Code Shape III
Booleans, Relationals, & Control flow

Boolean & Relational Values

How should the compiler represent them?

- Answer depends on the target machine

Two classic approaches

- Numerical representation
- Positional (implicit) representation

Correct choice depends on both context and ISA

Boolean & Relational Values

Numerical representation

- Assign values to TRUE and FALSE
- Use target machine's AND, OR, and NOT operations

Examples:

Use comparison to get a boolean from a relational expression

x < y	***becomes***	**cmp_LT** $r_x, r_y \Rightarrow r_1$
if (x < y) **then** $stmt_1$ **else** $stmt_2$	***becomes***	**cmp_LT** $r_x, r_y \Rightarrow r_1$ **cbr** $r1 \rightarrow L_1, L_2$ L_1: $stmt_1$ **jumpI** $\rightarrow L_3$ L_2: $stmt_2$ **jumpI** $\rightarrow L_3$ L_3: **nop**

Boolean & Relational Values

Condition code?

- Special register that summarize results of an operation

What if the ISA uses a condition code?

- Must use a conditional branch to interpret result of compare
- Necessitates branches in the evaluation

Example:

x < y	*becomes*		cmp	$r_x, r_y \Rightarrow cc_1$
			cbr_LT	$cc_1 \rightarrow L_T, L_F$
		L_T:	loadI	$1 \Rightarrow r_2$
			br	$\rightarrow L_E$
		L_F:	loadI	$0 \Rightarrow r_2$
		L_E:	…other stmts…	

Boolean & Relational Values

The last example actually encodes result in the PC

If result is used to control an operation, this may be enough

Example
if (x < y)
then a ← c + d
else a ← e + f

Variations on the ILOC Branch Structure

Straight Condition Codes			*Boolean Compares*		
	comp	$r_x,r_y \Rightarrow cc_1$		cmp_LT	$r_x,r_y \Rightarrow r_1$
	cbr_LT	$cc_1 \rightarrow L_1,L_2$		cbr	$r_1 \rightarrow L_1,L_2$
L_1:	add	$r_c,r_d \Rightarrow r_a$	L_1:	add	$r_c,r_d \Rightarrow r_a$
	br	$\rightarrow L_{OUT}$		br	$\rightarrow L_{OUT}$
L_2:	add	$r_e,r_f \Rightarrow r_a$	L_2:	add	$r_e,r_f \Rightarrow r_a$
	br	$\rightarrow L_{OUT}$		br	$\rightarrow L_{OUT}$
L_{OUT}:	nop		L_{OUT}:	nop	

Condition code version does not directly produce (x < y)

Boolean version does

Still, there is no significant difference in the code produced

Boolean & Relational Values

Conditional move & predication both simplify this code

Example
if (x < y)
then a ← c + d
else a ← e + f

Other Architectural Variations				
Conditional Move		***Predicated Execution***		
comp	$r_x, r_y \Rightarrow cc_1$		cmp_LT	$r_x, r_y \Rightarrow r_1$
add	$r_c, r_d \Rightarrow r_1$	$(r_1)?$	add	$r_c, r_d \Rightarrow r_a$
add	$r_e, r_f \Rightarrow r_2$	$(\neg r_1)?$	add	$r_e, r_f \Rightarrow r_a$
i2i_LT	$cc_1, r_1, r_2 \Rightarrow r_a$			

Both versions avoid the branches

Both are shorter than CCs or Boolean-valued compare

Are they better?

Boolean & Relational Values

Consider the assignment $x \leftarrow a < b \wedge c < d$

VARIATIONS ON THE ILOC BRANCH STRUCTURE	
Straight Condition Codes	***Boolean Compare***
comp $r_a, r_b \Rightarrow cc_1$ cbr_LT $cc_1 \rightarrow L_1, L_2$ L_1: comp $r_c, r_d \Rightarrow cc_2$ cbr_LT $cc_2 \rightarrow L_3, L_2$ L_2: loadI $0 \Rightarrow r_x$ br $\rightarrow L_{OUT}$ L_3: loadI $1 \Rightarrow r_x$ br $\rightarrow L_{OUT}$ L_{OUT}: nop	cmp_LT $r_a, r_b \Rightarrow r_1$ cmp_LT $r_c, r_d \Rightarrow r_2$ and $r_1, r_2 \Rightarrow r_x$

Here, the boolean compare produces much better code

Boolean & Relational Values

Conditional move & predication help here, too

$x \leftarrow a < b \wedge c < d$

Other Architectural Variations					
Conditional Move			*Predicated Execution*		
comp	r_a, r_b	$\Rightarrow cc_1$	cmp_LT	$r_a, r_b \Rightarrow r_1$	
i2i_LT	cc_1, r_T, r_F	$\Rightarrow r_1$	cmp_LT	$r_c, r_d \Rightarrow r_2$	
comp	r_c, r_d	$\Rightarrow cc_2$	and	$r_1, r_2 \Rightarrow r_x$	
i2i_LT	cc_2, r_T, r_F	$\Rightarrow r_2$			
and	r_1, r_2	$\Rightarrow r_x$			

