Superscalar Processing

CS 740
September 24-26, 2001

Intel Processors
- 486, Pentium, Pentium Pro

Superscalar Processor Design
- Use PowerPC 604 as case study
- Speculative Execution, Register Renaming, Branch Prediction

More Superscalar Examples
- MIPS R10000
- DEC Alpha 21264

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Intel x86 Processors

<table>
<thead>
<tr>
<th>Processor</th>
<th>Year</th>
<th>Transistors</th>
<th>MHz</th>
<th>Spec92 (Int/FP)</th>
<th>Spec95 (Int/FP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8086</td>
<td>'78</td>
<td>29K</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Basis of IBM PC & PC-XT
| i286      | '83  | 134K        | 8   |                |                |
| Basis of IBM PC-AT
| i386      | '86  | 275K        | 16  | 6 / 3          |                |
| '88       |      | 33          | 20  | 28 / 13        |                |
| Pentium   | '93  | 3.1M        | 66  | 78 / 64        | 4.3 / 3.0      |
| PentiumPro| '95  | 5.5M        | 150 | 181 / 125      | 6.1 / 4.8      |
|           |      | 200         | 320 / 283 | 8.2 / 6.0    |
| Pentium II| '97  | 7.5M        | 300 | 11.6 / 6.8     |                |
| Merced    | '00? | 14M         | ?   | ?             |                |

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Other Processors

<table>
<thead>
<tr>
<th>Processor</th>
<th>Year</th>
<th>Transistors</th>
<th>MHz</th>
<th>Spec92</th>
<th>Spec95</th>
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</thead>
<tbody>
<tr>
<td>MIPS R3000</td>
<td>'88</td>
<td>25</td>
<td>16.1 / 21.7</td>
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<tr>
<td>(DecStation 5000/120)</td>
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<tr>
<td>MIPS R5000</td>
<td>'90</td>
<td>3.6M</td>
<td>180</td>
<td>4.1 / 4.4</td>
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<td>(Wean Hall 5GIs)</td>
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<tr>
<td>MIPS R10000</td>
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<td>5.9M</td>
<td>200</td>
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<tr>
<td>(Most Advanced MIPS)</td>
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<tr>
<td>Alpha 21164a</td>
<td>'96</td>
<td>9.3M</td>
<td>417</td>
<td>500 / 750 / 11</td>
<td>17 / 500</td>
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<td>(Fastest Available)</td>
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<tr>
<td>Alpha 21264</td>
<td>'97</td>
<td>15M</td>
<td>500</td>
<td>30 / 60</td>
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<tr>
<td>(Fastest Announced)</td>
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</tbody>
</table>

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Architectural Performance

Metric
- Spec92/MHz: Normalizes with respect to clock speed
- But .. one measure of good arch. is how fast can run clock

Sampling

<table>
<thead>
<tr>
<th>Processor</th>
<th>MHz</th>
<th>SpecInt92</th>
<th>IntAP</th>
<th>SpecFP92</th>
<th>FltAP</th>
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<tbody>
<tr>
<td>i386/387</td>
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<td>6</td>
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<td>Pentium</td>
<td>150</td>
<td>181</td>
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<tr>
<td>PentiumPro</td>
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<tr>
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<td>16.1</td>
<td>0.6</td>
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<tr>
<td>MIPS R10000</td>
<td>200</td>
<td>300</td>
<td>1.5</td>
<td>600</td>
<td>3.0</td>
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<tr>
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<td>417</td>
<td>500</td>
<td>1.2</td>
<td>750</td>
<td>1.8</td>
</tr>
</tbody>
</table>
x86 ISA Characteristics

Multiple Data Sizes and Addressing Methods
- Recent generations optimized for 32-bit mode

Limited Number of Registers
- Stack-oriented procedure call and FP instructions
- Programs reference memory heavily (41%)

