Artificial & Computational Intelligence

AIMLCZG557

Contributors & Designers of document content : Cluster Course Faculty Team

M4 : Knowledge Representation Using Logics

Presented by
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Artificial and Computational Intelligence

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- I hereby acknowledge all the contributors for their material and inputs and gratefully acknowledge people others who made their course materials freely available online.
- .I have provided source information wherever necessary
- This is not a full fledged reading materials. Students are requested to refer to the textbook w.r.t detailed content of the presentation deck that is expected to be shared over e-learning portal - taxilla.
- I have added and modified the content to suit the requirements of the class dynamics & live session's lecture delivery flow for presentation

- **Slide Source / Preparation / Review:**
- From BITS Pilani WILP**:** Prof.Raja vadhana, Prof. Indumathi, Prof.Sangeetha
- From BITS Oncampus & External : Mr.Santosh GSK

BITS Pilani, Pilani Campus

Course Plan

M1 Introduction to AI

M2 Problem Solving Agent using Search

M3 Game Playing

M4 Knowledge Representation using Logics

M5 Probabilistic Representation and Reasoning

M6 Reasoning over time

M7 Ethics in AI

Knowledge Representation Using Logics

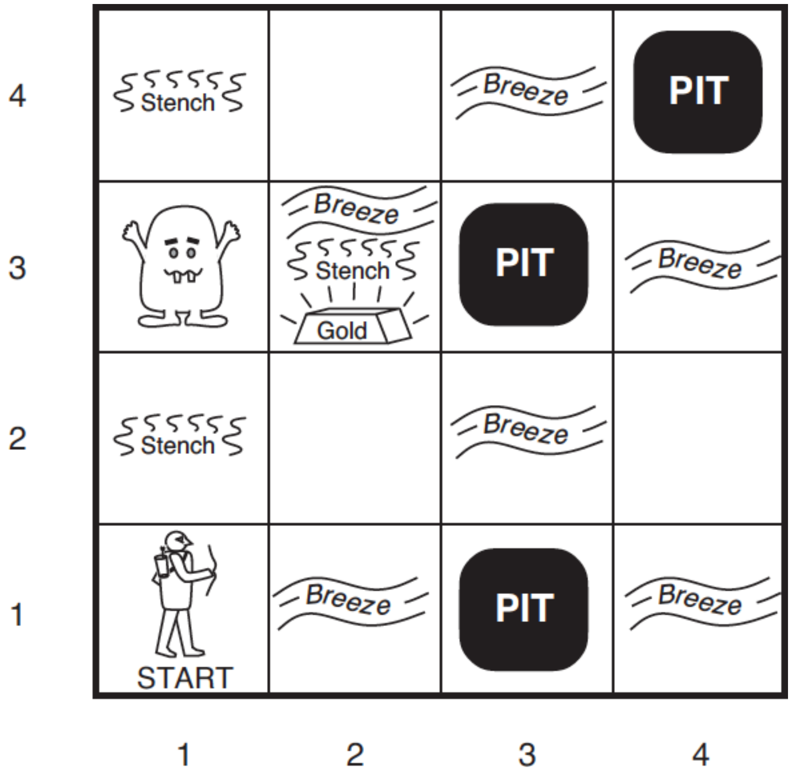
Learning Objective

At the end of this class , students Should be able to:

1. Represent a given knowledge base into logic formulation
2. Infer facts from KB using Resolution
3. Infer facts from KB using Forward Chaining
4. Infer facts from KB using Backward Chaining

Knowledge based Agent : Model & Represent

Concepts, logic Representation of a sample agent



Wumpus World Problem:

PEAS:

Performance Measure:

+1000 for climbing out with gold,

-1000 for falling into a pit or being eaten by Wumpus,

-1 for each action taken and

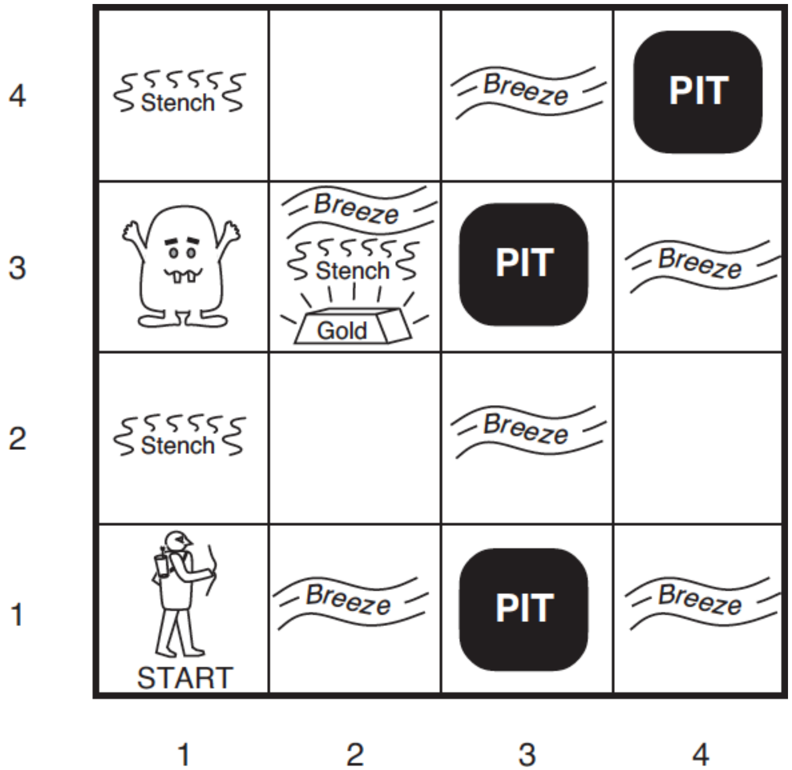
-10 for using an arrow

Environment: 4x4 grid of rooms. Always starts at [1, 1] facing right.

The location of Wumpus and Gold are random.

Agent dies if entered a pit or live Wumpus.

Concepts, logic Representation of a sample agent



Wumpus World Problem:

PEAS:

Actuators –

Forward,

TurnLeft by 90,

TurnRight by 90,

Grab – pick gold if present,

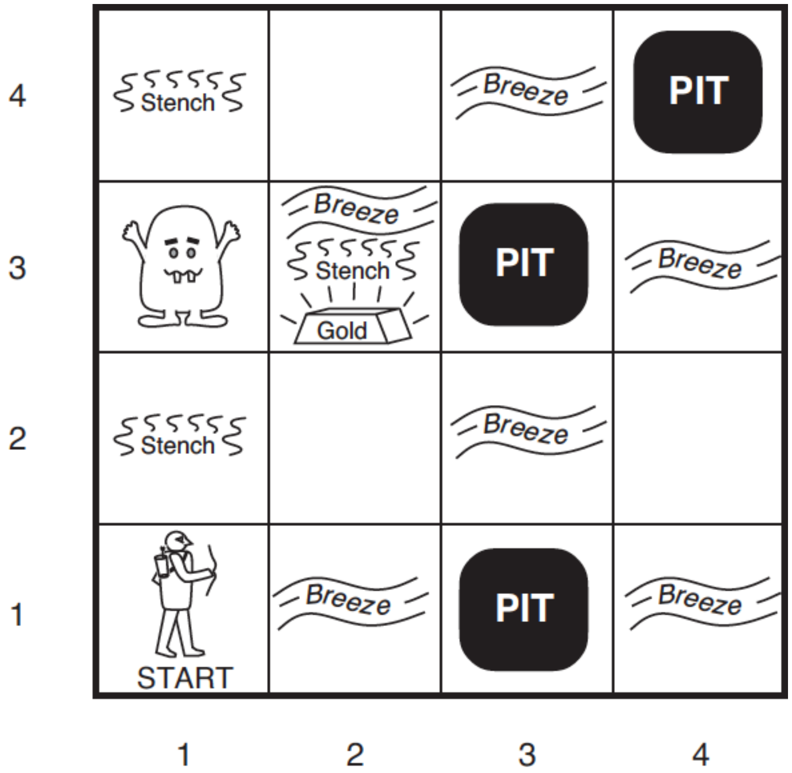
Shoot – fire an arrow, it either hits a wall or kills wumpus. Agent has only one arrow.

