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

Notation

Clausal form

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

$$\equiv$$

$$\forall x\, (\mathsf{P}(\mathsf{f}(x)) \lor \mathsf{f}(x) \not\approx \mathsf{a})$$

$$\land$$

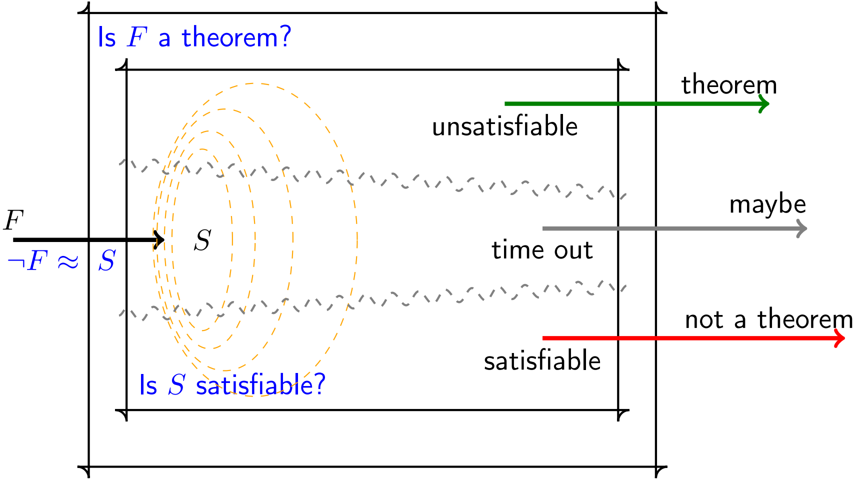
$$\forall xy\, (\mathsf{g}(x,y) \approx \mathsf{a} \lor \neg \mathsf{Q}(x,y))$$

$$\land$$

$$\forall\, \mathcal{V}\mathsf{ar}(\mathcal{C}_3)\, (\mathcal{C}_3)$$

Refutation

FOL Theorem Proving



Goal

A sound and refutation complete calculus.

Resolution (without equality)

Resolve and factor all clauses and literals in an unsatisfiable set.

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

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

With a fair strategy 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
   - e.g. Ordered Resolution
   - ...selection functions for clauses and literals
2. *Reduce* redundancy
   - e.g. ignore clause $\mathcal{D}$, if $\mathcal{C}$ subsumes $\mathcal{D}$, i.e. $\mathcal{C}\tau \subseteq \mathcal{D}$.
   - ...depends on the calculus

Example (forward subsumption)

$$S = \{{}^{1:}\mathsf{P}(x,y), {}^{2:}\neg\mathsf{P}(\mathsf{a},z)\} \cup \{{}^{3:}\mathsf{P}(\mathsf{a},z')\}$$

t_1 subsumes t_3

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

Resolution

$$S\bot = \{\mathsf{P}(\bot,\bot), \neg\mathsf{P}(\mathsf{a},\bot), \mathsf{P}(\mathsf{a},\bot)\}$$

InstGen/SMT

Goal

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

3. Quickly find
   - *variants* — variant removal
   - *instances* — backward subsumption
   - *generalizations* — forward subsumption
   - *unifiable terms* — resolution, etc.

   of a query term in a given set of terms.

Observation

Deduction rate drops quickly with linear search.

Improvement

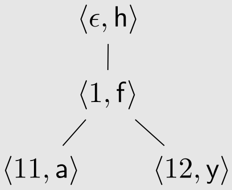
Term-Indexing

Position-Strings

Positions of a term

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

Traversals of $\mathsf{h}(\mathsf{f}(\mathsf{a}, y))$



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

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

$\langle\epsilon, \mathsf{h}\rangle\langle 1, \mathsf{f}\rangle\langle 12, y\rangle$	root to leaf y	$(\mathsf{h}1\mathsf{f}2y)$
$\langle\epsilon, \mathsf{h}\rangle\langle 1, \mathsf{f}\rangle\langle 11, \mathsf{a}\rangle\langle 12, y\rangle$	pre-order	$(\mathsf{hfa}y)$

Normalization of variable names

Forget

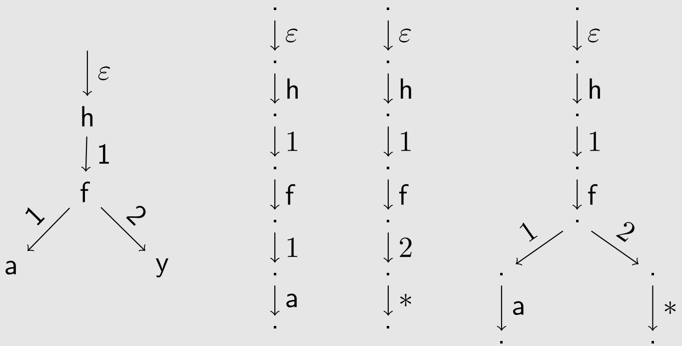
$$\begin{aligned} \text{path} : \mathsf{f}(x,y) &\mapsto \{\mathsf{f}1*, \mathsf{f}2*\} \\ \mathsf{f}(x,x) &\mapsto \{\mathsf{f}1*, \mathsf{f}2*\} \\ \text{pre-order} : \mathsf{f}(x,y) &\mapsto \mathsf{f}{*}{*} \\ \mathsf{f}(x,x) &\mapsto \mathsf{f}{*}{*} \end{aligned}$$

