

# Mathematical Logics

## 4. Reasoning in First order logic

Luciano Serafini

ITC-IRST, Trento, Italy

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# Reasoning tasks in FOL

In First order logics we have the same reasoning task as in propositional logics (and any other logics)

## Model checking

For a closed formula  $\phi$  check if  $\mathcal{I} \models \phi$

## Satisfiability

Find an interpretation  $\mathcal{I}$  that satisfies a closed formula  $\phi$ . I.e., check if there is a  $\mathcal{I}$  such that  $\mathcal{I} \models \phi$ .

## Validity

Check if a formula  $\phi$  is valid, i.e., if for all interpretations  $\mathcal{I}$ ,  $\mathcal{I} \models \phi$

## Logical consequence

Check if a formula  $\phi$  is a logical consequence of a set of formulas  $\Gamma$ , i.e.,  $\Gamma \models \phi$

# Reasoning tasks in FOL

- FOL has to do with objects which have some properties, we might be interested in knowing the set of objects which share a given property. More in general we might be interested in knowing the set of  $n$ -tuples of objects which are in a certain  $n$ -ary relation.
- This task is similar to what we do when we query a database. E.g. we want to know the set of people who earn more than 1300 euro per month, or the set of pair of people who works in the same project.
- A property in FOL can be expressed by a formula with free variable  $\phi(x_1, \dots, x_n$ .
- $person(x) \wedge earn(x, y) \wedge y > 1000$ : the persons (free variable  $x$ ) who earns more than 1000 euros
- $\exists z(worksFor(x, z) \wedge worksFor(y, z))$ : the pairs of people (the free variables  $\langle x, y \rangle$ ) who works in the same project.

# Query answering in FOL

## Semantic Query answering

Given an interpretation  $\mathcal{I}$  (a database instance) of a FOL  $\mathcal{L}$  and a formula  $\phi(x_1, \dots, x_n)$  with  $n$ -free variables, find all the  $n$ -tuples of elements of the domain  $\langle d_1, \dots, d_n \rangle \in (\Delta^{\mathcal{I}})^n$  such that  $\mathcal{I} \models \phi[a[x_1/d_1 \dots x_n/d_n]]$

## Deductive query answering

Given a set of formulas  $\Gamma$  (a Knowledge Base), in a FOL  $\mathcal{L}$  and a formula  $\phi(x_1, \dots, x_n)$  with  $n$ -free variables, find all the  $n$ -tuples of constants  $\langle c_1, \dots, c_n \rangle$  such that  $\Gamma \models \phi(c_1, \dots, c_n)$

# Example of semantic query

## Example

What is the result of the following queries against the interpretation above?

1  $friends(x, alice) \{1, 4\}$

2  $\neg friends(x, bob) \{2, 3, 5, 6\}$

3  $friends(x, y) \wedge friends(y, z) \left\{ \begin{array}{l} \langle 1, 2, 1 \rangle, \langle 1, 2, 4 \rangle, \langle 2, 1, 2 \rangle, \langle 2, 1, 4 \rangle, \\ \langle 3, 4, 3 \rangle, \langle 4, 3, 4 \rangle, \langle 4, 2, 4 \rangle, \langle 4, 1, 4 \rangle, \\ \langle 4, 4, 1 \rangle, \langle 4, 4, 2 \rangle, \langle 4, 4, 3 \rangle, \langle 4, 4, 4 \rangle \end{array} \right\}$

$$\exists y (friends(x, y) \wedge friends(y, z)) \left\{ \begin{array}{l} \langle 1, 1 \rangle, \langle 1, 4 \rangle, \langle 2, 2 \rangle, \langle 2, 4 \rangle, \\ \langle 3, 3 \rangle, \langle 4, 4 \rangle, \langle 4, 1 \rangle, \langle 4, 2 \rangle, \\ \langle 4, 3 \rangle \end{array} \right\}$$

4  $\forall y (friends(x, y) \rightarrow supervisor(x) = y) \{3, 5, 6\}$  Notice that 5 and 6 are there because they don't have any friends so the premise of the implication is always false.

