Reconciling Compiler Optimizations and WCET Estimation Using Iterative Compilation

Mickaël Dardaillon, Stefanos Skalistis, Isabelle Puaut, Steven Derrien

RTSS’19, Hong Kong
Typical Real-time workflow

1. **RT-Application**
   - C++
   - Binary executable

2. **Architecture Model**
   - RISC-V
   - ARM
   - Intel

3. **Compiler**
   - Timing Analysis

4. **Binary executable**

5. **Timing Analysis**

6. **WCET**

7. **Scheduling - Mapping**

8. **RTA Analysis**

21/11/2019
Static WCET analysis

RT-Application

Compiler

Binary executable

Data-flow, Value, Loop-bound Analysis

Microarchitectural Analysis

Static Timing Analysis

WCET
Static WCET analysis

RT-Application

Compiler

Binary executable

Data-flow, Value, Loop-bound Analysis

Static Timing Analysis

Microarchitectural Analysis

WCET

... highly depends on the compiler as well!
Compiler optimisations

- **WCET-aware compilers**
  - Limited number of optimisations
  - Limited combinations of optimisations
  - Suitable for real-time

- **Mainstream compilers:**
  - High number of optimisations
  - Allow any optimisation sequence (flags/passes)
  - No knowledge of optimisations impact
  - Can break static WCET analyzability
Compiler optimisations

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*Can mainstream compilers be utilised?*
WCET impact of compiler optimisations

1000 random sequences of optimisation passes:

- **Compiler**: LLVM for Leon3
- **Static WCET**: AbsInt aiT
- **Des**: embedded application (Mälardalen Benchmarks)
- **Harris**: image processing application (PolyMage)

![Histograms showing normalized estimated WCET for 'des' and 'harris' applications with different optimization levels (O0, O1, O2, O3).]
1000 random sequences of optimisation passes:

- **Compiler**: LLVM for Leon3
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- **Des**: embedded application (Mälardalen Benchmarks)
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Optimisations can worsen WCET
Impact on analyzability

Different Optimisations:

• Can render the binary non-analyzable

• Can make the compiler crash

Source of failure: 

Compiler  Analyzer
Impact on analyzability

Different Optimisations:

- Can render the binary non-analyzable
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Optimisations can break analyzability
Different optimisations:

• Varying behavior on different applications

Best sequence:

<table>
<thead>
<tr>
<th>Des</th>
<th>Optimisation sequence length</th>
</tr>
</thead>
</table>
### Impact on different applications

**Different optimisations:**

- Varying behavior on different applications

```
Des

Harris
```

**Best sequence:**

![Optimization sequence length](image)

**Optimisations behavior is application dependent**
Mainstream compiler optimisations sequences:

- Rich set of optimisation options
- Positive, Neutral, Negative impact on WCET
- Impact is application-dependent
- Vast search space to find the best sequence
Motivation

- **Mainstream compiler optimisations sequences:**
  - Rich set of optimisation options
  - *Positive, Neutral, Negative* impact on WCET
  - Impact is application-dependent
  - Vast search space to find the best sequence

- **Our Idea: Iterative compilation + Machine learning**
  - First systematic attempt for WCET
Outline

- Motivation

- Our approach:
  - Iterative compilation
  - Association-based learning strategy

- Evaluation
Iterative Compilation

- **Basic idea:**
  - Compile with different options
  - Evaluate the produced artifact
  - Iterate until result is satisfactory

- **Has been effectively used in best-effort systems**
Iterative Compilation

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  - Compile with different options
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Pass Characterization Strategy

- Sequences of optimization passes, e.g. $ABC$
  - A pass can appear multiple times, e.g. $ABA$
  - Sequence space is infinite
Pass Characterization Strategy

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- Given two sequences $S \subseteq S'$
  - $S'$ is *positive* if $\text{WCET}_{S'} < \text{WCET}_S$
  - $S'$ is *neutral* if $\text{WCET}_{S'} = \text{WCET}_S$
  - $S'$ is *negative* if $\text{WCET}_{S'} > \text{WCET}_S$
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- **Pass p characterization**
  - $p \in S \cap S'$: same as S
  - $p \notin S \cap S'$: same as S’
Pass Characterization Strategy

