Artificial Intelligence

Module 4 Reasoning

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Contents

- **Propositional Logic**
- **Reasoning Using First Order Logic**
- **Forward and Backward Reasoning**
- **Unification**
- **Resolution**

Propositional Logic

- A simple logic
- Boolean Logic
  - Represent any statement, or **proposition**, that can take on a truth value
    - Truth value - True – true proposition
    - Truth value - False – false proposition
  - Propositional symbol – The Atomic sentence
    - The indivisible syntactic elements
    - $P_{1,3}$ means Player in [1,3]. It is atomic and cannot be divided in meaningful part as P, 1, 3

	P1,3		

Propositional Logic

- The syntax of propositional logic defines the sentences that are permitted
- The atomic sentences consist of a single **proposition symbol**.
  - Each such symbol stands for a proposition that can be True proposition or False proposition.
    - P, Q, R, $W_{1,3}$ and North
- **Complex sentences** are constructed
  - From simpler sentences,
    - Using parentheses and
    - **Logical connectives**.

Connectives

- ¬ (not) → A sentence such as $\neg W_{1,3}$ is called the **negation** of $W_{1,3}$
- ∧ (and) → $W_{1,3} \wedge P_{3,1}$, is called a conjunction,
  - Parts are conjuncts
- ∨ (or) → $(W_{1,3} \wedge P_{3,1}) \vee W_{2,2}$ is disjunction
  - Parts are disjuncts
- ⇒ (implies). $(W_{1,3} \wedge P_{3,1}) \Rightarrow \neg W_{2,2}$ is called an **implication**
  - Its **premise** or **antecedent** is (W1,3 ∧P3,1)
  - **conclusion** or **consequent** is ¬W2,2
- ⇔ **biconditional** The sentence $W_{1,3} \Leftrightarrow \neg W_{2,2}$
  - if and only if ≡

Semantics of Propositional logic

- ¬P is true iff P is false in m.
- P ∧ Q is true iff both P and Q are true in m.
- P ∨ Q is true iff either P or Q is true in m.
- P ⇒ Q is true except when P is true and Q is false in m.
- P ⇔ Q is true iff P and Q are both true or both are false in 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*

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Propositional Logic

- It is raining RAINING
- It is Sunny SUNNY
- It is Windy WINDY
- If it is raining it is windy

  RAINING -> WINDY
- If it is raining it is not sunny

  RAINING -> ¬ SUNNY

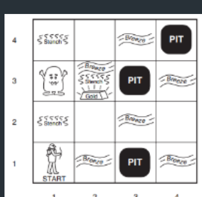
Wumpus World

Entailment => Logical inference

The relation between a sentence and another sentence that follow from it

- The semantics for propositional logic must
  - Specify how to compute the truth value of *any* sentence , given a model .
  - All sentences are constructed from atomic sentences and the five connectives
  - This is done recursively.
  - How to compute the truth of sentences formed with each of the five connectives?

Wumpus World



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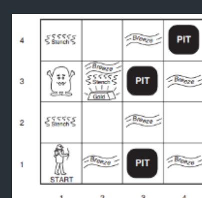
- A cave consisting of rooms connected by passageways.
- Somewhere in the cave is
  - The terrible wumpus, a beast that eats anyone who enters its room
- The wumpus can be shot by an agent,
  - But the agent has only one arrow
- Possibility of finding
  - A heap of gold

Wumpus World



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- Some rooms contain bottomless pits
  - Can trap anyone who wanders into these rooms
  - Except for the wumpus, which is too big to fall in
- Breeze in a room indicates
  - PIT in adjacent room

Wumpus World

- Environment
  - A 4 × 4 grid of rooms.

    The agent always starts in the square labeled [1,1], facing to the right.
  - Random, Uniform distribution of room for Wumpus and Gold
    - Each square other than the start can be a pit, with probability 0. 2

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- **Performance measure**:
  - +1000 for climbing out of the cave with the gold,
  - –1000 for falling into a pit or eaten by wumpus,
  - –1 for each action taken and
  - –10 for using up the arrow.
  - The game ends either when the agent dies or when the agent climbs out of the cave.

