13 November – Homework #4 Due

Project Proposals

Should receive comments by end of week.
OoO Superscalar Complexity

Out-of-order Superscalar
- Objective: Increase instruction-level parallelism.
- Cost: Hardware logic/mechanisms to track dependencies and dynamically schedule independent instructions.

Hardware Complexity
- Instructions can issue, complete out-of-order.
- Instructions must commit in-order
- Implement Tomasulo’s algorithm with a variety of structures
- Example: Reservation stations, reorder buffer, physical register file

Very Long Instruction Word (VLIW)
- Objective: Increase instruction-level parallelism.
- Cost: Software compilers/mechanisms to track dependencies and statically schedule independent instructions.
Review of Fetch/Decode

Fetch
- Load instruction by accessing memory at program counter (PC)
- Update PC using sequential address (PC+4) or branch prediction (BTB)

Decode/Rename
- Take instruction from fetch buffer
- Allocate resources, which are necessary to execute instruction:
  1. Destination physical register – if instruction writes a register, rename
  2. Reorder buffer (ROB) entry – support in-order commit
  3. Issue queue entry – hold instruction as it waits for execution
  4. Memory buffer entry – resolve dependencies through memory (next slide)
- Stall if resources unavailable
- Rename source/destination registers
- Update reorder buffer, issue queue, memory buffer
Review of Memory Buffer

Allocate memory buffer entry

Store Instructions
- Calculate store-address and place in buffer
- Take store-data and place in buffer
- Instruction commits in-order when store-address, store-data ready

Load Instructions
- Calculate load-address and place in buffer
- Instruction searches memory buffer for stores with matching address
- Forward load data from in-flight stores with matching address
- Stall load if buffer contains stores with un-resolved addresses
Review of Issue/Execute

Issue
- Instruction commits from reorder buffer
- A commit wakes-up an instruction by marking its sources ready
- Select logic determines which ready instructions should execute
- Issue when by sending instructions to functional unit

Execute
- Read operands from physical register file and/or forwarding path
- Execute instruction in functional unit
- Write result to physical register file, store buffer
- Produce exception status
- Write to reorder buffer
Review of Commit

Commit
- Instructions can complete and update reorder buffer out-of-order
- Instructions commit from reorder buffer in-order

Exceptions
- Check for exceptions
- If exception raised, flush pipeline
- Jump to exception handler

Release Resources
- Free physical register used by last writer to same architected register
- Free reorder buffer slot
- Free memory buffer slot
Control Logic Scaling

- Lifetime (L) – number of cycles an instruction spends in pipeline
- Lifetime depends on pipeline latency, time spent in reorder buffer
- Issue width (W) – maximum number of instructions issued per cycle

- As W increases, issue logic must find more instructions to execute in parallel and keep pipeline busy.
- More instructions must be fetched, decoded, and queued.
- \( W \times L \) instructions can impact any of the \( W \) issuing instructions (e.g. forwarding) and growth in hardware proportional to \( W \times (W \times L) \)
Control Logic (MIPS R10000)
Sequential Instruction Sets

Sequential source code

\[ a = \text{foo}(b); \]
\[ \text{for} \ (i=0, \ i<n) \]

Superscalar compiler

Find independent operations

Schedule operations

Sequential machine code

Superscalar processor

Check instruction dependencies

Schedule execution
Sequential Instruction Sets

Superscalar Compiler
- Takes sequential code (e.g., C, C++)
- Check instruction dependencies
- Schedule operations to preserve dependencies
- Produces sequential machine code (e.g., MIPS)

Superscalar Processor
- Takes sequential code (e.g., MIPS)
- Check instruction dependencies
- Schedule operations to preserve dependencies

Inefficiency of Superscalar Processors
- Performs dependency, scheduling dynamically in hardware
- Expensive logic rediscovers schedules that a compiler could have found
VLIW – Very Long Instruction Word

- Multiple operations packed into one instruction format
- Instruction format is fixed, each slot supports particular instruction type
- Constant operation latencies are specified (e.g., 1 cycle integer op)
- Software schedules operations into instruction format, guaranteeing
  (1) Parallelism within an instruction – no RAW checks between ops
  (2) No data use before ready – no data interlocks/stalls

|----------|----------|----------|----------|---------|---------|

Two Integer Units, Single Cycle Latency

Two Load/Store Units, Three Cycle Latency

Two Floating-Point Units, Four Cycle Latency
VLIW Compiler Responsibilities

Schedule operations to maximize parallel execution
- Fill operation slots

Guarantee intra-instruction parallelism
- Ensure operations within same instruction are independent

