CMSC 411
Computer Systems Architecture
Lecture 11
Instruction Level Parallelism 5
(Speculation)

Speculation to greater ILP

- Greater ILP: Overcome control dependence by hardware speculating on outcome of branches and executing program as if guesses were correct
  - Speculation ⇒ fetch, issue, and execute instructions as if branch predictions were always correct
  - Dynamic scheduling ⇒ only fetches and issues instructions
- Essentially a data flow execution model: Operations execute as soon as their operands are available

Speculation to greater ILP

- 3 components of HW-based speculation:
  - Dynamic branch prediction to choose which instructions to execute
  - Speculation to allow execution of instructions before control dependences are resolved
    - » + ability to undo effects of incorrectly speculated sequence
  - Dynamic scheduling to deal with scheduling of different combinations of basic blocks

speculatively executing post-branch instructions

Adding Speculation to Tomasulo

- Must separate execution from allowing instruction to finish or "commit"
  - This additional step called instruction commit
- When an instruction is no longer speculative, allow it to update the register file or memory
- Requires additional set of buffers to hold results of instructions that have finished execution but have not committed
  - This reorder buffer (ROB) is also used to pass results among instructions that may be speculated

Reorder Buffer (ROB)

- In Tomasulo's algorithm, once an instruction writes its result, any subsequently issued instructions will find result in the register file
- With speculation, the register file is not updated until the instruction commits
  - know definitively that the instruction should execute
- Thus, the ROB supplies operands in interval between completion of instruction execution and instruction commit
  - ROB is a source of operands for instructions, just as reservation stations (RS) provide operands in Tomasulo's algorithm
  - ROB extends architecture registers like RS

Reorder Buffer Entry

- Each entry in the ROB contains four fields:

1. Instruction type
   - a branch (has no destination result)
   - a store (has a memory address destination)
   - a register operation (ALU operation or load, which has register destinations)
2. Destination
   - Register number (for loads and ALU operations) or
     memory address (for stores) where the instruction result should be written

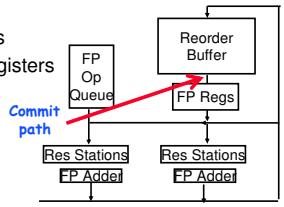
Reorder Buffer Entry (cont.)

- Each entry in the ROB contains four fields:

3. Value
   - Value of instruction result until the instruction commits
4. Ready
   - Indicates that instruction has completed execution, and the value is ready

Reorder Buffer operation

- Holds instructions in FIFO order, exactly as issued
- When instructions complete, results placed into ROB
  - Supplies operands to other instruction between execution complete & commit ⇒ more registers like RS
  - Tag results with ROB buffer number instead of reservation station
- Instructions commit ⇒values at head of ROB placed in registers
- As a result, easy to undo speculated instructions on mispredicted branches or on exceptions



Recall: 4 Steps of Speculative Tomasulo Algorithm

1. Issue—get instruction from FP Op Queue

   If reservation station and reorder buffer slot free, issue instr & send operands & reorder buffer no. for destination (this stage sometimes called "dispatch")

2. Execution—operate on operands (EX)

   When both operands ready then execute; if not ready, watch CDB for result; when both in reservation station, execute; checks RAW (sometimes called "issue")

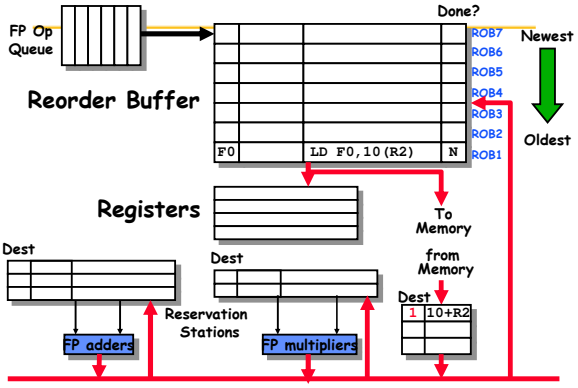
3. Write result—finish execution (WB)

   Write on Common Data Bus to all awaiting FUs & reorder buffer; mark reservation station available.