Wumpus World

- Actuators: The agent can move
  - *Forward*, *TurnLeft* by 90◦, or *TurnRight* by 90◦
  - A miserable death if it enters a square containing a pit or a live wumpus
  - It is safe, albeit smelly, to enter a square with a dead wumpus.)
    - If an agent tries to move forward and bumps into a wall, then the agent does not move
  - Grab gold
  - Shoot
  - Climb

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Wumpus World

- The agent has five sensors, each of which gives a single bit of information
  - In the square containing the wumpus and in the directly adjacent squares – not diagonal
    - The agent will perceive a *Stench*.
  - In the squares directly adjacent to a pit,
    - The agent will perceive a *Breeze*.
  - In the square where the gold is,
    - The agent will perceive a *Glitter*.
  - [Stench, Breeze, None, None, None]

Wumpus World

- Sensors
  - When an agent walks into a wall,
    - It will perceive a *Bump*.
  - When the wumpus is killed,
    - It emits a woeful *Scream* that can be perceived anywhere in the cave
- Wumpus environment
  - Discrete, Static, and Single-agent, Sequential,
  - Partially observable (Arrow, health, location)

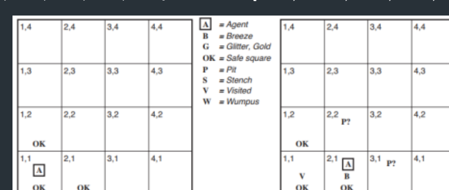
Wumpus World

- For an agent the main challenge is
  - Its initial ignorance of the configuration of the environment
    - Described by rules of environment
  - Overcoming this ignorance require logical reasoning.
- The agent must choose between
  - Going home empty-handed or
  - Risking death to find the gold.

Wumpus World

Starts with [1,1] , [1,1] is a safe square;
Sensors [None, None, None, None, None].

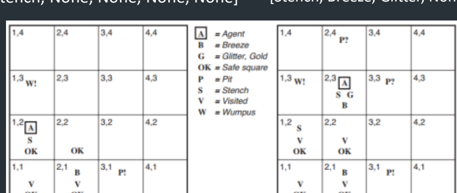
Sensors [None, Breeze, None, None, None].



Wumpus World

A cautious agent will move only into a square that it knows to be OK

[Stench, None, None, None, None] [Stench, Breeze, Glitter, None, None]



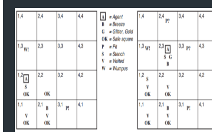
Logical reasoning and logical agent

- A fundamental property of logical reasoning.
  - In each case for which the agent draws a conclusion from the available information,
  - Conclusion is *guaranteed* to be correct if the available information is correct.
- How to build logical agents that
  - Can represent information and
  - Draw conclusions

Logic to wumpus world

- Logical entailment
  - α |= β means sentence α entails the sentence β.
  - if and only if, in every model in which α is true, β is also true
  - α is a *stronger* assertion than β
    - β may be true at more places, α is false
  - Sentence $x = 0$ entails the sentence $xy = 0$.

Logic to wumpus world



- Apply this to Wumpus world
  - The agent has detected nothing in [1,1] and a breeze in [2,1].
  - These percepts, combined with the agent's knowledge of the rules of the wumpus world, constitute the KB.
- The agent is interested in knowing
  - Whether the adjacent squares [1,2], [2,2], and [3,1] contain pits.

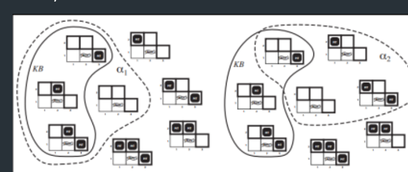
Logic to wumpus world

- The KB is false in models that contradict
  - What the agent knows
  - For example, the KB is false in any model in which [1,2] contains a pit → because there is no breeze in [1,1].
- Two possible conclusions:
  α1 = "There is no pit in [1,2]."
  α2 = "There is no pit in [2,2]."