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- **Pass $p$ characterization**
  - $p \in S \cap S'$: same as $S$
  - $p \notin S \cap S'$: same as $S'$

\[ \{ A^+, C^+ \} \]

\[ \text{WCET}_{\text{ABC}} = \text{WCET}_{\text{AC}} \]
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\[ \{ A^+, B^\circ, C^+ \} \]
\[ \{ A^+, C^+ \} \]

$\text{WCET}_{ABC} = \text{WCET}_{AC}$
Pass Selection Strategy

- **Assign weights to passes**
  - According to the characterisation

\[ W_{pass} = \frac{N^+}{N^0} \times 85\% + 15\% \]
Pass Selection Strategy

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\[ W_{\text{pass}} = \frac{N^+}{N^-} \times 85\% + 15\% \]

- **Intuition**
  - Frequently positive passes should be selected
  - Neutral pass should be avoided
Pass Selection Strategy

- **Assign weights to passes**
  - According to the characterisation
    \[
    W_{\text{pass}} = \frac{N^+}{N^-} * 85\% + 15\%
    \]

- **Intuition**
  - Frequently positive passes should be selected
  - Neutral pass should be avoided

- **Selection**
  - Random size of sequence
  - Weighted random for the sequences passes
Characterization Strategy: Example

- **1st Sequence: ABC**
  - $\text{WCET}_{ABC} < \text{WCET}_\emptyset$

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<tbody>
<tr>
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<td>0.15</td>
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\[
\begin{align*}
\{ A, B, C, D \} \\
\{ A, B, C \} \{ A, B, D \} \{ A, C, D \} \{ B, C, D \} \\
\{ A, B \} \{ A, C \} \{ A, D \} \{ B, C \} \{ B, D \} \{ C, D \} \\
\{ A \} \{ B \} \{ C \} \{ D \} \\
\{ \emptyset \} \text{ WCET}_\emptyset
\end{align*}
\]
Characterization Strategy: Example

- **1st Sequence: ABC**
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<td>0.15</td>
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</tbody>
</table>

\[
\{ A, B, C, D \}
\]

\[
\{ A^+, B^+, C^+ \}
\]

\[
\{ A, B \} \quad \{ A, C \} \quad \{ A, D \} \quad \{ B, C \} \quad \{ B, D \} \quad \{ C, D \}
\]

\[
WCET_{ABC} < WCET_\emptyset
\]

\[
\{ A \} \quad \{ B \} \quad \{ C \} \quad \{ D \}
\]

\[
\{ \emptyset \}
\]

\[
WCET_\emptyset
\]
Characterization Strategy: Example

- **1st Sequence: ABC**
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</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.15</td>
</tr>
</tbody>
</table>

\[
\{ A, B, C, D \}
\]

\[
\{ A^+, B^+, C^+ \}
\]

\[
\{ A, B \} \quad \{ A, C \} \quad \{ A, D \} \quad \{ B, C \} \quad \{ B, D \} \quad \{ C, D \}
\]

\[
WCET_{ABC} < WCET_{\emptyset}
\]

\[
\{ A \} \quad \{ B \} \quad \{ C \} \quad \{ D \}
\]

\[
\{ \emptyset \} \quad WCET_{\emptyset}
\]
Characterization Strategy: Example

- **1st Sequence: ABC**
  - $\text{WCET}_{ABC} < \text{WCET}_\emptyset$

- **Next Sequence: ACD**
  - $\text{WCET}_{ACD} > \text{WCET}_\emptyset$
  - Common flags AC