Variable Length Instructions
- First few bytes describe operation and operands
- Remaining ones give immediate data & address displacements
- Average is 2.5 bytes

i486 Pipeline

Fetch
- Load 16-bytes of instruction into prefetch buffer

Decode1
- Determine instruction length, instruction type

Decode2
- Compute memory address
- Generate immediate operands

Execute
- Register Read
- ALU operation
- Memory read/write

Write-Back
- Update register file

Pipeline Stage Details

Fetch
- Moves 16 bytes of instruction stream into code queue
- Not required every time
  - About 5 instructions fetched at once
  - Only useful if don’t branch
  - Avoids need for separate instruction cache

D1
- Determine total instruction length
  - Signals code queue aligner where next instruction begins
- May require two cycles
  - When multiple operands must be decoded
  - About 6% of “typical” DOS program

Stage Details (Cont.)

D2
- Extract memory displacements and immediate operands
- Compute memory addresses
  - Add base register, and possibly scaled index register
- May require two cycles
  - If index register involved, or both address & immediate operand
  - Approx. 5% of executed instructions

EX
- Read register operands
- Compute ALU function
- Read or write memory (data cache)

WB
- Update register result
**Data Hazards**

<table>
<thead>
<tr>
<th>Generated</th>
<th>Used</th>
<th>Handling</th>
</tr>
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<tbody>
<tr>
<td>ALU</td>
<td>ALU</td>
<td>EX-EX Forwarding</td>
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<tr>
<td>Load</td>
<td>ALU</td>
<td>EX-EX Forwarding</td>
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<tr>
<td>ALU</td>
<td>Store</td>
<td>EX-EX Forwarding</td>
</tr>
<tr>
<td>ALU</td>
<td>Eff. Address</td>
<td>(Stall) + EX-ID2 Forwarding</td>
</tr>
</tbody>
</table>

**Control Hazards**

**Jump Instruction Processing**
- Continue pipeline assuming branch not taken
- Resolve branch condition in EX stage
- Also speculatively fetch at target during EX stage

**Control Hazards (Cont.)**

**Branch Not Taken**
- Allow pipeline to continue
- Total of 1 cycle for instruction

**Branch taken**
- Flush instructions in pipe
- Begin ID1 at target
- Total of 3 cycles for instruction
- Total of 3 cycles for instruction

**Comparison with Our pAlpha Pipeline**

**Two Decoding Stages**
- Harder to decode CISC instructions
- Effective address calculation in D2

**Multicycle Decoding Stages**
- For more difficult decodings
- Stalls incoming instructions

**Combined Mem/EX Stage**
- Avoids load stall without load delay slot
  - But introduces stall for address computation
### Comparison to 386

<table>
<thead>
<tr>
<th>Instruction Type</th>
<th>386 Cycles</th>
<th>486 Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Store</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>ALU</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Jump taken</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Jump not taken</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Call</td>
<td>9</td>
<td>3</td>
</tr>
</tbody>
</table>

**Reasons for Improvement**
- On chip cache
- Faster loads & stores
- More pipelining

### Pentium Block Diagram

![Pentium Block Diagram](image)

(Microprocessor Report 10/28/92)

### Pentium Pipeline

![Pentium Pipeline](image)

### Superscalar Execution

**Can Execute Instructions I1 & I2 in Parallel if:**
- Both are "simple" instructions
  - Don't require microcode sequencing
  - Some operations require U-pipe resources
- 90% of SpecInt instructions
- I1 is not a jump
- Destination of I1 not source of I2
  - But can handle I1 setting CC and I2 being cond. jump
- Destination of I1 not destination of I2

**If Conditions Don't Hold**
- Issue I1 to U Pipe
- I2 issued on next cycle
  - Possibly paired with following instruction
Branch Prediction

Branch Target Buffer
- Stores information about previously executed branches
  - Indexed by instruction address
  - Specifies branch destination + whether or not taken
- 256 entries

