CS412/CS413

Introduction to Compilers

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Lecture 18-19: Intermediate Code

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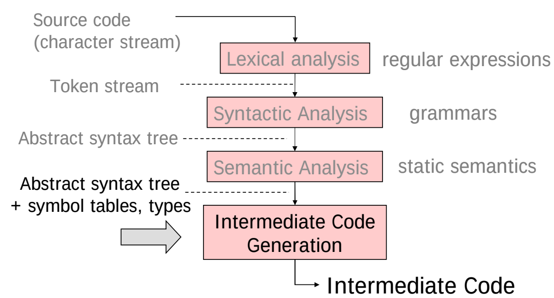
Summary: Semantic Analysis

- Check errors not detected by lexical or syntax analysis
- Scope errors:
  - Variables not defined
  - Multiple declarations
- Type errors:
  - Assignment of values of different types
  - Invocation of functions with different number of parameters or parameters of incorrect type
  - Incorrect use of return statements

Semantic Analysis

- Type checking
  - Use type checking rules
  - Static semantics = formal framework to specify type-checking rules
- There are also control flow errors:
  - Must verify that a break or continue statement is always enclosed by a while (or for) statement
  - Java: must verify that a break X statement is enclosed by a for loop with label X
  - Can easily check control-flow errors by recursively traversing the AST

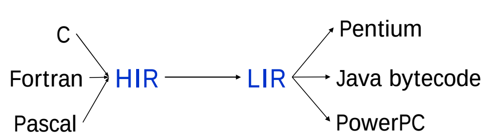
Where We Are



Intermediate Code

- Usually two IRs:

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



High-level IR

- Tree node structure, essentially ASTs
- 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, cont.

- 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)
fjump t1 falseb
t2 = n * n
m = m + t2
jump end
label falseb
m = m+n
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 in terms of a (recursive) translation of its constituents

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), T[e] 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, define T[v] to be v, i.e., 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
```

```
   OP
  /  \
e1    e2
```

- Unary operations: t = T[OP e]

```
t1 = T[ e ]
t = OP t1
```

```
OP
|
e
```


Translating Boolean Expressions

- t = T[e1 OR e2]

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

```
   OR
  /  \
e1    e2
```

- ... but how about short-circuit OR, for which we 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
```

```
  SC-OR
  /   \
e1     e2
```

- ... how about short-circuit AND?

Translating Short-Circuit AND

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

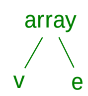
```
t = T[ e1 ]
fjump t Lend
t = T[ e2 ]
label Lend
```

```
  SC-AND
  /    \
e1      e2
```

Array and Field Accesses

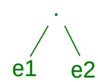
- Array access: t = T[v[e]]

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



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

  t1 = T[e1]
  t = t1.f



Nested Expressions

- In these translations, expressions may be nested;
- Translation recurses on the expression structure

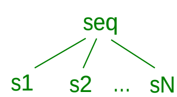
- Example: t = T[(a - b) * (c + d)]

  t1 = a
  t2 = b
  t3 = t1 – t2
  } T[(a - b)]
  t4 = b
  t5 = c
  t5 = t4 + t5
  } T[(c + d)]
  t = t3 * t5
  } T[(a - b) * (c + d)]

Translating Statements

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

  T[s1]
  T[s2]
  ...
  T[sN]

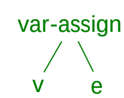


- IR instructions of a statement sequence = concatenation of IR instructions of statements

Assignment Statements

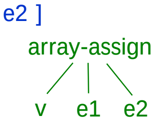
- Variable assignment: T[v = e]

  t = T[e]
  v = t
  [alternatively]
  v = T[e]



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

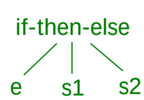
  t1 = T[e1]
  t2 = T[e2]
  v[t1] = t2



Translating If-Then-Else

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

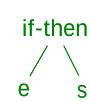
  t1 = T[e]
  fjump t1 Lfalse
  T[s1]
  jump Lend
  label Lfalse
  T[s2]
  label Lend



Translating If-Then

- T[if (e) then s]

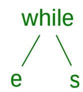
  t1 = T[e]
  fjump t1 Lend
  T[s]
  label Lend



While Statements

- T[while (e) { s }]

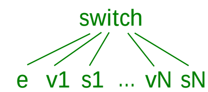
label Ltest
t1 = T[e]
fjump t1 Lend
T[s]
jump Ltest
label Lend



Switch Statements

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

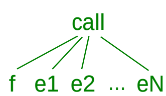
t = T[e]
c = t != v1
tjump c L2
T[s1]
jump Lend
label L2
c = t != v2
tjump c L3
T[s2]
jump Lend
...
label LN
c = t != vN
tjump c Lend
T[sN]
label Lend



Call and Return Statements

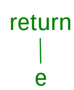
- T[call f(e1, e2, ..., eN)]

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



- T[return e]

t = T[e]
return t



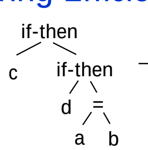
Nested Statements

- Same for statements as expressions: recursive translation
- Example: T[if c then if d then a = b]

t1 = c
fjump t1 Lend1
t2 = d
fjump t2 Lend2
t3 = b
a = t3
label Lend2
label Lend1

T[a = b]
T[if d ...]
T[if c then ...]

IR Lowering Efficiency



t1 = c
fjump t1 Lend1
t2 = d
fjump t2 Lend2
t3 = b
a = t3
label Lend2
label Lend1

fjump c Lend
fjump d Lend
a = b
Label Lend