Lecture 14

Decidable Theories

Logical theories, quantifier elimination, unbounded dense linear orders, linear arithmetic over the rationals, Presburger arithmetic

Introduction to Logic for Computer Science

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These slides are minor variants of those made by Prof Worrell and Dr Haase for their logic course at Oxford.

Logical theories

A **theory** $\mathcal{T}$ is a set of sentences closed under semantic entailment:

$$\mathcal{T} \models F \text{ implies } F \in \mathcal{T}.$$

A theory is **complete** if either $F \in \mathcal{T}$ or $\neg F \in \mathcal{T}$ for any F.

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Two recipes for generating theories:

- Pick a σ-structure $\mathcal{A}$. Define

  $$\mathrm{Th}(\mathcal{A}) = \{F \,:\, \mathcal{A} \models F \text{ and } F \text{ is a sentence}\}.$$

  $\mathrm{Th}(\mathcal{A})$ is called the **theory of** $\mathcal{A}$.

- Pick a set of **axioms** $\mathcal{S}$ (i.e., a set of setences). Define

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Ex1: Prove that both recipes give theories.

Ex2: Which one always generates a complete theory?

Ex3: Give an example of an incomplete theory.

Example (Structure-based Theory)

The theory of **linear arithmetic over the rationals** is

$$\mathcal{T}_{LAR} = \mathrm{Th}(\mathbb{Q}, 1, +, \{c\cdot\}_{c\in\mathbb{Q}}, <).$$

It tells the truth of the following sentences:

- The system of linear inequalities $A\boldsymbol{x} \leq \boldsymbol{b}$ has no solution.
- Every solution of $A\boldsymbol{x} \leq \boldsymbol{b}$ is also a solution of $C\boldsymbol{x} \leq \boldsymbol{d}$.

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Example (Axiom-based Theory)

The theory $\mathcal{T}_{UDLO}$ of **unbounded dense linear orders** is the set of sentences entailed by the following set of axioms:

$$\begin{array}{ll}
F_1 & \forall x\,\forall y\,(x < y \rightarrow \neg(x = y \vee y < x)) \\
F_2 & \forall x\,\forall y\,\forall z\,(x < y \wedge y < z \rightarrow x < z) \\
F_3 & \forall x\,\forall y\,(x < y \vee y < x \vee x = y) \\
F_4 & \forall x\,\forall y\,(x < y \rightarrow \exists z\,(x < z \wedge z < y)) \\
F_5 & \forall x\,\exists y\,\exists z\,(y < x < z)\,.
\end{array}$$

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A theory $\mathcal{T}$ **admits quantifier-elimination** if for any $\exists x\, F$ with F quantifier-free, there is a quantifier-free formula G such that

$$\mathcal{T} \models \exists x\, F \leftrightarrow G.$$

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Theorem

A theory $\mathcal{T}$ is decidable if $\mathcal{T}$ has (i) a quantifier-elimination (QE) procedure, and (ii) a procedure for deciding $F \in \mathcal{T}$ for quantifier-free (QF) sentences F.

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Ex2: Design a QE procedure.

Hint: Given $\exists x\, F$ for a quantifier-free F, the proc. works as follows:

1. Transform $\exists x\, F$ to an equivalent $\bigvee_i((\exists x\, G_i) \wedge H_i)$ where H_i is QF and G_i is conjunction of $x < y$ or $y < x$ for some variable $y \neq x$.

2. Transform $\exists x\, G$ to an equivalent quantifier-free G'.

Find out how to do both steps.

1. Transform $\exists x\, F$ to an equivalent $\bigvee_i ((\exists x\, G_i) \wedge H_i)$ where H_i is QF and G_i is conjunction of $x = y$, $x < y$ or $y < x$ for some variable y.

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How to do the step 2?

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Assume that $G \equiv (l_1 < x \wedge \ldots \wedge l_m < x \wedge x < u_1 \wedge \ldots \wedge x < u_n)$.

