VLIW/EPIC: Statically Scheduled ILP

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Based on the material prepared by
Krste Asanovic and Arvind
Little’s Law

Parallelism = Throughput * Latency

or

\[ \overline{N} = \overline{T} \times \overline{L} \]

Throughput per Cycle

One Operation

Latency in Cycles
Example Pipelined ILP Machine

Max Throughput, Six Instructions per Cycle

Latency in Cycles

- Two Integer Units, Single Cycle Latency
- Two Load/Store Units, Three Cycle Latency
- Two Floating-Point Units, Four Cycle Latency

One Pipeline Stage

• How much instruction-level parallelism (ILP) required to keep machine pipelines busy?

\[ \bar{T} = 6 \quad \bar{L} = \frac{2 \times 1 + 2 \times 3 + 2 \times 4}{6} = 2 \frac{2}{3} \quad \bar{N} = 6 \times 2 \frac{2}{3} = 16 \]
Each issued instructions must make interlock checks against $W \times L$ instructions, i.e., growth in interlocks $\propto W^2 (W \times L)$

For in-order machines, $L$ is related to pipeline latencies

For out-of-order machines, $L$ also includes time spent in instruction buffers (instruction window or ROB)

As $W$ increases, larger instruction window is needed to find enough parallelism to keep machine busy => greater $L$

$\Rightarrow$ Out-of-order control logic grows faster than $W^2$ ($\sim W^3$)
Out-of-Order Control Complexity: MIPS R10000

[ SGI/MIPS Technologies Inc., 1995 ]
Sequential ISA Bottleneck

Superscalar compiler

Find independent operations

Schedule operations

Sequential source code

a = foo(b);
for (i=0, i<

Sequential machine code

Superscalar processor

Check instruction dependencies

Schedule execution

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VLIW: Very Long Instruction Word

- Multiple operations packed into one instruction
- Each operation slot is for a fixed function
- Constant operation latencies are specified
- Architecture requires guarantee of:
  - Parallelism within an instruction => no x-operation RAW check
  - No data use before data ready => no data interlocks
VLIW Compiler Responsibilities

The compiler:

- Schedules to maximize parallel execution
- Guarantees intra-instruction parallelism
- Schedules to avoid data hazards (no interlocks)
  - Typically separates operations with explicit NOPs
Early VLIW Machines

- **FPS AP120B (1976)**
  - scientific attached array processor
  - first commercial wide instruction machine
  - hand-coded vector math libraries using software pipelining and loop unrolling

- **Multiflow Trace (1987)**
  - commercialization of ideas from Fisher’s Yale group including “trace scheduling”
  - available in configurations with 7, 14, or 28 operations/instruction
  - 28 operations packed into a 1024-bit instruction word

- **Cydrome Cydra-5 (1987)**
  - 7 operations encoded in 256-bit instruction word
  - rotating register file
Loop Execution

for (i=0; i<N; i++)

Compile

loop:  ld f1, 0(r1)
    add r1, 8
    fadd f2, f0, f1
    sd f2, 0(r2)
    add r2, 8
    bne r1, r3, loop

How many FP ops/cycle?

1 fadd / 8 cycles = 0.125
Loop Unrolling

Unroll inner loop to perform 4 iterations at once

Need to handle values of N that are not multiples of unrolling factor with final cleanup loop
Scheduling Loop Unrolled Code

Unroll 4 ways

```
loop:  ld f1, 0(r1)
      ld f2, 8(r1)
      ld f3, 16(r1)
      ld f4, 24(r1)
      add r1, 32
      fadd f5, f0, f1
      fadd f6, f0, f2
      fadd f7, f0, f3
      fadd f8, f0, f4
      sd f5, 0(r2)
      sd f6, 8(r2)
      sd f7, 16(r2)
      sd f8, 24(r2)
      add r2, 32
      bne r1, r3, loop
```

Schedule

```
<table>
<thead>
<tr>
<th>Int1</th>
<th>Int 2</th>
<th>M1</th>
<th>M2</th>
<th>FP+</th>
<th>FPx</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ld f1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ld f2</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ld f3</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>fadd f5</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>fadd f6</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>fadd f7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fadd f8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>add r1</td>
<td>ld f4</td>
<td></td>
<td></td>
<td>fadd f5</td>
<td></td>
</tr>
<tr>
<td>ld f4</td>
<td></td>
<td></td>
<td></td>
<td>fadd f6</td>
<td></td>
</tr>
<tr>
<td>fadd f6</td>
<td></td>
<td></td>
<td></td>
<td>fadd f7</td>
<td></td>
</tr>
<tr>
<td>fadd f7</td>
<td></td>
<td></td>
<td></td>
<td>fadd f8</td>
<td></td>
</tr>
<tr>
<td>add r2</td>
<td>bne</td>
<td></td>
<td></td>
<td>sd f8</td>
<td></td>
</tr>
</tbody>
</table>
```

How many FLOPS/cycle?