Branch Processing
- Look for instruction in BTB
- If found, start fetching at destination
- Branch condition resolved early in WB
  - If prediction correct, no branch penalty
  - If prediction incorrect, lose ~3 cycles
  - Which corresponds to > 3 instructions
- Update BTB

Superscalar Terminology

Basic
- Superscalar: Able to issue > 1 instruction / cycle

Superpipelined
- Deep, but not superscalar pipeline.
  - E.g., MIPS R5000 has 8 stages

Branch prediction
- Logic to guess whether or not branch will be taken, and possibly branch target

Advanced
- Out-of-order: Able to issue instructions out of program order
- Speculation: Execute instructions beyond branch points, possibly nullifying later
- Register renaming: Able to dynamically assign physical registers to instructions
- Retire unit: Logic to keep track of instructions as they complete.

Superscalar Execution Example

Assumptions
- Single FP adder takes 2 cycles
- Single FP multiplier takes 5 cycles
- Can issue add & multiply together
- Must issue in-order

Data Flow

Critical Path = 9 cycles

Out Of Order Issue
- Can start y as soon as adder available
- Must hold back z until $f10$ not busy & adder available

With Register Renaming
- Able to dynamically assign physical registers to instructions

Adding Advanced Features
**Pentium Pro (P6)**

**History**
- Announced in Feb. '95
- Delivering in high end machines now

**Features**
- Dynamically translates instructions to more regular format
  - Very wide RISC instructions
- Executes operations in parallel
  - Up to 5 at once
- Very deep pipeline
  - 12-18 cycle latency

**PentiumPro Operation**

Translates instructions dynamically into "Uops"
- 118 bits wide
- Holds operation, two sources, and destination

Executes Uops with "Out of Order" engine
- Uop executed when
  - Operands available
  - Functional unit available
- Execution controlled by "Reservation Stations"
  - Keeps track of data dependencies between uops
  - Allocates resources

**Branch Prediction**

Critical to Performance
- 11-15 cycle penalty for misprediction

Branch Target Buffer
- 512 entries
- 4 bits of history
- Adaptive algorithm
  - Can recognize repeated patterns, e.g., alternating taken/not taken

Handling BTB misses
- Detect in cycle 6
- Predict taken for negative offset, not taken for positive
  - Loops vs. conditionals

**PentiumPro Block Diagram**

Microprocessor Report 2/16/95
Limitations of x86 Instruction Set

Not enough registers
- too many memory references

Intel is switching to a new instruction set for Merced
- IA-64, joint with HP
- Will dynamically translate existing x86 binaries

PPC 604

Superscalar
- Up to 4 instructions per cycle

Speculative & Out-of-Order Execution
- Begin issuing and executing instructions beyond branch

Other Processors in this Category
- MIPS R10000
- Intel PentiumPro & Pentium II
- Digital Alpha 21264

General Principles

Must be Able to Flush Partially-Executed Instructions
- Branch mispredictions
- Earlier instruction generates exception

Special Treatment of "Architectural State"
- Programmer-visible registers
- Memory locations
- Don't do actual update until certain instruction should be executed

Emulate "Data Flow" Execution Model
- Instruction can execute whenever operands available
Processing Stages

**Fetch**
- Get instruction from instruction cache

**Dispatch (~ Decode)**
- Get available operands
- Assign to hardware execution unit

**Execute**
- Perform computation or memory operation
  - Stores are only buffered

**Retire / Commit (~ = Writeback)**
- Allow architectural state to be updated
  - Register update
  - Buffered store

Fetching Instructions

- Up to 4 fetched from instruction cache in single cycle

**Branch Target Address Cache (BTAC)**
- Target addresses of recently-executed, predicted-taken branches
  - 64 entries
  - Indexed by instruction address
- Accessed in parallel with instruction fetch
- If hit, fetch at predicted target starting next cycle

Branch Prediction

**Branch History Table (BHT)**
- 512 state machines, indexed by low-order bits of instruction address
- Encode information about prior history of branch instructions
  - Small chance of two branch instructions aliasing
- Predict whether or not branch will be taken
  - 3 cycle penalty if mispredict

**Interaction with BTAC**
- BHT entries start in state No!
- When make transition from No? to Yes?, allocate entry in BTAC
- Deallocate when make transition from Yes? to No?
Dispatching Actions

Generate Entry in Retirement Buffer
- 16-entry buffer tracking instructions currently "in flight"
  - Dispatched but not yet completed
  - Circular buffer in program order
  - Instruction tagged with branches they depend on
    - Easy to flush if mispredicted

Assign Rename Register as Target
- Additional registers (12 integer, 8 FP) used as targets for in-flight instructions
- Instruction updates this register
- Update of actual architectural register occurs only when instruction retired

Hazard Handling with Renaming

Dispatch Unit Maintains Mapping
- From register ID to actual register
- Could be the actual architectural register
  - Not target of currently-executing instruction
- Could be rename register
  - Perhaps already written by instruction that has not been retired
    - E.g., still waiting for confirmation of branch prediction
  - Perhaps instruction result not yet computed
    - Grab later when available

Hazards
- RAW: Mapping identifies operand source
- WAR: Write will be to different rename register
- WAW: Writes will be to different rename register

Read-after-Write (RAW) Dependencies

Also known as a "true" dependence
Example:
S1: addq r1, r2, r3
S2: addq r3, r4, r4

How to optimize?
- cannot be optimized away

Write-after-Read (WAR) Dependencies

Also known as an "anti" dependence
Example:
S1: addq r1, r2, r3
S2: addq r4, r5, r1
    ...
    addq r1, r6, r7

How to optimize?
- rename dependent register (e.g., r1 in S2 -> r8)
S1: addq r1, r2, r3
S2: addq r4, r5, r8
    ...
    addq r8, r6, r7
Write-after-Write (WAW) Dependences

Also known as an “output” dependence

Example:

S1:
addq r1, r2, r3
S2:
addq r4, r5, r8
...
addq r3, r6, r7

How to optimize?

• rename dependent register (e.g., r3 in S2 -> r8)

S1:
addq r1, r2, r3
S2:
addq r4, r5, r8
...
addq r8, r6, r7

Moving Instructions Around

Reservation Stations

• Buffers associated with execution units
• Hold instructions prior to execution
  - Plus those operands that are available
• May be waiting for one or more operands
  - Operand mapped to rename register that is not yet available
• May be waiting for unit to be available

Completion Busses

• Results generated by execution units
• Tagged by rename register ID
• Monitored by reservation stations
  - So they can get needed operands
  - Effectively implements bypassing
• Supply results to completion unit

Execution Resources

Integer

• Two units to handle regular integer instructions
• One for “complex” operations
  - Multiply with latency 3--4 and throughput once per 1--2 cycles
  - Unpipelined divide with latency 20

Floating Point

• Add/multiply with latency 3 and throughput 1
• Unpipelined divide with latency 18--31

Load Store Unit

• Own address ALU
• Buffer of pending store instructions
  - Don’t perform actual store until ready to retire instruction
• Loads can be performed speculatively
  - Check to see if target of pending store operation

Retiring Instructions

Retire in Program Order

• When instruction is at head of buffer
• Up to 4 per cycle
• Enable change of architectural state
  - Transfer from rename register to architectural
  - Free rename register for use by another instruction
• Allow pending store operation to take place

Flush if Should not be Executed

• Tagged by branch that was mispredicted
• Follows instruction that raised exception
• As if instructions had never been fetched
### 604 Chip

- Originally 200 mm²
  - 0.65µm process
  - 100 MHz
- Now 148 mm²
  - 0.35µm process
  - bigger caches
  - 300 MHz
- Performance requires real estate
  - 11% for dispatch & completion units
  - 6% for register files
  - Lots of ports

