CIS 371
Computer Organization and Design

Unit 9: Superscalar Pipelines

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with sources that included University of Wisconsin slides
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A Key Theme: Parallelism

• Previously: pipeline-level parallelism
  • Work on execute of one instruction in parallel with decode of next

• Next: instruction-level parallelism (ILP)
  • Execute multiple independent instructions fully in parallel

• Then:
  • Static & dynamic scheduling
    • Extract much more ILP
  • Data-level parallelism (DLP)
    • Single-instruction, multiple data (one insn., four 64-bit adds)
  • Thread-level parallelism (TLP)
    • Multiple software threads running on multiple cores
This Unit: (In-Order) Superscalar Pipelines

- Idea of instruction-level parallelism

- Superscalar hardware issues
  - Bypassing and register file
  - Stall logic
  - Fetch

- “Superscalar” vs VLIW/EPIC
Readings

- Textbook (MA:FSPTCM)
  - Sections 3.1, 3.2 (but not “Sidebar” in 3.2), 3.5.1
  - Sections 4.2, 4.3, 5.3.3
So far we have looked at **scalar pipelines**

- One instruction per stage
  - With control speculation, bypassing, etc.
    - Performance limit (aka “Flynn Bottleneck”) is $\text{CPI} = \text{IPC} = 1$
    - Limit is never even achieved (hazards)
    - Diminishing returns from “super-pipelining” (hazards + overhead)
An Opportunity...

• But consider:
  
  \[\text{ADD } r_1, r_2 \rightarrow r_3\]
  \[\text{ADD } r_4, r_5 \rightarrow r_6\]

  • Why not execute them \textit{at the same time}? (We can!)

• What about:
  
  \[\text{ADD } r_1, r_2 \rightarrow r_3\]
  \[\text{ADD } r_4, r_3 \rightarrow r_6\]

  • In this case, \textit{dependences} prevent parallel execution

• What about three instructions at a time?
  • Or four instructions at a time?
What Checking Is Required?

- For two instructions: 2 checks
  
  \[
  \text{ADD } \text{src}_1^1, \text{src}_2^1 \rightarrow \text{dest}_1^1 \\
  \text{ADD } \text{src}_1^2, \text{src}_2^2 \rightarrow \text{dest}_2^2 \quad (2 \text{ checks})
  \]

- For three instructions: 6 checks
  
  \[
  \text{ADD } \text{src}_1^1, \text{src}_2^1 \rightarrow \text{dest}_1^1 \\
  \text{ADD } \text{src}_1^2, \text{src}_2^2 \rightarrow \text{dest}_2^2 \quad (2 \text{ checks}) \\
  \text{ADD } \text{src}_1^3, \text{src}_2^3 \rightarrow \text{dest}_3^3 \quad (4 \text{ checks})
  \]

- For four instructions: 12 checks
  
  \[
  \text{ADD } \text{src}_1^1, \text{src}_2^1 \rightarrow \text{dest}_1^1 \\
  \text{ADD } \text{src}_1^2, \text{src}_2^2 \rightarrow \text{dest}_2^2 \quad (2 \text{ checks}) \\
  \text{ADD } \text{src}_1^3, \text{src}_2^3 \rightarrow \text{dest}_3^3 \quad (4 \text{ checks}) \\
  \text{ADD } \text{src}_1^4, \text{src}_2^4 \rightarrow \text{dest}_4^4 \quad (6 \text{ checks})
  \]

- Plus checking for load-to-use stalls from prior \( n \) loads
What Checking Is Required?

- For two instructions: 2 checks
  \[
  \text{ADD } \text{src}_1, \text{src}_2 \rightarrow \text{dest}_1 \\
  \text{ADD } \text{src}_1, \text{src}_2 \rightarrow \text{dest}_2 \quad (2 \text{ checks})
  \]

- For three instructions: 6 checks
  \[
  \text{ADD } \text{src}_1, \text{src}_2 \rightarrow \text{dest}_1 \\
  \text{ADD } \text{src}_1, \text{src}_2 \rightarrow \text{dest}_2 \quad (2 \text{ checks}) \\
  \text{ADD } \text{src}_1, \text{src}_2 \rightarrow \text{dest}_3 \quad (4 \text{ checks})
  \]

- For four instructions: 12 checks
  \[
  \text{ADD } \text{src}_1, \text{src}_2 \rightarrow \text{dest}_1 \\
  \text{ADD } \text{src}_1, \text{src}_2 \rightarrow \text{dest}_2 \quad (2 \text{ checks}) \\
  \text{ADD } \text{src}_1, \text{src}_2 \rightarrow \text{dest}_3 \quad (4 \text{ checks}) \\
  \text{ADD } \text{src}_1, \text{src}_2 \rightarrow \text{dest}_4 \quad (6 \text{ checks})
  \]