Climb – Used to climb out of cave, only from [1, 1]

Knowledge based Agent : Model & Represent

innovate achieve lead

Concepts, logic Representation of a sample agent



Why do we need Factored representation

- To reason about steps
- To learn new knowledge about the environment
- To adapt to changes to the existing knowledge
- Accept new tasks in the form of explicit goals
- To overcome partial observability of environment

Representation

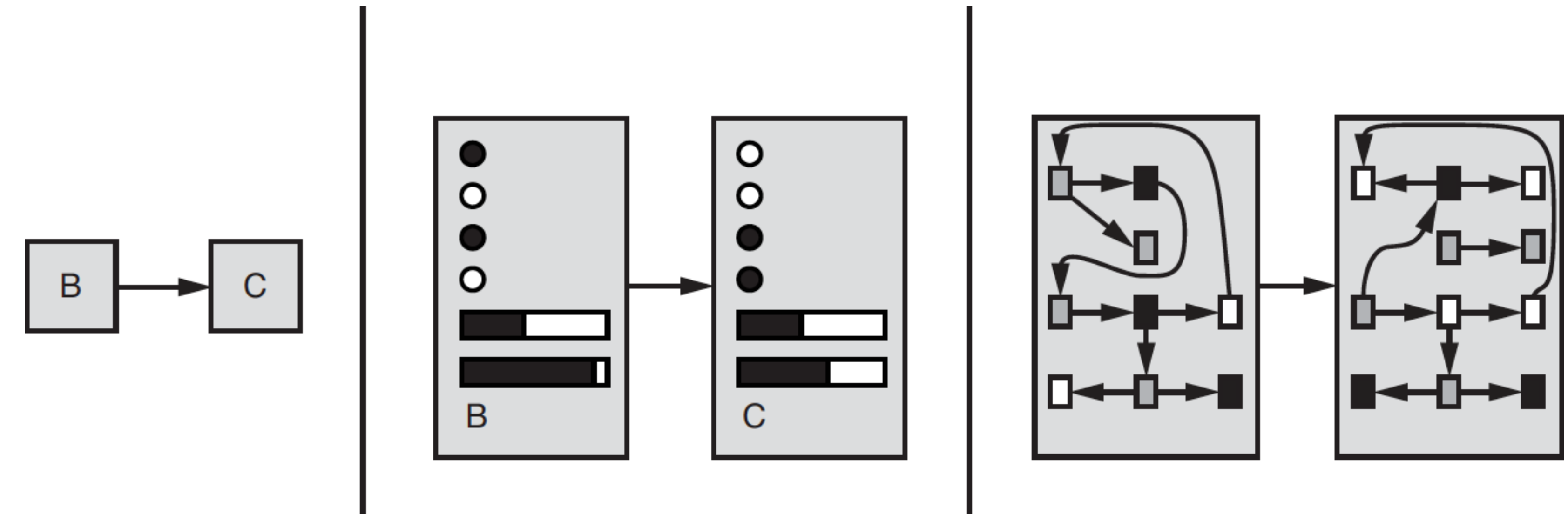
Agents based on Propositional logic, TT-Entail for inference from truth table

Syntax
Semantics
Model

Logic

Propositional Logic

Predicate Logic



(a) Atomic (b) Factored (b) Structured

Search Strategies Propositional Logic First Order Logic

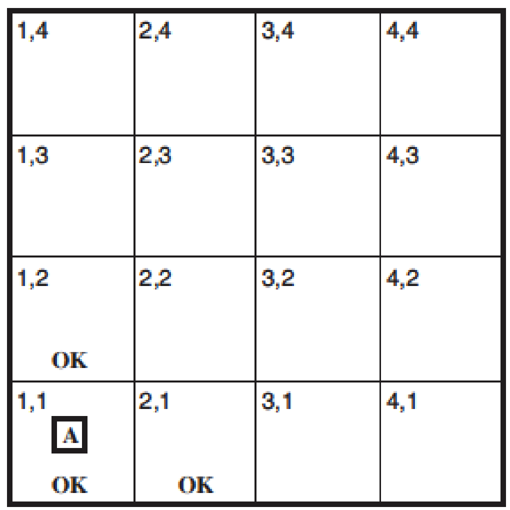
Propositional Logic

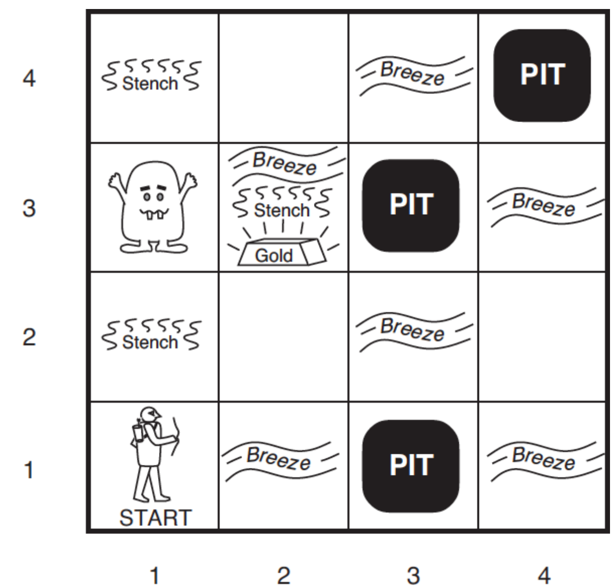
Agents based on Propositional logic, TT-Entail for inference from truth table

A simple representation language for building knowledge-based agents

Proposition Symbol – A symbol that stands for a proposition.
E.g., W1,3 – "Wumpus in [1,3]" is a proposition and $W_{1,3}$ is the symbol
Proposition can be true or false

Atomic : $W_{1,3}$
Conjuncts : $W_{1,3} \wedge P_{3,1}$
Disjuncts : $W_{1,3} \vee P_{3,1}$
Implications :
$(W_{1,3} \wedge P_{3,1}) \Rightarrow \neg W_{2,2}$
Biconditional : $W_{1,3} \Leftrightarrow \neg W_{2,2}$





Tie break in search:

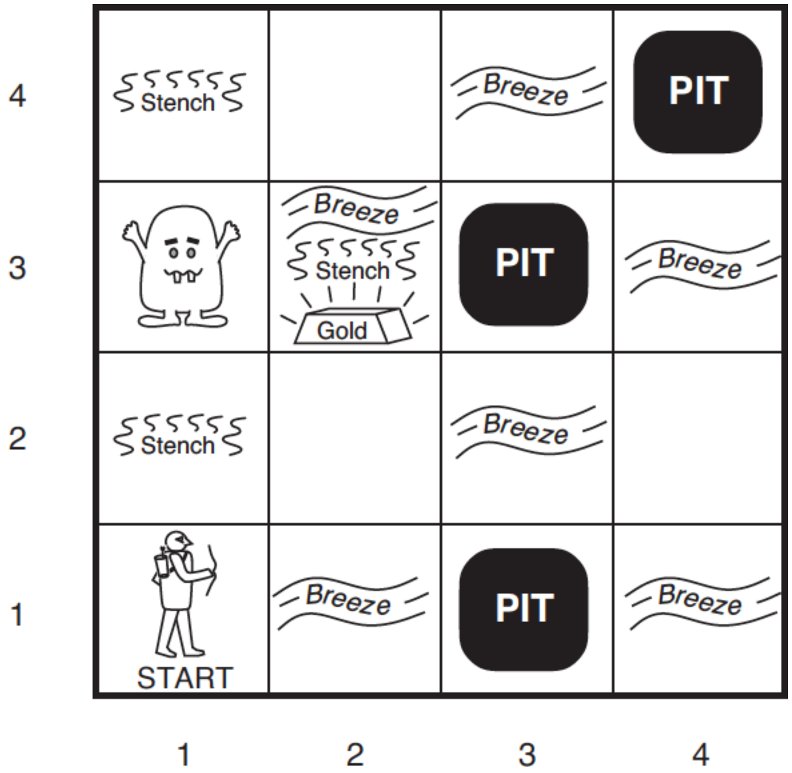
$\neg$, $\wedge$, $\vee$, $\Rightarrow$, $\Leftrightarrow$

