EECS 470
Lecture 12
Memory Speculation

Fall 2007
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http://www.eecs.umich.edu/courses/eecs470

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Announcements

HW # 4 (deadline pushed to 11/2)
- Will be posted by Wednesday

Milestone 1 (due 10/29)
- Create handin/milestone1 in your svn repository
- `make syn` and `make test` should do something
- I will review these after 10/29 to provide feedback
Readings

For Wednesday:
  - H&P C.1-C.2, 5.1-5.2
Exam Statistics

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Course policies (from syllabus)
- You must pass both projects and exams to pass course
- Rough guide for passing (C): ~2 std.dev. under median

With assignments figured in, overall course stats:
- Mean: 83%, Median: 84%, Std. Dev: 10%

60% of your grade is still undetermined
Memory Dataflow Techniques

Instruction Flow

Register Data Flow

Instruction Flow

Memory Data Flow
Out of Order Memory Operations

All insns are easy in out-of-order...
- Register inputs only
- Register renaming captures all dependences
- Tags tell you exactly when you can execute

... except loads
- Register and memory inputs (older stores)
- Register renaming does not tell you all dependences
- How do loads find older in-flight stores to same address (if any)?
Dynamic Reordering of Memory Operations

Storing to memory irrevocably in-order state
Hence, hold stores until retire (ROB head)

*No memory WAW or WAR*

Allow OoO Loads that don’t have RAW memory-dependence

What is hard about managing memory-dependence?

- memory address are much wider than reg names
- memory dependencies are not static
  - a load (or store) instruction’s address can change
  - addresses need to be calculated and translated first
- memory instructions take longer to execute
Uniprocessor Load and Store Semantics

Given \( \text{Store}_i( a, v ) \ll \text{Load}_j( a ) \) (”\ll “ means precedes)

Load(\(a\)) must return \(v\) if there does not exist another \(\text{Store}_k\) such that

\[ \text{Store}_i( a, v ) \ll \text{Store}_k( a, v' ) \ll \text{Load}_j(a) \]

This can be guaranteed by observing data dependence

- \(\text{RAW}\) \(\text{Store}(a, v)\) followed by \(\text{Load}(a)\)
- \(\text{WAW}\) \(\text{Store}(a, v')\) followed by \(\text{Store}(a, v)\)
- \(\text{WAR}\) \(\text{Load}(a)\) followed by \(\text{Store}(a, v')\)

For a uniprocessor, do we need to worry about loads and stores to different addresses? What about SMPs?
Some trivial ways to handle Loads

Allow only one load or store in OoO core
- Stall other operations at dispatch – very slow
- No need for LSQ

Load may only issue when LSQ head
- Stall other operations at dispatch
- Loads always get value from cache, only 1 outstanding load

More aggressive options:
- Load to store forwarding
- Speculative load-to-store forwarding – requires rewind mechanism

Several hardware realizations
- Unified LSQ (easier to understand, but nasty hardware)
- Separate LQ and SQ (more complicated, but elegant)
HW #1: Unified Load/Store Queue

Operates as a circular FIFO
- allocate on dispatch
- de-allocate on retirement

Calc address in register dataflow order

A NxN comparator matrix detects memory address dependence (also considers relative age of entries)
- store ops are held until retirement
- load ops are issued when no dependency exists & all older store addresses known
HW#2: Split Queues

D$/TLB + structures to handle in-flight loads/stores

- Performs four functions
  - **In-order store retirement**
    - Writes stores to D$ in order
    - Basic, implemented by store queue (SQ)
  - **Store-load forwarding**
    - Allows loads to read values from older un-retired stores
    - Also basic, also implemented by store queue (SQ)
  - **Memory ordering violation detection**
    - Checks load speculation (more later)
    - Advanced, implemented by load queue (LQ)
  - **Memory ordering violation avoidance**
    - Advanced, implemented by dependence predictors
Simple Data Memory FU: D$/TLB + SQ

Just like any other FU

- 2 register inputs (addr, data in)
- 1 register output (data out)
- 1 non-register input (load pos)?

Store queue (SQ)

- In-flight store address/value
- In program order (like ROB)
- Addresses associatively searchable
- Size heuristic: 15-20% of ROB

But what does it do?
Data Memory FU “Pipeline”

Stores
- **Dispatch (D)**
  - Allocate entry at SQ tail
- **Execute (X)**
  - Write address and data into corresponding SQ slot
- **Retire (R)**
  - Write address/data from SQ head to D$, free SQ head

Loads
- **Dispatch (D)**
  - Record current SQ tail as “load position”
- **Execute (X)**
  - Where the good stuff happens
"Out-of-Order" Load Execution

In parallel with D$ access

Send address to SQ

- Compare with all store addresses
- CAM: like FA$, or RS tag match
- Select all matching addresses

