



Logic

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Outline

- 1. Summary of Previous Lecture**
- 2. Quantifier Equivalences**
- 3. Intermezzo**
- 4. Unification**
- 5. Intermezzo**
- 6. Skolemization**
- 7. Further Reading**

Definitions

- ▶ **model** \mathcal{M} for pair $(\mathcal{F}, \mathcal{P})$ with set \mathcal{F} of function symbols and set \mathcal{P} of predicate symbols consists of
 - ① non-empty set A (universe of concrete values)
 - ② function $f^{\mathcal{M}}: A^n \rightarrow A$ for every n -ary function symbol $f \in \mathcal{F}$
 - ③ subset $P^{\mathcal{M}} \subseteq A^n$ for every n -ary predicate symbol $P \in \mathcal{P}$
 - ④ $=^{\mathcal{M}}$ is identity relation on A
- ▶ **environment** (look-up table) for model $\mathcal{M} = (A, \{f^{\mathcal{M}}\}_{f \in \mathcal{F}}, \{P^{\mathcal{M}}\}_{P \in \mathcal{P}})$ is mapping I from variables to elements of A
- ▶ value $t^{\mathcal{M}, I}$ of term t in model \mathcal{M} relative to environment I is defined inductively:

$$t^{\mathcal{M}, I} = \begin{cases} I(t) & \text{if } t \text{ is variable} \\ f^{\mathcal{M}}(t_1^{\mathcal{M}, I}, \dots, t_n^{\mathcal{M}, I}) & \text{if } t = f(t_1, \dots, t_n) \end{cases}$$

- ▶ **satisfaction** relation $\mathcal{M} \models_I \varphi$ is defined inductively:

$$\begin{array}{l}
 \mathcal{M} \models_I \top \\
 \mathcal{M} \not\models_I \perp \\
 \mathcal{M} \models_I \varphi \iff
 \end{array}
 \left\{ \begin{array}{ll}
 (t_1^{M,I}, \dots, t_n^{M,I}) \in P^{\mathcal{M}} & \text{if } \varphi = P(t_1, \dots, t_n) \\
 \mathcal{M} \not\models_I \psi & \text{if } \varphi = \neg \psi \\
 \mathcal{M} \models_I \psi_1 \text{ and } \mathcal{M} \models_I \psi_2 & \text{if } \varphi = \psi_1 \wedge \psi_2 \\
 \mathcal{M} \models_I \psi_1 \text{ or } \mathcal{M} \models_I \psi_2 & \text{if } \varphi = \psi_1 \vee \psi_2 \\
 \mathcal{M} \not\models_I \psi_1 \text{ or } \mathcal{M} \models_I \psi_2 & \text{if } \varphi = \psi_1 \rightarrow \psi_2 \\
 \mathcal{M} \models_{I[x \mapsto a]} \psi \text{ for all } a \in A & \text{if } \varphi = \forall x \psi \\
 \mathcal{M} \models_{I[x \mapsto a]} \psi \text{ for some } a \in A & \text{if } \varphi = \exists x \psi
 \end{array} \right.$$

- ▶ formula ψ is **satisfiable** if $\mathcal{M} \models_I \psi$ for some model \mathcal{M} and environment I
- ▶ formula ψ is **valid** if $\mathcal{M} \models_I \psi$ for all (appropriate) models \mathcal{M} and environments I

Definitions

(possibly infinite) set of formulas Γ

- ▶ Γ is **satisfiable** (**consistent**) if $\mathcal{M} \models_I \varphi$ for all $\varphi \in \Gamma$, for some model \mathcal{M} and environment I
- ▶ $\Gamma \models \psi$ (**semantic entailment**) if $\mathcal{M} \models_I \psi$ whenever $\mathcal{M} \models_I \varphi$ for all $\varphi \in \Gamma$, for all (appropriate) models \mathcal{M} and environments I

Definitions

- ▶ **equality introduction**

$$\frac{}{t = t} =i$$

- ▶ **equality elimination**

$$\frac{t_1 = t_2 \quad \varphi[t_1/x]}{\varphi[t_2/x]} =e$$

"replace equals by equals"

provided t_1 and t_2 are free for x in φ

Definitions

▶ \forall elimination

$$\frac{\forall x \varphi}{\varphi[t/x]} \forall e$$

provided t is free for x in φ

▶ \forall introduction

$$\frac{\boxed{\begin{array}{c} x_0 \\ \vdots \\ \varphi[x_0/x] \end{array}}}{\forall x \varphi} \forall i$$

where x_0 is fresh variable that is used only inside box

\exists introduction

$$\frac{\varphi[t/x]}{\exists x \varphi} \exists i$$

\exists elimination

$$\frac{\exists x \varphi \quad \boxed{\begin{array}{c} x_0 \quad \varphi[x_0/x] \\ \vdots \\ \chi \end{array}}}{\chi} \exists e$$

