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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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- 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) $\sigma = \text{simple mgu } (l, u)$, 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) $r\sigma \times l\sigma$.
- (111) 10 2 10
- (iv) $t\sigma \not\succeq s\sigma$,
- (v) / 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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Conclusion

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 ∪ {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_2 | Α | В | Ν |
|-------|-------|-------|---|---|---|
| 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 | 2 | N | Ν | Y |

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| | f_1 | f ₂ | 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 | Y | Υ | Υ | N | N |
| В | Y | Υ | Υ | Υ | Υ |
| N | N | 2 | 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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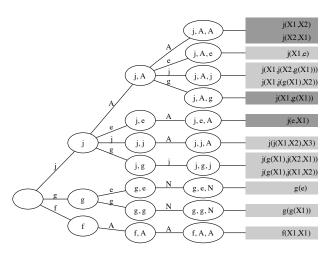
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Fingerprint Indexing – Example Fingerprint Index



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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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Creating the Fingerprint Index

- 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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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.

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Conclusion

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

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

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

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

Demodulation
$$\frac{l \to r \quad s[u] \approx t \lor D}{s[r\sigma] \approx t \lor D}$$

Where $I\sigma = u$

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

- 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 ₂ | 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 |
| A | Y | Υ | Υ | Υ | N | Υ | Y | Υ | Υ |
| В | Y | Υ | Υ | Υ | Υ | Υ | Υ | 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 |
| A + | N | N | Υ | Υ | N | Y | Y | Y | Υ |
| B+ | N | N | Υ | Υ | Υ | Y | Υ | Υ | Y |

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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 | ınts | 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 | 146861 | 35326 | 1960 | 58119897 | 17641 | 39916687 |

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 | 18.74 | 17.58 | 168.79 | 30.56 | 2.12 | 259.02 | | | |

¹This version failed to solve two out of the fifty problems within 8 hours.

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Time Spent Per Inference

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

| Version | Superposition | Demodulation | NegUnit Simplification |
|------------|---------------|--------------|------------------------|
| Unmodified | 1.7ms | 0.3ms | 17.5ms |
| Standard | 1.5ms | 1.0ms | 1.3ms |
| Enhanced | 1.1ms | 0.8ms | 1.0ms |

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• Most typical application of Demodulation is a Literal like $X \to f(a)$. X will match anything, making fingerprint indexing a waste of time.

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Time Spent Per Inference

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- Most typical application of Demodulation is a Literal like X → f(a). X will match anything, making fingerprint indexing a waste of time.
- When excluding PUZ037-1.p we have 0.29, 0.39 and 0.31 milliseconds per Demodulation.

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Theorem Prove Term Indexing Fingerprint Indexing

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Recult

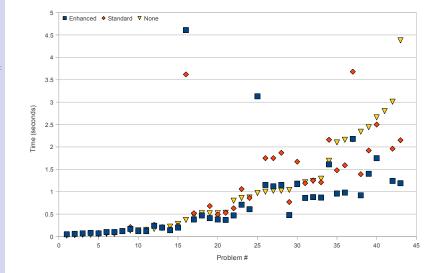
Evaluation Metrics Beagle

Comparisons Sample Positi

Sample Positio Comparisons

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Runtimes under 5 seconds



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Motivation

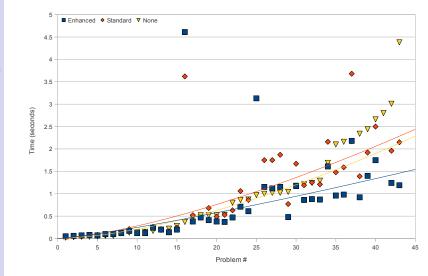
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Runtimes under 5 seconds



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Results Analysis

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

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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 NegUn | | TotalFound | SupFP | SimpFP |
| FP3W | 162218 | 42402 | 2472 | 13913606 | 69429 | 1815992 |
| FP4M | 147798 | 35709 | 1963 | 13469779 | 26847 | 1851515 |
| FP6M | 144505 | 35326 | 1959 | 12601762 | 16406 | 1694731 |
| FP7 | 159055 | 41005 | 2440 | 13011130 | 21281 | 1596575 |
| FP8X2 | 159385 | 40876 | 2438 | 12819184 | 11229 | 1602033 |

Table: Totalled timing results for various Fingerprint sampling sets.

| | | | Time Spent (seconds) | | | | | | | |
|---|------------|----------|----------------------|--------|-------|---------|--------|--|--|--|
| | Sample Set | Indexing | Retrieving | Sup | Demod | NegUnit | Total | | | |
| Ī | FP3W | 11.52 | 14.02 | 170.37 | 9.26 | 1.78 | 237.75 | | | |
| | FP4M | 13.09 | 14.12 | 164.95 | 9.51 | 1.82 | 230.68 | | | |
| | FP6M | 16.82 | 16.5 | 159.93 | 10.78 | 2.11 | 229.59 | | | |
| | FP7 | 19.98 | 18.74 | 170.83 | 12.37 | 2.37 | 249.22 | | | |
| | FP8X2 | 45.56 | 32.59 | 181.43 | 21.45 | 4.06 | 294.8 | | | |

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