8. Intermediate Code

- Intermediate code is closer to the target machine than the source language, and hence easier to generate code from.
- Unlike machine language, intermediate code is (more or less) machine independent. This makes it easier to retarget the compiler.
- It allows a variety of optimizations to be performed in a machine-independent way.
- Typically, intermediate code generation can be implemented via syntax-directed translation, and thus can be folded into parsing by augmenting the code for the parser.

Intermediate Languages: Design Issues

- The set of operators in the intermediate language must be rich enough to allow the source language operations to be implemented.
- A small set of operations in the intermediate language makes it easy to retarget the compiler to a new machine.
- Intermediate code operations that are closely tied to a particular machine or architecture may make it harder to port the compiler to other architectures.
- A small set of intermediate code operations may lead to long instruction sequences for some source language constructs. This may require more work during optimization.

High-Level Intermediate Representations

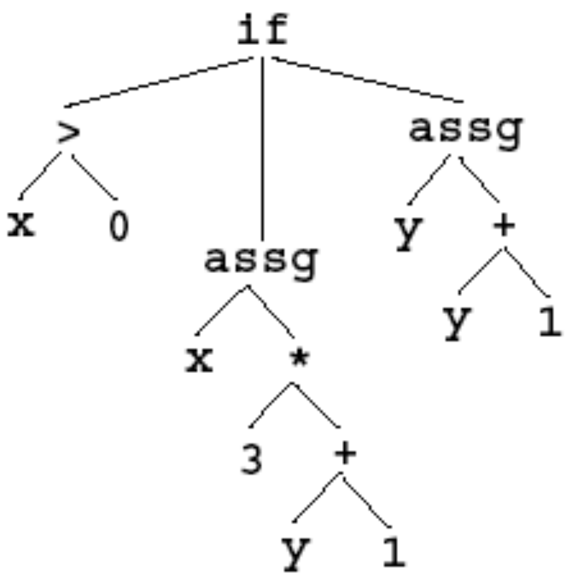
Examples : syntax trees, DAGs:

- *(abstract) syntax trees* : a compact form of a parse tree that represents the hierarchical structure of the program: nodes represent operators, the children of a node represent what it operates on.

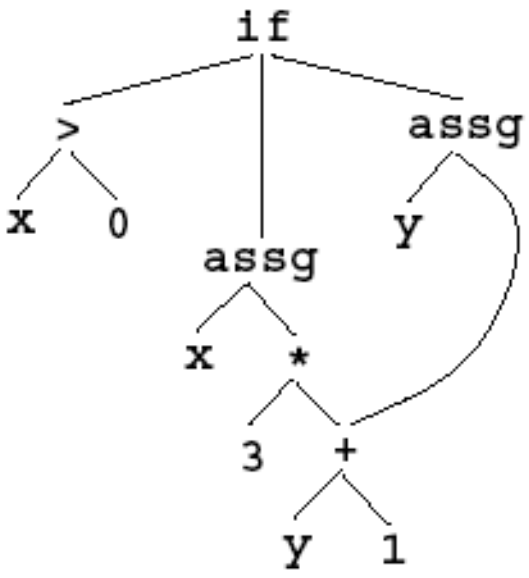
- *DAGs* : similar to syntax trees, except that common subexpressions are represented by a single node.

Example :

if $(x > 0)$ **then** $x := 3 * (y + 1)$ **else** $y := y + 1;$



syntax tree



DAG

8.1.1. Low-Level Intermediate Representations

Examples : Three Address Code

- This is a sequence of instructions of the form

```
x := y op z
```

  where x, y, and z are *variable names*, *constants*, or *compiler generated variables* ("temporaries").

- Only one operator is permitted on the RHS, so there are no "built-up" expressions. Instead, expressions are computed using temporaries. E.g. the source language construct

```
x := y + z*w
```

  might translate to

```
t1 := z * w
x := y + t1
```

Different Kinds of Three-Address Statements

Assignment :

x := y op z, op binary
x := op y, op unary
x := y

Jumps :

goto L,
jumpt t L,
jumpf t L, L a label

if x $relop$ y goto L, L a label

Procedure Call/Return :

param x,	x an actual parameter
call p, n,	$n =$ no. of params to p
enter	initialization (if any)
exit	cleanup actions (if any)
return	
return x	
retrieve x	save returned value in x

