332
Advanced Computer Architecture
Chapter 3

Instruction Level Parallelism and Dynamic Execution

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These lecture notes are partly based on the course text, Hennessy and Patterson's *Computer Architecture, a quantitative approach (3rd 4th eds),* and on the lecture slides of David Patterson and John Kubiatowicz's Berkeley course *(CS252)*

Recall from Pipelining Review

- Pipeline CPI = Ideal pipeline CPI + Structural Stalls + Data Hazard Stalls + Control Stalls
  - Ideal pipeline CPI: measure of the maximum performance attainable by the implementation
  - Structural hazards: HW cannot support this combination of instructions
  - Data hazards: Instruction depends on result of prior instruction still in the pipeline
  - Control hazards: Caused by delay between the fetching of instructions and decisions about changes in control flow (branches and jumps)

Instruction-Level Parallelism (ILP)

- Basic Block (BB) ILP is quite small
  - BB: a straight-line code sequence with no branches in except to the entry and no branches out except at the exit
  - average dynamic branch frequency 15% to 25% => 4 to 7 instructions execute between a pair of branches
  - Plus instructions in BB likely to depend on each other
- To obtain substantial performance enhancements, we must exploit ILP across multiple basic blocks
- Simplest: loop-level parallelism to exploit parallelism among iterations of a loop
  - Vector is one way
  - If not vector, then either dynamic via branch prediction or static via loop unrolling by compiler

Data Dependence and Hazards

- Instr$_J$ is data dependent on Instr$_I$
  Instr$_J$ tries to read operand before Instr$_I$ writes it

```
I: add r1,r2,r3
J: sub r4,r1,r3
```

- or Instr$_J$ is data dependent on Instr$_K$ which is dependent on Instr$_I$
- Caused by a "True Dependence" (compiler term)
- If true dependence caused a hazard in the pipeline, called a Read After Write (RAW) hazard

Data Dependence and Hazards

- Dependences are a property of programs
- Presence of dependence indicates potential for a hazard, but actual hazard and length of any stall is a property of the pipeline
- Importance of the data dependencies

1) indicates the possibility of a hazard

2) determines order in which results must be calculated

3) sets an upper bound on how much parallelism can possibly be exploited

- Today looking at HW schemes to avoid hazard

Name Dependence #1: Anti-dependence

- Name dependence: when 2 instructions use same register or memory location, called a name, but no flow of data between the instructions associated with that name
- There are two kinds:
- Name dependence #1: anti-dependence/WAR
  - Instr$_J$ writes operand *before* Instr$_I$ reads it

```
I: sub r4,r1,r3
J: add r1,r2,r3
K: mul r6,r1,r7
```

Called an "anti-dependence" by compiler writers.
This results from reuse of the name "r1"

  - If anti-dependence caused a hazard in the pipeline, called a Write After Read (WAR) hazard

Name Dependence #2: Output dependence

- Instr$_J$ writes operand *before* Instr$_I$ writes it.

```
I: sub r1,r4,r3
J: add r1,r2,r3
K: mul r6,r1,r7
```

- Called an "output dependence" by compiler writers
  This also results from the reuse of name "r1"
- If anti-dependence caused a hazard in the pipeline, called a Write After Write (WAW) hazard

ILP and Data Hazards

- HW/SW must preserve program order: order instructions would execute in if executed sequentially 1 at a time as determined by original source program
- HW/SW goal: exploit parallelism by preserving program order only where it affects the outcome of the program
- Instructions involved in a name dependence can execute simultaneously if name used in instructions is changed so instructions do not conflict
  - Register renaming resolves name dependence for regs
  - Either by compiler or by HW

Control Dependencies

- Every instruction is control dependent on some set of branches, and, in general, these control dependencies must be preserved to preserve program order

```
 if p1 {
  S1;
 };
 if p2 {
  S2;
 }
```

- S1 is control dependent on p1, and S2 is control dependent on p2 but not on p1.

Control Dependence Ignored

- Control dependence need not be preserved
  - willing to execute instructions that should not have been executed, thereby violating the control dependences, if can do so without affecting correctness of the program
- Instead, two properties critical to program correctness are **exception behavior** and **data flow**

Exception Behavior

- Preserving exception behavior => any changes in instruction execution order must not change how exceptions are raised in program (=> no new exceptions)
- Example:

```
    DADDU     R2,R3,R4
    BEQZ      R2,L1
    LW        R1,0(R2)
L1:
```

- Problem with moving LW before BEQZ?

Data Flow

- Data flow: actual flow of data values among instructions that produce results and those that consume them
  - branches make flow dynamic, determine which instruction is supplier of data
- Example:

```
DADDU    R1,R2,R3
BEQZ     R4,L
DSUBU    R1,R5,R6
L:  …
OR       R7,R1,R8
```

- OR depends on DADDU or DSUBU? Must preserve data flow on execution

Advantages of Dynamic Scheduling

- Handles cases when dependences unknown at compile time
  - (e.g., because they may involve a memory reference)
- It simplifies the compiler
- Allows code that compiled for one pipeline to run efficiently on a different pipeline
- Hardware speculation, a technique with significant performance advantages, that builds on dynamic scheduling

HW Schemes: Instruction Parallelism

- Key idea: Allow instructions behind stall to proceed

```
DIVD  F0,F2,F4
ADDD  F10,F0,F8
SUBD  F12,F8,F14
```

- Enables out-of-order execution and allows out-of-order completion
- We will distinguish when an instruction is issued, *begins execution* and when it *completes execution*; between these two times, the instruction is *in execution*
- In a dynamically scheduled pipeline, all instructions pass through issue stage in order (in-order issue)

Dynamic Scheduling Step 1

- Simple pipeline had 1 stage to check both structural and data hazards: Instruction Decode (ID), also called Instruction Issue
- Split the ID pipe stage of simple 5-stage pipeline into 2 stages:
- *Issue*—Decode instructions, check for structural hazards
- *Read operands*—Wait until no data hazards, then read operands

A Dynamic Algorithm: Tomasulo's Algorithm

- For IBM 360/91 (before caches!)
- Goal: High Performance without special compilers
- Small number of floating point registers (4 in 360) prevented interesting compiler scheduling of operations
  - This led Tomasulo to try to figure out how to get more effective registers — renaming in hardware!
- Why study a 1966 Computer?
- The descendents of this have flourished!
  - Alpha 21264, HP 8000, MIPS 10000/R12000, Pentium II/III/4, AMD K5,K6,Athlon, PowerPC 603/604/G3/G4/G5, …

IBM360/91

- CPU cycle time: 60 nanoseconds
- memory cycle time (to fetch and store eight bytes in parallel): 780ns
- Standard memory capacity: 2,097,152B interleaved 16 ways (magnetic cores)
- Up to 6,291,496 bytes of main storage
- Up to 16.6-million additions/second
- Ca.120K gates, ECL
- Solid Logic Technology (SLT), an IBM invention which encapsulated 5-6 transistors into a small module--a transition technology between discrete transistors and the IC
- About 12 were made

NASA Center for Computational Sciences

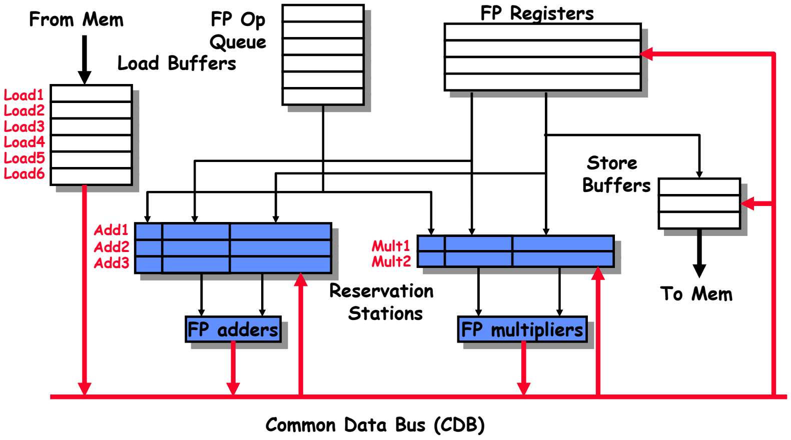
Source: http://www.columbia.edu/acis/history/36091.html

NASA's Space Flight Center in Greenbelt, Md, January 1968

Tomasulo Algorithm

- Control & buffers distributed with Function Units (FU)
  - FU buffers called "reservation stations"; have pending operands
- Registers in instructions replaced by values or pointers to reservation stations(RS); called register renaming ;
  - avoids WAR, WAW hazards
  - More reservation stations than registers, so can do optimizations compilers can't
- Results to FU from RS, not through registers, over Common Data Bus that broadcasts results to all FUs
- Load and Stores treated as FUs with RSs as well
- Integer instructions can go past branches, allowing FP ops beyond basic block in FP queue

Tomasulo Organization



Reservation Station Components

Op: Operation to perform in the unit (e.g., + or –)

Vj, Vk: Value of Source operands

- Store buffers has V field, result to be stored

Qj, Qk: Reservation stations producing source registers (value to be written)

- Note: Qj,Qk=0 => ready
- Store buffers only have Qi for RS producing result

Busy: Indicates reservation station or FU is busy

Register result status—Indicates which functional unit will write each register, if one exists. Blank when no pending instructions that will write that register.

Three Stages of Tomasulo Algorithm

1. Issue—get instruction from FP Op Queue
   If reservation station free (no structural hazard), control issues instr & sends operands (renames registers).
2. Execute—operate on operands (EX)
   When both operands ready then execute; if not ready, watch Common Data Bus for result
3. Write result—finish execution (WB)
   Write on Common Data Bus to all awaiting units; mark reservation station available

- Normal data bus: data + destination ("go to" bus)
- Common data bus: data + source ("come from" bus)
  - 64 bits of data + 4 bits of Functional Unit source address
  - Write if matches expected Functional Unit (produces result)
  - Does the broadcast
- Example speed:
  3 clocks for Fl .pt. +,-; 10 for * ; 40 clks for /

360/91 pipeline

- The IBM 360/91's pipeline:

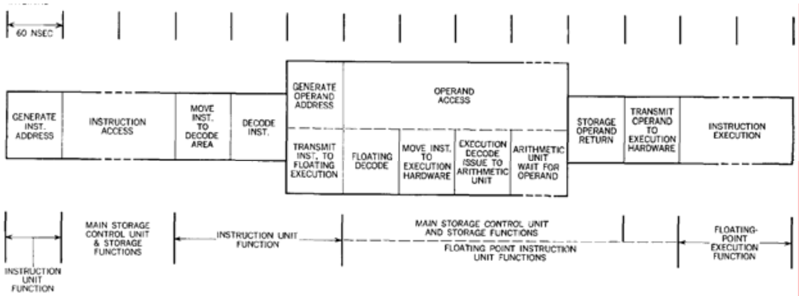

60 NSEC
GENERATE INST. ADDRESS
INSTRUCTION ACCESS
MOVE INST. TO DECODE AREA
DECODE INST.
GENERATE OPERAND ADDRESS
OPERAND ACCESS
TRANSMIT INST. TO FLOATING EXECUTION
FLOATING DECODE
MOVE INST. TO EXECUTION HARDWARE
EXECUTION DECODE ISSUE TO ARITHMETIC UNIT
ARITHMETIC UNIT WAIT FOR OPERAND
STORAGE OPERAND RETURN
TRANSMIT OPERAND TO EXECUTION HARDWARE
INSTRUCTION EXECUTION
INSTRUCTION UNIT FUNCTION
MAIN STORAGE CONTROL UNIT & STORAGE FUNCTIONS
INSTRUCTION UNIT FUNCTION
MAIN STORAGE CONTROL UNIT AND STORAGE FUNCTIONS
FLOATING POINT INSTRUCTION UNIT FUNCTIONS
FLOATING-POINT EXECUTION FUNCTION

Figure 3 CPU "assembly-line stations required to accommodate a typical floating-point storage-to-register instruction.

- 11-12 circuit levels per pipeline stage, of 5-6ns each
- CPU consists of three physical frames, each having dimensions 66" L X 15" D X 78" H

See: The IBM System/360 Model 91: Machine Philosophy and Instruction-Handling,by D. W. Anderson, F. J. Sparacio, R. M. Tomasulo. IBM J. R&D (1967), http://www.research.ibm.com/journal/rd/111/ibmrd1101C.pdf

Tomasulo Example

Instruction stream

Instruction status:

Instruction		j	k	Issue	Exec Comp	Write Result
LD	F6	34+	R2			
LD	F2	45+	R3			
MULTD	F0	F2	F4			
SUBD	F8	F6	F2			
DIVD	F10	F0	F6			
ADDD	F6	F8	F2			

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

3 Load/Buffers

Reservation Stations:

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS Qj	RS Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	No					
	Mult2	No					

FU count down

3 FP Adder R.S.
2 FP Mult R.S.

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
0	FU									

Clock cycle counter

Tomasulo Example Cycle 1

Instruction status:

Instruction		j	k	Issue	Exec Comp	Write Result
LD	F6	34+	R2	1		
LD	F2	45+	R3			
MULTD	F0	F2	F4			
SUBD	F8	F6	F2			
DIVD	F10	F0	F6			
ADDD	F6	F8	F2			

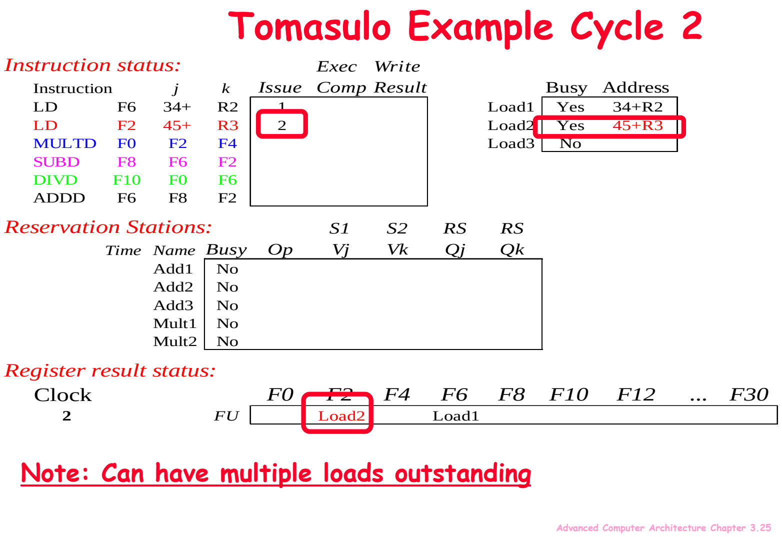
	Busy	Address
Load1	Yes	34+R2
Load2	No	
Load3	No	

Reservation Stations:

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS Qj	RS Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	No					
	Mult2	No					

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
1	FU				Load1					



Tomasulo Example Cycle 2

Instruction status:

Instruction		*j*	*k*	*Issue*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1		
LD	F2	45+	R3	2		
MULTD	F0	F2	F4			
SUBD	F8	F6	F2			
DIVD	F10	F0	F6			
ADDD	F6	F8	F2			

	Busy	Address
Load1	Yes	34+R2
Load2	Yes	45+R3
Load3	No	

Reservation Stations:

				S1	*S2*	*RS*	*RS*
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	No					
	Mult2	No					

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
2	*FU*		Load2		Load1					

Note: Can have multiple loads outstanding

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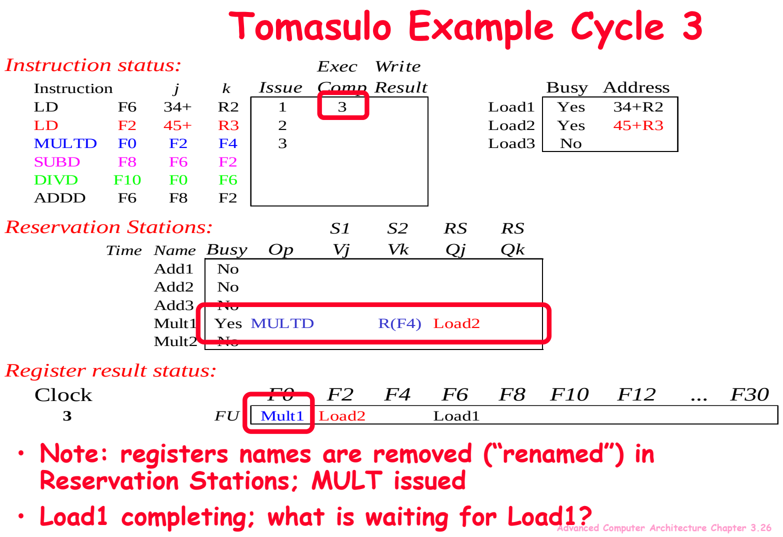

Tomasulo Example Cycle 3

Instruction status:

Instruction		*j*	*k*	*Issue*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	3	
LD	F2	45+	R3	2		
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2			
DIVD	F10	F0	F6			
ADDD	F6	F8	F2			

	Busy	Address
Load1	Yes	34+R2
Load2	Yes	45+R3
Load3	No	

Reservation Stations:

				S1	*S2*	*RS*	*RS*
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	MULTD		R(F4)	Load2	
	Mult2	No					

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
3	*FU*	Mult1	Load2		Load1					

- Note: registers names are removed ("renamed") in Reservation Stations; MULT issued
- Load1 completing; what is waiting for Load1?

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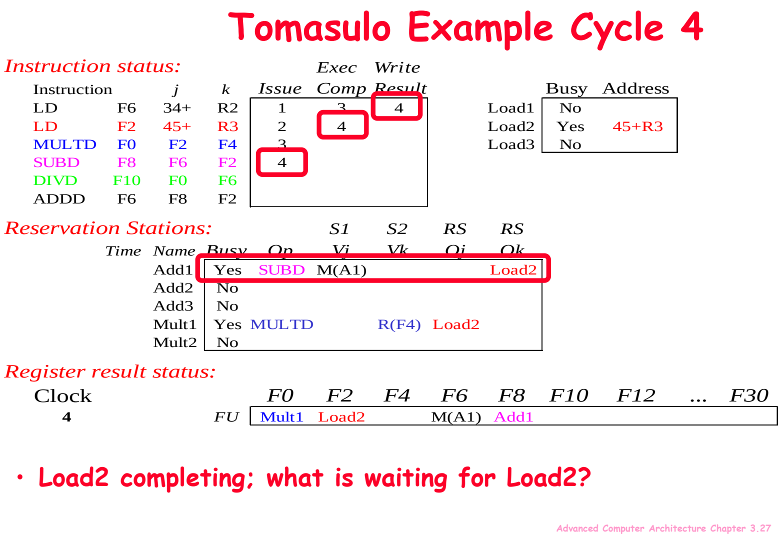

Tomasulo Example Cycle 4

Instruction status:

Instruction		*j*	*k*	*Issue*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4		
DIVD	F10	F0	F6			
ADDD	F6	F8	F2			

	Busy	Address
Load1	No	
Load2	Yes	45+R3
Load3	No	

Reservation Stations:

				S1	*S2*	*RS*	*RS*
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	Yes	SUBD	M(A1)			Load2
	Add2	No					
	Add3	No					
	Mult1	Yes	MULTD		R(F4)	Load2	
	Mult2	No					

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
4	*FU*	Mult1	Load2		M(A1)	Add1				

- Load2 completing; what is waiting for Load2?

