	…	…	…	…	…	…	…
	true	true	true	true	true	true	true	false	false

$\alpha_1 = \neg P_{1,2}$

KB is true when all the 5 sentences in KB is true

$\neg P_{1,1}$; $\neg B_{1,1}$; $B_{2,1}$;
$B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$;
$B_{2,1} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{3,1})$

KB $\vDash \alpha_1$ why?

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

Goto p.32

How to program it??

Inference by enumeration

Build the complete truth table by recursive calls forming a depth-first tree(?)

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

function TT-Entails? (*KB*, α) **returns** *true* **or** *false*
  symbols ← a list of 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** // row completed in TT
    if PL-True?(*KB*, *model*) **then return** PL-True?(α, *model*) // T⇒T/F ⇔ T/F
    else return *true* // F⇒T/F ⇔ T
  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

Extend(*P*, ***true***, *model*) returns a new partial model in which P has the value ***true***

Extend(*P*, ***false***, *model*) returns a new partial model in which P has the value ***false***

S

T F *Symbols*−1 (*P*)

T F T F *Symbols*−2 (*P*)

T F T F T F T F *Symbols*−3 (*P*)

- TTT FTT
- TTF FTF
- TFT FFT
- TFF FFF

function TT-Check-All(*KB*, *α*, *symbols*, *model*) **returns** *true* ***or*** *false*
  if Empty?(*symbols)* **then** // row completed in TT
    if PL-True?(*KB*, *model)* **then return** PL-True?(*α*, *model*) // T⇒T/F ⇔ T/F
    else return *true* // F⇒T/F ⇔ T
  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*)

Logical Equivalence

Two sentences are logically equivalent iff true in same models:

$\alpha \equiv \beta$ if and only if $\alpha \vDash \beta$ and $\beta \vDash \alpha$

$(\alpha \wedge \beta) \equiv (\beta \wedge \alpha)$ 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 $\wedge$

Back to p.40

Validity and satisfiability

A sentence is valid if it is true in **all** models,

e.g. True, $A \lor \neg A$, $A \Rightarrow A$, $(A \land (A \Rightarrow B)) \Rightarrow B$

Validity is connected to inference via the Deduction Theorem:

$KB \models \alpha$ if and only if $(KB \Rightarrow \alpha)$ is valid

A sentence is satisfiable if it is true in some models

e.g. $A \lor B$, C

A sentence is unsatisfiable if it is true in no models Back to p.41

e.g. $A \land \neg A$

Satisfiability is connected to inference via the following:

$KB \models \alpha$ iff $(KB \land \neg \alpha)$ is unsatisfiable; $(\neg(\neg KB \lor \alpha) \equiv KB \land \neg \alpha)$

$(\neg(KB \Rightarrow \alpha))$

i.e. prove α by *reductio ad absurdum* (reduction to an absurd thing)

- prove by refutation or by contradiction

Proof methods

Proof methods divide into (roughly) two kinds:

- Application of inference rules (FC, BC, resolution)
  - 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 algorithm
  - Typically require translation of sentences into a normal form
- Model checking
  - Truth table enumeration (always exponential in n)
  - Improved backtracking, e.g. Davis–Putnam–Logemann–Loveland
  - 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) ⇒ symbol

E.g. $C \wedge (B \Rightarrow A) \wedge (C \wedge D \Rightarrow B)$

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

$$\frac{\alpha_1, \ldots, \alpha_n, \quad \alpha_1 \wedge \ldots \wedge \alpha_n \Rightarrow \beta}{\beta}$$

inference rule

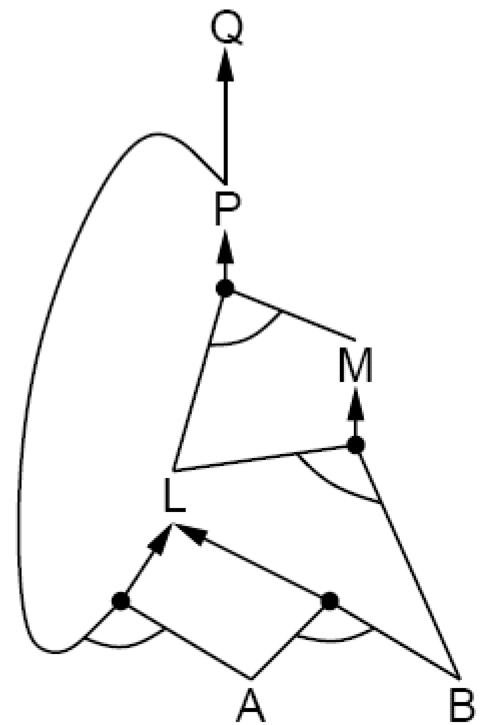
Can be used with forward chaining or backward chaining.
Their algorithms are very natural and run in linear time

Forward chaining

Idea: fire any rule whose premises are satisfied in the KB. Add its conclusion to the KB, until query *Q* is found.

