Computer Language Engineering

- How to give instructions to a computer?
  - **Programming Languages.**
- How to make the computer carryout the instructions efficiently?
  - **Compilers.**

Anatomy of a Compiler

Program (character stream)
↓
Lexical Analyzer (Scanner)
↓ Token Stream
Syntax Analyzer (Parser)
↓ Parse Tree
Intermediate Code Generator
↓ Intermediate Representation
Intermediate Code Optimizer
↓ Optimized Intermediate Representation
Code Generator
↓ Assembly code

What is a Lexical Analyzer?

Source program text → Tokens

- Examples of Token
  - Operators = + - > ({ := == <>
  - Keywords if while for int double
  - Numeric literals 43 6.035 -3.6e10 0x13F3A
  - Character literals 'a' '~' '\''
  - String literals "3.142" "Fall" "\"\" = empty"
- Examples of non-token
  - White space space(' ') tab('\t') end-of-line('\n')
  - Comments /*this is not a token*/

Lexical Analyzer in Action

f	o	r		v	a	r	1		=		1	0			v	a	r	1	<	=	

for ID("var1") eq_op Num(10) ID("var1") leq_op

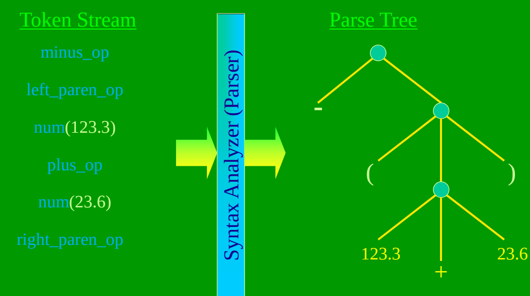
- Partition input program text into sequence of tokens, attaching corresponding attributes.
  - E.g., C-lexeme "015" token NUM attribute 13
- Eliminate white space and comments

Syntax and Semantics of a programming language

- Syntax
  - What is the structure of the program?
  - Textual representation.
    - Formally defined using context-free grammars (Backus-Naur Formalism)
- Semantics
  - What is the meaning of a program?
    - Harder to give a mathematical definition.

Input to and output of a parser

Input: - (123.3 + 23.6)



Example: A CFG for expressions

- Simple arithmetic expressions with + and *
  - 8.2 + 35.6
  - 8.32 + 86 * 45.3
  - (6.001 + 6.004) * (6.035 * -(6.042 + 6.046))
- Terminals (or tokens)
  - **num** for all the numbers
  - plus_op, minus_op, times_op, left_paren_op, right_paren_op
- What is the grammar for all possible expressions?

Example: A CFG for expressions

<expr> → <expr> <op> <expr>
<expr> → (<expr>)
<expr> → - <expr>
<expr> → **num**
<op> → +
<op> → *

Context-Free Grammars (CFGs)

- *Terminals*
  - Symbols for strings or tokens **{ num, (,), +, *, - }**
- *Nonterminals*
  - Syntactic variables **{ <expr>, <op> }**
- *Start symbol*
  - A special nonterminal **<expr>**
- *Productions*
  - The manner in which terminals and nonterminals are combined to form strings.
  - A nonterminal in LHS and a string of terminals and non-terminals in RHS. **<expr> → - <expr>**

English Language

- Letters: a,b,c, …
- Alphabet: { a,b, …, z} U { A, B, …, Z}
- Tokens (Terminals) : English words
- Nonterminals: <Sentence>, <Subject>, <Clause>, …
- Context-free aspect: Replacing <Noun> by <Proper Noun> or <Common Noun>
- Context-sensitive aspects: Agreement among words w.r.t. number, gender, tense, etc.

Example Derivation

<expr> ⇒ <expr> <op> <expr>
⇒ num <op> <expr>
⇒ num * <expr>
⇒ num * (<expr>)
⇒ num * (<expr> <op> <expr>)
⇒ num * (num <op> <expr>)
⇒ num * (num + <expr>)
⇒ num * (num + num)
num * (num + num)

Another Example Derivation

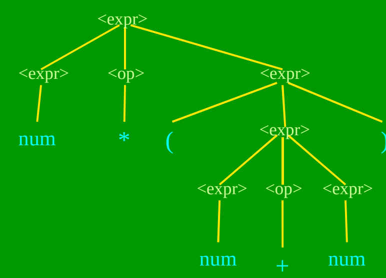
<expr> ⇒ <expr> <op> <expr>
⇒ <expr> * <expr>
⇒ <expr> * (<expr>)
⇒ <expr> * (<expr> <op> <expr>)
⇒ <expr> * (num <op> <expr>)
⇒ <expr> * (num + <expr>)
⇒ <expr> * (num + num)
⇒ num * (num + num)

Parse/Derivation Tree

- Graphical Representation of the parsed structure
- Shows the sequence of derivations performed
  - Internal nodes are non-terminals.
  - Leaves are terminals.
  - Each parent node is LHS and the children are RHS of a production.
- *Abstracts* the details of sequencing of the rule applications, but *preserves* decomposition of a non-terminal.