Indexed Assignment :

x := y[i]
x[i] := y

Address and Pointer Assignments :

x := &y
x := *y
x := y

Miscellaneous :

label L

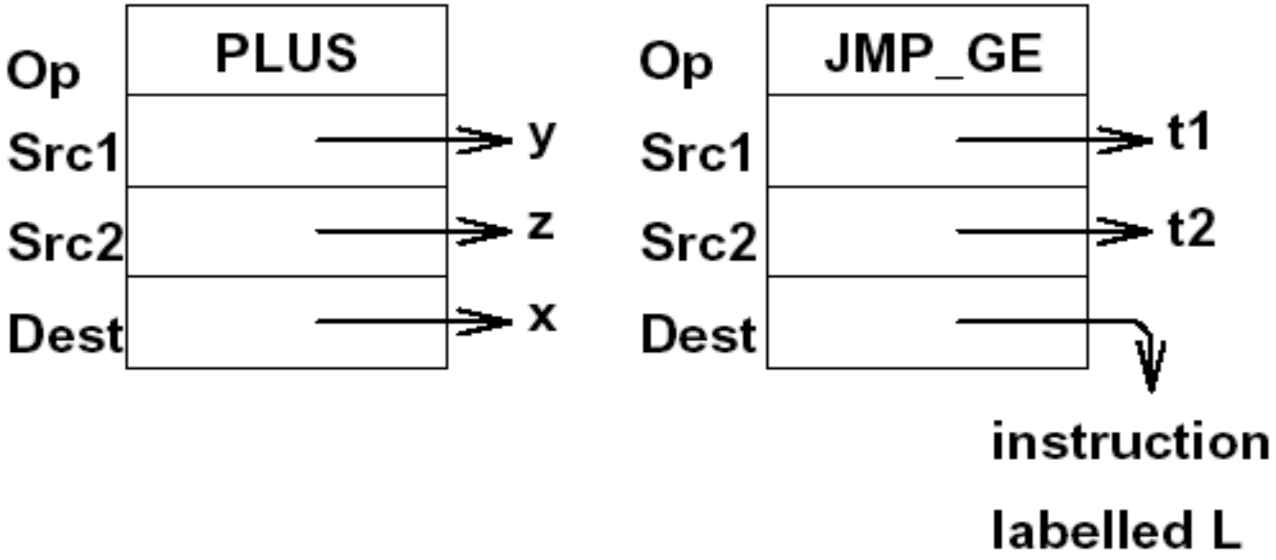
8.1.2. Implementing Three-Address Instructions

Each instruction is implemented as a structure called a *quadruple*:

- contains (upto) 4 fields: operation, (upto) two operands, and destination;
- for operands: use a bit to indicate whether it's a constant or a pointer into the symbol table.

`x := y + z`

`if t1 >= t2 goto L`



8.2. Intermediate Code Generation

- Source language constructs are decomposed to simpler constructs at the intermediate code level.

- When generating code to evaluate expressions, temporary names must be made up for internal nodes in the syntax tree for the expression.

Example:

Source : **if** $x + 2 > 3 * (y - 1) + 4$ **then** z := 0;

Intermediate Code :

```
t1 := x+2
t2 := y-1
t3 := 3*t2
t4 := t3+4
if t1 <= t4 goto L
z := 0
label L
```

Intermediate Code Generation

Syntax-Directed Translation :

- Intermediate code represented as a list of instructions. Instruction sequences are concatenated using the operator $||$.

  (In practice, we might choose to write the intermediate code instructions out into a file.)

- *Attributes for Expressions* E :
  - $E.place$: denotes the location that holds the value of E.
  - $E.code$: denotes the instruction sequence that evaluates E.

- *Attributes for Statements* S :
  - $S.begin$: denotes the first instruction in the code for S.
  - $S.after$: denotes the first instruction *after* the code for S.
  - $S.code$: denotes the instruction sequence that represents S.

- *Auxiliary Functions* :
  - `newtemp()` : returns a *new* temporary each time it is called.
    - returns a pointer to the ST entry of a temp.
    - may take a parameter specifying the type of the temp (useful if reusing temps).
  - `newlabel()` : returns a new label name each time it is called.

- *Notation* : we write

  gen(x ':=' y '+' z)

  to represent the instruction $x := y + z$.

