

First-Order Term-Indexing

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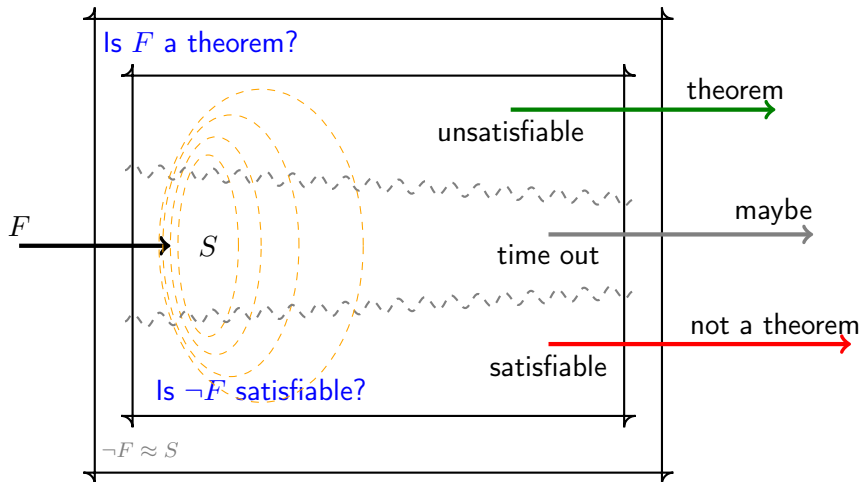
References



R. Sekar, I. V. Ramakrishnan, and Andrei Voronkov, *Term indexing*, Handbook of Automated Reasoning (Alan Robinson and Andrei Voronkov, eds.), Elsevier Science Publishers B. V., Amsterdam, The Netherlands, 2001, pp. 1853–1964.

Outline

- 1 Motivation
- 2 Term Structure
- 3 Path Indexing
- 4 Discrimination Trees
- 5 Substitution Trees
- 6 Search times



Clausal form

$$\{ P(f(x)) \vee f(x) \not\approx a, g(x, y) \approx a \vee \neg Q(x, y), \mathcal{C}_3 \}$$

$$\equiv$$

$$\forall x (P(f(x)) \vee f(x) \not\approx a)$$

$$\wedge$$

$$\forall xy (g(x, y) \approx a \vee \neg Q(x, y))$$

$$\wedge$$

$$\forall \text{Var}(\mathcal{C}_3) (\mathcal{C}_3)$$

Goal

A sound and refutation complete calculus.

Resolution (without equality)

Resolve and factor all clauses and literals in an unsatisfiable set

$$\frac{A \vee \mathcal{C} \quad \neg B \vee \mathcal{D}}{(C \vee D)\sigma} (\sigma) \text{ resolution} \qquad \frac{A \vee B \vee \mathcal{C}}{(A \vee C)\sigma} (\sigma) \text{ factoring}$$

$$\sigma = \text{mgu}(A, B)$$

and the empty clause will be derived eventually.

Observation

Usually the set grows too fast to obtain a result.

Goal

A sound, refutation complete, and *effective* calculus.

- 1 *Reduce* search space
 - Ordered Resolution, Strategies, ...
 - ... with selection functions for clauses and literals
- 2 *Reduce* redundancy
 - e.g. discard clauses that are subsumed by other clauses
 - ... depending on the calculus

Example (forward subsumption)

$$S = \{^1P(x, y), ^2\neg P(a, z)\} \cup \{^3P(a, z')\} \quad t_1 \text{ subsumes } t_3$$

$$\frac{P(x, y) \quad \neg P(a, z)}{\square} \{x \mapsto a, y \mapsto z\} \quad \text{Resolution}$$

$$S \perp = \{P(\perp, \perp), \neg P(a, \perp), P(a, \perp)\} \quad \text{InstGen / SMT}$$

Goal

A sound, refutation complete, and effective calculus.

3 Quickly find

- *variants*
- *instances*
- *generalizations*
- *unifiable terms*

variant removal
backward subsumption
forward subsumption
resolution, demodulation

of a query term in a given set of terms.

Observation

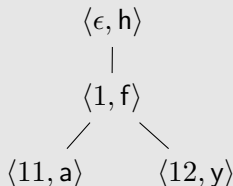
Deduction rate drops quickly with sequential search.

Term Indexing

Data structures and algorithms for fast retrieval of matching terms.

