IR

Intermediate Representation

CMPT 379: Compilers

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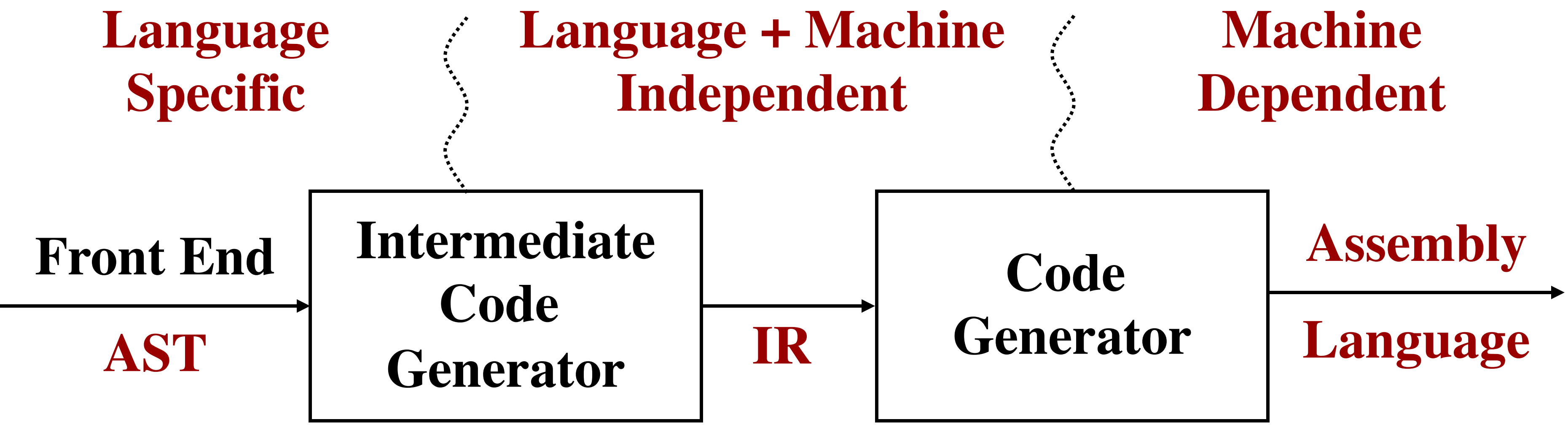
Intermediate Representation



Provides an intermediate level of abstraction

- **More details than source (programming language)**
- **Fewer details than target (assembly language)**

IR: 3-Address Code

- High level assembly
- Instructions that operate on named locations and labels
- Locations
  - Each location is some place to store 4 bytes
    - Pretend we can make infinitely many of them
  - Or global variable
    - Referred to by global name
- Labels (you generate as needed)
- 3-address code = at most three addresses in each instructions

IR: 3-Address Code

- Address or locations:
  - Names/Labels
    - we allow source-program names in TAC (implemented as a pointer to the symbol table)
  - Constants
  - Temporaries

IR: 3-Address Code

- Instructions:
  - assignments:
    - *x = y op z* (op: binary arithmetic or logical operation)
    - *x = op y* *(op: unary operation)*
  - copy: *x = y*
  - unconditional jump:
    - *goto L (L is a symbolic label of a statement)*
  - conditional jumps:
    - *if x goto L*
    - *IfFalse x goto L*
    - *if x relop y goto L (relop: relation operator: <,==,<=)*

IR: 3-Address Code

Instructions:

- Procedure calls: p(x1,x2,…,xn)
  - *param x1*
  - *param x2*
  - *…*
  - *param xn*
  - *call p, n*
- Return statement:
  - *return y*

  You can use it: *y = call p, n*

IR: 3-Address Code

Instructions:

- Indexed assignments (Arrays):
  - *x = y[i]*
  - *x[i] = y*
- Address assignments:
  - x = &y   (which sets x to the location of y)
- Pointers assignments:
  - *x = *y   (y is a pointer, sets x to the value pointed by y)*
  - **x = y*