Logic to wumpus world

α1 = There is no pit in [1,2]
α2 = There is no pit in [2,2]

- KB |= α1: there is no pit in [1,2]. KB entails α1, not other way. Some models in which KB is true.



- α2 is false
  KB | ≠ α2 , KB does not entail α2

Logic to wumpus world

- Entailment can be applied to derive
  - Conclusions - **logical inference**
- The set of all consequences of KB as a haystack
  - α as a needle.
  - Entailment is like the needle being in the haystack
  - Inference is like finding it.

Wumpus world in Propositional logic

- The *immutable* aspects of the wumpus world
- $P_{x,y}$ is true if there is a pit in [x, y].
- $W_{x,y}$ is true if there is a wumpus in [x, y], dead or alive.
- $B_{x,y}$ is true if the agent perceives a breeze in [x, y].
- $S_{x,y}$ is true if the agent perceives a stench in [x, y].

Wumpus world in Propositional logic

- There is no pit in [1,1]:
  - R1 : ¬P1,1
  - R4 : ¬B1,1 .
  - R5 : B2,1 .
- A square is breezy if and only if there is a pit in a neighboring square.
  - R2 : B1,1 ⇔ (P1,2 ∨ P2,1) .
  - R3 : B2,1 ⇔ (P1,1 ∨ P2,2 ∨ P3,1)

Pros and cons of propositional logic

☺ Propositional logic is declarative

☺ Propositional logic allows partial/disjunctive/negated information

- Unlike most data structures and databases

☺Propositional logic is compositional:

- Meaning of $B_{1,1} \wedge P_{1,2}$ is derived from meaning of $B_{1,1}$ and of $P_{1,2}$

Pros and cons of propositional logic

☹ Propositional logic has very limited expressive power

- B1,1 ⇔ (P1,2 ∨ P2,1)
- Unlike natural Language
  - E.g., cannot say "pits cause breezes in adjacent squares " except by writing one sentence for **each square**

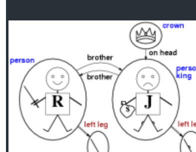
Standard logical equivalences

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

First-order logic

- Whereas propositional logic assumes the world contains facts
- First-order logic (like natural language) assumes the world contains
  - Objects: people, houses, numbers, colors, baseball games, wars, …
  -
  - Relations: red, round, prime, brother of, bigger than, part of, comes between, …
  - Functions: father of, best friend, one more than, plus, …

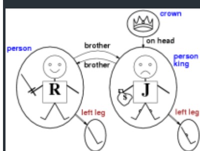
First-order logic



- A relation
  - The set of **tuples** of objects that are related.
    - A tuple is a collection of objects
    - Arranged in a fixed order
    - Written with angle brackets surrounding the objects
  - {<Richard the Lionheart, King John>, <King John, Richard the Lionheart > }
    - Picture may be used in place of name

First-order logic

- A function
  - A object is related to one object in function way
    - Left leg of, Mother of,
- Total function in FOL
  - Value for each tuple
  - Each object

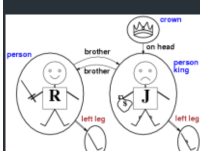


Syntax of FOL: First-order logic

- Symbols – Begin with upper case latter
  - Constant Symbols
    - Objects
      - Richard, John , 2, VIT
  - Predicate symbols
    - Relation
      - Brother, OnHead, Person, >, King ,
  - Function Symbols
    - LeftLegOf, SqrtOf

Syntax of FOL: First-order logic

- **Interpretation (Intended Interpretation)**
  - Constant, Predicate, and Function symbols refer to
    - Specific objects, relations and functions
      - Richard refers to Richard the Lionheart
      - John refers to the evil King John
      - Brother refers to the brotherhood relation
    - OnHead refers to the "on head" relation
      - Between Crown and John
    - Person, King, and Crown refer to Set of objects
      - Persons, Kings, and Crowns