Intermediate Code Generation : *Simple Expressions*

PRODUCTION	SEMANTIC RULE
$E \longrightarrow \mathbf{id}$	$E.place := \mathbf{id}.place;$ $E.code := '' \;;$
$E \longrightarrow (\ E_1\ )$	$E.place := E_1.place;$ $E.code := E_1.code;$
$E \longrightarrow E_1 + E_2$	$E.place :=$ `newtemp();` $E.code := E_1.code \;\|\|$ $E_2.code \;\|\|$ gen$(E.place$ ':=' $E_1.place$ '+' $E_2.place)$
$E \longrightarrow -E_1$	$E.place :=$ `newtemp();` $E.code := E_1.code \;\|\|$ gen$(E.place$ ':=' '−' $E_1.place)$

8.3.2. Accessing Array Elements I

- Array elements can be accessed quickly if the elements are stored in a block of consecutive locations.

- Assume:
  - we want the i^{th} element of an array A whose subscript ranges from lo to hi;
  - the address of the first element of the array is $base$.

- We can avoid address computations in the intermediate code if we have indexed "addressing modes" at the intermediate code level.

  In this case, $A[i]$ is the $(i - lo)^{th}$ element of the array located at $base$ (starting at element 0). So a reference `A[i]` translates to the code

```
t1 := i - lo
t2 := A[t1]
```

8.3.2. Accessing Array Elements II

- Address computations can't be avoided in general, because of pointer and record types.

- The simple approach using indexed expressions may recompute base addresses repeatedly, leading to inefficient code.

- Assume:
  - we want the i^{th} element of an array A whose subscript ranges from lo to hi;
  - the address of the first element of the array is $base$;
  - each element of A has width w.

Then, the address of $x[i]$ is

$$\begin{aligned}&base + (i - lo) * w\\ &= (base - lo * w) + i * w\\ &= C_A + i * w\end{aligned}$$

where C_A depends on the array A and is known at compile time.

Note : C_A is a memory address if A is a global, and is a stack displacement if A is a local.

- The idea extends to multidimensional arrays in the obvious way: need to know whether the elements are stored in row-major or column-major order.

8.4. Logical Expressions

$$BExp \longrightarrow E_1 \ \mathbf{relop} \ E_2$$

8.4.3. Naive but Simple Approach :

Intermediate Code (TRUE == 1, FALSE == 0) :

```
  t1 ← value of $E_1$

  t2 ← value of $E_2$
t3 := TRUE
if t1 relop t2 goto L
t3 := FALSE
label L
```

Disadvantage : Lots of (usually unnecessary) memory traffic.

8.4.1. Code Generation for Conditionals

Production : $S \longrightarrow \textbf{if } E \textbf{ then } S_1 \textbf{ else } S_2$

Semantic Rule :

$$
\begin{array}{l}
\{\ S.begin := newlabel();\\
\quad S.after := newlabel();\\
\quad S.code := gen(\text{‘}\textbf{label}\text{‘}\ S.begin)\ \|\\
\qquad\quad E.code\ \|\\
\qquad\quad gen(\text{‘}if\text{‘}E.place\text{‘} = \text{“}0\text{“}goto\text{‘}S_2.begin)\ \|\\
\qquad\quad S_1.code\ \|\\
\qquad\quad gen(\text{‘}\textbf{goto}\text{‘}\ S.after)\ \|\\
\qquad\quad S_2.code\ \|\\
\qquad\quad gen(\text{‘}\textbf{label}\text{‘}\ S.after)\\
\}
\end{array}
$$

8.4.1. Code Generation for Loops

Production : $S \longrightarrow \textbf{while } E \textbf{ do } S_1$

Structure of Generated Code :

```
L1 :
    [ evaluate E
    if (E == FALSE) goto L2
    [
    [  Code for S1
    [
    goto L1
L2 : . . .
```

Semantic Rule :

```
{ S.begin := newlabel();
  S.after := newlabel();
  S.code := gen('label' S.begin) ||
        E.code ||
        gen('if'E.place' = "0"goto'S.after) ||
        S1.code ||
        gen('goto' S.begin) ||
        gen('label' S.after)
}
```

Intermediate Code Generation: Assignment

- Grammar productions:

$$S \longrightarrow Lhs \;\; := \;\; Rhs$$

- Semantic Rule:

$$\begin{aligned}\{\ S.code := {} & Lhs.code \;\| \\ & Rhs.code \;\| \\ & gen(Lhs.place \text{ ':=' } Rhs.place)\ \}\end{aligned}$$

Relational Expressions: Better Approach

- Often, relational expressions occur in the context of boolean conditions of **control** statements.
- Instead of creating temporaries which are set to true or false, based upon the outcome of evaluating a boolean condition, generate direct branches to true and false targets.
- Short circuit evaluation of boolean expressions can also be handled effectively by this approach.

