CS156: The Calculus of Computation

Zohar Manna Autumn 2008

Chapter 3: First-Order Theories

First-Order Theories I

First-order theory T consists of

- Signature Σ_T - set of constant, function, and predicate symbols
- Set of axioms A_T - set of closed (no free variables) Σ_T-formulae

A Σ_T-formula is a formula constructed of constants, functions, and predicate symbols from Σ_T, and variables, logical connectives, and quantifiers.

The symbols of Σ_T are just symbols without prior meaning — the axioms of T provide their meaning.

First-Order Theories II

A Σ_T-formula F is valid in theory T (T-valid, also $T \models F$), iff every interpretation I that satisfies the axioms of T,
  i.e. $I \models A$ for every $A \in A_T$ (T-interpretation)
also satisfies F,
  i.e. $I \models F$

A Σ_T-formula F is satisfiable in T (T-satisfiable), if there is a T-interpretation (i.e. satisfies all the axioms of T) that satisfies F

Two formulae F_1 and F_2 are equivalent in T (T-equivalent), iff $T \models F_1 \leftrightarrow F_2$,
  i.e. if for every T-interpretation I, $I \models F_1$ iff $I \models F_2$

Note:
- $I \models F$ stands for "F true under interpretation I"
- $T \models F$ stands for "F is valid in theory T"

Fragments of Theories

A fragment of theory T is a syntactically-restricted subset of formulae of the theory.

  Example: a quantifier-free fragment of theory T is the set of quantifier-free formulae in T.

A theory T is decidable if $T \models F$ (T-validity) is decidable for every Σ_T-formula F;

  i.e., there is an algorithm that always terminate with "yes", if F is T-valid, and "no", if F is T-invalid.

A fragment of T is decidable if $T \models F$ is decidable for every Σ_T-formula F obeying the syntactic restriction.

Theory of Equality T_E I

Signature:

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

consists of

- $=$, a binary predicate, interpreted with meaning provided by axioms
- all 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 integer n and n-ary function symbol f,
   $$\forall x_1, \ldots, x_n, y_1, \ldots, y_n.\ \bigwedge_i x_i = y_i$$
   $$\rightarrow\ f(x_1, \ldots, x_n) = f(y_1, \ldots, y_n) \quad \text{(function congruence)}$$

Theory of Equality T_E II

5. for each positive integer n and n-ary predicate symbol p,
   $$\forall x_1, \ldots, x_n, y_1, \ldots, y_n.\ \bigwedge_i x_i = y_i$$
   $$\rightarrow\ (p(x_1, \ldots, x_n) \leftrightarrow p(y_1, \ldots, y_n)) \quad \text{(predicate congruence)}$$

(function) and (predicate) are axiom schemata.

Example:

(function) for binary function f for $n = 2$:

$$\forall x_1, x_2, y_1, y_2.\ x_1 = y_1 \wedge x_2 = y_2 \rightarrow f(x_1, x_2) = f(y_1, y_2)$$

(predicate) for unary predicate p for $n = 1$:

$$\forall x, y.\ x = y \rightarrow (p(x) \leftrightarrow p(y))$$

Note: we omit "congruence" for brevity.

Decidability of T_E I

> T_E is undecidable.
> The quantifier-free fragment of T_E is decidable. Very efficient algorithm.

Semantic argument method can be used for T_E

Example: Prove

$$F : a = b \wedge b = c \rightarrow g(f(a), b) = g(f(c), a)$$

is T_E-valid.

Decidability of T_E II

Suppose not; then there exists a T_E-interpretation I such that $I \not\models F$. Then,

1.	I	$\not\models$ F	assumption
2.	I	$\models$ $a = b \wedge b = c$	1, $\rightarrow$
3.	I	$\not\models$ $g(f(a), b) = g(f(c), a)$	1, $\rightarrow$
4.	I	$\models$ $a = b$	2, $\wedge$
5.	I	$\models$ $b = c$	2, $\wedge$
6.	I	$\models$ $a = c$	4, 5, (transitivity)
7.	I	$\models$ $f(a) = f(c)$	6, (function)
8.	I	$\models$ $b = a$	4, (symmetry)
9.	I	$\models$ $g(f(a), b) = g(f(c), a)$	7, 8, (function)
10.	I	$\models$ $\bot$	3, 9 contradictory

F is T_E-valid.

