Code Generation 2

Roadmap (Where are we?)

Last lecture

- Code generation
  - → Code shape
  - → Expressions
  - → Assignments

This lecture

- Code generation
  - → Arrays
  - → Boolean and relational values
  - → Control flow

How does the compiler handle A[i,j] ?

First, must agree on a storage scheme

Row-major order (most languages)

- Lay out as a sequence of consecutive rows
- Rightmost subscript varies fastest
- A[1,1], A[1,2], A[1,3], A[2,1], A[2,2], A[2,3]

Column-major order (Fortran)

- Lay out as a sequence of columns
- Leftmost subscript varies fastest
- A[1,1], A[2,1], A[1,2], A[2,2], A[1,3], A[2,3]

Indirection vectors (Java)

- Vector of pointers to pointers to … to values
- Takes much more space, trades indirection for arithmetic
- Not amenable to analysis

Laying Out Arrays

The Concept

A

1,1	1,2	1,3	1,4
2,1	2,2	2,3	2,4

These have distinct & different cache behavior

Row-major order

A

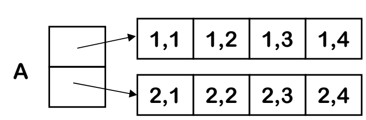
1,1	1,2	1,3	1,4	2,1	2,2	2,3	2,4

Column-major order

A

1,1	2,1	1,2	2,2	1,3	2,3	1,4	2,4

Indirection vectors



Computing an Array Address

A[i]

- @A + (i - low) x sizeof(A[1])
- In general: base(A) + (i - low) x sizeof(A[1])

int A[1:10] ⇒ low is 1
Make low 0 for faster access (saves a –)

Almost always a power of 2, known at compile-time
⇒ use a shift for speed

Computing an Array Address

A[i]

- @A + (i - low) x sizeof(A[1])
- In general: base(A) + (i - low) x sizeof(A[1])

What about $A[i_1,i_2]$?

This stuff looks expensive!
Lots of implicit +, -, x ops

Row-major order, two dimensions

$@A + ((i_1 - low_1) \times (high_2 - low_2 + 1) + i_2 - low_2) \times sizeof(A[1])$

Column-major order, two dimensions

$@A + ((i_2 - low_2) \times (high_1 - low_1 + 1) + i_1 - low_1) \times sizeof(A[1])$

Indirection vectors, two dimensions

$*(A[i_1])[i_2]$ — where $A[i_1]$ is, itself, a 1-d array reference

Optimizing Address Calculation for A[i,j]

In row-major order where w = sizeof(A[1,1])

$$@A + (i-low_1)(high_2-low_2+1) \times w + (j - low_2) \times w$$

Which can be factored into

$$@A + i \times (high_2-low_2+1) \times w + j \times w$$
$$- (low_1 \times (high_2-low_2+1) \times w) + (low_2 \times w)$$

If low_i, $high_i$, and w are known, the last term is a constant

Define $@A_0$ as

$$@A - (low_1 \times (high_2-low_2+1) \times w + low_2 \times w$$

And len_2 as $(high_2-low_2+1)$

Then, the address expression becomes

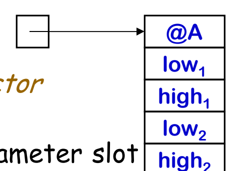
$$@A_0 + (i \times len_2 + j) \times w$$

Compile-time constants

Array References

What about arrays as actual parameters?

Whole arrays, as call-by-reference parameters



- Need dimension information ⇒ build a *dope vector*
- Store the values in the calling sequence
- Pass the address of the dope vector in the parameter slot
- Generate complete address polynomial at each reference

Some improvement is possible

- Save len_i and low_i rather than low_i and $high_i$
- Pre-compute the fixed terms in prologue sequence

What about call-by-value?

- Most c-b-v languages pass arrays by reference
- This is a language design issue

Array References

What about A[12] as an actual parameter?

If corresponding parameter is a scalar, it's easy

- Pass the address or value, as needed
- Must know about both formal & actual parameter
- Language definition must force this interpretation

What is corresponding parameter is an array?

- Must know about both formal & actual parameter
- Meaning must be well-defined and understood
- Cross-procedural checking of conformability

⇒ Again, this is a language design issue

Example: Array Address Calculations in a Loop

```
DO J = 1, N
   A[I,J] = A[I,J] + B[I,J]
END DO
```

- Naïve: Perform the address calculation twice

```
DO J = 1, N
   R1 = @A0 + (J x len1 + I ) x floatsize
   R2 = @B0 + (J x len1 + I ) x floatsize
   MEM(R1) = MEM(R1) + MEM(R2)
END DO
```

Example: Array Address Calculations in a Loop

```
DO J = 1, N
   A[I,J] = A[I,J] + B[I,J]
END DO
```

- Sophisticated: Move common calculations out of loop

```
R1 = I x floatsize
c = len1 x floatsize    ! Compile-time constant
R2 = @A0 + R1
R3 = @B0 + R1
DO J = 1, N
   a = J x c
   R4 = R2 + a
   R5 = R3 + a
   MEM(R4) = MEM(R4) + MEM(R5)
END DO
```


Example: Array Address Calculations in a Loop

```
DO J = 1, N
   A[I,J] = A[I,J] + B[I,J]
END DO
```

