CSCI 3230

Fundamentals of Artificial Intelligence

Chapter 8

First Order Logic

Most commonly used Logic in AI with Prolog: natural language processing, vision understanding, human reasoning; CSP

Fall 2019

Outline

- Syntax and Semantics
- Extensions and Notational Variations
- Using First-Order Logic (FOL)
- Logical Agents for the Wumpus World
- A Simple Reflex Agent
- Representing Change in the World (Model-Based)
- Deducing Hidden Properties of the World
- Toward a Goal-Based Agent
- Knowledge Engineering Process

First-order logic
First-order Predicate Logic

basic categories and their relations

- First-order logic makes a stronger set of ontological (entities) commitments. The world consists of objects, i.e., things with individual identities and properties that distinguish them from other objects.
- Among these objects, various relations hold. Some relations are functions – relations with only one "value" for a given "input".
  - Objects: people, houses, numbers, theories, Ronald McDonald, colors, baseball games, wars, centuries…terms
  - Relations (Predicate): brother of, bigger than, inside, part of, has color, occurred after, owns…
  - Properties (unary relations): red, round, bogus, prime, multistoried…
  - Functions: father of, best friend, third inning of, one more than…terms
  - Facts: "One plus two equals three", "Squares neighboring the wumpus are smelly"…(atomic sentences)

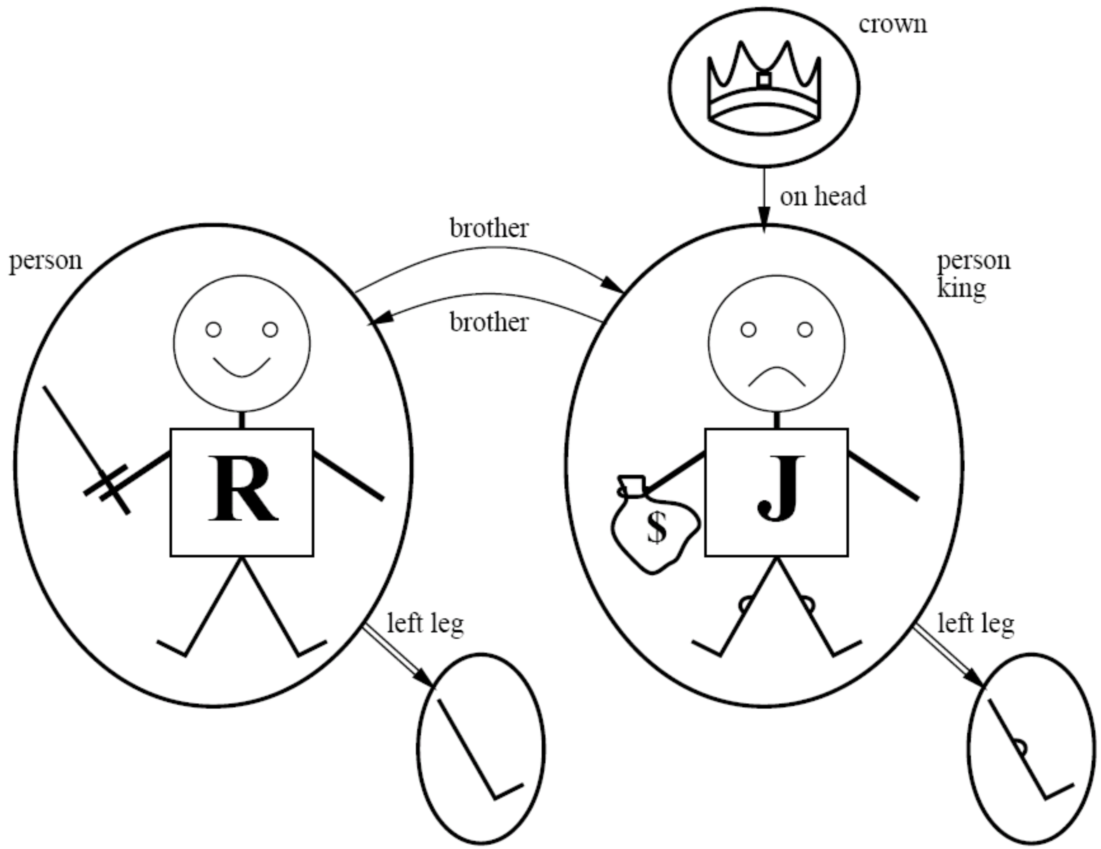
First-order logic

Objects?

Binary relations?

Unary relations
/properties?

Unary function?



predicates

Fig.8.0 A model containing 5 objects, 2 binary relations (brother, on head), 3 unary relations/properties (person, king, crown), and 1 unary function (left-leg).

First-order logic (FOL)

- FOL commits to the existence of objects and relations, it does not make an ontological commitment to such things as categories, time, and events. cf. OO classes
  E.g. John fell in love with Mary 2 hours ago.

