Chapter 3 – Instruction-Level Parallelism and its Exploitation (Part 1)

ILP vs. Parallel Computers
Dynamic Scheduling (Section 3.4, 3.5)
Dynamic Branch Prediction (Section 3.3, 3.9, and Appendix C)
Hardware Speculation and Precise Interrupts (Section 3.6)
Multiple Issue (Section 3.7)
Static Techniques (Section 3.2, Appendix H)
Limitations of ILP
Multithreading (Section 3.11)
Putting it Together (Mini-projects)
ILP vs. Parallel Computers

Instruction-Level Parallelism (ILP)

Instructions of single process (or thread) executed in parallel
Parallel components must appear to execute in sequential program order

Parallel Computers or Multiprocessors

Program divided into multiple processes (or threads)
Instructions of multiple threads executed in parallel
Typically also involves ILP within each thread
No a priori sequential order between parallel threads
Dynamic Scheduling - Basics

The situation:
DIV.D F0, F2, F4
ADD.D F10, F0, F8
MULT.D F6, F6, F14

The problem:
ADD stalls due to RAW hazard
MULT stalls because ADD stalls

Example

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIV.D</td>
<td>IF</td>
<td>ID</td>
<td>E/</td>
<td>E/</td>
<td>E/</td>
<td>E/</td>
<td>MEM</td>
</tr>
<tr>
<td>ADD.D</td>
<td>IF</td>
<td>ID</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>E+</td>
<td>E+</td>
</tr>
<tr>
<td>MULT.D</td>
<td>IF</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>ID</td>
<td>E*</td>
<td>why stall?</td>
</tr>
</tbody>
</table>

In-order execution limits performance
Dynamic Scheduling - Basics (Cont.)

Solutions

Static Scheduling
Dynamic Scheduling

Static Scheduling (Software)
  Compiler reorganizes instructions
  +
  +
  +
  (Will see more later)

Dynamic Scheduling (Hardware)
  Hardware reorganizes instructions
  +
  +
Solutions

Static Scheduling
Dynamic Scheduling

Static Scheduling (Software)
  Compiler reorganizes instructions
  + Simpler hardware
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  Hardware reorganizes instructions
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Dynamic Scheduling - Basics (Cont.)

Solutions

Static Scheduling
Dynamic Scheduling

Static Scheduling (Software)
  Compiler reorganizes instructions
  + Simpler hardware
  + Can use more powerful algorithms
  (Will see more later)

Dynamic Scheduling (Hardware)
  Hardware reorganizes instructions
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Dynamic Scheduling - Basics (Cont.)*

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Static Scheduling
Dynamic Scheduling

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Compiler reorganizes instructions
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Hardware reorganizes instructions
+ Handles dependences unknown at compile time
+
Dynamic Scheduling - Basics (Cont.)

Solutions

Static Scheduling
Dynamic Scheduling

Static Scheduling (Software)
  Compiler reorganizes instructions
  + Simpler hardware
  + Can use more powerful algorithms
  (Will see more later)

Dynamic Scheduling (Hardware)
  Hardware reorganizes instructions
  + Handles dependences unknown at compile time
  + Software is more portable
In-order execution - Static

- Instructions sent to execution units sequentially
- Stall instruction $i + 1$ if instruction $i$ stalls for lack of operands

Out-of-order execution - Dynamic

- Send independent instructions to execution units as soon as possible
Original simple pipeline
  ID – decode, check all hazards, read operands
  EX – execute

Dynamic pipeline
  Split ID (“issue to execution unit”) into two parts
    Check for structural hazards
    Wait for data dependences

New organization (conceptual):
  Issue – decode, check structural hazards, read ready operands
  ReadOps – wait until data hazards clear, read operands, begin execution

  Issue stays in-order; ReadOps/beginning of EX is out-of-order
**Dynamic Scheduling Basics (Cont.)**

Original simple pipeline
   - ID – decode, check all hazards, read operands
   - EX – execute

Dynamic pipeline
   - Split ID (“issue to execution unit”) into two parts
     - Check for structural hazards
     - Wait for data dependences

New organization (conceptual):
   - Issue – decode, check structural hazards, read ready operands
   - ReadOps – wait until data hazards clear, read operands, begin execution

Dispatch

Issue stays in-order; ReadOps/beginning of EX is out-of-order
Dynamic scheduling can create WAW, WAR hazards, and imprecise exceptions