$(\neg A) \wedge B$ has precedence over $\neg (A \wedge B)$

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*

Knowledge based Agent : Model & Represent

Concepts, logic Representation of a sample agent



Wumpus World Problem:

PEAS:

Sensors. The agent has five sensors

Stench: In all adjacent (but not diagonal) squares of Wumpus

Breeze: In all adjacent (but not diagonal) squares of a pit

Glitter: In the square where gold is

Bump: If agent walks into a wall

Scream: When Wumpus is killed, it can be perceived everywhere

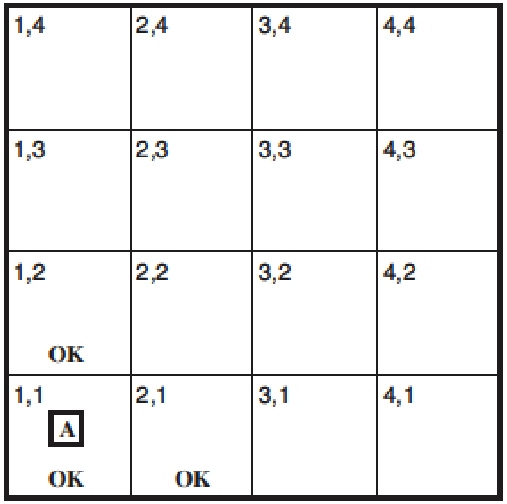
Percept Format:

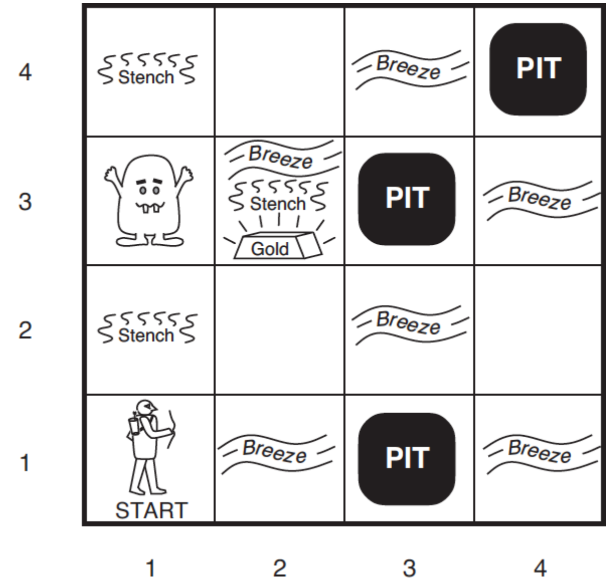
[Stench?, Breeze?, Glitter?, Bump?, Scream?]

E.g., [Stench, Breeze, None, None, None]

Percept 1: [None, None, None, None, None]