Control Flow

- Consider the statement:

```
while (a[i] < v) { i = i+1; }
```

Labels can be implemented using position numbers

```
L1:
  t1 = i
  t2 = t1 * 8
  t3 = a[ t2 ]
  ifFalse t3 < v goto L2
  t4 = i
  t4 = t4 + 1
  i = t4
  goto L1
L2: ...
```

```
100: t1 = i
101: t2 = t1 * 8
102: t3 = a[ t2 ]
103: ifFalse t3 < v goto 108
104: t4 = i
105: t4 = t4 + 1
106: i = t4
107: goto 100
108:
```

```
int gcd(int x, int y)
{
   int d;
   d = x - y;
   if (d > 0)
      return gcd(d, y);
   else if (d < 0)
      return gcd(x, -d);
   else
      return x;
}
```

```
gcd:
      t0 = x - y
      d = t0
      t1 = d
      t2 = t1 > 0
      ifFalse t2 goto L0
      param y
      param d
      t3 = call gcd, 2
      return t3
L0:
      t4 = d
      t5 = t4 < 0
      ...
```

Avoiding redundant gotos

```
if t2 goto L1
goto L0
L1: ...
```

Short-circuiting Booleans

- More complex if statements:
  - if (a or b and not c) { … }
- Typical sequence:

```
t1 = not c
t2 = b and t1
t3 = a or t2
```

- Short-circuit is possible in this case:
  - if (a and b and c) { … }
- Short-circuit sequence:

```
t1 = a
if t1 goto L0 /* sckt */
goto L4
L0: t2 = b
if t2 goto L1
goto L4
L1: t3 = c
…
```

```
void main() {
    int i;
    for (i = 0; i < 10; i = i + 1)
        print(i);
}
```

More Control Flow: for loops

```
main:
        t0 = 0
        i = t0
L0:
        t1 = 10
        t2 = i < t1
        ifFalse t2 goto L1
        param i, 1
        call PrintInt, 1
        t3 = 1
        t4 = i + t3
        i = t4
        goto L0
L1:
        return
```

Translation of Expressions

symbol table

• $S \rightarrow id = E$	• $$.code = concat($3.code, $1.lexeme = $3.addr)
• $E \rightarrow E + E$	• $$.addr = new Temp(); $$.code = concat($1.code, $3.code, $$.addr = $1.addr + $3.addr)
• $E \rightarrow - E$	• $$.addr = new Temp(); $$.code = concat($2.code, $$.addr = - $2.addr)
• $E \rightarrow (E)$	• $$.addr = $2.addr; $$.code = $2.code
• $E \rightarrow id$	• $$.addr = symtbl($1.lexeme); $$.code = ‘’

Backpatching in Control-Flow

- Implementing the translations can be done in one or two passes
- The difficulty with code generation in one pass is that we may not know the target label for jump statements
- *Backpatching* allows one pass code generation
  - Generate jump statements with the empty targets (temporarily unspecified)
  - Put each of these statements into a list
  - When the target is known, fill the proper labels in the jump statements (backpatching)

Backpatching

- If (a < b) then i = i+1; else j = i+1;

```
 99:   t0 = a < b
100:   if t0  goto 102
101:   goto ???
102:   t1 = 1
103:   t2 = i + t1
104:   i = t2
105:   goto ???
106:   t1 = 1
107:   t2 = i+t1
108:   j = t2
109:
```

falselist

nextlist

backpatch({101}, 106)
backpatch({105}, 109)

Backpatching

- We maintain a list of statements that need patching by future statements
- Three lists are maintained:
  - truelist: for targets when evaluation is true
  - falselist: for targets when evaluation is false
  - nextlist: the statement that ends the block
- These lists can be implemented as a synthesized attribute
  - Using marker non-terminals

- S → if ‘(‘ B ’)’ M block

  {backpatch(B.truelist, M.instr);

