Pipelining – Part 2

CSE 410, Spring 2007
Computer Systems

http://www.cs.washington.edu/410

Reading and References

• *Computer Organization and Design, Patterson and Hennessy*
  » Section 6.4 Data Hazards and Forwarding
  » Section 6.5 Data Hazards and Stalls
  » Section 6.6 Branch Hazards

Control Hazards

• Branch instructions cause **control hazards** (aka **branch hazards**) because we don’t know which instruction to fetch next

  \[
  \text{bne } s0, s1, \text{skip} \\
  \text{add } s4, s3, s0 \\
  ... \\
  \text{skip:} \\
  \text{sub } s4, s3, s0
  \]

  ![Control Hazards Diagram]

Idea: Stall for branch hazard

• Stall until we know which instruction to execute next
  » would introduce a 4-cycle pipeline bubble in the basic pipeline

  \[
  \text{bne } s0, s1, \text{next} \\
  \text{sub } s4, s3, s0 \\
  \text{...} \\
  \text{next:} \\
  \text{sub } s4, s3, s0
  \]

  ![Idea: Stall for branch hazard Diagram]
Idea: Move Branch Logic to ID

- Move the branch hardware to ID stage
  - Hardware to compare two registers is simpler than hardware to add them
- We still have to stall for one cycle
- And we can’t move the branch up any more

Branch Delay Slot

- A branch now causes a stall of one cycle
- Try to execute an instruction instead of nop
- The compiler (assembler, programmer) must find an instruction to fill the branch delay slot
  - 50% of the instructions are useful
  - 50% are nop which don’t do anything

Idea: Reorder Instructions

- Reordering instructions is a common technique for avoiding pipeline stalls
- Static reordering
  - programmer, compiler, and assembler do this
- Dynamic reordering
  - modern processors can see several instructions
  - they execute any that have no dependency
  - this is known as out-of-order execution and is complicated to implement but effective

Branch Delay Slot execution

- Instruction in the branch delay slot always executes, no matter what the branch does
  - it follows the branch in memory
  - but it “piggybacks” and is always executed
  - no bubble at all
beq with delay slot

```assembly
.set noreorder
.set nomacro
beq $v0,$zero,$L4
move $s1,$s4
.set macro
.set reorder
```

delay slot

jal with delay slot

```assembly
move $a0,$s3
move $a1,$s0
.set noreorder
.set nomacro
jal QuickSort
move $a2,$s4
.set macro
.set reorder
```

delay slot

Idea: Predict the branch action

- For example, assume the branch is not taken
  - Execute the next instruction in memory
- If we guessed right, we’re golden
  - no bubble at all
- If we guessed wrong, then we lose a little
  - squash the partially completed instructions.
  - This is called flushing the pipeline
  - Wasted time, but would have stalled anyway

Squash

- Must be able to completely suppress the effects of guessing wrong
  - An instruction cannot write to memory or a register until we’re sure it should execute
Assume Branch Not Taken

Branch not taken

Branch taken

Static Branch Prediction

• Most backwards branches are taken (80%)
  » they are part of loops
• Half of forward branches are taken (50%)
  » if statements
• Common static branch prediction scheme is
  » predict backwards branches are taken
  » predict forward branches are not taken
• This does okay (70-80%), but not great

Dynamic Branch Prediction

• Most programs are pretty regular
  » Most of the time only execute a small subset of the program code
  » Same branch instructions execute repeatedly
• A particular branch instruction is usually:
  » taken if it was taken last time
  » not taken if it was not taken last time
• If we keep a history of each branch instruction, then we can predict much better

Dynamic Branch Prediction

• The CPU records what happened last time we executed the branch at this address
• Generally record last two results
  » simple 4-state transition table makes prediction
• Dynamic branch prediction is 92-98% accurate
2-bit prediction scheme

Implementing Branch Prediction

- There is not room to store every branch instruction address
  - so last few bits of the instruction address are used to index into a table
  - some instructions collide like a hash table
  - but that’s okay, it just means we’re wrong once in a while

Branch Prediction Table

<table>
<thead>
<tr>
<th>Address</th>
<th>state?</th>
<th>Predict</th>
<th>correct?</th>
<th>new state</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0x000401234</td>
<td>11</td>
<td>not taken</td>
<td>yes</td>
<td>11</td>
</tr>
<tr>
<td>0x0004F0238</td>
<td>00</td>
<td>taken</td>
<td>no</td>
<td>01</td>
</tr>
<tr>
<td>0x00040223C</td>
<td>10</td>
<td>not taken</td>
<td>no</td>
<td>00</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Importance of Branch Prediction

- Branches occur very frequently
  - every five instructions on average
- Modern processors execute up to 4 instructions per cycle
  - so a branch occurs every 2 cycles
- Newer pipelines are getting longer
  - 8,9,11,13 cycles
  - error penalty is 3-5 cycles instead of 1 cycle
  - hard to fill branch delay slots