The Microarchitecture of Superscalar Processors
Program Representation

- An application is written as a program, typically using a high level language
- Program is compiled into static machine code (binary)
- Sequencing model implicit in the program
- The sequence of executed instructions forms a dynamic instruction stream
- The address of the next dynamic instruction:
  - Incremented program counter
  - Target of a taken branch
Sequential Execution Model

- Inherent in instruction sets and program binaries
- Led to the concept of precise architecture state
  - Interrupt and restart
  - Exceptions
  - Branch mispredictions
- Out of order issue deviates from sequential execution
  - But we still need to maintain binary compatibility and retain appearance of sequential execution
Dependences and Parallel Execution

- To execute more instructions in parallel, control dependences need to be addressed:
  - Program Counter (PC)
  - Branches

- To overcome PC dependence, one can view the program as a collection of basic blocks, separated by branches

- There is a limited number of parallel instructions on average within basic blocks
Dependences and Parallel Execution (cont.)

- Instructions have be serialized according to true data dependences
  - A true dependence appears as a read after write (RAW) sequence

- Ideally, we should eliminate output dependences and anti-dependences
  - An output dependence appears as write after write (WAW) sequence
  - An anti-dependence appears as write after read (WAR) sequence
Elements of Superscalar Processing

- **Fetch**: Strategies for fetching multiple instructions every cycle, supported by
  - Predicting branch outcomes
  - Fetching beyond conditional branch instructions, well before branches are executed

- **Decode**: Methods for determining true register dependencies and eliminating artificial dependencies
  - Register renaming
  - Mechanisms to communicate register values during execution

- **Issue/Dispatch**: Methods for issuing multiple instructions in parallel
  - Based upon availability of inputs, not upon program order
Elements of Superscalar Processing (cont.)

- **Execution**: Parallel execution resources
  - Multiple pipelined functional units
  - Memory hierarchies capable of simultaneously serving multiple memory requests

- **Memory**: Methods for communicating data through memory via load and store instructions, potentially issued out of order
  - Memory interfaces have to allow for the dynamic and often unpredictable behavior of memory hierarchies

- **Commit**: Methods for committing architecture state in order
  - Maintain an outward appearance of sequential execution
Typical Superscalar Microarchitecture

- Fig. 3 (Paper): Parallel execution model
- Fig. 4 (Paper): Microarchitecture or hardware organization of a typical superscalar processor
Instruction Fetch

- Read instructions from the instruction cache and write them to a queue (instr. buffer in Fig 4)
  - The number of instructions fetched per cycle should at least match the peak decode rate (why?)
  - The fetcher must be told the address of the next block of instructions to fetch

- An instruction cache is usually organized as lines of several instructions
  - A cache line starts on a fixed boundary (regardless of the instruction needed from the line)
  - Question: What are the pros and cons of having separate I- and D- caches?
Instruction Fetch (Cont.)

- Calculating the next address to fetch
  - Non-branch instructions:
    - PC is incremented by the number of bytes in current instruction
    - Can require fetching next cache block
  - Branch instructions: the fetch unit has to
    - Recognize a branch
    - Determine its outcome (taken or not taken)
    - Compute branch target address
    - Fetch the next block using
      - Next sequential address or
      - Branch target address
Instruction Fetch (Cont.)

- Branch prediction is used to avoid having to wait for the branch execution to complete
  - Target comes from Branch target buffer (BTB)
  - Outcome comes from
    - Static prediction based on branch type or profile (or even compiler hints)
    - Dynamic prediction based on result of previous branches

- If branch is mispredicted, we must be able to undo the work and fetch the correct instruction
  - This incurs a significant misprediction penalty

- Branch prediction discussed in more detail next week
Instruction Fetch (Cont.)

- Transferring control to target address on a taken branch could cause pipeline bubbles
  - Stockpile instructions in instruction queue
  - Or keep next address in cache block
  - Or use delayed branches?

- The instruction queue helps
  - Smooth fetch irregularities caused by cache misses
  - Sustain fetch bandwidth in cycles when fewer than the maximum number of instructions can be fetched
Instruction Fetch (Cont.)

- Superscalar machines pay a penalty for instruction misalignment
  - Branches and targets don't always fall on cache line boundaries
  - Fetched instructions that are not executed waste fetch bandwidth
  - Sometimes called instruction cache fragmentation due to branches
# ICache Fragmentation

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| X+188 |   |   |

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Instruction Fetch (Cont.)

- Cache fragmentation caused by branches places a severe limit on very wide superscalars
  - Easy to fetch sequential runs of instructions
  - However, the average sequential run length is ~6 for general integer programs
  - The distribution is very broad, with a few long runs raising the average
  - How many decode cycles are needed for 6 fetched instructions?
    - 3 decode cycles for a two instruction decoder
    - Only 1.5 decode cycles for a four instruction decoder
Instruction Fetch (Cont.)