- Existence defined by quantifiers: ∀ | ∃

- But FOL is universal in the sense that it can express anything that can be programmed. cf. Turing Machine
  any algorithm

Syntax and Semantics

- In propositional logic every expression is a sentence, which represents a fact; proposition symbol: constant.
- FOL has sentences, but also terms, which represent objects: Constant symbols, variables, and function symbols are used to build terms
- quantifiers and predicate symbols are used to build sentences.
  - Constant symbols: A, B, C, John…
    - An interpretation must specify which object in the world is referred to by each constant symbol.

Syntax and Semantics

- Predicate symbols: Brother, Bigger… e.g. Brother(John, Peter)
  - A predicate symbol refers to a particular relation in the model.
  - In a model, the relation is defined by the set of tuples of objects that satisfy it.
  - A tuple is a collection of objects arranged in a fixed order.

    (Extensional definition)

    E.g. { <John, Peter> … <examples of brothers>}

- Function symbols: Cosine, FatherOf, LeftLegOf…
  - Some relations are functional – i.e., any given object (John) is related to exactly one other object (LeftLeg) by the relation. E.g.LeftLegOf(John).

Syntax and Semantics

Sentence → Atomic-Sentence
| Sentence Connective Sentence
| Quantifier Variable, … Sentence
| ¬ Sentence | (Sentence)
Atomic-Sentence → Predicate(*Term*, …) | *Term* = *Term* *// facts*
Term → Function(*Term*, …) | Constant | Variable *// objects*
Connective → ⇒ | ∧ | ∨ | ⇔
Quantifier → ∀ | ∃
Constant → *A* | X_1 | *John* | …
Variable → *a* | *x* | *s*
Predicate → Before | HasColor | Raining | … *// relations:- unary(property) & binary*
Function → Mother | LeftLegof | … *// objects (functional relation)*

Fig 8.1 The syntax of first-order logic (with equality) in BNF (Backus-Naur Form)

Syntax and Semantics

- Terms: Function(Term, …) | Constant | Variable
  - A term is a logical expression that refers to an object. Constant symbols are ∴ terms.
  - The semantics of function: specifies a functional relation referred to by the *function symbol*, and objects (e.g. John) referred to by the arguments' terms. E.g. John's left leg: LeftLegOf(John)
- Atomic sentences
  - Atomic sentences state facts. An atomic sentence is formed from a predicate symbol followed by a parenthesized list of terms. e.g.,

    Brother (Richard, John)

    states, under the interpretation given before, that Richard the Lionheart is the brother of King John.

Syntax and Semantics

- Unary predicate (property):
  - hair_colour(John)=red,
  - Female (m)

Syntax and Semantics

Atomic sentences can have arguments that are complex terms:

Married(FatherOf(Richard), MotherOf(John))

states that Richard the Lionheart's father is married to King John's mother

(again, under a suitable interpretation)

- An atomic sentences is true if the relation (Teacher) referred to by the predicate symbol holds between the objects (Leung, CSCI 3230) referred to by the arguments.
  E.g. Teacher (Leung, CSCI 3230) is true

Syntax and Semantics

- Complex sentences semantics
  - We can use logical connectives to construct more complex sentences, like propositional calculus.
    - *Brother(Richard, John)* ∧ *Brother(John, Richard)* is true when John is the brother of Richard and Richard is the brother of John.
    - *Older(John, 30)* ∨ *Younger(John, 30)* is true when

      John is older than 30 or John is younger than 30.
    - *Older(John, 30)* ⇒ ¬ *Younger(John, 30)* states that

      if John is older than 30, then he is not younger than 30.
    - ¬ *Brother(Robin, John)* is true when

      Robin is not the brother of John.

Syntax and Semantics

- Quantifiers
  - Universal quantification (∀) (read: for all)
    - "All cats are mammals"

$$\forall x\ Cat(x) \Rightarrow Mammal(x)$$

    - The preceding sentence is therefore equivalent to

$$
\begin{aligned}
Cat(Spot) &\Rightarrow Mammal(Spot) \land \\
Cat(Rebecca) &\Rightarrow Mammal(Rebecca) \land \\
Cat(Felix) &\Rightarrow Mammal(Felix) \land \\
Cat(Richard) &\Rightarrow Mammal(Richard) \land \\
Cat(John) &\Rightarrow Mammal(John) \land \\
&\ldots.
\end{aligned}
$$

    - Thus, it is true iff all these sentences are true, i.e., if P is true for all object x in the universe. Hence ∀ is called a universal quantifier.

Syntax and Semantics

- Existential quantification ($\exists$) (read: there exist(s))
  - We can make a statement about some object in the universe without naming it using an existential quantifier. To say, e.g., that Spot has a sister who is a cat:

$$\exists x\ Sister(x, Spot) \wedge Cat(x)$$

  - In general $\exists x$ is true for some object in the universe.

$$\begin{gathered}(Sister(Spot, Spot) \wedge Cat(Spot)) \vee \\ (Sister(Rebecca, Spot) \wedge Cat(Rebecca)) \vee \\ (Sister(Felix, Spot) \wedge Cat(Felix)) \vee \\ (Sister(Richard, Spot) \wedge Cat(Richard)) \vee \\ (Sister(John, Spot) \wedge Cat(John)) \vee \\ \ldots\end{gathered}$$

(?? c.f. propositional logic??) The existentially quantified sentence is *true* just in case at least *one* of these disjuncts is true.