Definition

(possibly infinite) set of formulas Γ , formula ψ

- ▶ **sequent** $\Gamma \vdash \psi$ is **valid** if there exists (finite) natural deduction proof of ψ in which all premises are from Γ

Theorem (Gödel's Completeness Theorem)

natural deduction for predicate logic is **sound** and **complete**:

$$\Gamma \models \psi \iff \Gamma \vdash \psi \text{ is valid}$$

Decision Problem (Church's Theorem)

instance: set of formulas Γ , first-order formula ψ

question: $\Gamma \models \psi$?

is **undecidable** even when $\Gamma = \emptyset$

Part I: Propositional Logic

algebraic normal forms, binary decision diagrams, conjunctive normal forms, DPLL, Horn formulas, natural deduction, Post's adequacy theorem, resolution, SAT, semantics, sorting networks, soundness and completeness, syntax, Tseitin's transformation

Part II: Predicate Logic

natural deduction, quantifier equivalences, resolution, semantics, Skolemization, syntax, undecidability, unification

Part III: Model Checking

adequacy, branching-time temporal logic, CTL*, fairness, linear-time temporal logic, model checking algorithms, symbolic model checking

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Example

Consider the universe A consisting of the set of all humans. Given the following premises:

- 1 Every child likes sweets or is already full (or both).
- 2 If a human is sad, they no longer like sweets.
- 3 There is at least one child who is sad.

Using natural deduction, prove that there is at least one child who is full.

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$$\forall x (C(x) \rightarrow L(x) \vee F(x))$$

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countermodel \mathcal{M}

- ▶ Diana, Jamie $\in A$

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- ▶ $\mathcal{M} \models \forall x (C(x) \rightarrow L(x) \vee F(x))$ $\mathcal{M} \models S(x) \rightarrow \neg L(x)$ $\mathcal{M} \models \exists x (C(x) \wedge S(x))$

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- ▶ $\mathcal{M} \not\models \exists x (C(x) \wedge F(x))$

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Notation

$\varphi \dashv\vdash \psi$ denotes validity of both $\varphi \vdash \psi$ and $\psi \vdash \varphi$

Theorem

$$\neg \forall x \varphi \dashv\vdash \exists x \neg \varphi$$

$$\forall x \varphi \wedge \forall x \psi \dashv\vdash \forall x (\varphi \wedge \psi)$$

$$\forall x \forall y \varphi \dashv\vdash \forall y \forall x \varphi$$

$$\neg \exists x \varphi \dashv\vdash \forall x \neg \varphi$$

$$\exists x \varphi \vee \exists x \psi \dashv\vdash \exists x (\varphi \vee \psi)$$

$$\exists x \exists y \varphi \dashv\vdash \exists y \exists x \varphi$$

if x is not free in ψ then

$$\forall x \varphi \wedge \psi \dashv\vdash \forall x (\varphi \wedge \psi)$$

$$\exists x \varphi \wedge \psi \dashv\vdash \exists x (\varphi \wedge \psi)$$

$$\psi \rightarrow \forall x \varphi \dashv\vdash \forall x (\psi \rightarrow \varphi)$$

$$\psi \rightarrow \exists x \varphi \dashv\vdash \exists x (\psi \rightarrow \varphi)$$

$$\forall x \varphi \vee \psi \dashv\vdash \forall x (\varphi \vee \psi)$$

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$$\exists x \varphi \rightarrow \psi \dashv\vdash \forall x (\varphi \rightarrow \psi)$$

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$$\exists x \varphi \rightarrow \psi \dashv\vdash \forall x (\varphi \rightarrow \psi)$$

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$$\exists x \varphi \vee \psi \dashv\vdash \exists x (\varphi \vee \psi)$$

$$\exists x \varphi \rightarrow \psi \dashv\vdash \forall x (\varphi \rightarrow \psi)$$

$$\forall x \varphi \rightarrow \psi \dashv\vdash \exists x (\varphi \rightarrow \psi)$$

$\exists x \neg \varphi \vdash \neg \forall x \varphi$ is valid:

1	$\exists x \neg \varphi$	premise
2	$\forall x \varphi$	assumption
3	$x_0 \ (\neg \varphi)[x_0/x]$	assumption
4	$\neg(\varphi[x_0/x])$	identical
5	$\varphi[x_0/x]$	$\forall e$ 2
6	\perp	$\neg e$ 5, 4
7	\perp	$\exists e$ 1, 3-6
8	$\neg \forall x \varphi$	$\neg i$ 2-7

$\exists x \varphi \vee \exists x \psi \vdash \exists x (\varphi \vee \psi)$ is valid:

