Compact Trace Trees in Dynamic Binary Translators

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Intel Corporation

Workshop on Architectural and Micro-Architectural Support for Binary Translation, 2009
Outline

1. Motivation
   - Trace Collection
   - Previous Work

2. Examples
   - MRET
   - Trace Tree
   - Compact Trace Tree

3. Experimental Results
Outline

1 Motivation
   - Trace Collection
   - Previous Work

2 Examples
   - MRET
   - Trace Tree
   - Compact Trace Tree

3 Experimental Results
Why Is It So Important

- The Pareto Principle.
- Legacy ISA Support
- Multi-core Processors
Why Is It So Important

- The Pareto Principle.
- Legacy ISA Support.
- Multi-core Processors.

<table>
<thead>
<tr>
<th>Base Architecture</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base2Target</td>
<td></td>
</tr>
</tbody>
</table>

| Target Architecture |
Why Is It So Important

- The Pareto Principle.
- Legacy ISA Support
- Multi-core Processors

<table>
<thead>
<tr>
<th>Single Threaded Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallelizing DBT</td>
</tr>
<tr>
<td>n cores</td>
</tr>
</tbody>
</table>
Previous DBT Approaches

- **DAISY** [Ebcioğlu - 1996]
  - 100% Compatibility
  - Clever approaches for handling Branches

- **DynamoSim** [Bala - 2000]
Previous DBT Approaches

- DAISY [Ebcioğlu - 1996]
- DynamoSim [Bala - 2000]
  - Optimizer
Previous Trace Collection Strategies.

- Most **Frequently** Executed Tail [Cifuentes - 2000]
  - Requires Edge Profiling
- Most **Recently** Executed Tail [Duesterwald - 2000]
- Trace Trees [Gal - 2006]
Previous Trace Collection Strategies.

- **Most Frequently** Executed Tail [Cifuentes - 2000]
- **Most Recently** Executed Tail [Duesterwald - 2000]
  - Lower Overhead
- Trace Trees [Gal - 2006]
Previous Trace Collection Strategies.

- Most **Frequently** Executed Tail [Cifuentes - 2000]
- Most **Recently** Executed Tail [Duesterwald - 2000]
- Trace Trees [Gal - 2006]
  - Low Overhead
  - Highly Specialized Traces
Outline

1 Motivation
   • Trace Collection
   • Previous Work

2 Examples
   • MRET
   • Trace Tree
   • Compact Trace Tree

3 Experimental Results
MRET Creation

New Superblock:

TRACE CACHE
MRET Creation

New Superblock:

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang

CTTs in DBTs
### MRET Creation

**New Superblock:**

![Diagram of a trace tree](image)

- **F**
- **G**
**MRET Creation**

**New Superblock:**

F G I

**TRACE CACHE**
MRET Creation

New Superblock:

\[ F \quad G \quad I \quad J \]

TRACE CACHE
MRET Creation

New Superblock:
MRET Creation

New Superblock:

![Diagram of MRET Creation](image-url)
MRET Creation

New Superblock:

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang  CTTs in DBTs
MRET Creation

New Superblock: 

TRACE CACHE

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MRET Creation

New Superblock:
H  I  J

TRACE CACHE

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CTTs in DBTs
MRET Creation

New Superblock:
MRET Creation

New Superblock:
MRET Creation

New Superblock:

```
TRACE CACHE
F G I J
H I J
```

```
A
B
C
D
E
F
G
H
I
J
K
L
```
MRET Creation

New Superblock:

TRACE CACHE

```
F G I J
H I J
```

```
A
  B
  C
  D
  E
  F
  G
  H
  I
  J
  K
  L
```
MRET Creation

New Superblock:
New Superblock:

```
K
```

**TRACE CACHE**

```
F G I J
```

```
H I J
```

```
A
```

```
B
```

```
C
```

```
E
```

```
D
```

```
F
```

```
G H I
```

```
J
```

```
K L
```

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CTTs in DBTs
New Superblock:

K  B
MRET Creation

New Superblock:

K B C

TRACE CACHE

MRET
Trace Tree
Compact Trace Tree

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CTTs in DBTs
MRET Creation

New Superblock:

```
K B C D
```

TRACE CACHE

![Trace Tree Diagram]

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CTTs in DBTs
MRET Creation

New Superblock:
MRET Creation

New Superblock:

![Diagram of MRET Creation with nodes A to K and branches connecting them]
MRET Creation

New Superblock:
MRET Creation

New Superblock:

TRACE CACHE

A
B
C
D
E
F
G
H
I
J
K
L

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CTTs in DBTs
MRET Creation

New Superblock:

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang   CTTs in DBTs
MRET Creation