- Given enough fetch bandwidth, the fetcher can realign or merge instructions from multiple lines to make more efficient use of the decoder
  - For a branch target in the middle of a cache line, the fetcher combines the cache line with the one following it
  - Decoder "lines" are not aligned with cache lines
  - Harder to find the program counter associated with one instruction

- Trace cache discussed in more detail later in the course
Instruction Decode

- Instructions are removed from the instruction queue
- Execution tuples are set for each decoded instruction containing
  - Opcode: Operation to be executed
  - Sources: Identities of storage elements where the inputs reside
  - Destination: Identity of the storage element where result must be placed
Instruction Decode (Cont.)

- In the static program, the input and output identifiers represent
  - Storage locations in the “logical” register file OR
  - Storage locations in memory

- To overcome WAR and WAW hazards, register renaming maps the register “logical” identifiers into “physical” storage locations

- Allocation logic assigns each instruction physical storage for the result as well as entries in all required instruction buffers
Instruction Rename

- The decoder looks at one or more instructions and releases them to scheduling stations after renaming.

- Register values created by an instruction are assigned physical locations, and recorded in a map table.
  - Map table has as many entries as there are logical registers.

- Source register mappings are read from the map table and attached to the instruction.

- Renaming happens sequentially.
  - Map table bypass is sometimes necessary.

- Subsequent stages in the pipeline use mappings attached to an instruction tuple to read and write the physical locations of register values.
Rename Map Table

Allocate physical registers from free pool

Register Map Table

Logical Source Registers

Physical Source Registers

Logical Destination Registers

Physical Destination Registers
Renaming Methods

- There are two methods commonly used:
  - Renaming with a physical register file larger than the logical register file
  - Renaming using a Reorder Buffer (ROB) and a physical register file equal in size to the number of logical registers
Renaming with a Physical RF

- Paper Fig. 5
- A free list of unused physical registers is kept
- New register results are assigned physical registers from the free list
- Reclaiming of physical registers into the free list:
  - Usage count is 0 and logical register has been renamed to another physical register
  - Subsequent instruction writing to the same logical register is committed
- Register map table is checkpointed at conditional branches (why?)
Freeing Physical Registers at Retirement

I1 → R5 → P3

I4 → R5 → P5 (free P3 when retired)

I7 ← R5 ← P5
Renaming with a Reorder Buffer

- Physical registers are allocated sequentially in the Reorder Buffer
- Physical registers are freed and their values are copied to the register file at retirement
- Mapping table maps logical registers to entries in the Reorder Buffer or the Register File
- Paper Fig 6 and 7
- Branch handling options:
  - Map table checkpoints
  - Resume renaming from the correct path after mispredicted branch has retired
Instruction Issue

- After instructions are fetched, decoded and renamed, they are placed in instruction buffers where they wait until issue.
- An instruction can be issued when its input operands are ready, and there is a functional unit available.
- Paper Fig. 8. is an example of parallel execution schedule.
Instruction Issue (Cont.)

- All out-of-order issue methods must handle the same basic steps
  - Identify all instructions that are ready to issue
  - Select among ready instructions to issue as many as possible
  - Issue the selected instructions, e.g., pass operands and other information to the functional units
  - Reclaim instruction window storage used by the now issued instructions
Methods of Organizing Instruction Issue Buffers

- Single shared queue
  - Only for in-order issue
- Multiple queues, one per instruction type
- Multiple reservation stations, one per instruction type
  - Fig. 10. Shows a typical reservation station
- Single central reservation stations buffer
Multiple Queues

- Requiring instructions to be issued in order at a functional unit greatly simplifies the identification and selection logic
- Instructions from different queues could be allowed to issue out of order
Reservation Stations

Benefits
- Logic to identify and select ready instructions is simpler since it need only consider a few locations
- Storage can be optimized for each type of functional unit
  - e.g., stores need not have storage for two source operands

Drawback
- Storage is statically allocated to functional units
- This can result in either wasted storage or a resource bottleneck for some programs
Central Window

Benefits

- Only one copy of identification and selection logic
- Only one copy of storage reclamation logic
- Dynamically allocated storage

Drawbacks

- Complex identification and selection logic
- Complex storage reclamation logic
- Each storage location must be as big as the largest instruction
- Functional unit arbitration must be handled
Memory Ordering

- Stores consist of address and data uops
- Store addresses are buffered in a queue
- Store addresses remain buffered until:
  - Store data is available
  - Store instruction is committed in the reorder buffer
- New load addresses are checked with the waiting store addresses. If there is a match:
  - The load waits OR
  - Store data is bypassed to the matching load
- Fig. 11. shows typical memory ordering logic
- Memory ordering discussed later in the course
- More details in ECE 588
Commit (Retire)

- Implements appearance of sequential execution
- Recovering a precise state:
  - Need to maintain both state required for recovery and state being updated
  - Recovery options:
    - History buffer
    - Future File
- Precise interrupts discussed later in the course
Reading Assignments

Monday:

Wednesday:
- SimpleScalar tutorial (Skim)

HW1 due Monday (email to me)