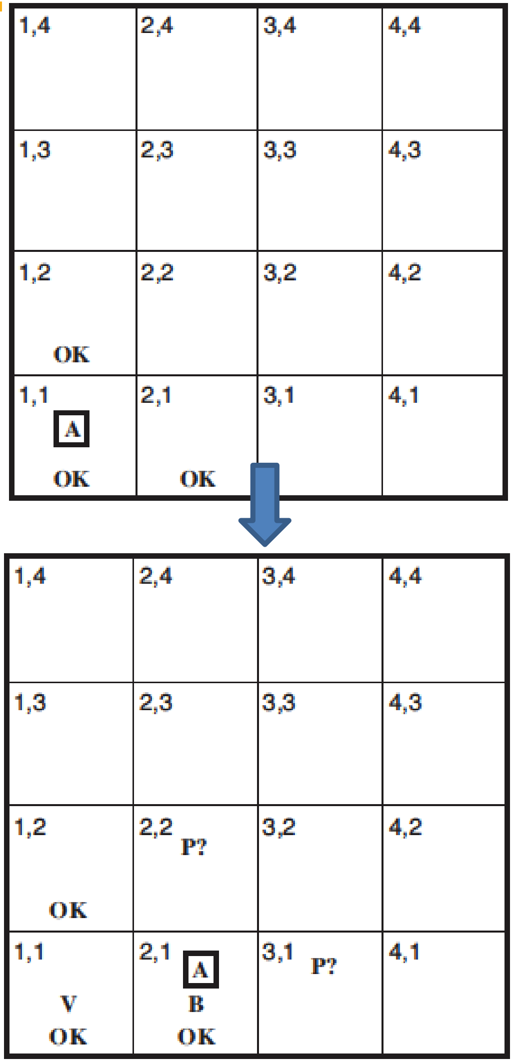
Action: Forward

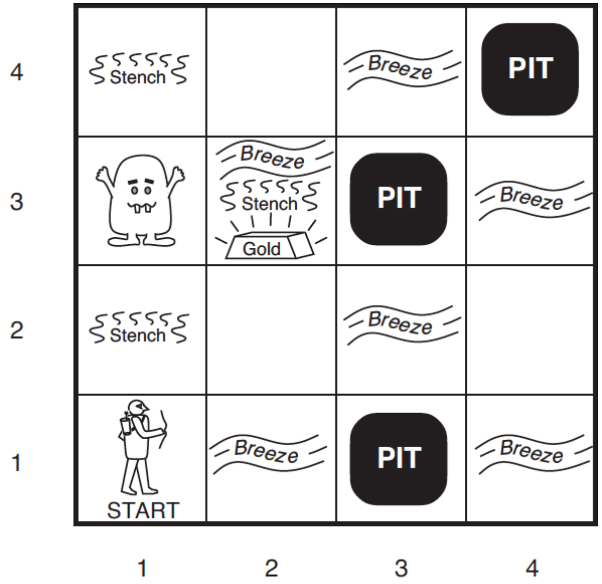




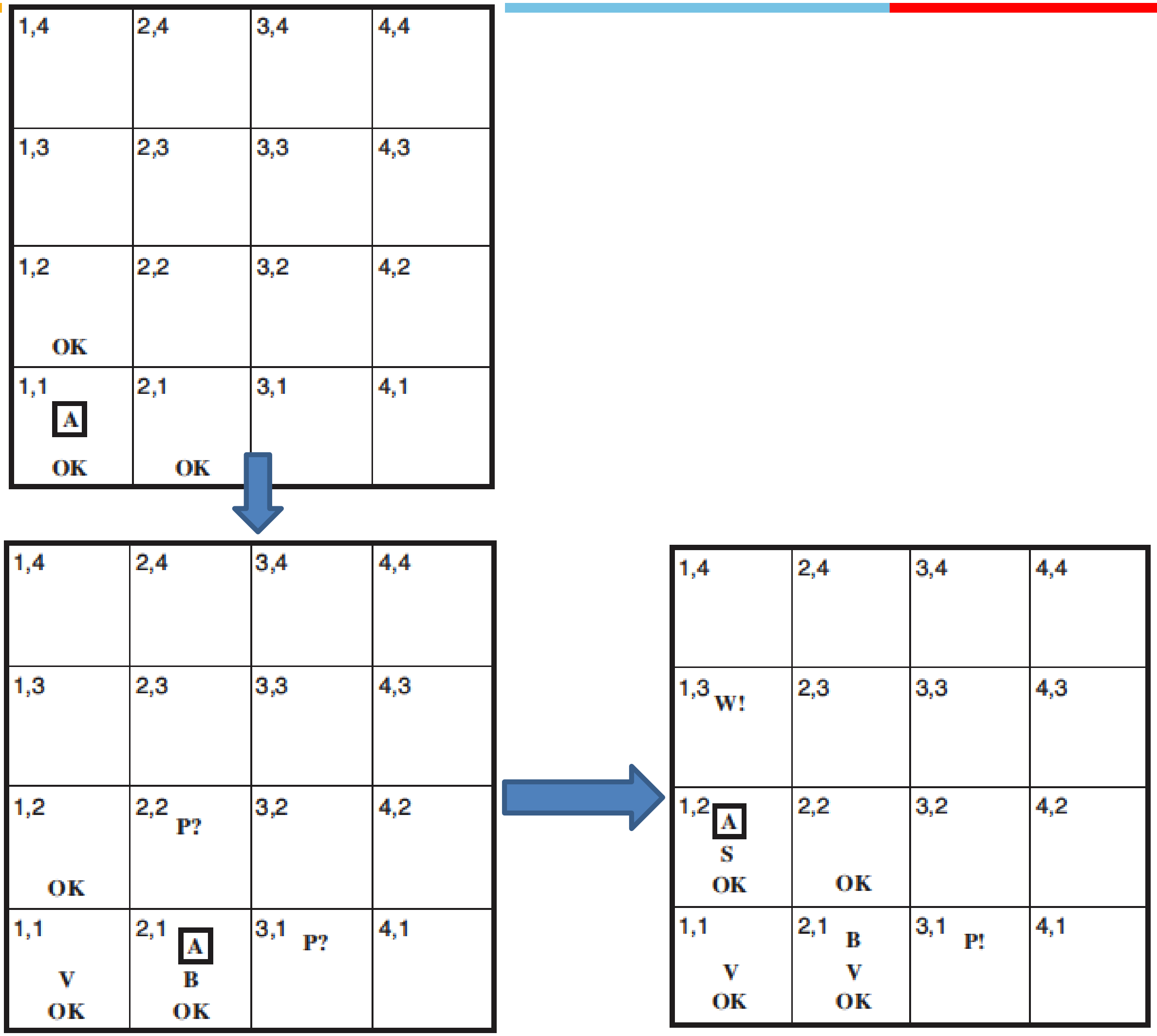
Percept Format:
[Stench?, Breeze?, Glitter?, Bump?, Scream?]

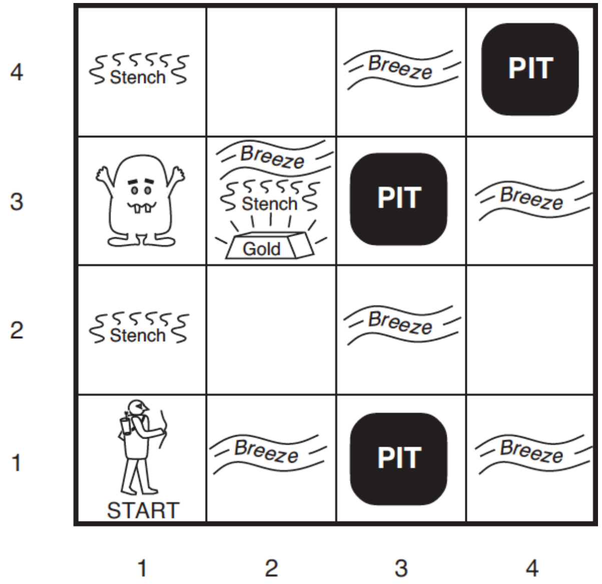
Percept 2: [None , Breeze, None, None, None, None]





Percept 3: [Stench, None, None, None, None]
Action: Move to [2, 2]
Remembers (2,2) as possible PIT and no Stench.





Representation by Propositional Logic

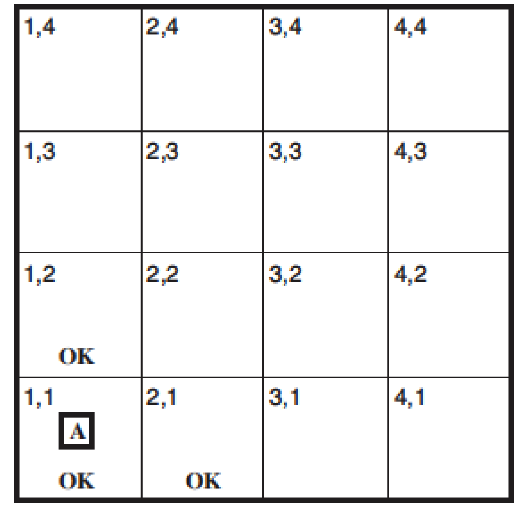
For each [x, y] location

$P_{x,y}$ is true if there is a pit in [x, y]

$W_{x,y}$ is true if there is a wumpus in [x, y]

$B_{x,y}$ is true if agent perceives a breeze in [x, y]

$S_{x,y}$ is true if agent perceives a stench in [x, y]



----------------------- R is the sentence in KB

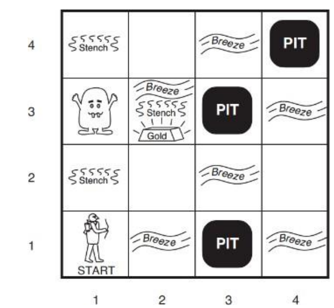
$R_1 : \neg P_{1,1}$

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

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

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

$R_5 : B_{2,1}$



$Query : \neg P_{1,2}$ entailed by our KB?

TT – Entails Inference – Example

$\neg P_{1,2}$ entailed by our KB?

Way – 1 :

1. Get sufficient information $B_{1,1}$, $B_{2,1}$, $P_{1,1}$, $P_{1,2}$, $P_{2,1}$, $P_{2,2}$, $P_{3,1}$
2. Enumerate all models with combination of truth values to propositional symbols
3. In all the models, find those models where KB is true, i.e., every sentence R_1, R_2, R_3, R_4, R_5 are true
4. In those models where KB is true, find if query sentence $\neg P_{1,2}$ is true
5. If query sentence $\neg P_{1,2}$ is true in all models where KB is true, then it entails, otherwise it won't

$B_{1,1}$	$B_{2,1}$	$P_{1,1}$	$P_{1,2}$	$P_{2,1}$	$P_{2,2}$	$P_{3,1}$	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*
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
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*
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
true	*true*	*true*	*true*	*true*	*true*	*true*	*false*	*true*	*true*	*false*	*true*	*false*

TT – Entails Inference – Example

Agents based on Propositional logic, TT-Entail for inference from truth table

$B_{1,1}$	$B_{2,1}$	$P_{1,1}$	$P_{1,2}$	$P_{2,1}$	$P_{2,2}$	$P_{3,1}$	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*
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
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*
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
true	*true*	*true*	*true*	*true*	*true*	*true*	*false*	*true*	*true*	*false*	*true*	*false*

Inference : Properties

1. Entailment : $\alpha \models \beta$
2. Equivalence : $\alpha \equiv \beta$ if and only if $\alpha \models \beta$ and $\beta \models \alpha$
3. Validity
4. Satisfiability

Inference : Example – Theorem Proving (Self Study)