**WAW hazards with dynamic scheduling**

```
DIV.D F0, F2, F4
ADD.D F10, F0, F8
MUL.D F10, F8, F14
```

**WAR hazards with dynamic scheduling**

```
DIV.D F0, F2, F4
ADD.D F10, F0, F8
MUL.D F8, F8, F14
```

Can always stall,

but more aggressive solution with *register renaming*
Register Renaming - Tomasulo’s Algorithm

Registers are *Names* for data values

Think of register specifiers as *tags*

NOT storage locations

*Tomasulo's algorithm exploited above in IBM 360/91*

WAW hazards:

\[
\begin{align*}
\text{DIV.D} & \quad F0, \quad F2, \quad F4 \\
\text{ADD.D} & \quad F10, \quad F0, \quad F8 \\
\text{MUL.D} & \quad F10, \quad F8, \quad F14
\end{align*}
\]

WAR hazards:

\[
\begin{align*}
\text{DIV.D} & \quad F0, \quad F2, \quad F4 \\
\text{ADD.D} & \quad F10, \quad F0, \quad F8 \\
\text{MUL.D} & \quad F8, \quad F8, \quad F14
\end{align*}
\]
Some History - IBM 360/91

Fast 360 for scientific code

  Completed in 1967

  Predates cache memories

Pipelined, rather than multiple, functional units (FU)

  We will assume multiple functional units

360 had register memory instructions, we don’t
Register Renaming - Tomasulo’s Algorithm

Tomasulo’s algm uses reservation stations for register renaming

Instruction is “issued” to a reservation station

A pending operand is designated via a tag

Tag = reservation station that will provide the operand

Reservation station with pending instruction fetches and buffers the operand when it becomes available

All FUs place output on the common data bus (CDB) with tag

Waiting reservation station gets the data from the CDB (register bypass)
Tomasulo’s Algorithm - Implementation

Extend simple pipeline as example for Tomasulo's algorithm

Assume multiple FUs
Figure 3.10 The basic structure of a RISC-V floating-point unit using Tomasulo’s algorithm. Instructions are sent from the instruction unit into the instruction queue from which they are issued in first-in, first-out (FIFO) order. The reservation stations include the operation and the actual operands, as well as information used for detecting and resolving hazards. Load buffers have three functions: (1) hold the components of the effective address until it is computed, (2) track outstanding loads that are waiting on the memory, and (3) hold the results of completed loads that are waiting for the CDB. Similarly, store buffers have three functions: (1) hold the components of the effective address until it is computed, (2) hold the destination memory addresses of outstanding stores that are waiting for the data value to store, and (3) hold the address and value to store until the memory unit is available. All results from either the FP units or the load unit are put on the CDB, which goes to the FP register file as well as to the reservation stations and store buffers. The FP adders implement addition and subtraction, and the FP multipliers do multiplication and division.
**Our Tomasulo Pipeline**

3-stage Execution (ignore IF and MEM)

**Issue**
- Get instruction from queue
- ALU Op: Check for available reservation station
- Load/Store: Check for available load/store buffer
- If not, stall due to structural hazard

**Execute**
- If operands available, execute operation
- If not, monitor CDB for operand

**Write**
- If CDB available, write it on CDB
- If not, stall
Reservation Stations

Handle distributed hazard detection and instruction control

Everything, except store buffers, has a *tag*

- 4-bit tag specifies reservation station or load buffer
- Specifies which FU will produce result

Register specifier is used to assign tags

THEN IT'S DISCARDED!

Register specifiers are ONLY used in ISSUE
Our Tomasulo Pipeline, cont

Reservation Stations
- **Op**: Opcode
- $Q_j, Q_k$: Tag Fields
- $V_j, V_k$: Operand values
- **Busy**: Currently in use

Register File and Store Buffer
- $Q_i$: Tag Field
- **Busy**: Currently in use

Load and Store Buffers
- **Busy**: Currently in use
- **A**: Address

Latencies: FP+ = 2, FP* = 10, FP/ = 40, Load/int = 1
**Tomasulo Example**

Example code

```plaintext
L.D   F6,34(R2)
L.D   F2,45(R3)
MULT.D F0,F2,F4
SUB.D  F8,F6,F2
DIV.D  F10,F0,F6
ADD.D  F10,F8,F2
ADD.D  F6,F0,F2
```
# Tomasulo Example

### Instruction Status (for illustration only)

<table>
<thead>
<tr>
<th>Instruction</th>
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</tr>
</thead>
<tbody>
<tr>
<td>L.D</td>
<td>F6, 34(R2)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>L.D</td>
<td>F2, 45(R3)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>MULT.D</td>
<td>F0, F2, F4</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>SUB.D</td>
<td>F8, F6, F2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIV.D</td>
<td>F10, F0, F6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD.D</td>
<td>F10, F8, F2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD.D</td>
<td>F6, F0, F2</td>
<td></td>
<td></td>
</tr>
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Latencies:
- FP+ = 2,
- FP* = 10,
- FP/ = 40,
- Load/int = 1