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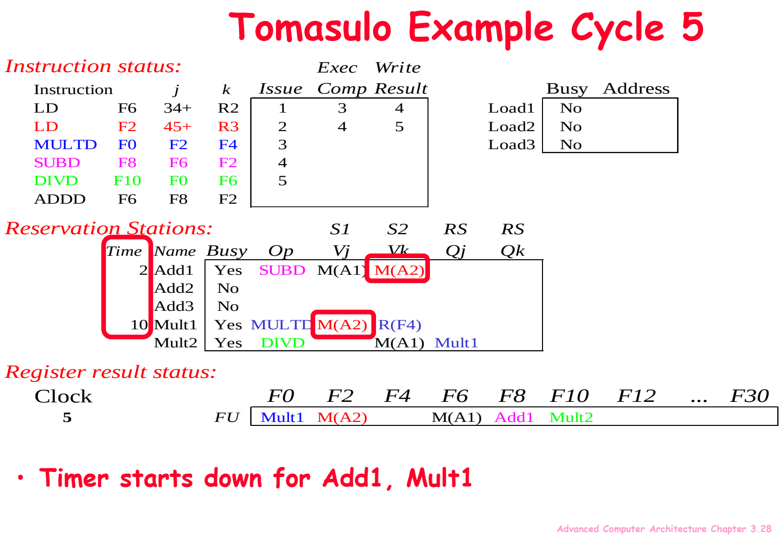

Tomasulo Example Cycle 5

Instruction status:

Instruction		*j*	*k*	*Issue*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4		
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2			

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

				S1	*S2*	*RS*	*RS*
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
2	Add1	Yes	SUBD	M(A1)	M(A2)		
	Add2	No					
	Add3	No					
10	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
5	*FU*	Mult1	M(A2)		M(A1)	Add1	Mult2			

- Timer starts down for Add1, Mult1

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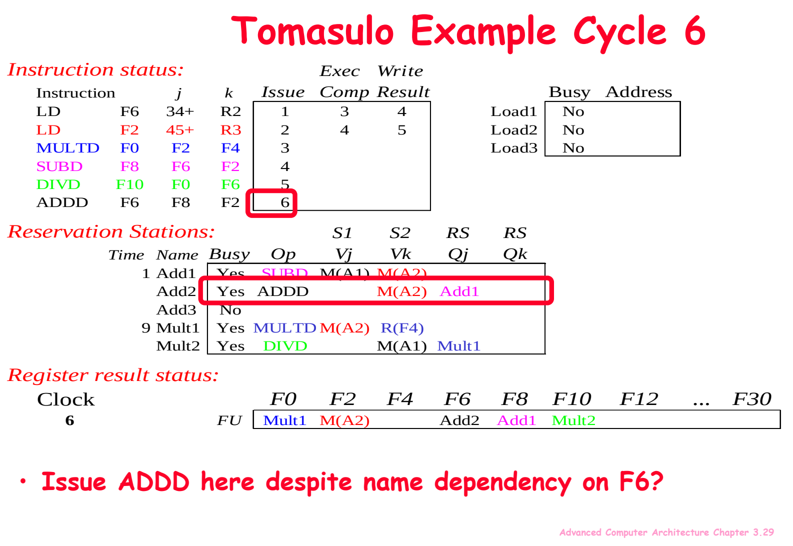


Tomasulo Example Cycle 6

Instruction status:

Instruction		*j*	*k*	*Issue*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4		
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6		

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

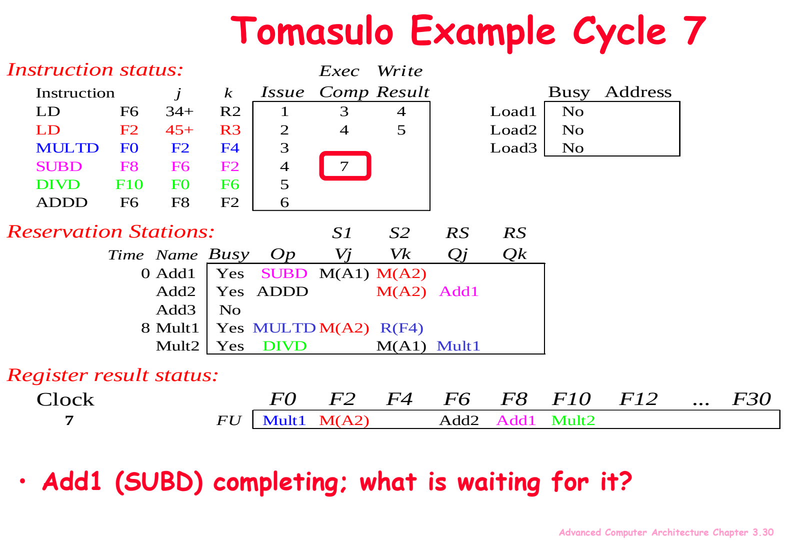
Reservation Stations:

Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS Qj*	*RS Qk*
1	Add1	Yes	SUBD	M(A1)	M(A2)		
	Add2	Yes	ADDD		M(A2)	Add1	
	Add3	No					
9	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
6	*FU*	Mult1	M(A2)		Add2	Add1	Mult2			

- **Issue ADDD here despite name dependency on F6?**



Tomasulo Example Cycle 7

Instruction status:

Instruction		*j*	*k*	*Issue*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4	7	
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6		

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

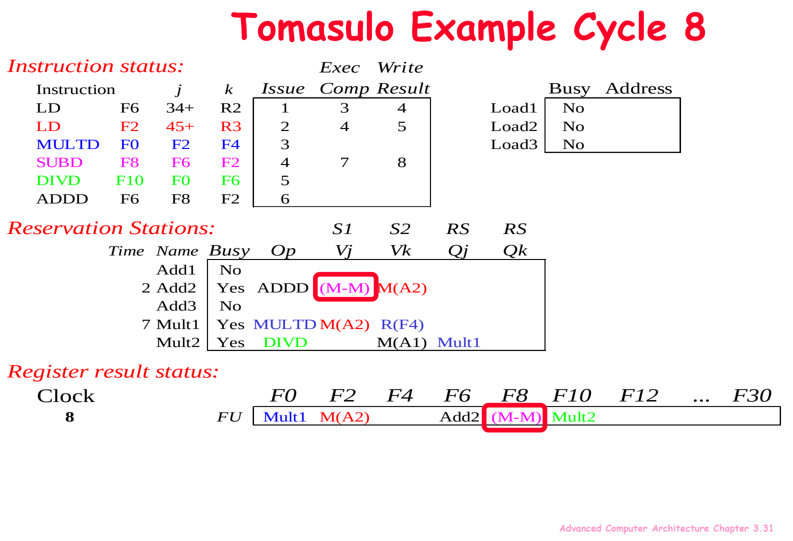
Reservation Stations:

Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS Qj*	*RS Qk*
0	Add1	Yes	SUBD	M(A1)	M(A2)		
	Add2	Yes	ADDD		M(A2)	Add1	
	Add3	No					
8	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
7	*FU*	Mult1	M(A2)		Add2	Add1	Mult2			

- **Add1 (SUBD) completing; what is waiting for it?**



Tomasulo Example Cycle 8

Instruction status:

Instruction		*j*	*k*	*Issue*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6		

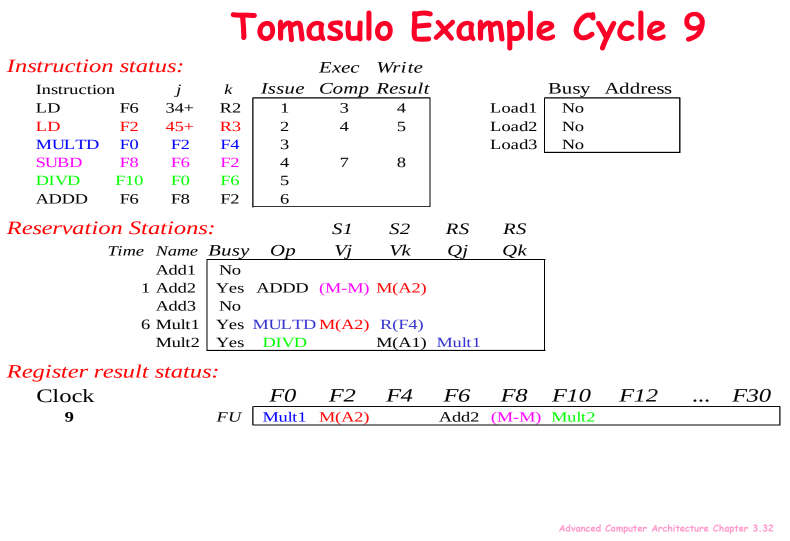
	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS Qj*	*RS Qk*
	Add1	No					
2	Add2	Yes	ADDD	(M-M)	M(A2)		
	Add3	No					
7	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
8	*FU*	Mult1	M(A2)		Add2	(M-M)	Mult2			



Tomasulo Example Cycle 9

Instruction status:

Instruction		*j*	*k*	*Issue*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6		

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS Qj*	*RS Qk*
	Add1	No					
1	Add2	Yes	ADDD	(M-M)	M(A2)		
	Add3	No					
6	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
9	*FU*	Mult1	M(A2)		Add2	(M-M)	Mult2			

Tomasulo Example Cycle 10

Instruction status:

					Exec	Write
Instruction		j	k	Issue	Comp	Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6	10	

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

				S1	S2	RS	RS
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
0	Add2	Yes	ADDD	(M-M)	M(A2)		
	Add3	No					
5	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
10	*FU*	Mult1	M(A2)		Add2	(M-M)	Mult2			

- **Add2 (ADDD) completing; what is waiting for it?**

Tomasulo Example Cycle 11

Instruction status:

					Exec	Write
Instruction		j	k	Issue	Comp	Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6	10	11

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

				S1	S2	RS	RS
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
4	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
11	*FU*	Mult1	M(A2)		(M-M+M	(M-M)	Mult2			

- **Write result of ADDD here?**
- **All quick instructions complete in this cycle!**

Tomasulo Example Cycle 12

Instruction status:

					Exec	Write
Instruction		j	k	Issue	Comp	Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6	10	11

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

				S1	S2	RS	RS
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
3	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
12	*FU*	Mult1	M(A2)		(M-M+N	(M-M)	Mult2			

Tomasulo Example Cycle 13

Instruction status:

					Exec	Write
Instruction		j	k	Issue	Comp	Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6	10	11

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

				S1	S2	RS	RS
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
2	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
13	*FU*	Mult1	M(A2)		(M-M+N	(M-M)	Mult2			

Tomasulo Example Cycle 14

Instruction status:

Instruction		j	k	Issue	Exec Comp	Write Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3		
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6	10	11

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

				S1	S2	RS	RS
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
1	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
14	FU	Mult1	M(A2)		(M-M+M	(M-M)	Mult2			

Tomasulo Example Cycle 15

Instruction status:

Instruction		j	k	Issue	Exec Comp	Write Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3	15	
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6	10	11

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

				S1	S2	RS	RS
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
0	Mult1	Yes	MULTD	M(A2)	R(F4)		
	Mult2	Yes	DIVD		M(A1)	Mult1	

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
15	FU	Mult1	M(A2)		(M-M+M	(M-M)	Mult2			

- **Mult1 (MULTD) completing; what is waiting for it?**

Tomasulo Example Cycle 16

Instruction status:

Instruction		j	k	Issue	Exec Comp	Write Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3	15	16
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6	10	11

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

				S1	S2	RS	RS
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	No					
40	Mult2	Yes	DIVD	M*F4	M(A1)		

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
16	FU	M*F4	M(A2)		(M-M+M	(M-M)	Mult2			

- **Just waiting for Mult2 (DIVD) to complete**

Skip a few cycles: Cycle 55

Instruction status:

Instruction		j	k	Issue	Exec Comp	Write Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3	15	16
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5		
ADDD	F6	F8	F2	6	10	11

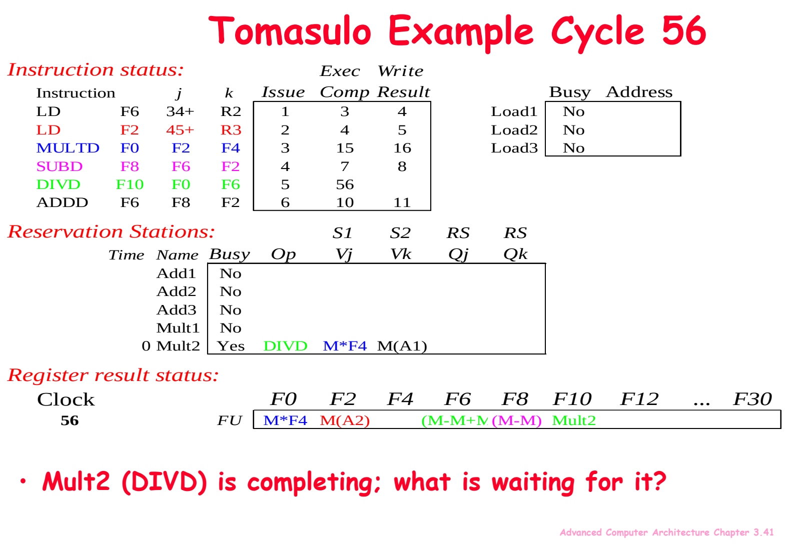
	Busy	Address
Load1	No	
Load2	No	
Load3	No	

Reservation Stations:

				S1	S2	RS	RS
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	No					
1	Mult2	Yes	DIVD	M*F4	M(A1)		

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
55	FU	M*F4	M(A2)		(M-M+M	(M-M)	Mult2			



Tomasulo Example Cycle 56

Instruction status:

Instruction		j	k	Issue	Exec Comp	Write Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3	15	16
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5	56	
ADDD	F6	F8	F2	6	10	11

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

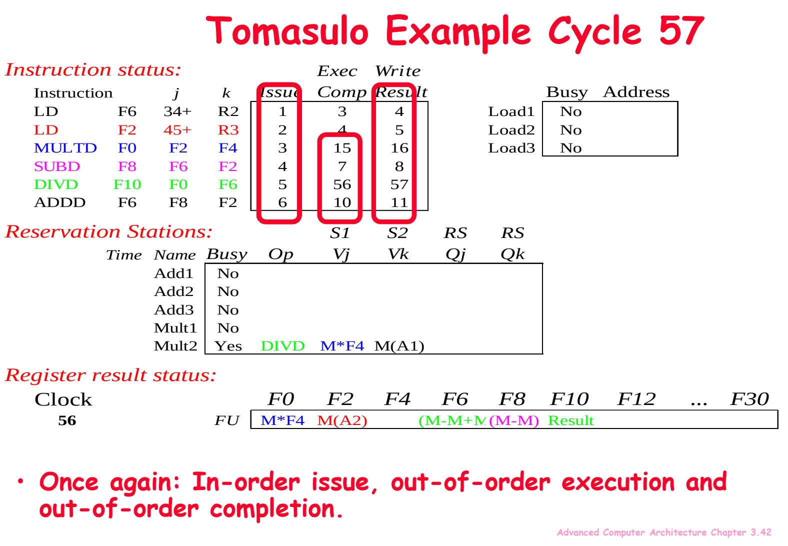
Reservation Stations:

				S1	S2	RS	RS
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	No					
0	Mult2	Yes	DIVD	M*F4	M(A1)		

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
56	FU	M*F4	M(A2)		(M-M+M	(M-M)	Mult2			

- Mult2 (DIVD) is completing; what is waiting for it?



Tomasulo Example Cycle 57

Instruction status:

Instruction		j	k	Issue	Exec Comp	Write Result
LD	F6	34+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MULTD	F0	F2	F4	3	15	16
SUBD	F8	F6	F2	4	7	8
DIVD	F10	F0	F6	5	56	57
ADDD	F6	F8	F2	6	10	11

	Busy	Address
Load1	No	
Load2	No	
Load3	No	

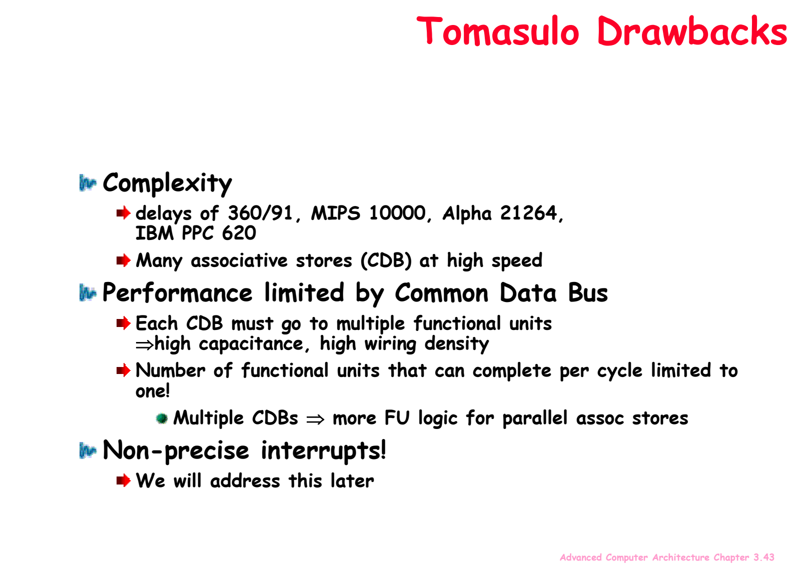
Reservation Stations:

				S1	S2	RS	RS
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	No					
	Mult2	Yes	DIVD	M*F4	M(A1)		

Register result status:

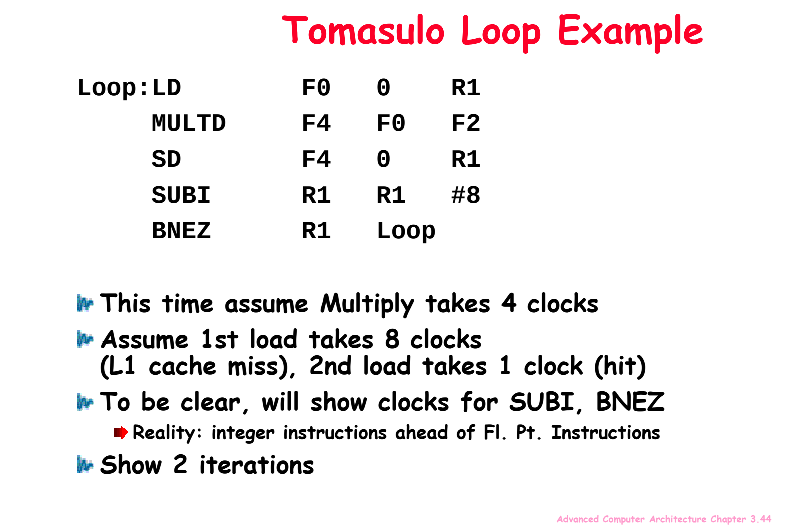
Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
56	FU	M*F4	M(A2)		(M-M+M	(M-M)	Result			

- Once again: In-order issue, out-of-order execution and out-of-order completion.



