

First Order Logic – Semantics (3A)

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Based on

Contemporary Artificial Intelligence,
R.E. Neapolitan & X. Jiang

Logic and Its Applications,
Burkey & Foxley

Examples of Terms

no expression involving a **predicate symbol** is a term.

x y $f(x)$ $g(x, y)$

$father(x)$ A function returns neither True nor False

The father of x

$Father(x)$ A predicate returns always True or False

Is x a father?

$\forall x \text{ love}(x, y)$: free variable y
 $\forall x \text{ tall}(x)$: no free variable

Bound variable x

Free variable y

https://en.wikipedia.org/wiki/First-order_logic#Formation_rules

Terms

Terms

1. **Variables**. Any variable is a term.
2. **Functions**. Any expression $f(t_1, \dots, t_n)$ of n arguments is a term where each argument t_i is a term and f is a function symbol of valence n . In particular, symbols denoting **individual constants** are **0-ary function symbols**, and are thus terms.

Only expressions which can be obtained by finitely many applications of rules 1 and 2 are terms.

no expression involving a **predicate symbol** is a term.

https://en.wikipedia.org/wiki/First-order_logic#Formation_rules

Formulas

Formulas (wffs)

Predicate symbols.

Equality.

Negation.

Binary connectives.

Quantifiers.

$P(x)$ $Q(x, y)$

$x = f(y)$

$\neg Q(x, y)$

$P(x) \wedge \neg Q(x, y)$

$\forall x, y (P(x) \wedge \neg Q(x, y))$

Only expressions which can be obtained by finitely many applications of rules 1–5 are formulas.

The formulas obtained from the first two rules are said to be **atomic formulas**.

https://en.wikipedia.org/wiki/First-order_logic#Formation_rules

Formulas

Formulas (wffs)

Predicate symbols. If P is an n -ary predicate symbol and t_1, \dots, t_n are terms then $P(t_1, \dots, t_n)$ is a formula.

Equality. If the equality symbol is considered part of logic, and t_1 and t_2 are terms, then $t_1 = t_2$ is a formula.

Negation. If φ is a formula, then $\neg\varphi$ is a formula.

Binary connectives. If φ and ψ are formulas, then $(\varphi \rightarrow \psi)$ is a formula. Similar rules apply to other binary logical connectives.

Quantifiers. If φ is a formula and x is a variable, then $\forall x \varphi$ (for all x , holds) and $\exists x \varphi$ (there exists x such that φ) are formulas.

$$P(x) \quad Q(x, y)$$

$$x = f(y)$$

$$\neg Q(x, y)$$

$$P(x) \wedge \neg Q(x, y)$$

$$\forall x, y (P(x) \wedge \neg Q(x, y))$$

https://en.wikipedia.org/wiki/First-order_logic#Formation_rules

Atoms and Compound Formulas

a formula that contains **no logical connectives**

a formula that has **no strict subformulas**

Atoms :

the **simplest** well-formed formulas of the logic.

$$P(x) \quad Q(x, y)$$

Compound formulas :

formed by combining the atomic formulas using the **logical connectives**.

$$P(x) \wedge \neg Q(x, y)$$

$$\forall x, y (P(x) \wedge \neg Q(x, y))$$

https://en.wikipedia.org/wiki/Atomic_formula

Atomic Formula

for **propositional logic**

the atomic formulas are the **propositional variables**

p

q

for **predicate logic**

the atoms are **predicate symbols** together with their **arguments**,
each argument being a **term**.

$P(x)$

$Q(x, f(y))$

In **model theory**

atomic formula are merely strings of symbols with a given signature
which may or may not be satisfiable with respect to a given model

https://en.wikipedia.org/wiki/Atomic_formula

A Signature

First specify a **signature**

Constant Symbols $\{c_1, c_2, \dots, c_n\} = D$

Predicate Symbols $\{P_1, P_2, \dots, P_m\}$

Function Symbols $\{f_1, f_2, \dots, f_l\}$

A Language

Determines the **language**

Given a language

A **model** is specified

A **domain of discourse**

a set of entities

$\{\text{entity}_1, \text{entity}_2, \dots, \text{entity}_n\}$

An **interpretation**

constant assignments

$\{c_1, c_2, \dots, c_n\} = D$

function assignments

$f_1(), f_2(), \dots, f_l()$

truth value assignments

$P_1(), P_2(), \dots, P_m()$

Interpretation

Constant assignments

$\{entity_1, entity_2, \dots, entity_n\}$

$\{c_1, c_2, \dots, c_n\} = D$

Function assignments

$f_1(), f_2(,), \dots$

Truth value assignments

$P_1(), P_2(,), \dots$

always return T / F

Interpretation

Propositional Logic

	A	B
Interpretation I_1 →	T	T
Interpretation I_2 →	T	F
Interpretation I_3 →	F	T
Interpretation I_4 →	F	F