The interpretation  $\mathcal{I}$  is defined as follows:

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<b>Symbols</b>	Constants: <i>alice, bob, carol, robert</i> Function: <i>supervisor</i> (with arity equal to 1) Predicate: <i>friends</i> (with arity equal to 2)
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**Domain**  $\Delta^{\mathcal{I}} = \{1, 2, 3, 4, 5, 6\}$

**Interpretation**  $\mathcal{I}(alice) = 1, \mathcal{I}(bob) = 2, \mathcal{I}(carol) = 3,$   
 $\mathcal{I}(robert) = 2$

$$\mathcal{I}(supervisor) = S \quad \begin{array}{ll} S(1) = 3 & S(2) = 1 \\ S(3) = 4 & S(4) = 5 \\ S(5) = 5 & S(6) = 5 \end{array}$$

$$\mathcal{I}(friends) = F = \left\{ \begin{array}{lll} \langle 1, 2 \rangle, & \langle 2, 1 \rangle, & \langle 3, 4 \rangle, \\ \langle 4, 3 \rangle, & \langle 4, 2 \rangle, & \langle 2, 4 \rangle, \\ \langle 4, 1 \rangle, & \langle 1, 4 \rangle, & \langle 4, 4 \rangle \end{array} \right\}$$

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$$\exists y (friends(x, y) \wedge friends(y, z)) \left\{ \begin{array}{l} \langle 1, 1 \rangle, \langle 1, 4 \rangle, \langle 2, 2 \rangle, \langle 2, 4 \rangle, \\ \langle 3, 3 \rangle, \langle 4, 4 \rangle, \langle 4, 1 \rangle, \langle 4, 2 \rangle, \\ \langle 4, 3 \rangle \end{array} \right\}$$

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$$\mathcal{I}(\text{friends}) = F = \left\{ \begin{array}{lll} \langle 1, 2 \rangle, & \langle 2, 1 \rangle, & \langle 3, 4 \rangle, \\ \langle 4, 3 \rangle, & \langle 4, 2 \rangle, & \langle 2, 4 \rangle, \\ \langle 4, 1 \rangle, & \langle 1, 4 \rangle, & \langle 4, 4 \rangle \end{array} \right\}$$

# Example of semantic query

## Example

What is the result of the following queries against the knowledge base below:

- 1  $friends(x, \text{alice})$  { *bob* }
- 2  $\neg friends(x, \text{alice})$  { *carol* }
- 3  $friends(x, y) \wedge friends(y, z)$  { (*bob, alice, bob*) , (*alice, bob, alice*) }
- 4  $\exists y (friends(x, y) \wedge friends(y, z))$  { (*alice, alice*) , (*bob, bob*) }
- 5  $\forall y (friends(x, y) \rightarrow supervisor(x) = y)$  { }

The knowledge base is defined as follows:

**Symbols** Constants: *alice, bob, carol, robert*  
Function: *supervisor* (with arity equal to 1)  
Predicate: *friends* (with arity equal to 2)

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**Axioms**  $\exists x_1 \dots x_6 \bigwedge_{i < j \in \{1..6\}} x_i \neq x_j \wedge \forall y \bigvee_{i=1}^6 y = x_i$   
*bob = robert, alice ≠ bob, alice ≠ carol, bob ≠ carol*  
*supervisor(alice) = carol*  
*supervisor(bob) = alice*  
 $\forall xy (friends(x, y) \supset friends(y, x))$   
*friends(alice, bob), ¬friends(alice, carol)*  
 $\exists x (friends(carol, x) \wedge x \neq \text{alice} \wedge x \neq \text{bob} \wedge x \neq \text{carol})$

# Example of semantic query

## Example

What is the result of the following queries against the knowledge base below:

