Chapter 7
Intermediate Representation

Motivation

- ASTs are too high level and grammar dependent
  - Different languages entail different implementations.
  - Different machines entail different implementations.
  - We need something lower, closer to machine code so that
    - The ASTs from various languages can be translated into this uniform IR.
    - Translations to various machine code can be done with the IR.

What are the difference between AST and low level IR

- Conditionals
  - If-then-else does not exist in machine level instructions. Instead, comparisons and conditional jumps (to only one target).
- Array and field references
  - At low level, we need to think about heap/stack, and decide the corresponding addressing mechanism.
- Method calls
  - In AST, we may have various numbers of arguments.
  - At low level, we have only one “call” instruction.

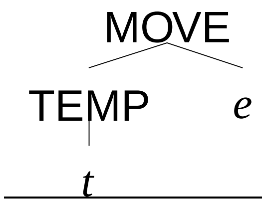
Low Level Tree Representations

- Such tree representation is also used in compilers such as GCC (called RTL and RTX there).
- Translation to Intermediate Code is indeed a process of tree rewriting.

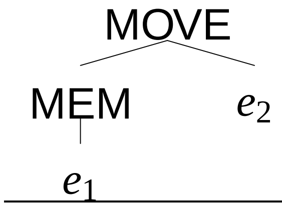
IR trees: Expressions

CONST i	Integer constant i	
NAME n	Symbolic constant n	[a code label]
TEMP t	Temporary t	[one of any number of “registers”]
BINOP e_1 e_2	Application of binary operator: ADD, SUB, MUL, DIV AND, OR, XOR SLL, SRL SRA to integer operands e_1 (evaluated first) and e_2 (evaluated second)	 [arithmetic] [bitwise logical] [logical shifts] [arithmetic right-shift]
MEM e	Contents of a word of memory starting at address e	
CALL f $[e_1, \ldots, e_n]$	Procedure call; expression f is evaluated before arguments $e_1, \ldots, e_n$	
ESEQ s e	Expression sequence; evaluate s for side-effects, then e for result	

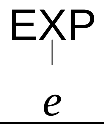
IR trees: Statements



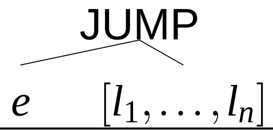
Evaluate e into temporary t



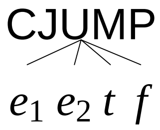
Evaluate e_1 yielding address a, e_2 into word at a



Evaluate e and discard result



Transfer control to address e; $l_1, \ldots, l_n$ are all possible values for e

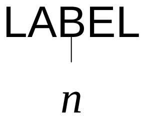


Evaluate e_1 then e_2, yielding a and b, respectively; compare a with b using relational operators:

BEQ, BNE	[signed and unsigned integers]
BLT, BGT, BLE, BGE	[signed]

jump to t if true, f if false

Statement s_1 followed by s_2



Define constant value of name n as current code address; NAME(n) can be used as target of jumps, calls, etc.

Some Examples

- A[i]=x+y;

- if (x>y)

  ```
  if (x>y)
     x=2
  else
     x=3
  ```

Things are Not That Easy

- The translations for (x>3) in
  - y= x>3
  - if (x>3) s1 else s2
- The translations for x=3 in
  - x=3; …
  - if (x=3)
- Solution:
  - *Let expressions, statements, and conditionals share the same base class Translate.exp so that one can be converted to the other in various contexts.*

Kinds of expressions

Expression kinds indicate “how expression might be used”

Ex(exp) expressions that compute a value

Nx(stm) statements: expressions that compute no value

Cx conditionals (jump to true and false destinations)

- **RelCx.*op*(left, right)** eq, ne, gt, lt, ge, le

IfThenElseExp expression or statement, depending on use

Conversion operators allow use of one form in context of another:

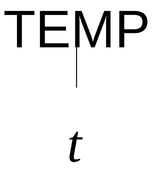
unEx convert to tree expression that computes value of inner tree

unNx convert to tree statement that computes inner tree but returns no value

unCx(t, f) convert to statement that evaluates inner tree and branches to true destination if non-zero, false destination otherwise

Translating MiniJava

Local variables: Allocate as a temporary t


TEMP

t

Ex(TEMP t)

Array elements: Array expression is reference to array in heap.

For exressions e and i, translate $e[i]$ as:

Ex(MEM(ADD(e.unEx(), $\times$(i.unEx(), CONST(w)))))

where w is the target machine's word size: all values are word-sized (scalar) in MiniJava

Array bounds check: array index $i <$ e.`size`; runtime will put size in word preceding array base

Object fields: Object expression is reference to object in heap.

For expression e and field f, translate e.`f` as:

Ex(MEM(ADD(e.unEx(), CONST(o))))

where o is the byte offset of the field `f` in the object

Null pointer check: object expression must be non-null (i.e., non-zero)

Translating MiniJava

String literals: Allocate statically:

```
          .word 11
label:    .ascii "hello world"
```

Translate as reference to label:

Ex(NAME(`label`))

Object creation: Allocate object in heap.