Natural Numbers and Integers

Natural numbers $\mathbb{N} = \{0, 1, 2, \cdots\}$
Integers $\mathbb{Z} = \{\cdots, -2, -1, 0, 1, 2, \cdots\}$

Three variations:

▶ Peano arithmetic T_{PA}: natural numbers with addition, multiplication, $=$

▶ Presburger arithmetic $T_{\mathbb{N}}$: natural numbers with addition, $=$

▶ Theory of integers $T_{\mathbb{Z}}$: integers with $+, -, >, =,$ multiplication by constants

---

1. Peano Arithmetic T_{PA} (first-order arithmetic)

$$\Sigma_{PA} : \{0, 1, +, \cdot, =\}$$

Equality Axioms: (reflexivity), (symmetry), (transitivity)
two (function) for $+$, two (function) for $\cdot$.

And the axioms:

1. $\forall x. \neg(x + 1 = 0)$		(zero)
2. $\forall x, y. \ x + 1 = y + 1 \rightarrow x = y$		(successor)
3. $F[0] \wedge (\forall x. F[x] \rightarrow F[x+1]) \rightarrow \forall x. F[x]$		(induction)
4. $\forall x. \ x + 0 = x$		(plus zero)
5. $\forall x, y. \ x + (y + 1) = (x + y) + 1$		(plus successor)
6. $\forall x. \ x \cdot 0 = 0$		(times zero)
7. $\forall x, y. \ x \cdot (y + 1) = x \cdot y + x$		(times successor)

Line 3 is an axiom schema.

Example: $3x + 5 = 2y$ can be written using Σ_{PA} as

$$x + x + x + 1 + 1 + 1 + 1 + 1 = y + y$$

Note: we have $>$ and $\geq$ since

$3x + 5 > 2y$ write as $\exists z. \ z \neq 0 \wedge 3x + 5 = 2y + z$

$3x + 5 \geq 2y$ write as $\exists z. \ 3x + 5 = 2y + z$

Example:

Existence of pythagorean triples (F is T_{PA}-valid):

$F : \exists x, y, z. \ x \neq 0 \wedge y \neq 0 \wedge z \neq 0 \wedge x \cdot x + y \cdot y = z \cdot z$

Decidability of Peano Arithmetic

T_{PA} is undecidable. (Gödel, Turing, Post, Church)
The quantifier-free fragment of T_{PA} is undecidable.
(Matiyasevich, 1970)

Remark: Gödel's first incompleteness theorem

Peano arithmetic T_{PA} does not capture true arithmetic:
There exist closed Σ_{PA}-formulae representing valid propositions of number theory that are not T_{PA}-valid.
The reason: T_{PA} actually admits *nonstandard interpretations*.

For decidability: no multiplication

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

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

Axioms of $T_\mathbb{N}$ (equality axioms, with 1-5):

1. $\forall x. \neg(x + 1 = 0)$ (zero)
2. $\forall x, y. \; x + 1 = y + 1 \; \rightarrow \; x = y$ (successor)
3. $F[0] \wedge (\forall x. \; F[x] \; \rightarrow \; F[x + 1]) \; \rightarrow \; \forall x. \; F[x]$ (induction)
4. $\forall x. \; x + 0 = x$ (plus zero)
5. $\forall x, y. \; x + (y + 1) = (x + y) + 1$ (plus successor)

Line 3 is an axiom schema.

> $T_\mathbb{N}$-satisfiability (and thus $T_\mathbb{N}$-validity) is decidable
> (Presburger, 1929)

---

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

Signature:

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

where

- $\ldots, -2, -1, 0, 1, 2, \ldots$ are constants
- $\ldots, -3\cdot, -2\cdot, 3\cdot, \ldots$ are unary functions
  (intended meaning: $2 \cdot x$ is $x + x$, $-3 \cdot x$ is $-x - x - x$)
- $+, -, >, =$ have the usual meanings.