Schedule to avoid data hazards
- Separate options with explicit NOPs
for (i=0; i<N; i++)

loop: ld f1, 0(r1)
  add r1, 8
  fadd f2, f0, f1
  sd f2, 0(r2)
  add r2, 8
  bne r1, r3, loop

- The latency of each instruction is fixed (e.g., 3 cycle ld, 4 cycle fadd)
- Instr-1: Load A[i] and increment i (r1) in parallel
- Instr-2: Wait for load
- Instr-3: Wait for add. Store B[i], increment i (r2), branch in parallel
- How many flops / cycle? \( \frac{1 \text{ fadd}}{8 \text{ cycles}} = 0.125 \)
Loop Unrolling

- Unroll inner loop to perform \( k \) iterations of computation at once.
- If \( N \) is not a multiple of unrolling factor \( k \), insert clean-up code.
- Example: unroll inner loop to perform 4 iterations at once

```c
for (i=0; i<N; i++)
```

```c
for (i=0; i<N; i+=4)
{
}
```
Scheduling Unrolled Loops

loop:  ld f1, 0(r1)
       ld f2, 8(r1)
       ld f3, 16(r1)
       ld f4, 24(r1)
       add r1, 32
       fadd f5, f0, f1
       fadd f6, f0, f2
       fadd f7, f0, f3
       fadd f8, f0, f4
       sd f5, 0(r2)
       sd f6, 8(r2)
       sd f7, 16(r2)
       sd f8, 24(r2)
       add r2, 32
       bne r1, r3, loop

- Unroll loop to execute 4 iterations
- Reduces number of empty operation slots
- How many flops/cycle? 4 fadds / 11 cycles = 0.36
Software Pipelining

Exploit independent loop iterations

- If loop iterations are independent, then get more parallelism by scheduling instructions from different iterations

- Example: Loop iterations are independent in the code sequence below.
- Construct the data-flow graph for one iteration

```
for (i=0; i<N; i++)
```

```
load A[i]  C
   +
store B[i]
```
Software Pipelining (Illustrated)

Not pipelined

1. load $A[0]$
2. $C$
3. $+$
4. store $B[0]$
5. load $A[1]$
6. $C$
7. $+$
8. store $B[1]$
10. $C$
11. $+$
12. store $B[2]$
14. $C$
15. $+$
16. store $B[3]$

Pipelined

Fill

1. Load $A[0]$
2. $C$
3. $+$
4. load $A[1]$
5. $C$

Steady State

1. store $B[0]$
2. $+$
4. $C$
5. store $B[1]$
6. $+$
7. load $A[3]$
8. $C$
10. $+$
12. $C$
13. store $B[3]$
14. $+$
16. $C$

Drain

1. store $B[4]$
2. $+$
3. store $B[5]$

Steady State
Unroll the loop to perform 4 iterations at once. Then SW pipeline.

\[
\text{for (i=0; i<N; i++)}
\]
\[
\]

loop:  
- \text{ld f1, 0(r1)}
- \text{ld f2, 8(r1)}
- \text{ld f3, 16(r1)}
- \text{ld f4, 24(r1)}
- \text{add r1, 32}
- \text{fadd f5, f0, f1}
- \text{fadd f6, f0, f2}
- \text{fadd f7, f0, f3}
- \text{fadd f8, f0, f4}
- \text{sd f5, 0(r2)}
- \text{sd f6, 8(r2)}
- \text{sd f7, 16(r2)}
- \text{add r2, 32}
- \text{sd f8, -8(r2)}

\text{bne r1, r3, loop}

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Int1} & \text{Int 2} & \text{M1} & \text{M2} & \text{FP+} & \text{FPx} \\
\hline
\text{ld f1} & & & & & \\
\hline
\text{ld f2} & & & & & \\
\hline
\text{ld f3} & & & & & \\
\hline
\text{add r1} & \text{ld f4} & & & & \\
\hline
\text{ld f1} & & \text{fadd f5} & & & \\
\hline
\text{ld f2} & & \text{fadd f6} & & & \\
\hline
\text{ld f3} & & \text{fadd f7} & & & \\
\hline
\text{add r1} & \text{ld f4} & & \text{fadd f8} & & \\
\hline
\text{ld f1} & \text{sd f5} & \text{fadd f5} & & & \\
\hline
\text{ld f2} & \text{sd f6} & \text{fadd f6} & & & \\
\hline
\text{add r2} & \text{ld f3} & \text{sd f7} & \text{fadd f7} & & \\
\hline
\text{add r1} & \text{bne} & \text{ld f4} & \text{sd f8} & \text{fadd f8} & \\
\hline
\text{ld f1} & \text{sd f5} & \text{fadd f5} & & & \\
\hline
\text{ld f2} & \text{sd f6} & \text{fadd f6} & & & \\
\hline
\text{add r2} & \text{sd f7} & \text{fadd f7} & & & \\
\hline
\text{bne} & \text{sd f8} & \text{fadd f8} & & & \\
\hline
\text{sd f5} & & & & & \\
\hline
\end{array}
\]
What if there are no loops?