New Superblock:
MRET Creation

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MRET Creation

New Superblock:
MRET Creation

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MRET Creation

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MRET Creation

New Superblock:
MRET Creation

New Superblock:

TRACE CACHE

CTTs in DBTs
MRET Creation

New Superblock:
MRET Creation

New Superblock:

TRACE CACHE

MRET
Trace Tree
Compact Trace Tree

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CTTs in DBTs
MRET Creation

New Superblock:

TRACE CACHE

MRET
Trace Tree
Compact Trace Tree
M RET  C reation

New Superblock:
MRET Creation

New Superblock:
MRET Creation

New Superblock:
MRET Creation

New Superblock:
MRET Creation

New Superblock:
MRET Creation

New Superblock:
MRET Creation

New Superblock:

TRACE CACHE

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CTTs in DBTs
MRET Creation

New Superblock:
MRET Creation

New Superblock:
MRET Creation

New Superblock:

TRACE CACHE
MRET Creation

New Superblock:
Trace Tree Creation

New Superblock:

```
TRACE CACHE
```

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Trace Tree Creation

New Superblock:

TRACE CACHE

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CTTs in DBTs
Trace Tree Creation

New Superblock:

\[ F \quad G \]

TRANCE CACHE
Trace Tree Creation

New Superblock:

F  G  I

TRACE CACHE
Trace Tree Creation

New Superblock:

F, G, I, J

TRACE CACHE

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CTTs in DBTs
Trace Tree Creation

New Superblock:

```
TRACE CACHE
F
G
I
J
```
Trace Tree Creation

New Superblock:

TRACE CACHE

F
G
I
J
Trace Tree Creation

New Superblock:

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang

CTTs in DBTs
Trace Tree Creation

New Superblock:

TRACE CACHE

H
I

Porto, Araujo, Wu, Borin, Wang

CTTs in DBTs
Trace Tree Creation

New Superblock:

H I J

TRACE CACHE

F G I J

Porto, Araujo, Wu, Borin, Wang

CTTs in DBTs
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:

TRACE CACHE

<table>
<thead>
<tr>
<th>F</th>
<th>G</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>I</td>
<td>J</td>
<td></td>
</tr>
</tbody>
</table>

DIAGRAM:

A → B → C → E → F → G → H → I → J → K → L
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang CTTs in DBTs
Trace Tree Creation

New Superblock:

K  B

TRACE CACHE

F  G  I  J

H  I  J

MRET
Trace Tree
Compact Trace Tree

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Trace Tree Creation

New Superblock:

```
K  B  C
```

```
TRACE CACHE

F
G
I
J
```

```
A

B

C

D

E

F

G

H

I

J

K

L
```
Trace Tree Creation

New Superblock:

K  B  C  D

TRACE CACHE

A

B

C

E

D

F

G

H

I

J

K

L
Trace Tree Creation

New Superblock:

K B C D K

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang

CTTs in DBTs
Trace Tree Creation

New Superblock:

\[ \begin{array}{cccccc}
  K & B & C & D & K & B \\
\end{array} \]
Trace Tree Creation

New Superblock:

K B C D K B C

TRACE CACHE

F G I J

H J J

A

B

C

E

D

F

G H

I

J

K

L

Porto, Araujo, Wu, Borin, Wang

CTTs in DBTs
Trace Tree Creation

New Superblock:

K B C D K B C E

TRACE CACHE

A

B

C

D

E

F

G

H

I

J

K

L

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CTTs in DBTs
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang  CTTs in DBTs
Trace Tree Creation

New Superblock:
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Trace Tree Creation

New Superblock:

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang  CTTs in DBTs
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:

```
TRACE CACHE
```

```
 F
 G
 I
 J
```

```
 H
 I
 J
```

```
 K
 B
 C
 D
 E
```
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:
Trace Tree Creation

New Superblock:
New Superblock:

\[ K \]

TRACE CACHE

\[ \begin{array}{c}
F \\
G \\
I \\
J \\
\end{array} \quad \begin{array}{c}
H \\
I \\
J \\
\end{array} \quad \begin{array}{c}
K \\
B \\
C \\
D \\
K \\
B \\
C \\
E \\
\end{array} \]
Trace Tree Creation

New Superblock:

K  B

K  B  C  D  E

TRACE CACHE

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Trace Tree Creation

New Superblock:

\[ K \quad B \quad C \]

TRACE CACHE

\[ \begin{array}{c}
F \\
G \\
I \\
J \\
\end{array} \quad \begin{array}{c}
H \\
I \\
J \\
\end{array} \quad \begin{array}{c}
K \\
B \\
C \\
D \\
K \\
B \\
C \\
E \\
\end{array} \]

