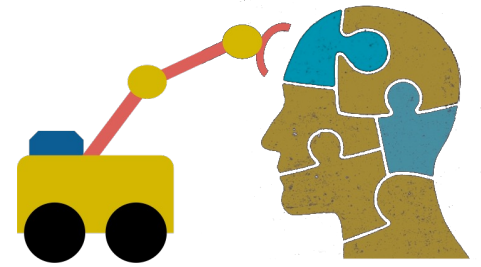


9.3.1



First-Order Logic (FOL) part 1

FOL Overview

- First Order logic (FOL) is a powerful knowledge representation (KR) system
- Used in AI systems in various ways, e.g., to
 - Directly represent & reason about concepts & objects
 - Formally specify meaning of KR systems (e.g., [OWL](#))
 - For programming languages (e.g., [Prolog](#)) and [rule-based systems](#)
 - For semantic database systems ([Datalog](#)) and knowledge graphs ([Wikidata](#), [Schema.org](#))
 - Provide features useful in neural network deep learning systems

First-order logic

- First-order logic (FOL) models the world in terms of
 - **Objects**: things with individual identities
 - **Properties** of objects that distinguish them from others
 - **Relations** that hold among sets of objects
 - **Functions**, a subset of relations where there is only one “value” for any given “input”
- Examples:
 - Objects: students, lectures, companies, cars ...
 - Relations: isa, hasBrother, biggerThan, outside, hasPart, color, occursAfter, owns, visits, precedes, ...
 - Properties: blue, oval, even, large, ...
 - Functions: hasFather, hasSSN, ...

User provides

- **Constant symbols** representing individuals in world
 - BarackObama, Green, John, 3, “John Smith”
- **Predicate symbols** map individuals to truth values
 - greater(5,3)
 - green(Grass)
 - color(Grass, Green)
 - hasProperty(Grass, Color, Green)
- **Function symbols** map individuals to individuals
 - hasFather(SashaObama) = BarackObama
 - colorOf(Sky) = Blue

How to represent properties and relations depends on our goals

What do these mean?



- We must indicate what these mean in ways humans will understand
 - i.e., map to their own internal representations
- May be done via a combination of
 - Choosing good names for formal terms, e.g., calling a concept `HumanBeing` instead of [Q5](#)
 - Add comments in the definition `#human being`
 - Descriptions and examples in documentation
 - Reference to other representations , e.g., `sameAs` [Q5](#) in Wikidata and [Person](#) in schema.org
 - Give examples like *Donald Trump* and *Luke Skywalker* to help distinguish concepts of real and fictional person

FOL Provides

Notations
differ, of
course!

- **Variable symbols** (syntax varies)
 - e.g., X , Y , $?x$, $?foo$, $?number$
- **Connectives**
 - Same as propositional logic: not (\neg), and (\wedge), or (\vee), implies (\rightarrow), iff (\leftrightarrow), equivalence (\equiv), ...
- **Quantifiers**
 - Universal $\forall x$ or **(Ax)**
 - Existential $\exists x$ or **(Ex)**

Sentences: built from terms and atoms

- **term** (denoting an individual): constant or variable symbol, or n-place function of n terms, e.g.:
 - **Constants:** john, umbc
 - **Variables:** X, Y, Z
 - **Functions:** mother_of(john), phone(mother(x))
- **Ground terms** have no variables in them
 - **Ground:** john, father_of(father_of(john))
 - **Not Ground:** father_of(?X)
- Syntax varies, e.g., variables start with a “?” or a capital letter, or identified by qualifiers ($\forall \mathbf{x}$, $\exists \mathbf{y}$)

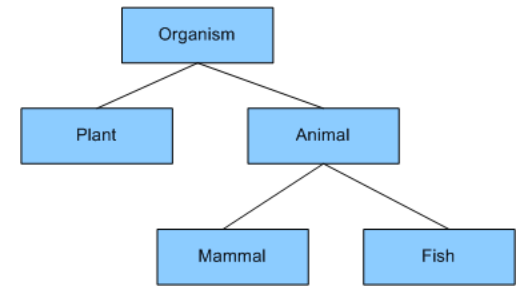
Sentences: built from terms and atoms

- **atomic sentences** (which are either true or false) are n-place predicates of n terms, e.g.:
 - green(kermit)
 - between(philadelphia, baltimore, dc)
 - loves(X, mother(X))
- **complex sentences** formed from atomic ones connected by the standard logical connectives with quantifiers if there are variables, e.g.:
 - loves(mary, john) \vee loves(mary, bill)
 - $\forall x$ loves(mary, x)

What do atomic sentences mean?