4 fadds / 11 cycles = 0.36
Software Pipelining

Unroll 4 ways first

loop:  ld f1, 0(r1)
      ld f2, 8(r1)
      ld f3, 16(r1)
      ld f4, 24(r1)
      add r1, 32
      fadd f5, f0, f1
      fadd f6, f0, f2
      fadd f7, f0, f3
      fadd f8, f0, f4
      sd f5, 0(r2)
      sd f6, 8(r2)
      sd f7, 16(r2)
      add r2, 32
      sd f8, -8(r2)
      bne r1, r3, loop

How many FLOPS/cycle?
4 fadd / 4 cycles = 1
Software Pipelining vs. Loop Unrolling

Software pipelining pays startup/wind-down costs only once per loop, not once per iteration.
What if there are no loops?

- Branches limit basic block size in control-flow intensive irregular code
- Difficult to find ILP in individual basic blocks

Basic block
Trace Scheduling \cite{Fisher,Ellis}

- Pick string of basic blocks, a \textit{trace}, that represents most frequent branch path
- Use \textit{profiling feedback} or compiler heuristics to find common branch paths
- Schedule whole “trace” at once
- Add fixup code to cope with branches jumping out of trace
Problems with “Classic” VLIW

• Object-code compatibility
  – have to recompile all code for every machine, even for two machines in same generation

• Object code size
  – instruction padding wastes instruction memory/cache
  – loop unrolling/software pipelining replicates code

• Scheduling variable latency memory operations
  – caches and/or memory bank conflicts impose statically unpredictable variability

• Knowing branch probabilities
  – Profiling requires an significant extra step in build process

• Scheduling for statically unpredictable branches
  – optimal schedule varies with branch path
VLIW Instruction Encoding

- Schemes to reduce effect of unused fields
  - Compressed format in memory, expand on I-cache refill
    » used in Multiflow Trace
    » introduces instruction addressing challenge
  - Mark parallel groups
    » used in TMS320C6x DSPs, Intel IA-64
  - Provide a single-op VLIW instruction
    » Cydra-5 UniOp instructions
Rotating Register Files

Problems: Scheduled loops require lots of registers, lots of duplicated code in prolog, epilog

Solution: Allocate new set of registers for each loop iteration
Rotating Register File

Rotating Register Base (RRB) register points to base of current register set. Value added on to logical register specifier to give physical register number. Usually, split into rotating and non-rotating registers.

<table>
<thead>
<tr>
<th>Prolog</th>
<th>Loop</th>
<th>Epilog</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{ld} r1, ()</td>
<td>\textit{add} r3, r2, #1</td>
<td>\textit{add} r2, r1, #1</td>
</tr>
<tr>
<td>\textit{ld} r1, ()</td>
<td>\textit{add} r3, r2, #1</td>
<td>\textit{st} r4, ()</td>
</tr>
<tr>
<td>\textit{ld} r1, ()</td>
<td>\textit{add} r3, r2, #1</td>
<td>\textit{st} r4, ()</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\textit{st} r4, ()</td>
</tr>
</tbody>
</table>
Rotating Register File  
(Previous Loop Example)

Three cycle load latency  
encoded as difference of 3  
in register specifier  
number (f4 - f1 = 3)

Four cycle fadd latency  
encoded as difference of 4  
in register specifier  
number (f9 – f5 = 4)

<table>
<thead>
<tr>
<th>ld P9, ()</th>
<th>fadd P13, P12,</th>
<th>sd P17, ()</th>
<th>bloop</th>
</tr>
</thead>
<tbody>
<tr>
<td>ld P8, ()</td>
<td>fadd P12, P11,</td>
<td>sd P16, ()</td>
<td>bloop</td>
</tr>
<tr>
<td>ld P7, ()</td>
<td>fadd P11, P10,</td>
<td>sd P15, ()</td>
<td>bloop</td>
</tr>
<tr>
<td>ld P6, ()</td>
<td>fadd P10, P9,</td>
<td>sd P14, ()</td>
<td>bloop</td>
</tr>
<tr>
<td>ld P5, ()</td>
<td>fadd P9, P8,</td>
<td>sd P13, ()</td>
<td>bloop</td>
</tr>
<tr>
<td>ld P4, ()</td>
<td>fadd P8, P7,</td>
<td>sd P12, ()</td>
<td>bloop</td>
</tr>
<tr>
<td>ld P3, ()</td>
<td>fadd P7, P6,</td>
<td>sd P11, ()</td>
<td>bloop</td>
</tr>
<tr>
<td>ld P2, ()</td>
<td>fadd P6, P5,</td>
<td>sd P10, ()</td>
<td>bloop</td>
</tr>
</tbody>
</table>

