CS412/413

Introduction to Compilers

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Lecture 17: IR Lowering

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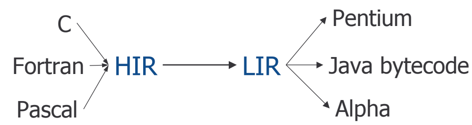
Intermediate Code

- Usually two IRs:

High-level IR	Low-level IR
Language-independent (but closer to language)	Machine independent (but closer to machine)



High-level IR

- Tree node structure very similar to the AST
- Contains high-level constructs common to many languages
  - Expression nodes
  - Statement nodes
- Expression nodes for:
  - Integers and program variables
  - Binary operations: e1 OP e2
    - Arithmetic operations
    - Logic operations
    - Comparisons
  - Unary operations: OP e
  - Array accesses: e1[e2]

High-level IR

- Statement nodes:
  - Block statements (statement sequences): (s1, …, sN)
  - Variable assignments: v = e
  - Array assignments: e1[e2] = e3
  - If-then-else statements: if c then s1 else s2
  - If-then statements: if c then s
  - While loops: while (c) s
  - Function call statements: f(e1, …, eN)
  - Return statements: return or return e
- May also contain:
  - For loop statements: for(v = e1 to e2) s
  - Break and continue statements
  - Switch statements: switch(e) { v1: s1, …, vN: sN }

Low-Level IR

- Low-level representation is essentially an instruction set for an abstract machine
- Alternatives for low-level IR:
  - Three-address code or quadruples (Dragon Book):

    a = b OP c
  - Tree representation (Tiger Book)
  - Stack machine (like Java bytecode)

Three-Address Code

- In this class: three-address code

  a = b OP c
- Has at most three addresses (may have fewer)
- Also named quadruples because can be represented as: (a, b, c, OP)
- Example:

a = (b+c)*(-e);

```
t1 = b + c
t2 = − e
a = t1 * t2
```

Low IR Instructions

- Assignment instructions:
  - Binary operations: a = b OP c
    - arithmetic: ADD, SUB, MUL, DIV, MOD
    - logic: AND, OR, XOR
    - comparisons: EQ, NEQ, LT, GT, LEQ, GEQ
  - Unary operation a = OP b
    - Arithmetic MINUS or logic NEG
  - Copy instruction: a = b
  - Load /store: a = *b, *a = b
  - Other data movement instructions

Low IR Instructions (Ctd)

- Flow of control instructions:
  - label L : label instruction
  - jump L : Unconditional jump
  - cjump a L : conditional jump
- Function call
  - call f(a_1, …., a_n)
  - a = call f(a_1, …., a_n)
  - Is an extension to quads
- … IR describes the Instruction Set of an abstract machine

Example

```
m = 0;
if (c  == 0) {
   m = m+ n*n;
} else {
   m = m + n;
}
```

```
m = 0
t1 = c == 0
tjump t1 trueb
m = m+n
jump end
label trueb
t2 = n * n
m = m + t2
label end
```


How To Translate?

- May have nested language constructs
  - Nested if and while statements
- Need an algorithmic way to translate
- Solution:
  - Start from the AST representation
  - Define translation for each node in the AST
  - Recursively translate nodes in the AST

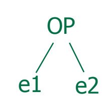
Notation

- Use the following notation:
  T[e] = the low-level IR representation of high-level IR construct e
- T[e] is a sequence of Low-level IR instructions
- If e is an expression (or a statement expression), it represents a value
- Denote by t = T[e] the low-level IR representation of e, whose result value is stored in t
- For variable v: t = T[v] is the copy instruction t = v

Translating Expressions

- Binary operations: t = T[e1 OP e2]
  (arithmetic operations and comparisons)

  t1 = T[e1]
  t2 = T[e2]
  t = t1 OP t2



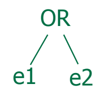
- Unary operations: t = T[OP e]

  t1 = T[e]
  t = OP t1

Translating Boolean Expressions

- t = T[e1 OR e2]

t1 = T[e1]
t2 = T[e2]
t = t1 OR t2

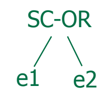


- … how about short-circuit OR?
- Should compute e2 only if e1 evaluates to false

Translating Short-Circuit OR

- Short-circuit OR: t = T[e1 SC-OR e2]

t = T[e1]
tjump t Lend
t = T[e2]
label Lend

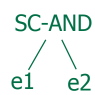


- … how about short-circuit AND?