1	$\exists x \varphi \vee \exists x \psi$	premise
2	$\exists x \varphi$	assumption
3	$x_0 \varphi[x_0/x]$	assumption
4	$\varphi[x_0/x] \vee \psi[x_0/x]$	$\vee i_1$ 3
5	$\exists x (\varphi \vee \psi)$	$\exists i$ 4
6	$\exists x (\varphi \vee \psi)$	$\exists e$ 2, 3–5
7	$\exists x \psi$	assumption
8	$x_0 \psi[x_0/x]$	assumption
9	$\varphi[x_0/x] \vee \psi[x_0/x]$	$\vee i_2$ 8
10	$\exists x (\varphi \vee \psi)$	$\exists i$ 9
11	$\exists x (\varphi \vee \psi)$	$\exists e$ 7, 8–10
12	$\exists x (\varphi \vee \psi)$	$\vee e$ 1, 2–6, 7–11

$\exists x (\varphi \vee \psi) \vdash \exists x \varphi \vee \exists x \psi$ is valid:

1	$\exists x (\varphi \vee \psi)$	premise
2	$x_0 (\varphi \vee \psi)[x_0/x]$	assumption
3	$\varphi[x_0/x] \vee \psi[x_0/x]$	identical
4	$\varphi[x_0/x]$	assumption
5	$\exists x \varphi$	$\exists i$ 4
6	$\exists x \varphi \vee \exists x \psi$	$\vee i_1$ 5
7	$\psi[x_0/x]$	assumption
8	$\exists x \psi$	$\exists i$ 7
9	$\exists x \varphi \vee \exists x \psi$	$\vee i_2$ 8
10	$\exists x \varphi \vee \exists x \psi$	$\vee e$ 3, 4–6, 7–9
11	$\exists x \varphi \vee \exists x \psi$	$\exists e$ 1, 2–10

$\forall x \forall y \varphi \vdash \forall y \forall x \varphi$ is valid:

1	$\forall x \forall y \varphi$	premise
2	y_0	
3	x_0	$(\forall y \varphi)[x_0/x]$ $\forall e$ 1
4	$\forall y (\varphi[x_0/x])$	identical
5	$\varphi[x_0/x][y_0/y]$	$\forall e$ 4
6	$\varphi[y_0/y][x_0/x]$	identical
7	$\forall x (\varphi[y_0/y])$	$\forall i$ 3–6
8	$(\forall x \varphi)[y_0/y]$	identical
9	$\forall y \forall x \varphi$	$\forall i$ 2–8

$\exists x \exists y \varphi \vdash \exists y \exists x \varphi$ is valid:

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2	$x_0 (\exists y \varphi)[x_0/x]$	assumption
3	$\exists y (\varphi[x_0/x])$	identical
4	$y_0 \varphi[x_0/x][y_0/y]$	assumption
5	$\varphi[y_0/y][x_0/x]$	identical
6	$\exists x (\varphi[y_0/y])$	$\exists i 5$
7	$(\exists x \varphi)[y_0/y]$	identical
8	$\exists y \exists x \varphi$	$\exists i 7$
9	$\exists y \exists x \varphi$	$\exists e 3,4-8$
10	$\exists y \exists x \varphi$	$\exists e 1,2-9$

$\forall x \varphi \wedge \psi \vdash \forall x (\varphi \wedge \psi)$ is valid (provided x is not free in ψ):

1 $\forall x \varphi \wedge \psi$ premise

2 $\forall x \varphi$ $\wedge e_1$ 1

3 ψ $\wedge e_2$ 1

4 $x_0 \quad \varphi[x_0/x]$ $\forall e$ 2

5 $\varphi[x_0/x] \wedge \psi$ $\wedge i$ 4, 3

6 $(\varphi \wedge \psi)[x_0/x]$ identical

7 $\forall x (\varphi \wedge \psi)$ $\forall i$ 4–6

Proof

$\forall x \varphi \wedge \psi \vdash \forall x (\varphi \wedge \psi)$ is valid (**provided x is not free in ψ**):

1	$\forall x \varphi \wedge \psi$	premise
2	$\forall x \varphi$	$\wedge e_1$ 1
3	ψ	$\wedge e_2$ 1
4	$x_0 \quad \varphi[x_0/x]$	$\forall e$ 2
5	$\varphi[x_0/x] \wedge \psi$	$\wedge i$ 4, 3
6	$(\varphi \wedge \psi)[x_0/x]$	identical
7	$\forall x (\varphi \wedge \psi)$	$\forall i$ 4-6

Remark

freeness condition is essential

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Remark

freeness condition is essential: $\forall x P(x) \wedge Q(x) \not\equiv \forall x (P(x) \wedge Q(x))$

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freeness condition is essential: $\forall x P(x) \wedge Q(x) \not\equiv \forall x (P(x) \wedge Q(x))$

► model \mathcal{M} with universe $\{0, 1\}$, $P^{\mathcal{M}} = \{0, 1\}$, $Q^{\mathcal{M}} = \{0\}$ and environment $I(x) = 0$

Proof

$\forall x \varphi \wedge \psi \vdash \forall x (\varphi \wedge \psi)$ is valid (**provided x is not free in ψ**):