Relation between $T_\mathbb{Z}$ and $T_\mathbb{N}$:

     $T_\mathbb{Z}$ and $T_\mathbb{N}$ have the same expressiveness:
- For every $\Sigma_\mathbb{Z}$-formula there is an equisatisfiable $\Sigma_\mathbb{N}$-formula.
- For every $\Sigma_\mathbb{N}$-formula there is an equisatisfiable $\Sigma_\mathbb{Z}$-formula.

     $\Sigma_\mathbb{Z}$-formula F and $\Sigma_\mathbb{N}$-formula G are *equisatisfiable* iff:

$$F \text{ is } T_\mathbb{Z}\text{-satisfiable} \quad \text{iff} \quad G \text{ is } T_\mathbb{N}\text{-satisfiable}$$

$\Sigma_\mathbb{Z}$-formula to $\Sigma_\mathbb{N}$-formula I

Example: consider the $\Sigma_\mathbb{Z}$-formula

$$F_0 : \; \forall w, x. \; \exists y, z. \; x + 2y - z - 7 > -3w + 4.$$

Introduce two variables, v_p and v_n (range over the nonnegative integers) for each variable v (range over the integers) of F_0:

$$F_1 : \begin{array}{l} \forall w_p, w_n, x_p, x_n. \; \exists y_p, y_n, z_p, z_n. \\ (x_p - x_n) + 2(y_p - y_n) - (z_p - z_n) - 7 > -3(w_p - w_n) + 4 \end{array}$$

Eliminate $-$ by moving to the other side of $>$:

$$F_2 : \begin{array}{l} \forall w_p, w_n, x_p, x_n. \; \exists y_p, y_n, z_p, z_n. \\ x_p + 2y_p + z_n + 3w_p > x_n + 2y_n + z_p + 7 + 3w_n + 4 \end{array}$$

$\Sigma_\mathbb{Z}$-formula to $\Sigma_\mathbb{N}$-formula II

Eliminate $>$ and numbers:

$$F_3 : \begin{array}{l} \forall w_p, w_n, x_p, x_n. \; \exists y_p, y_n, z_p, z_n. \; \exists u. \\ \neg(u = 0) \; \wedge \; x_p + y_p + y_p + z_n + w_p + w_p + w_p \\ \qquad = x_n + y_n + y_n + z_p + w_n + w_n + w_n + u \\ \qquad \quad + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 \end{array}$$

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

$\Sigma_\mathbb{Z}$-formula to $\Sigma_\mathbb{N}$-formula III

Example: The $\Sigma_\mathbb{N}$-formula

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

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

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

To decide $T_\mathbb{Z}$-validity for a $\Sigma_\mathbb{Z}$-formula F:

- transform $\neg F$ to an equisatisfiable $\Sigma_\mathbb{N}$-formula $\neg G$,
- decide $T_\mathbb{N}$-validity of G.

Rationals and Reals

Signatures:

$$\Sigma_\mathbb{Q} = \{0, 1, +, -, =, \geq\}$$
$$\Sigma_\mathbb{R} = \Sigma_\mathbb{Q} \cup \{\cdot\}$$

- Theory of Reals $T_\mathbb{R}$ (with multiplication)

$$x \cdot x = 2 \quad \Rightarrow \quad x = \pm\sqrt{2}$$

- Theory of Rationals $T_\mathbb{Q}$ (no multiplication)

$$\underbrace{2x}_{x+x} = 7 \quad \Rightarrow \quad x = \frac{7}{2}$$

Note: strict inequality okay; simply rewrite

$$x + y > z$$

as follows:

$$\neg(x + y = z) \wedge x + y \geq z.$$

1. Theory of Reals $T_\mathbb{R}$

Signature:

$$\Sigma_\mathbb{R} : \{0, 1, +, -, \cdot, =, \geq\}$$

with multiplication. Axioms in text.

Example:

$$\forall a, b, c. \ b^2 - 4ac \geq 0 \ \leftrightarrow \ \exists x. \ ax^2 + bx + c = 0$$

is $T_\mathbb{R}$-valid.