Syntax and Semantics

- Nested quantifiers
  - Express more complex sentences using multiple quantifiers. E.g., "For all x and all y, if x is the parent of y then y is the child of x" becomes

$$\forall x, y \; Parent(x, y) \Rightarrow Child(y, x)$$

    - $\forall x, y$ is equivalent to $\forall x \; \forall y$

All persons

  - Can have mixtures. "Everybody loves somebody" means that for every person, there is someone that person loves:

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

  - To say "There is someone who is loved by everyone" we write

?

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

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

There is someone loves everybody; Everybody is loved by someone

y, x (x,y) =>passive voice

Syntax and Semantics

- The order of quantification is ∴ important.
- $\forall x\ (\exists y\ P(x, y))$, where $P(x, y)$ says that *every* object x in the relation P to *some* y.
- $\exists x\ (\forall y\ P(x, y))$ says that there is *some* object in the world that has the property of being related by P to every object in the world.
- A minor difficulty – 2 quantifiers with the same variable name.
  - $\forall x\ [Cat(x) \vee (\exists x\ Brother(Richard, x))]$ Standardize apart; overloaded variable name;
  - One interpretation: $\exists x\ Brother(Richard, x)$ is a sentence about Richard (that he has a brother), not about x: So putting a $\forall x$ outside it has no effect.
- The term well-formed formula or wff is sometimes used for sentences that have all their variables properly introduced. E.g. $\forall x\ P(x, y)$, y is not properly introduced.

Syntax and Semantics

- Connections between $\forall$ and $\exists$
  - The 2 quantifiers are connected through negation.
  - When one says that everyone dislikes parsnips, one is also saying that there does not exist someone who likes them; and vise versa:

$$\forall x \, \neg Likes(x, Parsnips) \equiv \neg \exists x \, Likes(x, Parsnips)$$

  - "Everyone like ice-cream" means that there is no one who does not like ice-cream:

$$\forall x \, Likes(x, Ice\text{-}cream) \equiv \neg \exists x \, \neg Likes(x, Ice\text{-}cream)$$

  - De Morgan rules: thus, we do not really need both $\forall$ and $\exists$, just as we do not need both $\wedge$ and $\vee$. $\neg(\alpha \wedge \beta) \equiv (\neg \alpha \vee \neg \beta)$;
  - De Morgan for quantified sentences: $\neg \forall x \, R(x, y)) \equiv \exists x \, \neg R(x, y)$; $\forall x \, \neg R(x, y)) \equiv \neg \exists x \, R(x, y)$
  - De Morgan: $\forall x \, P \equiv \neg \exists x \, \neg P$; $\exists x \, P \equiv \neg \forall x \, \neg P$

Syntax and Semantics "=“

Equality

- FOL includes one more way to make atomic sentences, other than a predicate and terms. We can use the equality symbol to make statements that 2 terms refer to the same object. E.g.,

Prefix function

Father (John) = Henry *// infix*

- Equality can be viewed as a predicate symbol with a predefined meaning, i.e., identity relation.

Syntax and Semantics “=“

- The equality symbol can be used to describe the properties of a given function,

  e.g.: Father (John) = Henry

- It can also be used with negation to insist that two terms are not the same object. To say that Spot has at least 2 sisters:

  $\exists x, y\ Sister(Spot, x) \wedge Sister(Spot, y) \wedge \neg(x = y)$

- Simply writing $\exists x, y$ Sister(Spot, x) $\wedge$ Sister(Spot, y) would not assert the existence of 2 distinct sisters, $\because$ nothing says that x and y have to be different.

Extensions and Notational Variations
-Higher-order logic

- Named FOL ∵ it can quantify over objects (the first-order entities existed in the world) but not over relations or functions on those objects.

- Higher-order logic allows us to quantify over relations and functions as well as over objects. E.g., in higher-order logic 2 objects are equal iff all properties, p, applied to them are equivalent:

unary relations

$$\forall x, y\ (x = y) \Leftrightarrow \forall p\ p(x) \Leftrightarrow p(y))$$

- 2 functions, f & g, are equal iff they have the same value for all arguments:

$$\forall f, g\ (f = g) \Leftrightarrow \forall x\ f(x) = g(x))$$

- Higher-order logics have strictly more expressive power. But, logicians have little understanding of how to reason effectively with sentences in HOL, and the general problem is undecidable. (true or false)

Extensions and Notational Variations

–Functional and predicate expressions using the λ operator

(without defining the name of f or p)

- Useful to be able to construct complex predicates and functions from simpler components (e.g. $P \wedge Q$), or complex terms from simpler ones (e.g. $x^2 + y^3$).
- The operator λ (the Greek letter lambda) is used for this purpose. The function that takes the difference of the squares of its first and second arguments:

$$\lambda x, y \;\; x^2 - y^2$$

- This λ-expression can then be applied to arguments to yield a logical term in the same way that an ordinary, named function can:

$$(\lambda x, y \; x^2 - y^2)(25,24) = 25^2 - 24^2 = 49$$

$f(x,y)$

Extensions and Notational Variations

–Functional and predicate expressions using the λ operator

- E.g., the two-place predicate "are of differing gender and of the same address" can be written

  $\lambda x, y \;\; Gender(x) \neq Gender(y) \;\wedge\; Address(x) = Address(y)$

  the application of a predicate λ-expression to an appropriate number of arguments yields a logical sentence.

