# Lecture 6: Lexers & Parsers

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# Homework

- First line:
  - module Hmwk2 where
  - Next line should be name as comment
  - Name of program file should be Hmwk2.hs

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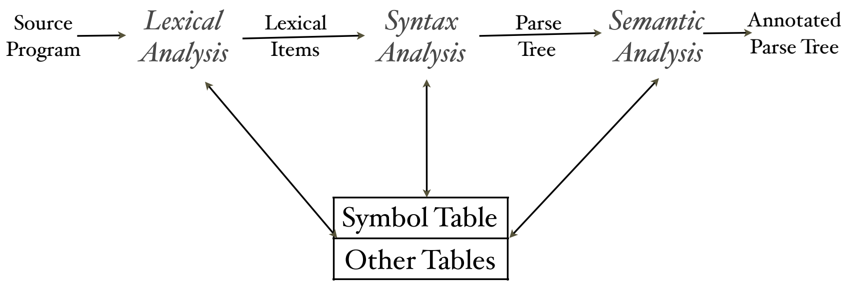
# Analysis


Source Program
*Lexical Analysis*
Lexical Items
*Syntax Analysis*
Parse Tree
*Semantic Analysis*
Annotated Parse Tree
Symbol Table
Other Tables

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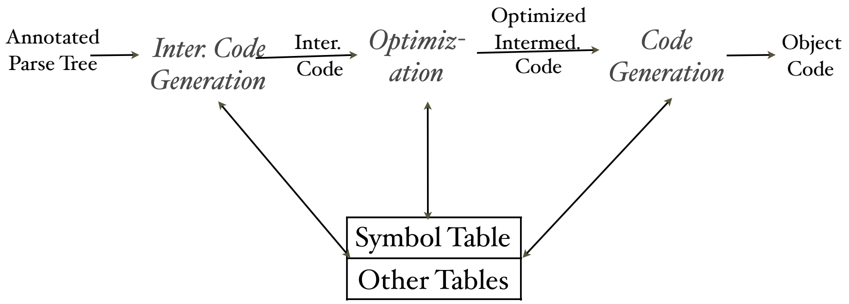
# Synthesis


Annotated Parse Tree
*Inter. Code Generation*
Inter. Code
*Optimiz-ation*
Optimized Intermed. Code
*Code Generation*
Object Code
Symbol Table
Other Tables

# Step 1: Lexical Analysis

# Lexing

- Lexer returns a list of all tokens from the input stream.
- Build from either regular expressions or (equivalently) finite automaton recognizing the tokens.
- See program LexArith.hs in class examples.
    - Haskell program uses modules to hide info

# Explaining LexArith

- module LexArith(...) where
    - lists funcs and types exported (includes constructors)
- code details follow in file
    - getid :: [Char] -> [Char] -> ([Char], [Char])
        - takes string and prefix of id to first full id and rest of string to be processed
    - getnum :: [Char] -> Int -> (Int, [Char])
        - similar
    - getToken: [Char] → (Token, [Char])
        - takes string to pair of first recognized token and rest of list to be processed

# Parsing

# Parsing

- Build parse tree from an expression
- Interested in abstract syntax tree
  - drops irrelevant details from parse tree

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# Arithmetic grammar

```
 <exp> ::= <exp> <addop> <term>
         | <term>
  <term> ::= <term> <mulop> <factor>
         | <factor>
<factor> ::= ( <exp> )
         | NUM
         | ID
 <addop> ::= + | -
 <mulop> ::= * | /
```

*Look at parse tree & abstract syntax tree for 2 * 3 + 7*

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# Recursive Descent Parser

Base recognizer (*ignore building tree now*) on productions:

```
  <exp> ::= <exp> <addop> <term>

addop (fst:rest) = if fst==’+’ or fst==’-‘ then rest
                   else error ...

exp input = let
       inputAfterExp = exp input
       inputAfterAddop = addOp inputAfterExp
       rest = term inputAfterAddop
     in
       rest
```

*or*

```
fun exp input = term(addOp(exp input));
```

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# Problems

- How do we select which production to use when alternatives?
- Left-recursive - never terminates

# Rewrite Grammar

```
      <exp> ::= <term> <termTail>                      (1)
 <termTail> ::= <addop> <term> <termTail>              (2)
              | ε                                      (3)
     <term> ::= <factor> <factorTail>                  (4)
<factorTail> ::= <mulop> <factor> <factorTail>         (5)
              | ε                                      (6)
   <factor> ::= ( <exp> )                              (7)
              | NUM                                    (8)
              | ID                                     (9)
    <addop> ::= + | -                                 (10)
    <mulop> ::= * | /                                 (11)
```

*No left recursion*

*How do we know which production to take?*

# Predictive Parsing

Goal: $a_1a_2\dots a_n$

$$\begin{aligned} S &\rightarrow \alpha \\ &\dots \\ &\rightarrow a_1a_2X\beta \end{aligned}$$

*Want next terminal character derived to be* $a_3$

*$a_3$ in First($\gamma$)*

Need to apply a production $X ::= \gamma$ where

1) $\gamma$ can eventually derive a string starting with $a_3$ or

2) If X can derive the empty string, and also if $\beta$ can derive a string starting with $a_3$.

*$a_3$ in Follow(X)*

# FIRST

- *Intuition*: $b \in$ First(X) iff there is a derivation $X \rightarrow^* b\omega$ for some $\omega$.