Tomasulo Drawbacks

- Complexity
  - delays of 360/91, MIPS 10000, Alpha 21264, IBM PPC 620
  - Many associative stores (CDB) at high speed
- Performance limited by Common Data Bus
  - Each CDB must go to multiple functional units ⇒high capacitance, high wiring density
  - Number of functional units that can complete per cycle limited to one!
    - Multiple CDBs ⇒ more FU logic for parallel assoc stores
- Non-precise interrupts!
  - We will address this later



Tomasulo Loop Example

```
Loop:LD      F0   0    R1
     MULTD   F4   F0   F2
     SD      F4   0    R1
     SUBI    R1   R1   #8
     BNEZ    R1   Loop
```

- This time assume Multiply takes 4 clocks
- Assume 1st load takes 8 clocks (L1 cache miss), 2nd load takes 1 clock (hit)
- To be clear, will show clocks for SUBI, BNEZ
  - Reality: integer instructions ahead of Fl. Pt. Instructions
- Show 2 iterations

Loop Example

Instruction status:

ITER	Instruction	j	k	Issue	Exec Comp	Write Result
1	LD	F0	0	R1		
1	MULTD	F4	F0	F2		
1	SD	F4	0	R1		
2	LD	F0	0	R1		
2	MULTD	F4	F0	F2		
2	SD	F4	0	R1		

Iter-ation Count

	Busy	Addr	Fu
Load1	No		
Load2	No		
Load3	No		
Store1	No		
Store2	No		
Store3	No		

Added Store Buffers

Reservation Stations:

				S1	S2	RS	
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	No					
	Mult2	No					

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Instruction Loop

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
0	80	*Fu*									

Value of Register used for address, iteration control

Loop Example Cycle 1

Instruction status:

ITER	Instruction	j	k	Issue	Exec Comp	Write Result
1	LD	F0	0	R1	1	

	Busy	Addr	Fu
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	No		
Store2	No		
Store3	No		

Reservation Stations:

				S1	S2	RS	
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	No					
	Mult2	No					

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
1	80	*Fu*	Load1								

Loop Example Cycle 2

Instruction status:

ITER	Instruction	j	k	Issue	Exec Comp	Write Result
1	LD	F0	0	R1	1	
1	MULTD	F4	F0	F2	2	

	Busy	Addr	Fu
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	No		
Store2	No		
Store3	No		

Reservation Stations:

				S1	S2	RS	
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	Multd		R(F2)	Load1	
	Mult2	No					

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
2	80	*Fu*	Load1		Mult1						

Loop Example Cycle 3

Instruction status:

ITER	Instruction	j	k	Issue	Exec Comp	Write Result
1	LD	F0	0	R1	1	
1	MULTD	F4	F0	F2	2	
1	SD	F4	0	R1	3	

	Busy	Addr	Fu
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations:

				S1	S2	RS	
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	Multd		R(F2)	Load1	
	Mult2	No					

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
3	80	*Fu*	Load1		Mult1						

- **Implicit renaming sets up data flow graph**

Loop Example Cycle 4

Instruction status:

ITER	Instruction		j	k	Issue	Exec Comp	Write Result
1	LD	F0	0	R1	1		
1	MULTD	F4	F0	F2	2		
1	SD	F4	0	R1	3		

	Busy	Addr	Fu
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations:

				S1	S2	RS	
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	Multd		R(F2)	Load1	
	Mult2	No					

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
4	80	Fu	Load1		Mult1						

- Dispatching SUBI Instruction (not in FP queue)

Loop Example Cycle 5

Instruction status:

ITER	Instruction		j	k	Issue	Exec Comp	Write Result
1	LD	F0	0	R1	1		
1	MULTD	F4	F0	F2	2		
1	SD	F4	0	R1	3		

	Busy	Addr	Fu
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations:

				S1	S2	RS	
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	Multd		R(F2)	Load1	
	Mult2	No					

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
5	72	Fu	Load1		Mult1						

- And, BNEZ instruction (not in FP queue)

Loop Example Cycle 6

Instruction status:

ITER	Instruction		j	k	Issue	Exec Comp	Write Result
1	LD	F0	0	R1	1		
1	MULTD	F4	F0	F2	2		
1	SD	F4	0	R1	3		
2	LD	F0	0	R1	6		

	Busy	Addr	Fu
Load1	Yes	80	
Load2	Yes	72	
Load3	No		
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations:

				S1	S2	RS	
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	Multd		R(F2)	Load1	
	Mult2	No					

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
6	72	Fu	Load2		Mult1						

- Notice that F0 never sees Load from location 80

Loop Example Cycle 7

Instruction status:

ITER	Instruction		j	k	Issue	Exec Comp	Write Result
1	LD	F0	0	R1	1		
1	MULTD	F4	F0	F2	2		
1	SD	F4	0	R1	3		
2	LD	F0	0	R1	6		
2	MULTD	F4	F0	F2	7		

	Busy	Addr	Fu
Load1	Yes	80	
Load2	Yes	72	
Load3	No		
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations:

				S1	S2	RS	
Time	Name	Busy	Op	Vj	Vk	Qj	Qk
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	Multd		R(F2)	Load1	
	Mult2	Yes	Multd		R(F2)	Load2	

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
7	72	Fu	Load2		Mult2						

- Register file completely detached from computation
- First and Second iteration completely overlapped

Loop Example Cycle 8

Instruction status:

						Exec	Write
ITER	Instruction		*j*	*k*	*Issue*	*Comp*	*Result*
1	LD	F0	0	R1	1		
1	MULTD	F4	F0	F2	2		
1	SD	F4	0	R1	3		
2	LD	F0	0	R1	6		
2	MULTD	F4	F0	F2	7		
2	SD	F4	0	R1	8		

	Busy	*Addr*	*Fu*
Load1	Yes	80	
Load2	Yes	72	
Load3	No		
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations:

					S1	*S2*	*RS*
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	Multd		R(F2)	Load1	
	Mult2	Yes	Multd		R(F2)	Load2	

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
8	**72**	*Fu*	Load2		Mult2						

Loop Example Cycle 9

Instruction status:

						Exec	Write
ITER	Instruction		*j*	*k*	*Issue*	*Comp*	*Result*
1	LD	F0	0	R1	1	9	
1	MULTD	F4	F0	F2	2		
1	SD	F4	0	R1	3		
2	LD	F0	0	R1	6		
2	MULTD	F4	F0	F2	7		
2	SD	F4	0	R1	8		

	Busy	*Addr*	*Fu*
Load1	Yes	80	
Load2	Yes	72	
Load3	No		
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations:

					S1	*S2*	*RS*
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	Multd		R(F2)	Load1	
	Mult2	Yes	Multd		R(F2)	Load2	

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
9	**72**	*Fu*	Load2		Mult2						

- Load1 completing: who is waiting?
- Note: Dispatching SUBI

Loop Example Cycle 10

Instruction status:

						Exec	Write
ITER	Instruction		*j*	*k*	*Issue*	*Comp*	*Result*
1	LD	F0	0	R1	1	9	10
1	MULTD	F4	F0	F2	2		
1	SD	F4	0	R1	3		
2	LD	F0	0	R1	6	10	
2	MULTD	F4	F0	F2	7		
2	SD	F4	0	R1	8		

	Busy	*Addr*	*Fu*
Load1	No		
Load2	Yes	72	
Load3	No		
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations:

					S1	*S2*	*RS*
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
4	Mult1	Yes	Multd	M[80]	R(F2)		
	Mult2	Yes	Multd		R(F2)	Load2	

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
10	**64**	*Fu*	Load2		Mult2						

- Load2 completing: who is waiting?
- Note: Dispatching BNEZ

Loop Example Cycle 11

Instruction status:

						Exec	Write
ITER	Instruction		*j*	*k*	*Issue*	*Comp*	*Result*
1	LD	F0	0	R1	1	9	10
1	MULTD	F4	F0	F2	2		
1	SD	F4	0	R1	3		
2	LD	F0	0	R1	6	10	11
2	MULTD	F4	F0	F2	7		
2	SD	F4	0	R1	8		

	Busy	*Addr*	*Fu*
Load1	No		
Load2	No		
Load3	Yes	64	
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations:

					S1	*S2*	*RS*
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
3	Mult1	Yes	Multd	M[80]	R(F2)		
4	Mult2	Yes	Multd	M[72]	R(F2)		

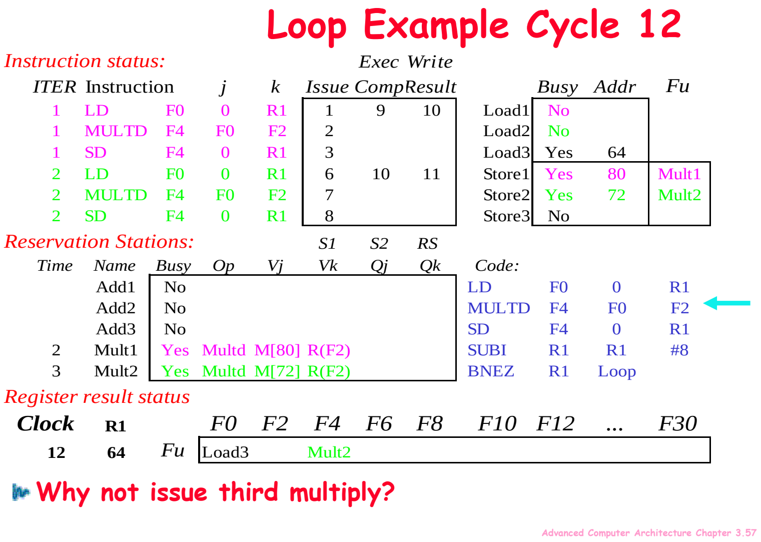
Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
11	**64**	*Fu*	Load3		Mult2						

- Next load in sequence



Loop Example Cycle 12

Instruction status:

ITER	Instruction	j	k	Issue	Exec Comp	Write Result		Busy	Addr	Fu
1	LD F0	0	R1	1	9	10	Load1	No		
1	MULTD F4	F0	F2	2			Load2	No		
1	SD F4	0	R1	3			Load3	Yes	64	
2	LD F0	0	R1	6	10	11	Store1	Yes	80	Mult1
2	MULTD F4	F0	F2	7			Store2	Yes	72	Mult2
2	SD F4	0	R1	8			Store3	No		

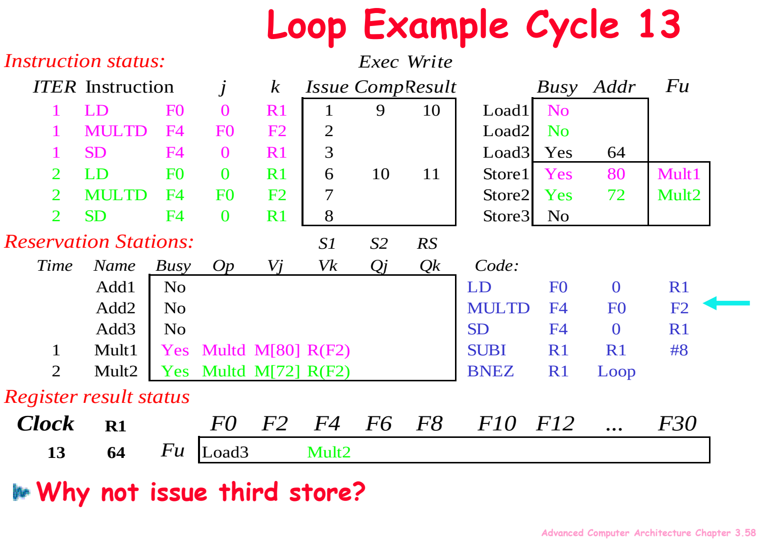
Reservation Stations:

					S1	S2	RS				
Time	Name	Busy	Op	Vj	Vk	Qj	Qk	Code:			
	Add1	No						LD	F0	0	R1
	Add2	No						MULTD	F4	F0	F2
	Add3	No						SD	F4	0	R1
2	Mult1	Yes	Multd	M[80]	R(F2)			SUBI	R1	R1	#8
3	Mult2	Yes	Multd	M[72]	R(F2)			BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
12	64	Fu	Load3		Mult2						

- Why not issue third multiply?



Loop Example Cycle 13

Instruction status:

ITER	Instruction	j	k	Issue	Exec Comp	Write Result		Busy	Addr	Fu
1	LD F0	0	R1	1	9	10	Load1	No		
1	MULTD F4	F0	F2	2			Load2	No		
1	SD F4	0	R1	3			Load3	Yes	64	
2	LD F0	0	R1	6	10	11	Store1	Yes	80	Mult1
2	MULTD F4	F0	F2	7			Store2	Yes	72	Mult2
2	SD F4	0	R1	8			Store3	No		

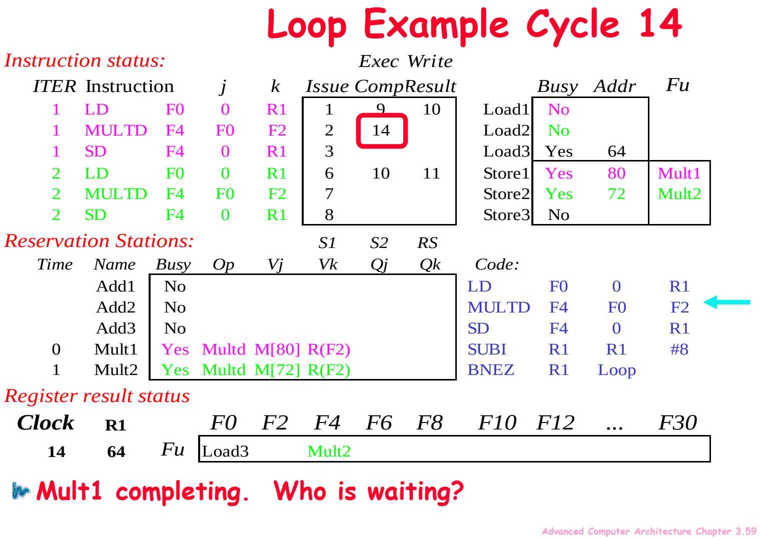
Reservation Stations:

					S1	S2	RS				
Time	Name	Busy	Op	Vj	Vk	Qj	Qk	Code:			
	Add1	No						LD	F0	0	R1
	Add2	No						MULTD	F4	F0	F2
	Add3	No						SD	F4	0	R1
1	Mult1	Yes	Multd	M[80]	R(F2)			SUBI	R1	R1	#8
2	Mult2	Yes	Multd	M[72]	R(F2)			BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
13	64	Fu	Load3		Mult2						

- Why not issue third store?



Loop Example Cycle 14

Instruction status:

ITER	Instruction	j	k	Issue	Exec Comp	Write Result		Busy	Addr	Fu
1	LD F0	0	R1	1	9	10	Load1	No		
1	MULTD F4	F0	F2	2	14		Load2	No		
1	SD F4	0	R1	3			Load3	Yes	64	
2	LD F0	0	R1	6	10	11	Store1	Yes	80	Mult1
2	MULTD F4	F0	F2	7			Store2	Yes	72	Mult2
2	SD F4	0	R1	8			Store3	No		

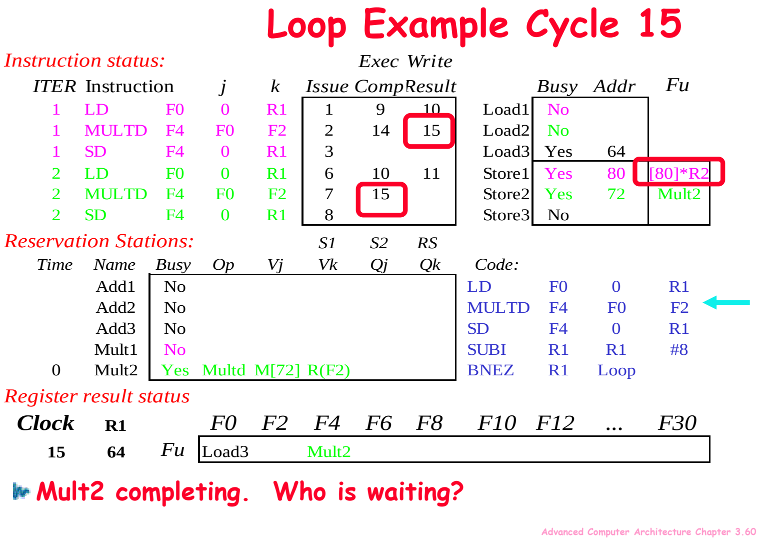
Reservation Stations:

					S1	S2	RS				
Time	Name	Busy	Op	Vj	Vk	Qj	Qk	Code:			
	Add1	No						LD	F0	0	R1
	Add2	No						MULTD	F4	F0	F2
	Add3	No						SD	F4	0	R1
0	Mult1	Yes	Multd	M[80]	R(F2)			SUBI	R1	R1	#8
1	Mult2	Yes	Multd	M[72]	R(F2)			BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
14	64	Fu	Load3		Mult2						

- Mult1 completing. Who is waiting?



Loop Example Cycle 15

Instruction status:

ITER	Instruction	j	k	Issue	Exec Comp	Write Result		Busy	Addr	Fu
1	LD F0	0	R1	1	9	10	Load1	No		
1	MULTD F4	F0	F2	2	14	15	Load2	No		
1	SD F4	0	R1	3			Load3	Yes	64	
2	LD F0	0	R1	6	10	11	Store1	Yes	80	[80]*R2
2	MULTD F4	F0	F2	7	15		Store2	Yes	72	Mult2
2	SD F4	0	R1	8			Store3	No		

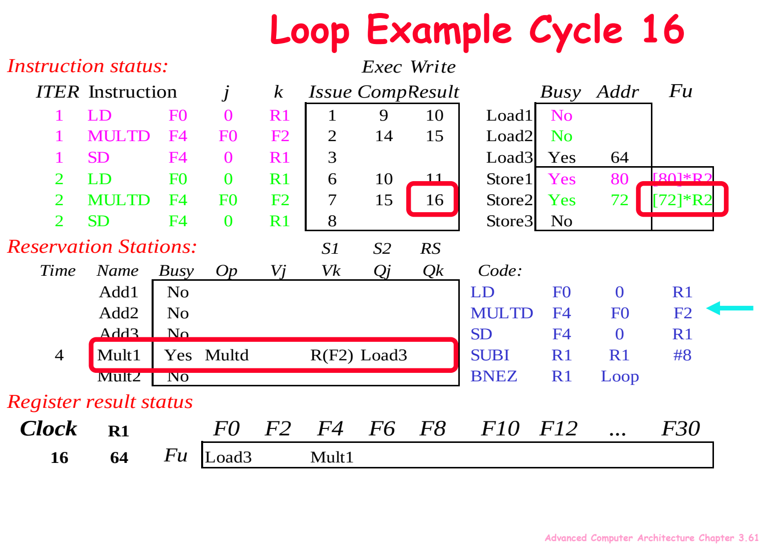
Reservation Stations:

					S1	S2	RS				
Time	Name	Busy	Op	Vj	Vk	Qj	Qk	Code:			
	Add1	No						LD	F0	0	R1
	Add2	No						MULTD	F4	F0	F2
	Add3	No						SD	F4	0	R1
	Mult1	No						SUBI	R1	R1	#8
0	Mult2	Yes	Multd	M[72]	R(F2)			BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
15	64	Fu	Load3		Mult2						

- Mult2 completing. Who is waiting?