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### Execution Example

#### Assumptions
- Two-way issue with renaming
- Rename registers $f0$, $f2$, etc.
- 1 cycle add.d latency, 2 cycle mult.d

#### Execution Example Cycle 1

**Actions**
- Instructions $v$ & $w$ issued
  - $v$ target set to $f0$
  - $w$ target set to $f2$

<table>
<thead>
<tr>
<th>Value</th>
<th>Rename</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v2$</td>
<td>10.0</td>
</tr>
<tr>
<td>$v4$</td>
<td>20.0</td>
</tr>
<tr>
<td>$v6$</td>
<td>40.0</td>
</tr>
<tr>
<td>$v8$</td>
<td>80.0</td>
</tr>
<tr>
<td>$v10$</td>
<td>160.0</td>
</tr>
<tr>
<td>$v12$</td>
<td>320.0</td>
</tr>
</tbody>
</table>

#### Value Rename

<table>
<thead>
<tr>
<th>Value</th>
<th>Renames</th>
<th>Valid</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v2$</td>
<td>$v2$</td>
<td>$f2$</td>
</tr>
<tr>
<td>$v4$</td>
<td>$f4$</td>
<td></td>
</tr>
<tr>
<td>$v6$</td>
<td>$f6$</td>
<td></td>
</tr>
<tr>
<td>$v8$</td>
<td>$f8$</td>
<td></td>
</tr>
<tr>
<td>$v10$</td>
<td>$f10$</td>
<td>$f2$</td>
</tr>
<tr>
<td>$v12$</td>
<td>$f12$</td>
<td>$f4$</td>
</tr>
</tbody>
</table>

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#### Execution Example Cycle 2

**Actions**
- Instructions $x$ & $y$ issued
  - $x$ & $y$ targets set to $f4$ and $f6$
- Instruction $v$ executed

<table>
<thead>
<tr>
<th>Value</th>
<th>Rename</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v2$</td>
<td>10.0</td>
</tr>
<tr>
<td>$v4$</td>
<td>20.0</td>
</tr>
<tr>
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<td>320.0</td>
</tr>
</tbody>
</table>

#### Value Rename

<table>
<thead>
<tr>
<th>Value</th>
<th>Renames</th>
<th>Valid</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v2$</td>
<td>$v2$</td>
<td>$f2$</td>
</tr>
<tr>
<td>$v4$</td>
<td>$f4$</td>
<td></td>
</tr>
<tr>
<td>$v6$</td>
<td>$f6$</td>
<td></td>
</tr>
<tr>
<td>$v8$</td>
<td>$f8$</td>
<td></td>
</tr>
<tr>
<td>$v10$</td>
<td>$f10$</td>
<td>$f2$</td>
</tr>
<tr>
<td>$v12$</td>
<td>$f12$</td>
<td>$f4$</td>
</tr>
</tbody>
</table>

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**ADD**

<table>
<thead>
<tr>
<th>Op1</th>
<th>Op2</th>
<th>Dest</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>20.0</td>
<td>$v4$</td>
</tr>
<tr>
<td>40.0</td>
<td>160.0</td>
<td>$v2$</td>
</tr>
</tbody>
</table>

**MULT**

<table>
<thead>
<tr>
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<th>Op2</th>
<th>Dest</th>
</tr>
</thead>
<tbody>
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<td>20.0</td>
<td>80.0</td>
<td>$v6$</td>
</tr>
<tr>
<td>40.0</td>
<td>160.0</td>
<td>$v2$</td>
</tr>
</tbody>
</table>
Cycle 3

- Instruction v retired
  - But does not change $f_{10}$
- Instruction w begins execution
  - Moves through 2 stage pipeline
  - Instruction y executed
  - Instruction z stalled
    - Not enough reservation stations