First Order Logic

	P1() ... P2() ...	S1	S2
Interpretation I_1 →	T T		
Interpretation I_2 →	T F		
Interpretation I_3 →	F T		
Interpretation I_4 →	F F		

Sentences

$\{\text{entity}_1, \text{entity}_2, \dots, \text{entity}_n\}$

$\{c_1, c_2, \dots, c_n\} = D$

$f_1(), f_2(,), \dots$

$P_1(), P_2(,), \dots$

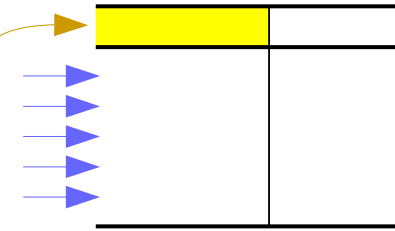
always return **T / F**

A Model

A **model** or a **possible world**:

Every **atomic proposition** is assigned a value **T** or **F**

The **set of all these assignments** constitutes
A **model** or a **possible world**

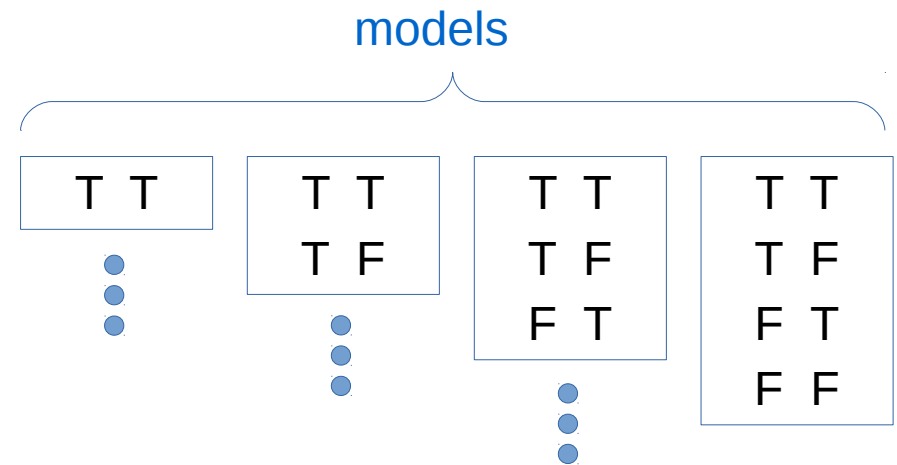


All possible worlds (assignments) are **permissible**

A	B	$A \wedge B$	$A \wedge B \Rightarrow A$
T	T	T	T
T	F	F	T
F	T	F	T
F	F	F	T



Every **atomic proposition** : A, B



$$2^4 = 16$$

Models and Signatures

$\{c_1, c_2, \dots, c_n\} = D1$

$f1(), f2(,), \dots$

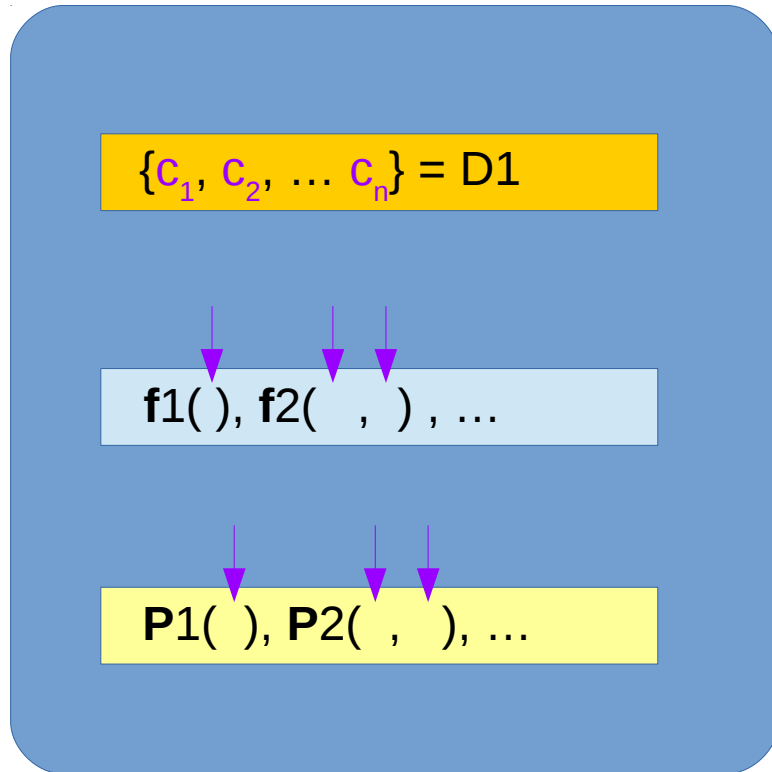
$P1(), P2(,), \dots$

$\{d_1, d_2, \dots, d_m\} = D2$

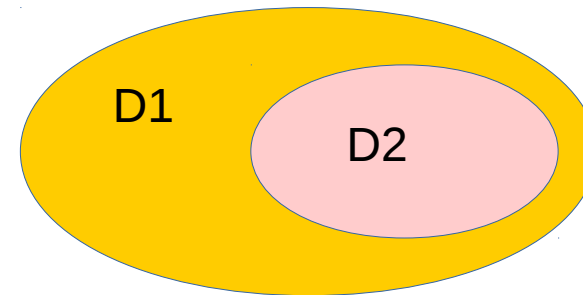
$f1(), f2(,), \dots$

$P1(), P2(,), \dots$

Models



$$\{d_1, d_2, \dots, d_m\} = D2$$



Truth values of sentences

Propositional Logic

	A	B
Interpretation I_1 →	T	T
Interpretation I_2 →	T	F
Interpretation I_3 →	F	T
Interpretation I_4 →	F	F

First Order Logic

Sentences

	P1()	P2()	...	S1	S2
Interpretation I_1 →	T	T			
Interpretation I_2 →	T	F			
Interpretation I_3 →	F	T			
Interpretation I_4 →	F	F			

terms	x y $f(x)$ $g(x, y)$
atomic formulas	$P(x)$ $Q(x, y)$
formulas / sentences	$\forall x, y (P(x) \wedge \neg Q(x, y))$