Propositional theorem proving - Proof by resolution

Logical Equivalence rules can be used as inference rules

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

Inference : Example – Theorem Proving

1. **Modes Ponens**
2. AND Elimination

α : I walk in rain without the umbrella

β : I get wet

$\alpha \rightarrow \beta$ **α**

β

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

Inference : Example – Theorem Proving

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α : I walk in rain without the umbrella

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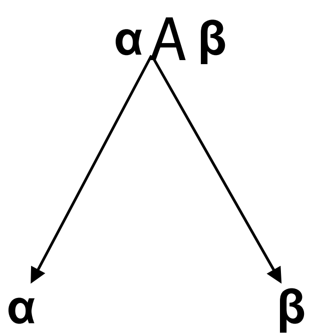

$$
\begin{aligned}
(\alpha \wedge \beta) &\equiv (\beta \wedge \alpha) && \text{commutativity of } \wedge \\
(\alpha \vee \beta) &\equiv (\beta \vee \alpha) && \text{commutativity of } \vee \\
((\alpha \wedge \beta) \wedge \gamma) &\equiv (\alpha \wedge (\beta \wedge \gamma)) && \text{associativity of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

Inference : Example – Theorem Proving

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

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

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

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

$R_5 : B_{2,1}$

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

Query: $\neg P_{1,2}$. Can we prove if this sentence be entailed from KB using inference rules?_______________

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

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

$R_7 : ((P_{1,2} \vee P_{2,1}) \Rightarrow B_{1,1})$ And Elimination

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

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

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

R11: $\neg P_{1,2}$ And Elimination

Propositional Logic

Proof by Contradiction

Inference = FALSE → Assumption is False → Given Query is TRUE

Inference = TRUE → Assumption is TRUE → Given Query is FALSE innovate achieve lead

Towards Predicate Logic

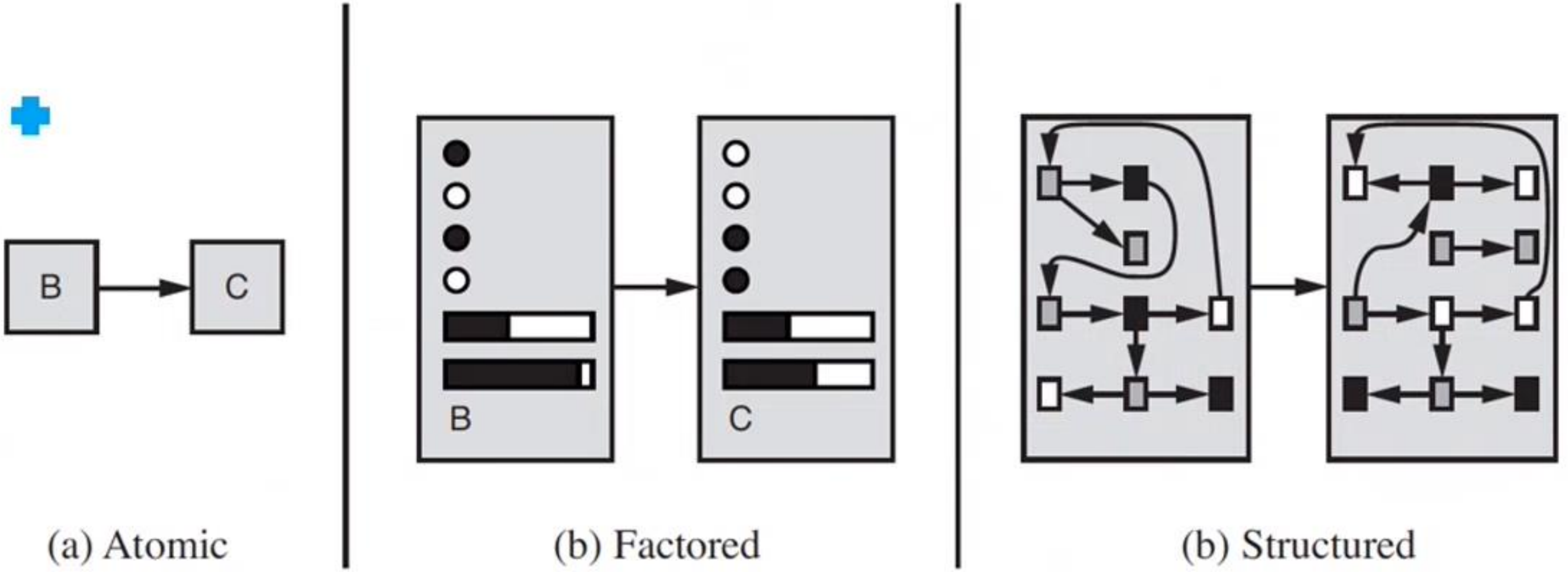
All courses are offered and interesting

All offered courses are interesting

Some of the courses are offered and interesting [Atleast one of the offered courses is interesting]

Some of the offered courses are interesting

Towards Predicate Logic



(a) Atomic (b) Factored (b) Structured

Predicate Logic

Squares neighboring the wumpus are smelly

Objects: squares, wumpus

Unary Relation (properties of an object): smelly N-ary

Relation (between objects): neighboring

Function: -

Primary difference between propositional and first-order logic lies in “ontological commitment” – the assumption about the nature of reality.

Predicate Logic – Sample Modelling

1. "Squares neighboring the wumpus are smelly"

$\forall x,y\ Neighbour(x,y) \wedge Wumpus(y) \Rightarrow Smelly(x)$

Order of quantifiers is important

Predicate Logic – Sample Modelling

2. “Everybody loves somebody”

$\forall x\ \exists y\ Loves(x, y)$

3. “There is someone who is loved by everyone”