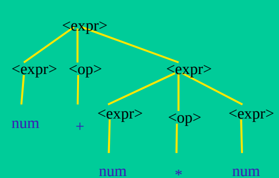
Parse/Derivation Tree Example

num * (num + num)



Expression – One possible parse tree

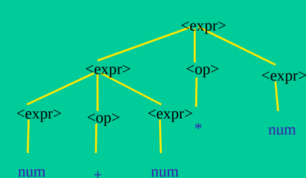
num + num * num



124 + (23.5 * 86) = 2145

Expression – Another possible parse tree

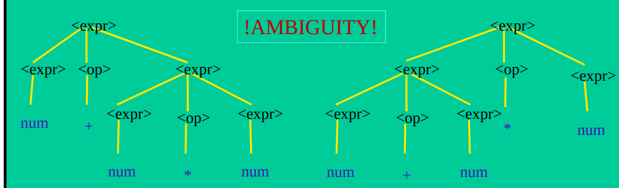
num + num * num



(124 + 23.5) * 86 = 12685

Same string – Two distinct parse (derivation) trees

num + num * num



124 + (23.5 * 86) = 2145 (124 + 23.5) * 86 = 12685

Ambiguous Grammar

- Applying different derivation orders produces different parse trees.
  - This can lead to ambiguous/unexpected results.
  - Note that multiple derivations leading to the same parse tree is not a problem.
- A CFG is *ambiguous* if the same string can be associated with two distinct parse trees.
  - E.g., The expression grammar can be shown to be ambiguous using expressions containing binary infix operators and non-fully parenthesized expressions.

Removing Ambiguity

- Sometimes rewriting a grammar to reflect *operator precedence* with additional nonterminals will eliminate ambiguity.
  - ❑ * more binding than +.
  - ❑ && has precedence over ||.
- One can view the rewrite as “breaking the symmetry” through “stratification” .

Eliminating Ambiguity

<expr> → <term> + <expr>
<expr> → <term>
<term> → <unit> * <term>
<term> → <unit>
<unit> → **num**
<unit> → (<expr>)

<expr> → <expr> <op> <expr>
<expr> → (<expr>)
<expr> → **num**
<op> → +
<op> → *

Extended BNF (Backus Naur Formalism)

<expr> → <term> (+ <term>) *

<term> → <unit> (* <unit>) *

<unit> → **num** | (<expr>)

★ Kleene Star : Zero or more occurrences

<expr> → <expr> (<op> <expr>) *
<expr> → (<expr>)
<expr> → **num**
<op> → + | *

Expression Parser Fragment (String => Parse Tree)

```
Node expr() {
       // PRE: Expects lookahead token.
       // POST: Consume an Expression
       //        and update Lookahead token.
       Node temp = term();
       while ( inTok.ttype == '+') {
            inTok.nextToken();
            Node temp1 = term();
            temp = new OpNode(temp,'+',temp1);
       }
       return temp;
  }
```


Arithmetic Expressions (with variables)

(ambiguous)

<expr> → <expr> + <expr>
| <expr> * <expr>
| (<expr>)
| <variable>
| <constant>

<variable> → x | y | z

<constant> → 0 | 1 | 2

Resolving Ambiguity in Expressions

- Different operators : ***precedence relation***
- Same operator : ***associativity relation***

5-2-3

5-2 - 3 5- 2-3

= 0 **= 6**

2**3**4

2^12 *2^81*

Left Associative ((5-2)-3) Right Associative (2**(3**4))

C++ Operator Precedence and Associativity

Level	Operator	Function
17R	::	global scope (unary)
17L	::	class scope (binary)
16L	-> , .	member selectors
16L	[]	array index
16L	()	function call
16L	()	type construction
15R	sizeof	size in bytes
15R	++ , --	increment, decrement
15R	~	bitwise NOT
15R	!	logical NOT
15R	+ , -	uniary minus, plus
15R	* , &	dereference, address-of
15R	()	type conversion (cast)
15R	new , delete	free store management
14L	->* , .*	member pointer select
13L	* , / , %	multiplicative operators

<table>
<tr><th>Level</th><th>Operator</th><th>Function</th></tr>
<tr><td>12L</td><td>+ , -</td><td>arithmetic operators</td></tr>
<tr><td>11L</td><td><< , >></td><td>bitwise shift</td></tr>
<tr><td>10L</td><td>< , <= , > , >=</td><td>relational operators</td></tr>
<tr><td>9L</td><td>== , !=</td><td>equaltity, inequality</td></tr>
<tr><td>8L</td><td>&</td><td>bitwise AND</td></tr>
<tr><td>7L</td><td>^</td><td>bitwise XOR</td></tr>
<tr><td>6L</td><td>|</td><td>bitwise OR</td></tr>
<tr><td>5L</td><td>&&</td><td>logical AND</td></tr>
<tr><td>4L</td><td>||</td><td>logical OR</td></tr>
<tr><td>3L</td><td>?:</td><td>arithmetic if</td></tr>
<tr><td>2R</td><td>= , *= , /= , %= , += , -=
<<= , >>= , &= , |= , ^=</td><td>assignment operators</td></tr>
<tr><td>1L</td><td>,</td><td>comma operator</td></tr>
</table>