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CTTs in DBTs
New Superblock:

K B C E

TRACE CACHE

A
B
C
D
E
F
G
H
I
J
K
L

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CTTs in DBTs
Trace Tree Creation

New Superblock:

TRACE CACHE

TRACE TREE
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

![Diagram of Compact Trace Tree](image-url)
Compact Trace Tree Creation

New Superblock:

TRACE CACHE
Compact Trace Tree Creation

**New Superblock:**

\[ \text{TRACE CACHE} \]

\[ \text{Compact Trace Tree Creation} \]
Compact Trace Tree Creation

New Superblock:

F  G  I

TRACE CACHE
Compact Trace Tree Creation

New Superblock:

F G I J

TRACE CACHE
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

A
  ↓
B
  ↓
C
  ↓
D
  ↓
E
  ↓
F
  ↓
G
  ↓
H
  ↓
I
  ↓
J
  ↓
K
  ↓
L
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

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Compact Trace Tree Creation

New Superblock:

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang

CTTs in DBTs
Compact Trace Tree Creation

New Superblock:

H I J

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang  CTTs in DBTs
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

<table>
<thead>
<tr>
<th>F</th>
<th>G</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>I</td>
<td>J</td>
<td></td>
</tr>
</tbody>
</table>

MRET
Trace Tree
Compact Trace Tree

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CTTs in DBTs
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

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Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

CTTs in DBTs
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

MRET
Trace Tree
Compact Trace Tree
Compact Trace Tree Creation

New Superblock:

```
K
```

TRACE CACHE

```
F
G
I
J
H
I
J
```

```
A
B
C
E
D
F
G
H
I
J
K
L
```
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

Porto, Araujo, Wu, Borin, Wang  CTTs in DBTs
Compact Trace Tree Creation

New Superblock:

K  B  C
New Superblock:

```
K  B  C  D
```

TRACE CACHE

```
F  G
I  J
H  I  J
```

Diagram showing the relationship between nodes A, B, C, D, E, F, G, H, I, J, K, and L.
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

A

B

C

D

E

F

G

H

I

J

K

L

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CTTs in DBTs
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

MRET
Trace Tree
Compact Trace Tree
Compact Trace Tree Creation

New Superblock:

```
<table>
<thead>
<tr>
<th>F</th>
<th>G</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>I</td>
<td>J</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>
```

```
A
B
C
E
D
G
H
I
J
K
L
```

TRACE CACHE
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

A

B

C

E

D

F

G

H

I

J

K

L

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CTTs in DBTs
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

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CTTs in DBTs
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:


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CTTs in DBTs
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

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Compact Trace Tree Creation

New Superblock:

TRACE CACHE

CTTs in DBTs
Compact Trace Tree Creation

New Superblock:

TRACE CACHE

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Compact Trace Tree Creation

**New Superblock:**

```
K  B  C
```

**TRACE CACHE**
Compact Trace Tree Creation

New Superblock:

K  B  C  E

TRACE CACHE

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CTTs in DBTs
Compact Trace Tree Creation

New Superblock:
CTT Implementation Issues

- Detecting Anchors
- Indirect Branches
- Trace Expansion
CTT Implementation Issues

- Detecting Anchors
- Indirect Branches
- Trace Expansion
CTT Implementation Issues

- Detecting Anchors
- Indirect Branches
- Trace Expansion
Outline

1 Motivation
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   - Previous Work

2 Examples
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   - Trace Tree
   - Compact Trace Tree

3 Experimental Results
Coverage (SPEC2k)

![Graph showing average coverage vs threshold (blocks)](image)

Coverage (SPEC2k)

Average Coverage

- Coverage (Standard Deviation of Coverage)
- Coverage (Sharing on Blocks)
- Coverage (Sharing on Blocks)

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CTTs in DBTs
Duplication (SPEC2k)

Average Duplication

- CTT
- MRET
- TT

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CTTs in DBTs
Memory Overhead (SPEC2k)

Total Memory Usage

- CTT
- MRET
- TT

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CTTs in DBTs
Time Overhead (SPEC2k)

Total Time in the Runtime

- CTT
- MRET
- TT

Threshold (Blocks)

Time (s)

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CTTs in DBTs
Trace Trees did not perform well on IA32 DBT.
Summary

- **Trace Trees** did not perform well on IA32 DBT.
- **Compact Trace Trees** address the issues found with Trace Trees.
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- **Compact Trace Trees** address the issues found with Trace Trees.
- **MRET** is fast, but is not specialized.

**Future Work**
- Use CTTs as compilation units in DBT.
A. Gal and M. Franz
*Incremental Dynamic Code Generation with Trace Trees.*
TR 06-16, University of California, Irvine.