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<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.15</td>
</tr>
</tbody>
</table>

\[
\{ \text{A, B, C, D} \} \\
\{ \text{A, B, D} \} \
\{ \text{A, C, D} \} \
\{ \text{B, C, D} \} \\
\{ \text{A, B} \} \
\{ \text{A, C} \} \
\{ \text{A, D} \} \
\{ \text{B, C} \} \
\{ \text{B, D} \} \
\{ \text{C, D} \} \\
\{ \text{A} \} \
\{ \text{B} \} \
\{ \text{C} \} \\
\{ \text{D} \} \\
\{ \emptyset \} \\
\text{WCET}_\emptyset
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<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>WCET $\emptyset$</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.15</td>
</tr>
</tbody>
</table>

\[\{A, B, C, D\}\]
\[\{A^+, B^+, C^+\}\]
\[\{B, C, D\}\]
\[\{A, B, D\}\]
\[\{A, C\}\]
\[\{A, D\}\]
\[\{B, C\}\]
\[\{B, D\}\]
\[\{C, D\}\]
\[\{A\}\]
\[\{B\}\]
\[\{C\}\]
\[\{D\}\]
\[\{\emptyset\}\]

\[\text{WCET}_{ACD} > \text{WCET}_\emptyset\]
\[\text{WCET}_\emptyset\]
Characterization Strategy: Example

1\textsuperscript{st} Sequence: ABC
- $WCET_{ABC} < WCET_\emptyset$

Next Sequence: ACD
- $WCET_{ACD} > WCET_\emptyset$
- Common flags AC

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<tr>
<td></td>
<td>1.00</td>
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<td>1.00</td>
<td>0.15</td>
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</tbody>
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\[\{A, B, C, D\}\]
\[\{A^+, B^+, C^+\}\]
\[\{A^-, C^-, D^-\}\]
\[\{A, B\}\] \[\{A, C\}\] \[\{A, D\}\] \[\{B, C\}\] \[\{B, D\}\] \[\{C, D\}\]
\[\{A\}\] \[\{B\}\] \[\{C\}\] \[\{D\}\]
\[\{\emptyset\}\]

\[WCET_{ACD} > WCET_\emptyset\]
Characterization Strategy: Example

- **1st Sequence: ABC**
  - $WCET_{ABC} < WCET_{\emptyset}$

- **Next Sequence: ACD**
  - $WCET_{ACD} > WCET_{\emptyset}$
  - Common flags AC

- **Next Sequence: AC**
  - $WCET_{AC} < WCET_{\emptyset}$
  - $WCET_{AC} < WCET_{ACD}$
  - $WCET_{ABC} = WCET_{AC}$

<table>
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<tr>
<td></td>
<td>1.00</td>
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\[
\{ A , B , C , D \} \\
\{ A^+, B^+, C^+ \} \{ A , B , D \} \{ A^-, C^-, D^- \} \{ B , C , D \} \\
\{ A , B \} \{ A , C \} \{ A , D \} \{ B , C \} \{ B , D \} \{ C , D \} \\
\{ A \} \{ B \} \{ C \} \{ D \} \\
\{ \emptyset \} \ WCET_{\emptyset} \]
Characterization Strategy: Example

1st Sequence: \( ABC \)
- \( WCET_{ABC} < WCET_{\emptyset} \)

Next Sequence: \( ACD \)
- \( WCET_{ACD} > WCET_{\emptyset} \)
- Common flags \( AC \)

Next Sequence: \( AC \)
- \( WCET_{AC} < WCET_{\emptyset} \)
- \( WCET_{AC} < WCET_{ACD} \)
- \( WCET_{ABC} = WCET_{AC} \)

\[
\begin{array}{cccc}
A & B & C & D \\
1.00 & 1.00 & 1.00 & 0.15
\end{array}
\]
Characterization Strategy: Example

1\textsuperscript{st} Sequence: $ABC$
- $WCET_{ABC} < WCET_{\emptyset}$

Next Sequence: $ACD$
- $WCET_{ACD} > WCET_{\emptyset}$
- Common flags $AC$

Next Sequence: $AC$
- $WCET_{AC} < WCET_{\emptyset}$
- $WCET_{AC} < WCET_{ACD}$
- $WCET_{ABC} = WCET_{AC}$