Rules, implications
Facts
Antecedent-consequence
-conclusion
-*Head* in the program
Premises: elements of Ante.

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



Where to check *Q* first??

Forward chaining algorithm

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

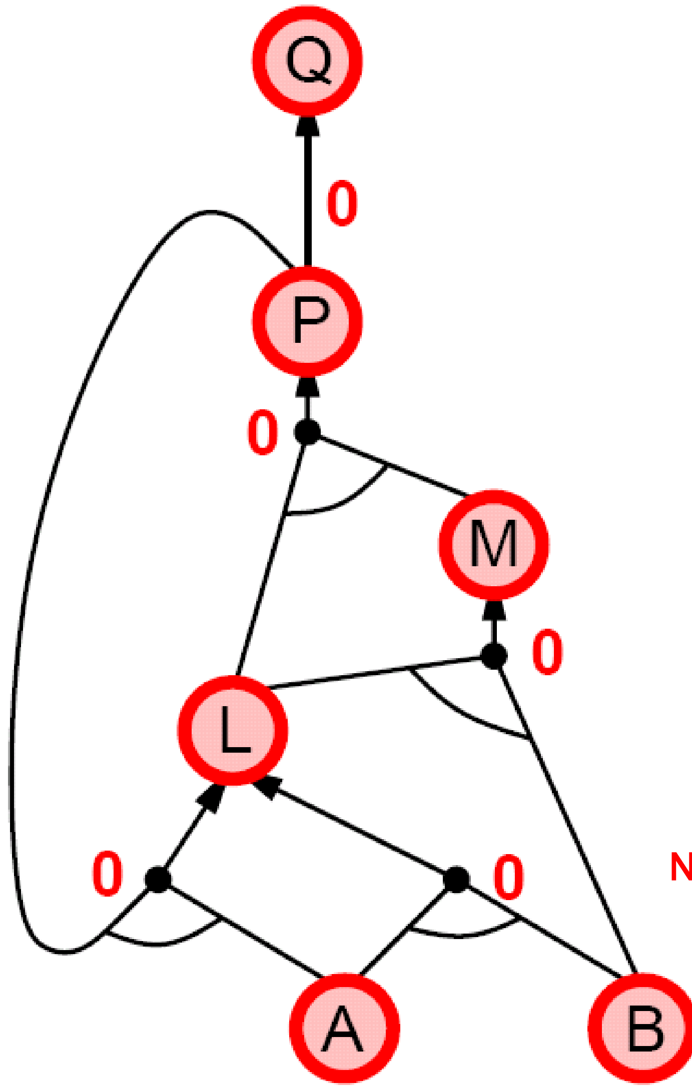
```
function PL-FC-Entails? (KB, q) return true or false //q=query
    local variables:
            count, a table, indexed by clause, initially the number of premises //clause=rule
            inferred, a table, indexed by symbol, each entry initially false
            agenda , a list of symbols, initially the symbols known to be true //fact base

    while agenda is not empty do
        p ← Pop(agenda)
        unless inferred[p] do  //check for repeating inferred symbols
            inferred[p] ← true
            for each Horn clause c in whose premise p appears do //matched premise
                decrement count[c]  //c^th rule
                if count[c] = 0 then do //c^th rule fired
                    if Head[c] = q then return true
                    Push (Head[c], agenda)  //Don't push if inferred[Head[c]]
    return false
```

Forward chaining algorithm

- Forward-chaining(FC) for proposition logic(PL)
- *agenda*: symbols know to be true but not yet “processed”
- *count*: how many premises of each implication are yet unknown
- Whenever a new symbol p from the agenda is processed, the count is reduced by 1 for each implication in whose premise p appears.
- If a count = 0, all the premises of the implication are known, so fire and its conclusion *Head [c]* is added to the agenda
- Keep track of symbols processed; no need to add an inferred symbol to the agenda if it has been processed previously. This avoids <u>redundant</u> work and prevents <u>infinite loops</u> such $P \Rightarrow Q$ and $Q \Rightarrow P$. (*inferred[Head[c]]*)

Forward chaining Example



Agenda

A

B

L

M

P

Q

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

Nos.: counts of unknown nos. of premises of rules

Backward chaining

Idea: work backwards from query q:

