Lecture 5
First-Order Theories I

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slides acknowledgements: Zohar Manna

Announcements

- Homework 1 is due tomorrow

Last Time

- First-order logic
  - Syntax and semantics
  - Quantifiers
  - Undecidable
- Proving validity with semantic argument method

This Time

- First-order theories
- Reading: Chapter 3

First-Order Theories

- Software manipulates structures
  - Numbers, arrays, lists, bitvectors,…
- Software (and hardware) verification
  - Reasoning about such structures
- First-order theories
  - Formalize structures to enable reasoning about them
  - Validity is sometimes decidable

Definition

- First-order theory T defined by:
  - Signature Σ_T – set of constant, function, and predicate symbols
    - Have no meaning
  - Axioms A_T – set of closed (no free variables) Σ_T–formulae
    - Provide meaning for symbols of Σ_T

Σ_T-formula

- Σ_T-formula is a formula constructed of:
  - Constants, functions, and predicate symbols from Σ_T
  - Variables, logical connectives, and quantifiers

T-interpretation

- Interpretation I is T-interpretation if it satisfies all axioms A_T of T:

$$I \models A \text{ for every } A \in A_T$$

Satisfiability and Validity

- Σ_T-formula F is satisfiable in theory T (T-satisfiable) if there is a T-interpretation I that satisfies F

- Σ_T-formula F is valid in theory T (T-valid, $T \vDash F$) if every T-interpretation I satisfies F
  - Theory T consists of all closed T-valid formulae

- Two Σ_T-formulae F_1 and F_2 are equivalent in T (T-equivalent) if $T \vDash F_1 \leftrightarrow F_2$

Fragment of a Theory

- Fragment of theory T is a syntactically restricted subset of formulae of the theory
- Example:
  - Quantifier-free fragment of theory T is the set of formulae without quantifiers that are valid in T
- Often decidable fragments for undecidable theories

Decidability

- Theory T is decidable if T-validity is decidable for every Σ_T-formula F
  - There is an algorithm that always terminates with "yes" if F is T-valid, and "no" if F is T-invalid
- Fragment of T is decidable if T-validity is decidable for every Σ_T-formula F in the fragment

Common First-Order Theories

- Theory of equality
- Peano arithmetic
- Presburger arithmetic
- Linear integer arithmetic
- Reals
- Rationals
- Arrays
- Recursive data structures

Theory of Equality T_E

Signature

$$\Sigma_E : \{=, a, b, c, \ldots, f, g, h, \ldots, p, q, r, \ldots\}$$

consists of:

- a binary predicate “=“ interpreted using provided axioms
- constant, function, and predicate symbols

Axioms of T_E

1. $\forall x.\ x{=}x$ (reflexivity)
2. $\forall x,y.\ x{=}y \rightarrow y{=}x$ (symmetry)
3. $\forall x,y,z.\ x{=}y \wedge y{=}z \rightarrow x{=}z$ (transitivity)
4. for each positive int. n and n-ary function symbol *f*,

   $$\forall x_1,\ldots,x_n,y_1,\ldots,y_n.\ (\bigwedge_{i=1}^{n} x_i{=}y_i) \rightarrow f(x_1,\ldots,x_n) = f(y_1,\ldots,y_n)$$

   (function congruence)
5. for each positive int. n and n-ary predicate symbol *p*,

   $$\forall x_1,\ldots,x_n,y_1,\ldots,y_n.\ (\bigwedge_{i=1}^{n} x_i{=}y_i) \rightarrow (p(x_1,\ldots,x_n) \leftrightarrow p(y_1,\ldots,y_n))$$

   (predicate congruence)

Decidability of T_E

- Bad news
  - T_E is undecidable
- Good news
  - Quantifier-free fragment of T_E is decidable
  - Very efficient algorithms

Z3 Example

$$x = y \wedge y = z \rightarrow g(f(x), y) = g(f(z), x)$$

Arithmetic: Natural Numbers and Integers

Natural numbers $\mathbb{N} = \{0,1,2,\ldots\}$

Integers $\mathbb{Z} = \{\ldots,-2,-1,0,1,2,\ldots\}$

Three theories:

- Peano arithmetic T_{PA}
  - Natural numbers with addition (+), multiplication (*), equality (=)
- Presburger arithmetic $T_{\mathbb{N}}$
  - Natural numbers with addition (+), equality (=)
- Theory of integers $T_{\mathbb{Z}}$
  - Integers with addition (+), subtraction (-), comparison (>), equality (=), multiplication by constants

Peano Arithmetic T_{PA}

Σ_{PA} : {0,1,+,*,=}

- T_{PA}-satisfiability and T_{PA}-validity are undecidable
  - Restrict the theory more

Presburger Arithmetic $T_{\mathbb{N}}$

$\Sigma_{\mathbb{N}}$: {0,1,+,=}   no multiplication!

