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# Term Indexing for the Beagle Theorem Prover

### Tim Cosgrove

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### The Beagle Theorem Prover

 Beagle is a First-Order-Logic resolution theorem prover with equality, built to show off the capabilities of the Hierarchic Superposition with Weak Abstraction Calculus.

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### The Beagle Theorem Prover

- Beagle is a First-Order-Logic resolution theorem prover with equality, built to show off the capabilities of the Hierarchic Superposition with Weak Abstraction Calculus.
- This calculus is capable of *hierarchic reasoning* by incorporating a *background prover*.
- Background provers act as a black box which can instantly prove known facts. For example integer arithmetic.

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### The Beagle Theorem Prover

- Beagle is a First-Order-Logic resolution theorem prover with equality, built to show off the capabilities of the Hierarchic Superposition with Weak Abstraction Calculus.
- This calculus is capable of *hierarchic reasoning* by incorporating a *background prover*.
- Background provers act as a black box which can instantly prove known facts. For example integer arithmetic.
- The calculus is carefully constructed with a process known as weak abstraction in order to ensure consistency and completeness.

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### Extensions to Beagle

- Beagle has some major shortcomings which prevent it being more than a proof of concept.
- In particular, it lacks an efficient manner of locating terms for inference

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## Extensions to Beagle

- Beagle has some major shortcomings which prevent it being more than a proof of concept.
- In particular, it lacks an efficient manner of locating terms for inference
- Enter 'Term Indexing', a method for efficiently managing and collecting these terms.

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# Terminology Used in this Presentation

- First Order Logic
- Positions

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# Terminology Used in this Presentation

- First Order Logic
- Positions
- Substitutions:
  - s is 'unifiable' with  $t : \sigma s = \sigma t$
  - s 'subsumes' t:  $\sigma s = t$

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The Superposition Calculus

Normal Superposition rule

Positive Superposition

$$\frac{I \approx r \lor C \qquad s[u] \approx t \lor D}{(s[r] \approx t \lor C \lor D)\sigma}$$

Where (i)  $\sigma = \text{simple mgu } (I, u)$ , and (ii) u is not a variable.

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# The Hierarchic Superposition with Weak Abstraction Calculus

• Extension of the Superposition Calculus to accommodate hierarchic reasoning.

# Positive Superposition

$$\frac{I \approx r \lor C \qquad s[u] \approx t \lor D}{\mathsf{abstr}((s[r] \approx t \lor C \lor D)\sigma)}$$

Where (i)  $\sigma = \text{simple mgu } (I, u)$ ,

- (ii) u is not a variable,
- (iii)  $r\sigma \neq l\sigma$ ,
- (iv)  $t\sigma \times s\sigma$ .
- (v) I and u are not pure background terms,
- (vi)  $(l \approx r)\sigma$  is strictly maximal in  $(l \approx r \lor C)\sigma$ ,

and (vii)  $(s \approx t)\sigma$  is strictly maximal in  $(s \approx t \vee D)\sigma$ .

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### Term Indexing Techniques

 Term indexers aim to collect all FOL terms which potentially match a 'query' term.

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## Term Indexing Techniques

- Term indexers aim to collect all FOL terms which potentially match a 'query' term.
- Top-Symbol Hashing.
- Discrimination Trees.
- Path Indexing.

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# Fingerprint Indexing

• Maintain a collection of *fingerprints* for terms.

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# Fingerprint Indexing

- Maintain a collection of *fingerprints* for terms.
- A term fingerprint is an array over  $F \cup \{A, B, N\}$ , the *Fingerprint Features*.

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## Fingerprint Indexing

- Maintain a collection of *fingerprints* for terms.
- A term fingerprint is an array over  $F \cup \{A, B, N\}$ , the *Fingerprint Features*.