1. First(b) = b for b a terminal or the empty string
2. If have $X ::= \omega_1 \mid \omega_2 \mid \dots \mid \omega_n$ then
   $\text{First}(X) = \text{First}(\omega_1) \cup \dots \cup \text{First}(\omega_n)$
3. For any right hand side $u_1u_2\dots u_n$
   - $\text{First}(u_1) \subseteq \text{First}(u_1u_2\dots u_n)$
   - if all of $u_1, u_2\dots, u_{i-1}$ can derive the empty string then also $\text{First}(u_i) \subseteq \text{First}(u_1u_2\dots u_n)$
   - empty string is in $\text{First}(u_1u_2\dots u_n)$ iff all of $u_1, u_2\dots, u_n$ can derive the empty string

# First for Arithmetic

FIRST(<addop>) = { +, - }

FIRST(<mulop>) = { *, / }

FIRST(<factor>) = { (, NUM, ID }

FIRST(<term>) = { (, NUM, ID }

FIRST(<exp>) = { (, NUM, ID }

FIRST(<termTail>) = { +, -, ε }

FIRST(<factorTail>) = { *, /, ε }

# Follow

- *Intuition:* A terminal b ∈ Follow(X) iff there is a derivation S →* vXbω for some v and ω.

1. If S is the start symbol then put EOF ∈ Follow(S)
2. For all rules of the form A ::= wXv,
    a. Add all elements of First(v) to Follow(X)
    b. If v can derive the empty string then add all elts of Follow(A) to Follow(X)

- Follow(X) only used if can derive empty string from X.

# Follow for Arithmetic

*Only needed to calculate for <termTail>, <factorTail> !*

FOLLOW(<exp>) = { EOF, ) }

FOLLOW(<termTail>) = FOLLOW(<exp>) = { EOF, ) }

FOLLOW(<term>) = FIRST(<termTail>) ∪
FOLLOW(<exp>) ∪ FOLLOW(<termTail>)
= { +, -, EOF, ) }

FOLLOW(<factorTail>) = { +, -, EOF, ) }

*FOLLOW(<factor>) = { *, /, +, -, EOF }*
*FOLLOW(<addop>) = { (, NUM, ID }*
*FOLLOW(<mulop>) = { (, NUM, ID }*
} *Not needed!*

# Predictive Parsing, redux

Goal: $a_1a_2...a_n$

$S \rightarrow \alpha$
...
$\rightarrow a_1a_2X\beta$

*Want next terminal character derived to be* $a_3$

Need to apply a production X ::= γ where
1) γ can eventually derive a string starting with $a_3$ or
2) If X can derive the empty string, then see if β can derive a string starting with $a_3$.

# Building Table

- Put X ::= α in entry (X,a) if either
    - a in First(α), or
    - e in First(α) and a in Follow(X)
- Consequence: X ::= α in entry (X,a) iff there is a derivation s.t. applying production can eventually lead to string starting with a.

# Need Unambiguous

- *No table entry should have more than one production* to ensure it's unambiguous, as otherwise we don't know which rule to apply.
- Laws of predictive parsing:
  - If $A ::= \alpha_1 \mid \ldots \mid \alpha_n$ then for all $i \neq j$, $\mathrm{First}(\alpha_i) \cap \mathrm{First}(\alpha_j) = \emptyset$.
  - If $X \to^* \varepsilon$, then $\mathrm{First}(X) \cap \mathrm{Follow}(X) = \emptyset$.

- Laws of predictive parsing:
  - If $A ::= \alpha_1 \mid \ldots \mid \alpha_n$ then for all $i \neq j$, $\mathrm{First}(\alpha_i) \cap \mathrm{First}(\alpha_j) = \emptyset$.
  - If $X \to^* \varepsilon$, then $\mathrm{First}(X) \cap \mathrm{Follow}(X) = \emptyset$.
- 2nd is OK for arithmetic:
  - FIRST(<termTail>) = { +, -, ε }
  - FOLLOW(<termTail>) = { EOF, ) }
  - FIRST(<factorTail>) = { *, /, ε }
  - FOLLOW(<factorTail>) = { +, -, EOF, ) }

*no overlap!*

*See ArithParse.hs*

| *Non-terminals* | *ID* | *NUM* | *Addop* | *Mulop* | *(* | *)* | *EOF* |
|---|---|---|---|---|---|---|---|
| *<exp>* | 1 | 1 | | | 1 | | |
| *<termTail>* | | | 2 | | | 3 | 3 |
| *<term>* | 4 | 4 | | | 4 | | |
| *<factTail>* | | | 6 | 5 | | 6 | 6 |
| *<factor>* | 9 | 8 | | | 7 | | |
| *<addop>* | | | 10 | | | | |
| *<mulop>* | | | | 11 | | | |

*Read off from table which production to apply!*

# More Options

- Parser Combinators
  - Domain specific language for parsing.
  - Even easier to tie to grammar than recursive descent
  - Build into Haskell and Scala, definable elsewhere
    - Talk about when cover Scala

# Parser Combinators in Scala

*Syntax tree building code omitted*

```
def multOp = ("*" | "/")

def addOp = ("+" | "-")

def factor = "(" ~> expr <~ ")" |  numericLit ^^ {...}

def term = factor ~ (factorTail*) ^^ {...}

def factorTail = multOp ~ factor ^^{...}

def expr  = term ~ (termTail*) ^^ {...}

def termTail = addOp ~ term ^^{...}
```