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- ▶ model \mathcal{M} with universe $\{0, 1\}$, $P^{\mathcal{M}} = \{0, 1\}$, $Q^{\mathcal{M}} = \{0\}$ and environment $I(x) = 0$
- ▶ $\mathcal{M} \models \forall x P(x) \wedge Q(x)$

Proof

$\forall x \varphi \wedge \psi \vdash \forall x (\varphi \wedge \psi)$ is valid (**provided x is not free in ψ**):

1	$\forall x \varphi \wedge \psi$	premise
2	$\forall x \varphi$	$\wedge e_1$ 1
3	ψ	$\wedge e_2$ 1
4	$x_0 \quad \varphi[x_0/x]$	$\forall e$ 2
5	$\varphi[x_0/x] \wedge \psi$	$\wedge i$ 4, 3
6	$(\varphi \wedge \psi)[x_0/x]$	identical
7	$\forall x (\varphi \wedge \psi)$	$\forall i$ 4-6

Remark

freeness condition is essential: $\forall x P(x) \wedge Q(x) \not\equiv \forall x (P(x) \wedge Q(x))$

- ▶ model \mathcal{M} with universe $\{0, 1\}$, $P^{\mathcal{M}} = \{0, 1\}$, $Q^{\mathcal{M}} = \{0\}$ and environment $I(x) = 0$
- ▶ $\mathcal{M} \models \forall x P(x) \wedge Q(x)$ and $\mathcal{M} \not\models \forall x (P(x) \wedge Q(x))$

$\forall x (\varphi \wedge \psi) \vdash \forall x \varphi \wedge \psi$ is valid (provided x is not free in ψ):

1 $\forall x (\varphi \wedge \psi)$ premise

2 $x_0 (\varphi \wedge \psi)[x_0/x]$ $\forall e$ 1

3 $\varphi[x_0/x] \wedge \psi$ identical

4 ψ $\wedge e_2$ 3

5 $\varphi[x_0/x]$ $\wedge e_1$ 3

6 $\forall x \varphi$ $\forall i$ 2–5

7 $\forall x \varphi \wedge \psi$ $\wedge i$ 6, 4

$\forall x (\varphi \wedge \psi) \vdash \forall x \varphi \wedge \psi$ is valid (provided x is not free in ψ):

1	$\forall x (\varphi \wedge \psi)$	premise	
2	$x_0 (\varphi \wedge \psi)[x_0/x]$	$\forall e$ 1	
3	$\varphi[x_0/x] \wedge \psi$	identical	
4	ψ	$\wedge e_2$ 3	
5	$\varphi[x_0/x]$	$\wedge e_1$ 3	
6	$\forall x \varphi$	$\forall i$ 2–5	
7	$\forall x \varphi \wedge \psi$	$\wedge i$ 6,4	???

$\forall x (\varphi \wedge \psi) \vdash \forall x \varphi \wedge \psi$ is valid (provided x is not free in ψ):

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4	ψ	$\wedge e_2$ 3
5	$\varphi[x_0/x]$	$\wedge e_1$ 3
6	$\forall x \varphi$	$\forall i$ 2–5
7	$(\varphi \wedge \psi)[x/x]$	$\forall e$ 1
8	$\varphi \wedge \psi$	identical
9	ψ	$\wedge e_2$ 8
10	$\forall x \varphi \wedge \psi$	$\wedge i$ 6,9

$\forall x \varphi \vee \psi \vdash \forall x (\varphi \vee \psi)$ is valid (provided x is not free in ψ):

1	$\forall x \varphi \vee \psi$	premise
2	$\forall x \varphi$	assumption
3	$x_0 \quad \varphi[x_0/x]$	$\forall e \ 2$
4	$\varphi[x_0/x] \vee \psi[x_0/x]$	$\vee i_1 \ 3$
5	$(\varphi \vee \psi)[x_0/x]$	identical
6	$\forall x (\varphi \vee \psi)$	$\forall i \ 3-5$
7	ψ	assumption
8	$x_0 \quad \varphi[x_0/x] \vee \psi$	$\vee i_2 \ 7$
9	$(\varphi \vee \psi)[x_0/x]$	identical
10	$\forall x (\varphi \vee \psi)$	$\forall i \ 8-9$
11	$\forall x (\varphi \vee \psi)$	$\forall e \ 1, 2-6, 7-10$

$\forall x (\varphi \vee \psi) \vdash \forall x \varphi \vee \psi$ is valid (provided x is not free in ψ):

1	$\forall x (\varphi \vee \psi)$	premise	5
2	$\psi \vee \neg\psi$	LEM	6
3	ψ	assumption	7
4	$\forall x \varphi \vee \psi$	$\forall i_1$ 3	8
			9
			10
			11
			12
			13
			14
			15