- λ does not increase the formal expressive power of FOL, ∵ any sentence with a λ-expression can be rewritten by "plugging in" its arguments to yield a standard term or sentence.

Extensions and Notational Variations
–The uniqueness quantifier ∃!

- Some authors use the notation

$$\exists ! x \ \mathrm{King}(x)$$

to mean "there exists a unique object x satisfying King(x)" or more informally, "there's exactly one King."

–not a new quantifier, ∃!, but a convenient abbreviation for the longer sentence

$$\exists x \ \mathrm{King}(x) \land \forall y \ \mathrm{King}(y) \Rightarrow x = y$$

- A more complex example is "Every country has exactly one ruler":

$$\forall c \ \mathrm{Country}\ (c) \Rightarrow \exists ! r \ \mathrm{Ruler}\ (r, c)$$

Extensions and Notational Variations
–The uniqueness operator ι

- More convenient to have a term representing the unique object directly. The notation $\iota x\ P(x)$ is commonly used.

  (The symbol ι is the Greek letter iota).

- To say that "the unique ruler of Freedonia is dead" or equivalently "the r that is the ruler of Freedonia is dead", we write (Note iota has a freer format and can be put inside brackets):

$$Dead(\iota\ r\ Ruler(r, Freedonia))$$

- This is just an abbreviation for the following sentence:

$$\exists! r\ Ruler(r, Freedonia) \wedge \forall s\ Ruler(s, Freedonia) \Rightarrow Dead(s)$$

Notational variations

The first-order logic notation used in this book is the *de facto* standard for artificial intelligence; one can safely use the notation in a journal article without defining it, because it is recognizable to most readers. Several other notations have been developed, both within AI and especially in other fields that use logic, including mathematics, computer science, and philosophy. Here are some of the variations:

Syntax item	This book	Others
Negation (not)	$\neg P$	$\sim P \quad \overline{P}$
Conjunction (and)	$P \wedge Q$	$P \& Q \quad P \cdot Q \quad PQ \quad P.Q$
Disjunction (or)	$P \vee Q$	$P \mid Q \quad P;Q \quad P+Q$
Implication (if)	$P \Rightarrow Q$	$P \rightarrow Q \quad P \supset Q$
Equivalence (iff)	$P \Leftrightarrow Q$	$P \equiv Q \quad P \leftrightarrow Q$
Universal (all)	$\forall x \; P(x)$	$(\forall x)P(x) \quad \bigwedge x \, P(x) \quad P(x)$
Existential (exists)	$\exists x \; P(x)$	$(\exists x)P(x) \quad \bigvee x \, P(x) \quad P(Skolem_i)$
Relation	$R(x, y)$	$(R \; x \; y) \quad Rxy \quad xRy$

Extensions and Notational Variations
–Notational variations

Some variations: (see table)

Prolog has 3 main differences:

- It uses uppercase letters for variables and lowercase for constants.
- Prolog also reverses the order of implications, writing Q:–P instead of P ⇒ Q.
- A comma is used both to separate arguments and for conjunction, and a period marks the end of a sentence:

Cat (X) :- furry(X), meows(X), has(X, claws).

Because Lisp does not distinguish between uppercase and lowercase symbols, variables are usually distinguished by an initial ? or $ character, e.g.:

(forall ?x (implies (and (furry ?x) (meows ?x) (has ?x claws)) (cat ?x)))

Using First-Order Logic
-The kinship domain

In knowledge representation, a domain is a section of the world about which we wish to express some knowledge.

The kinship domain

includes facts such as "Elizabeth is the mother of Charles" and "Charles is the father of William." and

rules such as "If x is the mother of y and y is a parent of z, then x is a grandmother of z."

