Tree Traversal Scheduling: A Global Scheduling Technique for VLIW/EPIC Processors

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Presentation Outline

• Introduction
• Tree Traversal Scheduling (TTS) Algorithm
• Efficient Data Flow Analysis in TTS
• Simulation Methodology
• Results
• Conclusions
Introduction

• Global Scheduling
  - Arrange the order of the instructions to minimize the execution time and maintain the program semantics.
  - Schedule instructions beyond the basic block scope.
  - Containing two phases in Treegion framework:
    • Treegion formation & treegion scheduling

• Treegion
  - A single-entry / multiple-exit nonlinear region with CFG forming a tree (i.e., no merge points and back-edges in a treegion)
  - Basic scheduling unit in tree traversal scheduling (TTS)
Introduction

• Treegion Formation
  - Treegion is formed only based on the program CFG.
Introduction

- Tree region enlargement optimization: tail duplication at merge points

- Tree region formation algorithm [W. A. Havanki, et al. HPCA - 4]
Introduction

• Treecgion Attributes
  – Only depending on the topology of the program’s CFG, which makes it suitable for dynamic optimization
  – Containing multiple execution paths
    • Potential to speedup multiple paths
    • Large scheduling scope for ILP extraction
    • High resource utilization for wide issue processors

• LEGO: the ILP research compiler developed by Tinker Research Group at N. C. State University

www.tinker.ncsu.edu
LEGO (code generator)
Profile studio (arc, block, path) / trace annotator
Cluster assigner
WELD: Treegion based multithread
Iterative modulo scheduler
I- & D-cache
Branch Predictor
VLIW/EPIC Processor Timing Simulator
Intermediate code: Elcor compatible PlayDoh semantics CFG-based

LEGO IR library
- analysis routines
- IR file I/O
- generic opt support

LEGO Front-end
- Tregeion formation
- Classical Optimization
  - Munger: high-level IR to low-level IR translation
  - Register allocator
  - Global Scheduler
  - Iterative modulo scheduler
  - WELD: Tregeion based multithread
  - Cluster assigner
  - Profile studio: profiler (arc, block, path) / trace annotator
  - Intermediate code: Elcor compatible PlayDoh semantics CFG-based

YULA (code generator)
C (inline emulation)

Jointly developed by: Prof. Tom Conte and his students
Tree Traversal Scheduling Algorithm

- **Objective**
  - Speedup each execution path in a tree region
  - If profile information is available, speed up each path based on its execution frequency

- **Common Scheduling techniques**
  - List scheduling
  - Renaming
  - Speculative code motion
Speculation in a tree region

- **Over-aggressive speculation**
  - May cause the delay to non-speculative instructions due to the contention of machine resources

Diagram:

1: add r5, r6, 1  
2: br bb2, r5 > 100

80

3: add r7, r8, r6  
4: add r11, r8, r10

20

5: ld r9, r10, 5

Basic block 1  Basic block 2

<table>
<thead>
<tr>
<th>Sch_Time</th>
<th>ALU/BR</th>
<th>ALU/LD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle n:</td>
<td>add r5, r6, 1</td>
<td>add r7, r8, r6</td>
</tr>
<tr>
<td>Cycle n+1:</td>
<td>add r11, r8, r10</td>
<td>ld r9, r10, 5</td>
</tr>
<tr>
<td>Cycle n+2:</td>
<td>br bb2, r5 &gt; 100</td>
<td></td>
</tr>
</tbody>
</table>

Average execution time: 4 cycles

- **Over-conservative speculation**
  - The operation latencies are not hidden enough. Less a problem for wide issue processors
Speculation in TTS

- Solve over-aggressive speculation by a cycle based scheduling with prioritizing the instructions according to:
  (a) Execution frequency
  (b) Exit count [Deitrich, et al., MCIRO29] heuristic to resolve ties from (a), and
  (c) Data dependence height to resolve ties from (b)

- Allow early schedule of branches even with downward code motion

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<td>add r7, r8</td>
</tr>
<tr>
<td>Cycle n+1:</td>
<td>br bb2, r5 &gt; 100</td>
<td>add r11, r8, r10</td>
</tr>
<tr>
<td>Cycle n+2:</td>
<td>(ld r9, r10, 5)</td>
<td></td>
</tr>
</tbody>
</table>

Average execution time: 3 + 2*0.2 = 3.4 cycles
TTS Algorithm

• Step 1. Construct the control/data dependence graph and perform instruction ordering.

• Step 2. Cycle scheduling of the instructions in a tree region
  a. For each cycle, select the candidate operation according to the order of Step 1.
  b. If machine resource is available for the candidate operation, check for whether the scheduling of the candidate is speculative.
  c. For the speculative code motion, check whether the renaming is necessary to support the speculation.
  d. If the candidate is a branch operation, downward code motion and multiway branch transformation may result.
Scheduling of Branches in TTS

current_block

current_op: if p1, br1

Inst i: add r2, r3, 1
Inst i+1: ld r4, r2

if p2, br2

candidate_op

current_block

current_block

current_op: if p1, br1

Inst i: Inst i+1:

Inst i:

Inst i+1:

if p, br

Inst i:

Inst i+1:

current_block

current_op: if p2, br2

if p1, br1

Inst i: Inst i+1:

Inst i:

Inst i+1:
Logic View of TTS

1. For a treegion, sort the basic blocks according to a depth-first traversal order with the child block selected with highest execution frequency.
2. Start list scheduling at the root basic block.
3. During the scheduling of a basic block, consider speculation for instructions dominated by this basic block.
4. After scheduling the block-ending branch, traverse to the next basic block and go back to 3.