Model Theory

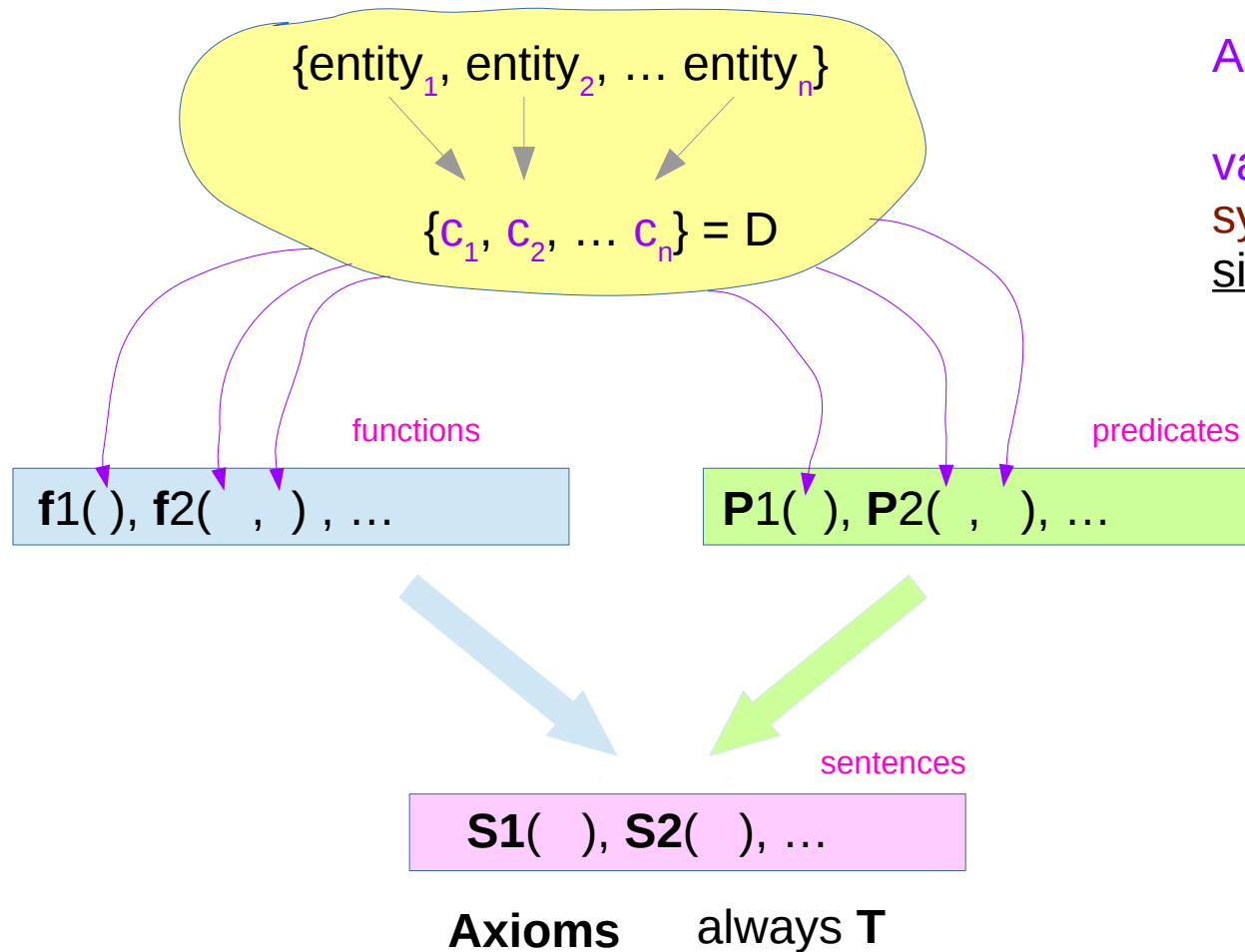
A first-order **theory** of a particular signature is
a set of **axioms**,
which are **sentences**
consisting of **symbols** from that signature.

The set of axioms is
often finite or
recursively enumerable,
in which case the theory is called effective.

Sometimes theories often include
all logical consequences of the **axioms**.