- 1  $friends(x, \text{alice}) \{ \text{bob} \}$
- 2  $\neg friends(x, \text{alice}) \{ \text{carol} \}$
- 3  $friends(x, y) \wedge friends(y, z) \{ \langle \text{bob}, \text{alice}, \text{bob} \rangle, \langle \text{alice}, \text{bob}, \text{alice} \rangle \}$
- 4  $\exists y (friends(x, y) \wedge friends(y, z)) \{ \langle \text{alice}, \text{alice} \rangle, \langle \text{bob}, \text{bob} \rangle \}$
- 5  $\forall y (friends(x, y) \rightarrow supervisor(x) = y) \{ \}$

The knowledge base is defined as follows:

**Symbols** Constants: *alice*, *bob*, *carol*, *robert*  
Function: *supervisor* (with arity equal to 1)  
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**Axioms**  $\exists x_1 \dots x_6 \bigwedge_{i < j \in \{1..6\}} x_i \neq x_j \wedge \forall y \bigvee_{i=1}^6 y = x_i$   
 $bob = robert, \text{alice} \neq bob, \text{alice} \neq carol, bob \neq carol$   
 $supervisor(alice) = carol$   
 $supervisor(bob) = alice$   
 $\forall xy (friends(x, y) \supset friends(y, x))$   
 $friends(alice, bob), \neg friends(alice, carol)$   
 $\exists x (friends(carol, x) \wedge x \neq alice \wedge x \neq bob \wedge x \neq carol)$



# Hilbert style axiomatization

**Axioms for propositional connectives** They are the same as in propositional logic

$$\mathbf{A1} \quad \phi \supset (\psi \supset \phi)$$

$$\mathbf{A2} \quad (\phi \supset (\psi \supset \theta)) \supset ((\phi \supset \psi) \supset (\phi \supset \theta))$$

$$\mathbf{A3} \quad (\neg\psi \supset \neg\phi) \supset ((\neg\psi \supset \phi) \supset \psi)$$

$$\mathbf{MP} \quad \frac{\phi \quad \phi \supset \psi}{\psi}$$

**Axioms and rules for quantifiers**

$$\mathbf{A4} \quad \forall x.(\phi(x)) \supset \phi(t) \text{ if } t \text{ is free for } x \text{ in } \phi(x)$$

$$\mathbf{A5} \quad \forall x.(\phi \supset \psi) \supset (\phi \supset \forall x.\psi) \text{ if } x \text{ does not occur free in } \phi$$

$$\mathbf{Gen} \quad \frac{\phi}{\forall x.\phi}$$

# Tableaux Calculus

- The Tableaux Calculus is an algorithm solving the problem of satisfiability.
- If a formula is satisfiable, then there exists an open branch in the tableaux of this formula.
- the procedure attempts to construct the tableaux for a formula. Sometimes it's not possible since the model of the formula is infinite.
- The basic idea is to incrementally build the model by looking at the formula, by decomposing it in a top/down fashion. The procedure exhaustively looks at all the possibilities, so that it can possibly prove that no model could be found for unsatisfiable formulas.

# Semantic tableaux

## Definition

A tableau is a rooted tree, where each node carries a first order sentence (closed formula), and the children of a node  $n$  are generated by applying a set of **expansion rules** to  $n$  or to one of the ancestors of  $n$ .

## Definition

The expansion rules for a first order semantic tableaux are those for the propositional semantic tableaux, extended with the following rules that deal with the quantifiers:

$$\gamma \text{ rules} \quad \frac{\forall x.\phi(x)}{\phi(t)} \quad \frac{\neg\exists x.\phi(x)}{\neg\phi(t)} \quad \text{Where } t \text{ is a term free for } x \text{ in } \phi$$

$$\delta \text{ rules} \quad \frac{\neg\forall x.\phi(x)}{\neg\phi(c)} \quad \frac{\exists x.\phi(x)}{\phi(c)} \quad \text{where } c \text{ is a new constant not previously appearing in the tableaux}$$