Loop Example Cycle 16

Instruction status:

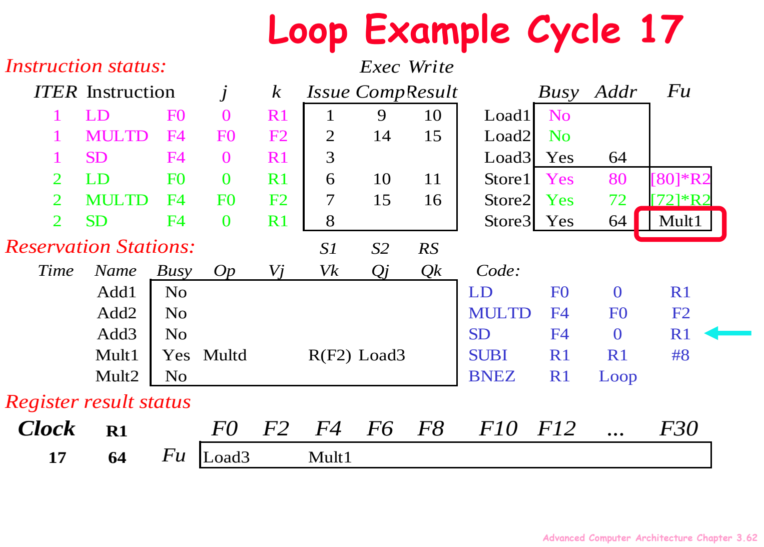
ITER	Instruction	*j*	*k*	*Issue*	*Exec Comp*	*Write Result*		*Busy*	*Addr*	*Fu*
1	LD	F0	0	R1	1	9	10	Load1	No		
1	MULTD	F4	F0	F2	2	14	15	Load2	No		
1	SD	F4	0	R1	3			Load3	Yes	64	
2	LD	F0	0	R1	6	10	11	Store1	Yes	80	[80]*R2
2	MULTD	F4	F0	F2	7	15	16	Store2	Yes	72	[72]*R2
2	SD	F4	0	R1	8			Store3	No		

Reservation Stations:

					S1	*S2*	*RS*				
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*	*Code:*			
	Add1	No						LD	F0	0	R1
	Add2	No						MULTD	F4	F0	F2
	Add3	No						SD	F4	0	R1
4	Mult1	Yes	Multd		R(F2)	Load3		SUBI	R1	R1	#8
	Mult2	No						BNEZ	R1	Loop	

Register result status

Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
16	**64**	*Fu*	Load3		Mult1						



Loop Example Cycle 17

Instruction status:

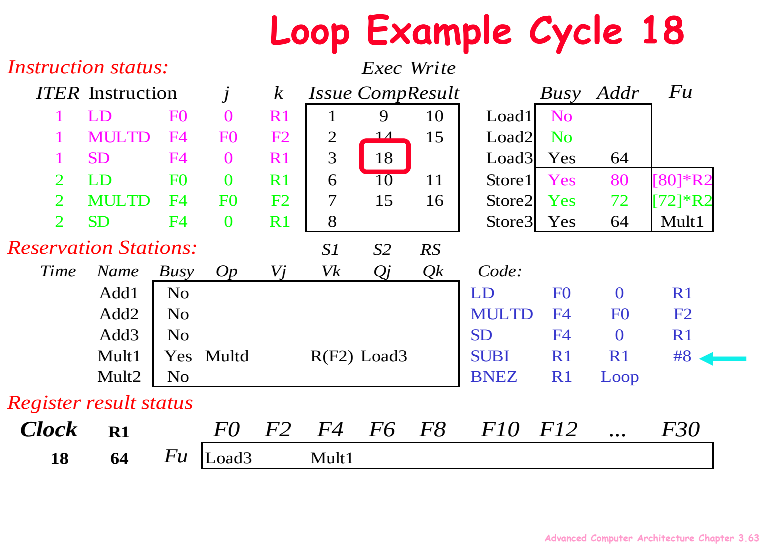
ITER	Instruction	*j*	*k*	*Issue*	*Exec Comp*	*Write Result*		*Busy*	*Addr*	*Fu*
1	LD	F0	0	R1	1	9	10	Load1	No		
1	MULTD	F4	F0	F2	2	14	15	Load2	No		
1	SD	F4	0	R1	3			Load3	Yes	64	
2	LD	F0	0	R1	6	10	11	Store1	Yes	80	[80]*R2
2	MULTD	F4	F0	F2	7	15	16	Store2	Yes	72	[72]*R2
2	SD	F4	0	R1	8			Store3	Yes	64	Mult1

Reservation Stations:

					S1	*S2*	*RS*				
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*	*Code:*			
	Add1	No						LD	F0	0	R1
	Add2	No						MULTD	F4	F0	F2
	Add3	No						SD	F4	0	R1
	Mult1	Yes	Multd		R(F2)	Load3		SUBI	R1	R1	#8
	Mult2	No						BNEZ	R1	Loop	

Register result status

Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
17	**64**	*Fu*	Load3		Mult1						



Loop Example Cycle 18

Instruction status:

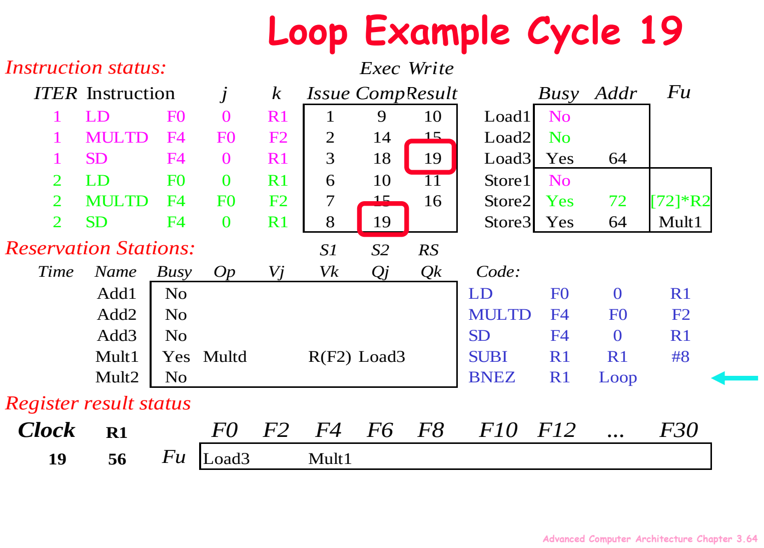
ITER	Instruction	*j*	*k*	*Issue*	*Exec Comp*	*Write Result*		*Busy*	*Addr*	*Fu*
1	LD	F0	0	R1	1	9	10	Load1	No		
1	MULTD	F4	F0	F2	2	14	15	Load2	No		
1	SD	F4	0	R1	3	18		Load3	Yes	64	
2	LD	F0	0	R1	6	10	11	Store1	Yes	80	[80]*R2
2	MULTD	F4	F0	F2	7	15	16	Store2	Yes	72	[72]*R2
2	SD	F4	0	R1	8			Store3	Yes	64	Mult1

Reservation Stations:

					S1	*S2*	*RS*				
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*	*Code:*			
	Add1	No						LD	F0	0	R1
	Add2	No						MULTD	F4	F0	F2
	Add3	No						SD	F4	0	R1
	Mult1	Yes	Multd		R(F2)	Load3		SUBI	R1	R1	#8
	Mult2	No						BNEZ	R1	Loop	

Register result status

Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
18	**64**	*Fu*	Load3		Mult1						



Loop Example Cycle 19

Instruction status:

ITER	Instruction	*j*	*k*	*Issue*	*Exec Comp*	*Write Result*		*Busy*	*Addr*	*Fu*
1	LD	F0	0	R1	1	9	10	Load1	No		
1	MULTD	F4	F0	F2	2	14	15	Load2	No		
1	SD	F4	0	R1	3	18	19	Load3	Yes	64	
2	LD	F0	0	R1	6	10	11	Store1	No		
2	MULTD	F4	F0	F2	7	15	16	Store2	Yes	72	[72]*R2
2	SD	F4	0	R1	8	19		Store3	Yes	64	Mult1

Reservation Stations:

					S1	*S2*	*RS*				
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*	*Code:*			
	Add1	No						LD	F0	0	R1
	Add2	No						MULTD	F4	F0	F2
	Add3	No						SD	F4	0	R1
	Mult1	Yes	Multd		R(F2)	Load3		SUBI	R1	R1	#8
	Mult2	No						BNEZ	R1	Loop	

Register result status

Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
19	**56**	*Fu*	Load3		Mult1						

Loop Example Cycle 20

Instruction status:

ITER	Instruction		*j*	*k*	Issue	Exec Comp	Write Result
1	LD	F0	0	R1	1	9	10
1	MULTD	F4	F0	F2	2	14	15
1	SD	F4	0	R1	3	18	19
2	LD	F0	0	R1	6	10	11
2	MULTD	F4	F0	F2	7	15	16
2	SD	F4	0	R1	8	19	20

	Busy	*Addr*	*Fu*
Load1	Yes	56	
Load2	No		
Load3	Yes	64	
Store1	No		
Store2	No		
Store3	Yes	64	Mult1

Reservation Stations:

					S1	*S2*	*RS*
Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*
	Add1	No					
	Add2	No					
	Add3	No					
	Mult1	Yes	Multd		R(F2)	Load3	
	Mult2	No					

Code:

LD	F0	0	R1
MULTD	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
20	**56**	*Fu*	Load1		Mult1						

- Once again: In-order issue, out-of-order execution and out-of-order completion.

Why can Tomasulo overlap iterations of loops?

- **Register renaming**
  - Multiple iterations use different physical destinations for registers (dynamic loop unrolling).
- **Reservation stations**
  - Permit instruction issue to advance past integer control flow operations
  - Also buffer old values of registers - totally avoiding the WAR stall that we saw in the scoreboard.
- **Other perspective: Tomasulo building data flow dependency graph on the fly.**

Tomasulo's scheme offers two major advantages

(1) the distribution of the hazard detection logic

- distributed reservation stations and the CDB
- If multiple instructions waiting on single result, & each instruction has other operand, then instructions can be released simultaneously by broadcast on CDB
- If a centralized register file were used, the units would have to read their results from the registers when register buses are available.

(2) the elimination of stalls for WAW and WAR hazards

What about Precise Interrupts?

- Tomasulo had:

  In-order issue, out-of-order execution, and out-of-order completion

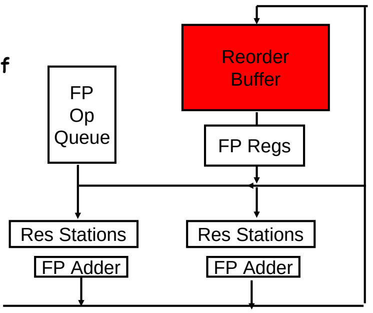
- Need to "fix" the out-of-order completion aspect so that we can find precise breakpoint in instruction stream.

Relationship between precise interrupts and speculation:

- Speculation is a form of guessing.
- Important for branch prediction:
  - Need to "take our best shot" at predicting branch direction.
- If we speculate and are wrong, need to back up and restart execution at point at which we predicted incorrectly:
  - This is exactly same as precise exceptions!
- Technique for both precise interrupts/exceptions and speculation: *in-order completion or commit*

HW support for precise interrupts

- Need HW buffer for results of uncommitted instructions: *reorder buffer*
  - 3 fields: instr, destination, value
  - Use reorder buffer number instead of reservation station when execution completes
  - Supplies operands between execution complete & commit
  - (Reorder buffer can be operand source => more registers like RS)
  - Instructions commit
  - Once instruction commits, result is put into register
  - As a result, easy to undo speculated instructions on mispredicted branches or 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 (this stage sometimes called "dispatch")

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; checks RAW (sometimes called "issue")

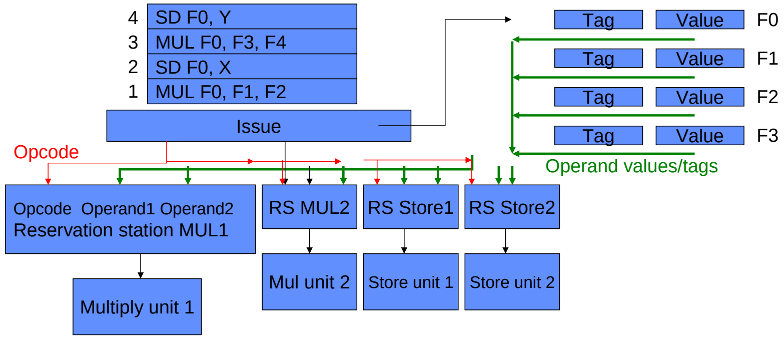
3. Write result—finish execution (WB)

   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. Mispredicted branch flushes reorder buffer (sometimes called "graduation")

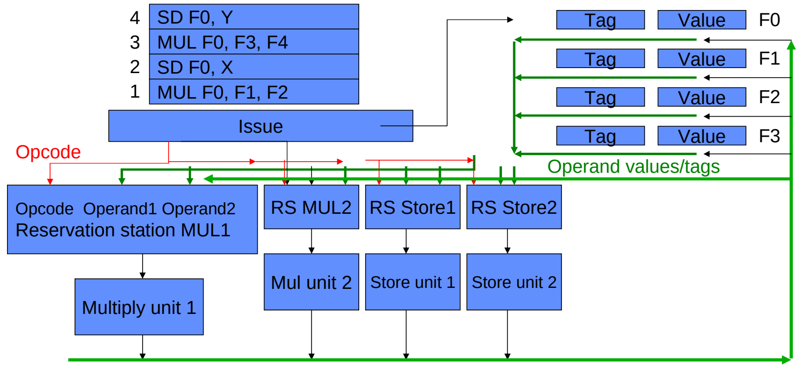
Tomasulo without Re-order Buffer



Issue:

- Each instruction is issued in order
- Issue unit collects operands from the two instruction's source registers
- Result may be a value, or, if value will be computed by an uncompleted instruction, the tag of the RS to which it was issued.
- **When instruction 1 is issued, F0 is updated to get result from MUL1**
- **When instruction 3 is issued, F0 is updated to get result from MUL2**

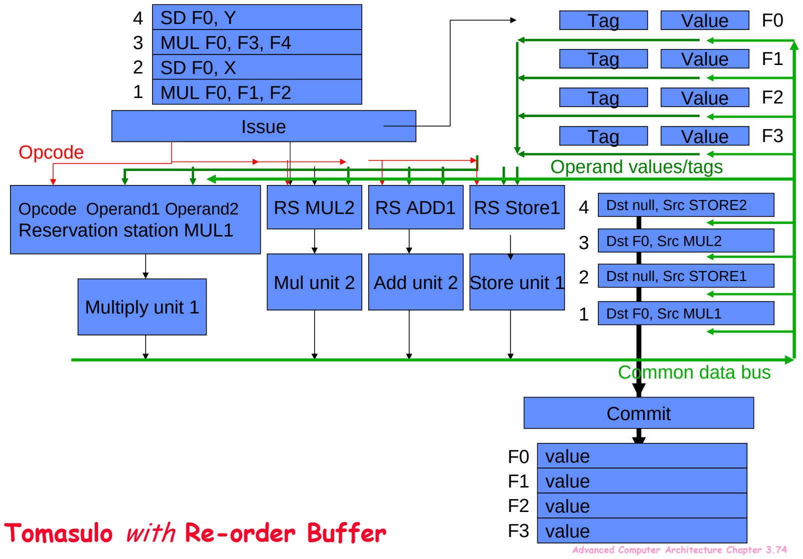
Tomasulo without Re-order Buffer

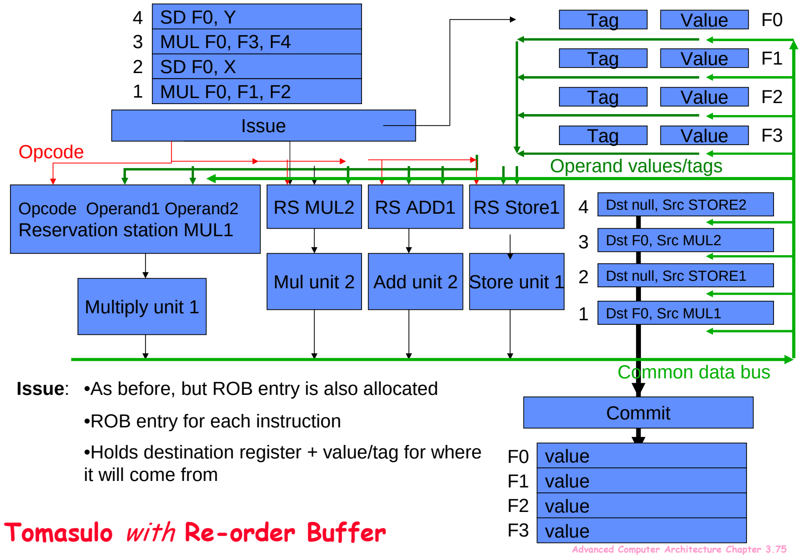


Write-back:

- Instructions may complete out of order
- Result is broadcast on CDB
- Carrying tag of RS to which instruction was originally issued
- All RSs and registers monitor CDB and collect value if tag matches
- Any RS which has both operands and whose FU is free fires.
- **When MUL1 completes result goes to store unit but not F0**

Tomasulo *with* Re-order Buffer

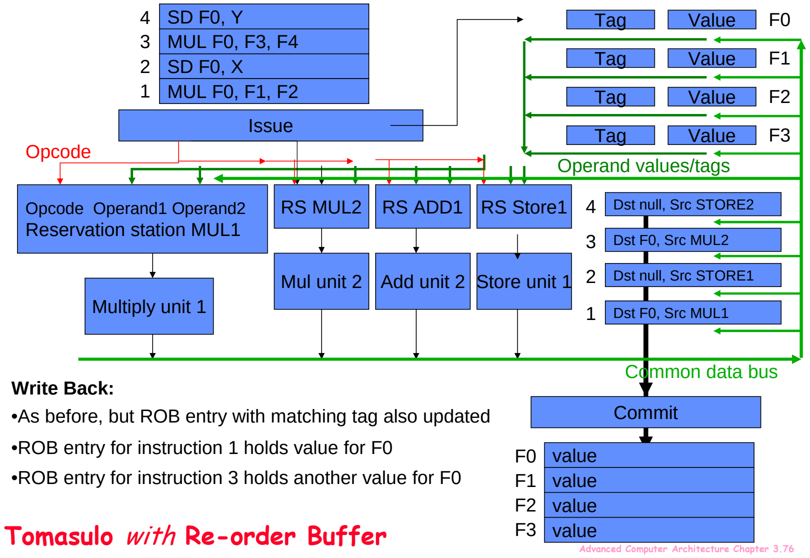




Issue:

- As before, but ROB entry is also allocated
- ROB entry for each instruction
- Holds destination register + value/tag for where it will come from

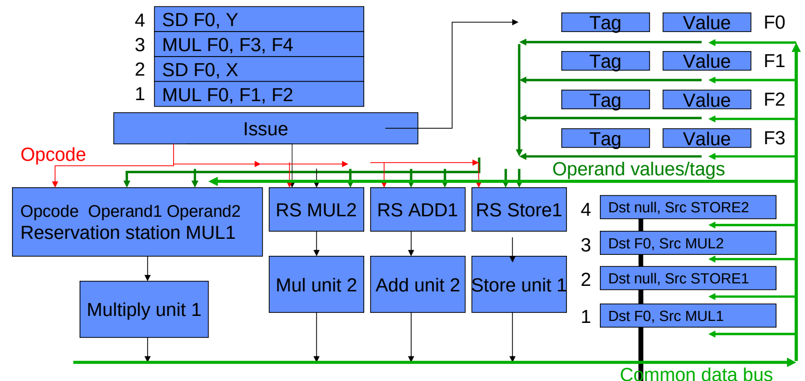
Tomasulo *with* Re-order Buffer



Write Back:

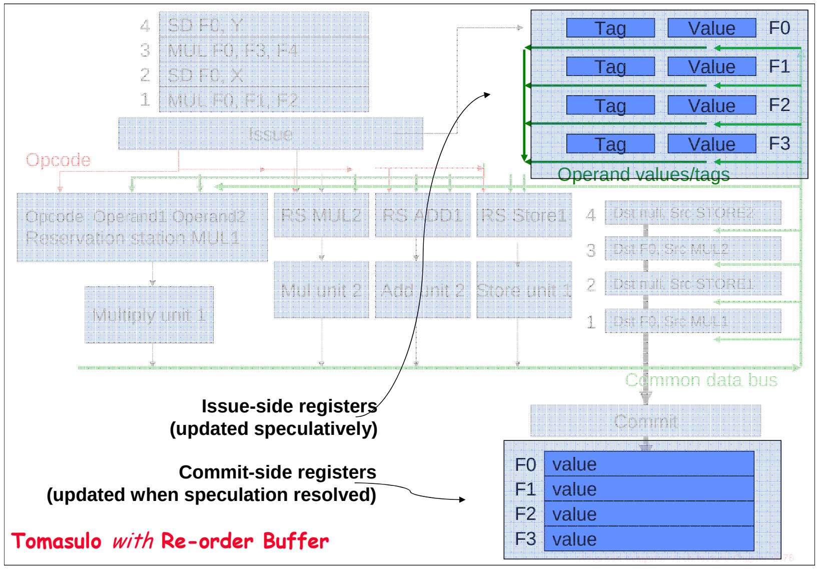
- As before, but ROB entry with matching tag also updated
- ROB entry for instruction 1 holds value for F0
- ROB entry for instruction 3 holds another value for F0

Tomasulo *with* Re-order Buffer



Commit:

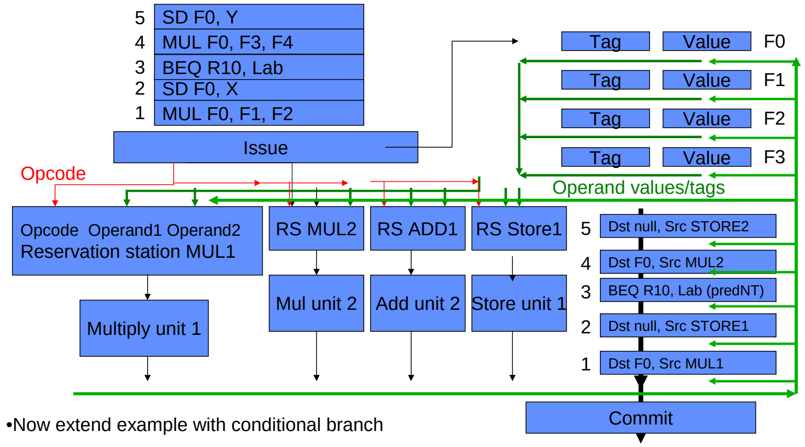
- •Commit unit processes ROB entries in issue order
- •Each instruction waits in turn and commits when its operands are completed
- •Committed registers updated with values from ROB
- •F0 is updated first with result from MUL1 then result from MUL2