Relational Expressions: Example

$$E = a < b \; or \; c < d \; and \; e < f$$

$$\begin{array}{ll} 100: & if \; a < b \; goto \; \_\_ \\ 101: & goto \; 102 \\ 102: & if \; c < d \; goto \; 104 \\ 103: & goto \; \_\_ \\ 104: & if \; e < f \; goto \; \_\_ \\ 105: & goto \; \_\_ \end{array}$$

$$E.truelist = \{100, 104\}$$
$$E.falselist = \{103, 105\}$$

$E \longrightarrow E_1\ or\ M\ E_2$

$\{$

$backpatch(E_1.falselist, M.quad);$

$E.truelist = merge(E_1.truelist, E_2.truelist);$

$E.falselist = E_2.falselist;$

$\}$

$M \longrightarrow \epsilon$

$\{M.quad = nextquad\}$

$E \longrightarrow E_1\ and\ M\ E_2$

$\{$

$backpatch(E_1.truelist, M.quad);$

$E.truelist = E_2.truelist;$

$E.falselist = merge(E_1.falselist, E_2.falselist);$

$\}$

Relational Expressions: cont'd.

$E \longrightarrow not\ E_1$

$\{$

$E.truelist = E_1.falselist;$

$E.falselist = E_1.truelist;$

$\}$

$E \longrightarrow (E_1)$

$\{$

$E.truelist = E_1.truelist;$

$E.falselist = E_1.falselist;$

$\}$

$E \longrightarrow id_1\ relop\ id_2$

$\{$

$E.truelist = makelist(nextquad);$

$E.falselist = makelist(nextquad + 1);$

$generate(if\ id_1.addr\ relop\ id_2.addr\ goto\_\_)$

$generate(goto\_\_)$

$\}$

```
E → true
      {
          E.truelist = makelist ( nextquad );
          generate ( goto__ )
      }

E → false
      {
          E.falselist = makelist ( nextquad );
          generate ( goto__ )
      }
```

Code Generation for Loops and Conditionals

- Straightforward approach can introduce branch instructions whose targets are unconditional jumps.

```
while  a<b  do
          if  x<y  then   S  endif
endwhile
```

```
100:  if a < b go to 102
101:  go to 106
102:  if x < y go to 104
103:  go to ~~105~~ 100
104:  S.code
105:  go to 100
106:
```

- We can avoid this by maintaining an additional attribute for statements called the *nextlist*. This attribute tracks branches in the statements whose target should be set to code that follows them in the execution sequence.

Loops and Conditionals: cont'd.

$S \longrightarrow if\ E\ then\ M_1\ S_1\ N\ else\ M_2\ S_2$

$\{$

$backpatch(E.truelist, M_1.quad);$

$backpatch(E.falselist, M_2.quad);$

$S.nextlist = merge(S_1.nextlist, merge(N.nextlist, S_2.nextlist))$

$\}$

$N \longrightarrow \epsilon$

$\{$

$N.nextlist = makelist(nextquad);$

$generate(goto\_)$

$\}$

$M \longrightarrow \epsilon$

$\{M.quad = nextquad\}$

$S \longrightarrow if\ E\ then\ M\ S_1$

$\{$

$backpatch(E.truelist, M.quad);$

$S.nextlist = merge(E.falselist, S_1.nextlist)$

$\}$

Loops and Conditionals: cont'd.

$S \longrightarrow while\ M_1\ E\ do\ M_2\ S_1$
$\{$
$\boxed{backpatch(S_1.nextlist, M_1.quad);}$ ← **Optimization takes place here**
$backpatch(E.truelist, M_2.quad);$
$S.nextlist = E.falselist;$
$generate(goto M_1.quad);$
$\}$
$S \longrightarrow begin\ L\ end$
$\{S.nextlist = L.nextlist\}$
$S \longrightarrow A$
$\{S.nextlist = nil\}$
$L \longrightarrow L_1\ ;\ M\ S$
$\{$
$backpatch(L_1.nextlist, M.quad);$
$L.nextlist = S.nextlist;$
$\}$
$L \longrightarrow S$
$\{L.nextlist = S.nextlist\}$

```
while  a<b  do
          while  x<y  do
                    S
          endwhile
endwhile
```

```
100:  if a < b go to 102
101:  go to 107
102:  if x < y go to 104
103:  go to ~~106~~  100
104:  S.code
105:  go to 102
106:  go to 100
107:  ….
```

Intermediate Code Generation: `case` Statements

Implementation issue : Need to generate code so that we can (efficiently) choose one of a set of different alternatives, depending on the value of an expression.