https://en.wikipedia.org/wiki/First-order_logic#First-order_theories.2C_models.2C_and_elementary_classes

Axioms of a model theory



Axioms

valid sentences consisting of symbols from a particular signature.

Models

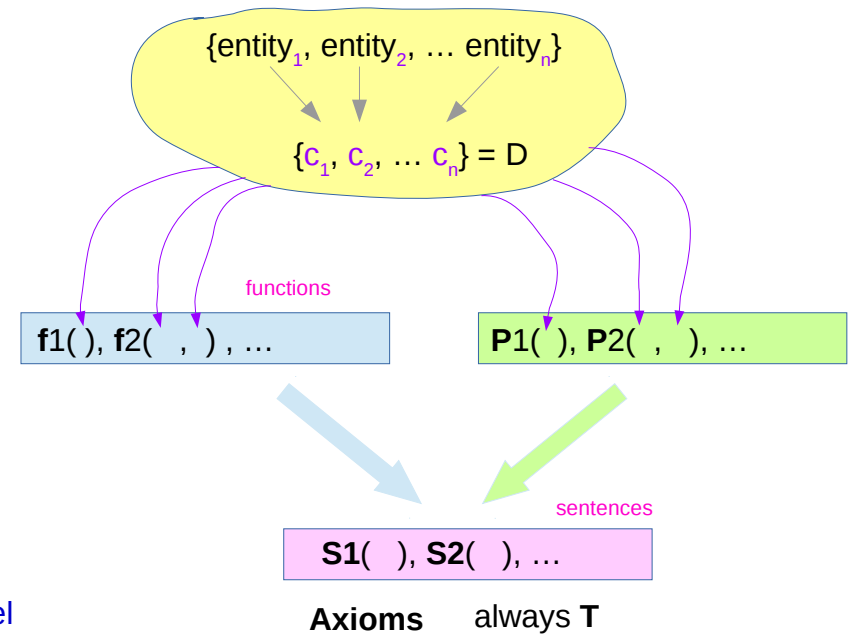
Propositional Logic

	A	B		
Interpretation I_1	T	T		
Interpretation I_2	T	F	T T T	→ a model
Interpretation I_3	F	T	T T T	→ a model
Interpretation I_4	F	F		

