CS412/CS413

Introduction to Compilers

Tim Teitelbaum

Lecture 18: Intermediate Code

29 Feb 08

Summary: Semantic Analysis

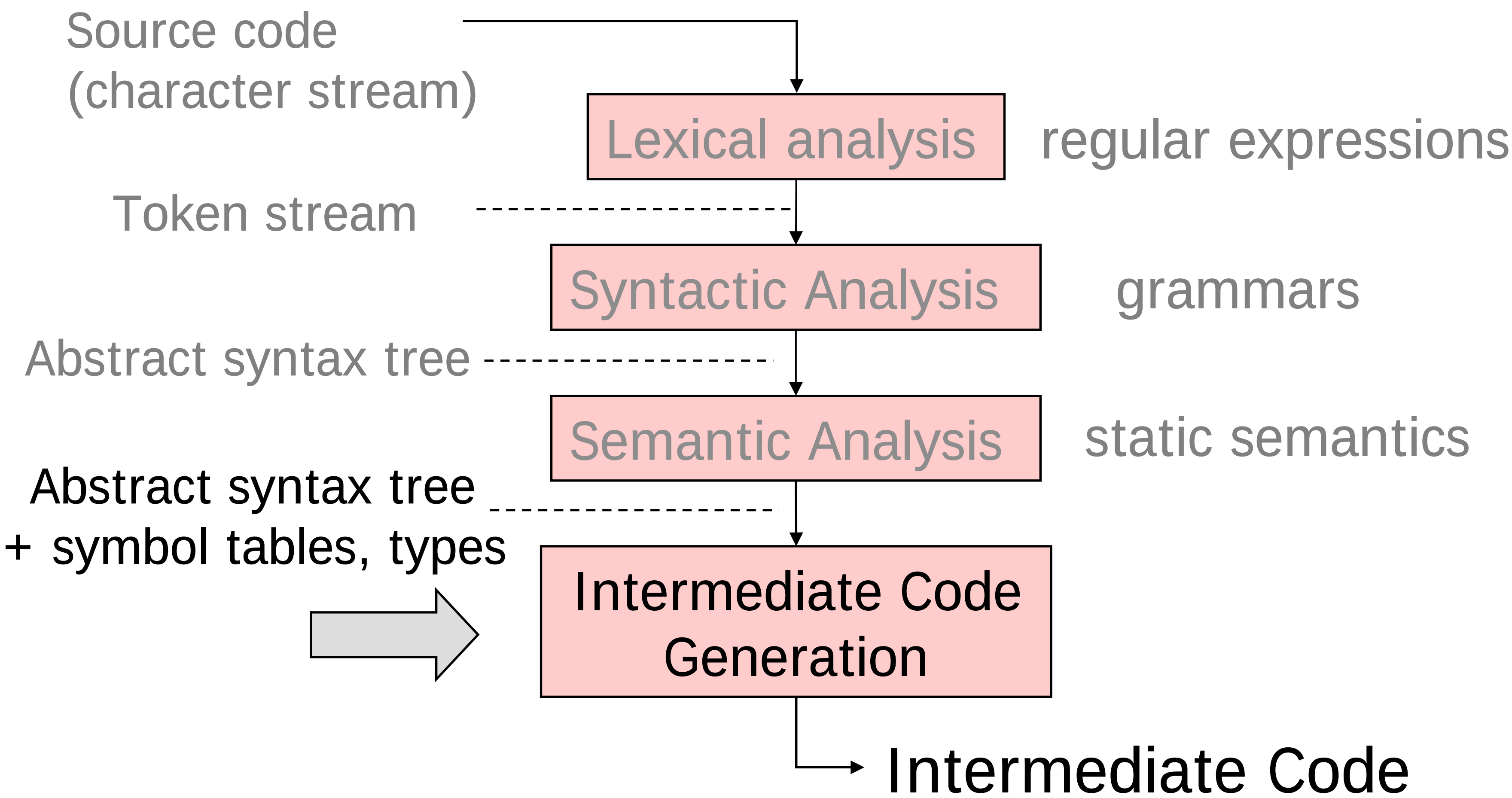
- Check errors not detected by lexical or syntax analysis
- Scope errors:
  - Variables not defined
  - Multiple declarations
- Type errors:
  - Assignment of values of different types
  - Invocation of functions with different number of parameters or parameters of incorrect type
  - Incorrect use of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



