HW support for More ILP

- **Speculation**: allow an instruction to issue that is dependent on branch predicted to be taken *without* any consequences (including exceptions) if branch is not actually taken (“HW undo”)
- Often combined with dynamic scheduling
- Tomasulo: separate *speculative* bypassing of results from real bypassing of results
  - When instruction no longer speculative, write results (*instruction commit*)
  - execute out-of-order but commit in order

Hardware Speculative Execution

- Need HW buffer for results of uncommitted instructions: *reorder buffer*
  - Reorder buffer can be operand source
  - Once operand commits, result is found in register
  - 3 fields: instr. type, destination, value
  - Use reorder buffer number instead of reservation station
  - Instructions commit in order
  - As a result, easy to undo speculated instructions on mispredicted branches or on exceptions

Four Steps of Speculative Tomasulo Algorithm

1. **Issue**—get instruction from FP Op Queue
   - If reservation station and reorder buffer slot free, issue instr & send operands & reorder buffer no. for destination. Operands may be read from register file or reorder buffer.
2. **Execution**—operate on operands (EX)
   - When both operands ready then execute; if not ready, watch CDB for result; when both in reservation station, execute
3. **Write result**—finish execution (WB)
   - Write on Common Data Bus to all awaiting FUs & reorder buffer; mark reservation station available.
4. **Commit**—update register with reorder result
   - When instr. at head of reorder buffer & result present, update register with result (or store to memory) and remove instr from reorder buffer.

Tomasulo – cycle 0
Tomasulo – cycle 11

Loop: ADDD F4, F2, F0

MULD F8, F4, F2
ADDD F6, F8, F6
SUBD F8, F2, F0
SUBI ...
BNEZ ...

Instruction Queue

F0 0.0
F2 2.0
F4 2.0
F6 6.0
F8 8.0

ROB

MULD F8 -
ADDD F6 -
SUBD F8 2.0
SUBI ...
ADDD F4, F2, F0
BNEZ ...
ADDI ...
BNEZ ...

2.0 (ROB6)

FP adders

FP mult's

Tomasulo – cycle 15

Loop: ADDD F4, F2, F0

MULD F8, F4, F2
ADDD F6, F8, F6
SUBD F8, F2, F0
SUBI ...
BNEZ ...

Instruction Queue

F0 0.0
F2 2.0
F4 2.0
F6 6.0
F8 8.0

ROB

MULD F8 -
ADDD F6 -
SUBD F8 2.0
SUBI ...
ADDD F4, F2, F0
BNEZ ...
ADDI ...
BNEZ ...

4.0 (ROB1)

FP adders

FP mult's

Tomasulo – cycle 16

Loop: ADDD F4, F2, F0

MULD F8, F4, F2
ADDD F6, F8, F6
SUBD F8, F2, F0
SUBI ...
BNEZ ...

Instruction Queue

F0 0.0
F2 2.0
F4 2.0
F6 6.0
F8 4.0

ROB

MULD F8 -
ADDD F6 -
SUBD F8 2.0
SUBI ...
ADDD F4, F2, F0
BNEZ ...
ADDI ...
BNEZ ...

Branch Mispredicted!

FP adders

FP mult's

Tomasulo – cycle 17

Loop: ADDD F4, F2, F0

MULD F8, F4, F2
ADDD F6, F8, F6
SUBD F8, F2, F0
SUBI ...
BNEZ ...

Instruction Queue

F0 0.0
F2 2.0
F4 2.0
F6 6.0
F8 4.0

ROB

flushed
ADDD F6 -
SUBD F8 2.0
SUBI ...
ADDD F4, F2, F0
BNEZ ...
ADDI ...
BNEZ ...

flushed

integer

flushed

flushed

flushed

flushed

flushed

Branch Mispredicted!

FP adders

FP mult's
Speculative Execution

- The re-order buffer and in-order commit allow us to flush the speculative instructions from the machine when a misprediction is discovered.
- ROB is another possible source of operands
- ROB can provide precise exceptions in an out-of-order machine
- ROB allows us to ignore exceptions on speculative code.

