Basis for automated proof: Skolemization

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Overview

Plan

Introduction

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For formulae with existential quantification, use skolemization.

This transformation was introduced by Thoralf Albert Skolem (1887 - 1963), Norvegian mathematician and logician.

General view

Skolemization

- transforms a set of closed formulae to the domain closure of a set of formulae with no quantifier.

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- transforms a set of closed formulae to the domain closure of a set of formulae with no quantifier.
- preserves the existence of a model.

Plan

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   Indeed, let I be a model of $\exists x P(x)$. Hence there exists $d \in P_I$.

   Let J be the interpretation such that $P_J = P_I$ and $a_J = d$.

   J is model of $P(a)$.

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   Let I be a model of $\forall x \exists y Q(x,y)$ and let D be the domain of I.

   For every $d \in D$, the set $\{e \in D \mid (d,e) \in Q_I\}$ is not empty, hence there exists a function $g : D \rightarrow D$ such that for every $d \in D$, $g(d) \in \{e \in D \mid (d,e) \in Q_I\}$.

   Let J be the interpretation J such that $Q_J = Q_I$ and $f_J = g$: J is a model of $\forall x Q(x, f(x))$.

Properties

Skolemization **eliminates existential quantifiers** and **transforms a closed formula** A **to a formula** B such that :

- A is a consequence of B, ($B \models A$)
- every model of A « provides » a model of B

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- A is a consequence of B, ($B \models A$)
- every model of A « provides » a model of B

Hence, A **has a model if and only if** B **has a model** : skolemization preserves the existence of a model, in other words it preserves satisfiability.

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- The formula $\forall x (P(x) \Rightarrow \exists y R(x, y))$ is **proper**.

Definitions : generalized normal form

A first-order logic formula is in **normal** form if it does not contain equivalences, implications, and if negations only apply to atomic formulae.

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   This transformation only preserves the existence of a model.

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1. B = normalization of A
2. C = make B proper
3. D= Elimination of existential quantifiers from C.
   This transformation only preserves the existence of a model.
4. E = Transformation of the closed, normal, proper formula with no existential quantifiers D into a normal formula without quantifiers.

Normalization

1. Eliminate the equivalences
2. Eliminate the implications
3. Move the negations towards the atomic formulae

Rules

$$A \Leftrightarrow B \equiv (A \Rightarrow B) \wedge (B \Rightarrow A)$$

$$A \Rightarrow B \equiv \neg A \vee B$$

$$\neg\neg A \equiv A$$

$$\neg(A \wedge B) \equiv \neg A \vee \neg B$$

$$\neg(A \vee B) \equiv \neg A \wedge \neg B$$

$$\neg \forall x A \equiv \exists x \neg A$$

$$\neg \exists x A \equiv \forall x \neg A$$

Hint : replace $\neg(A \Rightarrow B)$ by $A \wedge \neg B$

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First, elimination of equivalences :

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

Then, move negations :

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

Transformation to a proper formula

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  $\forall x (P(x) \Rightarrow \exists z Q(z) \wedge \exists y R(x, y))$

Elimination of existential quantifiers

Theorem 5.2.9

Let A be a closed normal and proper formula having one occurrence of the sub-formula $\exists yB$. Let $x_1, \dots x_n$ be the free variables of $\exists yB$, with $n \geq 0$. Let f be a symbol not appearing in A. Let A' be the formula obtained by replacing this occurrence of $\exists yB$ by $B < y := f(x_1, \dots x_n) >$ (If $n = 0$, f is a constant).
The formula A' is a closed normal and proper formula satisfying :

1. A is a consequence of A'
2. If A has a model then A' has an identical model up to the truth value of f.

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Since the formula A is closed and proper, the free variables of $\exists yB$, which are bound outside $\exists yB$, are not bound by any quantifier in B (otherwise the proper property would not be respected), hence the term $f(x_1, \ldots x_n)$ is free for y in B.

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According to corollary 4.3.38 : $B < y := f(x_1, \dots x_n) >$ has as consequence $\exists yB$. Hence, we deduce that A is a consequence of A'.