Table: Fingerprint Feature comparison tables for *unification* (left) and *subsumption* (right)

	$f_1$	$f_2$	Α	В	N
$f_1$	Υ	N	Υ	Υ	N
$f_2$	N	Υ	Υ	Υ	N
Α	Y	Υ	Υ	Υ	N
В	Y	Υ	Υ	Υ	Υ
N	N	N	N	Υ	Υ

	$f_1$	f <sub>2</sub>	Α	В	N
$f_1$	Υ	N	N	N	N
$f_2$	N	Υ	N	N	N
Α	Υ	Υ	Υ	N	N
В	Υ	Υ	Υ	Υ	Υ
N	N	N	N	N	Υ

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## Fingerprint Indexing

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	$f_1$	f <sub>2</sub>	Α	В	N
$f_1$	Υ	N	Υ	Υ	N
$f_2$	N	Υ	Υ	Υ	N
Α	Υ	Υ	Υ	Υ	N
В	Υ	Υ	Υ	Υ	Υ
N	N	N	N	Υ	Υ

	$f_1$	$f_2$	Α	В	N
$f_1$	Υ	N	N	N	N
$f_2$	N	Υ	N	N	N
Α	Υ	Υ	Υ	N	N
В	Υ	Υ	Υ	Υ	Υ
N	N	N	N	N	Υ

Schulz, Stephan: Fingerprint Indexing for Paramodulation and Rewriting.
 In: Lecture Notes in Computer Science volume 7364 pp. 447–483 (2012).

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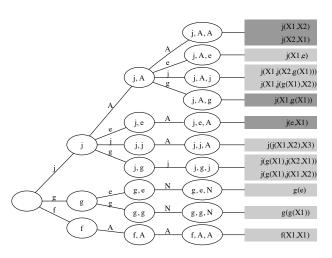
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# Fingerprint Indexing – Example Fingerprint Index



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# Why Fingerprint Indexing?

New and not thoroughly tested technique.

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# Why Fingerprint Indexing?

- New and not thoroughly tested technique.
- Currently showing very promising results.

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# Why Fingerprint Indexing?

- New and not thoroughly tested technique.
- Currently showing very promising results.
- Highly customisable and configurable.

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### Creating the Fingerprint Index

· Addition of terms.

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### Creating the Fingerprint Index

- Addition of terms.
- Requires an Fingerprint generation along with implementation and traversal of the Index tree structure.

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### Creating the Fingerprint Index

- Addition of terms.
- Requires an Fingerprint generation along with implementation and traversal of the Index tree structure.
- Retrieval of terms.

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- Addition of terms.
- Requires an Fingerprint generation along with implementation and traversal of the Index tree structure.
- Retrieval of terms.
- Requires implementation of the comparison tables and a more complex Index traversal algorithm.

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## Beagle's Main Procedure

Maintain two Clause Sets, new and old.
 Remove Clauses from new one at a time, simplify them and then attempt inference rules.

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## Beagle's Main Procedure

- Maintain two Clause Sets. new and old. Remove Clauses from *new* one at a time, simplify them and then attempt inference rules.
- Two key areas of improvement (O(n)) operations:
- Inferences via the Superposition rules.
- Simplifying Clauses.

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# Indexing Superposition

• Refer to rule. Requires...

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- Simplification rules exist to implement special cases of the rules in the Hierarchic Superposition with Weak Abstraction Calculus.
- These special cases allow redundant Clauses to be removed; preventing clutter in the inference process.

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## Indexing Simplification

- Simplification rules exist to implement special cases of the rules in the Hierarchic Superposition with Weak Abstraction Calculus.
- These special cases allow redundant Clauses to be removed; preventing clutter in the inference process.
- The two main simplification rules used by Beagle are *Negative Unit Simplification* and *Demodulation*

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### Indexing Simplification

- Simplification rules exist to implement special cases of the rules in the Hierarchic Superposition with Weak Abstraction Calculus.
- These special cases allow redundant Clauses to be removed; preventing clutter in the inference process.
- The two main simplification rules used by Beagle are *Negative Unit Simplification* and *Demodulation*
- These rules require checking for subsumption, which requires implementing a new comparison table for Fingerprint Indexing.