	$\neg\psi$	assumption
x_0	$(\varphi \vee \psi)[x_0/x]$	$\forall e$ 1
	$\varphi[x_0/x] \vee \psi$	identical
	$\varphi[x_0/x]$	assumption
	ψ	assumption
	\perp	$\neg e$ 9, 5
	$\varphi[x_0/x]$	$\perp e$ 10
	$\varphi[x_0/x]$	$\forall e$ 7, 8–8, 9–11
	$\forall x \varphi$	$\forall i$ 6–12
	$\forall x \varphi \vee \psi$	$\forall i_1$ 13
	$\forall x \varphi \vee \psi$	$\forall e$ 2, 3–4, 5–14

$\forall x (\psi \rightarrow \varphi) \vdash \psi \rightarrow \forall x \varphi$ is valid (provided x is not free in ψ):

1	$\forall x (\psi \rightarrow \varphi)$	premise
2	ψ	assumption
3	$x_0 (\psi \rightarrow \varphi)[x_0/x]$	$\forall e$ 1
4	$\psi \rightarrow \varphi[x_0/x]$	identical
5	$\varphi[x_0/x]$	$\rightarrow e$ 4, 2
6	$\forall x \varphi$	$\forall i$ 3–5
7	$\psi \rightarrow \forall x \varphi$	$\rightarrow i$ 2–6

$\psi \rightarrow \forall x \varphi \vdash \forall x (\psi \rightarrow \varphi)$ is valid (provided x is not free in ψ):

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3	ψ	assumption
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5	$\varphi[x_0/x]$	$\forall e$ 4
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7	$(\psi \rightarrow \varphi)[x_0/x]$	identical
8	$\forall x (\psi \rightarrow \varphi)$	$\forall i$ 2–7

Outline

1. Summary of Previous Lecture
2. Quantifier Equivalences
- 3. Intermezzo**
4. Unification
5. Intermezzo
6. Skolemization
7. Further Reading

Question

Which of the following statements are true ?

- A** $\forall x \exists y (P(x) \rightarrow Q(y)) \vdash \forall x (P(x) \rightarrow \exists y Q(y))$
- B** $\exists x \forall y \varphi \dashv\vdash \forall y \exists x \varphi$ for every formula φ
- C** $\exists y \forall z \exists x (\neg P(x) \rightarrow \forall x Q(x, y, z)) \dashv\vdash \exists x P(x) \vee \exists y \forall z \forall x Q(x, y, z)$
- D** $\exists x (P(x) \rightarrow Q(x)) \dashv\vdash \forall x P(x) \rightarrow \exists x Q(x)$



Question

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- $\exists x \forall y \varphi \dashv\vdash \forall y \exists x \varphi$ for every formula φ
- $\exists y \forall z \exists x (\neg P(x) \rightarrow \forall x Q(x, y, z)) \dashv\vdash \exists x P(x) \vee \exists y \forall z \forall x Q(x, y, z)$
- $\exists x (P(x) \rightarrow Q(x)) \dashv\vdash \forall x P(x) \rightarrow \exists x Q(x)$



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Definitions

- ▶ **substitution** is set of variable bindings $\theta = \{x_1 \mapsto t_1, \dots, x_n \mapsto t_n\}$ with pairwise different variables x_1, \dots, x_n and terms t_1, \dots, t_n

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- ▶ given substitution $\theta = \{x_1 \mapsto t_1, \dots, x_n \mapsto t_n\}$ and expression E , **instance** $E\theta$ of E is obtained by simultaneously replacing each occurrence of x_i in E by t_i

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Example

$$\theta = \{x \mapsto g(y, z), y \mapsto a\}$$

$$E = P(f(y), x, y)$$

$$\sigma = \{x \mapsto f(y), z \mapsto f(x)\}$$

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- ▶ **composition** of substitutions $\theta = \{x_1 \mapsto t_1, \dots, x_n \mapsto t_n\}$ and $\sigma = \{y_1 \mapsto s_1, \dots, y_k \mapsto s_k\}$ is substitution $\theta\sigma = \{x_1 \mapsto t_1\sigma, \dots, x_n \mapsto t_n\sigma\} \cup \{y_i \mapsto s_i \mid y_i \neq x_j \text{ for all } 1 \leq j \leq n\}$

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Lemma

composition of substitutions is associative: $(\rho\sigma)\tau = \rho(\sigma\tau)$

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unifiers $\{x \mapsto h(u), y \mapsto u, z \mapsto h(u)\}$

$$\{x \mapsto h(g(u)), y \mapsto g(u), z \mapsto h(g(u)), u \mapsto g(u)\}$$

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unifiers $\{x \mapsto h(u), y \mapsto u, z \mapsto h(u)\}$ mgu

$$\{x \mapsto h(g(u)), y \mapsto g(u), z \mapsto h(g(u)), u \mapsto g(u)\} \qquad \{u \mapsto g(u)\}$$