- Plus checking for load-to-use stalls from prior \( n \) loads
How do we build such “superscalar” hardware?
Multiple-Issue or “Superscalar” Pipeline

- Overcome this limit using **multiple issue**
  - Also called **superscalar**
  - Two instructions per stage at once, or three, or four, or eight...
  - “**Instruction-Level Parallelism (ILP)**” [Fisher, IEEE TC’81]

- Today, typically “4-wide” (Intel Core i7, AMD Opteron)
  - Some more (Power5 is 5-issue; Itanium is 6-issue)
  - Some less (dual-issue is common for simple cores)
A Typical Dual-Issue Pipeline (1 of 2)

- Fetch an entire 16B or 32B cache block
  - 4 to 8 instructions (assuming 4-byte average instruction length)
  - Predict a single branch per cycle
- Parallel decode
  - Need to check for conflicting instructions
    - Is output register of \( I_1 \) is an input register to \( I_2 \)?
  - Other stalls, too (for example, load-use delay)
A Typical Dual-Issue Pipeline (2 of 2)

- Multi-ported register file
  - Larger area, latency, power, cost, complexity
- Multiple execution units
  - Simple adders are easy, but bypass paths are expensive
- Memory unit
  - Single load per cycle (stall at decode) probably okay for dual issue
  - Alternative: add a read port to data cache
    - Larger area, latency, power, cost, complexity
How Much ILP is There?

- The compiler tries to “schedule” code to avoid stalls
  - Even for scalar machines (to fill load-use delay slot)
  - Even harder to schedule multiple-issue (superscalar)
- How much ILP is common?
  - Greatly depends on the application
    - Consider memory copy
    - Unroll loop, lots of independent operations
  - Other programs, less so
- Even given unbounded ILP, superscalar has implementation limits
  - IPC (or CPI) vs clock frequency trade-off
  - Given these challenges, what is reasonable today?
    - ~4 instruction per cycle maximum
Superscalar Implementation Challenges
Superscalar Challenges - Front End

- **Superscalar instruction fetch**
  - Modest: fetch multiple instructions per cycle
  - Aggressive: buffer instructions and/or predict multiple branches

- **Superscalar instruction decode**
  - Replicate decoders

- **Superscalar instruction issue**
  - Determine when instructions can proceed in parallel
  - More complex stall logic - order $N^2$ for $N$-wide machine
  - Not all combinations of types of instructions possible

- **Superscalar register read**
  - Port for each register read (4-wide superscalar $\Rightarrow$ 8 read “ports”)
  - Each port needs its own set of address and data wires
    - Latency & area $\propto \#\text{ports}^2$
Superscalar Challenges - Back End

- **Superscalar instruction execution**
  - Replicate arithmetic units (but not all, for example, integer divider)
  - Perhaps multiple cache ports (slower access, higher energy)
    - Only for 4-wide or larger (why? only ~35% are load/store insn)

- **Superscalar bypass paths**
  - More possible sources for data values
  - Order \(N^2 \times P\) for \(N\)-wide machine with execute pipeline depth \(P\)

- **Superscalar instruction register writeback**
  - One write port per instruction that writes a register
  - Example, 4-wide superscalar \(\Rightarrow\) 4 write ports

- **Fundamental challenge:**
  - Amount of ILP (instruction-level parallelism) in the program
  - Compiler must schedule code and extract parallelism
Superscalar Bypass

- **N^2 bypass network**
  - N+1 input muxes at each ALU input
  - N^2 point-to-point connections
  - Routing lengthens wires
  - Heavy capacitive load

- And this is just one bypass stage (MX)!
  - There is also WX bypassing
  - Even more for deeper pipelines

- One of the big problems of superscalar
  - Why? On the critical path of single-cycle “bypass & execute” loop
Not All $N^2$ Created Equal

- $N^2$ bypass vs. $N^2$ stall logic & dependence cross-check
  - Which is the bigger problem?