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# Indexing Negative Unit Simplification

## **Negative Unit Simplification**

$$\frac{1 \not\approx r \qquad s \approx t \lor C}{C}$$

Where (i)  $\exists \sigma \ s.t. \ (l \approx r)\sigma \equiv s \approx t.$ 

The clause  $s \approx t \vee C$  may be removed.

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# Indexing Negative Unit Simplification

## **Negative Unit Simplification**

$$\frac{1 \not\approx r \qquad s \approx t \vee C}{C}$$

Where (i)  $\exists \sigma$  s.t.  $(l \approx r)\sigma \equiv s \approx t$ .

The clause  $s \approx t \vee C$  may be removed.

- Searching for valid subsuming Literals is extremely time consuming.
- Requires an index capable of matching Equations rather than Terms.

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## Indexing Demodulation

$$\frac{I \to r \qquad s[u] \approx t \lor D}{s[r\sigma] \approx t \lor D}$$

Where  $I\sigma = u$ 

The clause  $s[u] \approx t \vee D$  may be removed.

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### Indexing Demodulation

$$\frac{I \to r \qquad s[u] \approx t \vee D}{s[r\sigma] \approx t \vee D}$$

Where  $I\sigma = u$ 

The clause  $s[u] \approx t \vee D$  may be removed.

- Like in Negative Unit Simplification, the most costly operation is searching for subsuming / Terms.
- We must perform this search for every possible subterm u of s.

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# Fingerprint Indexing for the Hierarchic Superposition with Weak Abstraction Calculus

 The Hierarchic Superposition with Weak Abstraction Calculus imposes many restrictions on what can be used for inference.

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# Fingerprint Indexing for the Hierarchic Superposition with Weak Abstraction Calculus

- The Hierarchic Superposition with Weak Abstraction Calculus imposes many restrictions on what can be used for inference.
- We may take advantage of some of these conditions to increase the effectiveness of Fingerprint Indexing.

Table: Fingerprint comparison table for unification; extended by considering the term hierarchy.

		$f_1$	f <sub>2</sub>	Α	В	N	$f_1+$	$f_2+$	A+	B+
	$f_1$	Υ	N	Υ	Υ	N	N	N	N	N
	$f_2$	N	Υ	Υ	Υ	N	N	N	N	N
	Α	Y	Υ	Υ	Υ	N	Y	Y	Υ	Υ
•	В	Y	Υ	Υ	Υ	Y	Y	Y	Υ	Υ
	N	N	N	N	Υ	Υ	N	N	N	Y
	$f_1+$	N	N	Υ	Υ	N	Υ	N	Υ	Υ
	$f_2+$	N	N	Υ	Υ	N	N	Y	Y	Υ
	<b>A</b> +	N	N	Υ	Υ	N	Y	Y	Y	Υ
	B+	N	N	Υ	Υ	Υ	Y	Y	Υ	Υ

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## Metrics for Analysing Indexing Performance

• Speed - Not necessarily relevant

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## Metrics for Analysing Indexing Performance

- Speed Not necessarily relevant
- False Positives Relevant, but can be misleading depending on number of positions being sampled.

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#### Metrics for Analysing Indexing Performance

- Speed Not necessarily relevant
- False Positives Relevant, but can be misleading depending on number of positions being sampled.
- Time Spent per Inference Booyah

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#### Comparing Varieties of Beagle

Table: Totalled inference counts and indexing statistics for various versions of beagle.

	Inf	erence Cou	unts	Indexing Results		
Version	Sup Demod NegUnit		TotalFound	SupFP	SimpFP	
Unmodified 1	414216	29097	1826	0	0	0
Standard	162881	41414	2452	61884768	15525	39778148
Enhanced	162997	41435	2454	58535681	15401	39779224

Table: Totalled timing results for various versions of beagle.

	Time Spent (seconds)							
Version	Indexing	Retrieving	Sup	Demod	NegUnit	Total		
Unmodified 1	0	0	730.44	9.44	31.99	5623.21		
Standard	28.4	38.73	254.17	41.66	3.18	381.36		
Enhanced	22.91	20.29	180.54	32.6	2.51	281.38		

<sup>&</sup>lt;sup>1</sup>This version failed to solve two out of the fifty problems within 8 hours.