Enumerate

$$\begin{aligned} \text{path} : \mathsf{f}(x,y) &\mapsto \{\mathsf{f}1*_1, \mathsf{f}2*_2\} \\ \mathsf{f}(x,x) &\mapsto \{\mathsf{f}1*_1, \mathsf{f}2*_1\} \\ \text{pre-order} : \mathsf{f}(x,y) &\mapsto \mathsf{f}{*_1}{*_2} \\ \mathsf{f}(x,x) &\mapsto \mathsf{f}{*_1}{*_1} \end{aligned}$$

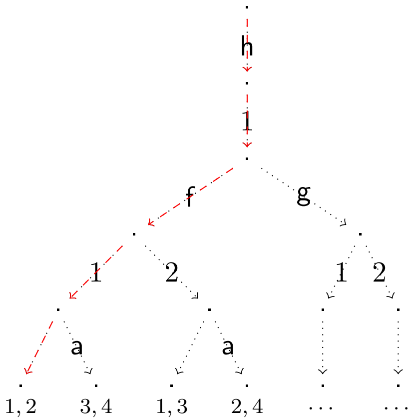
Path-Strings

The path-strings of $\mathsf{h}(\mathsf{f}(\mathsf{a}, y))$ are $\mathtt{h1f1a}$ and $\mathtt{h1f2}{*}$.



Pre-order Strings

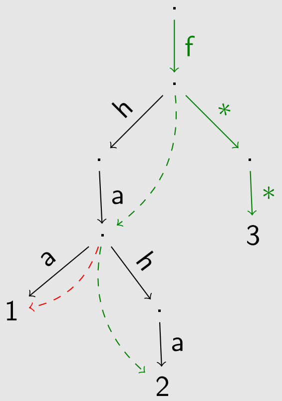
Path-Index



Discrimination Tree

hi!

Non-linear terms

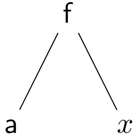


$\{^{1:}\mathsf{f}(\mathsf{h}(\mathsf{a}),\mathsf{a}),^{2:}\mathsf{f}(\mathsf{h}(\mathsf{a}),\mathsf{h}(\mathsf{a}))\},^{3:}\mathsf{f}(x,y)\}$

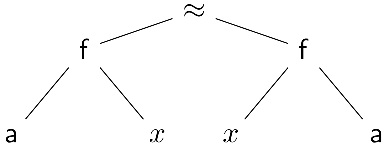
The terms $\mathsf{f}(x,y)$ and $\mathsf{f}(z,z)$
share the preorder-term $\mathsf{f}{*}{*}$.

But $\mathsf{f}(\mathsf{h}(\mathsf{a}),\mathsf{a})$ is not an instance of $\mathsf{f}(z,z)$.

$\mathsf{f}(\mathsf{a}, x)$

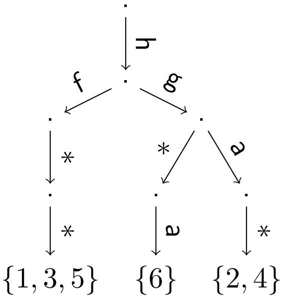


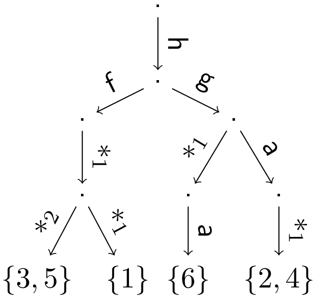
$\mathsf{f}(\mathsf{a}, x) \approx \mathsf{f}(x, \mathsf{a})$



Perfect filtering

$$\left\{ \begin{array}{lll} {}^{1:}\mathsf{h}(\mathsf{f}(x,x)), & {}^{2:}\mathsf{h}(\mathsf{g}(\mathsf{a},x)), & {}^{3:}\mathsf{h}(\mathsf{f}(y,z)), \\ {}^{4:}\mathsf{h}(\mathsf{g}(\mathsf{a},y)), & {}^{5:}\mathsf{h}(\mathsf{f}(y,x)), & {}^{6:}\mathsf{h}(\mathsf{g}(y,a)) \end{array} \right\}$$





$\mathsf{h}(\mathsf{f}(y,x)) \mapsto \mathsf{h.f.}{*}.{*}$

$\mathsf{h}(\mathsf{f}(y,x)) \mapsto' \mathsf{h.f.}{*_1}.{*_2}$