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Memory-architecture aware compilation

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http://www.artist-embedded.org/
The Problem with Memories

1. Increasing speed gap
2. Major consumer of electrical energy
3. Timing predictability difficult to achieve
4. ...

Or: Why work on processors if memory is where the bottleneck is?
Trends for the speeds

Speed gap between processor and main DRAM increases

Similar problems also for embedded systems & MPSoCs

- Memory access times >> processor cycle times (today: e.g. 100 x)
- “Memory wall” problem; uniform memory access a myth

Speed gap between processor and main DRAM increases

[O. Machanik: Approaches to Addressing the Memory Wall, TR Nov. 2002, U. Brisbane]
Importance of Energy Efficiency

© Hugo De Man, IMEC, 2007

IPE=Inherent power efficiency; Aml=Ambient Intelligence

O. Vargas (Infineon Technologies): Minimum power consumption in mobile-phone memory subsystems; Pennwell Portable Design - September 2005;
Dependency on the size

Applications are getting larger and larger …

+ locality of references

Memory hierarchies
Timing Predictability

Many embedded systems are real-time systems
- computations to be finished in a given amount of time

Most memory hierarchies (e.g. caches) for PC-like systems designed for good average case, not for good worst case behavior.

![Graph showing cycles vs cache size](image)

- Worst case execution time (WCET) larger than without cache
- G.721: using unified Cache@ARM7TDMI

See later slide for experimental setup
Vision

- Multiple objectives.
What are optimizing compilers actually optimizing for?
What is their cost model?

Specific (multi-objective?) optimizations for memory architectures;
Link/load-time optimizations would keep binary code memory architecture independent
Integration of various optimizations into framework

Memory Aware Compilation and Simulation Framework (for C) MACC

Application C code → Compilation tools

Memory architecture specification → Memory architecture specification

Profile report ← Simulation tools

Executable binary

MACC still under development;

Tools for specific optimizations exist

Related Work

- Optimizations exploiting burst mode for SDRAMs, using loop unrolling and architecture description language EXPRESSION (Dutt, Srivastava; UC Irvine)
- Smart linker (K. De Bosschere et al., U. Ghent)
- Architecture description language ArchC (G. Araujo, U. Campinas)
- Work on scratchpad optimizations (M. Kandemir, Penn State U.; R. Barua, U. Maryland; Egger+Lee, SNU; IMEC; Marwedel et al., TU Dortmund)
- 
Existing work covers only some of the aspects
What we have done:
Optimizations for Scratch Pad Memories (SPM)

SPMs are small, physically separate memories mapped into the address space;
Selection is by an appropriate address decoder (simple!)

**Example**

0

scratch pad memory

FFF..

**ARM7TDMI cores, well-known for low power consumption**

SPMs are fast, energy-efficient, timing-predictable
Predictability and scratch-pad memories

... **pre-run-time scheduling** is often the only practical means of providing predictability in a complex system.

... *In essence, we must reinvent computer science. Fortunately, we have quite a bit of knowledge and experience to draw upon. Architecture techniques such as software-managed caches promise to deliver much of the benefit of memory hierarchy without the timing unpredictability.*

Comparison of currents using measurements

E.g.: ATMEL board with ARM7TDMI and ext. SRAM

Even larger savings in terms of energy.
Why not just use a cache?

1. Timing predictability
2. Hardware complexity
3. Energy consumption (in tags, comparators and muxes)

Migration of data and instructions
- Global optimization model -

Which object (array, loop, etc.) to be stored in SPM?

Non-overlaying memory allocation:
Gain $g_k$ & size $s_k$ for each object $k$.
Maximise gain $G = \Sigma g_k$, respecting size of SPM SSP $\geq \Sigma s_k$.
Solution: Knapsack algorithm.

Overlaying allocation:
Moving objects back and forth between hierarchy levels
A first, non-overlaying approach for functions and global variables

Multi_sort (mix of sort algorithms)

Measured processor / external memory energy + CACTI values for SPM (combined model)

Extensions to smaller code blocks, stacks and heaps exist

Feasible with standard compiler & pre- or postpass optimization
Using these ideas in a pre-pass tool
Source is split into 2 different files by specially developed memory optimizer tool *.

