CS 5500 – The Structure of a Compiler

Intermediate Code Generation

Motivation

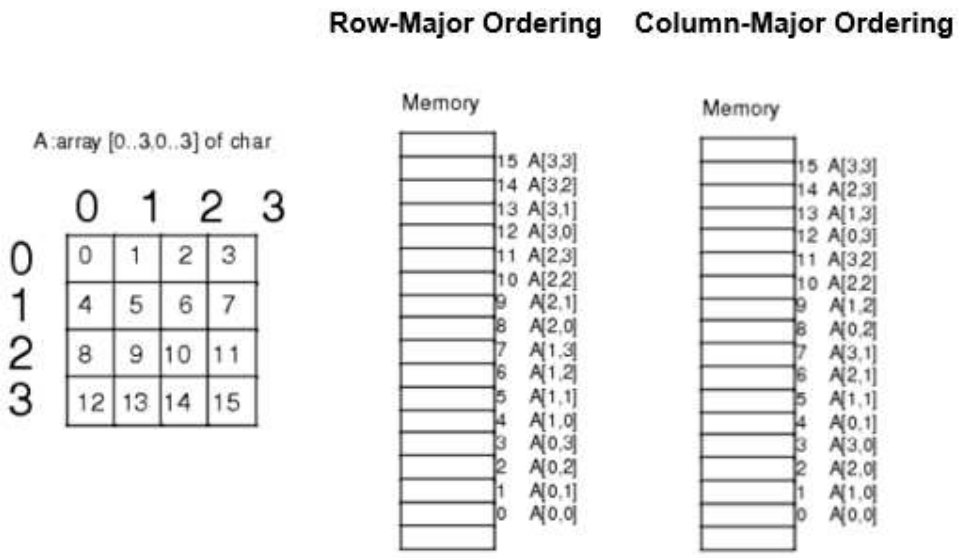
- Need a **simple representation** of source code that is: (1) easy to manipulate for code optimization, and (2) easier to translate to target code (e.g., Assembly language code)
- Should be **relatively independent of target machine**

Three-Address Code

- A label can be attached to any instruction by prefixing it with **L:** and then you can **goto L**
- Assignment statements are of the form **x = y** or **x = y *op* z**
- Conditional statements are of the forms: **ifFalse x goto L** and **ifTrue x goto L**
- Array references count as 2 addresses; for example, **x[y] = z** or **z = x[y]**
- Ex: A[i] = 2 * A[j-k]

```
t3 = j - k;
t2 = A[t3];
t1 = 2 * t2;
A[i] = t1
```

- **Multi-dimensional** arrays must be "converted" to **1D**; use **row-major ordering** (used for Java and C) or **column-major ordering** (used for Fortran and some versions of Basic)



- **Row-major ordering**

  Assume indexing starts at 0

  Let w = width of each array element

  base = relative address of A[0] (i.e., very 1st element in array)

  If A is 1D, then A[i] begins in location: **base + (i * w)**

  If A is 2D, let **n_2 = # elements along dimension 2**

  Then A[i_1][i_2] is in location: **base + (i_1 * n_2 + i_2) * w**

  If A is k dimensions, let **n_j = # elements along dimension j for 1 ≤ j ≤ k**

  Then A[i_1][i_2]…[i_k] is in location:

  base + ((… (i_1 * n_2 + i_2) * n_3 + i_3) …) * n_k + i_k) * w

  Note: If array indexing doesn't begin at 0, use **i_j – low_j** instead of just i_j

  Ex: A : array[1..10, 1..20] of integer
  integers take 4 bytes each
  array A stored starting at address 0

  Find the location of A[4, 5]

  base + ((i_1 – low_1) * n_2 + (i_2 – low_2)) * w

  0 + ((4-1) * 20 + (5-1)) * 4 = 256

  Compile-time precalculation:

  base + (i – low) * w can instead be **i * w + c where c = base – low * w**

  Store value of c in symbol table for this array identifier
  Then only generate code to compute i * w + c instead of generating code to compute base + (i – low) * w each time array is referenced

  Remember you only have 3 addresses per statement, so conserve!

Example of Syntax-Directed Intermediate Code Generation

Assume ***gen*** is a function that outputs its parameters to stdout, a file, or wherever you want the 3-address code to be output to

Temp() is a temp variable

get is a function that, given an ident token, returns its lexeme

addr, ***array***, and ***type*** are attributes associated with nonterminals

$S \rightarrow$ id = E ;	{ gen(get(id.lexeme), '=', E.addr); }
| L = E;	{ gen(L.addr.base, '[', L.addr, ']', '=', E.addr); }
$E \rightarrow E_1 + E_2$	{ E.addr = new Temp( ); gen(E.addr, '=', E_1.addr, '+', E_2.addr); }
| id	{ E.addr = get(id.lexeme); }
| L	{ E.addr = new Temp( ); gen(E.addr, '=', L.array.base, '[', L.addr, ']'); }
$L \rightarrow$ id [E]	{ L.array = get(id.lexeme); L.type = L.array.type.elem; L.addr = new Temp( ); gen(L.addr, '=', E.addr, '*', L.type.width); }

| L_1 [E]	{ L.array = L_1.array;
	L.type = L_1.type.elem;
	t = new Temp( );
	L.addr = new Temp( );
	gen(t, '=', E.addr, '*', L.type.width);
	gen(L.addr, '=', L_1.addr, '+', t); }