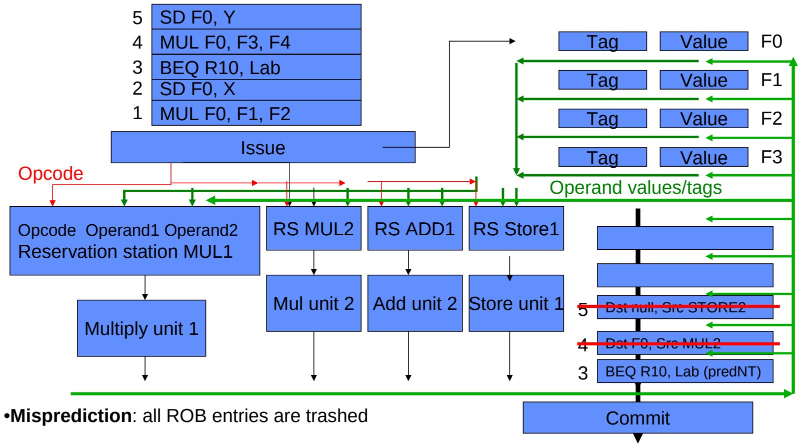
Issue-side registers (updated speculatively)

Commit-side registers (updated when speculation resolved)

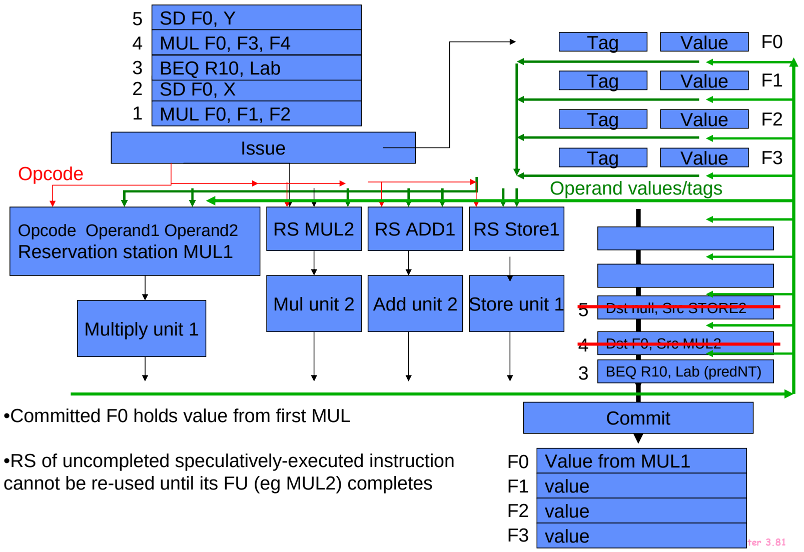
Tomasulo *with* Re-order Buffer



- •Now extend example with conditional branch
- •Assume predicted Not Taken
- •When BEQ reaches head of commit queue, all instructions which have been issued but have not yet committed are erroneous



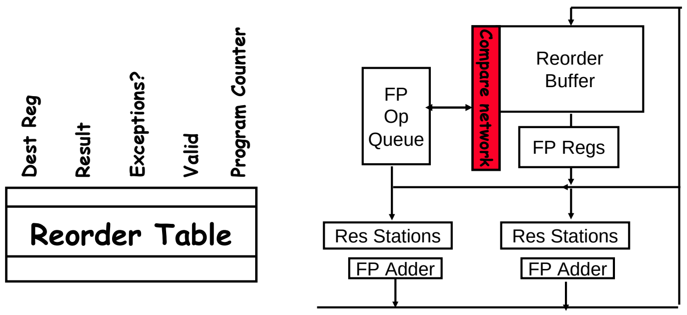
- •**Misprediction**: all ROB entries are trashed
- •Issue-side registers reset from commit-side registers
- •Correct branch target instruction fetched and issued



•Committed F0 holds value from first MUL

•RS of uncompleted speculatively-executed instruction cannot be re-used until its FU (eg MUL2) completes

What are the hardware complexities with reorder buffer (ROB)?



- How do you find the latest version of a register?
  - Looks like we need associative comparison network
  - Could use future file or just use the register result status buffer to track which specific reorder buffer has received the value
- Need as many ports on ROB as register file

See S. Weiss and J. E. Smith, “Instruction Issue Logic for Pipelined Supercomputers”. ISCA, 1984 (http://citeseer.nj.nec.com/weiss84instruction.html)

Some subleties…

- It’s vital to reduce the branch misprediction penalty. Does the Tomasulo+ROB scheme described here roll-back as soon as the branch is found to be mispredicted?

- Stores are buffered in the ROB, and committed only when the instruction is committed. A load can be issued while several stores (perhaps to the same address) are uncommitted. We need to make sure the load gets the right data.

- What if a second conditional branch is encountered, before the outcome of the first is resolved?

- This discussion has assumed a single-issue machine. How can these ideas be extended to allow multiple instructions to be issued per cycle?
  - Issue
  - Monitoring CDBs for completion
  - Handling multiple commits per cycle

Tomasulo + ROB: Summary

- Reservations stations: *implicit register renaming* to larger set of registers + buffering source operands
  - Prevents registers as bottleneck
  - Avoids WAR, WAW hazards of Scoreboard (see textbook)
  - Allows loop unrolling in HW
- Not limited to basic blocks
  (integer units gets ahead, beyond branches)
- Today, helps cache misses as well
  - Don’t stall for L1 Data cache miss (insufficient ILP for L2 miss?)
- Lasting Contributions
  - Dynamic scheduling
  - Register renaming
  - Load/store disambiguation
- 360/91 descendants are Pentium III, Pentium 4, Pentium M/Core; PowerPC 604; MIPS R10000; HP-PA 8000; Alpha 21264 and more

Resources

- Papers:
  - Instruction issue logic for high-performance, interruptable pipelined processors. G. S. Sohi, S. Vajapeyam. International Conference on Computer Architecture, 1987 (http://doi.acm.org/10.1145/30350.30354)
  - Towards Kilo-instruction processors. Cristal, Santana, Valero, Martinez ACM Trans. Architecture and Code Optimization (http://doi.acm.org/10.1145/1044823.1044825)
- Animations:
  - SATSim Simplescalar
    - http://www.ece.gatech.edu/research/pica/SATSim/satsim.html
  - WebHase Tomasulo model:
    - www.dcs.ed.ac.uk/home/hase/webhase/demo/tomasulo.html
  - Other WebHase animations – simple pipeline, Scoreboarding etc:
    - http://www.icsa.informatics.ed.ac.uk/research/groups/hase/javahase/app-list.html
  - Israel Koren at U Massachussetts Amhurst:
    - http://www.ecs.umass.edu/ece/koren/architecture/Tomasulo/AppletTomasulo.html
    - http://www.ecs.umass.edu/ece/koren/architecture/
- Processor performance
  - SPEC benchmarks – see http://www.spec.org/
    - CPU benchmarks: http://www.spec.org/cpu2000/results/cpu2000.html
    - HPC benchmarks: http://www.spec.org/hpc2002/results/hpc2002.html
  - Ace's hardware SPEC summary:
    - http://www.aceshardware.com/SPECmine/top.jsp
- Other simulators:
  - Liberty: http://liberty.cs.princeton.edu/
  - MicroLib: http://microlib.org/

360/91 design choices…

- Speculation:
  - "Rather than wait for a valid CC, fetches are initiated for two instruction double-words as a hedge against a successful branch. Following this, it is assumed that the branch will fail, and a "conditional mode" is established. In conditional mode, shown in Fig. 8, instructions are decoded and conditionally forwarded to the execution units, and concomitant operand fetches are initiated. The execution units are inhibited from completing conditional instructions. When a valid condition code appears, the appropriate branching action is detected and activates or cancels the conditional instructions."
- Prediction:
  - [after mispredict] "the role of conditional mode is reversed, i.e., when the conditional branch is next encountered, it will be assumed that the branch will be taken. The conditionally issued instructions are from the target path rather than from the nobranch path as is the case when not in loop mode. A cancel requires recovery from the branch guess."
- Right:
  - Organizationally, primary emphasis is placed on (1) alleviating the disparity between storage time and circuit speed, and (2) the development of high speed floating-point arithmetic algorithms.
- Wrong:
  - "The complications of conditional mode, coupled with the fact that it is primarily aimed at circumventing storage access delays, indicate that a careful re-examination of its usefulness will be called for as the access time decreases."

Tomasulo Algorithm and Branch Prediction

- 360/91 predicted branches, but lacked full speculation:
  - Instructions along predicted branch path can complete
  - But results cannot be forwarded until branch outcome resolved
- Speculation with Reorder Buffer allows execution past branch, and then discard if branch fails
  - The key difference is that speculative instructions can pass values to each other
  - just need to hold instructions in buffer until branch can commit

Case for Branch Prediction when Issue N instructions per clock cycle

1. Branches will arrive up to *n* times faster in an *n*-issue processor
2. Amdahl's Law => relative impact of the control stalls will be larger with the lower potential CPI in an *n*-issue processor

7 Branch Prediction Schemes

1. 1-bit Branch-Prediction Buffer
2. 2-bit Branch-Prediction Buffer
3. Correlating Branch Prediction Buffer
4. Tournament Branch Predictor
5. Branch Target Buffer
6. Integrated Instruction Fetch Units
7. Return Address Predictors

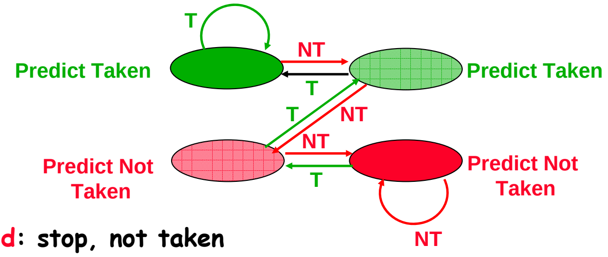
Dynamic Branch Prediction

- Performance = *ƒ*(accuracy, cost of misprediction)
- Branch History Table: Lower bits of PC address index table of 1-bit values
  - Says whether or not branch taken last time
  - No address check (saves HW, but may not be right branch)
- Problem: in a loop, 1-bit BHT will cause 2 mispredictions (avg is 9 iterations before exit):
  - End of loop case, when it exits instead of looping as before
  - First time through loop on *next* time through code, when it predicts *exit* instead of looping
  - Only 80% accuracy even if loop 90% of the time

Dynamic Branch Prediction

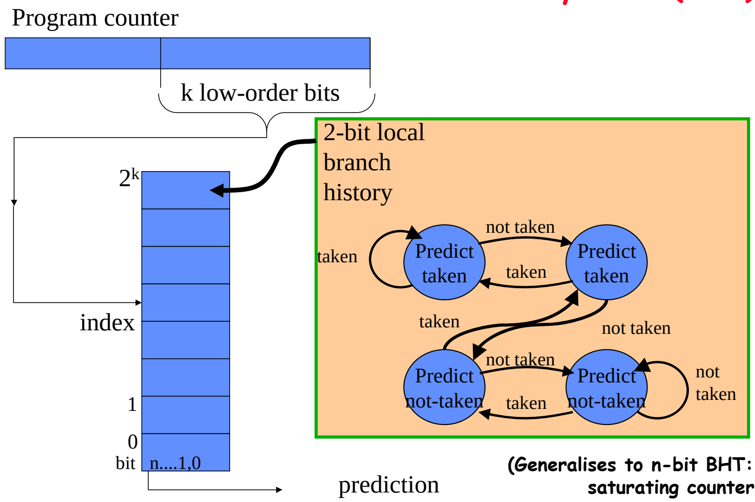
(Jim Smith, 1981)

- Solution: 2-bit scheme where change prediction only if get misprediction *twice:* (Figure 3.7, p. 198)



- Red: stop, not taken
- Green: go, taken
- Adds *hysteresis* to decision making process

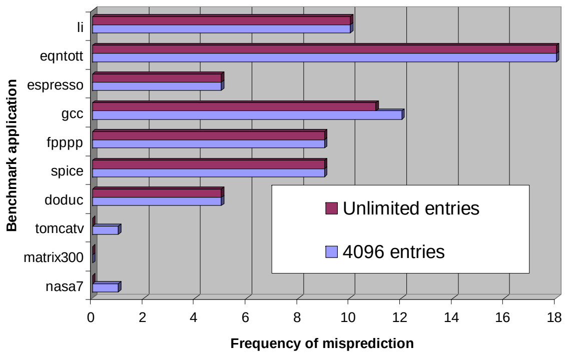
The 2-bit branch history table (BHT)



(Generalises to n-bit BHT: saturating counter)

n-bit BHT - how well does it work?

Prediction accuracy of an 4096-entry two-bit prediction buffer versus an infinite buffer for the SPEC89 benchmarks (H&P Fig 4.15)

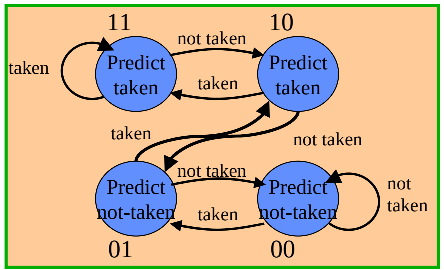


- 2-bit predictor often very good, sometimes awful
- Little evidence that BHT capacity is an issue
- 1-bit is usually worse, 3-bit is not usefully better

N-bit BHT - why does it work so well?

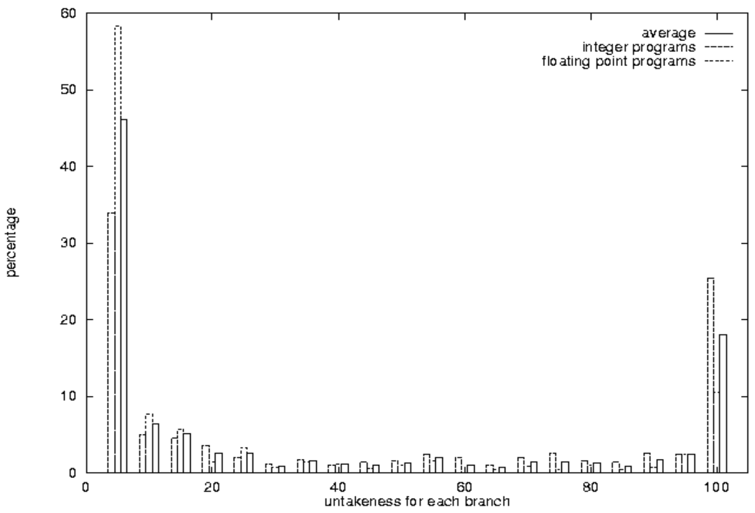
- n-bit BHT predictor essentially based on a saturating counter: taken increments, not-taken decrements
- predict taken if most significant bit is set

- Most branches are highly *__biased:__* either almost-always taken, or almost-always not-taken
- Works badly for branches which aren't



Often called the "bimodal" predictor

Bias



Zhendong Su and Min Zhou, A comparative analysis of branch prediction schemes (http://www.cs.berkeley.edu/~zhendong/cs252/project.html)

Is local history all there is to it?

- The bimodal predictor uses the BHT to record "local history" - the prediction information used to predict a particular branch is determined only by its memory address
- Consider the following sequence:

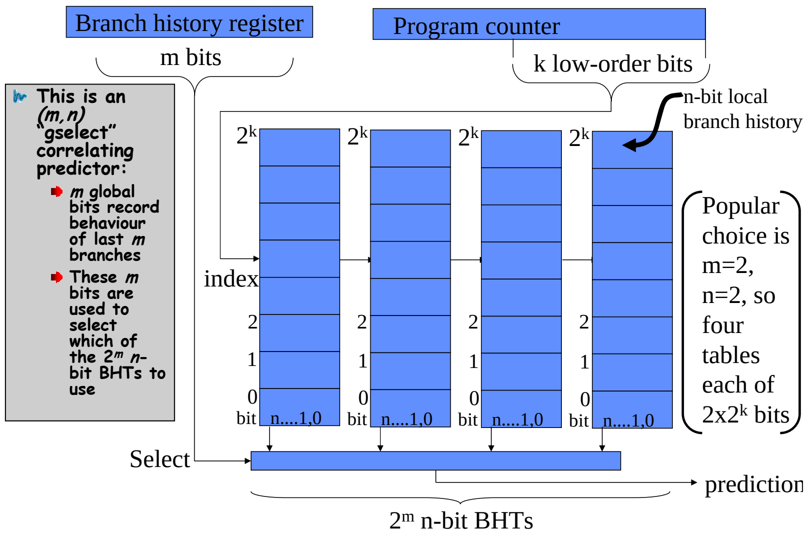
```
if (C1)  then
   S1;
endif
if (C2) then
   S2;
endif
if (C3) then
   S3;
endif
```

◎It is very likely that condition C2 is correlated with C1 - and that C3 is correlated with C1 and C2

◎How can we use this observation?

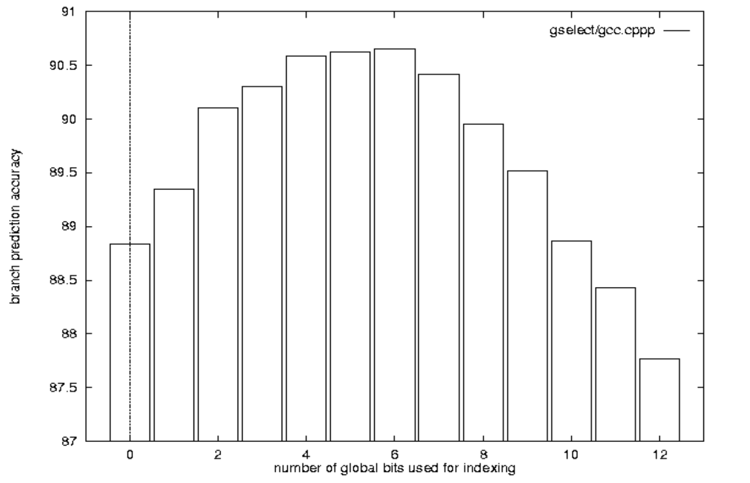
Global history

- Definition: <u>Global history</u>. The taken - not-taken history for all previously-executed branches.
- Idea: use global history to improve branch prediction
- Compromise: use *m* most recently-executed branches
- Implementation: keep an *m*-bit Branch History Register (BHR) - a shift register recording taken - not-taken direction of the last m branches
- Question: How to combine local information with global information?



- This is an *(m,n)* "gselect" correlating predictor:
  - *m* global bits record behaviour of last *m* branches
  - These *m* bits are used to select which of the 2^m *n*-bit BHTs to use

How many bits of branch history should be used?