# Tableaux production rules for propositional logic

... for propositional connectives

$\alpha$ rules	$\frac{\phi \wedge \psi}{\phi \quad \psi}$	$\frac{\neg(\phi \vee \psi)}{\neg\phi \quad \neg\psi}$	$\frac{\neg\neg\phi}{\phi}$	$\frac{\neg(\phi \supset \psi)}{\phi \quad \neg\psi}$	
$\beta$ rules	$\frac{\phi \vee \psi}{\phi \mid \psi}$	$\frac{\phi \supset \psi}{\neg\phi \mid \psi}$	$\frac{\neg(\phi \wedge \psi)}{\neg\phi \mid \neg\psi}$	$\frac{\phi \equiv \psi}{\phi \mid \neg\phi \quad \psi \mid \neg\psi}$	$\frac{\neg(\phi \equiv \psi)}{\phi \mid \neg\phi \quad \neg\psi \mid \psi}$

# Substitution $\phi[x/t]$

If  $\phi(x)$  is a free variable and  $t$  is a term, we use the notation  $\phi(t)$  instead of the more precise notation  $\phi[x/t]$  to represent the substitution of  $x$  for  $t$  in  $\phi$ .

## Substitution

$\phi[x/t]$  denotes the formula we get by replacing each free occurrence of the variable  $x$  in the formula  $\phi$  by the term  $t$ . This is admitted if  $t$  does not contain any variable  $y$  such that  $x$  occurs in the scope of a quantifier for  $y$  (i.e., in the scope of  $\forall y$  or  $\exists y$ ).

## Example (of substitution)

$$P(x, y, f(x))[x/a] = P(a, y, f(a))$$

$$\forall x P(x, y)[x/b] = \forall x P(x, y)$$

$$\exists x P(x, x) \wedge Q(x)[x/c] = \exists x P(x, x) \wedge Q(c)$$

$$P(x, g(y))[y/f(x)] = P(x, g(f(x)))$$

$$\forall x.P(x, y)[y/f(x)] =$$

Not allowed since  $f(x)$  is not free for  $y$  in  $\forall x.P(x, y)$

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Not allowed since  $f(x)$  is not free for  $y$  in  $\forall x.P(x, y)$

# Universal quantification rule

$$\frac{\forall x\phi(x)}{\phi(t)}$$

- $\forall x\phi(x)$  means that for every object of the domain, the property  $\phi(x)$  should be true.
- a term  $t$  that occurs in the tableaux denotes an object of the domain
- therefore,  $\phi(t)$  must be true for all the terms  $t$  that occurs in the tableaux. I.e., the  $\forall$  rule can be applied as many time as one want to any term that appear in the tableaux.



# Existential quantification rule

$$\frac{\exists x\phi(x)}{\phi(c)} \text{ for a new constant } c$$

- $\exists x\phi(x)$  means that **for some object** of the domain, the property  $\phi(x)$  should be true.
- we **don't know which object of the domain** has the property  $\phi$ , we know only that there is one.
- this means that this rule cannot be applied to the terms that already occur in the tableaux, since otherwise we would introduce an unjustified choice on the element that has the property  $\phi$ .
- the trick is to introduce a term to denote an unconditioned objects (sometimes called “fresh” constant/variable) for denoting an “unknown” object, i.e., an object on which we haven't done any commitment.
- therefore we allow only to infer  $\phi(c)$  from  $\exists x\phi(x)$ , where  $c$  is fresh. Only one application is possible.