Implementation choices :

1. linear search
2. binary search
3. jump table

Implementation considerations :

1. *Execution Cost* : linear or binary search may be cheaper if the no. of cases is small.

   For a large no. of cases, a jump table may be cheaper.

2. *Space cost* : a jump table may take too much space if the case values are not clustered closely together, e.g.:

```
switch (x) {
    case 1 : ...
    case 1000 : ...
    case 1000000 : ...
}
```

8.5. Code Generation for Function Calls

Calling Sequence: Caller :

- Evaluate actual parameters; place actuals where the callee wants them.

  Instruction : `param` t

- Save machine state (current stack and/or frame pointers, return address) and transfer control to callee.

  Instruction : `call` p, n (n = no. of actuals)

Calling Sequence: Callee :

- Save registers (if necessary); update stack and frame pointers to accommodate m bytes of local storage.

  Instruction : `enter` m.

Return Sequence: Callee :

- Place return value x (if any) where the caller wants it; adjust stack/frame pointers (maybe); jump to return address.

  Instruction : `return` x or `return`.

Return Sequence: Caller :

- Save the value returned by the callee (if any) into x.

  Instruction : `retrieve` x.

Intermediate Code for Function Calls: An Example

Source Code :

```
x = f(0,y+1)-1;
```

Intermediate Code Generated :

```
t1 := y+1
param t1        /* arg 2 */
param 0         /* arg 1 */
call f, 2
retrieve t2     /* t2 := f(0,t1) */
t3 := t2-1
x := t3
```

Suppose function `f` needs 24 bytes of space for its locals and temporaries. Its code has the form

```
enter 24
   ...
return t17
       /* suppose return value is in t17 */
```

Code Generation for Functions: Storage Allocation

Problem : The first instruction in a function is

`enter` n /* n = space for locals, temps */

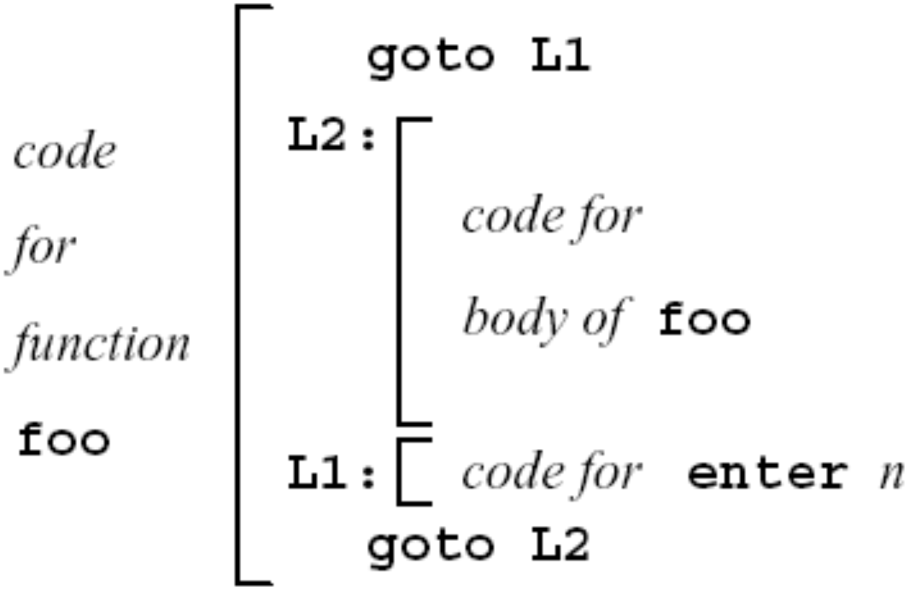
but n is not known until the whole function has been processed.

Solution 1 : generate final code into a list, "back-patch" the appropriate instructions after processing the function body.

Advantage : Can also do machine-dependent optimizations (e.g., instruction scheduling).

Disadvantage : slower, requires more memory.

Solution 2 : Generate code of the form



code for function **foo**

```
    goto L1
L2:
        code for
        body of foo
L1:     code for enter n
    goto L2
```

Reusing Temporaries

Storage requirements can be reduced considerably if we reuse temporaries:

- Maintain a free list of temporaries:
  - When a temporary is no longer necessary, it is returned to the free list.
  - The function *newtemp*() is modified to first search the free list, and to allocate a new temporary only if there is nothing in the free list.
- To handle objects of different sizes, we can maintain a free list for each type (or size).