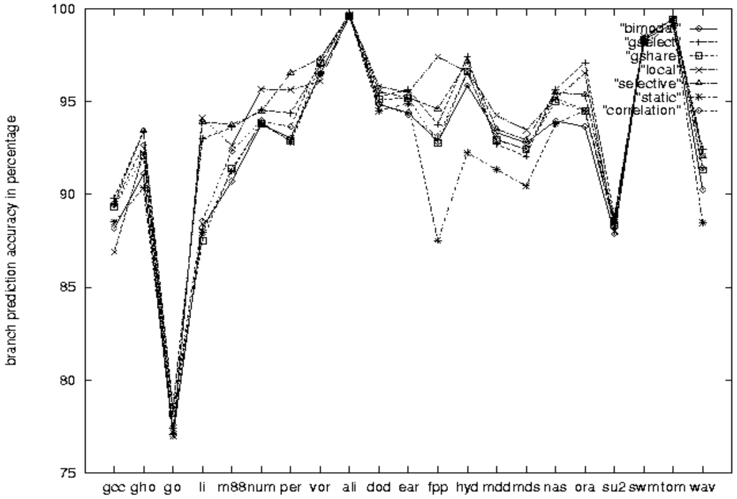
Zhendong Su and Min Zhou, A comparative analysis of branch prediction schemes (http://www.cs.berkeley.edu/~zhendong/cs252/project.html)

- (2,2) is good, (4,2) is better, (10,2) is worse

Variations

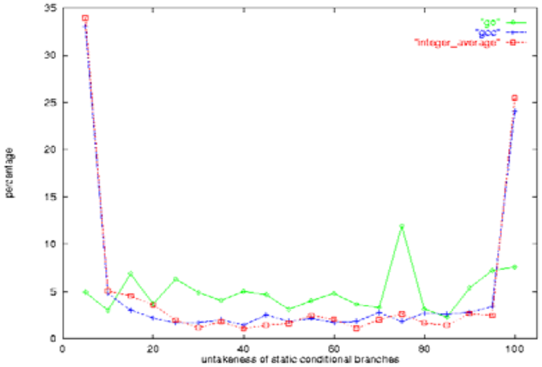
- There are many variations on the idea:
  - *gselect*: many combinations of *n* and *m*
  - *global*: use *only* the global history to index the BHT - ignore the PC of the branch being predicted (an extreme (n,m) gselect scheme)
  - *gshare*: arrange bimodal predictors in single BHT, but construct its index by XORing low-order PC address bits with global branch history shift register - claimed to reduce conflicts
  - *Per-address Two-level Adaptive using Per-address pattern history* (PAp): for each branch, keep a *k*-bit shift register recording its history, and use this to index a BHT *for this branch* (see Yeh and Patt, 1992)
- Each suits some programs well but not all

Horses for courses



Zendong Su and Min Zhou, A comparative analysis of branch prediction schemes (http://www.cs.berkeley.edu/~zhendong/cs252/project.html)

Extreme example - "go"

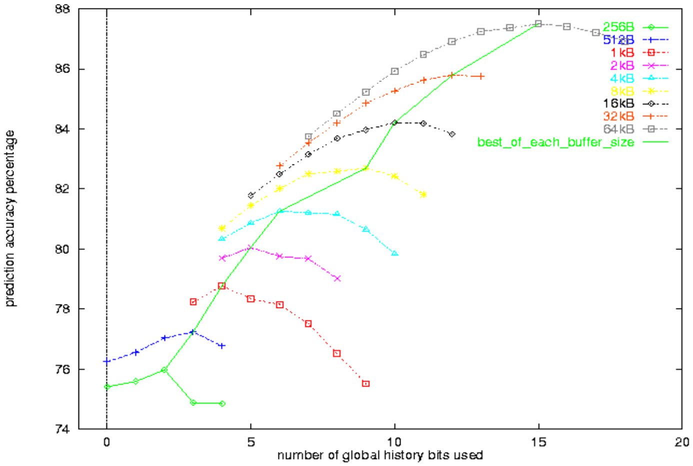


Zhendong Su and Min Zhou, A comparative analysis of branch prediction schemes (http://www.cs.berkeley.edu/~zhendong/cs252/project.html)

- "go" is a SPEC95 benchmark code with highly-dynamic, highly-correlated branch behaviour

- The bias of "go"s branches is more-or-less evenly spread between 0% taken and 100% taken
- All known predictors do badly

Some dynamic applications have highly-correlated branches



Zhendong Su and Min Zhou, A comparative analysis of branch prediction schemes (http://www.cs.berkeley.edu/~zhendong/cs252/project.html)

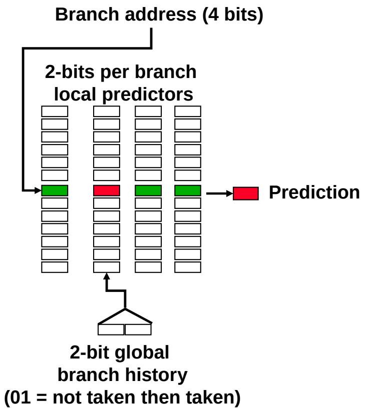
- For "go", optimum BHR size (m) is much larger

Review: Correlating Branches

Idea: taken/not taken of recently executed branches is related to behavior of next branch (as well as the history of that branch behavior)

- Then behavior of recent branches selects between, say, 4 predictions of next branch, updating just that prediction

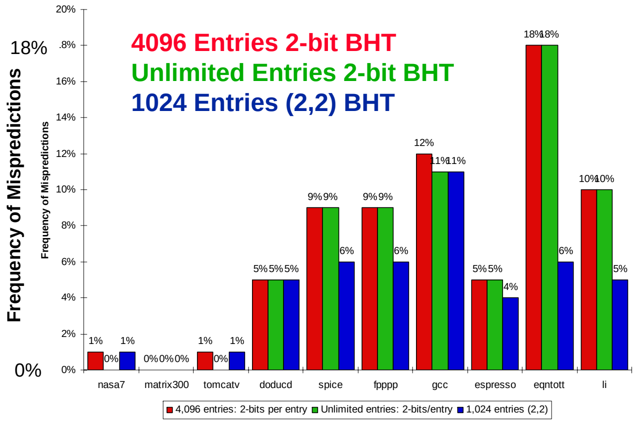
- (2,2) predictor: 2-bit global, 2-bit local



Branch address (4 bits)
2-bits per branch local predictors
Prediction
2-bit global branch history
(01 = not taken then taken)

Accuracy of Different Schemes

(H&P3ed Figure 3.15, p. 206)



Re-evaluating Correlation

- Several of the SPEC benchmarks have less than a dozen branches responsible for 90% of taken branches:

program	branch %	static	# = 90%
compress	14%	236	13
eqntott	25%	494	5
gcc	15%	9531	2020
mpeg	10%	5598	532
real gcc	13%	17361	3214

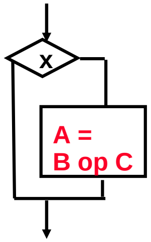
- Real programs + OS more like gcc
- Small benefits beyond benchmarks for correlation? problems with branch aliases?

Predicated Execution

- Avoid branch prediction by turning branches into conditionally executed instructions:

  if (x) then A = B op C else NOP

  - If false, then neither store result nor cause exception
  - Expanded ISA of Alpha, MIPS, PowerPC, SPARC have conditional move; PA-RISC can annul any following instr.
  - IA-64: 64 1-bit condition fields selected so conditional execution of any instruction
  - This transformation is called "if-conversion"



- Drawbacks to conditional instructions
  - Still takes a clock even if "annulled"
  - Stall if condition evaluated late
  - Complex conditions reduce effectiveness; condition becomes known late in pipeline

BHT Accuracy

- Mispredict because either:
  - Wrong guess for that branch
  - Got branch history of wrong branch when index the table
- 4096 entry table programs vary from 1% misprediction (nasa7, tomcatv) to 18% (eqntott), with spice at 9% and gcc at 12%
- For SPEC92, 4096 about as good as infinite table

Tournament Predictors

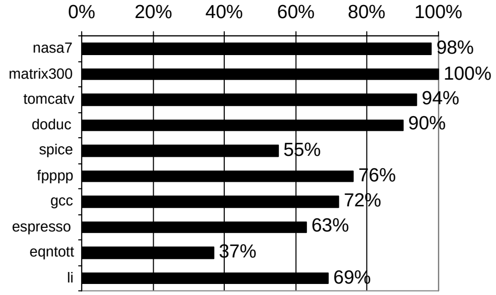
- Motivation for correlating branch predictors is 2-bit predictor failed on important branches; by adding global information, performance improved
- Tournament predictors: use 2 predictors, 1 based on global information and 1 based on local information, and combine with a selector
- Hopes to select right predictor for right branch

Tournament Predictor in Alpha 21264

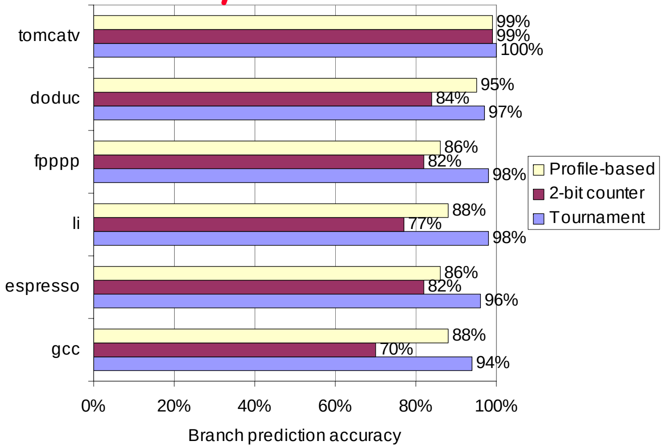
- 4K 2-bit counters to choose from among a global predictor and a local predictor
- Global predictor also has 4K entries and is indexed by the history of the last 12 branches; each entry in the global predictor is a standard 2-bit predictor
  - 12-bit pattern: ith bit 0 => ith prior branch not taken; ith bit 1 => ith prior branch taken;
- Local predictor consists of a 2-level predictor:
  - Top level a local history table consisting of 1024 10-bit entries; each 10-bit entry corresponds to the most recent 10 branch outcomes for the entry. 10-bit history allows patterns 10 branches to be discovered and predicted.
  - Next level Selected entry from the local history table is used to index a table of 1K entries consisting a 3-bit saturating counters, which provide the local prediction
- Total size: 4K*2 + 4K*2 + 1K*10 + 1K*3 = 29K bits!

  (~180,000 transistors)

% of predictions from local predictor in Tournament Prediction Scheme

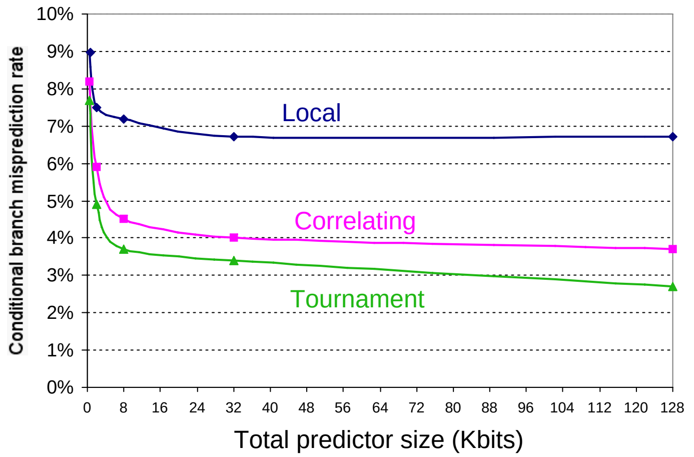


Accuracy of Branch Prediction



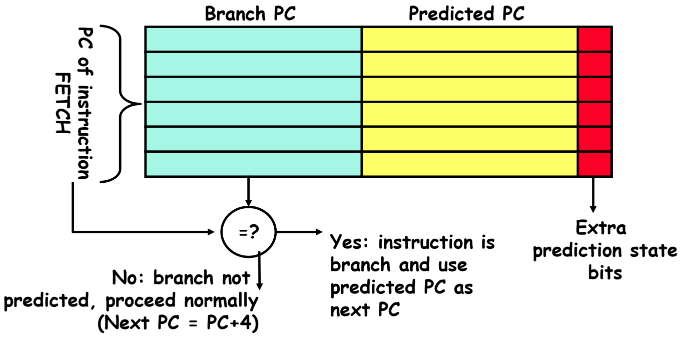
- Profile: branch profile from last execution
  (static in that in encoded in instruction, but profile)

Accuracy v. Size (SPEC89)



Need Address at Same Time as Prediction

- Branch Target Buffer (BTB): Address of branch index to get prediction AND branch address (if taken)
  - Note: must check for branch match now, since can't use wrong branch address (Figure 3.19, p. 262)



Branch PC

Predicted PC

PC of instruction FETCH

=?

No: branch not predicted, proceed normally (Next PC = PC+4)

Yes: instruction is branch and use predicted PC as next PC

Extra prediction state bits

Special Case Return Addresses

- Register Indirect branch hard to predict address
- SPEC89 85% such branches for procedure return
- Since stack discipline for procedures, save return address in small buffer that acts like a stack: 8 to 16 entries has small miss rate

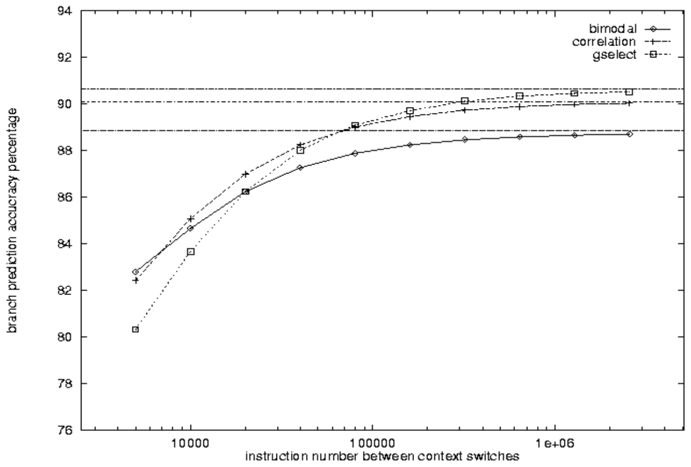
Pitfall: Sometimes bigger and dumber is better

- 21264 uses tournament predictor (29 Kbits)
- Earlier 21164 uses a simple 2-bit predictor with 2K entries (or a total of 4 Kbits)
- SPEC95 benchmarks, 21264 outperforms
  - 21264 avg. 11.5 mispredictions per 1000 instructions
  - 21164 avg. 16.5 mispredictions per 1000 instructions
- Reversed for transaction processing (TP) !
  - 21264 avg. 17 mispredictions per 1000 instructions
  - 21164 avg. 15 mispredictions per 1000 instructions
- TP code much larger & 21164 hold 2X branch predictions based on local behavior (2K vs. 1K local predictor in the 21264)

Warm-up effects and context-switching

- In real life, applications are interrupted and some other program runs for a while (if only the OS)
- This means the branch prediction is regularly trashed
- Simple predictors re-learn fast
  - in 2-bit bimodal predictor, all executions of given branch update same 2 bits
- Sophisticated predictors re-learn more slowly
  - for example, in (2,2) gselect predictor, prediction updates are spread across 4 BHTs
- *Selective* predictor may choose fast learner predictor until better predictor warms up

Warm-up...



- Best predictor takes 20,000 instructions to overtake bimodal

Zhendong Su and Min Zhou, A comparative analysis of branch prediction schemes (http://www.cs.berkeley.edu/~zhendong/cs252/project.html)

Dynamic Branch Prediction Summary

- Prediction becoming important part of scalar execution
- Branch History Table: 2 bits for loop accuracy
  - Saturating counter (bimodal) scheme handles highly-biased branches well
  - Some applications have highly dynamic branches
- Correlation: Recently executed branches correlated with next branch.
  - Either different branches
  - Or different executions of same branches
- Tournament Predictor: more resources to competitive solutions and pick between them
- Branch Target Buffer: include branch address & prediction
- Predicated Execution can reduce number of branches, number of mispredicted branches
- Return address stack for prediction of indirect jump

Branch prediction resources

- Design tradeoffs for the Alpha EV8 Conditional Branch Predictor (André Seznec, Stephen Felix, Venkata Krishnan, Yiannakis Sazeides)
  - SMT: 4 threads, wide-issue superscalar processor, 8-way issue, 512 registers (cancelled June 2001 when Alpha dropped)
  - Paper: http://citeseer.ist.psu.edu/seznec02design.html
  - Talk: http://ce.et.tudelft.nl/cecoll/slides/PresDelft0803.ppt
- Branch prediction in the Pentium family (Agner Fog)
  - Reverse engineering Pentium branch predictors using direct access to BTB
  - http://www.x86.org/articles/branch/branchprediction.htm
- Championship Branch Prediction Competition (CBP-1), organised by the Journal of Instruction-level Parallelism
  - http://www.jilp.org/cbp/

Getting CPI < 1: Issuing Multiple Instructions/Cycle

- Vector Processing: Explicit coding of independent loops as operations on large vectors of numbers
  - Multimedia instructions being added to many processors
- Superscalar: varying no. instructions/cycle (1 to 8), scheduled by compiler or by HW (Tomasulo)
  - IBM PowerPC, Sun UltraSparc, DEC Alpha, Pentium III/4
- (Very) Long Instruction Words (V)LIW: fixed number of instructions (4-16) scheduled by the compiler; put ops into wide templates (TBD)
  - Intel Architecture-64 (IA-64) 64-bit address
    - Renamed: "Explicitly Parallel Instruction Computer (EPIC)"
  - Will discuss shortly
- Anticipated success of multiple instructions lead to Instructions Per Clock cycle (IPC) vs. CPI

Getting CPI < 1: Issuing Multiple Instructions/Cycle

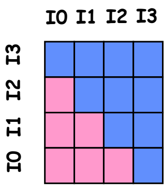
- Superscalar MIPS: 2 instructions, 1 FP & 1 anything
  - Fetch 64-bits/clock cycle; Int on left, FP on right
  - Can only issue 2nd instruction if 1st instruction issues
  - More ports for FP registers to do FP load & FP op in a pair

Type	*Pipe Stages*						
Int. instruction	IF	ID	EX	MEM	WB		
FP instruction	IF	ID	EX	MEM	WB		
Int. instruction		IF	ID	EX	MEM	WB	
FP instruction		IF	ID	EX	MEM	WB	
Int. instruction			IF	ID	EX	MEM	WB
FP instruction			IF	ID	EX	MEM	WB

- 1 cycle load delay expands to 3 instructions in SS
  - instruction in right half can't use it, nor instructions in next slot

Multiple Issue Issues

- issue packet: group of instructions from fetch unit that could potentially issue in 1 clock
  - If instruction causes structural hazard or a data hazard either due to earlier instruction in execution or to earlier instruction in issue packet, then instruction does not issue
  - 0 to N instruction issues per clock cycle, for N-issue
- Performing issue checks in 1 cycle could limit clock cycle time: $O(n^2-n)$ comparisons
  - issue stage usually split and pipelined
  - 1st stage decides how many instructions from within this packet can issue, 2nd stage examines hazards among selected instructions and those already been issued
  - higher branch penalties => prediction accuracy important



Multiple Issue Challenges

- While Integer/FP split is simple for the HW, get CPI of 0.5 only for programs with:
  - Exactly 50% FP operations AND 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; (N-issue ~$O(N^2-N)$ comparisons)
  - Register file: need 2x reads and 1x writes/cycle
  - Rename logic: must be able to rename same register multiple times in one cycle! For instance, consider 4-way issue:

```
add r1, r2, r3              add p11, p4, p7
sub r4, r1, r2      ⇒       sub p22, p11, p4
lw  r1, 4(r4)               lw  p23, 4(p22)
add r5, r1, r2              add p12, p23, p4
```

  Imagine doing this transformation in a single cycle!
  - Result buses: Need to complete multiple instructions/cycle
    - So, need multiple buses with associated matching logic at every reservation station.
    - Or, need multiple forwarding paths

Dynamic Scheduling in Superscalar The easy way

- How to issue two instructions and keep in-order instruction issue for Tomasulo?
  - Assume 1 integer + 1 floating point
  - 1 Tomasulo control for integer, 1 for floating point
- Issue 2X Clock Rate, so that issue remains in order
- Only loads/stores might cause dependency between integer and FP issue:
  - Replace load reservation station with a load queue; operands must be read in the order they are fetched
  - Load checks addresses in Store Queue to avoid RAW violation
  - Store checks addresses in Load Queue to avoid WAR,WAW

Register renaming, virtual registers versus Reorder Buffers

- Alternative to Reorder Buffer is a larger virtual set of registers and register renaming
- Virtual registers hold both architecturally visible registers + temporary values
  - replace functions of reorder buffer and reservation station
- Renaming process maps names of architectural registers to registers in virtual register set
  - Changing subset of virtual registers contains architecturally visible registers
- Simplifies instruction commit: mark register as no longer speculative, free register with old value
- Adds 40-80 extra registers: Alpha, Pentium,…
  - Size limits no. instructions in execution (used until commit)

How much to speculate?