- Unary predicates often used to encode a **type** or **class** that something is part of
 - **muppet(kermit)**: kermit is a muppet
 - **green(kermit)**: kermit is a green thing
 - **integer(X)**: X is an integer
- Non-unary predicates typically encode **relations** or **properties**
 - Loves(john, mary)
 - Greater_than(2, 1)
 - Between(newYork, philadelphia, baltimore)
 - hasName(john, “John Smith”)

Ontology



- Designing a logic representation is like designing a model in an object-oriented language
- **Ontology:** a “formal naming and definition of the types, properties, and relations of entities for a domain of discourse”
- E.g.: schema.org ontology used to put semantic data on Web pages to help search engines
 - Here’s the [semantic markup](#) Google sees on our site
 - It’s encoded as JSON, but the model is logic

Sentences: built from terms and atoms

- **quantified sentences** adds quantifiers \forall and \exists
 - $\forall x \text{ loves}(x, \text{mother}(x))$
 - $\exists x \text{ number}(x) \wedge \text{greater}(x, 100), \text{prime}(x)$
- **well-formed formula (wff)**: a sentence with no *free* variables or where all variables are *bound* by a universal or existential *quantifier*
 - In $(\forall x)P(x, y)$ x is bound & y is free so it's not a wff

Quantifiers: \forall and \exists

- **Universal quantification**

- $(\forall x)P(X)$ means P holds for **all** values of X in the domain associated with variable¹
- E.g., $(\forall X) \text{dolphin}(X) \rightarrow \text{mammal}(X)$
“all dolphins are mammals”

- **Existential quantification**

- $(\exists x)P(X)$ means P holds for **some** value of X in domain associated with variable
- E.g., $(\exists X) \text{mammal}(X) \wedge \text{lays_eggs}(X)$
“There is a mammal that lays eggs”
- Lets us make statements about an object without identifying it

¹ a variable's domain is often not explicitly stated and is assumed by the context

Universal Quantifier: \forall

- **Universal quantifiers typically used with *implies* to form *rules*:**

Logic: $\forall X \text{ student}(X) \rightarrow \text{smart}(X)$

Means: All students are smart

- **Universal quantification *rarely* used without *implies*:**

Logic: $\forall X \text{ student}(X) \wedge \text{smart}(X)$

Means: Everything is a student and is smart

- **What about this, though:**

– *Logic:* $\forall X \text{ alive}(X) \vee \text{dead}(X)$

– Means: everything is either alive or dead

Universal Quantifier: \forall

- **What about this, though:**

- *Logic:* $\forall X \text{ alive}(X) \vee \text{dead}(X)$

- Means: everything is either alive or dead

- **Can be rewritten using a standard tautology**

- $A \vee B \equiv \sim A \rightarrow B$

- **Giving both of these (since $A \vee B \equiv B \vee A$)**

- $\forall X \sim \text{alive}(X) \rightarrow \text{dead}(X)$

- $\forall X \text{ alive}(X) \rightarrow \sim \text{dead}(X)$

Existential Quantifier: \exists

- Existential quantifiers usually used with **and** to specify a list of properties about an individual

Logic: $(\exists X) \text{ student}(X) \wedge \text{ smart}(X)$

Meaning: There is a student who is smart

- Common mistake: represent this in FOL as:

Logic: $(\exists X) \text{ student}(X) \rightarrow \text{ smart}(X)$

Meaning: ?

Existential Quantifier: \exists

- Existential quantifiers usually used with **and** to specify a list of properties about an individual

Logic: $(\exists X) \text{ student}(X) \wedge \text{ smart}(X)$

Meaning: There is a student who is smart

- Common mistake: represent this in FOL as:

Logic: $(\exists X) \text{ student}(X) \rightarrow \text{ smart}(X)$

$P \rightarrow Q = \sim P \vee Q$

$\exists X \text{ student}(X) \rightarrow \text{ smart}(X) = \exists X \sim \text{ student}(X) \vee \text{ smart}(X)$