$\exists y\ \forall x\ Loves(x, y)$

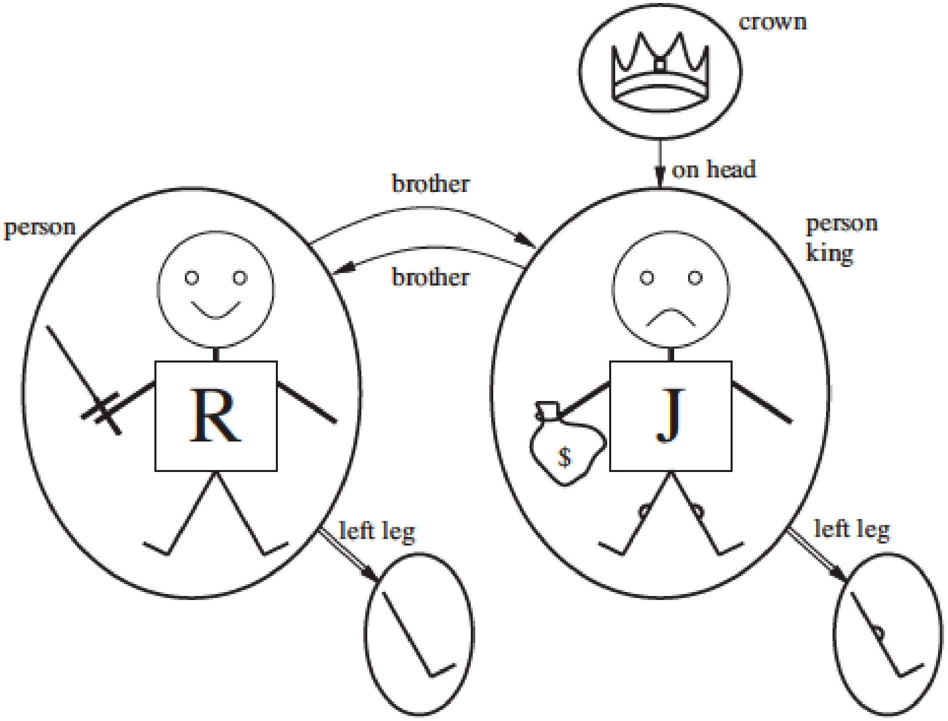
Order of quantifiers is important

Predicate Logic – Sample Modelling

$Brother(Richard, John) \land Brother(John, Richard)$

$King(Richard) \lor King(John)$

$\neg King(Richard) \Rightarrow King(John)$

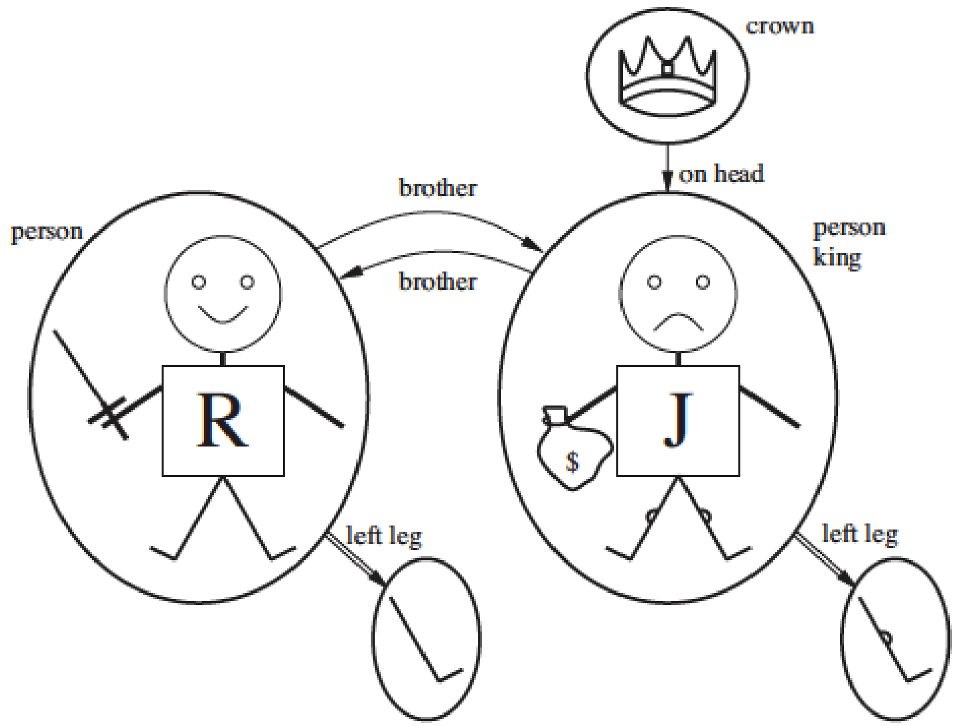


Predicate Logic – Sample Modelling Quantifiers

Brother(Richard, John) ∧ Brother(John, Richard)

King(Richard) ∨ King(John)

¬King(Richard) ⟹ King(John)



"All Kings are persons"

$\forall x\ King(x) \Longrightarrow Person(x)$

"King John has a crown on his head"

$\exists x\ Crown(x)\ \wedge OnHead(x, John)$

Ground Term: A term with no variables. E.g., King(Richard)

Predicate Logic – Inference

1. Substitute for Quantifiers
2. Convert into Propositional Logic
3. Apply inference tech

$\forall x\ King(x) \Longrightarrow Person(x)$

Richard the Lionheart is a king ⟹ Richard the Lionheart is a person

King John is a king ⟹ King John is a person

$\exists x\ Crown(x)\ \ \mathrm{A} OnHead(x, John)$

Crown(C_1) A OnHead(C_1, John) ||C1 is imputed assumed fact

Forward Chaining

- Consider the following problem:

The law says it is a crime for an American to sell weapons to hostile nations. The country Nono, an enemy of America, has some missiles, and all of its missiles were sold to it by Colonel West, who is American.

- We will prove that West is a criminal

Forward Chaining

- “All of its missiles were sold to it by Colonel West”

$$Missile(x) \wedge Owns(Nono, x) \Rightarrow Sells(West, x, Nono)$$

- Missiles are weapons

$$Missile(x) \Rightarrow Weapon(x)$$

- Hostile means enemy

$$Enemy(x, America) \Rightarrow Hostile(x)$$

- ”West, who is American”

$$American(West)$$

- “The country Nono, an enemy of America”

$$Enemy(Nono, America)$$

Forward Chaining

- First, we will represent the facts in First Order Definite Clauses

" … it is a crime for an American to sell weapons to hostile nations"

$$American(x) \land Weapon(y) \land Sells(x, y, z) \land Hostile(z) \Rightarrow Criminal(x)$$

"Nono … has some missiles"

$$\exists x \; Owns(Nono, x) \land Missile(x)$$

is transformed into two definite clauses by Existential Instantiation

$$Owns(Nono, M_1)$$
$$Missile(M_1)$$

Forward Chaining

1. $American(x) \wedge Weapon(y) \wedge Sells(x, y, z) \wedge Hostile(z) \Rightarrow Criminal(x)$
2. $Missile(x) \wedge Owns(Nono, x) \Rightarrow Sells(West, x, Nono)$
3. $Missile(x) \Rightarrow Weapon(x)$
4. $Enemy(x, America) \Rightarrow Hostile(x)$

Missile(M1)
Owns(Nono, M1)
American (West)
Enemy (Nono, America)

Forward Chaining

- Consider the following problem:

The law says it is a crime for an American to sell weapons to hostile nations. The country Nono, an enemy of America, has some missiles, and all of its missiles were sold to it by Colonel West, who is American.

- We will prove that West is a criminal

Algorithm:

1. Start from the facts
2. Trigger all rules whose premises are satisfied
3. Add the conclusion to known facts
4. Repeat the steps till no new facts are added or the query is answered

Forward Chaining

1. $American(x) \wedge Weapon(y) \wedge Sells(x, y, z) \wedge Hostile(z) \Rightarrow Criminal(x)$
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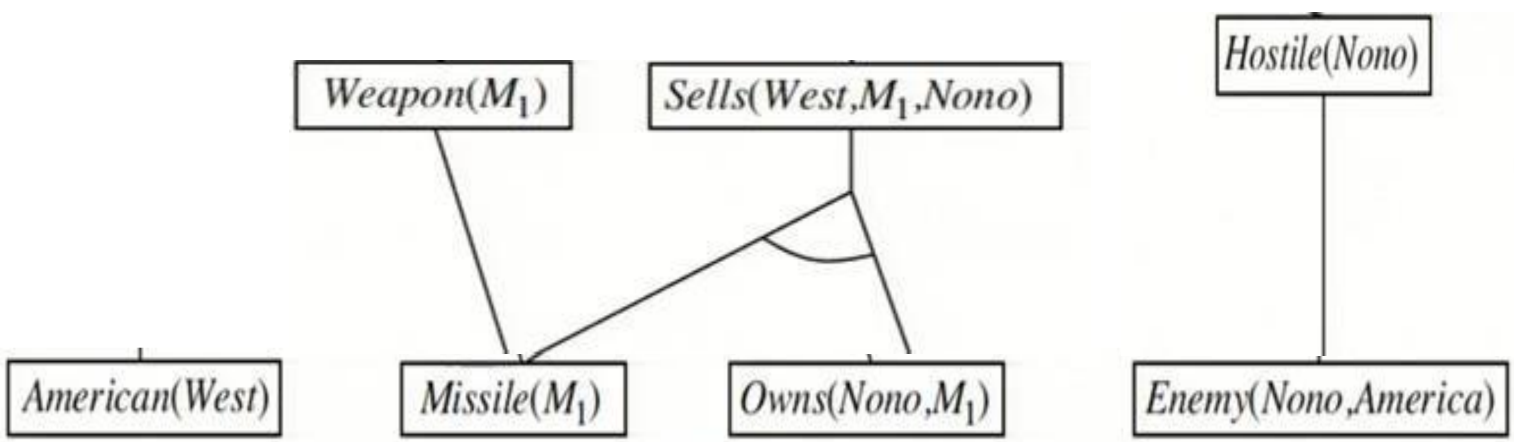