For class T, translate `new` $T()$ as:

Ex(CALL(NAME(”new”), CONST(fields), NAME(label for T’s vtable)))

Array creation: Allocate array in heap.

For type T, array expression e, translate `new`$T[e]$ as:

Ex(ESEQ(MOVE(TEMP(s), e.unEx()),
CALL(NAME(”new”), MUL(TEMP(s), CONST(w)), TEMP(s))))

where s is a fresh temporary, and w is the target machine’s word size.

Control structures

Basic blocks:

- a sequence of straight-line code
- if one instruction executes then they all execute
- a maximal sequence of instructions without branches
- a label starts a new basic block

Overview of control structure translation:

- control flow links up the basic blocks
- ideas are simple
- implementation requires bookkeeping
- some care is needed for good code

while loops

while (c) s:

1. evaluate c
2. if false jump to next statement after loop
3. evaluate loop body s
4. evaluate c
5. if true jump back to loop body

e.g.,

```
        if not($c$) jump done
body:
        $s$
        if $c$ jump body
done:
```

Nx(SEQ(SEQ(c.unCx(b, x), SEQ(LABEL(b), s.unNx())),
SEQ(c.unCx(b, x), LABEL(x))))

for loops

for $(i, c, u)\ s$

1. evaluate initialization statement i
2. evaluate c
3. if false jump to next statement after loop
4. evaluate loop body s
5. evaluate update statement u
6. evaluate c
7. if true jump to loop body

```
Nx(SEQ(i.unNx(),
           SEQ(SEQ(c.unCx(b, x), SEQ(LABEL(b), SEQ(s.unNx(), u.unNx()))),
                  SEQ(c.unCx(b, x), LABEL(x)))))
```

For **break** statements:

- when translating a loop push the *done* label on some stack
- **break** simply jumps to label on top of stack
- when done translating loop and its body, pop the label

Method calls

$e_0.m(e_1, \ldots, e_n)$:

> Ex(CALL(MEM(MEM(e_0.unEx(), $-w$), m.index $\times$ w), e_1.unEx(),
> $\ldots e_n$.unEx()))

Null pointer check: expression e_0 must be non-null (i.e., non-zero)

Comparisons

Translate a *op* b as:

RelCx.*op*(a.unEx(), b.unEx())

When used as a conditional unCx(t, f) yields:

CJUMP(a.unEx(), b.unEx(), t, f)

where t and f are labels.

When used as a value unEx() yields:

```
ESEQ(SEQ(MOVE(TEMP(r), CONST(1)),
             SEQ(unCx(t, f),
                   SEQ(LABEL(f),
                         SEQ(MOVE(TEMP(r), CONST(0)), LABEL(t))))),
     TEMP(r))
```

Conditionals

Translate short-circuiting Boolean operators (`&&`, `||`, `!`) as if they were conditionals

e.g., $x < 5$ `&&` $a > b$ is treated as $(x < 5)$ `?` $(a > b) : 0$

We translate e_1 `?` $e_2 : e_3$ into IfThenElseExp(e_1, e_2, e_3)

When used as a value IfThenElseExp.unEx() yields:

```
ESEQ(SEQ(SEQ(e1.unCx(t, f),
                    SEQ(SEQ(LABEL(t),
                                SEQ(MOVE(TEMP(r), e2.unEx()),
                                      JUMP(j))),
                          SEQ(LABEL(f),
                                SEQ(MOVE(TEMP(r), e3.unEx()),
                                      JUMP(j))))),
              LABEL(j)),
        TEMP(r))
```

As a conditional IfThenElseExp.unCx(t, f) yields:

```
SEQ(e1.unCx(tt, ff), SEQ(SEQ(LABEL(tt), e2.unCx(t, f)),
                            SEQ(LABEL(ff), e3.unCx(t, f))))
```

Conditionals: Example

Applying unCx(t, f) to $(x < 5)$ `?` $(a > b) : 0$:

SEQ(BLT(x.unEx(), CONST(5), tt, ff),
        SEQ(SEQ(LABEL(tt, BGT(a.unEx(), b.unEx(), t, f)),
                SEQ(LABEL(ff, JUMP(f))))

or more optimally:

SEQ(BLT(x.unEx(), CONST(5), tt, f),
        SEQ(LABEL(tt, BGT(a.unEx(), b.uneX(), t, f)))

One-dimensional fixed arrays: Pascal/Modula/C/C++

$\underline{\textbf{var}}\ a : \underline{\textbf{array}}\ [2..5]\ \underline{\textbf{of}}\ integer;$

$\ldots$

$a[e]$

translates to:

MEM(ADD(TEMP(FP), ADD(CONST $k - 2w$, $\times$(CONST w, e.unEx))))

where k is offset of static array from the frame pointer FP, w is word size

In Pascal, multidimensional arrays are treated as arrays of arrays, so `A[i,j]` is equivalent to A[i][j], so this translation works for subarrays. Not so in Fortran.