Theorem

unifiable terms have mgu which can be computed by unification algorithm

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Unification Algorithm

d decomposition

$$\frac{E_1, f(s_1, \dots, s_n) \approx f(t_1, \dots, t_n), E_2}{E_1, s_1 \approx t_1, \dots, s_n \approx t_n, E_2}$$

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t removal of trivial equations

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t removal of trivial equations

$$\frac{E_1, t \approx t, E_2}{E_1, E_2}$$

v variable elimination

$$\frac{E_1, x \approx t, E_2}{(E_1, E_2)\{x \mapsto t\}} \quad \text{and} \quad \frac{E_1, t \approx x, E_2}{(E_1, E_2)\{x \mapsto t\}}$$

if x does not occur in t (**occurs check**)

Example

$$f(x, g(y), x) \approx f(z, g(u), h(u))$$

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mgu {x ↦ z}{y ↦ u}{z ↦ h(u)}

$$y \approx u, z \approx h(u)$$

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mgu {x ↦ h(u), y ↦ u, z ↦ h(u)}

$$y \approx u, z \approx h(u)$$

v ↓ {y ↦ u}

$$z \approx h(u)$$

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□

Theorem

- ▶ there are no infinite derivations

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Optional Failure Rules

$$\frac{E_1, f(s_1, \dots, s_n) \approx g(t_1, \dots, t_m), E_2}{\perp}$$

$$\frac{E_1, x \approx t, E_2}{\perp}$$

$$\frac{E_1, t \approx x, E_2}{\perp}$$

if x occurs in t and $x \neq t$

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Example (黒どこ Kurodoko)

			3		3			
3					3			
	7	7	7					4
					5			
						3		
							4	
	3			5				
				2				4

Example (黒どこ Kurodoko)

			3		3			
3					3			
	7	7	7					4
					5			
						3		
							4	
	3			5				
				2				4

- ▶ cell can see other cells in same row or column

Example (黒とこ Kurodoko)

			3		3			
3					3			
	7	7	7					4
					5			
						3		
							4	
	3			5				
				2				4

- ▶ cell can see other cells in same row or column
- ▶ black cells block view of white cells

Example (黒どこ Kurodoko)

			3		3			
3					3			
	7	7	7					4
					5			
						3		
							4	
	3			5				
				2				4

- ▶ cell can see other cells in same row or column
- ▶ black cells block view of white cells
- ▶ number in cell tells how many white cells are seen by cell (including itself)

Example (黒どこ Kurodoko)

			3		3			
3					3			
	7	7	7					4
					5			
						3		
							4	
	3			5				
				2				4

- ▶ cell can see other cells in same row or column
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3					3			
	7	7	7					4
					5			
						3		
							4	
	3			5				
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3					3			
	7	7	7					4
					5			
						3		
							4	
	3			5				
				2				4

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			3		3			
3					3			
	7	7	7					4
					5			
						3		
				■			4	
	3			5				
			■	2	■			4

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			3		3			
3					3			
	7	7	7					4
					5			
				•		3		
			•	■	•		4	
	3		•	5	•			
		•	■	2	■	•		4

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			3		3			
3					3			
	7	7	7					4
					5			
				•		3		
			•	■	•		4	
	3	■	•	5	•			
		•	■	2	■	•		4

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			3		3			
3					3			
	7	7	7					4
					5			
				•		3		
		•	•	■	•		4	
	3	■	•	5	•	•	■	
		•	■	2	■	•		4

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			3		3			
3					3			
	7	7	7					4
					5			
				•		3		
		•	•	■	•		4	
	3	■	•	5	•	•	■	•
		•	■	2	■	•	•	4

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			3		3			
3					3			
	7	7	7					4
					5			
				•		3		•
		•	•	■	•		4	■
	3	■	•	5	•	•	■	•
		•	■	2	■	•	•	4

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			3		3			
3					3			
	7	7	7					4
					5			
				•		3		•
		•	•	■	•	■	4	■
	3	■	•	5	•	•	■	•
		•	■	2	■	•	•	4

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			3		3			
3					3			
	7	7	7				■	4
					5		•	
							•	
				•		3	•	•
		•	•	■	•	■	4	■
	3	■	•	5	•	•	■	•
		•	■	2	■	•	•	4

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			3		3			
3					3		•	
	7	7	7			•	■	4
					5		•	
					■		•	
				•	■	3	•	•
		•	•	■	•	■	4	■
	3	■	•	5	•	•	■	•
		•	■	2	■	•	•	4

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			3	■	3			
3					3		•	
	7	7	7		■	•	■	4
					5	•	•	
					•	■	•	
				•	■	3	•	•
		•	•	■	•	■	4	■
	3	■	•	5	•	•	■	•
		•	■	2	■	•	•	4

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			3	■	3	•	■	
3				•	3		•	
	7	7	7	•	■	•	■	4
					5	•	•	
					•	■	•	
				•	■	3	•	•
		•	•	■	•	■	4	■
	3	■	•	5	•	•	■	•
		•	■	2	■	•	•	4