### FU

<table>
<thead>
<tr>
<th>FU</th>
<th>Name</th>
<th>Busy</th>
<th>Op</th>
<th>Vj</th>
<th>Vj</th>
<th>Qj</th>
<th>Qj</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Add1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Add2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Add3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Mult1</td>
<td>x</td>
<td>*</td>
<td></td>
<td>&lt;F4&gt;</td>
<td>L2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Mult2</td>
<td></td>
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</table>

### Register Result Status

<table>
<thead>
<tr>
<th>Qi</th>
<th>Busy</th>
<th>*1</th>
<th>L2</th>
<th>L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>F2</td>
<td>F4</td>
<td>F6</td>
<td>F8</td>
</tr>
</tbody>
</table>

Busy: x
## Tomasulo Example

### Instruction Status (for illustration only)

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<th>Write</th>
</tr>
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<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>L.D F2, 45(R3)</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>MULT.D F0, F2, F4</td>
<td>3</td>
<td>5-14</td>
<td></td>
</tr>
<tr>
<td>SUB.D F8, F6, F2</td>
<td>4</td>
<td>5-6</td>
<td></td>
</tr>
<tr>
<td>DIV.D F10,F0, F6</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ADD.D F10,F8, F2</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD.D F6, F0, F2</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Latencies:
- FP+ = 2
- FP* = 10
- FP/ = 40
- Load/int = 1

### FU Name Busy Op Vj Vk Qj Qk

<table>
<thead>
<tr>
<th>FU</th>
<th>Name</th>
<th>Busy</th>
<th>Op</th>
<th>Vj</th>
<th>Vk</th>
<th>Qj</th>
<th>Qk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Add1</td>
<td>x</td>
<td>-</td>
<td>&lt;F6&gt;</td>
<td>&lt;L2&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Add2</td>
<td>x</td>
<td>+</td>
<td>&lt;F2&gt;</td>
<td></td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Add3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Mult1</td>
<td>x</td>
<td>*</td>
<td>&lt;L2&gt;</td>
<td>&lt;F4&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Mult2</td>
<td>x</td>
<td>/</td>
<td></td>
<td>&lt;F6&gt;</td>
<td>*1</td>
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</tr>
</tbody>
</table>

### Register Result Status

<table>
<thead>
<tr>
<th>Register</th>
<th>Qi</th>
<th>Busy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*1</td>
<td>x</td>
</tr>
<tr>
<td>F0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F8</td>
<td></td>
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</tr>
<tr>
<td>F10</td>
<td></td>
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</tr>
<tr>
<td>F12</td>
<td></td>
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<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F30</td>
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</tbody>
</table>

Qi: *1
Busy: x
# Tomasulo Example

## Instruction Status (for illustration only)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Issue</th>
<th>Execute</th>
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</tr>
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<tbody>
<tr>
<td>L.D F6, 34(R2)</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>L.D F2, 45(R3)</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>MULT.D F0, F2, F4</td>
<td>3</td>
<td>5-14</td>
<td></td>
</tr>
<tr>
<td>SUB.D F8, F6, F2</td>
<td>4</td>
<td>5-6</td>
<td>7</td>
</tr>
<tr>
<td>DIV.D F10,F0, F6</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD.D F10,F8, F2</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD.D F6, F0, F2</td>
<td>7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Latencies:
- FP+ = 2,
- FP* = 10,
- FP/ = 40,
- Load/int = 1

## FU Name Busy Op Vj Vk Qj Qk

<table>
<thead>
<tr>
<th>FU</th>
<th>Name</th>
<th>Busy</th>
<th>Op</th>
<th>Vj</th>
<th>Vk</th>
<th>Qj</th>
<th>Qk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>-</td>
<td>&lt;F6&gt;</td>
<td>&lt;L2&gt;</td>
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<td></td>
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<tr>
<td>2</td>
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<td>x</td>
<td>+</td>
<td>&lt;+1&gt;</td>
<td>&lt;F2&gt;</td>
<td>+1</td>
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<tr>
<td>3</td>
<td>Add3</td>
<td>x</td>
<td>+</td>
<td>&lt;F2&gt;</td>
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<td>+1</td>
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<tr>
<td>4</td>
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<td>x</td>
<td>*</td>
<td>&lt;L2&gt;</td>
<td>&lt;F4&gt;</td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>Mult2</td>
<td>x</td>
<td>/</td>
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<td>&lt;F6&gt;</td>
<td></td>
<td>*1</td>
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## Register Result Status