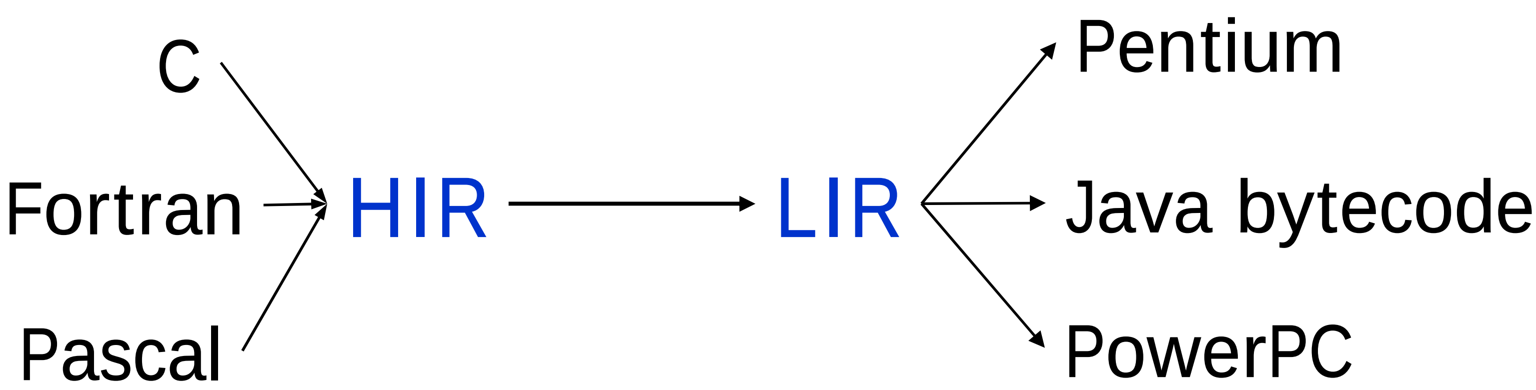
Source code
(character stream)
Lexical analysis
regular expressions
Token stream
Syntactic Analysis
grammars
Abstract syntax tree
Semantic Analysis
static semantics
Abstract syntax tree
+ symbol tables, types
Intermediate Code Generation
Intermediate Code

Intermediate Code

- Usually two IRs:

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

Low-level IR
Machine independent
(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 $f(a_1, \ldots., a_n)$
  - $a = \text{call } f(a_1, \ldots., a_n)$
  - 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 notation T[e] = low-level IR of high-level IR construct e
- T[e] is sequence of low-level IR instructions
- If e is expression (or statement expression), T[e] represents a value
- Denote by t = T[e] the low-level IR of e, whose result value is stored in t
- For variable v, define T[v] to be v, i.e., t = T[v] is copy instruction t = v

Translating Expressions

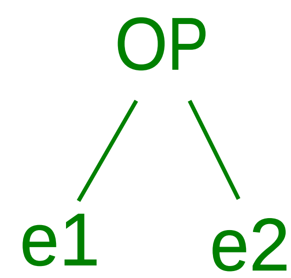
- Binary operations: t = T[e1 OP e2]

  (arithmetic operations and comparisons)

  t1 = T[e1]

  t2 = T[e2]

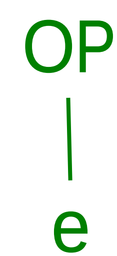
  t = t1 OP t2



- Unary operations: t = T[OP e]

  t1 = T[e]

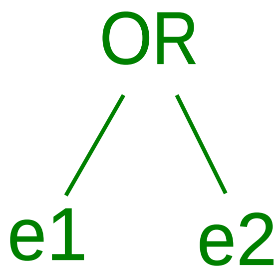
  t = OP t1



Translating Boolean Expressions

- t = T[e1 OR e2]

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

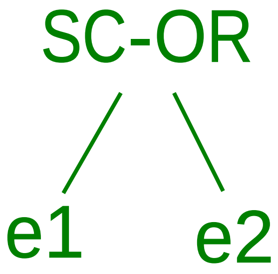


- ... but how about short-circuit OR, for which we should compute e2 only if e1 evaluates to false

Translating Short-Circuit OR

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

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

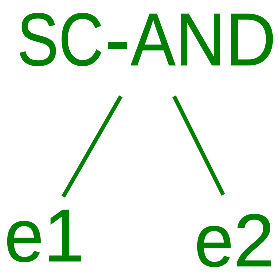


- ... how about short-circuit AND?

Translating Short-Circuit AND

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

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

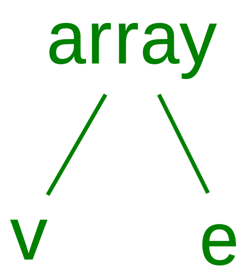


Array and Field Accesses

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

  t1 = T[e]

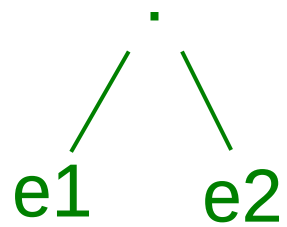
  t = v[t1]



- 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)]

$$\left.\begin{array}{l}\left.\begin{array}{l}t1 = a\\ t2 = b\\ t3 = t1 - t2\end{array}\right\} T[\ (a - b)\ ]\\ \left.\begin{array}{l}t4 = b\\ t5 = c\\ t5 = t4 + t5\end{array}\right\} T[\ (c + d)\ ]\\ t = t3 * t5\end{array}\right\} T[\ (a - b) * (c + d)\ ]$$

Translating Statements

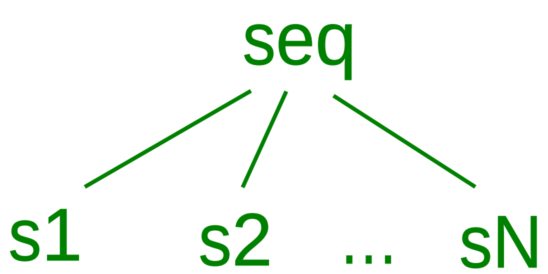
- Statement sequence: T[s1; s2; ...; sN]

T[s1]

T[s2]

...

