COMPILERS
Intermediate Code

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IR Trees

- An Intermediate Representation is a machine-independent representation of the instructions that must be generated.
- We translate ASTs into IR trees using a set of rules for each of the nodes.
- Why use IR?
  - IR is easier to apply optimisations to
  - IR is simpler than real machine code
  - Separation of front-end and back-end

IR Trees - Expressions

CONST i	Integer constant i
NAME n	Symbolic constant n
TEMP t	Temporary t - a register
MEM m	Contents of a word of memory starting at m

IR Trees - Expressions

BINOP op e1 e2	e1 op e2 - Binary operator *op* applied to *e1* and *e2*
CALL f (e1….en)	Procedure call:evaluate f then the arguments in order
ESEQ s e	Evaluate s for side effects then e for the result

IR Trees - Statements

MOVE TEMP t e	Evaluate e then move the result to temporary t
MOVE MEM e2 e1	Evaluate e1 giving address a, then evaluate e2 and move the move the result to address a
EXP e	Evaluate e then discard the result

IR Trees - Statements

JUMP e (l1….ln)	Transfer control to address e; labels l1..ln are possible values for e
CJUMP op e1 e2 t f	Evaluate e1 then e2; compare the results using relational operator op; jump to t if true, f if false
SEQ s1 s2	The statement S1 followed by statement s2
LABEL n	Define constant value of name *n* as current code address; NAME(*n*) can be used as target of jumps, calls, etc.

Kinds of Expressions

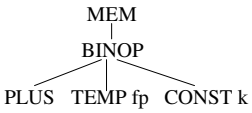
- Expression kinds indicate "how expression might be used"
- Ex(exp) expressions that compute a value
- Nx(stm) statements: expressions that compute no value
- Cx conditionals (jump to true and false destinations)
- RelCx conditionals (including operator and operands)
- IfThenElseExpression: special case for if!

Kinds of Expressions

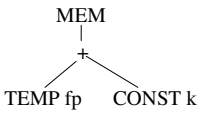
- Conversion operators allow use of one form in context of another:
- unEx convert to tree expression that computes value of inner tree
- unNx convert to tree statement that computes inner tree but returns no value
- unCx(t, f) convert to statement that evaluates inner tree and branches to true destination if non-zero, false destination otherwise

Translation

- Simple Variables
  - simple variable v in the current procedures stack frame



  - later becomes



Array Variables

- MiniJava arrays are pointers to array base, so fetch with a MEM like any other variable:
  - Ex(MEM(+(TEMP fp,CONST k)))
- Thus, for e[I]:
  - Ex(MEM(+(e.unEx,x(i.unEx, CONST w))))
  - *i* is index expression and *w* is word size – all values are word-sized (scalar)
- Note: must first check array index i<size(e); runtime will put size in word preceding array base

Record Variables

- Records are pointers to record base, so fetch like other variables. For e.f
  - Ex(MEM(+(e.unEx, CONST o)))
    - where o is the byte offset of the field in the record
- Note: must check record pointer is non-nil (i.e., non-zero)

Record Creation

- t{f1=e1;f2=e2;….;fn=en} in the (preferably GC'd) heap, first allocate the space then initialize it:
  - Ex(ESEQ(SEQ(MOVE(TEMP r, externalCall("allocRecord",[CONST n])),
  - SEQ(MOVE(MEM(TEMP r), e1.unEx)),
  - SEQ(...,
  - MOVE(MEM(+(TEMP r, CONST(n-1)w)),en.unEx))),
  - TEMP r))
  - where w is the word size

Array creation

- t[e1] of e2:
  - Ex(externalCall(”initArray”, [e1.unEx, e2.unEx]))

String Literals

- Statically allocated, so just use the string’s label
  - Ex(NAME(label))
- where the literal will be emitted as:
  - .word 11
  - label: .ascii "hello world"

Comparisons

- Translate a op b as:
  - RelCx(op, a.unEx, b.unEx)
- When used as a conditional unCx(t,f) yields:
  - CJUMP(op, 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 1/3

- The short-circuiting Boolean operators have already been transformed into if-expressions in MiniJava abstract syntax:
  - e.g., x < 5 & a > b turns into if x < 5 then a > b else 0
- Translate if e1 then e2 else e3 into:
  - IfThenElseExp(e1,e2,e3)
- When used as a value unEx yields:
  - ESEQ(SEQ(SEQ(e1 .unCx(t, f),SEQ(SEQ(LABEL t,SEQ(MOVE(TEMP r, e2.unEx),JUMP join)),SEQ(LABEL f,SEQ(MOVE(TEMP r, e3.unEx),JUMP join)))),LABEL join),TEMP r)