<table>
<thead>
<tr>
<th>Value</th>
<th>Rename</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{10}$</td>
<td>10.0 $f_{2}$</td>
</tr>
<tr>
<td>$f_{4}$</td>
<td>20.0 $f_{6}$</td>
</tr>
<tr>
<td>$f_{6}$</td>
<td>40.0 $f_{6}$</td>
</tr>
<tr>
<td>$f_{10}$</td>
<td>80.0 $f_{8}$</td>
</tr>
<tr>
<td>$f_{12}$</td>
<td>160.0 $f_{10}$</td>
</tr>
</tbody>
</table>

<table>
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<th>Op1</th>
<th>Op2</th>
<th>Dest</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{10}$</td>
<td>$f_{4}$</td>
<td>80.0 $f_{4}$</td>
</tr>
<tr>
<td>$f_{2}$</td>
<td>$f_{8}$</td>
<td>60.0 $f_{6}$</td>
</tr>
</tbody>
</table>

Execution Example Cycle 4

- Instruction w finishes execution
- Instruction y cannot be retired yet
- Instruction x issued
  - Assigned to %f_{10}

<table>
<thead>
<tr>
<th>Value</th>
<th>Rename</th>
</tr>
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<tbody>
<tr>
<td>$f_{2}$</td>
<td>10.0 $f_{2}$</td>
</tr>
<tr>
<td>$f_{4}$</td>
<td>20.0 $f_{6}$</td>
</tr>
<tr>
<td>$f_{6}$</td>
<td>40.0 $f_{6}$</td>
</tr>
<tr>
<td>$f_{8}$</td>
<td>80.0 $f_{8}$</td>
</tr>
<tr>
<td>$f_{10}$</td>
<td>160.0 $f_{10}$</td>
</tr>
<tr>
<td>$f_{12}$</td>
<td>320.0 $f_{12}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Op1</th>
<th>Op2</th>
<th>Dest</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{2}$</td>
<td>$f_{4}$</td>
<td>80.0 $f_{4}$</td>
</tr>
<tr>
<td>$f_{4}$</td>
<td>$f_{8}$</td>
<td>60.0 $f_{6}$</td>
</tr>
</tbody>
</table>

Execution Example Cycle 5

- Instruction w retired
  - But does not change $f_{10}$
- Instruction y cannot be retired yet
- Instruction x executed

<table>
<thead>
<tr>
<th>Value</th>
<th>Rename</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{2}$</td>
<td>10.0 $f_{2}$</td>
</tr>
<tr>
<td>$f_{4}$</td>
<td>20.0 $f_{6}$</td>
</tr>
<tr>
<td>$f_{6}$</td>
<td>40.0 $f_{6}$</td>
</tr>
<tr>
<td>$f_{8}$</td>
<td>80.0 $f_{8}$</td>
</tr>
<tr>
<td>$f_{10}$</td>
<td>160.0 $f_{10}$</td>
</tr>
<tr>
<td>$f_{12}$</td>
<td>320.0 $f_{12}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Op1</th>
<th>Op2</th>
<th>Dest</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{2}$</td>
<td>$f_{4}$</td>
<td>80.0 $f_{4}$</td>
</tr>
<tr>
<td>$f_{2}$</td>
<td>$f_{8}$</td>
<td>60.0 $f_{6}$</td>
</tr>
</tbody>
</table>

Execution Example Cycle 6

- Instruction x & y retired
  - Update %f_{10} and %f_{4}
- Instruction z executed

<table>
<thead>
<tr>
<th>Value</th>
<th>Rename</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{2}$</td>
<td>10.0 $f_{2}$</td>
</tr>
<tr>
<td>$f_{4}$</td>
<td>20.0 $f_{6}$</td>
</tr>
<tr>
<td>$f_{6}$</td>
<td>40.0 $f_{6}$</td>
</tr>
<tr>
<td>$f_{8}$</td>
<td>80.0 $f_{8}$</td>
</tr>
<tr>
<td>$f_{10}$</td>
<td>160.0 $f_{10}$</td>
</tr>
<tr>
<td>$f_{12}$</td>
<td>200.0 $f_{12}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Op1</th>
<th>Op2</th>
<th>Dest</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{2}$</td>
<td>$f_{4}$</td>
<td>80.0 $f_{4}$</td>
</tr>
<tr>
<td>$f_{4}$</td>
<td>$f_{8}$</td>
<td>60.0 $f_{6}$</td>
</tr>
</tbody>
</table>