Translating Short-Circuit AND

- Short-circuit AND: t = T[e1 SC-AND e2]

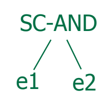
t = T[e1]
tjump t Lnext
jump Lend
label Lnext
t = T[e2]
label Lend



Another Translation

- Short-circuit AND: t = T[e1 SC-AND e2]

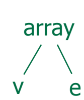
t = T[e1]
fjump t Lend
t = T[e2]
label Lend



Array and Field Accesses

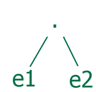
- Array access: t = T[v[e]]

t1 = T[e]
t = v[t1]



- Field access: t = T[e1.f]

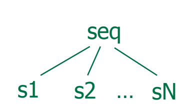
t1 = T[e1]
t = t1.f



Translating Statements

- Statement sequence: T[s1; s2; …; sN]

T[s1]
T[s2]
…
T[sN]

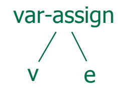


- IR instructions of a statement sequence = concatenation of IR instructions of statements

Assignment Statements

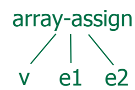
- Variable assignment: T[v = e]

  v = T[e]



- Array assignment: T[v[e1] = e2]

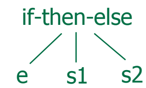
  t1 = T[e1]
  t2 = T[e2]
  v[t1] = t2



Translating If-Then-Else

- T[if (e) then s1 else s2]

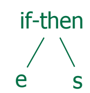
  t1 = T[e]
  fjump t1 Lfalse
  T[s1]
  jump Lend
  label Lfalse
  T[s2]
  label Lend



Translating If-Then

- T[if (e) then s]

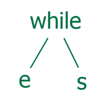
  t1 = T[e]
  fjump t1 Lend
  T[s]
  label Lend



While Statements

- T[while (e) { s }]

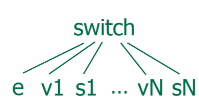
  label Ltest
  t1 = T[e]
  fjump t1 Lend
  T[s]
  jump Ltest
  label Lend



Switch Statements

- T[switch (e) { case v1: s1, …, case vN: sN }]

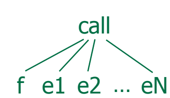
  t = T[e]
  c = t != v1
  tjump c L2
  T[s1]
  jump Lend
  label L2
  c = t != v2
  tjump c L3
  T[s2]
  jump Lend
  …
  label LN
  c = t != vN
  tjump c Lend
  T[sN]
  label Lend



Call and Return Statements

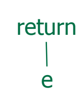
- T[call f(e1, e2, …, eN)]

  t1 = T[e1]
  t2 = T[e2]
  …
  tN = T[eN]
  call f(t1, t2, …, tN)



- T[return e]

  t = T[e]
  return t



Statement Expressions

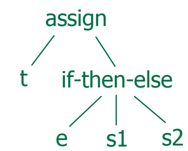
- So far: statements which do not return values
- Easy extensions for statement expressions:
  - Block statements
  - If-then-else
  - Assignment statements

- t = T[s] is the sequence of low IR code for statement s, whose result is stored in t

Statement Expressions

- t = T[if (e) then s1 else s2]

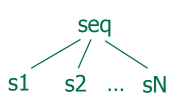
```
t1 = T[ e ]
cjump t1 Ltrue
t = T[ s2 ]
jump Lend
label Ltrue
t = T[ s1 ]
label Lend
```



Block Statements

- t = [s1; s2; …; sN]

```
[ s1 ]
[ s2 ]
…
t = [ sN ]
```

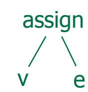


- Result value of a block statement = value of last statement in the sequence

Assignment Statements

- t = [v = e]

```
v = [ e ]
t = v
```



- Result value of an assignment statement = value of the assigned expression