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			3	■	3	•	■	•
3				•	3		•	•
	7	7	7	•	■	•	■	4
					5	•	•	•
				•	■	•	■	
				•	■	3	•	•
		•	•	■	•	■	4	■
	3	■	•	5	•	•	■	•
	•	•	■	2	■	•	•	4

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			3	■	3	•	■	•
3			■	•	3	■	•	•
	7	7	7	•	■	•	■	4
					5	•	•	•
					•	■	•	■
				•	■	3	•	•
		•	•	■	•	■	4	■
	3	■	•	5	•	•	■	•
	•	•	■	2	■	•	•	4

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•	•	3	•	3	•	•
3	•	•	•	3	•	•
7	7	7	•	•	•	4
•	•	•	•	5	•	•
•	•	•	•	•	•	•
•	•	•	•	•	3	•
•	•	•	•	•	•	4
3	•	•	5	•	•	•
•	•	•	2	•	•	4

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•	•	3	•	3	•	•
3	•	•	•	3	•	•
7	7	7	•	•	•	4
•	•	•	•	5	•	•
•	•	•	•	•	•	•
•	•	•	•	•	3	•
•	•	•	•	•	•	4
3	•	•	5	•	•	•
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•	•	3	•	3	•	•	
3	•	•	•	3	•	•	
7	7	7	•	•	•	4	
•	•	•	•	5	•	•	
•	•	•	•	•	•	•	
•	•	•	•	•	3	•	
•	•	•	•	•	•	4	
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•	•	3	•	3	•	•
3	•	•	•	3	•	•
•	7	7	7	•	•	4
		•	•	5	•	•
		•	•	•	•	•
		•	•	3	•	•
	•	•	•	•	4	•
	3	•	•	5	•	•
	•	•	2	•	•	4

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•	•	3	•	3	•	•
3	•	•	•	3	•	•
•	7	7	7	•	•	4
•			•	5	•	•
•			•	•	•	•
			•	3	•	•
		•	•	•	4	•
	3	•	5	•	•	•
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•	•	3	•	3	•	•	
3	•	•	•	3	•	•	
•	7	7	7	•	•	4	
•		•	•	5	•	•	
•	•	•	•	•	•	•	
•		•	•	•	3	•	
		•	•	•	•	4	
	3	•	•	5	•	•	
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•	•	3	•	3	•	•
3	•	•	•	3	•	•
•	7	7	7	•	•	4
•	•	•	•	5	•	•
•	•	•	•	•	•	•
•	•	•	•	•	3	•
•	•	•	•	•	•	4
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•	•	•	3	•	3	•	•	•
3	•	•	•	•	3	•	•	•
•	7	7	7	•	•	•	•	4
•	•	•	•	•	5	•	•	•
•	•	•	•	•	•	•	•	•
•	•	•	•	•	•	3	•	•
•	•	•	•	•	•	•	4	•
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Outline

1. Summary of Previous Lecture
2. Quantifier Equivalences
3. Intermezzo
4. Unification
5. Intermezzo
- 6. Skolemization**
7. Further Reading

Definitions

- ▶ **prenex normal form** is predicate logic formula

$$Q_1x_1 Q_2x_2 \dots Q_nx_n \varphi$$

with $Q_i \in \{\forall, \exists\}$ and φ quantifier-free

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Example

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

Definitions

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

clausal form $\{\{P(f(x)), \neg P(g(y)), Q(g(y))\}, \{\neg Q(g(y)), \neg P(g(y)), Q(g(x))\}\}$

Theorem

for every formula φ there exists prenex normal form ψ such that $\varphi \equiv \psi$

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Proof

- ① rename all bound variables such that all variables in quantifications are distinct
- ② push logical connectives through quantifiers:

$$\neg \forall x \varphi \equiv \exists x \neg \varphi$$

$$\forall x \varphi \wedge \psi \equiv \forall x (\varphi \wedge \psi)$$

$$\exists x \varphi \wedge \psi \equiv \exists x (\varphi \wedge \psi)$$

$$\forall x \varphi \vee \psi \equiv \forall x (\varphi \vee \psi)$$

$$\exists x \varphi \vee \psi \equiv \exists x (\varphi \vee \psi)$$

$$\forall x \varphi \rightarrow \psi \equiv \exists x (\varphi \rightarrow \psi)$$

$$\exists x \varphi \rightarrow \psi \equiv \forall x (\varphi \rightarrow \psi)$$

$$\neg \exists x \varphi \equiv \forall x \neg \varphi$$

$$\varphi \wedge \forall x \psi \equiv \forall x (\varphi \wedge \psi)$$

$$\varphi \wedge \exists x \psi \equiv \exists x (\varphi \wedge \psi)$$

$$\varphi \vee \forall x \psi \equiv \forall x (\varphi \vee \psi)$$

$$\varphi \vee \exists x \psi \equiv \exists x (\varphi \vee \psi)$$

$$\varphi \rightarrow \forall x \psi \equiv \forall x (\varphi \rightarrow \psi)$$