Conditional move is worse than Boolean compares

Predication is identical to Boolean compares

Context & hardware determine the appropriate choice

Control Flow

If-then-else

- Follow model for evaluating relationals & booleans with branches

Branching versus predication *(e.g., IA-64)*

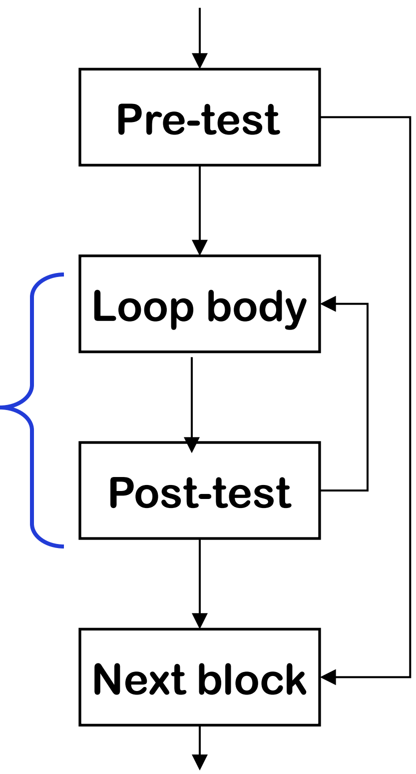
- Frequency of execution
  - → Uneven distribution ⇒ do what it takes to speed common case
- Amount of code in each case
  - → Unequal amounts means predication may waste issue slots
- Control flow inside the construct
  - → Any branching activity within the case base complicates the predicates and makes branches attractive

Control Flow

Loops

- Evaluate condition before loop (if needed)
- Evaluate condition after loop
- Branch back to the top (if needed)

Merges test with last block of loop body



while, for, do, & until all fit this basic model

Loop Implementation Code

for (i = 1; i< 100; i++) { *body* }

next statement

```
        loadI     1 ⇒ r1
        loadI     1 ⇒ r2
        loadI     100 ⇒ r3
        cmp_GE    r1, r3 ⇒ r4
        cbr       r4 ⇒ L2, L1
L1:     body
        add       r1, r2 ⇒ r1
        cmp_LT    r1, r3 ⇒ r5
        cbr       r5 ⇒ L1, L2
L2:     next statement
```

Initialization

Pre-test

Post-test

Break statements

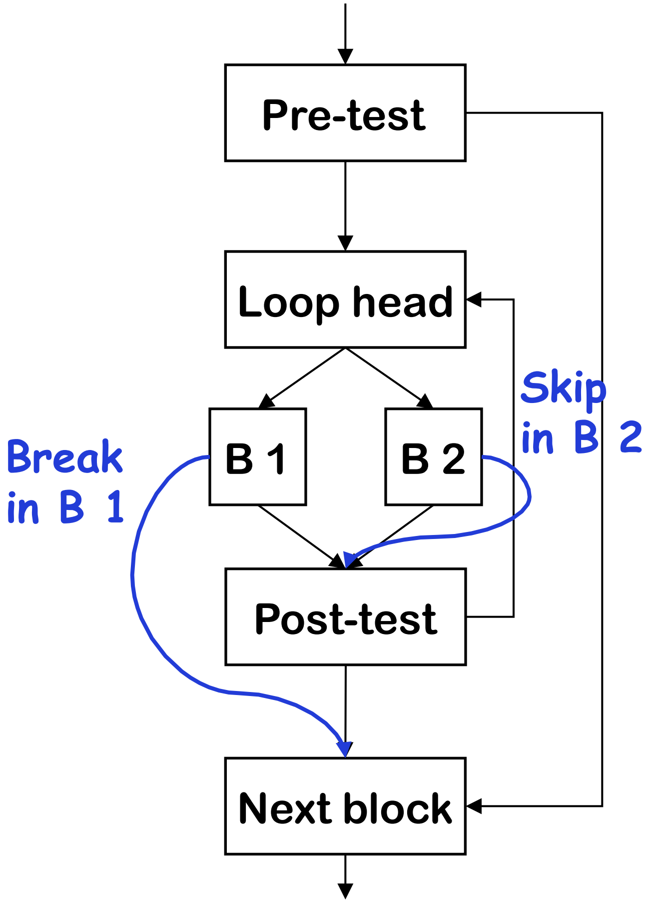
Many modern programming languages include a break

- Exits from the innermost control-flow statement
  - → Out of the innermost loop
  - → Out of a case statement

Translates into a jump

- Targets statement outside control-flow construct
- Creates multiple-exit construct
- Skip in loop goes to next iteration

Only make sense if loop has > 1 block



Control Flow

Case Statements

1 Evaluate the controlling expression

2 Branch to the selected case

3 Execute the code for that case

4 Branch to the statement after the case

Parts 1, 3, & 4 are well understood, part 2 is the key

Control Flow

Case Statements

1 Evaluate the controlling expression

2 Branch to the selected case

3 Execute the code for that case

4 Branch to the statement after the case (*use break*)

Parts 1, 3, & 4 are well understood, part 2 is the key

Surprisingly many compilers do this for all cases!

Strategies

- Linear search (nested if-then-else constructs)
- Build a table of case expressions & binary search it
- Directly compute an address (requires dense case set)