Page 12
**Execution Example Cycle 7**

- Instruction z retired

<table>
<thead>
<tr>
<th>Value</th>
<th>Rename</th>
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</thead>
<tbody>
<tr>
<td>$f2</td>
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</tr>
<tr>
<td>$f4</td>
<td>40.0</td>
</tr>
<tr>
<td>$f6</td>
<td>80.0</td>
</tr>
<tr>
<td>$f8</td>
<td>120.0</td>
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<tr>
<td>$f10</td>
<td>60.0</td>
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<tr>
<td>$f12</td>
<td>320.0</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Op1</th>
<th>Op2</th>
<th>Dest</th>
<th>Value</th>
<th>Renames</th>
<th>Valid</th>
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<tbody>
<tr>
<td>ADD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MULT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

```
static void loop1() {
    int i;
    data_t abs_sum = (data_t) 0;
    data_t prod = (data_t) 1;
    for (i = 0; i < CNT; i++) {
        data_t x = dat[i];
        data_t ax = ABS(x);
        abs_sum += ax;
        prod *= x;
    }
    answer = abs_sum+prod;
}
```

**Living with Expensive Branches**

- Mispredicted Branch Carries a High Cost
  - Must flush many in-flight instructions
  - Start fetching at correct target
  - Will get worse with deeper and wider pipelines

**Impact on Programmer / Compiler**

- Avoid conditionals when possible
  - Bit manipulation tricks
- Use special conditional-move instructions
  - Recent additions to many instruction sets
- Make branches predictable
  - Very low overhead when predicted correctly

**Branch Prediction Example**

- Compute sum of absolute values
- Compute product of original values

```
#define ABS(x) x < 0 ? -x : x
```

**MIPS Code**

```
0x6c4:  8c620000 lw r2,0(r3)
0x6c8:  24640001 addiu r4,4,1
0x6cc:  c4410002 bgez r2,0x6d8
0x6d0:  00a20018 mult r5,r3
0x6d4:  00021023 subu r2,r0,r2
0x6d8:  00c23021 addu r6,r6,r2
0x6dc:  28820400 addu r5,r6,r2
0x6e0:  14402f70 beqz r2,0x6e4
0x6e4:  24630008 addiu r3,r3,4
```

**Some Interesting Patterns**

- PPPPPPPP
  - Should give perfect prediction
  - Will mispredict 1/2 of the time
- RRRRRRRR
  - Should alternate between states No! and Yes?
- N*N[PNPN]
  - Should alternate between states No! and Yes?
- N*N[PPNN]
  - Should alternate between states No! and Yes?
Loop Performance (FP)

Observations
- 604 has prediction rates 0%, 50%, and 100% - Expected 50% from N*N[PNPN]
  - Expected 25% from N*N[PPNN]
  - Loop so tight that speculate through single branch twice?
- Pentium appears to be more variable, ranging 0 to 100%

Special Patterns Can be Worse than Random
- Only 50% of all people are “above average”

Pentium II
- Random shows clear penalty
- But others do well
  - More clever prediction algorithm

R10000
- Has special “conditional move” instructions
  - Compiler translates $a = \text{Cond ? } Texpr : Fexpr$ into
    $$a = Fexpr \quad \text{temp} = Texpr \quad \text{CMOV}(a, \text{temp, Cond})$$
  - Only valid if $Texpr \& Fexpr$ can’t cause error

P6 Branch Prediction

Two-Level Scheme
- Yeh & Patt, ISCA ’93
- Keep shift register showing past $k$ outcomes for branch
- Use to index $2^k$ entry table
- Each entry provides 2-bit, saturating counter predictor
- Very effective for any deterministic branching pattern

Branch Prediction Comparisons

Microprocessor Report
March 27, 1995
Effect of Loop Unrolling

Observations
- [PNPN] yields PPPP ... for one branch, NNNN ... for the other
- [PPNN] yields PNPN ... for both branches
  - 50% accuracy if start in state No?
  - 25% accuracy if start in state No!