First Order Logic

	P1() ... P2() ...	Sentences		
		S1	S2 ...	
Interpretation I_1	T T			
Interpretation I_2	T F			
Interpretation I_3	F T	T	T	→ a model
Interpretation I_4	F F	T	T	→ a model
		T	T	→ a model

Signature



Logical Axioms

Logical Axioms - axioms

Non-logical Axioms - postulate – deductive system

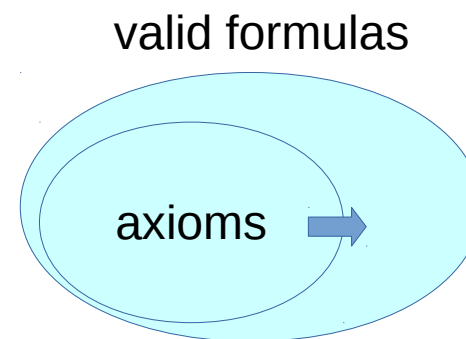
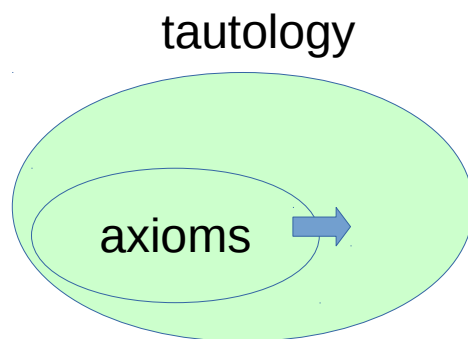
<https://en.wikipedia.org/wiki/Axiom>

Logical Axioms

formulas in a formal language that are **universally valid**
formulas that are **satisfied** by every assignment of values (**interpretations**)

usually one takes as **logical axioms**
at least some **minimal set of tautologies**
that is sufficient for proving **all tautologies** in the language

in the case of predicate logic more **logical axioms** than that are required,
in order to prove **logical truths** that are **not tautologies** in the **strict sense**.



<https://en.wikipedia.org/wiki/Axiom>

Non-logical Axioms

formulas that play the role of **theory-specific assumptions**

reasoning about **two different structures**,
for example the **natural numbers** and the **integers**,
may involve the same **logical axioms**;

the purpose is to find out
what is special about *a particular structure*
(or set of structures, such as groups).

Thus non-logical axioms are not **tautologies**.