Syntax of FOL: First-order logic

- Interpretation also mean
  - Richard to Crown
  - John to John's left leg
    - All possible combination of Symbol and objects
  - All objects may not have name
    - Some objects are without name, may have relation, function
    - crown, leg
  - An objects may have multiple name
    - Richard, John → crown

Syntax of FOL: First-order logic

- Variables x, y, a, b,...
  - Small letters
- Connectives $\neg, \Rightarrow, \wedge, \vee, \Leftrightarrow$
- Equality =
- Quantifiers $\forall, \exists$
- Predicate and Function symbol have an **arity**
  - Fixes the number of arguments

Term and Atomic sentences

- Term is logical expression that refers to a object
  - Constant Symbol is a term
  - Not all objects need have distinct symbols
    - Leftleg (John)
    - Left leg of King john is an object
- Atomic sentence = *predicate* $(term_1,\ldots,term_n)$ or $term_1 = term_2$
  - E.g., *Brother(KingJohn,RichardTheLionheart)*
  - *> (Length(LeftLegOf(Richard)), Length(LeftLegOf(KingJohn)))*
  - Married(Father(Richard), Mother(John))

Complex sentences

- $\neg S$,
- $S_1 \wedge S_2$,
- $S_1 \vee S_2$,
- $S_1 \Rightarrow S_2$,
- $S_1 \Leftrightarrow S_2$,

- Complex sentences are made from atomic sentences using connectives
  - *Sibling(KingJohn,Richard)* $\Rightarrow$ *Sibling(Richard,KingJohn)*
  - $>(1,2) \vee \leq (1,2)$
  - $>(1,2) \wedge \neg >(1,2)$

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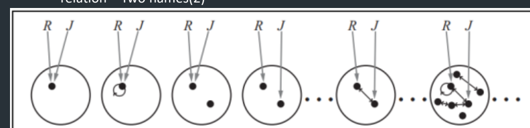
First-order logic

- Multiple Models
  - Relation with arrow referring to objects and Symbols
    - Same object two names(1)
    - One object with some relation – Two names(2)
- One object with no names(3)
- Separate objects name, with relation(4)(5)
- Many combinations(6)



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Truth in first-order logic

- An atomic sentence *predicate*$(term_1,\ldots,term_n)$ is true
  - iff the objects referred to by $term_1,\ldots,term_n$ are in the relation referred to by *predicate*

- Model contains objects (domain elements) and relations among them
- Sentences are true with respect to a model and an interpretation
- Interpretation specifies referents for

  constant symbols → objects

  predicate symbols → relations

  function symbols → functional relations

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Universal quantification

- $\forall$<variables> <sentence>

Everyone at VIT is smart:
$\forall$x At(x,VIT) $\Rightarrow$ Smart(x)

- $\forall$x *P* is true in a model *m*
  - iff *P* is true with *x* being each possible object in the model

- Roughly speaking, equivalent to the conjunction of instantiations of *P*

  At(KingJohn,VIT) $\Rightarrow$ Smart(KingJohn)
  $\wedge$ At(Richard,VIT) $\Rightarrow$ Smart(Richard)
  $\wedge$ At(VIT, VIT) $\Rightarrow$ Smart(VIT)
  $\wedge$ ...

[one sentence equal to many of prepositional logic and relation to all the objects]

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Universal quantification

- All romans were either loyal to Caesar or hated him
- $\forall$x: Roman(x) -> layalto(x, Caesar) $\vee$ hate(x, Caesar)

- $\forall$ x P is true , P = King(x) $\wedge$ Person(x)
  - Logical expression P is true for each object in the model
  - P is true for all possible extended interpretation from m
    - x refers to each domain element in each extended interpretation
  - The universally quantified sentence,
    - Equivalent to asserting a whole list of individual implications

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A common mistake to avoid

- Typically, $\Rightarrow$ is the main connective with $\forall$
- Common mistake: using $\wedge$ as the main connective with $\forall$

  $\forall$x At(x,VIT) $\wedge$ Smart(x)

  means “Everyone is at VIT and everyone is smart”

  - Do not use $\wedge$ with $\forall$x

  for “=>” the implication is true whenever its premise is false.