- Compiler speculation vs. hardware speculation?

Now what?

- CPI = 1.0 + BSPI + FPSPI + LdSPI
Multiple Instruction Issue

or

The insts go marching two by two, hurrah, hurrah...

Getting CPI < 1: Issuing Multiple Instructions/Cycle

• Superscalar
  – variable number of instructions issued each cycle
  – parallelism detected in hardware

• Very Long Instruction Words (VLIW)
  – fixed number of instructions issued each cycle
  – parallelism scheduled by the compiler
  – IA-64 (Merced, Itanium)

Superscalar MIPS Implications

• Superscalar MIPS: 2 instructions, 1 FP & 1 anything else
  – Fetch 64-bits/clock cycle; Int on left, FP on right
  – Can only issue 2nd instruction if 1st instruction issues

<table>
<thead>
<tr>
<th>Type</th>
<th>Pipe Stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int. instruction</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>FP instruction</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>Int. instruction</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>FP instruction</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>Int. instruction</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>FP instruction</td>
<td>IF ID EX MEM WB</td>
</tr>
</tbody>
</table>
Unrolled Loop that Minimizes Stalls for Scalar

1. Loop: LD F0,0(R1)
2. LD F6,-8(R1)
3. LD F10,-16(R1)
4. LD F14,-24(R1)
5. ADDD F4,F0,F2
6. ADDD F8,F6,F2
7. ADDD F12,F10,F2
8. ADDD F16,F14,F2
9. SD 0(R1),F4
10. SD -8(R1),F8
11. SD -16(R1),F12
12. SUBI R1,R1,#32
13. BNEZ R1,LOOP
14. SD 8(R1),F16 ; 8-32 = -24

CSE 240A 14 clock cycles, or 3.5 per iteration

Dynamic Scheduling in Superscalar

- Dependencies stop instruction issue in In-order SS
- Code compiled for scalar version will run poorly on SS
  - May want code to vary depending on how superscalar
- Simple approach: Combine Tomasulo with the ability to fetch and issue multiple instructions simultaneously
  - simplified if we don’t issue instructions that read the same register file in the same cycle.
  - requires multiple CDBs
  - can complicate updating of register bookkeeping if instructions are dependent, but can be done

Loop Unrolling in Superscalar

<table>
<thead>
<tr>
<th>Integer instruction</th>
<th>FP instruction</th>
<th>Clock cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LD F0,0(R1)</td>
<td>ADDD F4,F0,F2</td>
<td>1</td>
</tr>
<tr>
<td>LD F6,-8(R1)</td>
<td>ADDD F8,F6,F2</td>
<td>2</td>
</tr>
<tr>
<td>LD F10,-16(R1)</td>
<td>ADDD F12,F10,F2</td>
<td>3</td>
</tr>
<tr>
<td>LD F14,-24(R1)</td>
<td>ADDD F16,F14,F2</td>
<td>4</td>
</tr>
<tr>
<td>LD F18,-32(R1)</td>
<td>ADDD F20,F18,F2</td>
<td>5</td>
</tr>
<tr>
<td>SD 0(R1),F4</td>
<td>ADDD F16,F14,F2</td>
<td>6</td>
</tr>
<tr>
<td>SD -8(R1),F8</td>
<td>ADDD F20,F18,F2</td>
<td>7</td>
</tr>
<tr>
<td>SD -16(R1),F12</td>
<td>ADDD F20,F18,F2</td>
<td>8</td>
</tr>
<tr>
<td>SD -24(R1),F16</td>
<td>ADDD F20,F18,F2</td>
<td>9</td>
</tr>
<tr>
<td>SUBI R1,R1,#32</td>
<td>ADDD F20,F18,F2</td>
<td>10</td>
</tr>
<tr>
<td>BNEZ R1,LOOP</td>
<td>ADDD F20,F18,F2</td>
<td>11</td>
</tr>
<tr>
<td>SD -32(R1),F20</td>
<td>ADDD F20,F18,F2</td>
<td>12</td>
</tr>
</tbody>
</table>