<https://en.wikipedia.org/wiki/Axiom>

Mathematical Discourse

Also called

- **postulate**
- **axioms in mathematical discourse**

this does not mean that it is claimed
that they are true in some absolute sense

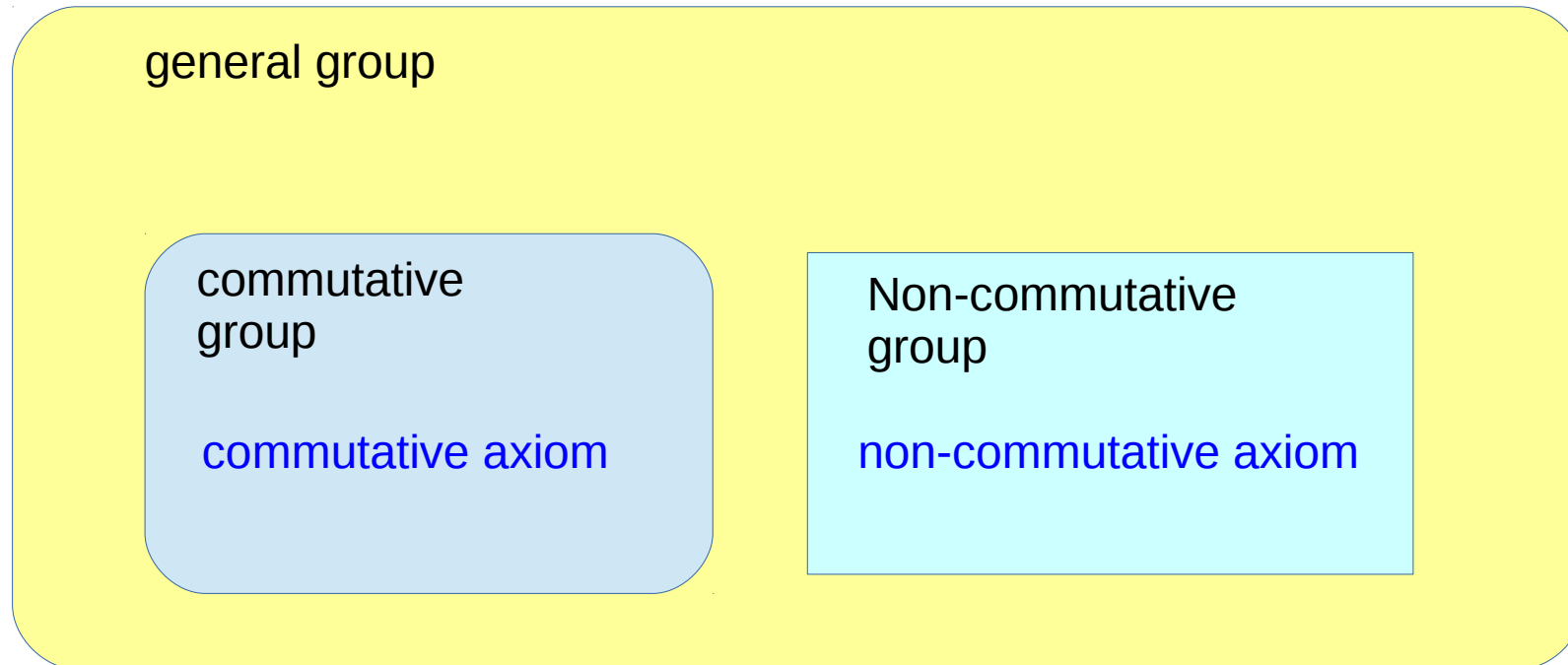
an elementary basis for a formal logic system

A deductive system

- **axioms** (non-logical)
- **rules of inference**

<https://en.wikipedia.org/wiki/Axiom>

Need not be tautologies



this does not mean that it is claimed
that they are true in some absolute sense

- Commutative axiom
- Non-commutative axiom

<https://en.wikipedia.org/wiki/Axiom>

Model Theory

The **axioms** are considered to *hold* within the **theory** and

From **axioms** other **sentences** that *hold* within the **theory** can be derived.

A first-order structure that satisfies **all** **sentences** in a given **theory** is said to be a **model** of the **theory**.

An **elementary class** is the set of **all** structures satisfying a particular **theory**.

These classes are a main subject of study in model theory.

https://en.wikipedia.org/wiki/First-order_logic#First-order_theories.2C_models.2C_and_elementary_classes

Truth values of sentences

Entailment in propositional logic can be computed
By enumerating the possible worlds (i.e. model checking)

How to enumerate possible worlds in FOL?

For each number of domain number n from 1 to infinity

For each k -ary predicate P_k in the vocabulary

For each possible k -ary relation on n objects

For each constant symbol C in the vocabulary

For each choice of referent for C from n objects. ..

Computing entailment in this way is not easy.

<https://www.cs.umd.edu/~nau/cm421/chapter08.pdf>

Model – domain of discourse

1. a nonempty set D of **entities** called a **domain of discourse**
 - this domain is a set
 - each element in the set : entity
 - each constant symbol : one entity in the domain

If we considering all individuals in a class,
The constant symbols might be

'Mary', - an entity
'Fred', - an entity
'John', - an entity
'Tom' - an entity

Model – interpretation

2. an **interpretation**

(a) an entity in D is assigned to each of the constant symbols.

Normally, every entity is assigned to a constant symbol.

(b) for each **function**,

an entity is assigned to each possible input of entities to the **function**

(c) the predicate '**True**' is always assigned **the value T**

The predicate '**False**' is always assigned **the value F**

(d) for every other **predicate**,

the value T or F is assigned

to each possible input of entities to the **predicate**

Each possible input of entities

Arity one: $C(n, 1)$
Arity two: $C(n, 2)$
Arity three: $C(n, 3)$

...

Arity one functions & predicates: $C(n, 1)$
Arity two: $C(n, 2)$
Arity three: $C(n, 3)$

...