The objects in our domain are people whose properties include gender, related by relations such as parenthood, brotherhood, marriage, and so on. ∴ have 2 unary predicates, Male and Female.

property

Using First-Order Logic
–The kinship domain

Most of the kinship relations will be binary predicates: *Parent, Sibling, Brother, Sister, Child, Daughter, Son, Spouse, Wife, Husband, Grandparent, Grandchild, Cousin, Aunt, Uncle, Nephew(male), Niece(f).* *How to define Mother from above terms?? Property: male | female.*

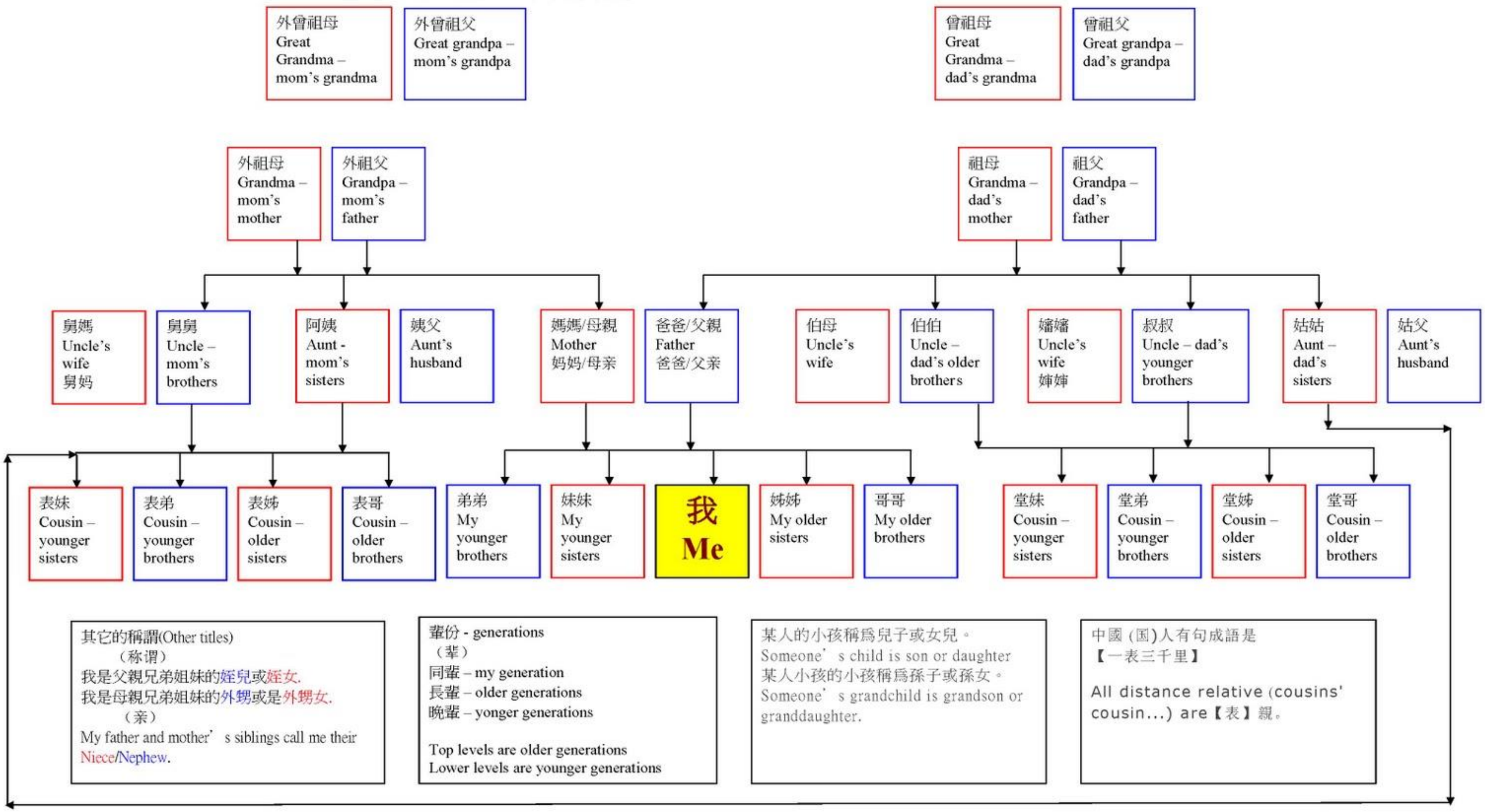
- Use functions for Mother and Father, ∵ every person has exactly one of each of these (at least according to nature's design).
- E.g. One's Mother is one's female parent:

$$\forall m, c\ \overset{\text{function}}{\text{Mother}}(c) = m \Leftrightarrow \overset{\text{property}}{\text{Female}}(m) \wedge \overset{\text{relation}}{\text{Parent}}(m, c)$$

- One's husband is one's male spouse:

$$\forall w, h\ \text{Husband}(h, w) \Leftrightarrow \text{Male}(h) \wedge \text{Spouse}(h, w)$$

中英文親戚稱謂表/亲戚称谓表/Relatives



Created by Tulan Hu 2009

Using First-Order Logic
–The kinship domain

- Male and female are disjoint categories:

  $\forall x\ Male(x) \Leftrightarrow \neg Female(x)$

- Parent and child are inverse relations:

  $\forall p, c\ Parent(p, c) \Leftrightarrow Child(c, p)$

- A grandparent is a parent of one's parent:

  $\forall g, c\ Grandparent(g, c) \Leftrightarrow \exists p\ Parent(g, p) \wedge Parent(p, c)$?∃p?

Sibling (parent)??