- $N^2$ bypass ... by far
  - 64-bit quantities (vs. 5-bit)
  - Multiple levels (MX, WX) of bypass (vs. 1 level of stall logic)
  - Must fit in one clock period with ALU (vs. not)

- Dependence cross-check not even 2nd biggest $N^2$ problem
  - Regfile is also an $N^2$ problem (think latency where $N$ is #ports)
  - And also more serious than cross-check
Mitigating $N^2$ Bypass & Register File

- **Clustering**: mitigates $N^2$ bypass
  - Group ALUs into $K$ clusters
  - Full bypassing within a cluster
  - Limited bypassing between clusters
    - **With 1 or 2 cycle delay**
      - Can hurt IPC, but faster clock
  - $(N/K) + 1$ inputs at each mux
  - $(N/K)^2$ bypass paths in each cluster

- **Steering**: key to performance
  - Steer dependent insns to same cluster

- **Cluster register file**, too
  - Replica a register file per cluster
  - All register writes update all replicas
  - Fewer read ports; only for cluster
Mitigating $N^2$ RegFile: Clustering++

- **Clustering**: split $N$-wide execution pipeline into $K$ clusters
  - With centralized register file, $2N$ read ports and $N$ write ports

- **Clustered register file**: extend clustering to register file
  - Replicate the register file (one replica per cluster)
  - Register file supplies register operands to just its cluster
  - All register writes go to all register files (keep them in sync)
  - Advantage: fewer read ports per register!
    - $K$ register files, each with $2N/K$ read ports and $N$ write ports
Another Challenge: Superscalar Fetch

- What is involved in fetching multiple instructions per cycle?
- In same cache block? → no problem
  - 64-byte cache block is 16 instructions (~4 bytes per instruction)
  - Favors larger block size (independent of hit rate)
- What if next instruction is last instruction in a block?
  - Fetch only one instruction that cycle
  - Or, some processors may allow fetching from 2 consecutive blocks
- What about taken branches?
  - How many instructions can be fetched on average?
  - Average number of instructions per taken branch?
    - Assume: 20% branches, 50% taken → ~10 instructions
- Consider a 5-instruction loop with an 4-issue processor
  - Without smarter fetch, ILP is limited to 2.5 (not 4, which is bad)
Increasing Superscalar Fetch Rate

- **Option #1:** over-fetch and buffer
  - Add a queue between fetch and decode (18 entries in Intel Core2)
  - Compensates for cycles that fetch less than maximum instructions
  - “decouples” the “front end” (fetch) from the “back end” (execute)

- **Option #2:** “loop stream detector” (Core 2, Core i7)
  - Put entire loop body into a small cache
    - Core2: 18 macro-ops, up to four taken branches
    - Core i7: 28 micro-ops (avoids re-decoding macro-ops!)
  - Any branch mis-prediction requires normal re-fetch

- **Other options:** next-next-block prediction, “trace cache”
Multiple-Issue Implementations

• **Statically-scheduled (in-order) superscalar**
  • What we’ve talked about thus far
    + Executes unmodified sequential programs
      - Hardware must figure out what can be done in parallel
    • E.g., Pentium (2-wide), UltraSPARC (4-wide), Alpha 21164 (4-wide)

• **Very Long Instruction Word (VLIW)**
  - Compiler identifies independent instructions, new ISA
    + Hardware can be simple and perhaps lower power
    • E.g., TransMeta Crusoe (4-wide)
  • **Variant: Explicitly Parallel Instruction Computing (EPIC)**
    • A bit more flexible encoding & some hardware to help compiler
      • E.g., Intel Itanium (6-wide)

• **Dynamically-scheduled superscalar (next topic)**
  • Hardware extracts more ILP by on-the-fly reordering
  • Core 2, Core i7 (4-wide), Alpha 21264 (4-wide)
Trends in Single-Processor Multiple Issue

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<th>Year</th>
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- Issue width has saturated at 4-6 for high-performance cores
  - Canceled Alpha 21464 was 8-way issue
  - Not enough ILP to justify going to wider issue
  - Hardware or compiler *scheduling* needed to exploit 4-6 effectively
    - More on this in the next unit

- For high-performance *per watt* cores (say, smart phones)
  - Typically 2-wide superscalar (but increasing each generation)
Multiple Issue Redux

• Multiple issue
  • Exploits insn level parallelism (ILP) beyond pipelining
  • Improves IPC, but perhaps at some clock & energy penalty
  • 4-6 way issue is about the peak issue width currently justifiable
    • Low-power implementations today typically 2-wide superscalar

• Problem spots
  • $N^2$ bypass & register file $\rightarrow$ clustering
  • Fetch + branch prediction $\rightarrow$ buffering, loop streaming, trace cache
  • $N^2$ dependency check $\rightarrow$ VLIW/EPIC (but unclear how key this is)

• Implementations
  • Superscalar vs. VLIW/EPIC
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