Exploiting Static Application Knowledge in a Java Compiler for Embedded Systems
A Case Study

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Motivation

Automotive industry

- High robustness requirements
- But: mass production, immense cost pressure
- \{Computational, memory\} efficiency is key!

Challenge for the deployment of Java applications
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Challenge for the deployment of Java applications

System model of the OSEK/AUTOSAR OS

- OS tailoring: only enable features needed by the application
- Completely static configuration of the application world:
  - Fixed number of tasks
  - No dynamic code loading
  - Fixed-priority scheduling

Let’s build a Java VM for this system model!
Java-to-C ahead-of-time compiler
VM tailoring, static configuration

Domain A
- Control Flows
  - TaskA1
  - TaskA2
  - ISR1
- Static Fields
- System Objects
  - TaskA1
  - TaskA2
  - Alarm1
  - Resource

Peripheral Device Access (KNI)

Domain B
- Service
- Shared Memory

Domain Zero (TCB)
- GC Task

OSEK API (KNI)

OSEK / AUTOSAR OS

Microcontroller
The KESO Multi-JVM

- Java-to-C ahead-of-time compiler
- VM tailoring, static configuration

Domain A
- Control Flows: TaskA1, TaskA2, ISR1
- Static Fields
- System Objects: TaskA1, TaskA2, Alarm1, Resource
- Peripheral Device Access (KNI)
- OSEK API (KNI)

Domain B
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- Domain Zero (TCB): GC Task

OSEK / AUTOSAR OS

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KESO Case Study (JTRES 2011)  Introduction
The KESO Multi-JVM

- Java-to-C ahead-of-time compiler
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**System architecture**

**Domain A**
- Control Flows: TaskA1, TaskA2, ISR1
- Static Fields
- Heap
- Portal
- System Objects: TaskA1, TaskA2, Alarm1, Resource

**Peripheral Device Access (KNI)**

**Domain B**
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- GC Task

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KESO Case Study (JTRES 2011)

Introduction
The KESO Multi-JVM System architecture

- Java-to-C ahead-of-time compiler
- VM tailoring, static configuration

Diagram:

- Domain A
  - Control Flows: TaskA1, TaskA2, ISR1
  - Static Fields
  - System Objects: TaskA1, TaskA2, Alarm1, Resource
  - Peripheral Device Access (KNI)
  - OSEK API (KNI)

- Domain B
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### System architecture

#### Domain A
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  - TaskA2
  - ISR1
- System Objects:
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#### Domain B
- Service
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#### Domain Zero (TCB)
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#### Microcontroller

#### Peripheral Device Access (KNI)

#### OSEK API (KNI)

#### OSEK / AUTOSAR OS

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Static knowledge

The basis for tailoring and optimizations in KESO

KESO relies upon the availability of extensive application knowledge at compile-time.

Sources of knowledge

1. System model
   - Abandon the aspects of the Java programming model that don’t fit the OSEK/AUTOSAR system model!
   - “Everything is static”
KESO relies upon the availability of extensive application knowledge at compile-time.

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   - Isolation domains
   - Entry points
   - System objects
Static knowledge

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3. Application bytecode
   - Analyze to gain additional knowledge
   - Optimize aggressively using the aggregated knowledge
Exploiting static knowledge in the compiler

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Exploiting static knowledge in the compiler

Results

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Optimizations

Static whole-program (or rather: whole-domain) analysis

- Starting at each domain’s entry points
- Combined control flow, data flow and class hierarchy analysis

Since the application’s static nature enables us to collect extensive information ahead of time, we can apply aggressive optimizations.
Optimizations

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Improved standard optimizations

- Method inlining
- Constant propagation & folding
- Escape analysis & stack allocation
- Runtime check elimination (null-, bounds checks)
- Dead-code elimination
- Devirtualization
Selective use of linked stack frames

“Henderson frames”

- Local references stored as compounds, stack frames linked in order to enable GC scanning
- Induces significant overhead!
- But: GC will only run in slack time

Optimization: Only enable Henderson frames in methods that can possibly block – i.e., methods directly or indirectly invoking the \texttt{WaitEvent()} OS function
Variant-specific constants

The final qualifier for field variables allows better optimizations

However...
- ... programmers may be lazy or unaware
- ... declaring a field as final is impossible in some cases:

```java
public final class Constants {
    public static int MAX_FRAMES = 1000;
    // ... more similar constants...
}
```

```java
public class Main {
    private static void parse(final String[] v) {
        // ...
        if (v[i].equals("MAX_FRAMES"))
            Constants.MAX_FRAMES = Integer.parseInt(v[i + 1]);
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    }
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Idea: deduce final qualifiers where possible and legal

→ constant unreachable
Bug detection at compile-time

System configuration

- Does a task have run-to-completion semantics according to the configuration, but invokes `WaitEvent()` anyway?
- Service protection: Does a task or ISR access system objects other than those specified in the configuration?
Bug detection at compile-time

A bonus feature

System configuration

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Used raw-memory areas

- Which address ranges are accessed from a specific domain?
- Would a raw-memory area intersect with the regular application memory?
- Which memory-mapped I/O ports are used by which domains?
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Test system

Software

- CDj 1.2, ported to KESO:
  - Real-time air traffic simulator and collision detector
  - Community-accepted benchmark
- CiAO OS (AUTOSAR programming interface)

Hardware

- TriCore TC1796 @ 150 MHz
- 2 MiB ROM
- 1 MiB SRAM
More than half of all virtual method invocations are either removed or bound statically.
How many checks are performed during execution?

CD$_j$ detector, 10,000 radar frames:

Over 40% of all runtime checks are elided.
Effectiveness of advanced optimizations

<table>
<thead>
<tr>
<th>Default</th>
<th>+ Optimized frames(^1)</th>
<th>+ Variant-specific constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exec. time(^2)</td>
<td>23.9 ms</td>
<td>15.9 ms (−33.5 %)</td>
</tr>
<tr>
<td>Code size</td>
<td>67.8 KiB</td>
<td>55.2 KiB (−18.6 %)</td>
</tr>
<tr>
<td>Data size</td>
<td>4.86 KiB</td>
<td>4.86 KiB (±0 %)</td>
</tr>
</tbody>
</table>

- Using Henderson frames selectively improves both execution time and code size significantly.
- Inferring the final qualifier for CD\(_j\)'s Configuration fields would drastically reduce the memory footprint.

\(^1\) Use of Henderson frames only where necessary
\(^2\) For detector run with 10,000 radar frames; median
Conclusion

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Summary

- KESO abandons the aspects of the Java programming model that don’t fit the static OSEK/AUTOSAR system model...
  - ... permitting aggressive whole-program optimizations
  - ... bringing the benefits of Java to deeply embedded systems
- Our smallest system to date: Robertino
  - Autonomous robot navigating around obstacles
  - Control software running on ATmega8535 (8-bit AVR, 8 KiB Flash, 512 B SRAM)
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Future work

- Implementation of more advanced optimizations
- Extensive evaluation of real-life embedded applications