Axioms:

1. equality axioms for =
2. $\forall x.\ \neg(x+1=0)$ (zero)
3. $\forall x,y.\ x+1=y+1 \rightarrow x=y$ (successor)
4. $F[0] \wedge (\forall x.F[x] \rightarrow F[\mathrm{x}+1]) \rightarrow \forall x.F[x]$ (induction)
5. $\forall x.\ x+0=x$ (plus zero)
6. $\forall x,y.\ x+(\mathrm{y}+1)=(\mathrm{x}+y)+1$ (plus successor)

Decidability of $T_{\mathbb{N}}$

- $T_{\mathbb{N}}$-satisfiability and $T_{\mathbb{N}}$-validity are decidable

Theory of Integers $T_{\mathbb{Z}}$

$\Sigma_{\mathbb{Z}}$: {…,-2,-1,0,1,2,…,-3*,-2*,2*,3*,…,+,-,=,>}

where

- …,-2,-1,0,1,2,… are constants
- …,-3*,-2*,2*,3*,… are unary functions (intended meaning: 2*x is x+x, -3*x is -x-x-x)
- +,-,>,= have the usual meaning

- $T_{\mathbb{N}}$ and $T_{\mathbb{Z}}$ have the same expressiveness
  - Every $\Sigma_{\mathbb{Z}}$-formula can be reduced to $\Sigma_{\mathbb{N}}$-formula
  - Every $\Sigma_{\mathbb{N}}$-formula can be reduced to $\Sigma_{\mathbb{Z}}$-formula

Example of $T_{\mathbb{Z}}$ to $T_{\mathbb{N}}$ Reduction

Consider $\Sigma_{\mathbb{Z}}$-formula

$F_0 : \forall w, x.\ \exists y, z.\ x + 2*y - z - 13 > -3*w + 5$

Introduce two variables v_p and v_n (range over natural numbers) for each variable v (range over integers) in F_0:

$F_1 : \forall w_p, w_n, x_p, x_n.\ \exists y_p, y_n, z_p, z_n.$
$(x_p - x_n) + 2*(y_p - y_n) - (z_p - z_n) - 13 > -3*(w_p - w_n) + 5$

Eliminate - by moving to the other side of >:

$F_2 : \forall w_p, w_n, x_p, x_n.\ \exists y_p, y_n, z_p, z_n.$
$x_p + 2*y_p + z_n + 3*w_p > x_n + 2*y_n + z_p + 13 + 3*w_n + 5$

Example of $T_{\mathbb{Z}}$ to $T_{\mathbb{N}}$ Reduction cont.

Eliminate * and >:

$$F_3 : \forall w_p, w_n, x_p, x_n.\ \exists y_p, y_n, z_p, z_n.\ \exists u.\ \neg(u=0) \wedge$$
$$x_p + y_p + y_p + z_n + w_p + w_p + w_p$$
$$= x_n + y_n + y_n + z_p + w_n + w_n + w_n + \mathrm{u}$$
$$+ 1+1+1+1+1+1+1+1+1$$
$$+ 1+1+1+1+1+1+1+1+1$$

- F_3 is a $\Sigma_{\mathbb{N}}$-formula equisatisfiable to F_0

Example of $T_{\mathbb{N}}$ to $T_{\mathbb{Z}}$ Reduction

Consider $\Sigma_{\mathbb{N}}$-formula

F : $\forall x.\ \exists y.\ x = y + 1$

F is equisatisfiable to $\Sigma_{\mathbb{Z}}$-formula

$\forall x.\ x > -1 \rightarrow \exists y.\ y > -1 \wedge x = y + 1$

Decidability of $T_{\mathbb{Z}}$

- $T_{\mathbb{Z}}$-satisfiability and $T_{\mathbb{Z}}$-validity are decidable

Z3 Example

$$x > z \wedge y >= 0 \rightarrow x + y > z$$

Next Time

- More on first-order theories
  - Arithmetic with rationals and reals
  - Arrays
  - Recursive data structures
- Complexities for theories