$\{\text{entity}_1, \text{entity}_2, \dots, \text{entity}_n\}$

$\{c_1, c_2, \dots, c_n\} = D$

$f1(), f2(,), \dots$

$P1(), P2(,), \dots$

always return **T / F**

Interpretation

Constant assignments

(a) an entity → the constant symbols.

Function assignments

(b) an entity → each possible input of entities to the **function**

Truth value assignments

(c) the value **T** → the predicate '**True**'
the value **F** → the predicate '**False**'

(d) for every other **predicate**,
the value **T** or **F** is assigned → every other predicate
to each possible input of entities to the **predicate**

Signature Model Examples A – (1)

Signature

1. constant symbols = { Mary, Fred, Sam }
2. predicate symbols = { married, young }
 - married(x, y) : arity two
 - young(x) : arity one

Model

1. domain of discourse D : the set of three particular *individuals*

- this domain is a set
- each element in the set : entity (= *individuals*)
- each constant symbol : one entity in the domain (= one *individual*)

2. interpretation

(a) a different *individual* is assigned to each of the **constant symbols**

(a) an entity in D is assigned to each of the constant symbols.
Normally, every entity is assigned to a constant symbol.

Signature Model Examples A – (2)

(b) for each **function**,
an entity is assigned to each possible input of entities to the **function**

(c) the predicate '**True**' is always assigned the value T
The predicate '**False**' is always assigned the value F

(d) the truth value assignments for every predicate

$\text{young}(\text{Mary}) = \text{F}$, $\text{young}(\text{Fred}) = \text{F}$, $\text{young}(\text{Sam}) = \text{T}$

$\text{married}(\text{Mary}, \text{Mary}) = \text{F}$, $\text{married}(\text{Mary}, \text{Fred}) = \text{T}$, $\text{married}(\text{Mary}, \text{Sam}) = \text{F}$
 $\text{married}(\text{Fred}, \text{Mary}) = \text{T}$, $\text{married}(\text{Fred}, \text{Fred}) = \text{F}$, $\text{married}(\text{Fred}, \text{Sam}) = \text{F}$
 $\text{married}(\text{Sam}, \text{Mary}) = \text{F}$, $\text{married}(\text{Sam}, \text{Fred}) = \text{F}$, $\text{married}(\text{Sam}, \text{Sam}) = \text{F}$

(d) for every other **predicate**,
the value T or F is assigned
to each possible input of entities to the **predicate**

(Mary, Mary), (Mary, Fred), (Mary, Sam)
(Fred, Mary), (Fred, Fred), (Fred, Sam)
(Sam, Mary), (Sam, Fred), (Sam, Sam)

Signature Model Examples B – (1)

Signature

1. constant symbols = { Fred, Mary, Sam }
2. predicate symbols = { love } love(x, y) : arity two
3. function symbols = { mother } mother(x) : arity one

Model

1. domain of discourse D : the set of three particular individuals
2. interpretation
 - (a) a different individual is assigned to each of the **constant symbols**
 - (b) **the truth value assignments for every predicate**
love(Fred, Fred) = F, love(Fred, Mary) = F, love(Fred, Ann) = F
love(Mary, Fred) = T, love(Mary, Mary) = F, love(Mary, Ann) = T
love(Ann, Fred) = T, love(Ann, Mary) = T, love(Ann, Ann) = F
 - (c) **the function assignments**
mother(Fred) = Mary, mother(Mary) = Ann, mother(Ann) = - (no assignment)

Signature Model Examples B – (2)

2. interpretation

(a) a different individual is assigned to each of the **constant symbols**

(a) an entity in D is assigned to each of the constant symbols.
Normally, every entity is assigned to a constant symbol.

(b) **the truth value assignments**

(b) for each **function**,
an entity is assigned to each possible input of entities to the **function**

love(Fred, Fred) = F, **love**(Fred, Mary) = F, **love**(Fred, Ann) = F
love(Mary, Fred) = T, **love**(Mary, Mary) = F, **love**(Mary, Ann) = T
love(Ann, Fred) = T, **love**(Ann, Mary) = T, **love**(Ann, Ann) = F

(c) **the function assignments**

(d) for every other **predicate**,
the value T or F is assigned
to each possible input of entities to the **predicate**

mother(Fred) = Mary, **mother**(Mary) = Ann, **mother**(Ann) = - (no assignment)

The truth value of sentences

The truth values of **all sentences** are assigned :

