Memory Ordering

Introduction

1. Load and store instructions can access the same memory without using the same register

Memory Access Ordering

1. Eliminated control dependencies
    - Branch prediction
2. Eliminated false dependencies on registers
    - Register renaming
3. Obey raw register dependencies
    - Tomasulo-like scheduling
4. How do we handle memory dependencies?
    - Dependence between value written by a store and read by a load if they're accessing the same address

When does Memory Write Happen?

1. Memory write occurs at commit
    - Unsafe to update memory before an instruction commits (could be cancelled)
2. When does a load get data? Does it have to happen at commit?
    - Want loads to happen as early as possible
3. Load-Store Queue

Load Store Queue Part 1

1. Loads need to happen as soon as possible, store happens at commit
2. Load-Store Queue: Structure just like a ROB
    - Insert instructions in order and remove at commit
    - Only contains loads and stores
    - Contains the following fields
        - L/S bit: Designate if instruction is load or store
        - Address: What address is accessed?
        - Value: Value to be stored
        - Complete: Instruction is complete
    - For every load inserted, check if any store matches that address
        - If there is no matching store, go to memory
        - If there is a matching store, do "store-to-load forwarding"
    - Store-to-load forwarding: Copy the value from the store accessing the same address into the load entry for the load

Load Store Queue Part 2

1. As long as the address computed by the store is known at the time of a subsequent load, store-to-load forwarding works well
2. However, it is possible that the target of the store is still being computed when the next load is enqueued. In this case, there are three options:
    - Make loads and stores execute in order
        - Guarantees correctness at the expense of performance
    - Wait for all previous store addresses to be known
        - Either go to memory or get the value from the store
    - Just let the load go anyway
        - If no addresses match, let the load go to memory

    - If an address does match, wait for that store to finish
    - If a store finishes and it turns out that the load retrieved the wrong value from memory, we need to reload the value and rerun any instruction that depended on that result
3. Most modern processors take the third approach
    - Accessing the same memory location is an uncommon case, so we get the best performance
    - Only rarely pay the cost of recovering from an incorrect load
    - Modern hardware also tries to predict whether or not a load is likely to access the same address as a previous store and waits in this case

Out of Order Load Store Execution

1. Consider the following program:

```
LOAD R3 = 0(R6)
ADD R7 = R3 + R4
STORE R4 -> 0(R7)
SUB R1 = R1 - R2
LOAD R8 = 0(R1)
```

2. Suppose the first load is a cache miss and takes many cycles to complete
    - The following ADD and STORE can't execute until this load finishes
    - The SUB finishes quickly and allows the LOAD to complete
3. Then, the first LOAD finishes
    - Once the address of the STORE is computed, there are two cases
        - The final load accessed a different memory location, in which case there is no issue
        - The final load accessed this memory location, in which case R8 should contain the value in R4, not whatever stale value was in memory

In Order Load Store Execution

1. With in-order execution, if there is any load with a previous store that has yet to complete, we stall
2. Store is considered done when the instruction is complete, not committed
3. Bad performance, but correct

Memory Ordering Quiz 0

1. If we do everything in order, when does each instruction read/write to memory? Assume loads take 40 cycles and stores take 1 cycle.

Instruction	-> Memory	Memory ->
LW R1,0(R2)	1	41
SW R1,4(R2)	42	43
LW R1,0(R3)	43	83
SW R1,4(R3)	84	85
LW R1,0(R4)	85	125
SW R1,4(R4)	125	126

Store to Load Forwarding

1. Load: Which earlier store do we get our value from?
    - Could be multiple stores going to the same address
2. Store: Which later load do I give my value to?
    - Could be multiple loads
3. This determination is made in the load-store queue

LSQ Example

1. Every load searches the load-store queue for previous instructions that access the same address (only use the most recent previous instruction)
   - If it finds one, it uses its value
   - Otherwise, it goes to the cache, then memory
2. When a load commits, it simply updates the ARF
3. When a store commits, it updates the value in the cache/memory

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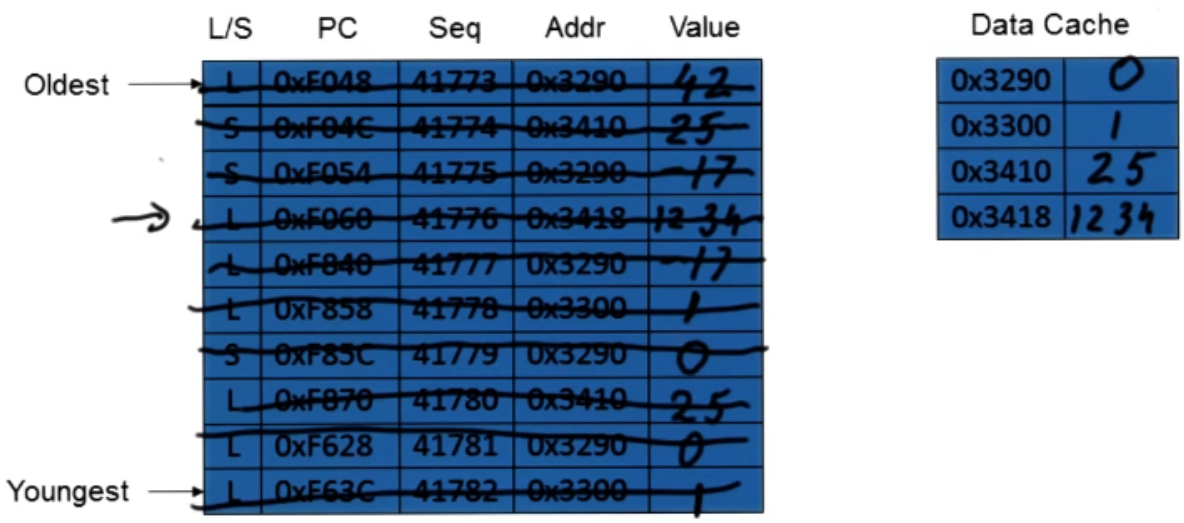

LSQ Example

LSQ-ROB-RS

1. Issuing a load/store requires:
   - A ROB entry
   - A LSQ entry
2. Issuing a non-load/store requires:
   - A ROB entry
   - A RS
3. Executing a load/store
   - Compute address
   - Produce value
4. For loads, computing the address and producing the value must happen in order
   - A load must broadcast its result to subsequent instructions
   - On commit, we free the ROB and LSQ entries
5. For stores, computing the address and producing the value can be out-of-order
   - On commit, we free the ROB and LSQ entries, as well as send the value to memory

Memory Ordering Quiz 1

1. Consider the following program:

```
SW R1 -> 0(R2)
LW R2 <- 0(R2)
```

2. Does LW access cache or memory?
   - No

Memory Ordering Quiz 2

1. Consider the following program:

```
SW R1 -> 0(R2)
LW R2 <- 0(R2)
```

2. The load gets its result from:
   - A result broadcast (false)
   - A reservation station (false)
   - A ROB entry (false)
   - An LSQ entry (true)

Conclusion

1. Load-store queue is used to track dependencies through memory to ensure correct execution of memory instructions in out-of-order processors