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)

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Beyond Pipelining (Section 3.7)

Limits on Pipelining

- Latch overheads & signal skew
- Unpipelined instruction issue logic (Flynn limit: CPI ≥ 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

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Simple 5-Stage Superscalar Pipeline

```
      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
```

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Superscalar, cont.

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?

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Example Superscalar

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 ....

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Superscalar (Cont.)

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 =

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Static Techniques for ILP - VLIW Processors

VLIW = Very Long Instruction Word Processors

Static multiple issue

- Compiler packs multiple *independent* operations into an instruction
- Like horizontal microcode

Versus Superscalar

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Limitations of Multi-Issue Machines

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

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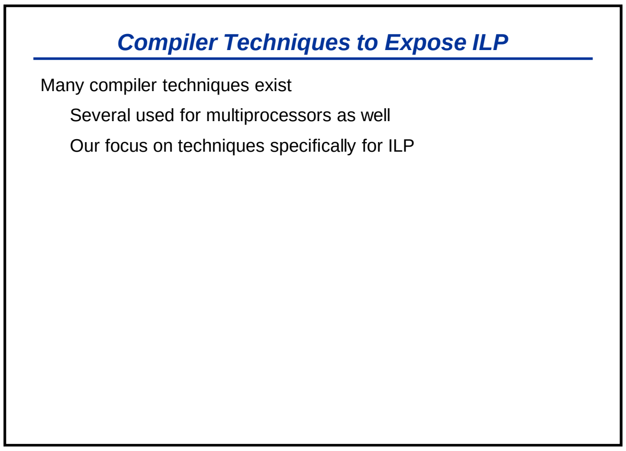

Compiler Techniques to Expose ILP

Many compiler techniques exist

- Several used for multiprocessors as well
- Our focus on techniques specifically for ILP

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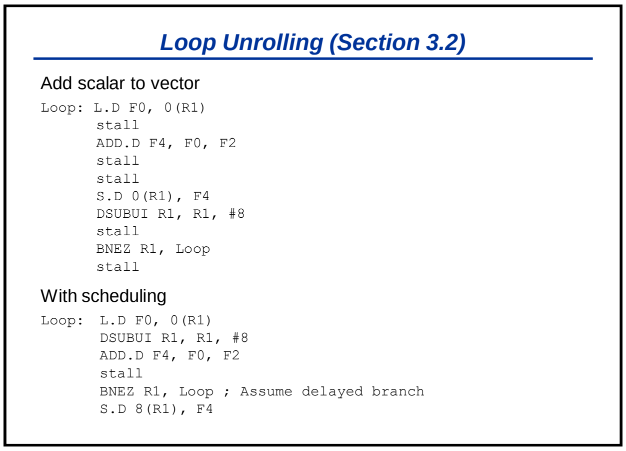

Loop Unrolling (Section 3.2)

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
```

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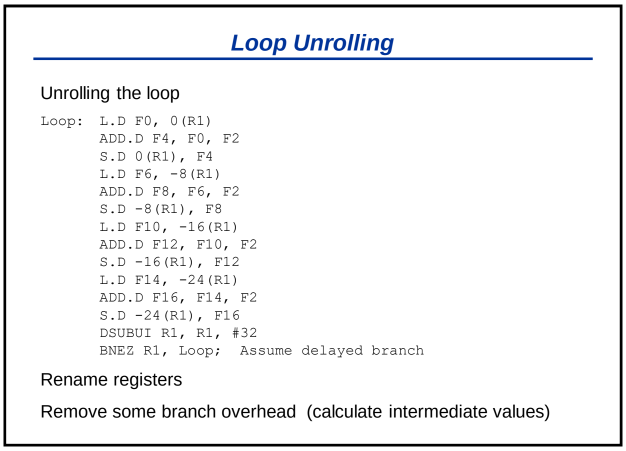

Loop Unrolling

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)

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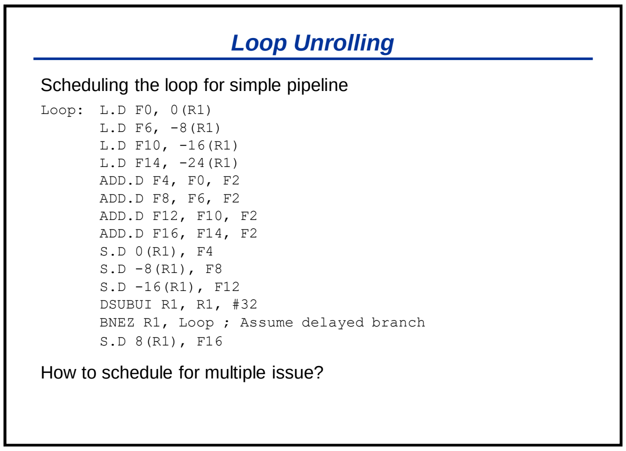

Loop Unrolling

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?

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Software Pipelining (Section H.3)

Pipeline loops in software

Pipelined loop iteration

- Executes instructions from multiple iterations of original loop
- Separates dependent instructions

Less code than unrolling

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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
```

```
                  LOOP
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
```

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Global Scheduling

Loop unrolling and software pipelining work well for straightline code

What if code has branches?

Global scheduling techniques

- Trace scheduling

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Trace Scheduling

Compiler predicts most frequently executed execution path (trace)

Schedules this path and inserts repair code for mispredictions

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Trace Scheduling - Example

```
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
```

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Hardware Support to Expose Compile-Time ILP

Compiler scheduling limited by knowledge of branch behavior

Hardware support to help compiler

- Predicated (or guarded or conditional) instructions
- Hardware support for compiler speculation

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Predicated Instructions (Section H.4)

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

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Predicated Instructions (Cont.)

Example

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

Convert to:

`R1` $\leftarrow$ 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

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Hardware Support for Compiler Speculation (Section H.5)

Successful compiler scheduling requires

- Preservation of exception behavior on speculation
- Mechanism to speculatively reorder memory operations

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Hardware for Preserving Exception Behavior

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

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Poison Bits

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

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Hardware for Memory Speculation

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

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