- Speculation Pro: uncover events that would otherwise stall the pipeline (cache misses)
- Speculation Con: speculate costly if exceptional event occurs when speculation was incorrect
- Typical solution: speculation allows only low-cost exceptional events (1st-level cache miss)
- When expensive exceptional event occurs, (2nd-level cache miss or TLB miss) processor waits until the instruction causing event is no longer speculative before handling the event
- Assuming single branch per cycle: aggressive designs may speculate across multiple branches!

Limits to ILP

- Conflicting studies of amount
  - Benchmarks (vectorized Fortran FP vs. integer C programs)
  - Hardware sophistication
  - Compiler sophistication
- How much ILP is available using existing mechanisms with increasing HW budgets?
- Do we need to invent new HW/SW mechanisms to keep on processor performance curve?
  - Intel MMX, SSE (Streaming SIMD Extensions): 64 bit ints
  - Intel SSE2: 128 bit, including 2 64-bit Fl. Pt. per clock
  - Motorola AltiVec: 128 bit ints and FPs
  - Supersparc Multimedia ops, etc.

Limits to ILP

Initial HW Model here; MIPS compilers.

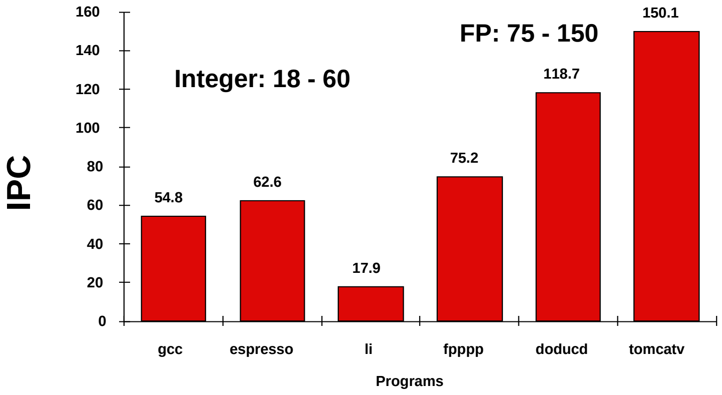
Assumptions for ideal/perfect machine to start:

1. *Register renaming* – infinite virtual registers => all register WAW & WAR hazards are avoided
2. *Branch prediction* – perfect; no mispredictions
3. *Jump prediction* – all jumps perfectly predicted 2 & 3 => machine with perfect speculation & an unbounded buffer of instructions available
4. *Memory-address alias analysis* – addresses are known & a store can be moved before a load provided addresses not equal

Also:
unlimited number of instructions issued/clock cycle;
perfect caches;
1 cycle latency for all instructions (FP *,/);

Upper Limit to ILP: Ideal Machine

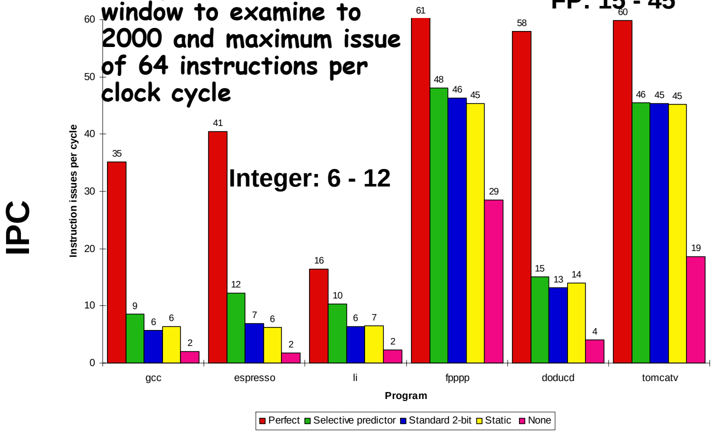
(H&P3ed Figure 3.35, page 242)



More Realistic HW: Branch Impact

cf H&P3ed Figure 3.39, Page 248

Change from Infinite window to examine to 2000 and maximum issue of 64 instructions per clock cycle

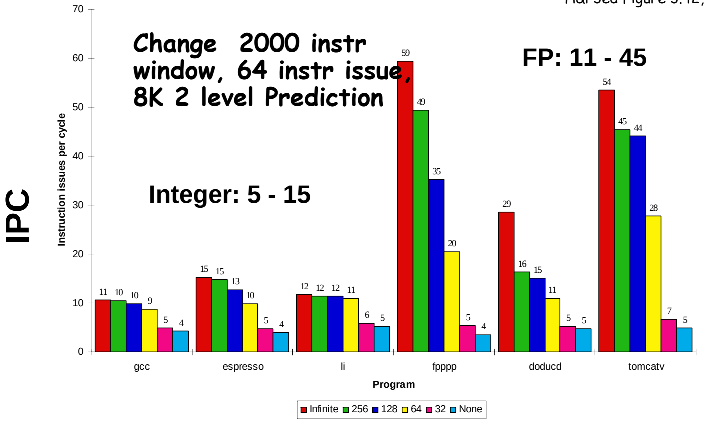


Perfect Tournament BHT (512) Profile No prediction

More Realistic HW: Renaming Register Impact

H&P3ed Figure 3.42, Page 251

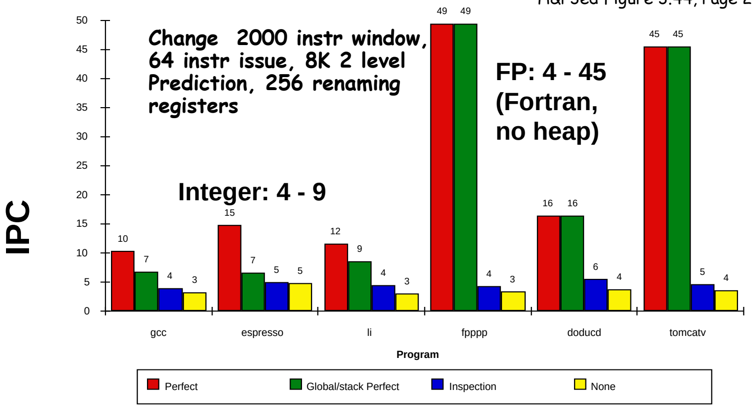
Change 2000 instr window, 64 instr issue, 8K 2 level Prediction



Infinite 256 128 64 32 None

More Realistic HW: Memory Address Alias Impact

H&P3ed Figure 3.44, Page 252



Change 2000 instr window, 64 instr issue, 8K 2 level Prediction, 256 renaming registers

Integer: 4 - 9

FP: 4 - 45 (Fortran, no heap)

Perfect

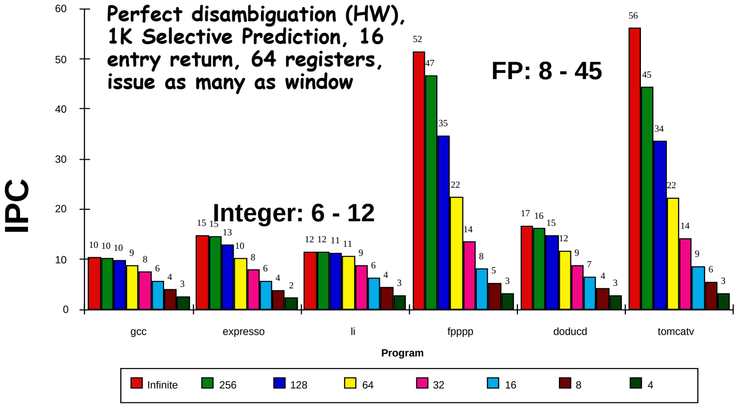
Global/Stack perf; heap conflicts

Inspec. Assem.

None

Realistic HW for '00: Window Impact

(Figure 3.45, Page 309)



Perfect disambiguation (HW), 1K Selective Prediction, 16 entry return, 64 registers, issue as many as window

Integer: 6 - 12

FP: 8 - 45

Infinite 256 128 64 32 16 8 4

Limits to ILP - resources

- Limits of Control Flow on Parallelism .
  Monica S. Lam, Robert P. Wilson.
  19th ISCA, May 1992, pages 19-21.
- Limits of Instruction-Level Parallelism .
  David W. Wall.
  DEC-WRL Research Report 93/6, Nov. 1993
- The Distribution of Instruction-Level and Machine Parallelism and Its Effect on Performance .
  Norman P. Jouppi.
  IEEE Transactions on Computers, Dec. 1989.

How to Exceed ILP Limits of this study?

- WAR and WAW hazards through memory: eliminated WAW and WAR hazards through register renaming, but not in memory usage
- Unnecessary dependences (compiler not unrolling loops so iteration variable dependence)
- Overcoming the data flow limit: value prediction, predicting values and speculating on prediction
  - Address value prediction and speculation predicts addresses and speculates by reordering loads and stores; could provide better aliasing analysis, only need predict if addresses =

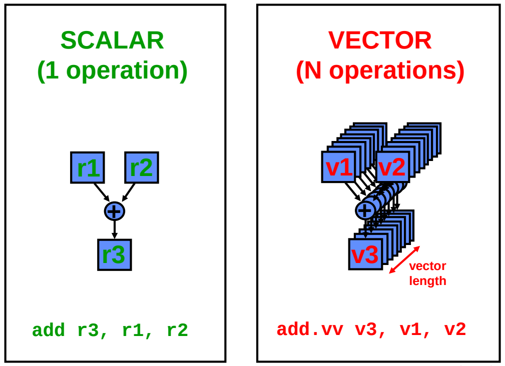
Value Locality and Load Value Prediction. Mikko H. Lipasti, Christopher B. Wilkerson, John Paul Shen. Slides by Kundan Nepal: http://www.lems.brown.edu/~iris/en291s9-04/lectures/kundanvalue_pred.pdf

How to Exceed ILP Limits of this study?

- Vector instructions
  - Next section of this Chapter
- Simultaneous Multi-threading
  - Later section of this Chapter
- Multiprocessors
  - Later Chapter

Alternative Model: Vector Processing

- Vector processors have high-level operations that work on linear arrays of numbers: "vectors"



Properties of Vector Processors

- Each result independent of previous result
  => long pipeline, compiler ensures no dependencies
  => high clock rate
- Vector instructions access memory with known pattern
  => highly interleaved memory
  => amortize memory latency of over - 64 elements
  => no (data) caches required! (Do use instruction cache)
- Reduces branches and branch problems in pipelines
- Single vector instruction implies lots of work (- loop)
  => fewer instruction fetches

Operation & Instruction Count: RISC v. Vector Processor

(from F. Quintana, U. Barcelona.)

Spec92fp	Operations (Millions)			Instructions (M)		
Program	RISC	Vector	R / V	RISC	Vector	R / V
swim256	115	95	1.1x	115	0.8	142x
hydro2d	58	40	1.4x	58	0.8	71x
nasa7	69	41	1.7x	69	2.2	31x
su2cor	51	35	1.4x	51	1.8	29x
tomcatv	15	10	1.4x	15	1.3	11x
wave5	27	25	1.1x	27	7.2	4x
mdljdp2	32	52	0.6x	32	15.8	2x

Vector reduces ops by 1.2X, instructions by 20X

Styles of Vector Architectures

- *memory-memory vector processors*: all vector operations are memory to memory
- *vector-register processors*: all vector operations between vector registers (except load and store)
  - Vector equivalent of load-store architectures
  - Includes all vector machines since late 1980s: Cray, Convex, Fujitsu, Hitachi, NEC
  - We assume vector-register for rest of lectures

Components of Vector Processor

- *Vector Register*: fixed length bank holding a single vector
  - has at least 2 read and 1 write ports
  - typically 8-32 vector registers, each holding 64-128 64-bit elements
- *Vector Functional Units (FUs)*: fully pipelined, start new operation every clock
  - typically 4 to 8 FUs: FP add, FP mult, FP reciprocal (1/X), integer add, logical, shift; may have multiple of same unit
- *Vector Load-Store Units (LSUs)*: fully pipelined unit to load or store a vector; may have multiple LSUs
- *Scalar registers*: single element for FP scalar or address
- Cross-bar to connect FUs , LSUs, registers

"DLXV" Vector Instructions

Instr.	Operands	Operation	Comment
ADDV	V1,V2,V3	V1=V2+V3	vector + vector
ADDSV	V1,F0,V2	V1=F0+V2	scalar + vector
MULTV	V1,V2,V3	V1=V2xV3	vector x vector
MULSV	V1,F0,V2	V1=F0xV2	scalar x vector
LV	V1,R1	V1=M[R1..R1+63]	load, stride=1
LVWS	V1,R1,R2	V1=M[R1..R1+63*R2]	load, stride=R2
LVI	V1,R1,V2	V1=M[R1+V2i,i=0..63]	indir.("gather")
CeqV	VM,V1,V2	VMASKi = (V1i=V2i)?	comp. setmask
MOV	VLR,R1	Vec. Len. Reg. = R1	set vector length
MOV	VM,R1	Vec. Mask = R1	set vector mask

Memory operations

- Load/store operations move groups of data between registers and memory
- Three types of addressing
  - Unit stride
    - Fastest
  - Non-unit (constant) stride
  - Indexed (gather-scatter)
    - Vector equivalent of register indirect
    - Good for sparse arrays of data
    - Increases number of programs that vectorize

DAXPY (Y = a * X + Y)

Assuming vectors X, Y are length 64

Scalar vs. Vector

```
LD     F0,a       ;load scalar a
LV     V1,Rx      ;load vector X
MULTS  V2,F0,V1   ;vector-scalar mult.
LV     V3,Ry      ;load vector Y
ADDV   V4,V2,V3   ;add
SV     Ry,V4      ;store the result
```

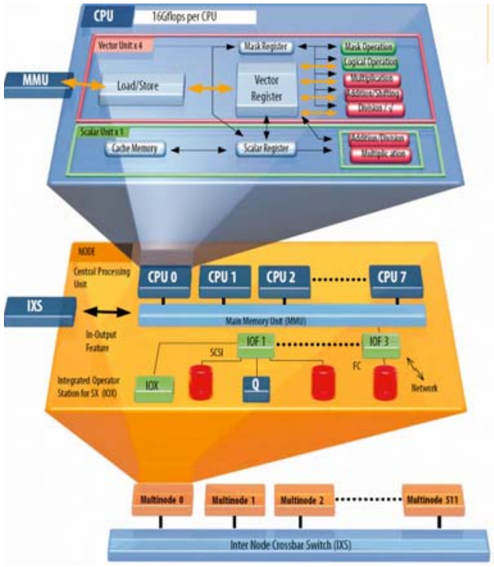
```
      LD    F0,a
      ADDI  R4,Rx,#512      ;last address to load
loop: LD    F2, 0(Rx)       ;load X(i)
      MULTD F2,F0,F2  ;a*X(i)
      LD    F4, 0(Ry) ;load Y(i)
      ADDD  F4,F2, F4 ;a*X(i) + Y(i)
      SD    F4 ,0(Ry) ;store into Y(i)
      ADDI  Rx,Rx,#8  ;increment index to X
      ADDI  Ry,Ry,#8  ;increment index to Y
      SUB   R20,R4,Rx ;compute bound
      BNZ   R20,loop  ;check if done
```

578 (2+9*64) vs.
321 (1+5*64) ops (1.8X)

578 (2+9*64) vs.
6 instructions (96X)

64 operation vectors + no loop overhead

also 64X fewer pipeline hazards



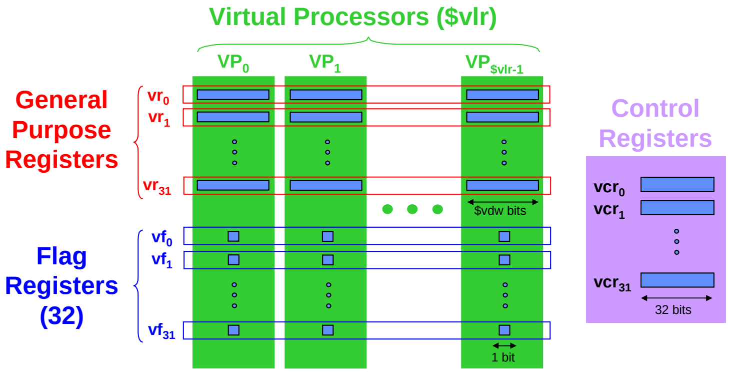
NEC SX-8

- 35 GFLOPs peak per CPU
- Eg University of Stuttgart installation:
  - Peak Performance 12 TFlops
  - 72 nodes, 8 CPUs per node
  - Memory 9.2 TB
  - Disk 160 TB shared disk, 72 * 140 GB local
  - 16GB/s node-to-node interconnect

Virtual Processor Vector Model

- Vector operations are SIMD (single instruction multiple data)operations
- Each element is computed by a virtual processor (VP)
- Number of VPs given by vector length
  - vector control register

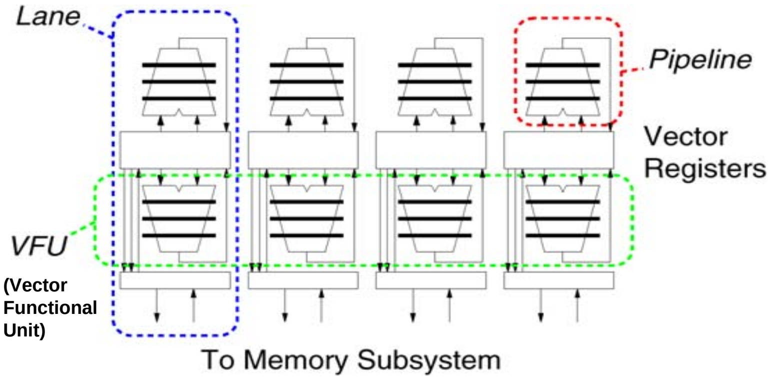
Vector Architectural State



Vector Implementation

- Vector register file
  - Each register is an array of elements
  - Size of each register determines maximum vector length
  - Vector length register determines vector length for a particular operation
- Multiple parallel execution units = "lanes" (sometimes called "pipelines" or "pipes")

Vector Terminology: 4 lanes, 2 vector functional units



Vector Execution Time

- Time = f(vector length, data dependicies, struct. hazards)
- *Initiation rate*: rate that FU consumes vector elements (= number of lanes; usually 1 or 2 on Cray T-90)
- *Convoy*: set of vector instructions that can begin execution in same clock (no struct. or data hazards)
- *Chime*: approx. time for a vector operation
- *m* convoys take *m* chimes; if each vector length is n, then they take approx. *m* x *n* clock cycles (ignores overhead; good approximization for long vectors)

```
1:  LV     V1,Rx       ;load vector X
2:  MULV   V2,F0,V1    ;vector-scalar mult.
    LV     V3,Ry       ;load vector Y
3:  ADDV   V4,V2,V3    ;add
4:  SV     Ry,V4       ;store the result
```

4 conveys, 1 lane, VL=64
=> 4 x 64 - 256 clocks
(or 4 clocks per result)

- *Start-up time*: pipeline latency time (depth of FU pipeline); another sources of overhead
- Operation Start-up penalty (from CRAY-1)
- Vector load/store 12
- Vector multply 7
- Vector add 6

Assume convoys don't overlap; vector length = n:

Convoy	*Start*	*1st result*	*last result*	
1. LV	0	12	11+n (12+n-1)	
2. MULV, LV	12+n	12+n+12	23+2n	*Load start-up*
3. ADDV	24+2n	24+2n+6	29+3n	*Wait convoy 2*
4. SV	30+3n	30+3n+12	41+4n	*Wait convoy 3*

Why startup time for each vector instruction?