  S.nextlist = merge(B.falselist, block.nextlist);}

- B → E1 **rel** E2

  next instruction number

  {B.truelist = makelist(nextinstr);

  B.falselist = makelist(nextinstr+1);

  print(‘if’ E1.addr **rel**.op E2.addr ‘goto –’);

  print(‘goto –’);

- B → **true**

  {B.truelist=makelist(nextinstr);

  print(‘goto –’);}

- B → **false**

  {B.falselist=makelist(nextinstr);

  print(‘goto –’);}

- M → ε {M.instr = nextinstr;}

If (a < b) {i = i+1;}

- 101: …
- 102: if a < b goto ~~–~~ 104
- 103: goto –
- 104: t1 = 1
- 105: t2 = i+t1
- 106: i = t2
- 107:

B.truelist={102},
B.falselist={103}
M.instr = 104
backpatch({102}, 104)
S.nextlist={103}

- $S \rightarrow$ while M1 ‘(‘ B ’)’ M2 block

  {backpatch(block.nextlist, M1.instr);

  backpatch(B.truelist, M2.instr);

  S.nextlist = B.falselist; print(‘goto’ M1.instr)}

- $B \rightarrow$ E1 **rel** E2

  {B.truelist = makelist(nextinstr);

  B.falselist = makelist(nextinstr+1);

  print(‘if’ E1.addr **rel**.op E2.addr ‘goto –’);

  print(‘goto –’);

- $B \rightarrow$ true

  {B.truelist=makelist(nextinstr);

  print(‘goto –’);}

- $B \rightarrow$ false

  {B.falselist=makelist(nextinstr);

  print(‘goto –’);}

- $M \rightarrow \varepsilon$ {M.instr = nextinstr;}

while (i < n) {i = i+1;}

- 101: …
- 102: if i < n goto ~~–~~ 104
- 103: goto –
- 104: t1 = 1
- 105: t2 = i+t1
- 106: i = t2
- 107: goto 102
- 108:

M1.instr = 102

B.truelist={102}, B.falselist={103}

M2.instr = 104

backpatch({102}, 104)

S.nextlist={103}

- S → while M1 ‘(‘ B ’)’ M2 block

  {backpatch(block.nextlist, M1.instr);
  backpatch(B.truelist, M2.instr);
  S.nextlist = merge(B.falselist; block.breaklist); }
  print(‘goto’ M1.instr)}
- S1 → break ;

  {S1.breaklist=makelist(nextinstr);
  print(‘goto –’);}
- S1 → continue ;

{S1.nextlist=makelist(nextinstr);print(‘goto –’);}

- B → E1 **rel** E2 {…}
- block → ‘{‘ S1 ‘}’

  {block.breaklist=S.breaklist;
  block.nextlist=S.nextlist;}
- M → ε {M.instr = nextinstr;}

while (i < n){continue;}

- 101: …
- 102: if i < n goto – 104
- 103: goto –
- 104: goto – 102
- 105: goto 102
- 106:

M1.instr = 102
B.truelist={102}, B.falselist={103}
M2.instr = 104
S1.nextlist=block.nextlist={104}
backpatch({104}, 102)
backpatch({102}, 104)
S.nextlist={103}

- S $\rightarrow$ while M1 ‘(‘ B ’)’ M2 block

  {backpatch(block.nextlist, M1.instr);
  backpatch(B.truelist, M2.instr);
  S.nextlist = merge(B.falselist; block.breaklist); }
  print(‘goto’ M1.instr)}

- S1 $\rightarrow$ break ;

  {S1.breaklist=makelist(nextinstr);
  print(‘goto –’);}

- S1 $\rightarrow$ continue ;

{S1.nextlist=makelist(nextinstr);print(‘goto –’);}

- B $\rightarrow$ E1 **rel** E2 {…}
- block $\rightarrow$ ‘{‘ S1 ‘}’