# Open and Closed Branches

- a tableaux rooted with  $\phi$  is a method to search an interpretation that satisfy  $\phi$
- Every branch of a tableaux with root equal to  $\phi$ , corresponds to an attempt to find an interpretation  $\mathcal{I}$  that satisfies  $\phi$ .
- The interpretation corresponding to a branch  $b$  of a tableaux should satisfy all the formulas that appear in the branch.
- If the branch contains two opposite literals, i.e.  $P(t_1, \dots, t_n)$  and  $\neg P(t_1, \dots, t_n)$ , then the branch cannot correspond to an interpretation, since there is no interpretation that satisfy at the same time  $P(t_1, \dots, t_n)$  and  $\neg P(t_1, \dots, t_n)$ . So we can consider this attempt to find an interpretation failed. In this case we say that the branch is **closed**.
- if in a branch  $b$  all the rules has been applied and there is no opposite literals, then this branch corresponds to an interpretation. We call such a branch **open**

# Open and Closed Branches

## Definition

- A branch of a tableau is said to be **closed** if it contains a pair of formulas  $\phi$  and  $\neg\phi$ .
- A branch of a tableau is said to be **open** if it is not closed.
- A tableau is said to be closed if each of its paths is closed.

# The tableaux method

- 1 To test a formula  $\phi$  for validity, form tableau starting with  $\neg\phi$ . If the tableau closes off, then  $\phi$  is logically valid.
- 2 To test whether  $\phi$  is a logical consequence of  $\Gamma$  form a tableau starting with each formula in  $\Gamma$  and  $\neg\phi$ . If the tableau closes off, then  $\phi$  is indeed a logical consequence of  $\Gamma$ .
- 3 To test a set of formulas  $\Gamma$  is satisfiable, form a tableau starting with  $\Gamma$  or equivalently an unsigned If the tableau closes off, then  $\Gamma$  is not satisfiable. If the tableau does not close off, then  $\Gamma$  is satisfiable, and from any open branch we can read off an interpretation satisfying  $\Gamma$ .

# Example

## Example

To check if the formula

$(\exists x(P(x) \vee Q(x))) \equiv ((\exists xP(x)) \vee (\exists xQ(x)))$  is satisfiable, we start with a tableaux with this formula:

$$\begin{array}{c} \neg((\exists x (Px \vee Qx)) \Leftrightarrow ((\exists x Px) \vee (\exists x Qx))) \\ / \qquad \qquad \qquad \backslash \\ \exists x (Px \vee Qx) \qquad \qquad \neg \exists x (Px \vee Qx) \\ \neg((\exists x Px) \vee (\exists x Qx)) \qquad (\exists x Px) \vee (\exists x Qx) \\ \neg \exists x Px \qquad \qquad \qquad / \qquad \qquad \qquad \backslash \\ \neg \exists x Qx \qquad \qquad \exists x Px \qquad \qquad \exists x Qx \\ Pa \vee Qa \qquad \qquad Pb \qquad \qquad Qc \\ / \qquad \backslash \qquad \qquad \neg(Pb \vee Qb) \qquad \neg(Pc \vee Qc) \\ Pa \qquad Qa \qquad \qquad \neg Pb \qquad \qquad \neg Pc \\ \neg Pa \qquad \neg Qa \qquad \qquad \neg Qb \qquad \qquad \neg Qc \end{array}$$

## Exercise

Show with the method of semantic tableaux that the following formulas are valid:

- $\forall xP(x) \supset \neg\exists x\neg P(x)$
- $\forall x(P(x) \vee A) \supset (\forall xP(x) \vee A)$  when  $x$  is not free in  $A$
- $\exists x(P(x) \supset \forall xP(x))$
- $\exists x\forall yP(x, y) \supset \forall y\exists xP(x, y)$

# Practicing with Semantic Tableaux

## Solution

$$\neg(\forall x P(x) \supset \neg \exists x \neg P(x))$$

$$\begin{array}{c} \forall x P(x) \\ \neg \neg \exists x \neg P(x) \end{array}$$

$$\exists x \neg P(x)$$

$$\neg P(a)$$

$$P(a)$$

x

$$\neg(\forall x(P(x) \vee A) \supset (\forall x P(x) \vee A))$$

$$\begin{array}{c} \forall x(P(x) \vee A) \\ \neg(\forall x P(x) \vee A) \end{array}$$