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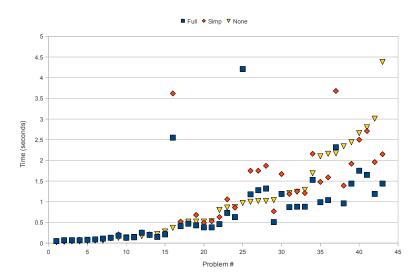
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#### Runtimes under 5 seconds



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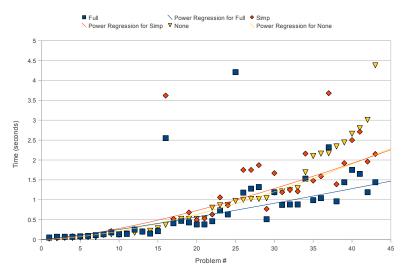
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#### Runtimes under 5 seconds



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#### Results Analysis

• Times per inference

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#### Results Analysis

#### • Times per inference

Table: Superposition time for the 6 most extreme problem examples.

	Problem	Enhanced	Standard	Unmodified
	DAT050=1.p	17.53	31.54	48.62
	DAT039=1.p	13.2	22.51	130.77
•	DAT040=1.p	14.49	21.29	190.71
	DAT038=1.p	12.53	24.04	294.86
	DAT043=1.p	18.67	26.08	N/A
	DAT048=1.p	17.65	35.77	N/A

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### Results Analysis

Times per inference

Table: Superposition time for the 6 most extreme problem examples.

	Problem	Enhanced	Standard	Unmodified
	DAT050=1.p	17.53	31.54	48.62
	DAT039=1.p	13.2	22.51	130.77
•	DAT040=1.p	14.49	21.29	190.71
	DAT038=1.p	12.53	24.04	294.86
	DAT043=1.p	18.67	26.08	N/A
	DAT048=1.p	17.65	35.77	N/A

 When taking number of inferences into account for DAT038=1.p we observe 1.2 milliseconds per superposition for the full implementation versus 2.2 milliseconds per superposition for unindexed beagle.

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### Fingerprint Sampling Varieties

• Reasoning. Cite shulz and FP/Speed balance

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Implementation

Implementing Fingerprint Indexing Indexing Applications Tailoring to

Result

Evaluation Metrics

Compariso

Sample Position Comparisons

#### Fingerprint Sampling Varieties

- Reasoning. Cite shulz and FP/Speed balance
- Different position samples

Tim Cosgrove

Outline

Project Overvi Motivation

First Order Logic Terminology The Beagle Theorem Prover

The Beagle Theorem Prove Term Indexing Fingerprint Indexing

Implementing

Fingerprint Indexing Indexing Applications Tailoring to

Resu

Metrics
Beagle
Compariso

Comparisons
Sample Position
Comparisons

### Fingerprint Sampling Varieties

Table: Totalled inference counts and indexing statistics for various Fingerprint sampling sets.

	Inf	erence Cou	ınts	Indexing Results			
Sample Set	Sup Demod NegUnit		TotalFound	SupFP	SimpFP		
FP3W 164574 42402		2473	59433145	72051	40037948		
FP4M	150154	35709	1964	58989318	29469	40073471	
FP6M 146861 35326		1960	58119897	17641	39916687		
FP7	161411	41005	2441	58530669	23903	39818531	
FP8X2	161741	40876	2439	58336597	11754	39823989	

Table: Totalled timing results for various Fingerprint sampling sets.

	Time Spent (seconds)								
Sample Set	Indexing	Retrieving	Sup	Demod	NegUnit	Total			
FP3W	12.48	14.86	177.82	28.98	1.79	265.65			
FP4M	14.37	15.02	173.32	31.53	1.83	261.84			
FP6M	18.74	17.58	168.79	30.56	2.12	259.02			
FP7	22.26	19.82	180.13	35.23	2.38	282.22			
FP8X2	51.73	34.23	195.18	42.75	4.07	331.01			