  {block.breaklist=S.breaklist;
  block.nextlist=S.nextlist;}

- M $\rightarrow$ ε {M.instr = nextinstr;}

while (i < n){break;}

- 101: …
- 102: if i < n goto ~~–~~ 104
- 103: goto –
- 104: goto –
- 105: goto 102

M1.instr = 102
B.truelist={102}, B.falselist={103}
M2.instr = 104
S1.breaklist=block.breaklist={104}
backpatch({102}, 104)
S.nextlist={103,104}

- S → if ‘(‘ B ’)’ M block

  {backpatch(B.truelist, M.instr);

  backpatch(B.falselist, block.nextlist);

  S.nextlist = merge(B.falselist, block.nextlist);}

- B → B1 || M B2

  {backpatch(B1.falselist, M.instr);

  B.truelist = merge(B1.truelist, B2.truelist);

  B.falselist = B2.falselist;}

- B → E1 **rel** E2

  {B.truelist = makelist(nextinstr);

  B.falselist = makelist(nextinstr+1);

  print(‘if’ E1.addr **rel**.op

  E2.addr ‘goto –’);

  print(‘goto –’);

- M → ε {M.instr = nextinstr;}

If (a < b || i < n) {i = i+1;}

- 101: …
- 102: if a < b goto –
- 103: goto –104
- 104: if i < n goto –
- 105: goto –

B1.truelist={102} B1.falselist={103}
M.instr = 104
B2.truelist={104} B2.falselist={105}
backpatch({103}, 104)
B.truelist={102,104}, B.falselist={105}

- $S \rightarrow$ if '(' B ')' M block

{backpatch(B.truelist, M.instr);

backpatch(B.falselist, block.nextlist);

S.nextlist = merge(B.falselist, block.nextlist);}

- $B \rightarrow B1 \mid\mid M\ B2$

{backpatch(B1.falselist, M.instr);

B.truelist = merge(B1.truelist, B2.truelist);

B.falselist = B2.falselist;}

- $B \rightarrow E1$ **rel** $E2$

{B.truelist = makelist(nextinstr);

B.falselist = makelist(nextinstr+1);

print('if' E1.addr **rel**.op

E2.addr 'goto –');

print('goto –');

- $M \rightarrow \varepsilon$ {M.instr = nextinstr;}

If (a < b || i < n) {i = i+1;}

- 101: …
- 102: if a < b goto ~~–~~106
- 103: goto 104
- 104: if i < n goto ~~–~~106
- 105: goto –
- 106: t1 = 1
- 107: t2 = i+t1
- 108: i = t2
- 109:

B.truelist={102,104}, B.falselist={105}

M.instr = 106

backpatch({102,104}, 106)

S.nextlist={105}

Array Elements

- Array elements are numbered *0, ..., n-1*
- Let *w* be the width of each array element
- Let *base* be the address of the storage allocated for the array
- Then the i^{th} element *A[i]* begins in location *base+i*w*
- The element *A[i][j]* with *n* elements in the 2nd dimension begins at: *base+(i*n+j)*w*

```
void foo(int[] arr)
      { arr[1] = arr[0] * 2 }
```

Array References

foo:

t0 = 1
t1 = 4
t2 = t1 * t0
t3 = arr + t2
t4 = *(t3)
t5 = 0
t6 = 4
t7 = t6 * t5
t8 = arr + t7
t9 = *(t8)
t10 = 2
t11 = t9 * t10
t4 = t11

Wrong

foo:

t0 = 1
t1 = 4
t2 = t1 * t0
t3 = arr + t2
t4 = 0
t5 = 4
t6 = t5 * t4
t7 = arr + t6
t8 = *(t7)
t9 = 2
t10 = t8 * t9
*(t3) = t10