Age logic selects youngest store that is older than load

- Uses load position input
- Any? load “forwards” value from SQ
- None? Load gets value from D$

D$/TLB
Conservative Load Scheduling

Why “” in “out-of-order”? 
- Load can execute out-of-order with respect to (wrt) other loads
- Stores can execute out-of-order wrt other stores
- **Loads must execute in-order wrt older stores**
  - Load execution requires knowledge of all older store addresses
    - Simple
    - Restricts performance
- Used in P6
Opportunistic Memory Scheduling

Observe: on average, < 10% of loads forward from SQ

- Even if older store address is unknown, chances are it won’t match
- Let loads execute in presence of older “ambiguous stores”
  - Increases performance
- But what if ambiguous store does match?

**Memory ordering violation**: load executed too early

- Must detect...
- And fix (e.g., by flushing/refetching insns starting at load)
D$/TLB + SQ + LQ

Load queue (LQ)
- In-flight load addresses
- In program-order (like ROB, SQ)
- Associatively searchable
- Size heuristic: 20-30% of ROB
Advanced Memory “Pipeline” (LQ Only)

Loads

- **Dispatch (D)**
  - Allocate entry at LQ tail
- **Execute (X)**
  - Write address into corresponding LQ slot

Stores

- **Dispatch (D)**
  - Record current LQ tail as “store position”
- **Execute (X)**
  - Where the good stuff happens
Detecting Memory Ordering Violations

Store sends address to LQ
- Compare with all load addresses
- Selecting matching addresses
- Matching address?
  - Load executed before store
  - Violation
  - Fix!

Age logic selects oldest load that is younger than store
- Use store position
- Processor flushes and restarts

Load queue (LQ)
- Store position
- flush?

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Intelligent Load Scheduling

Opportunistic scheduling better than conservative...
  - Avoids many unnecessary delays

...but not significantly
  - Introduces a few flushes, but each is much costlier than a delay

Observe: loads/stores that cause violations are “stable”
  - Dependences are mostly program based, program doesn’t change
  - Scheduler is deterministic

Exploit: intelligent load scheduling
  - Hybridize conservative and opportunistic
  - Predict which loads, or load/store pairs will cause violations
  - Use conservative scheduling for those, opportunistic for the rest
Memory Dependence Prediction

Store-blind prediction
- Predict load only, wait for all older stores to execute
  - Simple, but a little too heavy handed
  - Example: Alpha 21264

Store-load pair prediction
- Predict load/store pair, wait only for one store to execute
  - More complex, but minimizes delay
  - Example: Store-Sets
    - Load identifies the right dynamic store in two steps
    - Store-Set Table: load-PC → store-PC
    - Last Store Table: store-PC → SQ index of most recent instance
- Implemented in next Pentium? (guess)
Summary

Modern dynamic scheduling must support precise state
  - A software sanity issue, not a performance issue

Strategy: Writeback → Complete (OoO) + Retire (iO)

Two basic designs
  - P6: Tomasulo + re-order buffer, copy based register renaming
    - Precise state is simple, but fast implementations are difficult
  - R10K: implements true register renaming
    - Easier fast implementations, but precise state is more complex

Out-of-order memory operations
  - Store queue: conservative load scheduling (iO wrt older stores)
  - Load queue: opportunistic load scheduling (OoO wrt older stores)
  - Intelligent memory scheduling: hybrid
Once a store enters the store buffer, its effect cannot be undone. Must also be checked by load bypassing and forwarding.
Memory Ordering for Shared Memory Multiprocessors

Uniprocessors: Never wait to write memory

Multiprocessors: Must wait - order matters!

Much more on multiprocessor memory ordering later
Dataflow Limit on Superscalar Micros

- **m88ksim**
- **ijpeg**
- **perl**
- **li**

**Issue Width**

- Cycles before dispatch: ▲1 ▼2 ▶3

Assume infinite functional units
Breaking Dataflow Dependence: Prediction and Speculation

Branch prediction:
- Branch target history
- Branch direction history

Load value prediction:
- Value history for each static load

Register value prediction:
- Source or destination value history per static instruction operand

Assumes a very large transistor budget

1. Large complicated prediction logic for accuracy
2. Spare resources to spend on speculated computation
Dynamic Pipeline Contraction

Fold away pipeline stages via speculation:

- **Predict**: obtain semantic outcome of instruction early
- **Speculate**: allow dependent instr. to execute in parallel
- **Recover**: Perform fix-up when mis-speculation occurs
Load Value Prediction and Classification
Source Operand Value Prediction

Similar to earlier work on value prediction, but predicts source operands:

- Decouples execution from dependence checking
- Don’t care where value is coming from until validation

Confidence mechanism (CT) filters out wrong predictions