- to prove q by BC,

1. check if q is known already, or
2. prove by BC all premises of some rule(s) concluding q

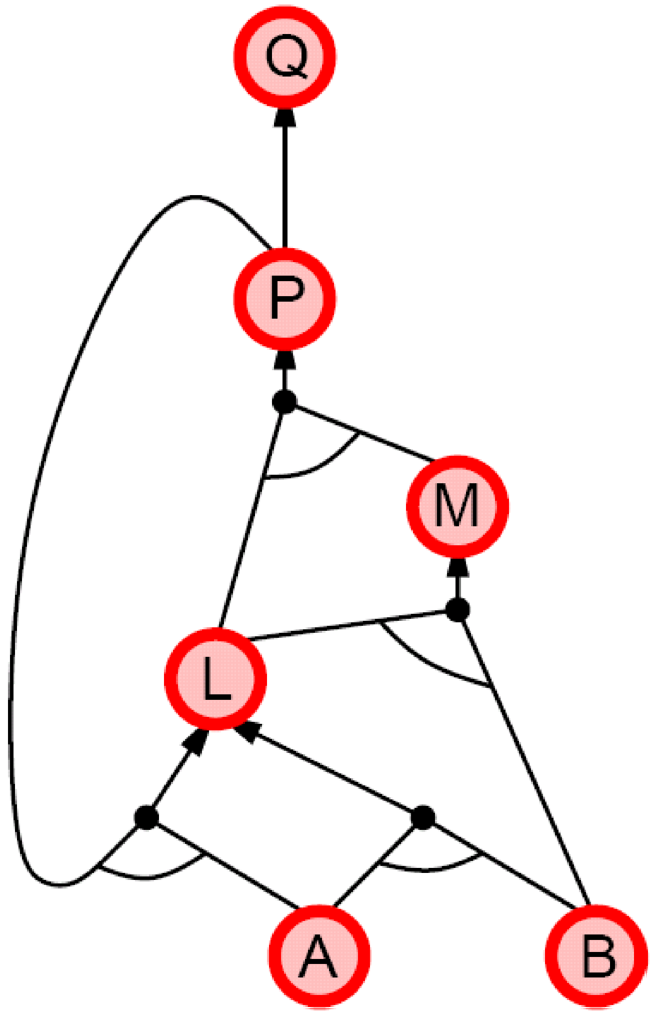
Avoid loops: check if new sub-goal is already on the goal stack

Avoid repeated work: check if new sub-goal

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

Backward chaining example

Fact	*Goal Stack*
A	A
B	B
L	L
M	M
P	P
Q	Q



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

Forward vs. backward chaining

Forward chaining:

- FC is data-driven, cf. automatic, unconscious processing, e.g. object recognition, routine decisions
- May do lots of works that is irrelevant to the goal

Backward chaining:

- 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

Conjunctive Normal Form (CNF-universal)

Conjunction of "disjunctions of literals" (clauses)

E.g. (A ∨ ¬ B) ∧ (B ∨ ¬ C ∨ ¬ D)

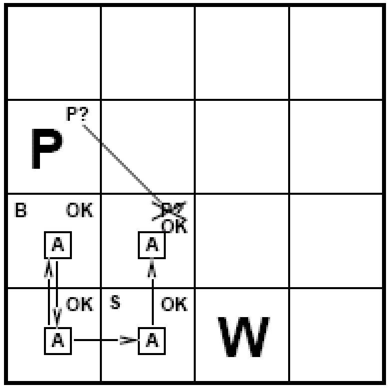
Cf. Horn Form (clauses)

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

$$\frac{l_1 \vee \ldots \vee l_k, \qquad m_1 \vee \ldots \vee m_n}{l_1 \vee \ldots \vee l_{i-1} \vee l_{i+1} \vee \ldots \vee l_k \vee m_1 \vee \ldots \vee m_{j-1} \vee m_{j+1} \vee \ldots \vee m_n}$$

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

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



Resolution is sound and complete for propositional logic

Conversion to CNF

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

Goto equivalent rules

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

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

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:

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

Conjunctive Normal Form

Resolution algorithm

To proof KB entails α $\neg(\text{KB} \Rightarrow \alpha) \equiv \text{KB} \wedge \neg \alpha$

Proof by contradiction, i.e. show KB $\wedge \neg \alpha$ unsatisfiable Goto p.28