Multidimensional arrays

Array allocation:

constant bounds

- allocate in static area, stack, or heap
- no run-time descriptor is needed

dynamic arrays: bounds fixed at run-time

- allocate in stack or heap
- descriptor is needed

dynamic arrays: bounds can change at run-time

- allocate in heap
- descriptor is needed

Multidimensional arrays

Array layout:

Contiguous:

1. *Row major*

   Rightmost subscript varies most quickly:

   ```
   A[1,1], A[1,2], ...
   A[2,1], A[2,2], ...
   ```

   Used in PL/1, Algol, Pascal, C, Ada, Modula, Modula-2, Modula-3

2. *Column major*

   Leftmost subscript varies most quickly:

   ```
   A[1,1], A[2,1], ...
   A[1,2], A[2,2], ...
   ```

   Used in FORTRAN

By vectors

Contiguous vector of *pointers* to (non-contiguous) subarrays

Multi-dimensional arrays: row-major layout

```
array [1..N,1..M] of T
≡ array [1..N] of array [1..M] of T
```

no. of elt's in dimension j: $D_j = U_j - L_j + 1$

position of `A[`i_1`, ..., `i_n`]`:

$$\begin{aligned}&(i_n - L_n)\\&+(i_{n-1} - L_{n-1})D_n\\&+(i_{n-2} - L_{n-2})D_n D_{n-1}\\&+\cdots\\&+(i_1 - L_1)D_n \cdots D_2\end{aligned}$$

which can be rewritten as

$$\begin{aligned}&\overbrace{i_1 D_2 \cdots D_n + i_2 D_3 \cdots D_n + \cdots + i_{n-1} D_n + i_n}^{\text{variable part}}\\&-\underbrace{(L_1 D_2 \cdots D_n + L_2 D_3 \cdots D_n + \cdots + L_{n-1} D_n + L_n)}_{\text{constant part}}\end{aligned}$$

Address of `A[`i_1`, ..., `i_n`]`:

address(`A`) + ((variable part $-$ constant part) $\times$ element size)

case (switch) statements

case E **of** V_1: S_1 $\ldots V_n$: S_n **end**

1. evaluate the expression
2. find value in case list equal to value of expression
3. execute statement associated with value found
4. jump to next statement after case

Key issue: finding the right case

- sequence of conditional jumps (small case set)
  $\mathbf{O}(|\text{ cases }|)$
- binary search of an ordered jump table (sparse case set)
  $\mathbf{O}(\log_2|\text{ cases }|)$
- hash table (dense case set)
  $\mathbf{O}(1)$

case (switch) statements

case E **of** V_1: $S_1 \ldots V_n$: S_n **end**

One translation approach:

```
         $t$ := expr
         jump test
$L_1$:   code for $S_1$
         jump next
$L_2$:   code for $S_2$
         jump next
         ...
$L_n$:   code for $S_n$
         jump next
test:    if $t = V_1$ jump $L_1$
         if $t = V_2$ jump $L_2$
         ...
         if $t = V_n$ jump $L_n$
         code to raise run-time exception
next:
```

Labels and gotos

A little complicated!

Resolving references to labels multiply-defined in different scopes:

```
begin
    L: begin
        goto L;
        ... { possible definition of L }
    end
end
```

- Scope labels like variables
- On use, label definition is either resolved or unresolved
- On definition, backpatch previous unresolved label uses

Jumping out of blocks or procedures:

1. Pop run-time stack
2. Fix display (if used); static chain needs no fixing
3. Restore registers if jumping out of a procedure

Parameter passing

Place information in formal parameter location for callee to access actual parameter:

- value
- address
- dope vector

Parameter passing modes:

value (*copy-in*), *result* (*copy-out*), *value-result*
Copy actual into formal on call, formal into actual on return

reference (**var**), *read-only*
Copy address of actual into formal

name, *formal procedures*, *label parameters*
Name parameters are re-evaluated on every reference

Data objects distinguish:

- values (constants)
- locations (ordinary variables)
- addresses of locations containing values
  (indirect references, **var** parameters)

Value, result, value-result parameters

Value:

- treat formal as a local variable initialized with actual
- actual can be any expression of correct type

Result:

- treat formal as uninitialized local variable
- on return formal is copied into actual
- actual must be an *l-value*

Value-result:

- treat formal as local variable initialized with actual
- on return formal is copied to actual
- actual must be an *l-value*

Value, result, value-result parameters

Implementation:

Scalars:

- result/value-result ⇒
  pass address of actual, copy value to/from local copy
- value ⇒ simply pass value directly

Arrays:

- pass dope vector
- static arrays ⇒ pass pointer to base of array
- result/value-result ⇒ two local dope vectors
- value ⇒ one local dope vector

Records:

- handle as scalar (since fixed in size)
- best to pass address, let callee copy
  (more compact calling sequences)

Reference and read-only parameters

Usually pass address

Scalars:

- reference ⇒ pass address of actual
- read-only ⇒ pass value (rather than address): copy actual into read-only local

Arrays: pass dope vector (simple pointer if static)

Records: pass base address