$$\neg \forall x P(x)$$

$$\neg A$$

$$\neg P(a)$$

$$P(a) \vee A$$

$$P(a)$$

$$A$$

x

x

# Practicing with Semantic Tableaux

## Solution

$$\neg \exists x(P(x) \supset \forall xP(x))$$

$$\neg(P(a) \supset \forall xP(x))$$

$$P(a)$$
$$\neg \forall xP(x)$$

$$\neg P(b)$$

$$\neg(P(b) \supset \forall xP(x))$$

$$P(b)$$
$$\neg \forall xP(x)$$

x

$$\neg(\exists x \forall y P(x, y) \supset \forall y \exists x P(x, y))$$

$$\exists x \forall y P(x, y)$$
$$\neg \forall y \exists x P(x, y)$$

$$\forall y P(a, y)$$

$$\neg \exists x P(x, b)$$

$$P(a, b)$$

$$\neg P(a, b)$$

x



# Example

## Example

Check if  $\forall xP(x) \wedge \exists x\neg P(f(x))$  is valid/satisfiable/unsatisfiable.

## Solution

$$\forall xP(x) \wedge \exists x\neg P(f(x))$$

|

$$\forall xP(x)$$

$$\exists x\neg P(f(x))$$

|

$$\neg P(f(c))$$

# Example

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|

$$\forall xP(x)$$

$$\exists x\neg P(f(x))$$

|

$$\neg P(f(c))$$

*Now to expand  $\forall xP(x)$ , we can use any ground term  $t$ . possible choices:  $c$ ,  $f(c)$ ,  $f(f(c))$ ,  $\dots$  we choose  $f(c)$  because we want to create a clash with  $\neg P(f(c))$ .*

# Example (Cont'd)

## Example

Check if  $\forall xP(x) \wedge \exists x\neg P(f(x))$  is valid/satisfiable/unsatisfiable.

## Solution

$$\forall xP(x) \wedge \exists x\neg P(f(x))$$

$$\begin{array}{c} | \\ \forall xP(x) \\ \exists x\neg P(f(x)) \end{array}$$

$$\begin{array}{c} | \\ \neg P(f(c)) \end{array}$$

$$\begin{array}{c} | \\ P(f(c)) \end{array}$$

x

# Example of tableaux

## Example

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

$$\begin{array}{c} | \\ \exists x(P(x) \wedge \neg Q(x)) \\ \forall y(P(y) \vee Q(y)) \end{array}$$

$$\begin{array}{c} | \\ P(a) \wedge \neg Q(a) \end{array}$$

$$\begin{array}{c} | \\ P(a) \\ \neg Q(a) \end{array}$$

$$\begin{array}{c} | \\ P(a) \vee Q(a) \end{array}$$

$$P(a)$$

$$Q(a)$$

OPEN

CLASH

# Termination

$$\exists x.P(x) \wedge \forall x(P(x) \supset P(f(x)))$$

$$\begin{array}{c} \exists x.P(x) \\ \forall x(P(x) \supset P(f(x))) \end{array}$$

$$P(a)$$

$$P(a) \supset P(f(a))$$

$$\neg P(a)$$

CLASH

$$P(f(a))$$

$$P(f(a)) \supset P(f(f(a)))$$

$$\neg P(f(a))$$

CLASH

$$P(f(f(a)))$$

For certain formulas the tableaux can go on for ever generating an infinite tree. Consider, for instance the tableaux for the formula

$$\exists x.P(x) \wedge (\forall xP(x) \supset P(f(x)))$$

## Exercise

Give tableau proofs for the following logical consequences:

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

# Some definition for tableaux

## Definition (Closed branch)

A **closed branch** is a branch which contains a formula and its negation.

## Definition (Open branch)

An **open branch** is a branch which is not closed

## Definition (Closed tableaux)

A tableaux is **closed** if all its branches are closed.