Positions of a term

$$\mathcal{Pos}(t) = \begin{cases} \{\epsilon\} & \text{if } t = x \in \mathcal{V} \\ \{\epsilon\} \cup \{ip \mid 1 \leq i \leq n \wedge p \in \mathcal{Pos}(t_i)\} & \text{if } t = f(t_1, \dots, t_n) \end{cases}$$

Traversals of $h(f(a, y))$ 

$$\mathcal{Pos}(h(f(a, y))) = \{\epsilon, 1, 11, 12\}$$

$$h(f(a, y))|_{12} = y \quad \langle 12, y \rangle$$

$$\langle \epsilon, h \rangle \langle 1, f \rangle \langle 12, y \rangle \quad \text{root to leaf } y$$

$$\langle \epsilon, h \rangle \langle 1, f \rangle \langle 11, a \rangle \langle 12, y \rangle \quad \text{pre-order}$$

Variables

Different terms generate the same position strings when

- variable names are ignored $f(z, y), f(y, x), f(x, x) \Rightarrow f(*, *)$
- or normalized $f(z, y), f(z, x) \Rightarrow f(*_1, *_2)$
 $f(x, x) \Rightarrow f(*_1, *_1)$

In the second case only variants of terms generate the same strings.

Notation

We abbreviate

- path strings $\langle \epsilon, h \rangle \langle 1, f \rangle \langle 12, * \rangle$ h.1.f.2.*
- and traversal strings $\langle \epsilon, h \rangle \langle 1, f \rangle \langle 11, * \rangle \langle 12, * \rangle$ h.f.a.*
 when traversal order and arity of symbols are fixed.

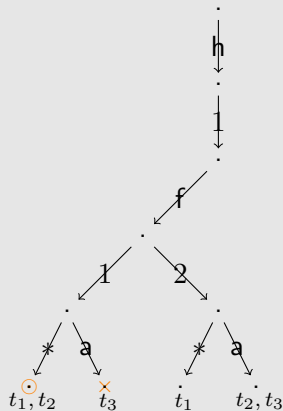
Build

$$t_1: h(f(x, y)), t_2: h(f(x, a)), t_3: h(f(a, a))$$

$$t_1 \Rightarrow \{h.1.f.1.*, h.1.f.2.*\}$$

$$t_2 \Rightarrow \{h.1.f.1.*, h.1.f.2.a\}$$

$$t_3 \Rightarrow \{h.1.f.1.a, h.1.f.2.a\}$$



Retrieve

$$^{t_1}h(f(x, y)), ^{t_2}h(f(x, a)), ^{t_3}h(f(a, a))$$

$$h(f(x, b))) \Rightarrow \{h.f.*, h.f.b\}$$

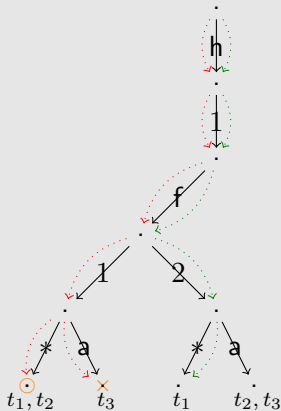
$$u : h(f(\textcolor{red}{x}', \textcolor{green}{b})) \mapsto \{\textcolor{teal}{t}_1, \textcolor{teal}{t}_2, \textcolor{teal}{t}_3\} \cap \{\textcolor{teal}{t}_1, \textcolor{teal}{t}_3\}$$

$$i : h(f(x', b)) \mapsto \{t_1, t_2, t_3\} \cap \{$$

$$g : h(f(x', b)) \mapsto \{t_1, t_2\} \cap \{t_1\}$$

$$v : \mathbf{h}(\mathbf{f}(x', \mathbf{b})) \mapsto \{t_1, t_2\} \cap \{$$

$$v : \mathbf{h}(\mathbf{f}(x', x')) \mapsto \{\textcolor{red}{t}_1, t_2\} \cap \{\textcolor{red}{t}_1\}$$



Unit Superposition Inference Rules

$$\frac{s \approx t \quad L[s']}{(L[t]) \cdot \sigma} \quad \begin{array}{l} \text{unit} \\ \text{paramodulation} \end{array}$$

where $\sigma = \text{mgu}(s, s')$, $s' \notin \mathcal{V}$, $t\sigma \neq s\sigma$

$$\frac{s \approx t \quad u[s'] \not\approx v}{(u[t] \not\approx v) \cdot \sigma} \quad \begin{array}{l} \text{unit} \\ \text{superposition} \end{array} \quad \frac{s \approx t \quad u[s'] \approx v}{(u[t] \approx v) \cdot \sigma}$$

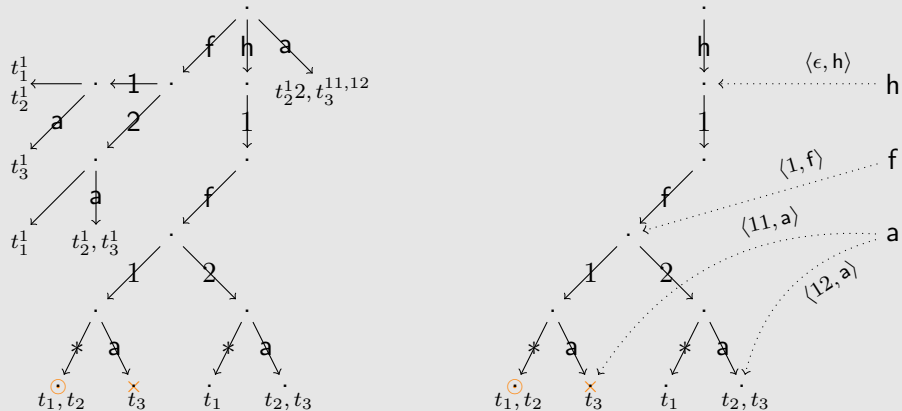
where $\sigma = \text{mgu}(s, s')$, $s' \notin \mathcal{V}$, $t\sigma \neq s\sigma$, $v\sigma \neq u[s']\sigma$