- A sibling is another child of one's parents:

  $\forall x, y\ Sibling(x, y) \Leftrightarrow \underline{x \neq y \wedge \exists p\ Parent(p, x) \wedge Parent(p, y)}$

Using First-Order Logic
-Axioms, definitions and theorems

- Mathematicians write axioms to capture the basic facts about a domain, define other concepts in terms of these basic facts, then use the axioms and definitions to prove theorems. Lemma
- Sentences in the knowledge base initially are sometimes called "axioms", or "definitions".
- Important question: have we written down enough axioms to fully specify a domain? In many domains, no clearly identifiable basic set.
- Converse problem: do we have too many sentences? E.g., do we need the following sentence, specifying that siblinghood is a symmetric relation? Commutative
    - $\forall x, y\ Sibling(x, y) \Leftrightarrow Sibling(y, x)$

Using First-Order Logic
–Axioms, definitions and theorems

- Answer is NO. From Sibling(John, Richard),
  we can infer that
  - $\exists p$ Parent(p , John) $\wedge$ Parent(p, Richard).

  And from that we can infer? Sibling(Richard, John). (last axiom, p29)

  $\forall x, y\ Sibling(x, y) \Leftrightarrow x \neq y \wedge \exists p\ Parent(p, x) \wedge Parent(p, y)$
- In mathematics, an independent axiom is one that cannot be derived from all the other axioms. Mathematicians strive to produce a minimal set of axioms that are all independent.
- In AI, common to include redundant axioms, not because of what can be proved, but make proof more efficient.
- An axiom of the form $\forall x, y\ P(x, y) \Leftrightarrow \ldots$ is often called a definition of P, $\because$ it defines exactly for what object/predicate P does and does not hold.
  - Possible to have several definitions; e.g., a triangle could be defined as a polygon with 3 sides or 3 angles.

Using First-Order Logic
–The domain of sets

Set is a predicate that is true only of sets. The following eight axioms provide this:

1. The only sets are the empty set and those made by adjoining something to a set.

$$\forall s\ Set(s) \Leftrightarrow (s = EmptySet)$$
$$\vee\ (\ \exists x, s_2\ \underline{Set(s_2)} \wedge \underline{s = Adjoin(x\ ,\ s_2)})$$

There does not exist

2. The empty set has no elements adjoined into it. (In other words, there is no way to decompose EmptySet in to a smaller set and an element.)

$$\neg\exists x, s\ Adjoin(x, s) = EmptySet$$

3. Adjoining an element already in the set has no effect:

$$\forall x, s\ Member(x, s) \Leftrightarrow \underline{s = Adjoin(x, s)}$$

Using First-Order Logic
-The domain of sets

4. The only members of a set are the elements that were adjoined into it. We express this recursively, saying that x is a member of s iff s is equal to some set s_2 adjoined with some element y, where either y is the same as x or x is a member of s_2.

$$\forall x, s \ \text{Member}(x, s) \Leftrightarrow$$
$$\exists y, s_2 \ (\underline{s = \text{Adjoin}(y, s_2)} \land (\overset{\text{newly added}}{\underline{x = y}} \lor \overset{\text{x already existed}}{\underline{\text{Member}(x, s_2)}}))$$

5. A set is subset of another iff all of the first set's members are members of the second set.

$$\forall s_1, s_2 \ \text{Subset}(s_1, s_2) \Leftrightarrow$$
$$(\forall x \ \text{Member}(x, s_1) \Rightarrow \text{Member}(x, s_2))$$

6. Two sets are equal iff each is a subset of the other.

$$\forall s_1, s_2 \ (s_1 = s_2) \Leftrightarrow (\text{Subset}(s_1, s_2) \land \text{Subset}(s_2, s_1))$$

Using First-Order Logic
-The domain of sets

7. An object is a member of the intersection of two sets if and only if it is a member of each of the sets.

$$\forall x, s_1, s_2\ Member(x, Intersection(s_1, s_2)) \Leftrightarrow Member(x, s_1) \land Member(x, s_2)$$

8. An object is a member of the union of two sets if and only if it is a member of either set.

$$\forall x, s_1, s_2\ Member(x, Union\ (s_1, s_2)) \Leftrightarrow Member(x, s_1) \lor Member(x, s_2)$$

The domain of <u>lists</u> is very similar to the domain of sets. The difference is that lists are <u>ordered</u>, and the same element can appear <u>more than once</u> in a list.

Using First-Order Logic
–Asking questions and getting answers

- To add the kinship sentences to a knowledge base KB, e.g.

  TELL(KB, ($\forall$m, c Mother (c) = m
  $\Leftrightarrow$ Female (m) $\wedge$ Parent (m, c)))

- If we tell it

  TELL(KB, Female(Maxi) $\wedge$ Parent(Maxi, Spot)
  $\wedge$ Parent(Spot, Boots)))

  then we can

  - ASK(KB, Grandparent(Maxi, Boots))

  and receive an affirmative answer.

- Add sentences using TELL – called assertions
- Ask questions using ASK – called queries or goals (different to an agent's desired states).