*Built with tool design suite ICD-C available from ICD (see www.icd.de/es)
Non-overlapping allocation problematic for multiple hot spots

- Overlapping allocation
  - Effectively results in a kind of compiler-controlled overlays for SPM
  - Address assignment within SPM required
Overlaying allocation by Verma et al. (1)

Based on control flow graph.

Overlaying allocation by Verma et al. (2)

Global set of ILP equations reflects cost/benefit relations of potential copy points

Code handled like data
Runtime/energy reduction with respect to non-overlaying ("static") allocation
Multi-process Scratchpad Allocation: Hybrid Context Switch

- Processes can use *shared* and *exclusively allocated* areas
- Saving/restoring required for shared area
- Optimization of sizes published by Verma
Multi-process Scratchpad Allocation: Results

Hybrid approach superior to using only exclusively allocated or only shared areas

edge detection, adpcm, g721, mpeg

SPA: Single Process Approach

Energy Consumption vs. Scratchpad Size (bytes) for different allocations:
- Exclusive
- Shared
- Hybrid
Dynamic set of applications

- 2 steps: compile-time analysis & runtime decisions
- No need to know all applications at compile-time
- Capable of managing runtime allocated memory objects
- Integrated with an embedded OS

Using MPArm simulator from U. Bologna
Dynamic set of applications: Comparison of SPMM to Caches

- Baseline: Main memory only
- SPMM peak energy reduction by 83% at 4k Bytes scratchpad
- Cache peak: 75% at 2k 2-way
- Application: sorting

<table>
<thead>
<tr>
<th>SPM Size</th>
<th>Δ 4-way</th>
</tr>
</thead>
<tbody>
<tr>
<td>1024</td>
<td>74.81%</td>
</tr>
<tr>
<td>2048</td>
<td>65.35%</td>
</tr>
<tr>
<td>4096</td>
<td>64.39%</td>
</tr>
<tr>
<td>8192</td>
<td>65.64%</td>
</tr>
<tr>
<td>16384</td>
<td>63.73%</td>
</tr>
</tbody>
</table>
Scratch-pad/tightly coupled memory based predictability

Time-triggered, statically scheduled operating systems

- Let’s do the same for the memory system
- Are SPMs really more timing predictable?
- Analysis using the aiT timing analyzer
Architectures considered

ARM7TDMI with 3 different memory architectures:

- **Main memory**
  LDR-cycles: (CPU,IF,DF)=(3,2,2)
  STR-cycles: (2,2,2)
  * = (1,2,0)

- **Main memory + unified cache**
  LDR-cycles: (CPU,IF,DF)=(3,12,6)
  STR-cycles: (2,12,3)
  * = (1,12,0)

- **Main memory + scratch pad**
  LDR-cycles: (CPU,IF,DF)=(3,0,2)
  STR-cycles: (2,0,0)
  * = (1,0,0)
Results for G.721

Using Scratchpad:

![Graph showing comparison of cycles for Scratchpad and WCET]

Using Unified Cache:

![Graph showing comparison of cycles for Unified Cache and WCET]

Yes, they are clearly more timing predictable!

Requirements on WCET Estimates

- **Safeness**: $\text{WCET} \leq \text{WCET}_{\text{EST}}$
- **Tightness**: $\text{WCET}_{\text{EST}} - \text{WCET} \rightarrow \text{minimal}$
A WCET-Aware C-Compiler (WCC)

Distinctive Features:

• Integration of timing models into compilation & optimization process.
• Tight coupling of WCET analyzer aiT into WCC’s backend.