- Why not overlap startup time of back-to-back vector instructions?
- Cray machines built from many ECL chips operating at high clock rates; hard to do?
- Berkeley vector design ("T0") didn't know it wasn't supposed to do overlap, so no startup times for functional units (except load)

Vector Load/Store Units & Memories

- Start-up overheads usually longer fo LSUs
- Memory system must sustain (# lanes x word) /clock cycle
- Many Vector Procs. use banks (vs. simple interleaving):

  1) support multiple loads/stores per cycle
  => multiple banks & address banks independently

  2) support non-sequential accesses (see soon)
- Note: No. memory banks > memory latency to avoid stalls
  - *m* banks => *m* words per memory lantecy *l* clocks
  - if *m* < *l*, then gap in memory pipeline:

clock:	0	…	*l*	*l*+1	*l*+2	…	*l*+*m*- 1	l+m	…	2 *l*
word:	--	…	0	1	2	…	*m*-1	--	…	*m*

  - may have 1024 banks in SRAM

Vector Length

- What to do when vector length is not exactly 64?
- *vector-length register* (VLR) controls the length of any vector operation, including a vector load or store. (cannot be > the length of vector registers)

```
     do 10 i = 1, n
10   Y(i) = a * X(i) + Y(i)
```

- Don't know n until runtime!
  n > Max. Vector Length (MVL)?

Strip Mining

- Suppose Vector Length > Max. Vector Length (MVL)?
- *Strip mining*: generation of code such that each vector operation is done for a size Š to the MVL
- 1st loop do short piece (n mod MVL), rest VL = MVL

```
     low = 1
     VL = (n mod MVL)  /*find the odd size piece*/
     do 1 j = 0,(n / MVL)  /*outer loop*/
       do 10 i = low,low+VL-1  /*runs for length VL*/
             Y(i) = a*X(i) + Y(i)  /*main operation*/
10     continue
       low = low+VL  /*start of next vector*/
       VL = MVL  /*reset the length to max*/
1      continue
```

Common Vector Metrics

- R_{∞}: MFLOPS rate on an infinite-length vector
  - vector "speed of light"
  - Real problems do not have unlimited vector lengths, and the start-up penalties encountered in real problems will be larger
  - (R_n is the MFLOPS rate for a vector of length n)
- $N_{1/2}$: The vector length needed to reach one-half of R_{∞}
  - a good measure of the impact of start-up
- N_V: The vector length needed to make vector mode faster than scalar mode
  - measures both start-up and speed of scalars relative to vectors, quality of connection of scalar unit to vector unit

Vector Stride

- Suppose adjacent elements not sequential in memory

```
  do 10 i = 1,100
      do 10 j = 1,100
             A(i,j) = 0.0
             do 10 k = 1,100
10                  A(i,j) = A(i,j)+B(i,k)*C(k,j)
```

- Either B or C accesses not adjacent (800 bytes between)
- *stride*: distance separating elements that are to be merged into a single vector (caches do unit stride) => LVWS (load vector with stride) instruction
- Strides => can cause bank conflicts (e.g., stride = 32 and 16 banks)
- Think of address per vector element

Compiler Vectorization on Cray XMP

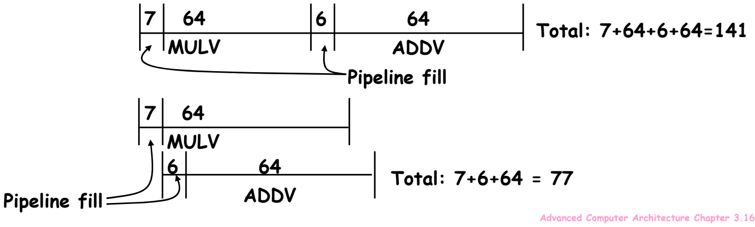
Benchmark	%FP	%FP in vector	
ADM	23%	68%	
DYFESM	26%	95%	
FLO52	41%	100%	
MDG	28%	27%	
MG3D	31%	86%	
OCEAN	28%	58%	
QCD	14%	1%	
SPICE	16%	7%	(1% overall)
TRACK	9%	23%	
TRFD	22%	10%	

Vector Opt #1: Chaining

- Suppose:

```
MULV    V1,V2,V3
ADDV    V4,V1,V5   ; separate convoy?
```

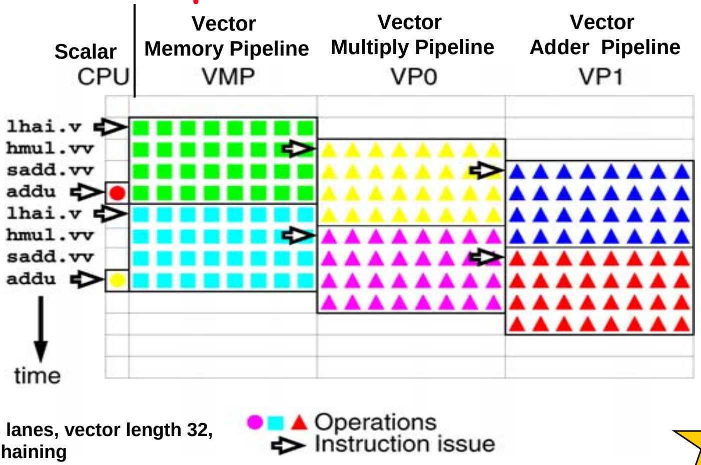
- *chaining*: vector register (V1) is not as a single entity but as a group of individual registers, then pipeline forwarding can work on individual elements of a vector
- *Flexible chaining*: allow vector to chain to any other active vector operation => more read/write port
- As long as enough HW, increases convoy size



Total: 7+64+6+64=141

Total: 7+6+64 = 77

Example Execution of Vector Code



8 lanes, vector length 32, chaining

Vector Opt #2: Conditional Execution

- Suppose:

```
    do 100 i = 1, 64
          if (A(i) .ne. 0) then
                A(i) = A(i) – B(i)
          endif
100 continue
```

- *vector-mask control* takes a Boolean vector: when *vector-mask register* is loaded from vector test, vector instructions operate only on vector elements whose corresponding entries in the vector-mask register are 1.
- Still requires clock even if result not stored; if still performs operation, what about divide by 0?

Vector Opt #3: Sparse Matrices

- Suppose:

```
            do   100 i = 1,n
100         A(K(i)) = A(K(i)) + C(M(i))
```

- *gather* (LVI) operation takes an *index vector* and fetches the vector whose elements are at the addresses given by adding a base address to the offsets given in the index vector => a nonsparse vector in a vector register
- After these elements are operated on in dense form, the sparse vector can be stored in expanded form by a *scatter* store (SVI), using the same index vector
- Can't be done by compiler since can't know Ki elements distinct, no dependencies; by compiler directive
- Use CVI to create index 0, 1xm, 2xm, ..., 63xm

Sparse Matrix Example

- Cache (1993) vs. Vector (1988)

	IBM RS6000	Cray YMP
Clock	72 MHz	167 MHz
Cache	256 KB	0.25 KB
Linpack	140 MFLOPS	160 (1.1)
Sparse Matrix (Cholesky Blocked)	17 MFLOPS	125 (7.3)

- Cache: 1 address per cache block (32B to 64B)
- Vector: 1 address per element (4B)

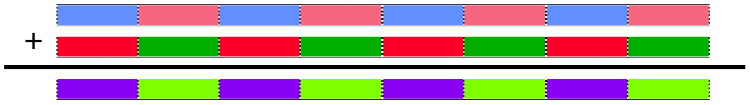
Applications

Limited to scientific computing?

- **Multimedia Processing** (compress., graphics, audio synth, image proc.)
- **Standard benchmark kernels** (Matrix Multiply, FFT, Convolution, Sort)
- **Lossy Compression** (JPEG, MPEG video and audio)
- **Lossless Compression** (Zero removal, RLE, Differencing, LZW)
- **Cryptography** (RSA, DES/IDEA, SHA/MD5)
- **Speech and handwriting recognition**
- **Operating systems/Networking** (memcpy, memset, parity, checksum)
- **Databases** (hash/join, data mining, image/video serving)
- **Language run-time support** (stdlib, garbage collection)
- **even SPECint95**

Vector for Multimedia?

- Intel MMX/SSE instruction set extensions
  - Similar extensions on other processor families, eg PowerPC AltiVec
- Idea: pack multiple short-word operands into one long register
  - Eg 128-bit register
    - 2 64-bit doubles
    - 4 32-bit floats or ints
    - 8 16-bit ints or fixed-point
    - 16 8-bit ints
    - Often with media-specific instructions eg saturated arithmetic



- Claim: overall speedup 1.5 to 2X for 2D/3D graphics, audio, video, speech, comm., ...
  - Initially hand-coded, accessible using special intrinsic functions
  - Delivered via libraries such as the Intel Performance Primitives (IPP)
  - Some support from compilers such as Intel's, but awkward constraints (eg alignment of operands)

Mediaprocessing: Vectorizable? Vector Lengths?

Kernel	Vector length
Matrix transpose/multiply	# vertices at once
DCT (video, communication)	image width
FFT (audio)	256-1024
Motion estimation (video)	image width, iw/16
Gamma correction (video)	image width
Haar transform (media mining)	image width
Median filter (image processing)	image width
Separable convolution (img. proc.)	image width

(from Pradeep Dubey - IBM,
`http://www.research.ibm.com/people/p/pradeep/tutor.html`)

Vector Pitfalls

- Pitfall: Concentrating on peak performance and ignoring start-up overhead: N_V (length faster than scalar) > 100!
- Pitfall: Increasing vector performance, without comparable increases in scalar performance
  (Amdahl's Law)
  - failure of Cray competitor from his former company
- Pitfall: Good processor vector performance without providing good memory bandwidth
  - MMX?

Vector Advantages

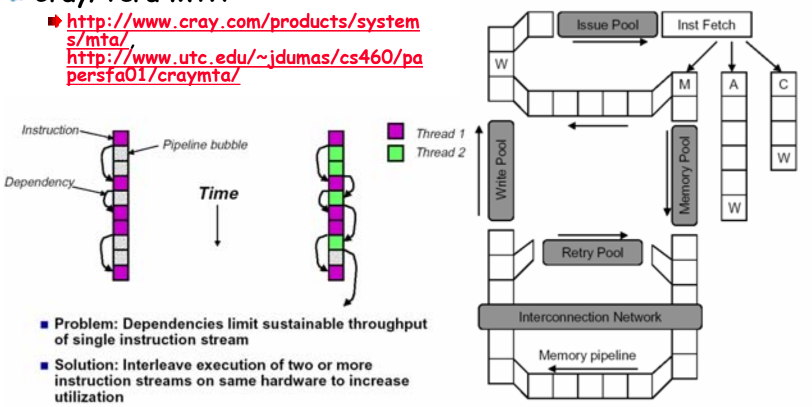
- Easy to get high performance; N operations:
  - are independent
  - use same functional unit
  - access disjoint registers
  - access registers in same order as previous instructions
  - access contiguous memory words or known pattern
  - can exploit large memory bandwidth
  - hide memory latency (and any other latency)
- Scalable (get higher performance as more HW resources available)
- Compact: Describe N operations with 1 short instruction (v. VLIW)
- Predictable (real-time) performance vs. statistical performance (cache)
- Multimedia ready: choose N * 64b, 2N * 32b, 4N * 16b, 8N * 8b
- Mature, developed compiler technology
- Vector Disadvantage: Out of Fashion

Vector Summary

- Alternate model accommodates long memory latency, doesn't rely on caches as does Out-Of-Order, superscalar/VLIW designs
- Much easier for hardware: more powerful instructions, more predictable memory accesses, fewer hazards, fewer branches, fewer mispredicted branches, ...
- What % of computation is vectorizable?
- Is vector a good match to new apps such as multimedia, DSP?

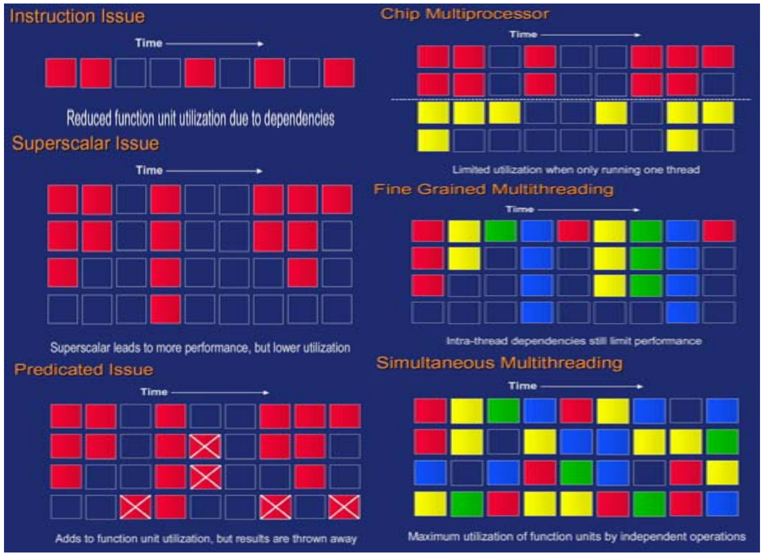
Beyond ILP: Multithreading, Simultaneous Multithreading (SMT)

- Cray/Tera MTA
  - http://www.cray.com/products/systems/mta/, http://www.utc.edu/~jdumas/cs460/papersfa01/craymta/



- Problem: Dependencies limit sustainable throughput of single instruction stream
- Solution: Interleave execution of two or more instruction streams on same hardware to increase utilization

(Source: Asanovic http://www.cag.lcs.mit.edu/6.893-f2000/lectures/l06-tera.pdf)



Instruction Issue

Reduced function unit utilization due to dependencies

Superscalar Issue

Superscalar leads to more performance, but lower utilization

Predicated Issue

Adds to function unit utilization, but results are thrown away

Chip Multiprocessor

Limited utilization when only running one thread

Fine Grained Multithreading

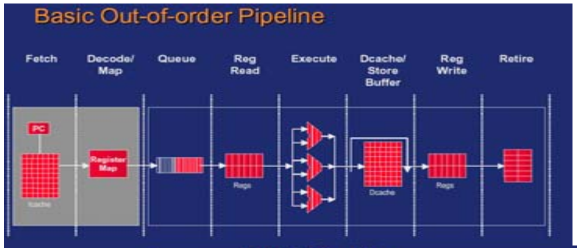
Intra-thread dependencies still limit performance

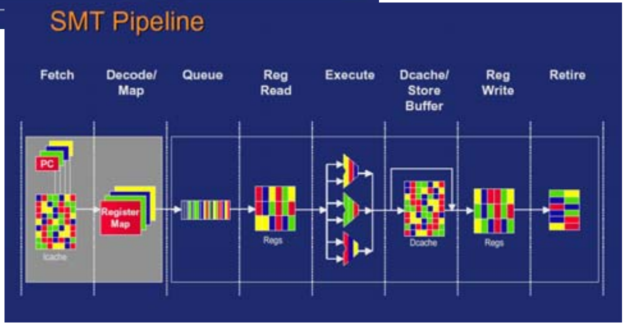
Simultaneous Multithreading

Maximum utilization of function units by independent operations

Compaq Alpha 21464 - http://research.ac.upc.es/pact01/keynotes/emer.pdf

SMT

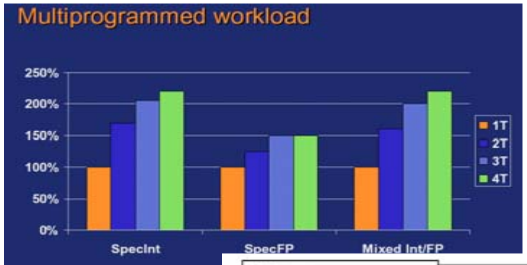




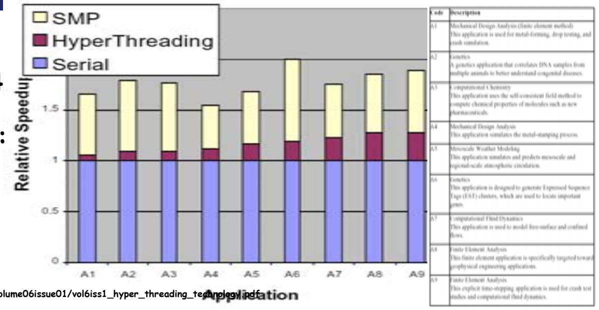
- Alpha 21464
- One CPU with 4 Thread Processing Units (TPUs)
- "6% area overhead over single-thread 4-issue CPU"

SMT performance

- Alpha 21464



- Intel Pentium 4 with hyperthreading:



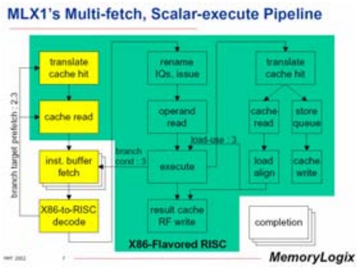
Code	Description
A1	Mechanical Design Analysis (finite element method) This application is used for metal-forming, drop testing, and crash simulation.
A2	Genetics A genetics application that correlates DNA samples from multiple animals to better understand congenital diseases.
A3	Computational Chemistry This application uses the self-consistent field method to compute chemical properties of molecules such as new pharmaceuticals.
A4	Mechanical Design Analysis This application simulates the metal-stamping process.
A5	Mesoscale Weather Modeling This application simulates and predicts mesoscale and regional-scale atmospheric circulation.
A6	Genetics This application is designed to generate Expressed Sequence Tags (EST) clusters, which are used to locate important genes.
A7	Computational Fluid Dynamics This application is used to model free-surface and confined flows.
A8	Finite Element Analysis This finite element application is specifically targeted toward geophysical engineering applications.
A9	Finite Element Analysis This explicit time-stepping application is used for crash test studies and computational fluid dynamics.

http://www.intel.com/technology/itj/2002/volume06issue01/vol6iss1_hyper_threading_technology.pdf

Beyond ILP: Multithreading, Simultaneous Multithreading (SMT)

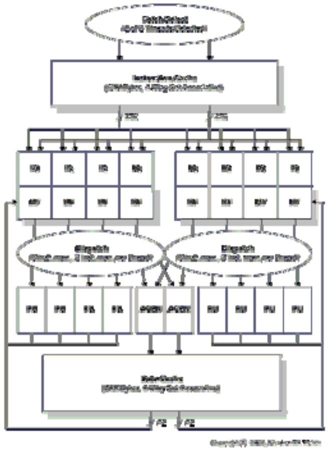
MLX1 - A Tiny Multithreaded 586 Core for Smart Mobile Devices

- http://www.cs.washington.edu/research/smt/memoryLogix.pdf
- "A tiny 'synthesis-friendly' 586 core for SoC solutions"
- For smart mobile devices that demand high MIPS / W
- Uses SMT to deliver more performance in smaller die area
- Leverages from the PC platform"



SMT in a network processor

- Clearwater Networks CNP810SP
  - http://www.zytek.com/~melvin/clearwater.html
  - 8 threads execute simultaneously, utilizing variable number of resources on a cycle by cycle basis.
  - In each cycle 0-3 instructions can be executed from each of the threads depending on instruction dependencies and availability of resources
  - Maximum IPC of the entire core is 10
  - In each cycle two threads are selected for fetch and their respective program counters (PCs) are supplied to the dual-ported instruction cache
  - Each port supplies eight instructions, so there is a maximum fetch bandwidth of 16 instructions
  - The two threads chosen for fetch in each cycle are the two that have the fewest number of instructions in their respective IQs
  - The 8 threads are divided into two clusters of 4 for ease of implementation.
  - Thus the dispatch logic is split into two groups where each group dispatches up to six instructions from four different threads
  - Eight function units are grouped into two sets of four, each set dedicated to a single cluster
  - There are also two ports to the data cache that are shared by both clusters.
  - A maximum of 10 instructions can be dispatched in each cycle. The function units are fully bypassed so that dependent instructions can be dispatched in successive cycles.



Conclusion

- 1985-2000: 1000X performance
  - Moore's Law transistors/chip => Moore's Law for Performance/MPU
- "industry been following a roadmap of ideas known in 1985 to exploit Instruction Level Parallelism and (real) Moore's Law to get 1.55X/year"
  - Caches, Pipelining, Superscalar, Branch Prediction, Out-of-order execution, …
- ILP limits: To make performance progress in future need to have explicit parallelism from programmer vs. implicit parallelism of ILP exploited by compiler, HW?
  - Otherwise drop to old rate of 1.3X per year?
  - Less than 1.3X because of processor-memory performance gap?
- Impact on you: if you care about performance, better think about explicitly parallel algorithms vs. rely on ILP?