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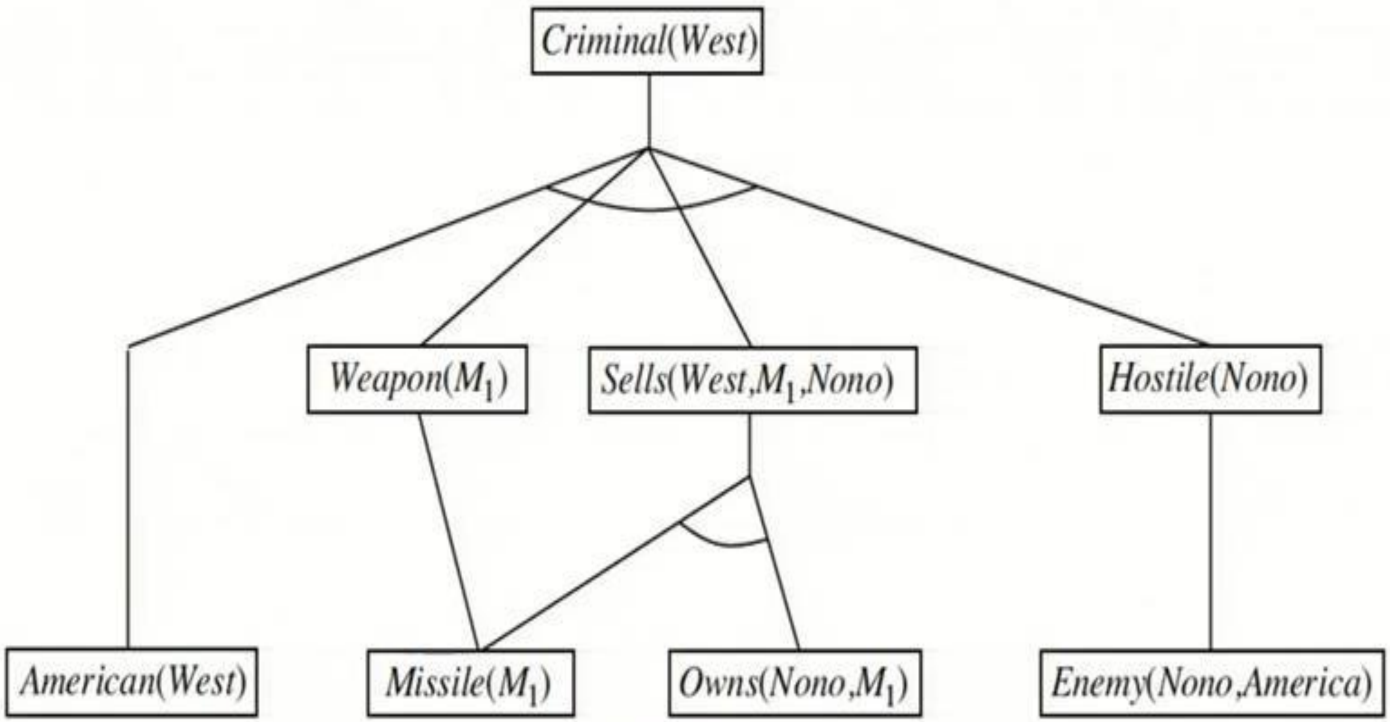

Forward Chaining

Algorithm:

1. Start from the facts - Conjunct Ordering
2. Trigger all rules whose premises are satisfied   - Pattern Matching
3. Add the conclusion to known facts – **Irrelevant Facts**
4. Repeat the steps till no new facts are added or the query is answered – Redundant Rule Matching

Backward Chaining

Algorithm:

1. Form Definite Clause
2. Start from the Goals
3. Search through rules to find the fact that support the proof
4. If it stops in the fact which is to be proved → Empty Set- LHS

Divide & Conquer Strategy

Substitution by Unification

Backward Chaining

innovate achieve lead

1. $American(x) \wedge Weapon(y) \wedge Sells(x, y, z) \wedge Hostile(z) \Rightarrow Criminal(x)$
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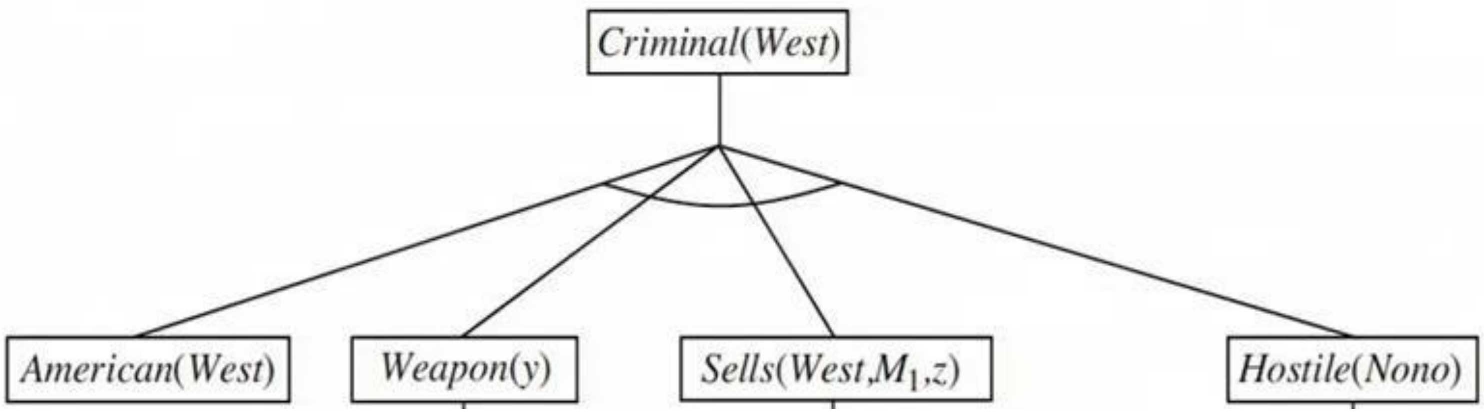