- Thus, a query with existential variables is asking "Is there an x such that ...," and we solve it by providing such an x. The standard form for an answer is a substitution or binding list – a set of variable/term pairs.

Logical Agents for the Wumpus World

We will consider 3 agent architectures:

1. reflex agents that merely classify their percepts and act accordingly;
2. model-based agents that construct an internal representation of the world and use it to act; and
3. goal-based agents that form goals and try to achieve them. (Goal-based agents are usually also model-based agents.)

> **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*

Fig 8.2 A generic knowledge-based agent

A Simple Reflex Agent

- The simplest kind of agent has rules directly connecting percepts to actions.
  - These rules resemble reflexes or instincts. E.g., if the agent sees a glitter, it does a grab to pick up the gold.

$$\forall s, b, u, c, t \; Percept([s, b, Glitter, u, c], t) \Rightarrow Action(Grab, t)$$

- The connection between percept and action can be mediated by rules for perception, which abstract the immediate perceptual input into more useful forms (e.g. concepts):

concepts

$$\forall b, g, u, c, t \; Percept([stench, b, g, u, c], t) \Rightarrow Stench(t)$$

$$\forall s, g, u, c, t \; Percept([s, Breeze, g, u, c], t) \Rightarrow Breeze(t)$$

$$\forall s, b, u, c, t \; Percept([s, b, Glitter, u, c], t) \Rightarrow AtGold(t)$$

…

Then a connection can be made from these predicates to action:

$$\forall t \; AtGold(t) \Rightarrow Action(Grab, t)$$

A Simple Reflex Agent

Limitations of simple reflex agents

- Have a hard time in the wumpus world.
- A pure reflex agent cannot know for sure when to climb, ∵ neither having the gold nor being in the start square is a percept; they are a representation (model) of the world. (state)
- They also cannot avoid infinite loops. Randomization provides some relief, but risking many fruitless actions.

Representing Change in the World

(+Situation) (Model Based Agents)

location only

- The easiest way to deal with change is to change the knowledge base; to erase the sentence that says the agent is at [1,1], and replace it with says at [1,2].
- But all past knowledge is lost, and it prohibits speculation about different possible futures.

Situation Calculus

- It conceives of the world as consisting of a sequence of situations, each of which is a "snapshot" of the state of the world.
- Situations are generated from previous situations by actions, as shown in the following figure:

Representing Change in the World
(+Situation)

location only

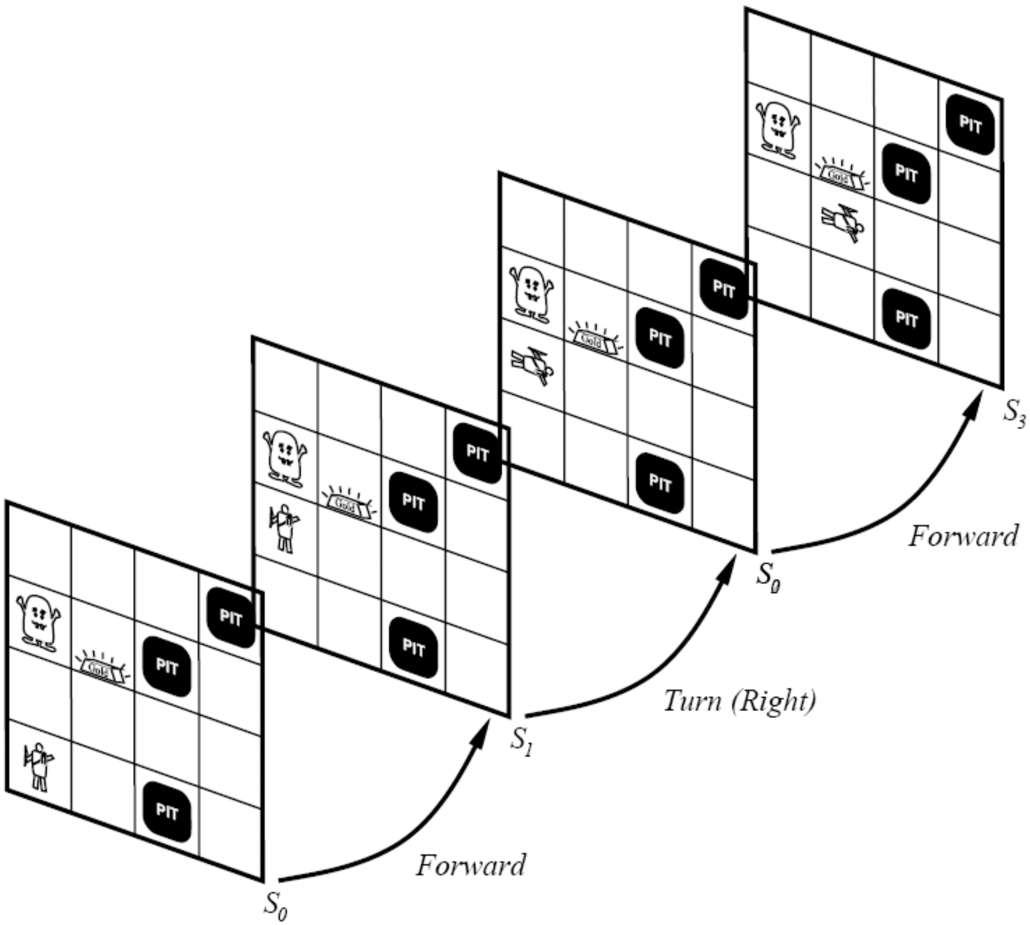


Fig 8.3, In situation calculus, the world is a sequence of situations linked by actions.

