Control Dependence

• Just as an instruction will be dependent on other instructions to provide its operands (dependence), it will also be dependent on other instructions to determine whether it gets executed or not (dependence or dependence).

• Control dependences are particularly critical with branches.

Branch Hazards

• Branch dependences can result in branch hazards (when they are too close to be handled correctly in the pipeline).
Dealing With Branch Hazards

- **Hardware**
  - stall until you know which direction
  - reduce hazard through earlier computation of branch direction
  - guess which direction
    - assume not taken (easiest)
    - more educated guess based on history (requires that you know it is a branch before it is even decoded!)
- **Hardware/Software**
  - nops, or instructions that get executed either way (delayed branch).

Stalling for Branch Hazards

- Seems wasteful, particularly when the branch isn’t taken.
- Makes all branches cost 4 cycles.

Assume Branch *Not Taken*

- works pretty well when you’re right
Assume Branch *Not Taken*

• same performance as stalling when you’re wrong

- **beq** $4, $0, there
  - and $12, $2, $5
  - or ...
  - add ...

- there: sub $12, $4, $2

- Performance depends on percentage of time you guess right.
- Flushing an instruction means to prevent it from changing any permanent state (registers, memory, PC).
  - sounds a lot like a bubble...
  - But notice that we need to be able to insert those bubbles later in the pipeline

Reducing the Branch Delay

• can easily get to 2-cycle stall

Stalling for Branch Hazards
Reducing the Branch Delay

- Harder, but possible, to get to 1-cycle stall

Stalling for Branch Hazards

The Pipeline with flushing for taken branches

- Notice the IF/ID flush line added.

Eliminating the Branch Stall

- There’s no rule that says we have to see the effect of the branch immediately. Why not wait an extra instruction before branching?
- The original SPARC and MIPS processors each used a single branch delay slot to eliminate single-cycle stalls after branches.
- The instruction after a conditional branch is always executed in those machines, regardless of whether the branch is taken or not!
Branch Delay Slot

Filling the branch delay slot

• The branch delay slot is only useful if you can find something to put there.
• If you can’t find anything, you must put a `nop` to insure correctness.

Branch Delay Slots

• This works great for this implementation of the architecture, but becomes a permanent part of the ISA.
• What about the MIPS R10000, which has a 5-cycle branch penalty, and executes 4 instructions per cycle???
Branch Prediction

• Always assuming the branch is not taken is a crude form of __________.
• What about loops that are 95% of the time?
  – we would like the option of assuming not taken for some branches, and taken for others, depending on ???

Two-bit predictors give better loop prediction

for (i=0; i<10; i++) {
  ...
  ...
  }

... add $i,$i, #1
beq $i,$i10, loop

Two different 2-bit schemes

Strongly Taken

Weakly Taken

Weakly Not Taken

Strongly Not Taken

Decrement when not taken

Increment when taken
Branch History Table

- has limited size
- 2 bits by N (e.g. 4K)
- uses low bits of branch address to choose entry

- what happens when table too small?
- what about even/odd branch?

Control Hazards -- Key Points

- Control (or branch) hazards arise because we must fetch the next instruction before we know if we are branching or where we are branching.
- Control hazards are detected in hardware.
- We can reduce the impact of control hazards through:
  - early detection of branch address and condition
  - branch prediction
  - branch delay slots

Pipeline performance

```
loop:  lw $15, 1000($2)
       add $16, $15, $12
       lw $18, 1004($2)
       add $19, $18, $12
       beq $19, $0, loop:
```