## Definition

Let  $\phi$  be a first-order formula and  $\Gamma$  a finite set of such formulas. We write  $\Gamma \vdash \phi$  to say that there exists a closed tableau for  $\Gamma \cup \{\neg\phi\}$

# Soundness and completeness

## Theorem (Soundness)

$$\Gamma \vdash \phi \quad \Longrightarrow \quad \Gamma \models \phi$$

## Theorem (Completeness)

$$\Gamma \models \phi \quad \Longrightarrow \quad \Gamma \vdash \phi$$

## Remark

The mere existence of a closed tableau does not mean that we have an effective method to build it! Concretely: we don't know how often and in which way we have to apply ] the  $\gamma$ -rules ( $\forall x\phi(x) \Rightarrow \phi[x/t]$ ), and what term to use in the substitution.



## Example

Check via tableaux if the validity/satisfiability of the formula  
 $\phi = \forall x, y(P(x) \supset Q(y)) \supset (\exists xP(x) \supset \forall yQ(y))$

## Solution

$$\neg(\forall xy(P(x) \supset Q(y)) \supset (\exists xP(x) \supset \forall yQ(y)))$$

$$\begin{array}{c} | \\ \forall xy(P(x) \supset Q(y)) \\ \neg(\exists xP(x) \supset \forall yQ(y)) \end{array}$$

$$\begin{array}{c} | \\ \exists xP(x) \\ \neg\forall yQ(y) \end{array}$$

$$P(a)$$

$$\neg Q(b)$$

$$P(a) \supset Q(b)$$

$$\neg P(a)$$

$$Q(b)$$

CLASH

CLASH

We try, with the tableaux, to build a model for the negation of  $\phi$ . Since the tableaux ends with all CLASHES, there is no such a model. In other words, for all  $\mathcal{I}$ ,  $\mathcal{I} \not\models \neg\phi$ . Which implies that for all  $\mathcal{I}$ ,  $\mathcal{I} \models \phi$ , i.e., that  $\phi$  is valid.

# Infinite domains

- Differently from Prop. Logic, in FOL, models can be infinite.
- There are formulas which are satisfied only by infinite models. For instance the following formula<sup>1</sup>

$$\phi = \left( \begin{array}{l} \forall x \neg R(x, x) \quad \wedge \\ \forall xyz. (R(x, y) \wedge R(y, z) \supset R(x, z)) \quad \wedge \\ \forall x. \exists y. R(x, y) \end{array} \right)$$

- If we build a tableaux for such a formula, searching for a model, we will end up in an infinite tableaux.

---

<sup>1</sup>To verify this, suppose that  $\mathcal{I} = \langle \Delta^{\mathcal{I}}, \cdot^{\mathcal{I}} \rangle$  is an interpretation that satisfies  $\phi$ , and suppose that  $|\Delta| = n$  for some finite number  $n$ . Consider the sequence  $\langle d_1, d_2, d_3, \dots, d_{n+1} \rangle$  of  $n + 1$  elements of  $\Delta$ , such that  $\langle d_i, d_{i+1} \rangle \in R^{\mathcal{I}}$ . This sequence exists, because for every  $d$  there is always a  $d'$  with  $\langle d, d' \rangle \in R^{\mathcal{I}}$ , since  $\mathcal{I} \models \forall x. \exists y. R(x, y)$ .  $\mathcal{I} \models \forall xyz. (R(x, y) \wedge R(y, z) \supset R(x, z))$ , implies that  $R^{\mathcal{I}}$  is transitive, and therefore for all  $0 \leq i < j \leq n + 1$ ,  $\langle d_i, d_j \rangle \in R^{\mathcal{I}}$ . The fact that  $\Delta$  contains at most  $n$  elements implies that for some  $1 \leq i < j \leq n + 1$ ,  $d_i = d_j$ , which means that  $\langle d_i, d_i \rangle \in R^{\mathcal{I}}$  for some  $1 \leq i \leq n$ . But this contradicts the fact that  $\mathcal{I} \models \forall x \neg R(x, x)$ .