Deducing Hidden Properties of the World
(Situation: location + properties)

- Once the agent knows where it is, it can associate properties, situations (s), with the places (l). l: location

  $\forall l, s\ At(Agent, l, s) \wedge Breeze(s) \Rightarrow Breezy(l)$

  $\forall l, s\ At(Agent, l, s) \wedge Stench(s) \Rightarrow Smelly(l)$

- It is useful to know if a place is breezy or smelly ∵ wumpuses and pits cannot move about.

Deducing Hidden Properties of the World
(Situation: location + properties)

2 main kinds of synchronic rules: (same world state(time))

Causal & Diagnostic rules

(1) *Causal rules:* reflect the assumed direction of causality in the world: some hidden property of the world causes certain percepts to be generated.

- E.g., rules stating that squares adjacent to wumpuses are smelly and squares adjacent to pits are breezy:

$$\forall l_1, l_2, s\ At(Wumpus, l_1, s) \wedge Adjacent(l_1, l_2) \Rightarrow Smelly(l_2)$$

$$\forall l_1, l_2, s\ At(Pit, l_1, s) \wedge Adjacent(l_1, l_2) \Rightarrow Breezy(l_2)$$

?percepts on the right

- Systems that reason with causal rules are called model-based reasoning systems, which help to understand the reasoning chain explicitly

causality ≠ co-existence ≠ coincidence

Deducing Hidden Properties of the World
(Situation: location + properties)

(2) *Diagnostic rules*: infer the presence of hidden properties directly from the percept-derived information.

$$\forall l, s\ At(Agent, l, s) \wedge Breeze(s) \Rightarrow Breezy(l)$$

- For deducing the presence of pits/wumpuses, a diagnostic rule can only draw weak conclusion.

$$\forall l_1, s\ Breezy(l_1) \Rightarrow \exists l_2\ At(Pit, l_2, s) \wedge Adjacent(l_1, l_2)$$

Symptoms (percepts) ⇒ diagnosis

- Bi-conditional sentence can be diagnostic and casual rules:

$$\forall l\ Breezy(l) \Leftrightarrow \exists r\ Pit(r) \wedge Adjacent(r, l)$$

Deducing Hidden Properties of the World
(Situation: location + properties)

- Diagnostic rules examples: The absence of stench or breeze implies that adjacent squares are OK:

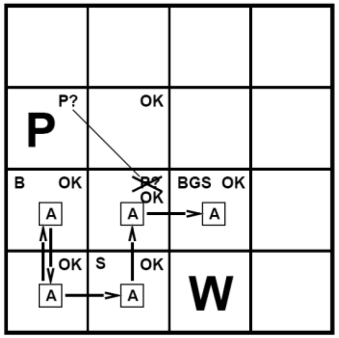
$$\forall x, y, g, u, c, s\ \text{Percept}([\text{None}, \text{None}, g, u, c], t) \wedge \text{At}(\text{Agent}, x, s) \wedge \text{Adjacent}(x, y) \Rightarrow \text{OK}(y)$$

- But sometimes a square can be OK even when smells and breezes abound.

- The model-based rule:

$$\forall x, t\ \neg\, \text{At}(\text{Wumpus}, x, t) \wedge \neg\, \text{Pit}(x)\,) \Leftrightarrow \text{OK}(x)$$

  is probably the best way to represent safety.



Toward a Goal-Based Agent

- Once the gold is found, the aim now is to return to the start square as quickly as possible. So have to infer that the agent has the goal of being at location [1,1]:

$$\forall s\ \text{Holding}(\text{Gold}, s) \Rightarrow \text{GoalLocation}([1,1], s)$$

- 3 ways to find the action sequence:
- Inference: Write axioms that allow us to ASK the KB for a sequence of actions to achieve the goal safely.
- Search: Use best-first search (Chap.4) to find a path to the goal.
- Planning: Use special-purpose reasoning systems designed to reason about action.

Knowledge Engineering Process

1. Identify the task (problem specification/ definition)
2. Assemble the relevant knowledge – knowledge acquisition (system analysis)
3. Decide on a vocabulary of predicates, function and constants (design)

iterate

4. Encode general knowledge about the domain (coding)
5. Encode a description of the specific problem instance – precepts/inputs/facts to handle (coding sub-programs, I/O)
6. Pose queries to the inference procedure to get answer (testing & evaluation)
7. Debug the knowledge base (testing & evaluation)