T[sN]

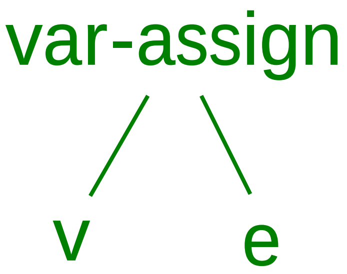


- IR instructions of a statement sequence = concatenation of IR instructions of statements

Assignment Statements

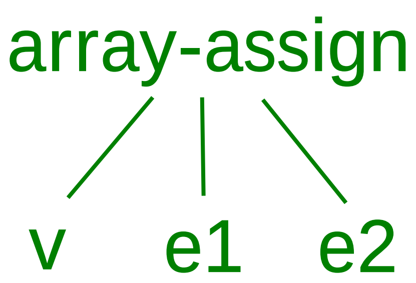
- Variable assignment: T[v = e]

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



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

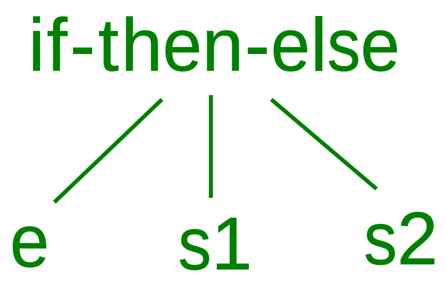
  t1 = T[e1]
  t2 = T[e2]
  v[t1] = t2



Translating If-Then-Else

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

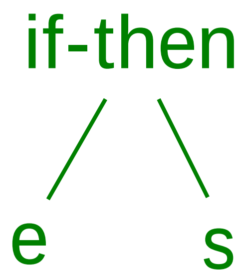
```
t1 = T[ e ]
fjump t1 Lfalse
T[ s1 ]
jump Lend
label Lfalse
T[ s2 ]
label Lend
```



Translating If-Then

- T[if (e) then s]

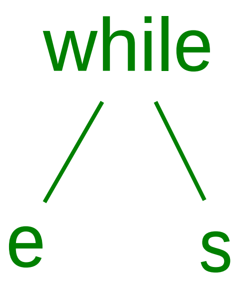
  t1 = T[e]
  fjump t1 Lend
  T[s]
  label Lend



While Statements

- T[while (e) { s }]

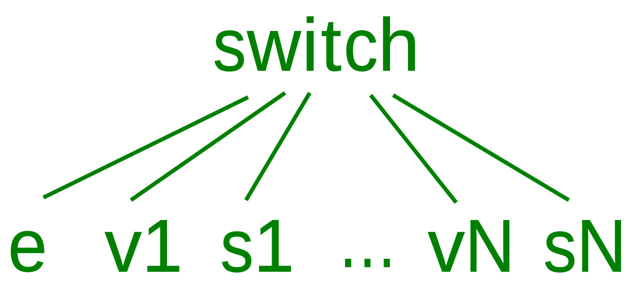
```
label Ltest
t1 = T[ e ]
fjump t1 Lend
T[ s ]
jump Ltest
label Lend
```



Switch Statements

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

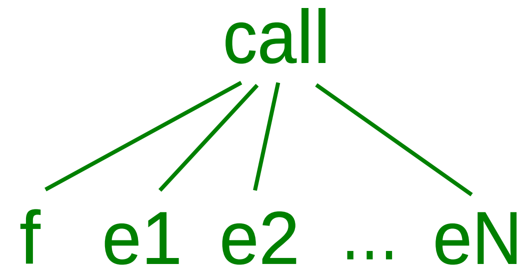
```
t = T[ e ]
c = t != v1
tjump c L2
T[ s1 ]
jump Lend
label L2
c = t != v2
tjump c L3
T[ s2 ]
jump Lend
...
label LN
c = t != vN
tjump c Lend
T[ sN ]
label Lend
```



Call and Return Statements

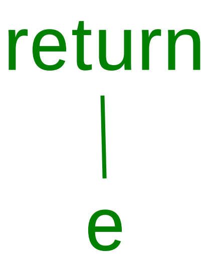
- T[call f(e1, e2, ..., eN)]

```
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]

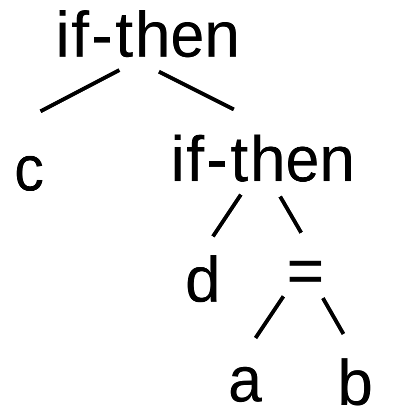
t1 = c
fjump t1 Lend1
t2 = d
fjump t2 Lend2
t3 = b
a = t3
label Lend2
label Lend1

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
```