Target Processor: Infineon TriCore TC1796
Imported WCET Data & Flow Facts in WCC

Most important WCET data imported into WCC:

• $\text{WCET}_{\text{EST}}$ of the entire program
• $\text{WCET}_{\text{EST}}$ of each single basic block
• Worst-Case execution frequencies of each CFG edge

Flow Fact Annotation within WCC:

• Annotation of e.g. loop iteration bounds directly in C source code:  
  \_Pragma("loopbound min 10 max 10");
• Since compiler optimizations may restructure loops and thus their annotated bounds, WCC automatically keeps Flow Facts consistent during all applied optimizations.
Problems during WCET_{EST} Minimization

The Worst-Case Execution Path (WCEP):

• WCET of a program $P$ = length of longest execution path of $P$ (WCEP)

• To minimize $P$’s WCET_{EST}, optimizations must exclusively focus on those parts of $P$ lying on the WCEP.

▶ Optimization of parts not lying on the WCEP don’t reduce WCET_{EST} at all!

▶ Optimization strategies for WCET_{EST} Minimization must have detailed knowledge about the WCEP.

▶ During optimization, the WCEP may switch within the CFG
Graph Colouring Register Allocation

1. **Initialisation:** Build Interference Graph $G = (V, E)$ with $G = \{\text{virtual registers}\} \cup \{K \text{ physical processor registers}\}$, $e = \{v, w\} \in E \Leftrightarrow \text{VREGs } v \text{ and } w \text{ may never share the same PHREG, i.e. } v \text{ and } w \text{ interfere}$

2. **Simplification:** Successively remove all $v \in V$ with deg. $< K$; push each $v$ onto stack $S$

3. **Spilling:** After step 2, each node of $G$ has degree $\geq K$. Select one $v \in V$; mark $v$ as potential spill; remove $v$ from $V$; push $v$ onto stack $S$

4. Repeat steps 2 and 3 until $G = \emptyset$.

Problem of Standard Graph Colouring

3. **Spilling**: After step 2, each node of $G$ has degree $\geq K$. Select one $v \in V$; mark $v$ as potential spill; remove $v$ from $V$; push $v$ onto stack $S$

Which node $v$ should be selected as potential spill?

Graph colouring implementations heuristically select …

- … either some arbitrary node or …
- … the node with highest degree or …
- … a node in some inner loop.

☞ Uncontrolled spill code generation – potentially along Worst-Case Execution Path (WCEP) defining the WCET!
A Chicken-Egg Problem

A WCET-aware Register Allocator…

• …relies on WCET data provided by WCET analysis
• …but can’t obtain WCET data since code containing virtual registers is not analysable!

The Way out:

• Start by spilling each VREG onto stack code is fully analysable
• Perform WCET analysis, get WCEP $P$
• Allocate VREGs of that basic block $b \in P$ with most worst-case spill code executions to PHREGs using standard GC
• Recompute WCEP
Results – WCET\textsubscript{EST} Reductions

100\% = WCET\textsubscript{EST} using Std. WCET-unaware Graph-Coloring
Results – Simulated Execution Times

100% = ACETs using Std. WCET-unaware Graph-Coloring
Other WCET-aware Optimizations

- **WCET-aware Procedure Cloning & Positioning**
  [Lokuciejewski, Falk et al., „WCET-driven Cache-based Procedure Positioning Optimizations“, ECRTS 2008.]

- **WCET-aware I-Cache Locking**
  [Falk, Plazar et al., „Compile Time Decided Instruction Cache Locking Using Worst-Case Execution Paths“, CODES+ISSS 2007.]

- **WCET-aware Scratchpad Memory Allocation**
  - First simple approaches proposed by I. Puaut et al.
  - Integrated ILP strategies under development at Dortmund, supported by PREDATOR
Future work

• Tight integration of tools and representation of memory architectures
• Making these optimizations available to the “average” software engineer for embedded systems
• Creating comprehensive set of SPM optimizations in the form of pre-pass optimizations
• Extensions focusing on multi-processor based systems
• Analysis of standard optimizations from the viewpoint of WCET reduction
• Analysis of tradeoffs between multiple objectives
Conclusion

• Current compiler technology does not reflect non-uniform memory access costs well

 Proposal for an introduction of optimizations driven by models of memory access costs

 First approaches focus on exploitation of scratch-pad memories

  Non-overlaying + overlaying approaches
  Single + multiple applications

 Optimizations driven by an explicit WCET model

  Significant WCET reductions even in well-established areas