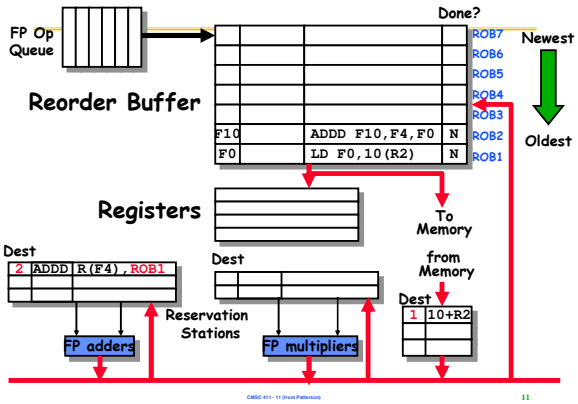
4. Commit—update register with reorder result

   When instr at head of reorder buffer & result present, update register with result (or store to memory) and remove instr from reorder buffer. Mispredicted branch flushes reorder buffer (sometimes called "graduation")

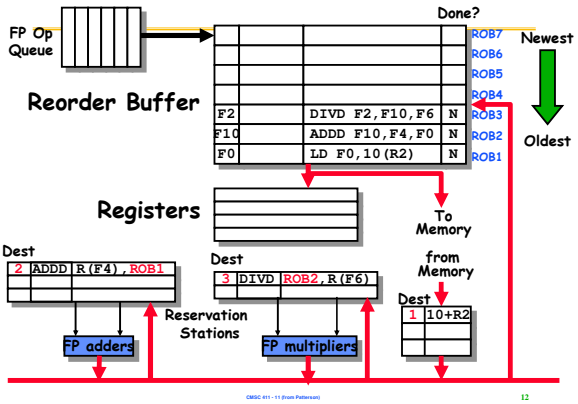
Tomasulo With Reorder buffer:



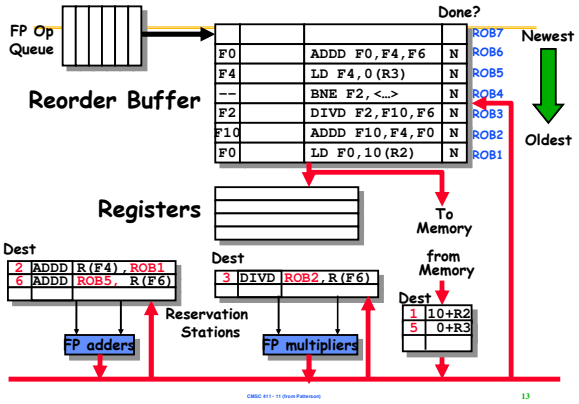
Tomasulo With Reorder buffer:



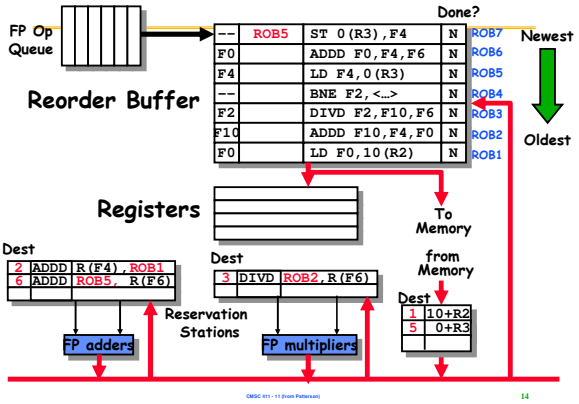
Tomasulo With Reorder buffer:



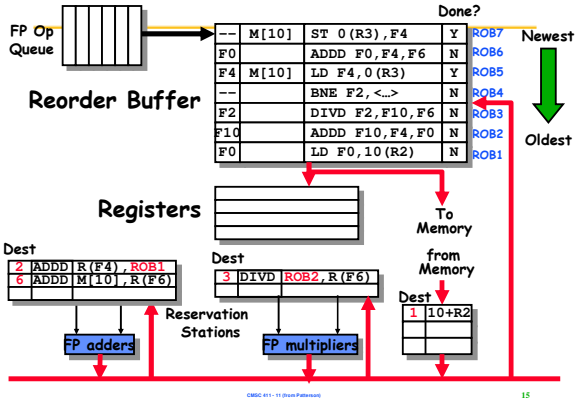
Tomasulo With Reorder buffer:



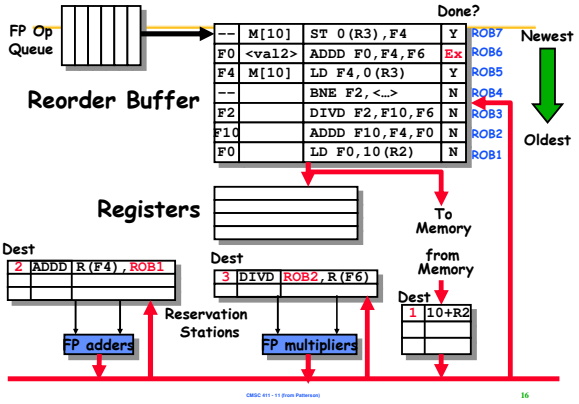
Tomasulo With Reorder buffer:



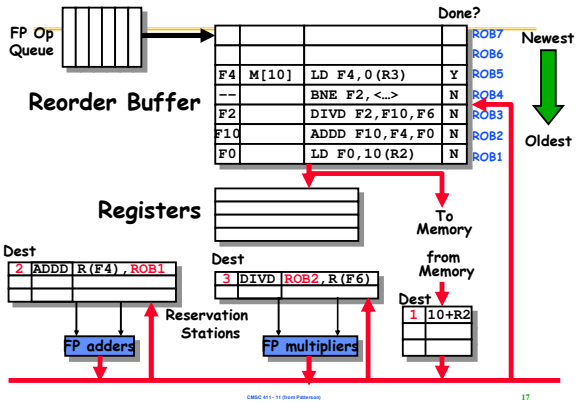
Tomasulo With Reorder buffer:



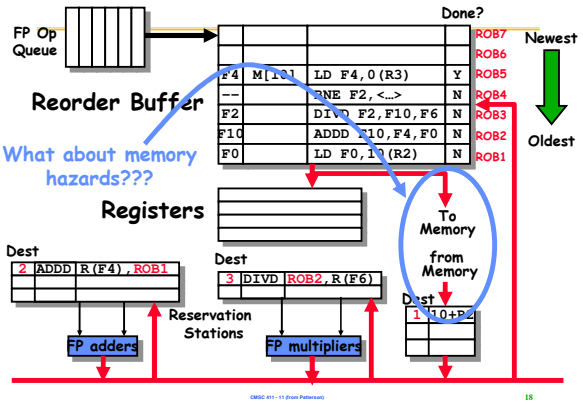
Tomasulo With Reorder buffer:



Tomasulo With Reorder buffer:



Tomasulo With Reorder buffer:



Avoiding Memory Hazards

- WAW and WAR hazards through memory are eliminated with speculation because actual updating of memory occurs in order, when a store is at head of the ROB, and hence, no earlier loads or stores can still be pending
- RAW hazards through memory are maintained by two restrictions:
  1. not allowing a *load* to initiate the second step of its execution if any active ROB entry occupied by a *store* has a Destination field that matches the value of the A field of the load, and
  2. maintaining the program order for the computation of an effective address of a load with respect to all earlier stores.
- These restrictions ensure that any load that accesses a memory location written to by an earlier store cannot perform the memory access until the store has written the data

Exceptions and Interrupts

- IBM 360/91 invented "imprecise interrupts"
  - Computer stopped at this PC; its likely close to this address
  - Not so popular with programmers
  - Also, what about Virtual Memory? (Not in IBM 360)
- Technique for both precise interrupts/exceptions and speculation: *in-order completion* and *in-order commit*
  - If we speculate and are wrong, need to back up and restart execution to point at which we predicted incorrectly
  - This is exactly same as need to do with precise exceptions
- Exceptions are handled by not recognizing the exception until instruction that caused it is ready to commit in ROB
  - If a speculated instruction raises an exception, the exception is recorded in the ROB
  - This is why reorder buffers in all new processors