

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)

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

	1	2	3	4	5	6	7	8
DIV.D	IF	ID	E/	E/	E/	E/	MEM	WB
ADD.D		IF	ID	**	**	**	E+	E+
MULT.D			IF	**	**	**	ID	E* why stall?

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

+

+

Dynamic Scheduling - Basics (Cont.)

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

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
Issue stays in-order; ReadOps/beginning of EX is out-of-order

Dynamic Scheduling Basics (Cont.)

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:

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

WAR hazards:

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

Some History - IBM 360/91

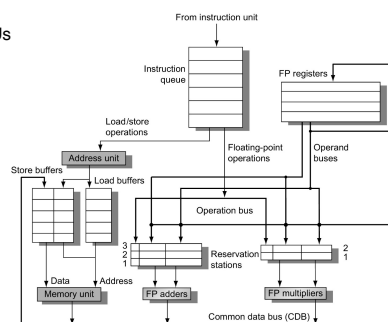
Fast 360 for scientific code
 Completed in 1967
 Predates cache memories
 Pipelined, rather than multiple, functional units (FU)
 We will assume multiple functional units
 360 had register memory instructions, we don't

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



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

Our Tomasulo Pipeline, cont

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

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 F6, F8, F2

Tomasulo Example

Instruction Status (For illustration ONLY)			
Instruction	Issue	Execute	Write
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	F6,F8,F2		

FU	Name	Busy	Op	Vj	Vk	Qj	Qk
1	Add1						
2	Add2						
3	Add3						
4	Mult1						
5	Mult2						

Register Result Status									
	F0	F2	F4	F6	F8	F10	F12	...	F30
Ql									
Busy									

Tomasulo Example

Instruction Status (For illustration ONLY)			
Instruction	Issue	Execute	Write
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	F6,F8,F2		

FU	Name	Busy	Op	Vj	Vk	Qj	Qk
1	Add1						
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3	Add3						
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5	Mult2						

Register Result Status									
	F0	F2	F4	F6	F8	F10	F12	...	F30
Q1									
Busy									

Tomasulo Example

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FU	Name	Busy	Op	Vj	Vk	Qj	Qk
1	Add1						
2	Add2						
3	Add3						
4	Mult1						
5	Mult2						

Register Result Status									
	F0	F2	F4	F6	F8	F10	F12	...	F30
Q1									
Busy									

Tomasulo, cont.

Out-of-order loads and stores?

CDB is a bottleneck
 Could duplicate
 Increases the required hardware
 Complex implementation

Tomasulo, cont.

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?