1. the truth values for **sentences** developed with the symbols \neg , \wedge , \vee , \Rightarrow , \Leftrightarrow are assigned as in propositional logic.
2. the truth values for two terms connected by the $=$ symbol is **T** if both terms refer to the same entity; otherwise it is **F**
3. the truth values for $\forall x p(x)$ has value **T** if $p(x)$ has value **T** for **every assignment** to x of an **entity** in the domain D ; otherwise it has value **F**
4. the truth values for $\exists x p(x)$ has value **T** if $p(x)$ has value **T** for **at least one assignment** to x of an **entity** in the domain D ; otherwise it has value **F**
5. the operator **precedence** is as follows \neg , $=$, \wedge , \vee , \Rightarrow , \Leftrightarrow
6. the **quantifiers** have precedence over the operators
7. **parentheses** change the order of the precedence

Formulas and Sentences

An **formula**

- A **atomic formula**
- The operator \neg followed by a **formula**
- Two formulas separated by \wedge , \vee , \Rightarrow , \Leftrightarrow
- A **quantifier** following by a variable followed by a formula

A **sentence**

- A **formula** with **no free variables**

$\forall x \text{ love}(x,y)$: free variable y	: not a sentence
$\forall x \text{ tall}(x)$: no free variable	: a sentence

Finding the truth value

Find the truth values of **all sentences**

1. \neg , \wedge , \vee , \Rightarrow , \Leftrightarrow

2. = symbol

3. $\forall x p(x)$

4. $\exists x p(x)$

5. the **operator precedence** is as follows \neg , =, \wedge , \vee , \Rightarrow , \Leftrightarrow

6. the **quantifiers** (\forall , \exists) have precedence over the **operators**

7. **parentheses** change the order of the precedence

Sentence Examples (1)

Signature

Constant Symbols = {Socrates, Plato, Zeus, Fido}

Predicate Symbols = {human, mortal, legs} all arity one

Model

D: the set of these four particular individuals

Interpretation

(a) a different individual is assigned to each of the constant symbols

(b) the truth value assignment

human(Socrates)=T, human(Plato)=T, human(Zeus)=F, human(Fido)=F

mortal(Socrates)=T, mortal(Plato)=T, mortal(Zeus)=F, mortal(Fido)=T

legs(Socrates)=T, legs(Plato)=T, legs(Zeus)=T, legs(Fido)=T

Sentence Examples (2)

Sentence 1: $\text{human}(\text{Zeus}) \wedge \text{human}(\text{Fido}) \vee \text{human}(\text{Socrates}) = \text{T}$
F \wedge F \vee T

Sentence 2: $\text{human}(\text{Zeus}) \wedge (\text{human}(\text{Fido}) \vee \text{human}(\text{Socrates})) = \text{F}$
F \wedge (F \vee T)

Sentence 3: $\forall x \text{human}(x) = \text{F}$
 $\text{human}(\text{Zeus})=\text{F}, \text{human}(\text{Fido})=\text{F}$

Sentence 4: $\forall x \text{mortal}(x) = \text{F}$
 $\text{mortal}(\text{Zeus})=\text{F}$

Sentence 5: $\forall x \text{legs}(x) = \text{T}$
 $\text{legs}(\text{Socrates})=\text{T}, \text{legs}(\text{Plato})=\text{T}, \text{legs}(\text{Zeus})=\text{T}, \text{legs}(\text{Fido})=\text{T}$

Sentence 6: $\exists x \text{human}(x) = \text{T}$
 $\text{human}(\text{Socrates})=\text{T}, \text{human}(\text{Plato})=\text{T}$

Sentence 7: $\forall x (\text{human}(x) \Rightarrow \text{mortal}(x)) = \text{T}$

Sentence Examples (3)

Sentence 7: $\forall x (\text{human}(x) \Rightarrow \text{mortal}(x)) = T$

$\text{human}(\text{Socrates})=T,$	$\text{mortal}(\text{Socrates})=T,$
$\text{human}(\text{Plato})=T,$	$\text{mortal}(\text{Plato})=T,$
$\text{human}(\text{Zeus})=F,$	$\text{mortal}(\text{Zeus})=F,$
$\text{human}(\text{Fido})=F$	$\text{mortal}(\text{Fido})=T$

$T \Rightarrow T : T$
$T \Rightarrow T : T$
$F \Rightarrow F : T$
$F \Rightarrow T : T$

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