Using this translation, generate 3-address code for **x + A[i][j]** where:

A : [0..1][0..2] of integer;
x, i, j : integer;

Assume an integer is 4 bytes

Type of **A** is **array(2, array(3, integer))**, and **width** is **24**
Type of **A[i]** is **array(3, integer)**, and width is **12**

E_1 => id => x — **E.addr = get(id.lexeme) = x**

E => id => i — **E.addr = get(id.lexeme) = i**

E => id => j — **E.addr = get(id.lexeme) = j**

L => id [E] => A [E]
=> A [id]
=> A[i] —
L.array = get(id.lexeme) = A
L.type = L.array.type.elem =
array(2, array(3, int)).elem = array(3, int)
L.addr = new Temp( ) = t1
gen(L.addr, '=', E.addr, '*', L.type.width)= "t1=i*12"

L => L_1 [E]
=>* A[i][E]
=> A[i][id]
=> A[i][j] —
L.array = L_1.array = A
L.type = L_1.type.elem = array(3, int).elem = int
t = new Temp( ) = t2
L.addr = new Temp( ) = t3
gen(t, '=', E.addr, '*', L.type.width) = "t2 = j * 4"
gen(L.addr, '=', L_1.addr, '+', t) = "t3 = t1 + t2"

E_2 => L =>*A[i][j] —
E.addr = new Temp( ) = t4
gen(E.addr, '=', L.array, '[', L.addr, ']') =
"t4 = A[t3]"

E => E_1 + E_2 —
E.addr = new Temp( ) = t5
gen(E.addr, '=', E_1.addr, '+', E_2.addr) = "t5 = x + t4"

So generated code is:
t1 = i * 12
t2 = j * 4
t3 = t1 + t2
t4 = A[t3]
t5 = x + t4

- Other kinds of statements:
  - Procedure calls: **param x_1**
    param x_2
    …
    param x_n
    call p, n or **y = call p, n**
  - Address and pointer assignments: **x = &y** or **x = *y** or ***x = y**
  - I/O: **read x** or **write x**

Representations

- **Quadruple** is of the form ***(op, arg1, arg2, result)***
- Exceptions: (1) Instructions with unary operators don't use arg_2
  (2) Copy statement uses = for *op*, and doesn't use arg_2
  (3) *param* doesn't use arg_2 or *result*
  (4) Jumps put the target label in *result*
- In actual implementation, arg_1, arg_2, and *result* are likely **references to symbol table entries**; temporary variables can be entered into symbol table as needed
- Example: a = b * -c + b * -d

t1 = minus c	**(minus, c, , t1)**
t2 = b * t1	**(*, b, t1, t2)**
t3 = minus d	**(minus, d, , t3)**
t4 = b * t3	**(*, b, t3, t4)**
t5 = t2 + t4	**(+, t2, t4, t5)**
a = t5	**(=, t5, , a)**

- **Triple** is of the form ***(op, arg1, arg2)***
- *result* is treated as **location of instruction** that's responsible for that value
- Example: a = (b * -c) + (b / -d)

	op	arg1	arg2
0	minus	c	
1	*	b	[0]
2	minus	d	
3	/	b	[2]
4	+	[1]	[3]
5	=	a	[4]

- ***Why are quadruples better than triples???***

  Hint: In an optimizing compiler, instructions often moved around!

  Quadruples: move an instrx that computes temp t, then instrx's that use t require no change

  Triples: result of operation is referred to by its position, so moving instrx may require changing all references to that result

- **Indirect triples** consist of a listing of pointers to triples, rather than just a listing of the triples themselves; facilitates moving instructions around!

- **Static Single-Assignment Form (SSA)** differs from 3-address code in 2 ways

- First, all assignments are to variables with **distinct names**

  Ex: p = a + b vs. p1 = a + b
  q = p – c q1 = p1 – c
  p = q * d p2 = q1 * d

- Second, uses Φ–function when it needs to "combine" definitions of a variable

  Ex: if (flag) x = -1; else x = 1; vs. … x1 = -1 … x2 = 1
  y = x * a; y = **?** * a;

  x3 = Φ(x1, x2);
  y = x3 * a;

  Φ–function returns the value of its arg that corresponds to the control-flow path taken to get to the statement containing the Φ–function

- Facilitates certain code optimizations…