<table>
<thead>
<tr>
<th>Qi</th>
<th>*1</th>
<th>+3</th>
<th>+1</th>
<th>*2→+2</th>
</tr>
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<tbody>
<tr>
<td>Busy</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<table>
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<tr>
<th>F0</th>
<th>F2</th>
<th>F4</th>
<th>F6</th>
<th>F8</th>
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<th>F30</th>
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<tbody>
<tr>
<td>Qi</td>
<td>*1</td>
<td>+3</td>
<td>+1</td>
<td>*2→+2</td>
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<td>4</td>
</tr>
<tr>
<td>MULT.D F0, F2, F4</td>
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<td>5-14</td>
<td>15</td>
</tr>
<tr>
<td>SUB.D F8, F6, F2</td>
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<td>5-6</td>
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</tr>
<tr>
<td>DIV.D F10,F0, F6</td>
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<td>ADD.D F6, F0, F2</td>
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Latencies:  
FP+ = 2,  
FP* = 10,  
FP/ = 40,  
Load/int = 1

**FU Name**

<table>
<thead>
<tr>
<th>FU</th>
<th>Name</th>
<th>Busy</th>
<th>Op</th>
<th>Vj</th>
<th>Vk</th>
<th>Qj</th>
<th>Qk</th>
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<tr>
<td>1</td>
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</table>

**Register Result Status**

<table>
<thead>
<tr>
<th>Qi</th>
<th>Busy</th>
</tr>
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<tr>
<td></td>
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</table>
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<td>L.D</td>
<td>F2, 45(R3)</td>
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<td>MULT.D</td>
<td>F0, F2, F4</td>
<td>3</td>
<td>5-14</td>
</tr>
<tr>
<td>SUB.D</td>
<td>F8, F6, F2</td>
<td>4</td>
<td>5-6</td>
</tr>
<tr>
<td>DIV.D</td>
<td>F10, F0, F6</td>
<td>5</td>
<td>16-55</td>
</tr>
<tr>
<td>xxx</td>
<td>F100, F10, F200</td>
<td>5.5</td>
<td>57</td>
</tr>
<tr>
<td>ADD.D</td>
<td>F10, F8, F2</td>
<td>6</td>
<td>8-9</td>
</tr>
<tr>
<td>ADD.D</td>
<td>F6, F0, F2</td>
<td>7</td>
<td>16-17</td>
</tr>
</tbody>
</table>

### FU Name and Busy Status

<table>
<thead>
<tr>
<th>FU</th>
<th>Name</th>
<th>Busy</th>
<th>Op</th>
<th>Vj</th>
<th>Vk</th>
<th>Qj</th>
<th>Qk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Add1</td>
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</tr>
<tr>
<td>2</td>
<td>Add2</td>
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</tr>
<tr>
<td>3</td>
<td>Add3</td>
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</tr>
<tr>
<td>4</td>
<td>Mult1</td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>Mult2</td>
<td></td>
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</tbody>
</table>

### Register Result Status

<table>
<thead>
<tr>
<th>F0</th>
<th>F2</th>
<th>F4</th>
<th>F6</th>
<th>F8</th>
<th>F10</th>
<th>F12</th>
<th>...</th>
<th>F30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qi</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Busy</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tomasulo, cont.

Out-of-order loads and stores?

CDB is a bottleneck
   Could duplicate
      Increases the required hardware

Complex implementation
Out-of-order loads and stores?

What about WAW, RAW, and WAR hazards?

- Compare all load addresses w/ address in store buffers
- Compare all store addresses w/ address in load/store buffers
- Stall if they match

CDB is a bottleneck

- Could duplicate
  - Increases the required hardware

Complex implementation
Advantages

Distribution of hazard detection
Elimination of WAR and WAW stalls

Common Data Bus
+ Broadcasts results to multiple instructions, bypasses registers
- Central bottleneck
  Could duplicate (increases required hardware)

Register Renaming
+ Eliminates WAR and WAW Hazards
+ Allows dynamic loop unrolling
  Especially important with only 4 registers
- Requires many associative lookups
Loops with Tomasulo’s Algorithm

Consider the following example:

FORTRAN:
DO I = 1, N
    C[I] = A[I] + s * B[I]

ASSEMBLY:
L.D F0, A(R1)
L.D F2, B(R1)
MUL.D F2, F2, F4 /* s in F4 */
ADD.D F2, F2, F0
S.D C(R1), F2
Branch code

What would Tomasulo’s algorithm do?