

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

ILP vs. Parallel Computers

Dynamic Scheduling (Section 3.4, 3.5)

Dynamic Branch Prediction (Section 3.3, 3.9, and Appendix C)

Hardware Speculation and Precise Interrupts (Section 3.6)

Multiple Issue (Section 3.7)

Static Techniques (Section 3.2, Appendix H)

Limitations of ILP

Multithreading (Section 3.11)

Putting it Together (Mini-projects)

## ***Beyond Pipelining (Section 3.7)***

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### Limits on Pipelining

- Latch overheads & signal skew

- Unpipelined instruction issue logic (Flynn limit:  $CPI \geq 1$ )

### Two techniques for parallelism in instruction issue

#### Superscalar or multiple issue

- Hardware determines which of next  $n$  instructions can issue in parallel

- Maybe statically or dynamically scheduled

#### VLIW – Very Long Instruction Word

- Compiler packs multiple independent operations into an instruction

# Simple 5-Stage Superscalar Pipeline

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	1	2	3	4	5	6	7	8	9
$i$	IF	ID	EX	MEM	WB				
$i+1$	IF	ID	EX	MEM	WB				
$i+2$		IF	ID	EX	MEM	WB			
$i+3$		IF	ID	EX	MEM	WB			
$i+4$			IF	ID	EX	MEM	WB		
$i+5$			IF	ID	EX	MEM	WB		
$i+6$				IF	ID	EX	MEM	WB	
$i+7$				IF	ID	EX	MEM	WB	
$i+8$					IF	ID	EX	MEM	WB
$i+9$					IF	ID	EX	MEM	WB

## *Superscalar, cont.*

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- IF      Parallel access to I-cache  
        Require alignment?
  - ID      Replicate logic  
        Fixed-length instructions?  
        HANDLE INTRA-CYCLE HAZARDS
  - EX      Parallel/pipelined (as before)
  - MEM    > 1 per cycle?  
        If so, hazards & multi-ported D-cache
  - WB      Different register files?  
        Multi-ported register files?
- Progression:    Integer + floating-point  
                  Any two instructions  
                  Any four instructions  
                  Any n instructions?

## *Example Superscalar*

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Assume two instructions per cycle

One integer, load/store, or branch

One floating point

Could require 64-bit alignment and ordering of instruction pair.

I F	I F	F I
I F	F I	F I
OK	NOT OK	NOT OK

Best case

$CPI = 0.5$

But ....

## *Superscalar (Cont.)*

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Hazards are a big problem

Loads

Latency is 1 cycle

Was 1 instruction

NOW 3 instructions

Branches

NOW 3 instructions

Floating point loads and stores

May cause structural hazards

Additional ports?

Additional stalls?

Parallelism required =

# ***Static Techniques for ILP - VLIW Processors***

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VLIW = Very Long Instruction Word Processors

Static multiple issue

Compiler packs multiple *independent* operations into an instruction

Like horizontal microcode

Versus Superscalar

# *Limitations of Multi-Issue Machines*

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Inherent limitations of ILP

Difficulties in building hardware

- Increase ports to registers

- Increase ports to memory

- Duplicate FUs

- Decoding in superscalar and impact on clock rate

Limitations specific to VLIW

- Code size, binary compatibility



# *Compiler Techniques to Expose ILP*

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Many compiler techniques exist

Several used for multiprocessors as well

Our focus on techniques specifically for ILP

# Loop Unrolling (Section 3.2)

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## Add scalar to vector

```
Loop: L.D F0, 0(R1)
      stall
      ADD.D F4, F0, F2
      stall
      stall
      S.D 0(R1), F4
      DSUBUI R1, R1, #8
      stall
      BNEZ R1, Loop
      stall
```

## With scheduling

```
Loop: L.D F0, 0(R1)
      DSUBUI R1, R1, #8
      ADD.D F4, F0, F2
      stall
      BNEZ R1, Loop ; Assume delayed branch
      S.D 8(R1), F4
```

# Loop Unrolling

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## Unrolling the loop

```
Loop:  L.D F0, 0(R1)
      ADD.D F4, F0, F2
      S.D 0(R1), F4
      L.D F6, -8(R1)
      ADD.D F8, F6, F2
      S.D -8(R1), F8
      L.D F10, -16(R1)
      ADD.D F12, F10, F2
      S.D -16(R1), F12
      L.D F14, -24(R1)
      ADD.D F16, F14, F2
      S.D -24(R1), F16
      DSUBUI R1, R1, #32
      BNEZ R1, Loop; Assume delayed branch
```

## Rename registers

Remove some branch overhead (calculate intermediate values)

# Loop Unrolling

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## Scheduling the loop for simple pipeline

```
Loop:  L.D F0, 0(R1)
      L.D F6, -8(R1)
      L.D F10, -16(R1)
      L.D F14, -24(R1)
      ADD.D F4, F0, F2
      ADD.D F8, F6, F2
      ADD.D F12, F10, F2
      ADD.D F16, F14, F2
      S.D 0(R1), F4
      S.D -8(R1), F8
      S.D -16(R1), F12
      DSUBUI R1, R1, #32
      BNEZ R1, Loop ; Assume delayed branch
      S.D 8(R1), F16
```

How to schedule for multiple issue?