- Basic block defined by sequence of consecutive instructions. Every basic block ends with a branch.

- Instruction-level parallelism is hard to find in basic blocks

- Basic blocks illustrated by control flow graph
Trace Scheduling

- **A trace** is a sequence of basic blocks (a.k.a., long string of straight-line code)

- **Trace Selection**: Use profiling or compiler heuristics to find common sequences/paths

- **Trace Compaction**: Schedule whole trace into few VLIW instructions.

- Add fix-up code to cope with branches jumping out of trace. Undo instructions if control flower diverges from trace.
Problems with “Classic” VLIW

Object Code Challenges
- Compatibility: Need to recompile code for every VLIW machine, even across generations.
- Compatibility: Code specific to operation slots in instruction format and latencies of operations
- Code Size: Instruction padding wastes instruction memory/cache with nops for unfilled slots.
- Code Size: Loop unrolling, software pipelining increases code footprint.

Scheduling Variable Latency Operations
- Effective schedules rely on known instruction latencies
- Caches, memories produce unpredictable variability
Problems with “Classic” VLIW

Object Code Challenges

- Compatibility: Need to recompile code for every VLIW machine, even across generations.
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Explicitly Parallel Instruction Computing (EPIC)
- Computer architecture style (e.g., CISC, RISC, EPIC)

IA-64
- Instruction set architecture (e.g., x86, MIPS, IA-64)
- IA-64 – Intel Architecture 64-bit

Implementations
- Merced, first implementation, 2001
- McKinley, second implementation, 2002
- Poulson, recent implementation, 2011
Intel Itanium, EPIC IA-64

- Eight cores
- 1-cycle 16KB L1 I&D caches
- 9-cycle 512KB L2 I-cache
- 8-cycle 256KB L2 D-cache
- 32 MB shared L3 cache
- 544mm$^2$ in 32nm CMOS
- 3 billion transistors

- Cores are 2-way multithreaded
- Each VLIW word is 128-bits, containing 3 instructions (op slots)
- Fetch 2 words per cycle $\rightarrow$ 6 instructions (op slots)
- Retire 4 words per cycle $\rightarrow$ 12 instructions (op slots)
VLIW and Control Flow Challenges

Challenge
- Mispredicted branches limit ILP
- Trace selection groups basic blocks into larger ones
- Trace compaction schedules instructions into a single VLIW
- Requires fix-up code for branches that exit trace

Solution – Predicated Execution
- Eliminate hard to predict branches with predicated execution
- IA-64 instructions can be executed conditionally under predicate
- Instruction becomes a NOP if predicate register is false
VLIW and Control Flow Challenges

Four basic blocks

\[ b0: \]
- \text{Inst 1}
- \text{Inst 2}
- \text{br a==b, b2}

\[ b1: \]
- \text{Inst 3}
- \text{Inst 4}
- \text{br b3}

\[ b2: \]
- \text{Inst 5}
- \text{Inst 6}

\[ b3: \]
- \text{Inst 7}
- \text{Inst 8}

\text{if}

\text{else}

Predication

\text{then}

\begin{align*}
\text{Inst 1} \\
\text{Inst 2} \\
p1, p2 & \leftarrow \text{cmp}(a==b) \\
(p1) \text{ Inst 3} & | | (p2) \text{ Inst 5} \\
(p1) \text{ Inst 4} & | | (p2) \text{ Inst 6} \\
\text{Inst 7} \\
\text{Inst 8}
\end{align*}

One basic block

On average >50% branches removed. Mahlke et al. 1995.
Limits of Static ILP

Software Instruction-level Parallelism (VLIW)

- Compiler complexity
- Code size explosion
- Unpredictable branches
- Variable memory latency and unpredictable cache behavior

Current Status

- Despite several attempts, VLIW has failed in general-purpose computing
- VLIW hardware complexity similar to in-order, superscalar hardware complexity. Limited advantage on large, complex applications
- Successful in embedded digital signal processing; friendly code
Summary

Out-of-order Superscalar

- Hardware complexity increases super-linearly with issue-width.

Very Long Instruction Word (VLIW)

- Compiler explicitly schedules parallel instructions
- Unrolling and software pipelining loops

Predication

- Mitigates branches in VLIW machines
- Predicate operations. If predicate false, operation does not affect architected state.
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