> $T_\mathbb{R}$ is decidable (Tarski, 1930)
> High time complexity

2. Theory of Rationals $T_\mathbb{Q}$

Signature:

$$\Sigma_\mathbb{Q} : \{0, 1, +, -, =, \geq\}$$

without multiplication. Axioms in text.

Rational coefficients are simple to express in $T_\mathbb{Q}$.

Example: Rewrite

$$\frac{1}{2}x + \frac{2}{3}y \geq 4$$

as the $\Sigma_\mathbb{Q}$-formula

$$3x + 4y \geq 24$$

> $T_\mathbb{Q}$ is decidable
> Quantifier-free fragment of $T_\mathbb{Q}$ is efficiently decidable

Recursive Data Structures (RDS) I

Tuples of variables where the elements can be instances of the same structure: e.g., linked lists or trees.

1. Theory T_{cons} (LISP-like lists)

Signature:

$$\Sigma_{cons} : \{cons, car, cdr, atom, =\}$$

where

$cons(a, b)$ – list constructed by concatenating a and b
$car(x)$ – left projector of x: $car(cons(a, b)) = a$
$cdr(x)$ – right projector of x: $cdr(cons(a,b)) = b$ <u>Note</u>: an
$atom(x)$ – true iff x is a <u>single-element list</u>
atom is simply something that is not a cons. In this formulation, there is no NIL value.

Recursive Data Structures (RDS) II

<u>Axioms</u>:
1. The axioms of <u>reflexivity</u>, <u>symmetry</u>, and <u>transitivity</u> of $=$
2. <u>Function Congruence</u> axioms

$$\forall x_1, x_2, y_1, y_2.\ x_1 = x_2 \wedge y_1 = y_2\ \rightarrow\ cons(x_1, y_1) = cons(x_2, y_2)$$
$$\forall x, y.\ x = y\ \rightarrow\ car(x) = car(y)$$
$$\forall x, y.\ x = y\ \rightarrow\ cdr(x) = cdr(y)$$

3. Predicate Congruence axiom

$$\forall x, y.\ x = y\ \rightarrow\ (atom(x) \leftrightarrow atom(y))$$

4. $\forall x, y.\ car(cons(x, y)) = x$ (left projection)
5. $\forall x, y.\ cdr(cons(x, y)) = y$ (right projection)
6. $\forall x.\ \neg atom(x)\ \rightarrow\ cons(car(x), cdr(x)) = x$ (construction)
7. $\forall x, y.\ \neg atom(cons(x, y))$ (atom)

<u>Note</u>: the behavior of car and cons on atoms is not specified.

> T_{cons} is undecidable
> Quantifier-free fragment of T_{cons} is efficiently decidable

Lists with equality

2. Theory T_{cons}^{E} (lists with equality)

$$T_{cons}^{E}\ =\ T_E \cup T_{cons}$$

Signature:

$$\Sigma_E \cup \Sigma_{cons}$$

(this includes uninterpreted constants, functions, and predicates)

<u>Axioms</u>: union of the axioms of T_E and T_{cons}

> T_{cons}^{E} is undecidable
> Quantifier-free fragment of T_{cons}^{E} is efficiently decidable

<u>Example</u>: The Σ_{cons}^{E}-formula

$$F: \begin{array}{l} car(x) = car(y) \wedge cdr(x) = cdr(y) \wedge \neg atom(x) \wedge \neg atom(y) \\ \rightarrow f(x) = f(y) \end{array}$$

is T_{cons}^{E}-valid.

Suppose not; then there exists a T_{cons}^E-interpretation I such that $I \not\models F$. Then,

1. $I \not\models F$ assumption
2. $I \models \text{car}(x) = \text{car}(y)$ $1, \rightarrow, \wedge$
3. $I \models \text{cdr}(x) = \text{cdr}(y)$ $1, \rightarrow, \wedge$
4. $I \models \neg\text{atom}(x)$ $1, \rightarrow, \wedge$
5. $I \models \neg\text{atom}(y)$ $1, \rightarrow, \wedge$
6. $I \not\models f(x) = f(y)$ $1, \rightarrow$
7. $I \models \text{cons}(\text{car}(x), \text{cdr}(x)) = \text{cons}(\text{car}(y), \text{cdr}(y))$
        2, 3, (function)
8. $I \models \text{cons}(\text{car}(x), \text{cdr}(x)) = a$ 4, (construction)
9. $I \models \text{cons}(\text{car}(y), \text{cdr}(y)) = b$ 5, (construction)
10. $I \models a = b$ 7, 8, 9, (transitivity)
11. $I \models f(x) = f(y)$ 10, (function)

Lines 6 and 11 are contradictory, so our assumption that $I \not\models F$ must be wrong. Therefore, F is T_{cons}^E-valid.