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Theorem

for every sentence φ there exists Skolem normal form ψ such that $\varphi \approx \psi$

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- ① transform φ into closed prenex normal form $Q_1 x_1 Q_2 x_2 \dots Q_n x_n \chi$ with χ in CNF
- ② repeatedly replace $\forall x_1 \dots \forall x_{i-1} \exists x_i Q_{i+1} x_{i+1} \dots Q_n x_n \psi$ by

$$\forall x_1 \dots \forall x_{i-1} Q_{i+1} x_{i+1} \dots Q_n x_n \psi[f(x_1, \dots, x_{i-1})/x_i]$$

where f is new function symbol of arity $i - 1$

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Remark

unification and **Skolemization** are required to extend resolution from propositional logic to predicate logic

Examples

$$① \quad \forall z \exists x \exists y ((P(x) \vee \neg P(y) \vee Q(z)) \wedge (\neg Q(x) \vee \neg P(y) \vee Q(z)))$$

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

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$$\forall z ((P(f(z)) \vee \neg P(g(z)) \vee Q(z)) \wedge (\neg Q(f(z)) \vee \neg P(g(z)) \vee Q(z)))$$

$$② \quad \forall x \exists y (\exists z P(z) \wedge (\exists u Q(x, u) \rightarrow \exists v Q(y, v)))$$

Examples

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

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$$\forall z ((P(f(z)) \vee \neg P(g(z)) \vee Q(z)) \wedge (\neg Q(f(z)) \vee \neg P(g(z)) \vee Q(z)))$$

$$② \quad \forall x \exists y (\exists z P(z) \wedge (\exists u Q(x, u) \rightarrow \exists v Q(y, v)))$$

\equiv

$$\forall x \exists y \exists z \forall u \exists v (P(z) \wedge (\neg Q(x, u) \vee Q(y, v)))$$

Examples

$$① \quad \forall z \exists x \exists y ((P(x) \vee \neg P(y) \vee Q(z)) \wedge (\neg Q(x) \vee \neg P(y) \vee Q(z)))$$

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

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$$② \quad \forall x \exists y (\exists z P(z) \wedge (\exists u Q(x, u) \rightarrow \exists v Q(y, v)))$$

\equiv

$$\forall x \exists y \exists z \forall u \exists v (P(z) \wedge (\neg Q(x, u) \vee Q(y, v)))$$

$$\approx \{y \mapsto f(x)\} \{z \mapsto g(x)\}$$

$$\forall x \forall u \exists v (P(g(x)) \wedge (\neg Q(x, u) \vee Q(f(x), v)))$$

Examples

$$① \quad \forall z \exists x \exists y ((P(x) \vee \neg P(y) \vee Q(z)) \wedge (\neg Q(x) \vee \neg P(y) \vee Q(z)))$$

$$\approx \{x \mapsto f(z)\}$$

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

$$\approx \{y \mapsto g(z)\}$$

$$\forall z ((P(f(z)) \vee \neg P(g(z)) \vee Q(z)) \wedge (\neg Q(f(z)) \vee \neg P(g(z)) \vee Q(z)))$$

$$② \quad \forall x \exists y (\exists z P(z) \wedge (\exists u Q(x, u) \rightarrow \exists v Q(y, v)))$$

\equiv

$$\forall x \exists y \exists z \forall u \exists v (P(z) \wedge (\neg Q(x, u) \vee Q(y, v)))$$

$$\approx \{y \mapsto f(x)\} \{z \mapsto g(x)\}$$

$$\forall x \forall u \exists v (P(g(x)) \wedge (\neg Q(x, u) \vee Q(f(x), v)))$$

$$\approx \{v \mapsto h(x, u)\}$$

$$\forall x \forall u (P(g(x)) \wedge (\neg Q(x, u) \vee Q(f(x), h(x, u))))$$

Outline

1. Summary of Previous Lecture
2. Quantifier Equivalences
3. Intermezzo
4. Unification
5. Intermezzo
6. Skolemization
- 7. Further Reading**

Huth and Ryan

- ▶ Section 2.3

Unification

- ▶ Wikipedia

[accessed December 27, 2024]

Huth and Ryan

- ▶ Section 2.3

Unification

- ▶ Wikipedia [accessed December 27, 2024]

Skolemization

- ▶ Wikipedia [accessed December 27, 2024]

Important Concepts

- ▶ at least as general
- ▶ composition
- ▶ decomposition
- ▶ instance
- ▶ most general unifier
- ▶ occurs check
- ▶ prenex normal form
- ▶ Skolem normal form
- ▶ Skolemization
- ▶ quantifier equivalences
- ▶ removal of trivial equations
- ▶ substitution
- ▶ unification algorithm
- ▶ unifier
- ▶ variable elimination

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homework for May 7