Correct

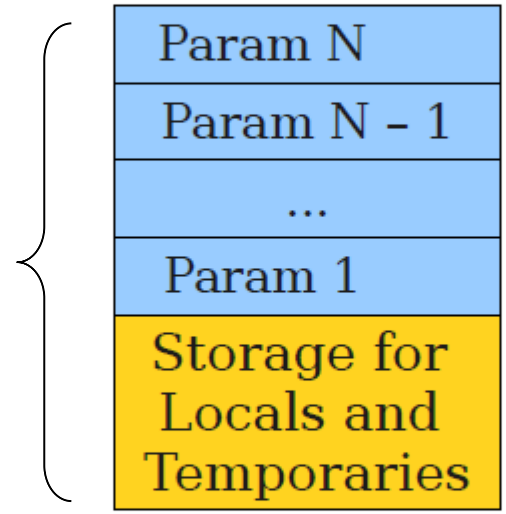
```
int factorial(int n)
{
 if (n <=1 ) return 1;
 return n*factorial(n-1);
}

void main()
{
   print(factorial(6));
}
```

```
factorial:
        t0 = 1
        t1 = n lt t
        t2 = n eq t
        t3 = t1 or t2
        ifFalse t3 goto L0
        t4 = 1
        return t4
L0:
        t5 = 1
        t6 = n - t5
        param t6
        t7 = call factorial, 1
        t8 = n * t7
        return t8
```