Proof of theorem 5.2.9

Let us show that every model of A provides a model of A'.

Suppose that A has a model I where I is an interpretation with domain D. Let $c \in D$. For all $d_1, \dots, d_n, \in D$, let $E_{d_1,\dots,d_n}$ be the set of elements $d \in D$ such that the formula B equals 1 in the interpretation I and the state $x_1 = d_1, \dots, x_n = d_n, y = d$ of its free variables. Let $g : D^n \to D$ be a function such that if $E_{d_1,\dots,d_n} \neq \emptyset$ then $g(d_1, \dots, d_n) \in E_{d_1,\dots,d_n}$ else $g(d_1, \dots, d_n) = c$. Let J be the interpretation identical to I except that $f_J = g$. We have :

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1. $[\exists y B]_{(I,e)} = [B < y := f(x_1, \ldots, x_n) >]_{(J,e)}$, according to the interpretation of f and of theorem 4.3.36, for every state e of the variables,

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2. $[\exists y B]_{(I,e)} = [\exists y B]_{(J,e)}$, since the symbol f is new, the value of $\exists y B$ does not depend of the truth value of f.

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3. $\exists y B \Leftrightarrow B < y := f(x_1, \ldots, x_n) > \models A \Leftrightarrow A'$, according to the property of replacement 1.3.10, which holds in first-order logic as well.

Proof of theorem 5.2.9

Let us show that every model of A provides a model of A'.

Suppose that A has a model I where I is an interpretation with domain D. Let $c \in D$. For all $d_1, \ldots, d_n, \in D$, let $E_{d_1,\ldots,d_n}$ be the set of elements $d \in D$ such that the formula B equals 1 in the interpretation I and the state $x_1 = d_1, \ldots, x_n = d_n, y = d$ of its free variables. Let $g : D^n \rightarrow D$ be a function such that if $E_{d_1,\ldots,d_n} \neq \emptyset$ then $g(d_1, \ldots, d_n) \in E_{d_1,\ldots,d_n}$ else $g(d_1, \ldots, d_n) = c$. Let J be the interpretation identical to I except that $f_J = g$. We have :

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2. $[\exists yB]_{(I,e)} = [\exists yB]_{(J,e)}$, since the symbol f is new, the value of $\exists yB$ does not depend of the truth value of f.
3. $\exists yB \Leftrightarrow B < y := f(x_1, \ldots, x_n) > \models A \Leftrightarrow A'$, according to the property of replacement 1.3.10, which holds in first-order logic as well.

According to these three points, we obtain $[A]_{(J,e)} = [A']_{(J,e)}$ and since f is not in A and since the formulae A and A' do not contain free variables, we have $[A]_I = [A']_J$. Since I is model of A, J is model of A'.

Remark 5.2.10

In theorem 5.2.9, note that the formula A' obtained from formula A by elimination of a quantifier remains closed, normal and proper.

Hence, by ≪ applying ≫ the theorem repeatedly, which implies choosing a new symbol for each eliminated quantifier, one can transform a closed, normal and proper formula A into a closed, normal, proper and without existential quantifier formula B such that :

- A is a consequence of B
- If A has a model, then B has an identical model except for the truth value of the new symbols

Example 5.2.11

By eliminating existential quantifiers in the formula $\exists x \forall y P(x, y) \wedge \exists z \forall u \neg P(z, u)$ we obtain $\forall y P(a, y) \wedge \forall u \neg P(b, u)$.

It is easy to observe that this formula has a model.

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It is easy to observe that this formula has a model.

Remark : If we mistakently eliminate the two existential quantifiers using the same constant a, we obtain the formula $\forall y P(a, y) \wedge \forall u \neg P(a, u)$, which is unsatisfiable, since it has as consequence $P(a, a)$ and $\neg P(a, a)$.

Therefore a new symbol must be used whenever an existential quantifier is eliminated.

