Compiler Design

Lecture 13: Code generation : Logical & Relational Operators, and Control Flow

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Logical & Relational Operators

How to represent the following in assembly?

```
x<10 && y>3
```

Answer: it depends on the target machine.

Several approaches:

- Numerical representation
- Positional Encoding (*e.g.* MIPS assembly)
- Conditional Move and Predication

Correct choice depends on both context and ISA (Instruction Set Architecture)

Numerical Representation

Assign numerical values to true and false

- In C, false = 0 and true = anything else.

Use comparison operator from the ISA to get a value from a relational operator:

- MIPS has `SLT` instruction (Set Less Than);
- and `SLTU` instruction (Set Less Than Unsigned)

Examples

Assuming x and y are in registers $x and $y.

`x < y`	`slt $t0, $x, $y`
`x <= y`	`slt $t0, $y, $x` `xori $t1, $t0, 0x1`
`x == y`	`xor $t0,$x,$y` `sltu $t1,$t0,1`
`x != y`	`xor $t0,$x,$y` `sltu $t1,$zero,$t0`

For the other two missing relational operators, swap the arguments.

Positional Encoding

What if the ISA does not provide comparison operators?

- Use conditional branch to interpret the result of a relational operator.

Example: `x<y`

```
     blt $x, $y, LT
     li  $t0, 0
     j   END
LT : li  $t0, 1
END: ...
```

The absence of comparison instructions is not as bad as you think.

Most boolean expressions are used with branching anyway.

Example

```
if (x < y)
  z = 3;
else
  z = 4;
```

Corresponding assembly code

```
      bge $x, $y, ELSE
      li $z, 3
      j END
ELSE: li $z, 4
END:  ...
```

What about logical operators && and || ?

In the general case, must use branching!

Example with function calls

```
foo() || bar()
```

If `foo()` evaluates to true, `bar` is never called!

Simpler example

```
x || y
```

Corresponding assembly code

```
      bne $x, $zero, TRUE
      bne $y, $zero, TRUE
      li $t0, 0
      j END
TRUE: li $t0, 1
END: ...
```

Combining Logical and Relational Operators

If supported by your ISA, simple approach consists of using numerical encoding for relational operators and positional for logical operators.

Example

x<4 || y<6

Corresponding assembly code

```
      li   $t0, 4
      slt  $t1, $x, $t0
      bne  $t1, $zero, TRUE

      li   $t2, 6
      slt  $t3, $y, $t2
      bne  $t3, $zero, TRUE

      li $t4, 0
      j END

TRUE: li $t4, 1
END:  ...
```

Conditional Move and Predication

Conditional move and predication can simplify code (if ISA supports it!).

Example

```
if (x < y)
  z = 3;
else
  z = 4;
```

Corresponding (naive) assembly code

Conditional Move	Predicated Execution

`slt  $t0, $x, $y`
`li   $t1, 3`
`li   $t2, 4`
`cmov $z, $t0, $t1, $t2`
	`    slt $t0, $x, $y`
	`$t0?li  $z, 3`
	`$t0?li  $z, 4`

Unfortunately, these instructions are not available on MIPS.

Last words on logical and relational operators

Best choice depends on two things

- ISA instructions available
- Context

Logical & Relational Operators

Implementation

Labels

Need to have unique labels that we can emit.

Label class

```
class Label {
  static counter = 0;
  String name;
  Label() { name = "label"+counter++; }
}
```

Visitor Implementation (Expression)

ExpressionVisitor

```
Register visitBinOp(BinOp bo) {
  Register lhsReg = bo.lhs.accept(this);
  Register resReg = newVirtualRegister();

  switch(bo.op) {
    ...
    case LT:
      Register rhsReg = bo.rhs.accept(this);
      emit("slt", resReg, lhsReg, rhsReg);
      break;
    ...
```

ExpressionVisitor (cont.)

```
    case OR:
      Label trueLbl = new Label();
      Label endLbl  = new Label();
      emit("bne", lhsReg, zeroReg, trueLbl);

      Register rhsReg = bo.rhs.accept(this);
      emit("bne", rhsReg, zeroReg, trueLbl);

      emit("li", resReg, 0);
      emit("j", endLbl);

      emit(trueLbl);
      emit("li", resReg, 1);

      emit(endLbl);
    ...
  }
  return resReg;
}
```

Control-Flow

Control-Flow

- If-then-else
- Loops (for, while, ...)
- Switch/case statements

If-then-else

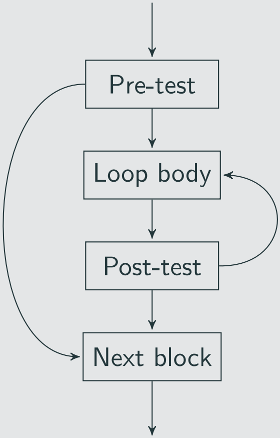
Follow the model for evaluating relational and boolean with branches.

Branching versus predication (*e.g.* IA-64, ARM ISA) trade-off:

- Frequency of execution:
  uneven distribution, try to speedup common case
- Amount of code in each case:
  unequal amounts means predication might waste issue slots
- Nested control flow:
  any nested branches complicates the predicates and makes branching attractive

Loops

Basic pattern



- evaluate condition before the loop (if needed)
- evaluate condition after the loop
- branch back to the top (if needed)

while, for and do while loops all fit this basic model.

Example: for loop

```
for (i=1; i<100; i++) {
  body
}
next stmt
```

Corresponding assembly

```
      li  $t0, 1
      li  $t1, 100
      bge $t0,$t1, NEXT

BODY: body
      addi $t0, $t0, 1
      blt  $t0, $t1, BODY

NEXT: next stmt
```

Exercise

Write the assembly code for the following while loop:

```
while (x >= y) {
  body
}
next stmt
```

Break/continue

Most modern programming languages include a break statement (loops, switch statements)

```
for (...) {
  ...
  if (...)
    break;
  ...
}
```

In such cases, use an unconditional branch to the next statement following the control-flow construct (loop or case statement).

For skip or continue statement, branch to the next iteration (loop start)

Case Statement (switch)

Case statement

```
switch (c) {
  case 'a': stmt1;
  case 'b': stmt2; break;
  case 'c': stmt3;
}
```

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

Part 2 is key!

Strategies:

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

Exercise

Knowing that the character `'a'` corresponds to the decimal value 97 (ASCII table), write the assembly code for the example below using linear search.

```
char c;
...
switch (c) {
  case 'a': stmt1;
  case 'b': stmt2; break;
  case 'c': stmt3; break;
  case 'd': stmt4;
}
stmt5;
```

Exercise : can you do it without any conditional jumps?

Hint: use the JR MIPS instruction which jumps directly to an address stored in a register.

Control-Flow

Implementation

Visitor Implementation (Statement)

If statement

```
StmtCodeGenVisitor implements Visitor<Void> {

 Void visitIf(If ifStmt) {
   Register cond = ifStmt.cond.accept(new ExprVisitor());

   Label elseLbl = new Label();
   Label endLbl  = new Label();

   emit("beq", cond, zeroReg, elseLbl);

   ifStmt.then.accept(this);
   emit("j", endLbl);

   emit(elseLbl);
   ifStmt.els.accept(this); // assumes else is present

   emit(endLbl);

   return null;
 }
```

Next lecture

More code generation:

- Memory Allocation
- Function Call
- References vs. Values