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Existential quantification

- $\exists$<*variables*> <*sentence*>
- Someone at VIT is smart:
- $\exists x\ At(x,VIT) \wedge Smart(x)$$
- $\exists x\ P$ is true in a model *m* iff *P* is true with *x* being some possible object in the model
- Equivalent to the disjunction of instantiations of *P*

$At(KingJohn,VIT) \wedge Smart(KingJohn)$
$\vee At(Richard,VIT) \wedge Smart(Richard)$
$\vee At(VIT,VIT) \wedge Smart(VIT)$
$\vee \ldots$

one sentence equal to many of prepositional logic with OR relation to all the objects

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Existential quantification

- $\exists$ x P , P = Crown(x) $\wedge$ OnHead(x, John)

The crown is a crown $\wedge$ the crown is on John's head

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A common mistake to avoid

Summary of use of qualifiers
$\Rightarrow$ and $\forall x$
$\wedge$ and $\exists x$

- Typically, $\wedge$ is the main connective with $\exists$
- Common mistake: using $\Rightarrow$ as the main connective with $\exists$:

$\exists x\ At(x,VIT) \Rightarrow Smart(x)$

  - One additional meaning,
    - Smart for object x is true even if anyone who is not at VIT!
    - Even if At(x,VIT) is false, Smart(x) is true.

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Properties of quantifiers

- $\forall x\ \forall y$ is the same as $\forall y\ \forall x$
- $\exists x\ \exists y$ is the same as $\exists y\ \exists x$
- $\exists x\ \forall y$ is not the same as $\forall y\ \exists x$
- $\exists x\ \forall y\ Loves(x,y)$
  - "There is a person who loves everyone in the world"
- $\forall y\ \exists x\ Loves(x,y)$
  - "Everyone in the world is loved by at least one person"

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Properties of quantifiers

- Some one like Broccoli

$\exists x\ Likes(x,Broccoli)$

- There is no one who does not like Broccoli

$\neg\forall x\ \neg Likes(x,Broccoli)$

- Quantifier duality:
  - Each of $\forall$, $\exists$ can be expressed using the other qualifier
- Every one like icecream Vs.

$\forall x\ Likes(x,IceCream)$

- There is no one who does not like ice cream

$\neg\exists x\ \neg Likes(x,IceCream)$

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Properties of quantifiers

- Every one does not likes (dislikes) FH vs.
  - There does not exist any one who likes FH
- $\forall x\ \neg Likes(x, FH) \equiv \neg\exists x\ Likes(x, FH)$

$\forall x\ \neg P \equiv \neg\exists x\ P$	$\neg(P \wedge Q) \equiv \neg P \vee \neg Q$
$\neg\forall x\ P \equiv \exists x\ \neg P$	$\neg(P \vee Q) \equiv \neg P \wedge \neg Q$
$\forall x\ P \equiv \neg\exists x\ \neg P$	$P \wedge Q \equiv \neg(\neg P \vee \neg Q)$
$\exists x\ P \equiv \neg\forall x\ \neg P$	$P \vee Q \equiv \neg(\neg P \wedge \neg Q)$

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Using FOL

Using FOL to build the knowledge base

- Assertion
  - Tell the KB → Add sentences to KB
    - TELL(KB, King(John))
    - TELL(KB, Person(Richard))
    - TELL(KB, ∀ x King(x) ⇒ Person(x))
- Ask questions , **queries** or **goals**
  - If logically entailed by the knowledge base it will be affirmative
    - ASK(KB, King(John)) returns true
    - ASK(KB, Person(John)) returns true
  - True, False is not sufficient