- Very sophisticated: Convert multiply to add
  (Operator Strength Reduction)

```
R1 = I x floatsize
c = len1 x floatsize  ! Compile-time constant
R2 = @A0 + R1 ;  R3 = @B0 + R1
DO J = 1, N
   R2 = R2 + c
   R3 = R3 + c
   MEM(R2) = MEM(R2) + MEM(R3)
END DO
```

Boolean & Relational Values

How should the compiler represent them?
- Answer depends on the target machine

Two classic approaches
- Numerical representation
- Positional (implicit) representation

Choice depends
- context
- instruction set architecture (ISA)

Boolean & Relational Values

Numerical representation
- Assign values to TRUE and FALSE
- Use hardware AND, OR, and NOT operations
- Use comparison to get a boolean from a relational expression

Examples

x < y	*becomes*	cmp_LT	$r_x, r_y \Rightarrow r_1$
if (x < y) then $stmt_1$ else $stmt_2$	*becomes*	cmp_LT cbr	$r_x, r_y \Rightarrow r_1$ $r1 \rightarrow \_stmt_1, \_stmt_2$

Boolean & Relational Values

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     rx, ry ⇒ cc1
      cbr_LT  cc1 → LT,LF
LT:   loadI   1 ⇒ r2
      br      → LE
LF:   loadI   0 ⇒ r2
LE:   ...other stmts...
```

Condition codes
- are an architect's hack
- allow ISA to avoid some comparisons
- complicates code for simple cases

This "positional representation" is much more complex

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_<	$cc_1,r_1,r_2 \Rightarrow r_a$			

Both versions avoid the branches

Both are shorter than CCs or Boolean-valued compare

Are they better? What about power?

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	$r_a,r_b \Rightarrow cc_1$		cmp_LT	$r_a,r_b \Rightarrow r_1$
	cbr_LT	$cc_1 \rightarrow L_1,L_2$		cmp_LT	$r_c,r_d \Rightarrow r_2$
L_1:	comp	$r_c,r_d \Rightarrow cc_2$		and	$r_1,r_2 \Rightarrow r_x$
	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				

Potential Problem: Optimized boolean expression

Here, the boolean compare produces much better code

Short Circuiting

- Function of programming language semantics
  - → Is evaluating all terms of boolean expression required?
  - → If not, can stop evaluation once value is established
    - ▪ Eliminates unnecessary work
  - → Examples
    - ▪ (false AND …) is false
    - ▪ (true OR …) is true

- May be required by some programming languages
  - → Java Example
    - ▪ if ((x != null) && x.isGood()) { … }
  - → Error if x is null and expression evaluation not short circuited

Control Flow

If-then-else

- Follow model for evaluating relationals & booleans with branches

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

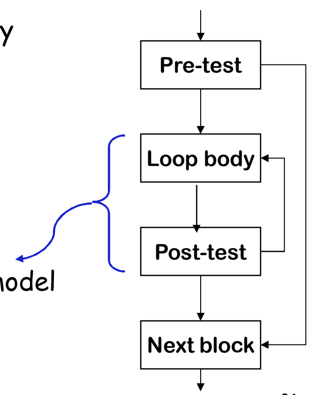
- Frequency of execution
  - → Uneven distribution ⇒ do what it takes to speed common case
- Amount of code in each case
  - → Unequal amounts means predication may waste issue slots
- Control flow inside the construct
  - → Any branching activity within the case base complicates the predicates and makes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

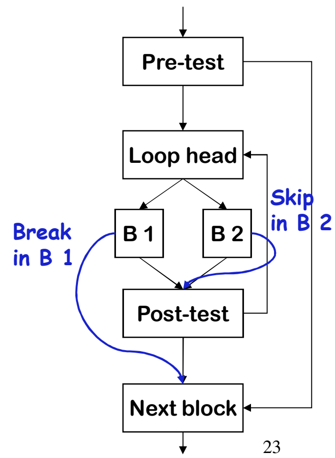
for (i = 1; i< 100; i++) { *body* }
    next statement

loadI $1 \Rightarrow r_1$	Initialization
loadI $1 \Rightarrow r_2$	
loadI $100 \Rightarrow r_3$	Pre-test
cmp_GE $r_1, r_3 \Rightarrow r_4$	
cbr $r_4 \Rightarrow L_2, L_1$	
L_1: *body*	
add $r_1, r_2 \Rightarrow r_1$	Post-test
cmp_LT $r_1, r_3 \Rightarrow r_5$	
cbr $r_5 \Rightarrow L_1, L_2$	
L_2: *next statement*	

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



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)

Generating Stack Code

- Boolean expressions
  - → Leave 1 on stack if true
  - → Leave 0 on stack if false

$E_1 == E_2$:
```
E1
E2
if_icmpeq L1
iconst_0
goto L2
L1:
iconst_1
L2:
```

$E_1 < E_2$:
```
E1
E2
if_icmplt L1
iconst_0
goto L2
L1:
iconst_1
L2:
```

E_1 && E_2:
```
E1
dup
ifeq L1
pop
E2
L1:
```

E_1 || E_2:
```
E1
dup
ifne L1
pop
E2
L1:
```

! E:
```
E
ifeq L1
iconst_0
goto L2
L1:
iconst_1
L2:
```

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Generating Stack Code

- Control structures
  - → Look for 1 or 0 on top of stack

x = E:
```
E
istore addr(x)
```

if (E) S:
```
E
ifeq L
S
L:
```

if (E) S_1 else S_2:
```
E
ifeq L1
S1
goto L2
L1:
S2
L2:
```

while (E) S:
```
L1:
E
ifeq L2
S
goto L1
L2:
```

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