Meaning: There's something that is either not a student or is smart

Quantifier Scope

- FOL sentences have structure, like programs
- In particular, variables in a sentence have a **scope**
- Suppose we want to say “everyone who is alive loves someone”

$$(\forall X) \text{ alive}(X) \rightarrow (\exists Y) \text{ loves}(X, Y)$$

- Here’s how we scope the variables

$$(\forall X) \text{ alive}(X) \rightarrow (\exists Y) \text{ loves}(X, Y)$$

 Scope of x
 Scope of y

Quantifier Scope

- **Switching order of two universal quantifiers *does not* change the meaning**
 - $(\forall X)(\forall Y) P(X,Y) \leftrightarrow (\forall Y)(\forall X) P(X,Y)$
 - Dogs hate cats (i.e., all dogs hate all cats)
- **You can switch order of existential quantifiers**
 - $(\exists X)(\exists Y) P(X,Y) \leftrightarrow (\exists Y)(\exists X) P(X,Y)$
 - A cat killed a dog
- **Switching order of universal and existential quantifiers *does* change meaning:**
 - Everyone likes someone: $(\forall X)(\exists Y) \text{likes}(X,Y)$
 - Someone is liked by everyone: $(\exists Y)(\forall X) \text{likes}(X,Y)$

```
def verify1():
```

```
    # Everyone likes someone:  $(\forall x)(\exists y) \text{ likes}(x,y)$ 
```

```
    for p1 in people():
```

```
        foundLike = False
```

```
        for p2 in people():
```

```
            if likes(p1, p2):
```

```
                foundLike = True
```

```
                break
```

```
        if not foundLike:
```

```
            print(p1, 'does not like anyone 😞')
```

```
            return False
```

```
    return True
```

Every person has at least one individual that they like

Procedural example 1

```
def verify2():
```

```
    # Someone is liked by everyone:  $(\exists y)(\forall x) \text{likes}(x,y)$ 
```

```
    for p2 in people():
```

```
        foundHater = False
```

```
        for p1 in people():
```

```
            if not likes(p1, p2):
```

```
                foundHater = True
```

```
                break
```

```
        if not foundHater
```

```
            print(p2, 'is liked by everyone 😊')
```

```
            return True
```

```
    return False
```

There is a person who is liked by every person in the universe

Procedural example 2

Connections between \forall and \exists

- We can relate sentences involving \forall and \exists using extensions to De Morgan's laws:

1. $(\forall x) P(x) \leftrightarrow \neg(\exists x) \neg P(x)$

2. $\neg(\forall x) P(x) \leftrightarrow (\exists x) \neg P(x)$

3. $(\exists x) P(x) \leftrightarrow \neg(\forall x) \neg P(x)$

4. $(\exists x) P(x) \leftrightarrow \neg(\forall x) \neg P(x)$

- Examples

1. All dogs don't like cats \leftrightarrow No dog likes cats

2. Not all dogs bark \leftrightarrow There is a dog that doesn't bark

3. All dogs sleep \leftrightarrow There is no dog that doesn't sleep

4. There is a dog that talks \leftrightarrow Not all dogs can't talk

Notational differences

- **Different symbols** for *and*, *or*, *not*, *implies*, ...

– $\forall \exists \Rightarrow \Leftrightarrow \wedge \vee \neg \bullet \supset$

– $p \vee (q \wedge r)$

– $p + (q * r)$

- **Different syntax** for variables vs. constants, predicates vs. functions, etc.

Notational differences

“anything that is furry, meows and has claws is a cat”

- **Typical logic notation**

$\forall x \exists y \text{furry}(x) \wedge \text{meows}(x) \wedge \text{has}(x, y) \wedge \text{claw}(y) \Rightarrow \text{cat}(x)$

- **Prolog**

`cat(X) :- furry(X), meows(X), has(X, Y), claw(Y).`

- **Lisp notations**

(forall ?x (implies (and (furry ?x) (meows ?x)
(has ?x ?y) (claw ?y))
(cat ?x)))

- **Python code**

e.g., AIMA python, [logic.ipynb](#)

- **Knowledge graph triples**

e.g., in [RDF/OWL](#) 

```
#Graph from http://www.doefamily.com/
@prefix doefamily: <http://www.doefamily.com/> .
@prefix foaf: <http://xmlns.com/foaf/0.1/> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix dbpedia: <http://dbpedia.org/resource/> .

doe:John rdf:type foaf:Person .
doe:John owl:sameAs dbpedia:John_Doe .
doe:John foaf:age 72 .
doe:John foaf:mbox <mailto:john@doe.com> .

doe:Jane rdf:type foaf:Person .
doe:Jane owl:sameAs dbpedia:Jane_Doe .
doe:Jane foaf:age 12 .
doe:Jane foaf:phone "512-475-6656" .
```

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