# ***Software Pipelining (Section H.3)***

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Pipeline loops in software

Pipelined loop iteration

- Executes instructions from multiple iterations of original loop

- Separates dependent instructions

Less code than unrolling

# Software Pipelining – Example

```

sum = 0.0;
for (i=1; i<=N; i++) {      ; sum = sum + a[i]*b[i]
    load a[i]                ; Ai
    load b[i]                ; Bi
    mult ab[i]               ; *i
    add sum[i]               ; +i
}

```

```

sum = 0.0;
START-UP-BLOCK
for (i=3; i<=N; i++) {
    load a[i]                ; Ai
    load b[i]                ; Bi
    mult ab[i-1]             ; *i-1
    add sum[i-2]             ; +i-2
}
FINISH-UP-BLOCK

```

START-UP		LOOP			FINISH-UP	
START-UP		i=3 ...	i=N	FINISH-UP		
-----		---	---	-----		
A1	A2	A3	Ai	AN		
B1	B2	B3	Bi	BN		
	*1	*2	*i-1	*N-1	*N	
		+1	+i-2	+N-2	+N-1	+N

# *Global Scheduling*

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Loop unrolling and software pipelining work well for straightline code

What if code has branches?

Global scheduling techniques

- Trace scheduling

# *Trace Scheduling*

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Compiler predicts most frequently executed execution path (trace)

Schedules this path and inserts repair code for mispredictions



# Trace Scheduling - Example

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```
b[i] = ``old''
a[i] =
if (a[i] == 0) then
    b[i] = ``new''; common case
else
    X
endif
c[i] =
```

Until done

- Select most common path - a trace
- Schedule trace across basic blocks
- Repair other paths

trace to be scheduled:

```
b[i] = ``old''
a[i] =
b[i] = ``new''
c[i] =
if (a[i] != 0) goto A
```

B:

repair code:

```
A: restore old b[i]
    X
    maybe recalculate c[i]
    goto B
```

# ***Hardware Support to Expose Compile-Time ILP***

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Compiler scheduling limited by knowledge of branch behavior

Hardware support to help compiler

- Predicated (or guarded or conditional) instructions

- Hardware support for compiler speculation

## ***Predicated Instructions (Section H.4)***

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Used to convert control dependence to data dependence

Instruction executed based on a predicate (or guard or condition)

If condition is false, then no result write or exceptions

# Predicated Instructions (Cont.)

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Example

```
if (condition) then {  
    A = B;  
}  
...
```

Convert to:

```
R1 ← result of condition evaluation  
A = B predicated on R1  
...
```

Hardware can schedule instructions across the branch

Alpha, MIPS, PowerPC, SPARC V9, x86 (Pentium) have conditional moves

IA-64 has general predication - 64 1-bit predicate bits

Limitations

Takes a clock even if annulled

## ***Hardware Support for Compiler Speculation (Section H.5)***

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Successful compiler scheduling requires

Preservation of exception behavior on speculation

Mechanism to speculatively reorder memory operations

# *Hardware for Preserving Exception Behavior*

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What if there is an exception on a speculative instruction?

Distinguish between two classes of exceptions

(1) Indicate program error and require termination (e.g., protection violation)

(2) Can be handled and program resumed (e.g., page fault)

Type (2) can be handled immediately even for speculative instructions

Type (1) requires more support

Poison bits

# *Poison Bits*

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Hardware support

- A poison bit for each register

- A speculation bit for each instruction

If a speculative instruction sees an exception

- it sets poison bit of destination

If a speculative instruction sees poison bit set for source

- it propagates poison bit to its destination

If normal instruction sees poison bit for source, takes exception

Normal instruction resets poison bit of destination register

# *Hardware for Memory Speculation*

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How to reorder memory ops if compiler is not sure of addresses?

Consider moving a load

- Insert a special check instruction at original location of load

- When load is executed, hardware saves its address

- If there is a store to L's address before the check instruction

  - Redo load

  - Branch to fix up code if other instructions already used load's value