<table>
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<th>A</th>
<th>B</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
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<td>0.15</td>
</tr>
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\[
\begin{align*}
\{ A, B, C, D \} \\
\{ A^+, B^+, C^0 \} & \quad \{ A, B, D \} & \quad \{ A^-, C^-, D^- \} & \quad \{ B, C, D \} \\
\{ A, B \} & \quad \{ A, D \} & \quad \{ B, C \} & \quad \{ B, D \} & \quad \{ C, D \} \\
\{ A^+ \} & \quad \{ B^+ \} & \quad \{ C^+ \} & \quad \{ D^+ \} \\
\{ \emptyset \} & \quad WCET_{\emptyset}
\end{align*}
\]

$WCET_{ABC} = WCET_{BC}$

$WCET_{BC} < WCET_{\emptyset}$
Characterization Strategy: Example

- **1st Sequence: ABC**
  - $WCET_{ABC} < WCET_\emptyset$

- **Next Sequence: ACD**
  - $WCET_{ACD} > WCET_\emptyset$
  - Common flags AC

- **Next Sequence: AC**
  - $WCET_{AC} < WCET_\emptyset$

\[
\begin{array}{cccc}
A & B & C & D \\
1.00 & 1.00 & 1.00 & 0.15 \\
\end{array}
\]

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\begin{align*}
\{A, B, C, D\} & \quad \{A^+, B^+, C^\circ\} & \quad \{A^+, C^+, D^-\} \\
\{A, B\} & \quad \{A, D\} & \quad \{B, C\} & \quad \{B, D\} & \quad \{C, D\} \\
\{A\} & \quad \{B\} & \quad \{C\} & \quad \{D\} \\
\{\emptyset\} & \quad WCET_\emptyset
\end{align*}
\]

$WCET_{AC} < WCET_{ACD}$

$WCET_{BC} < WCET_\emptyset$
Characterization Strategy: Example

1. **1st Sequence: ABC**
   - $WCET_{ABC} < WCET_{\emptyset}$

2. **Next Sequence: ACD**
   - $WCET_{ACD} > WCET_{\emptyset}$
   - Common flags AC

3. **Next Sequence: AC**
   - $WCET_{AC} < WCET_{\emptyset}$
   - $WCET_{AC} < WCET_{ACD}$
   - $WCET_{ABC} = WCET_{AC}$
A pass may be mischaracterized

- Pass C was characterized initially as positive, but then as neutral.

Iteratively remove passes that do not improve WCET

- Known technique in iterative compilation
Cleaning: Example

- 1st Sequence: \( ABC \)
  - \( WCET_{ABC} < WCET_\emptyset \)

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<tr>
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\{ \emptyset \} & WCET_\emptyset \\
\end{align*}
\]
Cleaning: Example

- **1st Sequence:** $ABC$
  - $WCET_{ABC} < WCET_{\emptyset}$
- **Next Sequence:** $AC$
  - $WCET_{AC} = WCET_{ABC}$

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<tbody>
<tr>
<td>0.15</td>
<td>0.15</td>
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<td></td>
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\end{align*}
\]
Cleaning: Example

- **1st Sequence: ABC**
  - $\text{WCET}_{ABC} < \text{WCET}_\emptyset$

- **Next Sequence: AC**
  - $\text{WCET}_{AC} = \text{WCET}_{ABC}$

- **Next Sequence: A**
  - $\text{WCET}_{AC} < \text{WCET}_A$
  - $\text{WCET}_A < \text{WCET}_\emptyset$

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<th>C</th>
<th>D</th>
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<tbody>
<tr>
<td>WCET</td>
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<td>0.15</td>
<td>0.15</td>
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\[
\{ A, B, C, D \} \\
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\{ \emptyset \} \quad \text{WCET}_\emptyset
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Cleaning: Example