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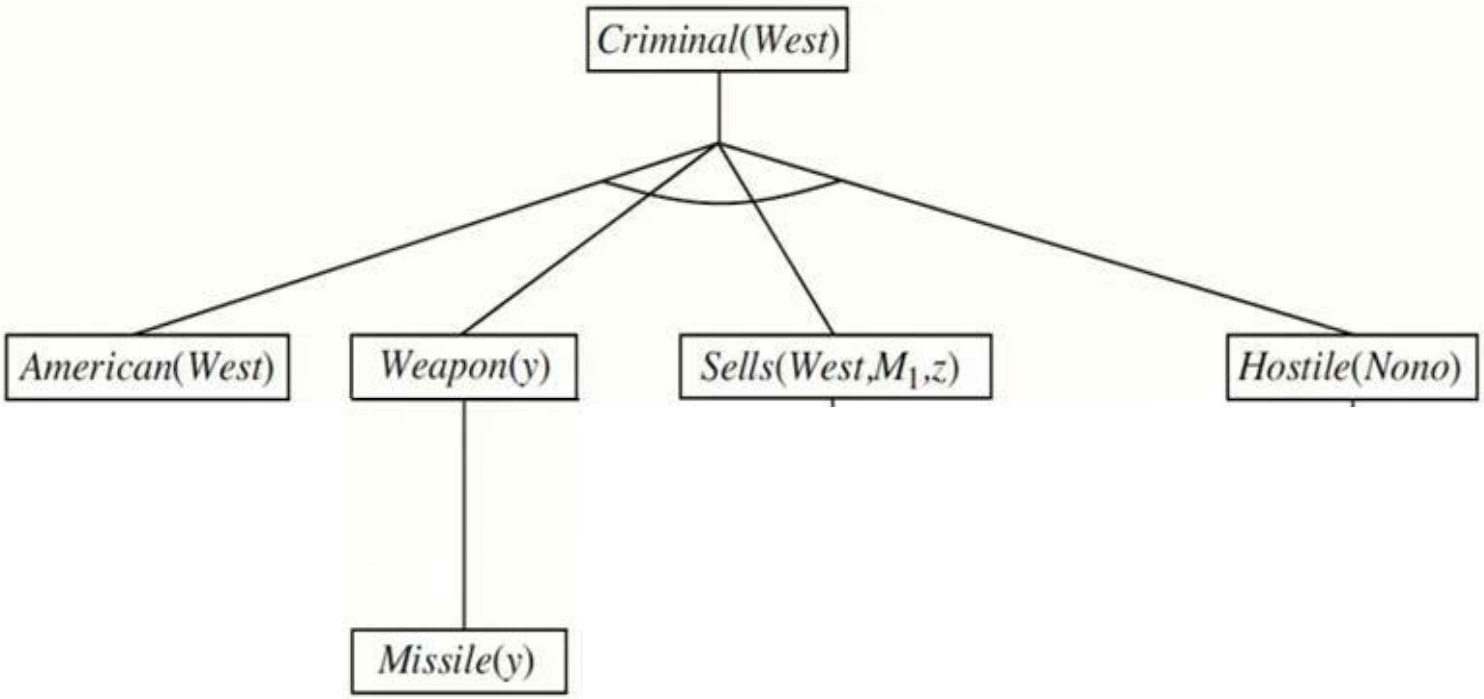

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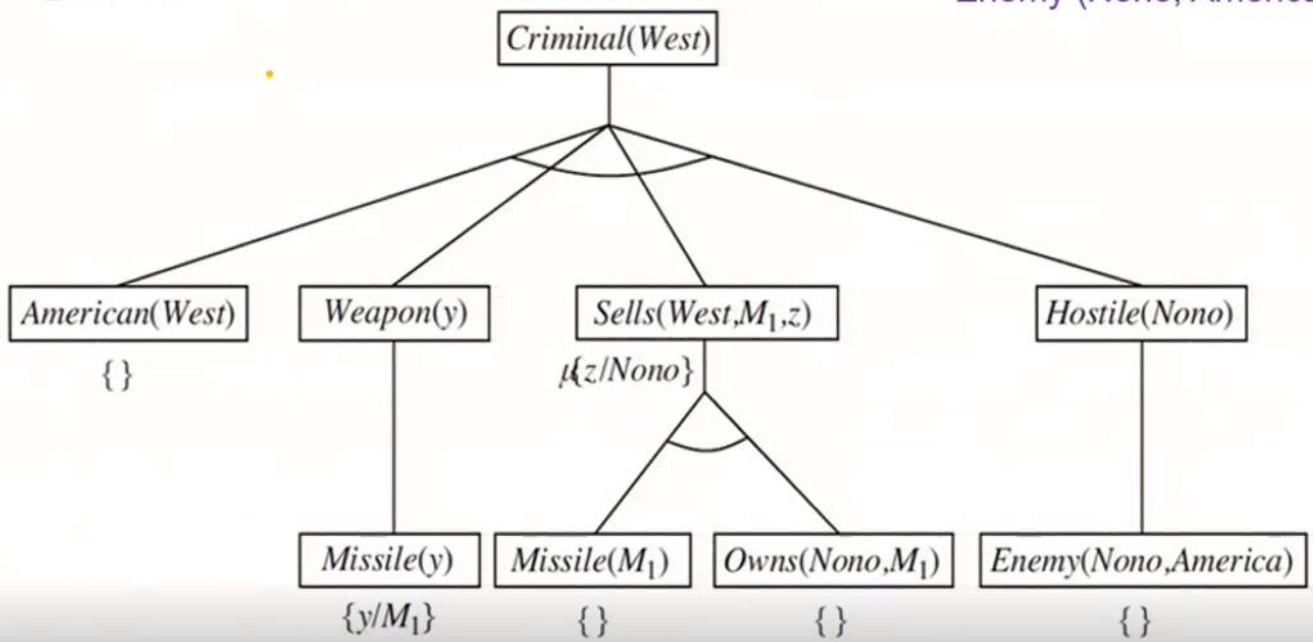

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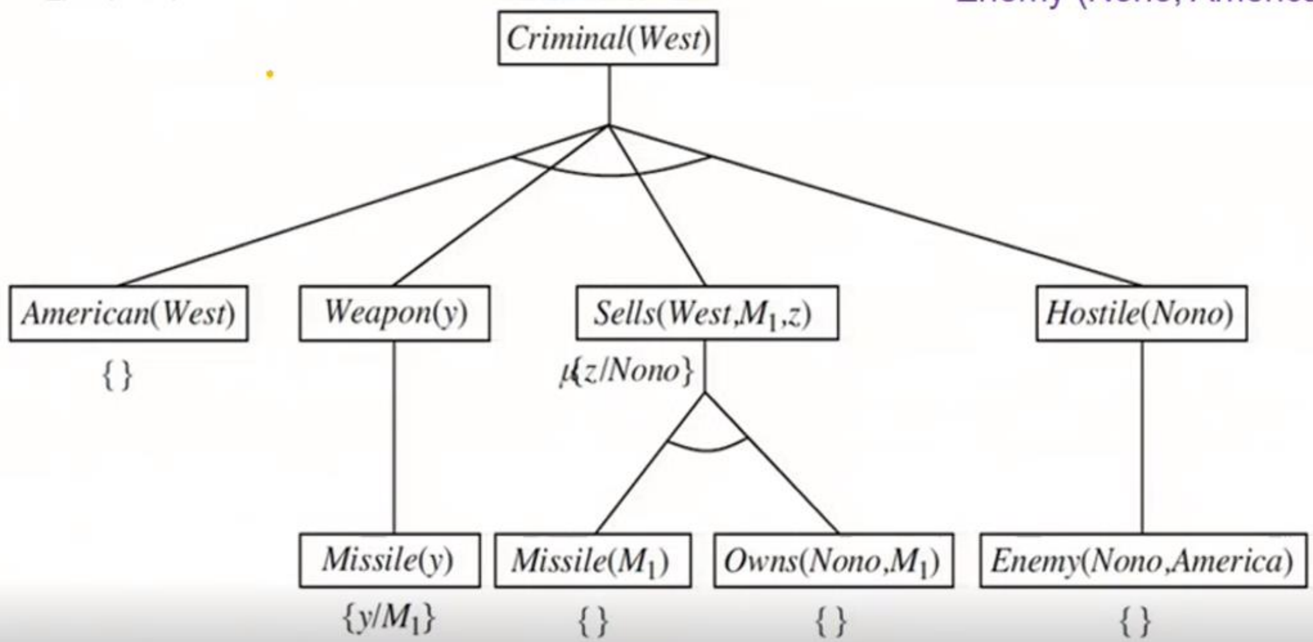

Required Reading: AIMA - Chapter # 4.1, #4.2, #5.1, #9

Next Session Plan:

- (Prerequisite Reading : Refresh the basics of probability , Bayes Theorem , Conditional Probability, Product Rule, Conditional Independence, Chain Rule)

- Inferences using Logic (Forward / Backward Chaining / DPLL algorithm)
- Bayesian Network
- Representation
- Inferences (Exact and approximate-only Direct sampling)

Thank You for all your Attention

Note : Some of the slides are adopted from AIMA TB materials