RRB=8
RRB=7
RRB=6
RRB=5
RRB=4
RRB=3
RRB=2
RRB=1
Cydra-5: Memory Latency Register (MLR)

Problem: Loads have variable latency
Solution: Let software choose desired memory latency

- Compiler schedules code for maximum load-use distance
- Software sets MLR to latency that matches code schedule
- Hardware ensures that loads take exactly MLR cycles to return values into processor pipeline
  - Hardware buffers loads that return early
  - Hardware stalls processor if loads return late
Five-minute break to stretch your legs
Intel EPIC IA-64

• EPIC is the style of architecture (cf. CISC, RISC)
  – Explicitly Parallel Instruction Computing

• IA-64 is Intel’s chosen ISA (cf. x86, MIPS)
  – IA-64 = Intel Architecture 64-bit
  – An object-code compatible VLIW

• Itanium (aka Merced) is first implementation (cf. 8086)
  – First customer shipment expected 1997 (actually 2001)
  – McKinley, second implementation shipped in 2002
IA-64 Instruction Format

128-bit instruction bundle

- Template bits describe grouping of these instructions with others in adjacent bundles
- Each group contains instructions that can execute in parallel
IA-64 Registers

- 128 General Purpose 64-bit Integer Registers
- 128 General Purpose 64/80-bit Floating Point Registers
- 64 1-bit Predicate Registers
- GPRs rotate to reduce code size for software pipelined loops
IA-64 Predicated Execution

Problem: Mispredicted branches limit ILP
Solution: Eliminate hard to predict branches with predicated execution
- Almost all IA-64 instructions can be executed conditionally under predicate
- Instruction becomes NOP if predicate register false

Four basic blocks

Predication

One basic block

Mahlke et al, ISCA95: On average >50% branches removed
Predicate Software Pipeline Stages

Single VLIW Instruction

(p1) ld r1   (p2) add r3   (p3) st r4   (p1) bloop

Dynamic Execution

(p1) ld r1
(p1) ld r1
(p1) ld r1
(p1) ld r1
(p2) add r3
(p2) add r3
(p2) add r3
(p2) add r3
(p3) st r4
(p3) st r4
(p3) st r4
(p3) st r4
(p1) bloop
(p1) bloop
(p1) bloop
(p1) bloop
(p1) bloop
(p1) bloop
(p1) bloop
(p1) bloop

Software pipeline stages turned on by rotating predicate registers ➔ Much denser encoding of loops
Fully Bypassed Datapath

Where does predication fit in?
IA-64 Speculative Execution

Problem: Branches restrict compiler code motion

Solution: Speculative operations that don’t cause exceptions

Inst 1
Inst 2
br a==b, b2

Load r1
Use r1
Inst 3

Can’t move load above branch because might cause spurious exception

Load.s r1
Inst 1
Inst 2
br a==b, b2

Speculative load never causes exception, but sets “poison” bit on destination register

Chk.s r1
Use r1
Inst 3

Check for exception in original home block jumps to fixup code if exception detected

Particularly useful for scheduling long latency loads early
IA-64 Data Speculation

Problem: Possible memory hazards limit code scheduling
Solution: Hardware to check pointer hazards

Inst 1
Inst 2
Store

Load r1
Use r1
Inst 3

Data speculative load adds address to address check table

Load.a r1
Inst 1
Inst 2
Store

Load.c
Use r1
Inst 3

Store invalidates any matching loads in address check table

Can’t move load above store because store might be to same address

Check if load invalid (or missing), jump to fixup code if so

Requires associative hardware in address check table
Clustered VLIW

- Divide machine into clusters of local register files and local functional units
- Lower bandwidth/higher latency interconnect between clusters
- Software responsible for mapping computations to minimize communication overhead
- Exists in some superscalar processors, e.g., Alpha 21264
- Common in commercial embedded processors, examples include TI C6x series DSPs, and HP Lx processor
Limits of Static Scheduling

• Unpredictable branches
• Variable memory latency (unpredictable cache misses)
• Code size explosion
• Compiler complexity

Question:
How applicable are the VLIW-inspired techniques to traditional RISC/CISC processor architectures?
Thank you!