Theory of Arrays T_A

Signature:

$$\Sigma_A: \{\cdot[\cdot], \cdot\langle\cdot \vartriangleleft \cdot\rangle, =\}$$

where

- $a[i]$ binary function –
  read array a at index i ("read(a,i)")
- $a\langle i \vartriangleleft v\rangle$ ternary function –
  write value v to index i of array a ("write(a,i,v)")

Axioms

1. the axioms of (reflexivity), (symmetry), and (transitivity) of T_E
2. $\forall a, i, j.\ i = j \ \rightarrow\ a[i] = a[j]$ (array congruence)
3. $\forall a, v, i, j.\ i = j \ \rightarrow\ a\langle i \vartriangleleft v\rangle[j] = v$ (read-over-write 1)
4. $\forall a, v, i, j.\ i \neq j \ \rightarrow\ a\langle i \vartriangleleft v\rangle[j] = a[j]$ (read-over-write 2)

<u>Note:</u> $=$ is only defined for array elements

$$F:\ a[i] = e \ \rightarrow\ a\langle i \vartriangleleft e\rangle = a$$

not T_A-valid, but

$$F':\ a[i] = e \ \rightarrow\ \forall j.\ a\langle i \vartriangleleft e\rangle[j] = a[j],$$

is T_A-valid.

Also

$$a = b \ \rightarrow\ a[i] = b[i]$$

is not T_A-valid: We have only axiomatized a restricted congruence.

> T_A is undecidable
> Quantifier-free fragment of T_A is decidable

---

2. Theory of Arrays $T_A^=$ (with extensionality)

Signature and axioms of $T_A^=$ are the same as T_A, with one additional axiom

$$\forall a, b.\ (\forall i.\ a[i] = b[i]) \ \leftrightarrow\ a = b \quad \text{(extensionality)}$$

<u>Example:</u>

$$F:\ a[i] = e \ \rightarrow\ a\langle i \vartriangleleft e\rangle = a$$

is $T_A^=$-valid.

> $T_A^=$ is undecidable
> Quantifier-free fragment of $T_A^=$ is decidable

First-Order Theories

	Theory	Decidable	QFF Dec.
T_E	Equality	–	✓
T_{PA}	Peano Arithmetic	–	–
$T_{\mathbb{N}}$	Presburger Arithmetic	✓	✓
$T_{\mathbb{Z}}$	Linear Integer Arithmetic	✓	✓
$T_{\mathbb{R}}$	Real Arithmetic	✓	✓
$T_{\mathbb{Q}}$	Linear Rationals	✓	✓
T_{cons}	Lists	–	✓
T_{cons}^E	Lists with Equality	–	✓

Combination of Theories

How do we show that

$$1 \leq x \ \wedge \ x \leq 2 \ \wedge \ f(x) \neq f(1) \ \wedge \ f(x) \neq f(2)$$

is ($T_E \ \cup \ T_{\mathbb{Z}}$)-unsatisfiable?
Or how do we prove properties about
   an array of integers, or
   a list of reals . . . ?

Given theories T_1 and T_2 such that

$$\Sigma_1 \ \cap \ \Sigma_2 \ = \ \{=\}$$

The combined theory $T_1 \ \cup \ T_2$ has
▸ signature $\Sigma_1 \ \cup \ \Sigma_2$
▸ axioms $A_1 \ \cup \ A_2$

Nelson & Oppen showed that,
if
▸ satisfiability of the quantifier-free fragment (qff) of T_1 is
   decidable,
▸ satisfiability of qff of T_2 is decidable, and
▸ certain technical simple requirements are met,
then satisfiability of qff of $T_1 \ \cup \ T_2$ is decidable.