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If $m = 0$ or $n = 0$, then $\mathcal{T}_{UDLO} \models (\exists x\, F) \leftrightarrow$ **true**. Thus, $G' =$ **true**.

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If $m = 0$ or $n = 0$, then $\mathcal{T}_{UDLO} \models (\exists x\, F) \leftrightarrow \textbf{true}$. Thus, $G' = \textbf{true}$.

Otherwise,

$$\mathcal{T}_{UDLO} \models (\exists x\, F) \leftrightarrow \bigwedge_{i=1}^{m} \bigwedge_{j=1}^{n} l_i < u_j.$$

Thus, $G' = \bigwedge_{i=1}^{m} \bigwedge_{j=1}^{n} l_i < u_j$.

Theorem

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Ex: Prove the theorem. Hint: The proof is very similar to the one for the decidability of $\mathcal{T}_{UDLO}$, which we have just studied.

Presburger arithmetic

Figure: Mojzesz Presburger (1904 - 1943).

$\mathrm{Th}(\mathbb{N}, 0, 1, +, <)$ is commonly known as **Presburger arithmetic**.

Natural numbers, not rationals. Only addition. No multiplication.

Simple number theory in Presburger arithmetic

Example

Every natural number is odd or even:

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Ex: Consider the following Chicken McNugget problem.

> *Given $a_1, \ldots, a_n \in \mathbb{N}$, is there some $c \in \mathbb{N}$ such that all numbers greater than c can be represented as a non-negative linear combination of $a_1, \ldots, a_n$?*

Express this problem for given $a_1, \ldots, a_n$ in Presburger arithmetic.

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Express this problem for given $a_1, \ldots, a_n$ in Presburger arithmetic.

Ans:

$$\exists x \, \forall y \, (x < y \rightarrow (\exists z_1 \ldots \exists z_n \, (y = a_1 \cdot z_1 + \cdots + a_n \cdot z_n))).$$

Here $a_i \cdot z_i$ is an abbreviation for $\underbrace{z_i + \ldots + z_i}_{a_i \text{ copies}}$.

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Solution: extend the signature with unary divisibility relations $c \mid \cdot$ for all $c > 0$ such that

$$c \mid n \text{ iff there is } k \in \mathbb{N} \text{ such that } n = k \cdot c.$$

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$\mathrm{Th}(\mathbb{N}, 0, 1, +, <, \{c \mid \cdot\}_{c>0})$ *has a QE procedure.*

Ex: Use the theorem and prove the decid. of Presburger arithmetic.

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$$F_l = \Big(\bigwedge_{i \in L} q_i(\vec{y}) < a_i \cdot x \wedge \bigwedge_{j \in U} a_j \cdot x < p_j(\vec{y}) \wedge \bigwedge_{k \in D} c_k \mid a_k \cdot x + r_k(\vec{y}) \Big).$$

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Step 1 is similar to what we did before. Will focus on step 2.

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Goal: Eliminate quantifiers from $\exists x \, F_l$.

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Ex1: Show that $\exists x\, F_l$ is equivalent to $\exists x\, H$ where

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Ex2: Show that $\exists x\, H$ is equivalent to

$$\begin{cases} \bigvee_{0 \le m < c} H[m/x] & \text{if } L = \emptyset, \\ \bigvee_{i \in L} \bigvee_{1 \le m \le c} H[((b/a_i) \cdot q_i(\vec{y}) + m)/x] & \text{otherwise.} \end{cases}$$

Time complexity of the decidability algorithm for Presburger arithmetic

Theorem (Oppen)

Presburger arithmetic is decidable in time $2^{2^{2^{O(n)}}}$.

Good article on Presburger arithmetic

A suvival guide to Presburger arithmetic.

Written by Christoph Hasse. Published in ACM SIGLOG News 2018.

https://dl.acm.org/citation.cfm?id=3242964.