$$\frac{s \not\approx t}{\square} \quad \begin{array}{l} \text{unit equality} \\ \text{resolution} \end{array}$$

$$\frac{A \quad \neg B}{\square} \quad \begin{array}{l} \text{unit} \\ \text{resolution} \end{array}$$

where s and t (A and B respectively) are unifiable

$${}^{t_4}\mathbf{f}(x, \mathbf{a}) \approx x$$



$$^{t_1}h(f(x, y)), ^{t_2}h(f(x, a)), ^{t_3}h(f(a, a))$$

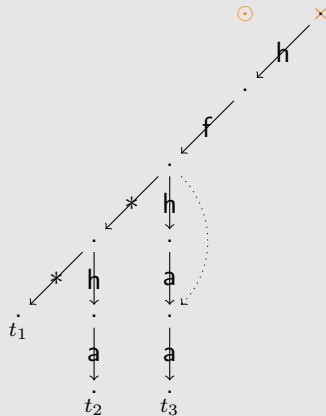
Insert

$$^{t_1:}h(f(x, y)), ^{t_2:}h(f(x, h(a))), ^{t_3:}h(f(h(a), a))$$

$$t_1 \Rightarrow \text{h.f.}.*.*$$

$$t_2 \Rightarrow \text{h.f.} * \text{h.a}$$

$$t_3 \Rightarrow \text{h.f.h.a.a}$$



Retrieve

$$^{t_1:}h(f(x, y)), ^{t_2:}h(f(x, h(a))), ^{t_3:}h(f(h(a), a))$$

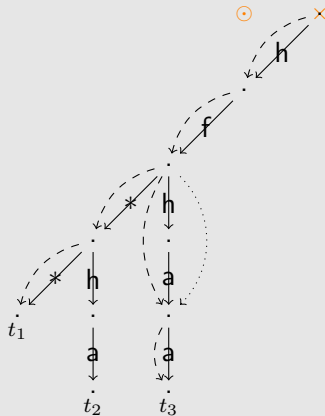
$$h(f(x', a)) \Rightarrow h.f.*.a$$

$$u : h(f(x', \mathbf{a})) \mapsto \{t_1, t_3\}$$

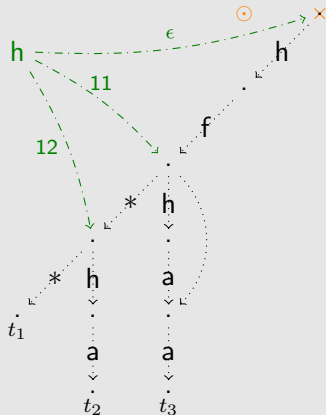
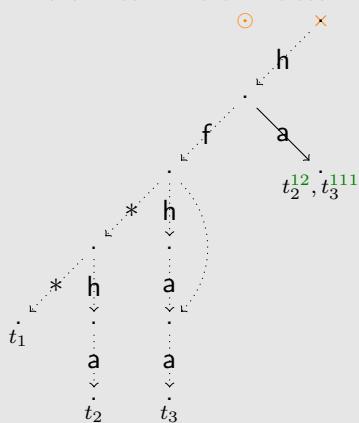
$$i : h(f(x', \mathbf{a})) \mapsto \{t_3\}$$

$$g : h(f(x', a)) \mapsto \{t_1\}$$

$$v : \mathbf{h}(\mathbf{f}(x', \mathbf{a})) \mapsto \{ \}$$



Subterms

 $t_1: h(f(x, y)), t_2: h(f(x, h(a))), t_3: h(f(h(a), a))$


TPTP/Problems/HWV/HWV134-1.p

2 332 428 formulae, 6 570 884 literals

literals:		(ℓ_1, ℓ_2)	$A, \neg B$	sequential search	index search	speed up
new	total					
1 000	1 000	500 000	761	726ms	70ms	10
1 000	2 000	1 500 000	812	2s	69ms	29
1 000	4 000	3 500 000	723	4s	75ms	53
1 000	8 000	7 500 000	433	9s	125ms	72
1 000	16 000	15 500 000	742	21s	221ms	95
1 000	32 000	31 500 000	592	40s	489ms	82
1 000	64 000	63 500 000	1167	80s	697ms	115
1 000	128 000	127 500 000	1479	160s	13s	12
1 000	256 000	255 500 000	1097	320s	440s	1
1 000	512 000	511 500 000	1440	640s	348s	2
1 000	1 024 000	1023 500 000	1534	1280s	348s	4