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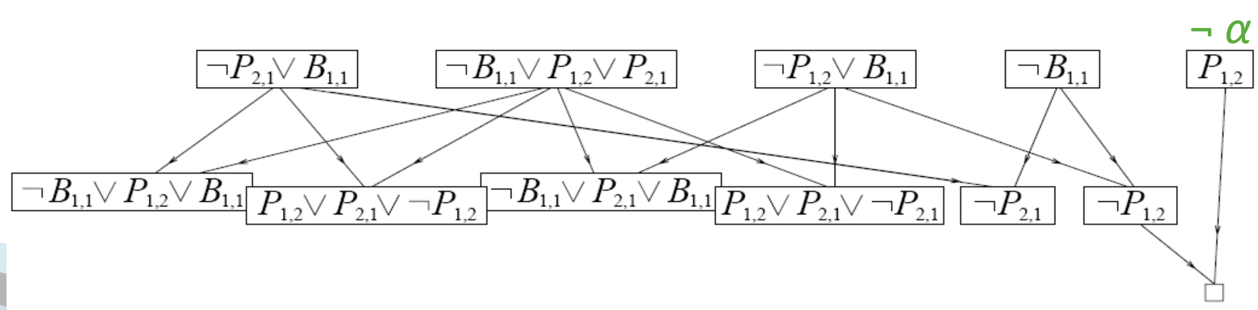
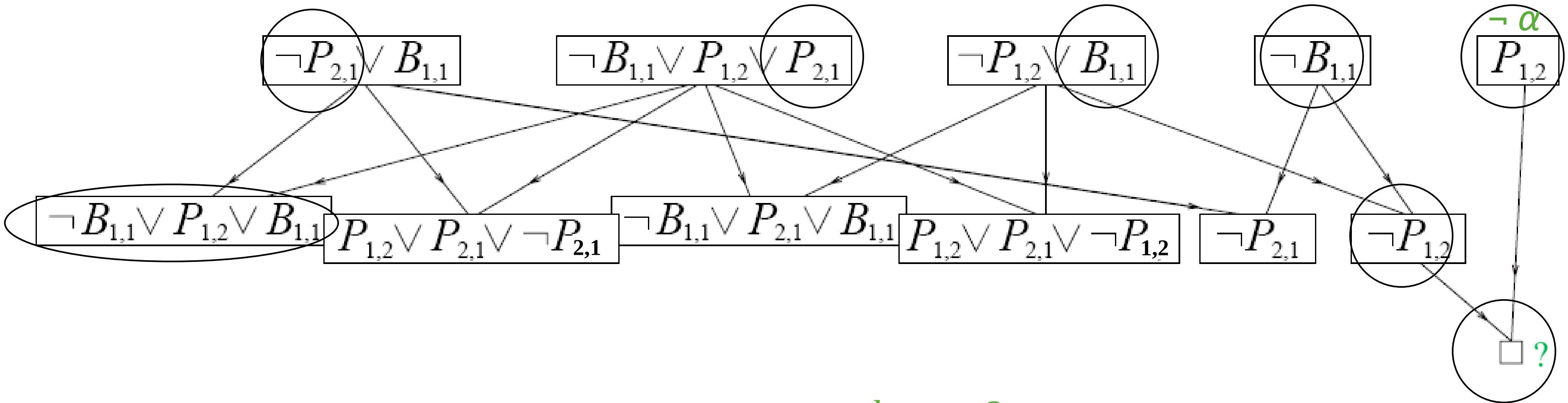
function PL-Resolution (KB, α ) returns true or false
    clauses ← the set of clauses in the CNF representation of KB ∧ ¬α
    new ← {}
    loop do
      for each Ci , Cj in clauses do
        resolvents ← PL-Resolve (Ci , Cj)
        if resolvents contains the empty clause then return true
        new ← new ∪ resolvents
     if new ⊆ clauses then return false //no new resolvents generated ⇒ proof failed
     clauses ← clauses ∪ new
```



Resolution example

No breeze in 1,1. Prove NO Pit in 1,2.

$$KB = (B_{1,1} \Leftrightarrow (P_{1,2} \lor P_{2,1})) \land \neg B_{1,1} \quad \alpha = \neg P_{1,2}$$



new ⊆ clauses ?

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 with respect to models
  - Entailment: necessary truth of one sentence given another
  - Inference: deriving sentences from other sentences
  - Soundness: derivations produce only entailed sentences
  - Completeness: derivations can produce all entailed sentences
- Wumpus world requires the ability to represent partial and negated information, reason by cases, etc.
- Forward, backward chaining are linear-time, complete for Horn clauses
- Resolution is complete for propositional logic
- Propositional logic lacks expressive power