t3 = n <= 1

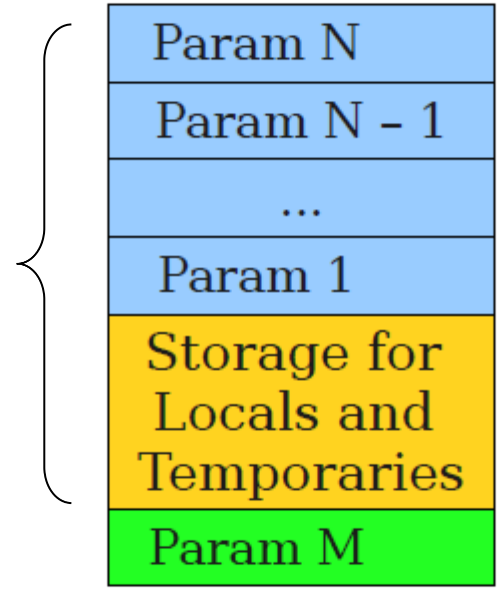
Function arguments

Stack frame for function $f(a_1, \ldots a_N)$

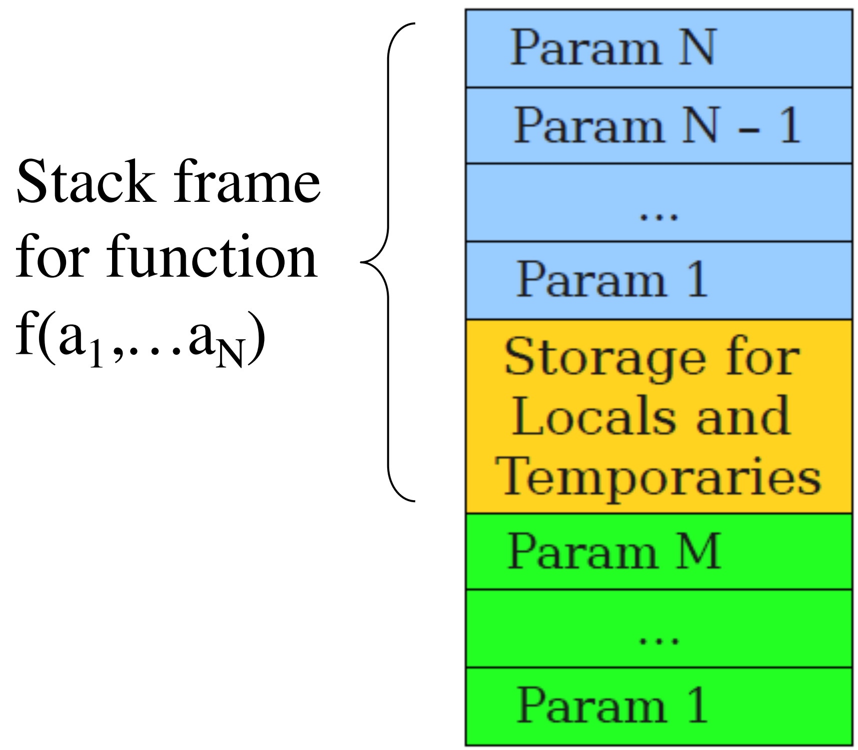


Function arguments

Stack frame for function $f(a_1, \ldots a_N)$

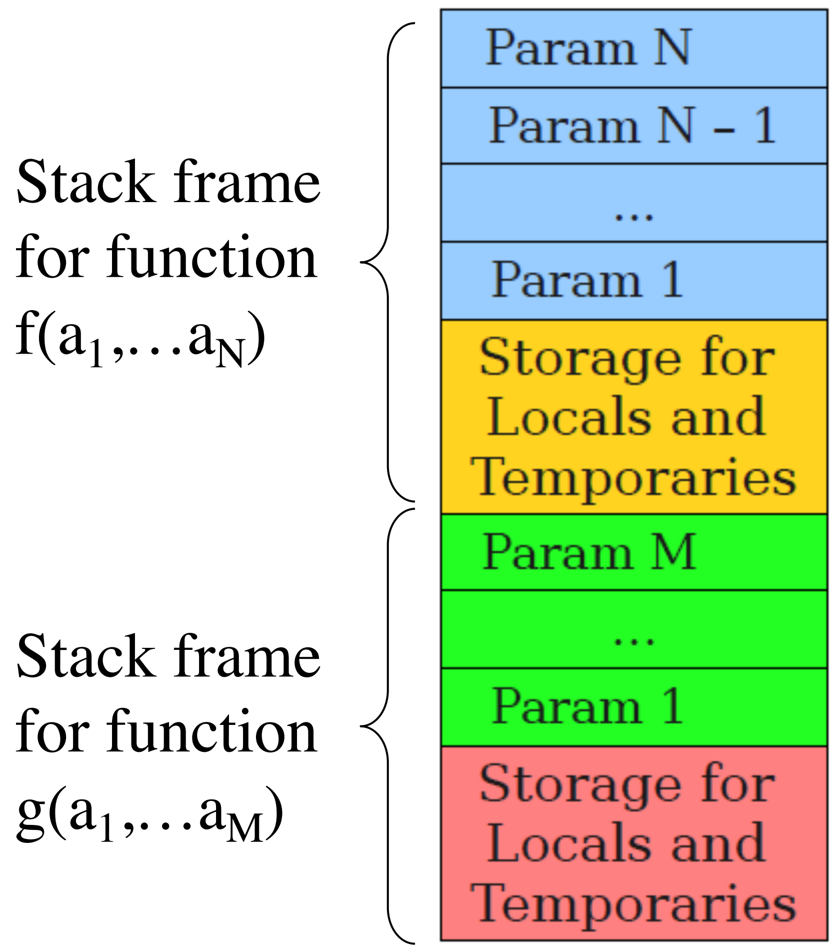


Function arguments



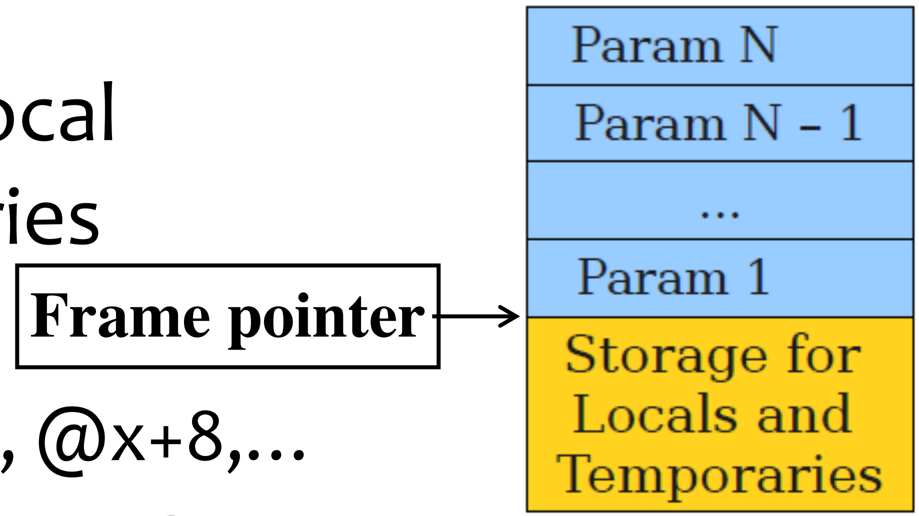
Function arguments

- Usually, stacks start at high memory addresses and grow to low memory addresses.



Function arguments

- Compute offsets for all incoming arguments, local variables and temporaries
  - Incoming arguments are at offset @x, @x+4, @x+8,…
  - Locals+Temps are at @-y-4, @-y-8, …



Computing Location Offsets

```
class A {
 void f (int a /* @x+4 */,
          int b /* @x+8 */,
          int c /* @x+12 */) {
    int s    // @-y-4
    if (c > 0) {
          int t ...      // @-y-8
    } else {
          int u          // @-y-12
          int t ...      // @-y-16
    }
 }
}
```

Location offsets for temporaries are ignored on this slide

You could reuse @-y-8 here, but okay if you don't

Implementing IR

- Quadruples:

  t1 = - c

  t2 = b * t1

  t3 = - c

  t4 = b * t3

  t5 = t2 + t4

  a = t5

op	arg1	arg2	result
minus	c		t1
*	b	t1	t2
minus	c		t3
*	b	t3	t4
+	t2	t4	t5
=	t5		a

Implementing IR

- Triples
  1. - c
  2. b * (1)
  3. - c
  4. b * (3)
  5. (2) + (4)
  6. a = (5)

	op	arg1	arg2
(1)	minus	c	
(2)	*	b	(1)
(3)	minus	c	
(4)	*	b	(3)
(5)	+	(2)	(4)
(6)	=	a	(5)

We refer to results of an operation x op y by its position

Code optimizer change the order of instructions

Implementing IR

- Indirect Triples

1. - c
2. b * (1)
3. - c
4. b * (3)