- Unrolled 5 times to avoid delays
- 12 clocks, or 2.4 clocks per iteration

Superscalar Dynamic Issue

- Issues/complications?
Performance of Dynamic SS

<table>
<thead>
<tr>
<th>Iteration Instructions</th>
<th>Issues</th>
<th>Executes</th>
<th>Writes result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LD F0,0(R1)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>ADDD F4,F0,F2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>SD 0(R1),F4</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>SUBI R1,R1,#8</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>BNE Z R1,LOOP</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>LD F0,0(R1)</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>ADDD F4,F0,F2</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>SD 0(R1),F4</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>SUBI R1,R1,#8</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>BNE Z R1,LOOP</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

- 4 clocks per iteration
Branches, Decrements still take 1 clock cycle

Limits of Superscalar

- While Integer/FP split is simple for the HW, get CPI of 0.5 only for programs with:
  - Exactly 50% FP operations
  - No hazards
- If more instructions issue at same time, greater difficulty of decode and issue
  - Even 2-scalar => examine 2 opcodes, 6 register specifiers, & decide if 1 or 2 instructions can issue

Superscalar Key Points

- Only way to get CPI < 1 is multiple instruction issue
- SS requires duplicated hardware, more dependence checking
- Without duplication of functional units, will see limited improvement
- SS combined with dynamic scheduling can be powerful

VLIW Processors

- Very Long Instruction Word
- N-wide VLIW issues packets of N instructions simultaneously. Compiler guarantees independence of those N instructions.

```
add r5, r4, r1
addl f6, f4, f2
lw r2, 0(r7)
sub r8, r6, r1
beqz r9, label

sub r1, r5, r1
add f8, f0, f6
sw r5, 8(r7)
nop
beqz r2, l2
```
Loop Unrolling in VLIW

<table>
<thead>
<tr>
<th>Memory reference 1</th>
<th>Memory reference 2</th>
<th>FP operation 1</th>
<th>FP operation 2</th>
<th>Int. op/branch</th>
<th>Clock</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD F0,0(R1)</td>
<td>LD F6,-8(R1)</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>LD F10,-16(R1)</td>
<td>LD F14,-24(R1)</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>LD F18,-32(R1)</td>
<td>LD F22,-40(R1)</td>
<td>ADDD F4,F0,F2</td>
<td>ADDD F8,F6,F2</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>LD F26,-48(R1)</td>
<td>LD F30,-56(R1)</td>
<td>ADDD F12,F10,F2</td>
<td>ADDD F16,F14,F2</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>SD 0(R1),F4</td>
<td>SD -8(R1),F8</td>
<td>ADDD F20,F18,F2</td>
<td>ADDD F24,F22,F2</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>SD -16(R1),F12</td>
<td>SD -24(R1),F16</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>SD -32(R1),F20</td>
<td>SD -40(R1),F24</td>
<td>SUBI R1,R1,#48</td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>SD -40(R1),F28</td>
<td></td>
<td>BNEZ R1,LOOP</td>
<td></td>
<td></td>
<td>8</td>
</tr>
</tbody>
</table>

- Unrolled 7 times to avoid delays
- 7 results in 9 clocks, or 1.3 clocks per iteration
- Need more registers in VLIW

Limits to Multi-Issue Machines

- 1 branch in 5 instructions => how to keep a 5-way VLIW busy?
- Latencies of units => many operations must be scheduled
  - Need about Pipeline Depth x No. Functional Units of independent operations to keep machines busy
- Instruction mix may not match hardware mix
  - need duplicate FUs, increased flexibility
- Increase ports to Register File (VLIW example needs 6 read and 3 write for Int. Reg. & 6 read and 4 write for FP reg)
- Increase ports to memory
- Decoding SS and impact on clock rate

Superscalar vs. VLIW

- Superscalar Positives

- VLIW Positives