Another stressor in the life of a benchmarker
- Must look carefully at what compiler is doing

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Cycles Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPPPPP</td>
<td>9.2 0</td>
</tr>
<tr>
<td>RRRRRR</td>
<td>12.6 3.4</td>
</tr>
<tr>
<td>N*N[PNPN]</td>
<td>15.8 6.6</td>
</tr>
<tr>
<td>N*P[PNPN]</td>
<td>15.9 6.7</td>
</tr>
<tr>
<td>N*N[PPNN]</td>
<td>12.5 3.3</td>
</tr>
<tr>
<td>N*P[PPNN]</td>
<td>12.5 3.3</td>
</tr>
</tbody>
</table>

MIPS R10000

(See attached handouts.)

More info available at:
- http://www.sgi.com/MIPS/products/z10k

DEC Alpha 21264

Fastest Announced Processor
- Spec95: 30 Int 60 FP
  - 500 MHz, 15M transistors, 60 Watts

Fastest Existing Processor is Alpha 21164
- Spec95: 12.6 Int 18.3 FP
  - 500 MHz, 9.2M transistors, 25 Watts

Uses Every Trick in the Book
- 4-6 way superscalar
- Out of order execution with renaming
- Up to 80 instructions in process simultaneously
- Lots of cache & memory bandwidth

21264 Block Diagram

4 Integer ALUs
- Each can perform simple instructions
- Handle address calculations

Register Files
- 32 arch / 80 physical Int
- 32 arch / 72 physical FP
- Int registers duplicated
  - Extra cycle delay from write in one to read in other
- Each has 6 read ports, 4 write ports
  - Attempt to issue consumer to producer side  

Microprocessor Report 10/28/96
21264 Pipeline

Very Deep Pipeline
- Can't do much in 2ns clock cycle!
- 7 cycles for simple instruction
- 9 cycles for load or store
- 7 cycle penalty for mispredicted branch
  - Elaborate branch prediction logic
  - Claim 95% accuracy

Microprocessor Report 10/28/96

21264 Branch Prediction Logic

- Purpose: Predict whether or not branch taken
- 35Kb of prediction information
- 2% of total die size
- Claim 0.7--1.0% misprediction

Microprocessor Report 10/28/96

Processor Comparisons

<table>
<thead>
<tr>
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<tbody>
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<td>35 W</td>
<td></td>
<td>665 MHz</td>
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<td></td>
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<td></td>
<td>64 Kb</td>
<td>$103</td>
<td>16 Kb</td>
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<tr>
<td>PowerPC 6010</td>
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<tr>
<td>Alpha 21164</td>
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<td></td>
</tr>
</tbody>
</table>

Microprocessor Report 10/20/96

Challenges Ahead

Diminishing Returns on Cost vs. Performance
- Superscalar processors require instruction level parallelism
- Many programs limited by sequential dependencies
Finding New Sources of Parallelism
- e.g., thread-level parallelism
Getting Design Correct Difficult
- Verification team larger than design team
- Devise tests for interactions between concurrent instructions
- May be 80 executing at once

Microprocessor Report 10/20/96
New Era for Performance Optimization

Data Resources are Free and Fast
- Plenty of computational units
- Most programs have poor utilization

Unexpected Changes in Control Flow Expensive
- Kill everything downstream when mispredict
- Even if will execute in near future where branches reconverge

Think Parallel
- Try to get lots of things going at once

Not a Truly Parallel Machine
- Bounded resources
- Access from limited code window