- **1st Sequence: ABC**
  - $WCET_{ABC} < WCET_{\emptyset}$
- **Next Sequence: AC**
  - $WCET_{AC} = WCET_{ABC}$
- **Next Sequence: A**
  - $WCET_{AC} < WCET_{A}$
  - $WCET_{A} < WCET_{\emptyset}$
- **Next Sequence: C**
  - $WCET_{AC} < WCET_{C}$
  - $WCET_{C} < WCET_{\emptyset}$

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\{ A^+ \} \{ B \} \{ C^+ \} \{ D \}
\{ \emptyset \} \]
Cleaning: Example

- **1st Sequence: ABC**
  - $WCET_{ABC} < WCET_{\emptyset}$
- **Next Sequence: AC**
  - $WCET_{AC} = WCET_{ABC}$
- **Next Sequence: A**
  - $WCET_{AC} < WCET_A$
  - $WCET_A < WCET_{\emptyset}$
- **Next Sequence: C**
  - $WCET_{AC} < WCET_C$
  - $WCET_C < WCET_{\emptyset}$

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<th>A</th>
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- $\{ A, B, C, D \}$
- $\{ A^+, B^-, C^+ \}$
- $\{ A, B, D \}$
- $\{ A, C, D \}$
- $\{ B, C, D \}$
- $\{ A, D \}$
- $\{ B, C \}$
- $\{ B, D \}$
- $\{ C, D \}$
- $\{ A^+ \}$
- $\{ B \}$
- $\{ C^+ \}$
- $\{ D \}$
- $\{ \emptyset \}$
Evaluation

- **46 Benchmarks from 4 suites**
  - Malardalen, Polybench, MiBench, PolyMage

- **Compiled with LLVM 4.0 for LEON3 processor**

- **Static WCET analysis using aiT**
  - 16 KB 2-way instruction and data caches

- **Four selection methods for iterative compilation (1000 sequences)**
  - Random
  - Genetic algorithm
  - Association-based learning
  - Association-based learning with cleaning
Iterative compilation can provide significant benefits
Assumptions cross validation

Application-dependent behaviour?
Apply sequences from other benchmarks
Assumptions cross validation

Application-dependent behaviour?
Apply sequences from other benchmarks

Frequent Neutral behaviour of passes?
Use existing characterisation
Pass / Sequence behavior

- Pass frequency in best sequence
  - For 1000 sequences / benchmark
Pass / Sequence behavior

- **Pass frequency in best sequence**
  - For 1000 sequences / benchmark

- **Best sequence length**
  - For 1000 sequences / benchmark
Runtime & Error susceptibility

- **Average runtime**
  - For 1000 sequences / benchmark

- **Average error rate**
  - For 1000 sequences / benchmark
Iterative Compilation: Results

Characterization of optimisation passes using association-based learning
Iterative Compilation: Results

Characterization of optimisation passes using association-based learning

<table>
<thead>
<tr>
<th>Method</th>
<th>(Geom.) Avg. WCET Improvement</th>
</tr>
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<tbody>
<tr>
<td>Random</td>
<td>16.8%</td>
</tr>
<tr>
<td>Genetic</td>
<td>17.6%</td>
</tr>
<tr>
<td>Association</td>
<td>19.4%</td>
</tr>
<tr>
<td>Association + Cleaning</td>
<td>20.3%</td>
</tr>
</tbody>
</table>
Characterization of optimisation passes using association-based learning

<table>
<thead>
<tr>
<th>Method</th>
<th>(Geom.) Avg. WCET Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random</td>
<td>16.8%</td>
</tr>
<tr>
<td>Genetic</td>
<td>17.6%</td>
</tr>
<tr>
<td>Association</td>
<td>19.4%</td>
</tr>
<tr>
<td>Association + Cleaning</td>
<td>20.3%</td>
</tr>
</tbody>
</table>

...thus providing significant WCET benefits!
Summary

- Iterative compilation + machine learning
  - Suitable for Static WCET analysis

- Shown effectiveness of such approaches
  - Proposed approach ~20% WCET reduction

- In the paper:
  - More technical details about parameter selection in aiT
Thank You

Questions?