## Exercise

Build a tableaux for

$$\forall x \neg R(x, x) \wedge \forall xyz. (R(x, y) \wedge R(y, z) \supset R(x, z)) \wedge \forall x. \exists y. R(x, y)$$

## Solution

$$\forall x \neg R(x, x) \wedge \forall xyz. (R(x, y) \wedge R(y, z) \supset R(x, z)) \wedge \forall x. \exists y. R(x, y)$$

$$\begin{array}{c} | \\ \forall x \neg R(x, x) \\ \forall xyz. (R(x, y) \wedge R(y, z) \supset R(x, z)) \\ \forall x. \exists y. R(x, y) \end{array}$$

$$\begin{array}{c} | \\ \exists y. R(a_0, y) \end{array}$$

$$\begin{array}{c} | \\ R(a_0, a_1) \end{array}$$

$$\begin{array}{c} | \\ \exists y. R(a_1, y) \end{array}$$

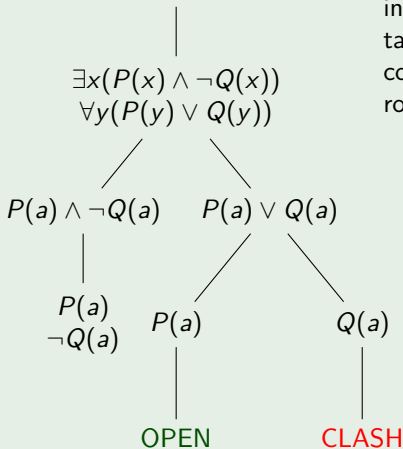
$$\begin{array}{c} | \\ \vdots \end{array}$$

*By applying the  $\gamma$ -rule to the axiom  $\forall x \exists y (R(x, y))$ , we generate  $\exists y R(a_0, y)$  for an initial constant  $a_0$ , and by applying the  $\delta$ -rule to this last formula we generate a new individual  $a_1$ . This allow to apply the  $\gamma$ -rule again to  $\forall x \exists y R(x, y)$ , obtaining  $\exists y R(a_1, y)$ , and again by applying  $\delta$ -rule to this new formula we generate another constant  $a_2$ . The process can go on infinitely without reaching any clash*

# Example of tableaux

## Example

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



From the formulas appearing in the **OPEN** branch of the tableaux it is possible to construct a model for the root formula.

- $\Delta = \{a\}$ , the constants appearing in the formulas
- $I(P) = \{a\}$ , since the formula  $P(a)$  appears in the open branch
- $I(Q) = \{\}$  since the formula  $\neg Q(a)$  appears in the open branch

# Termination fo FO tableaux

In contrast to what happens in propositional logic, the tableau construction is not guaranteed to terminate.

If the formula  $\phi$  that labels the root is unsatisfiable, in which case the construction is guaranteed to terminate and the tableau is closed.

If the formula  $\phi$  that labels the root is satisfiable then either the construction is guaranteed to terminate and the tableau is open, or the construction does not terminate.

# Saturated Branches

## Saturated open branches

An open branch is called **saturated** if every non-literal has been analyzed at least once and, additionally, every  $\gamma$ -formula ( $\gamma$ -formulas are of the form  $\forall x\phi$  and  $\neg\exists x\phi$ ) has been instantiated with every term we can construct using the function symbols on the branch.

## Failing proof

A tableau with an open saturated branch can never be closed, i.e. we can stop and declare the proof a failure.

## Is this the solution?

This only helps us in special cases though. (A single 1-place function symbol together with a constant is already enough to construct infinitely many terms ...)

# Countermodels

- If the construction of a tableaux ends in a saturated open branch, you can use it to help you define a model  $M$  for all the formulas on that branch.
- domain: set of all terms we can construct using the function symbols appearing on the branch (so-called Herbrand universe)
- terms are interpreted as themselves
- interpretation of predicate symbols: see literals on branch