Transformation in universal closure

Theorem 5.2.13

Let *A* be a closed, normal, proper formula without existential quantifier.
Let *B* be the formula obtained by removing from *A* all the universal quantifiers (*B* is the Skolem form of *A*).

Formula *A* is equivalent to the domain closure of *B*.

Transformation in universal closure

Theorem 5.2.13

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Let B be the formula obtained by removing from A all the universal quantifiers (B is the Skolem form of A).

Formula A is equivalent to the domain closure of B.

Proof.

According to the requirements on A its transformation into $\forall(B)$ is made of replacements of sub-formulae of the form

$(\forall x C) \wedge D$ by $\forall x(C \wedge D)$ where x not free in D

$(\forall x C) \vee D$ by $\forall x(C \vee D)$ where x not free in D

$D \wedge (\forall x C)$ by $\forall x(D \wedge C)$ where x not free in D

$D \vee (\forall x C)$ by $\forall x(D \vee C)$ where x not free in D

Since each of this replacements changes a formula into another equivalent formula, the formulae A and $\forall(B)$ are equivalent.

Property of the skolemization

Property 5.2.14

Let A be a closed formula and B the Skolem form of A.

- The formula $\forall(B)$ has as consequence the formula A
- if A has a model then $\forall(B)$ has a model

Hence A has a model if and only if $\forall(B)$ has a model.

Proof.

Let C be the closed proper formula in normal form, obtained at the end of the first two steps of the skolemization of A. Let D be the result of the elimination of the existential quantifiers applied to C. According to the remark 5.2.10 we have :

- The formula D has as consequence the formula C
- if C has a model then D has a model.

Since the first two steps change the formulae into equivalent formulae, A and C are equivalent. According to theorem 5.2.13, D is equivalent to $\forall(B)$. Hence we can replace above D by $\forall(B)$ and C by A, QED. □

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Let $A = \forall x(P(x) \Rightarrow Q(x)) \Rightarrow (\forall x P(x) \Rightarrow \forall x Q(x))$. We skolemize $\neg A$.

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

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2. The normal formula is transformed into the proper formula :
   $\forall x(\neg P(x) \vee Q(x)) \wedge \forall y P(y) \wedge \exists z \neg Q(z)$
3. The existential quantifier is ≪ replaced ≫ by a constant :
   $\forall x(\neg P(x) \vee Q(x)) \wedge \forall y P(y) \wedge \neg Q(a)$

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4. The universal quantifiers are eliminated :
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2. The normal formula is transformed into the proper formula :
   $\forall x(\neg P(x) \vee Q(x)) \wedge \forall y P(y) \wedge \exists z \neg Q(z)$
3. The existential quantifier is « replaced » by a constant :
   $\forall x(\neg P(x) \vee Q(x)) \wedge \forall y P(y) \wedge \neg Q(a)$
4. The universal quantifiers are eliminated :
   $(\neg P(x) \vee Q(x)) \wedge P(y) \wedge \neg Q(a)$.

Let us instantiate the Skolem form of $\neg A$ by replacing x and y by a. We obtain the formula $(\neg P(a) \vee Q(a)) \wedge P(a) \wedge \neg Q(a)$ which is unsatisfiable. Hence $\forall((\neg P(x) \vee Q(x)) \wedge P(y) \wedge \neg Q(a)$ is unsatisfiable. Since the skolemization preserves the existence of a model, $\neg A$ is unsatisfiable, hence A is valid.

Skolemizing a set of formulae

Corollary 5.2.16

Let Γ be a set of closed formulae. The skolemization of Γ consists in applying the skolemization to all formulae of Γ, by selecting a new symbol for each existential quantifier eliminated in the third step of skolemization.

We obtain a set Δ of formulae without quantifiers such that :

- Every model of $\forall(\Delta)$ is model of Γ
- If Γ has a model then $\forall(\Delta)$ has a model which is the same as for Γ up to the truth value of new symbols.

Plan

Today

- Skolemization

Next course

- Clausal form
- Unification
- First-order resolution
- Consistency
- Completeness