5. (2) + (4)
6. a = (5)

Instruction List:

35	(1)
36	(2)
37	(3)
38	(4)
39	(5)
40	(6)

	op	arg1	arg2
1	minus	c	
2	*	b	(1)
3	minus	c	
4	*	b	(3)
5	+	(2)	(4)
6	=	a	(5)

can be re-ordered by the code optimizer

Implementing IR

- Static Single Assignment (SSA)
  - All assignments are to variables with distinct names

instead of:

a = t1

b = a + t1

a = b + t1

the SSA form has:

a1 = t1

b1 = a1 + t1

a2 = b1 + t1

a variable is never reassigned

Correctness vs. Optimizations

- When writing backend, correctness is paramount
  - Efficiency and optimizations are secondary concerns at this point
- Don’t try optimizations at this stage

Basic Blocks

- A *basic block* is a sequence of statements that enters at the start and ends with a branch at the end
- Functions transfer control from one place (the caller) to another (the called function)
- Other examples include any place where there are branch instructions
- Code generation should create code for basic blocks and branch them together

Summary

- TAC is one example of an intermediate representation (IR)
- An IR should be close enough to existing machine code instructions so that subsequent translation into assembly is trivial
- In an IR we ignore some complexities and differences in computer architectures, such as limited registers, multiple instructions, branch delays, load delays, etc.

Extra Slides

What TAC doesn’t give you

- Check bounds (array indexing)
- Two or n-dimensional arrays
- Conditional branches other than **if** or **ifFalse**
- Field names in records/structures
  - Use base+offset load/store
- Object data and method access