Using FOL

Using knowledge base to get facts

- If we want to know what value of x
  - Makes the sentence true
    - ASKVARS(KB, Person(x))
    - Stream of answers
      - {x/John} and {x/Richard}
  - A **substitution** or **binding list**.
    - Every way of making the query true will bind the variables to specific values
      - IF KB has King(John) ∨ King(Richard)
      - there is no binding to x for the query ∃ x King(x) ASKVARS is not applicable

Using FOL

"Sibling" is symmetric

∀x,y *Sibling(x,y)* ⇔ *Sibling(y,x)*

The kinship domain:

- Brothers are siblings

  ∀x,y *Brother(x,y)* ⇔ *Sibling(x,y)*
- One's mother is one's female parent

  ∀m,c *Mother(c)* = m ⇔ *(Female(m)* ∧ *Parent(m,c))*

FOL Applications

- Takes(x, c, s): student x takes course c in semester s;
- Passes(x, c, s): student x passes course c in semester s;
- Score(x, c, s): the score obtained by student x in course c in semester s;
- x > y: x is greater than y;
- Buys(x,y,z): x buys y from z
- F and G: specific French and Greek courses

FOL Applications

- Some students took French in spring 2001.

∃x Student(x) ∧ Takes(x, F, Spring2001)

- Every student who takes French passes it.

∀x, s Student(x) ∧ Takes(x, F, s) ⇒ Passes(x, F, s).

FOL Applications

- Only one student took Greek in spring 2001.

∃x Student(x)∧Takes(x, G, Spring2001)
∧ ∀y y≠x ⇒ ¬Takes(y, G, Spring2001)

- No person buys an expensive policy.

∀x, y, z Person(x) ∧ Policy(y) ∧ Expensive(z) ⇒ ¬Buys(x, y, z).

FOL Applications

- There is an agent who sells policies only to people who are not insured.

$\exists x\ Agent(x) \land \forall y, z\ Policy(y) \land Sells(x, y, z) \Rightarrow (Person(z) \land \neg Insured(z))$

- There is a barber who shaves all men in town who do not shave themselves.

$\exists x\ Barber(x) \land \forall y\ Man(y) \land \neg Shaves(y, y) \Rightarrow Shaves(x, y)$

Artificial Intelligence: A Modern Approach, Stuart J . Russell and Peter Norvig

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FOL - Wumpus world

- First-order sentence stored in the KB
  - the percept and the time at which it occurred
    - Percept([Stench, Breeze, Glitter, None, None], 5)
  - Actions
    - Turn(Right), Turn(Left), Forward, Shoot, Grab, Climb
  - Best action query
    - ASKVARS(∃ a BestAction(a, 5))
  - Returns a binding list
    - {a/Grab}

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FOL - Wumpus world

- Current state from percept data
  - $\forall t, s, g, m, c\ Percept([s, Breeze, g, m, c], t) \Rightarrow Breeze(t)$
  - $\forall t, s, b, m, c\ Percept([s, b, Glitter, m, c], t) \Rightarrow Glitter(t)$
- Reflex behavior
  - $\forall t\ Glitter(t) \Rightarrow BestAction(Grab, t)$
- Squares $Square_{1,2}$
- Adjacency
  - $\forall x, y, a, b\ Adjacent([x, y], [a, b]) \Leftrightarrow$

$(x = a \land (y = b - 1 \lor y = b + 1)) \lor (y = b \land (x = a - 1 \lor x = a + 1))$

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FOL - Wumpus world

- Location of agent at Square s and at time t
  - At(Agent, s, t)
- Agent infers property of square from percept
  - $\forall s, t\ At(Agent, s, t) \land Breeze(t) \Rightarrow Breezy(s)$
- The agent can deduce pits & Wumpus
  - $\forall s\ Breezy(s) \Leftrightarrow \exists r\ Adjacent(r, s) \land Pit(r)$
    - More expressive than Propositional logic
- Agent's location & orientation(Space & Time)
  - Successive state

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