- Traversal order: BB1, BB2, BB4, BB7, BB6, BB5, BB3
- High resource utilization from speculation of dominated instructions.
- Reducing resource contention: e.g., when scheduling BB4, the instructions in BB5 will not compete for the resources.
Incremental Data Flow Analysis in TTS

• Motivation
  – The data flow analysis (liveness, reaching definition) obsolete due to code motions in TTS.
  – Recalculation takes too much computation time
  – Solution: incremental update (not accurate but conservative)

• Data flow analysis based on different categories of renaming (based on the renaming scope)
  – Speculation without renaming
  – Speculation with local renaming
  – Speculation with renaming with a copy
  – Speculation with global renaming
Data flow analysis for speculative code motion without renaming

• Example

Current block

edge 1

Live(edge 1) = {…}

edge 2

Live(edge 2) = {r2, r3,…}

Add r1, r2, r3 (*)

Current block

edge 1

Live(edge 1) = {…}

edge 2

Live(edge 2) = {r2, r3,…} ∪ {r1}

• Incremental update
  - Liveness is extended for the destination operand and added to each edge that the instruction traverse
  - Conservative liveness may cause unnecessary renaming (most of them are simple to process)
  - No changes in reaching definitions
Data flow analysis for speculative code motion with local renaming

- Local renaming is used when the renaming scope is within the tree region

- Incremental update
  - No change to liveness and reaching definitions
Data flow analysis for speculative code motion with renaming with a copy

- Renaming with a copy is used when the operand to be renamed is live outside the tree region and there is a ‘merge’ problem.

- Incremental update
  - No change in liveness and accurate update of reaching definition
Data flow analysis for speculative code motion with global renaming

- Global renaming is used when the renaming scope is beyond the treegion and there is no merge problem

**Update**
- Recalculate the liveness at procedural scope. No changes in reaching definitions.
Data flow analysis for downward code motion

- Result from the early schedule of block-ending branches

```
Block 1
  add r1, r2, r3
  br bb1, if p1 (*)
  r1 not live
  r1 live

Block 2
  add r1, r1, 1
```

- Incremental update
  - For each downward moved instruction, add its source operands into liveness set and remove the its destination operand from liveness set.
  - Processed in reverse program order
## VLIW/EPIC Processor Model Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Execution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dispatch/Issue/Retire bandwidth: 8;</td>
</tr>
<tr>
<td></td>
<td>Universal function units: 8;</td>
</tr>
<tr>
<td></td>
<td>Operation latency: ALU, ST, BR: 1 cycle; LD, floating-point (FP) add/subtract: 2 cycles;</td>
</tr>
<tr>
<td></td>
<td>FP multiply/divide: 3 cycles</td>
</tr>
<tr>
<td>I-cache</td>
<td>Compressed (zero-nop) and two banks with 32KB each bank (Direct Mapped) [Conte et. Al, MICRO29 ].</td>
</tr>
<tr>
<td></td>
<td>Line size: 16 operations with 4 bytes each operation.</td>
</tr>
<tr>
<td></td>
<td>Miss latency: 12 cycles</td>
</tr>
<tr>
<td>D-cache</td>
<td>Size/Associativity/Replacement: 64KB/4-way/LRU</td>
</tr>
<tr>
<td></td>
<td>Line size: 32 bytes</td>
</tr>
<tr>
<td></td>
<td>Miss Penalty: 14 cycles</td>
</tr>
<tr>
<td>Branch Predictor:</td>
<td>G-share style Multi-way branch prediction [Menezes, et. al., PACT’97, Hoogerbrugge, PACT’00]</td>
</tr>
<tr>
<td></td>
<td>Branch prediction table: 2(^{14}) entries;</td>
</tr>
<tr>
<td></td>
<td>Branch target buffer: 2(^{14}) entries/8-way/LRU</td>
</tr>
<tr>
<td></td>
<td>Branch misprediction penalty: 10 cycles</td>
</tr>
</tbody>
</table>
Speedup Results

- Speedup with ideal I-cache, D-cache, and branch predictor

![Speedup Results Graph]

- Lineartree Speedup
- Treeregion Speedup
Speedup Results

- Speedup with realistic I- & D- cache, Branch Predictor
D-Cache Performance

D-cache access increase over BB scheduled code

D-cache penalties over BB scheduled code
I-Cache Performance

**Code size increase of treegion scheduling**

- compress: 1.2
- gcc: 1.4
- go: 1.6
- ijpeg: 1.8
- li: 2.0
- m88ksim: 2.2
- perl: 2.4
- vortex: 2.6
- A-mean: 2.8

**I-cache access increase of treegion scheduling**

- compress: 0.65
- gcc: 0.70
- go: 0.75
- ijpeg: 0.80
- li: 0.85
- m88ksim: 0.90
- perl: 0.95
- vortex: 0.60
- A-mean: 0.70
Conclusion

- Significant speedup from tree traversal scheduling

- To fully take advantage of load speculation, the stall-on-use technique should be used in the in-order pipeline.

- Fewer multi-ops as a result of TTS results in fewer I-cache accesses while code expansion due to treegion formation usually introduces higher miss rates.
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