Conditionals 2/3

- As a conditional unCx(t,f) yields:
  - SEQ(e 1 .unCx(tt,ff),
  - SEQ(SEQ(LABEL tt, e 2 .unCx(t, f)),
  - SEQ(LABEL ff, e 3 .unCx(t, f))))

Conditionals 3/3

- Applying unCx(t,f) to if x<5 then a>b else 0:
  - SEQ(CJUMP(LT, x.unEx, CONST 5, tt, ff),
  - SEQ(SEQ(LABEL tt, CJUMP(GT, a.unEx, b.unEx, t, f)),
  - SEQ(LABEL ff, JUMP f)))
- or more optimally:
  - SEQ(CJUMP(LT, x.unEx, CONST 5, tt, f),
  - SEQ(LABEL tt, CJUMP(GT, a.unEx, b.uneX, t, f)))

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 do s:
  - evaluate c
  - if false jump to next statement after loop
  - if true fall into loop body
  - branch to top of loop
  - e.g.,
    - test:
    - if not(c)jump done
    - s
    - jump test
    - done:

While Loops

- The tree produced is:
- Nx(SEQ(SEQ(SEQ(LABEL test, c.unCx(body,done)),
- SEQ(SEQ(LABEL body, s.unNx), JUMP(NAME test))),
- LABEL done))
- repeat e1 until e2 is the same with the evaluate/compare/branch at bottom of loop

For Loops

- for i:= e 1 to e 2 do s
  - evaluate lower bound into index variable
  - evaluate upper bound into limit variable
  - if index > limit jump to next statement after loop
  - fall through to loop body
  - increment index
  - if index < limit jump to top of loop body

For Loops

- t1 <- e1
- t2 <- e2
- if t1 > t2 jump done
- body: s
- t1 <- t1 +1
- if t1 < t 2 jump body
- done:

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

Function Calls

- f(e1;….. ;en):
  - Ex(CALL(NAME label f ,[sl,e1 ,... en]))
- where sl is the static link for the callee f , found by following n static links from the caller, n being the difference between the levels of the caller and the callee
- In OO languages, you can also explicitly pass "this"

One Dimensional Fixed Arrays

- var a : ARRAY [2..5] of integer;
- ...
- a[e]
- translates to:
- MEM(+(TEMP fp, +(CONST k-2w,x(CONST w, e.unEx))))
  - where k is offset of static array from 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 can translate as above.

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:
    - 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-3
    - 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

Multidimensional Arrays

- array [1..N,1..M] of T
- array [1..N] of array [1..M] of T
- no. of elt's in dimension j:
  - Dj = U j - L j + 1
- position of A[i1, ...,in]:
  - $(i_n - L_n)$
  - $+ (i_{n-1} - L_{n-1})D_n$
  - $+ (i_{n-2} - L_{n-2})D_n * D_{n-1}$
  - + …
  - $+ (i_1 - L_1)D_n * D_{n-1} * \ldots * D_2$

Multidimensional Arrays

- which can be rewritten as
- i1*D2*…*Dn + i3*D3*…*Dn + … + in-1 * Dn + in (Variable part)
- - (L1 *D2*…*Dn + L3*D3*…*Dn + … + Ln-1 * Dn + Ln) (Constant part)
- address of A[i1,…,in]:
  - address(A) + ((variable part - constant part) * element size)

Case Statements

- case E of V 1 : S 1 ... Vn: Sn end
  - evaluate the expression
  - find value in list equal to value of expression
  - execute statement associated with value found
  - jump to next statement after case
- Key issue: finding the right case
  - sequence of conditional jumps (small case set)
    - O(|cases|)
  - binary search of an ordered jump table (sparse case set)
    - O(log 2 |cases|)
  - hash table (dense case set)
    - O(1)

Case Statement

- case E of V 1 : S 1 ... Vn: Sn end
- One translation approach:
  - t :=expr
  - jump test
  - L 1 : code for S1; jump next
  - L 2 : code for S 2; jump next
  - ...
  - Ln: code for Sn jump next
  - test: if t = V1 jump L 1
  - if t = V2 jump L 2
  - ...
  - if t = Vn jump Ln
  - code to raise run-time exception
  - next:

Case Statement

- Another translation approach:
  - t :=expr
  - check t in bounds of 0…n-1 if not code to raise run-time exception
  - jump jtable + t
  - L 1 : code for S1; jump next
  - L 2 : code for S 2; jump next
  - ...
  - Ln: code for Sn jump next
  - Jtable: jump L 1
  - jump L 2
  - ...
  - jump Ln
  - next: