Programming Languages and Compilers (CS 421)

Elsa L Gunter
2112 SC, UIUC

http://courses.engr.illinois.edu/cs421

Based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha
Three Main Topics of the Course

I. New Programming Paradigm

II. Language Translation

III. Language Semantics
II : Language Translation

Type Systems

Lexing and Parsing

Interpretation
Major Phases of a Compiler

Source Program

Lex

Tokens

Parse

Abstract Syntax

Semantic Analysis

Symbol Table

Translate

Intermediate Representation

Optimize

Optimized IR

Instruction Selection

Unoptimized Machine-Specific Assembly Language

Optimize

Optimized Machine-Specific Assembly Language

Emit code

Assembly Language

Assembler

Relocatable Object Code

Linker

Machine Code

Modified from “Modern Compiler Implementation in ML”, by Andrew Appel
Where We Are Going Next?

- We want to turn strings (code) into computer instructions
- Done in phases
- Turn strings into abstract syntax trees (parse)
- Translate abstract syntax trees into executable instructions (interpret or compile)
Meta-discourse

- Language Syntax and Semantics
- Syntax
  - Regular Expressions, DFSAs and NDFSAs
  - Grammars
- Semantics
  - Natural Semantics
  - Transition Semantics
Language Syntax

- Syntax is the description of which strings of symbols are meaningful expressions in a language.
- It takes more than syntax to understand a language; need meaning (semantics) too.
- Syntax is the entry point.
Syntax of English Language

- Pattern 1

<table>
<thead>
<tr>
<th>Subject</th>
<th>Verb</th>
</tr>
</thead>
<tbody>
<tr>
<td>David</td>
<td>sings</td>
</tr>
<tr>
<td>The dog</td>
<td>barked</td>
</tr>
<tr>
<td>Susan</td>
<td>yawned</td>
</tr>
</tbody>
</table>

- Pattern 2

<table>
<thead>
<tr>
<th>Subject</th>
<th>Verb</th>
<th>Direct Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>David</td>
<td>sings</td>
<td>ballads</td>
</tr>
<tr>
<td>The professor</td>
<td>wants</td>
<td>to retire</td>
</tr>
<tr>
<td>The jury</td>
<td>found</td>
<td>the defendant guilty</td>
</tr>
</tbody>
</table>
Elements of Syntax

- Character set – previously always ASCII, now often 64 character sets
- Keywords – usually reserved
- Special constants – cannot be assigned to
- Identifiers – can be assigned to
- Operator symbols
- Delimiters (parenthesis, braces, brackets)
- Blanks (aka white space)
Elements of Syntax

- Expressions
  
  \[
  \text{if} \ ... \ \text{then} \ \text{begin} \ ... \ ; \ ... \ \text{end} \ \text{else} \ \text{begin} \ ... \ ; \ ... \ \text{end}
  \]

- Type expressions
  
  \[
  \text{typexpr}_1 \rightarrow \ \text{typexpr}_2
  \]

- Declarations (in functional languages)
  
  \[
  \text{let} \ pattern = \ expr
  \]

- Statements (in imperative languages)
  
  \[
  a = b + c
  \]

- Subprograms
  
  \[
  \text{let} \ pattern_1 = \ expr_1 \ \text{in} \ expr
  \]
Elements of Syntax

- Modules
- Interfaces
- Classes (for object-oriented languages)
Lexing and Parsing

- Converting strings to abstract syntax trees done in two phases
  - **Lexing**: Converting string (or streams of characters) into lists (or streams) of tokens (the “words” of the language)
    - Specification Technique: Regular Expressions
  - **Parsing**: Convert a list of tokens into an abstract syntax tree
    - Specification Technique: BNF Grammars
Formal Language Descriptions

- Regular expressions, regular grammars, finite state automata
- Context-free grammars, BNF grammars, syntax diagrams
- Whole family more of grammars and automata – covered in automata theory
Grammars

- Grammars are formal descriptions of which strings over a given character set are in a particular language
- Language designers write grammar
- Language implementers use grammar to know what programs to accept
- Language users use grammar to know how to write legitimate programs
Regular Expressions - Review

- Start with a given character set – a, b, c...

- Each character is a regular expression
  - It represents the set of one string containing just that character
If $x$ and $y$ are regular expressions, then $xy$ is a regular expression

- It represents the set of all strings made from first a string described by $x$ then a string described by $y$

  If $x=\{a,ab\}$ and $y=\{c,d\}$ then $xy=\{ac,ad,abc,abd\}$.

If $x$ and $y$ are regular expressions, then $x \lor y$ is a regular expression

- It represents the set of strings described by either $x$ or $y$

  If $x=\{a,ab\}$ and $y=\{c,d\}$ then $x \lor y=\{a,ab,c,d\}$
Regular Expressions

- If $x$ is a regular expression, then so is $(x)$
  - It represents the same thing as $x$
- If $x$ is a regular expression, then so is $x^*$
  - It represents strings made from concatenating zero or more strings from $x$
    
    If $x = \{a, ab\}$ then $x^* = \{\text{“”}, a, ab, aa, aab, abab, \ldots\}$
- $\varepsilon$
  - It represents $\{\text{“”}\}$, set containing the empty string
- $\emptyset$
  - It represents $\{\}$, the empty set
Example Regular Expressions

- $(0\lor 1)^*1$
  - The set of all strings of 0’s and 1’s ending in 1, $\{1, 01, 11, \ldots\}$

- $a^*b(a^*)$
  - The set of all strings of a’s and b’s with exactly one b

- $((01) \lor (10))^*$
  - You tell me

- Regular expressions (equivalently, regular grammars) important for lexing, breaking strings into recognized words
Regular Grammars

- Subclass of BNF (covered in detail sool)
- Only rules of form
  \(<\text{nonterminal}> ::= <\text{terminal}> <\text{nonterminal}>\) or
  \(<\text{nonterminal}> ::= <\text{terminal}>\) or
  \(<\text{nonterminal}> ::= \varepsilon\)
- Defines same class of languages as regular expressions
- Important for writing lexers (programs that convert strings of characters into strings of tokens)
- Close connection to nondeterministic finite state automata – nonterminals \(\equiv\) states; rule \(\equiv\) edge
Example

- Regular grammar:
  \[
  \text{<Balanced>} ::= \varepsilon \\
  \text{<Balanced>} ::= 0\text{<OneAndMore>} \\
  \text{<Balanced>} ::= 1\text{<ZeroAndMore>} \\
  \text{<OneAndMore>} ::= 1\text{<Balanced}> \\
  \text{<ZeroAndMore>} ::= 0\text{<Balanced>}
  \]

- Generates even length strings where every initial substring of even length has same number of 0’s as 1’s
Example: Lexing

Regular expressions good for describing lexemes (words) in a programming language

- Identifier = \((a \lor b \lor ... \lor z \lor A \lor B \lor ... \lor Z) (a \lor b \lor ... \lor z \lor A \lor B \lor ... \lor Z \lor 0 \lor 1 \lor ... \lor 9)\)*
- Digit = \((0 \lor 1 \lor ... \lor 9)\)
- Number = \(0 \lor (1 \lor ... \lor 9)(0 \lor ... \lor 9)\)* \(\lor \sim (1 \lor ... \lor 9)(0 \lor ... \lor 9)\)*
- Keywords: if = if, while = while,...
Implementing Regular Expressions

- Regular expressions reasonable way to generate strings in language
- Not so good for recognizing when a string is in language
- Problems with Regular Expressions
  - which option to choose,
  - how many repetitions to make
- Answer: finite state automata
- Should have seen in CS374
Lexing

Different syntactic categories of “words”: tokens

Example:

Convert sequence of characters into sequence of strings, integers, and floating point numbers.

"asd 123 jkl 3.14" will become:

[String "asd"; Int 123; String "jkl"; Float 3.14]
Lex, ocamllex

- Could write the reg exp, then translate to DFA by hand
  - A lot of work
- Better: Write program to take reg exp as input and automatically generates automata
- Lex is such a program
- ocamllex version for ocaml
How to do it

To use regular expressions to parse our input we need:

- Some way to identify the input string — call it a lexing buffer
- Set of regular expressions,
- Corresponding set of actions to take when they are matched.
How to do it

- The lexer will take the regular expressions and generate a state machine.
- The state machine will take our lexing buffer and apply the transitions...
- If we reach an accepting state from which we can go no further, the machine will perform the appropriate action.
Mechanics

- Put table of reg exp and corresponding actions (written in ocaml) into a file `<filename>.mll`

- Call
  
  `ocamllex <filename>.mll`

- Produces Ocaml code for a lexical analyzer in file `<filename>.ml`
Sample Input

rule main = parse
['0'-'9']* { print_string "Int\n"}
| ['0'-'9']+'.'['0'-'9']* { print_string "Float\n"}
| ['a'-'z']* { print_string "String\n"}
| _ { main lexbuf }
{
let newlexbuf = (Lexing.from_channel stdin) in
print_string "Ready to lex.\n"
main newlexbuf
}
General Input

{ header }

let ident = regexp ...

rule entrypoint [arg1... argn] = parse
    regexp { action }
    | ...
    | ...
    | regexp { action }

and entrypoint [arg1... argn] = parse ...and ...

{ trailer }
Ocamllex Input

- *header* and *trailer* contain arbitrary ocaml code put at top and bottom of `<filename>.ml`

- let *ident* = *regexp* ... Introduces *ident* for use in later regular expressions
Ocamlllex Input

- `<filename>.ml` contains one lexing function per `entrypoint`
  - Name of function is name given for `entrypoint`
  - Each entry point becomes an Ocaml function that takes \( n+1 \) arguments, the extra implicit last argument being of type `Lexing.lexbuf`
- `arg1... argn` are for use in `action`
Ocamllex Regular Expression

- Single quoted characters for letters: ‘a’
- _: (underscore) matches any letter
- Eof: special “end_of_file” marker
- Concatenation same as usual
- “string”: concatenation of sequence of characters
- \( e_1 / e_2 \): choice - what was \( e_1 \lor e_2 \)
Ocamllex Regular Expression

- \([c_1 - c_2]\): choice of any character between first and second inclusive, as determined by character codes
- \([^c_1 - c_2]\): choice of any character NOT in set
- \(e^*\): same as before
- \(e+\): same as \(e \ e^*\)
- \(e?\): option - was \(e_1 \lor \epsilon\)
Ocamllex Regular Expression

- $e_1 \# e_2$: the characters in $e_1$ but not in $e_2$; $e_1$ and $e_2$ must describe just sets of characters

- **ident**: abbreviation for earlier reg exp in
  
  ```
  let ident = regexp
  ```

- $e_1$ as **id**: binds the result of $e_1$ to **id** to be used in the associated **action**
More details can be found at

http://caml.inria.fr/pub/docs/manual-ocaml/lexyacc.html
Example: test.mll

```ml
{ type result = Int of int | Float of float | String of string }  
let digit = ['0'-'9']  
let digits = digit +  
let lower_case = ['a'-'z']  
let upper_case = ['A'-'Z']  
let letter = upper_case | lower_case  
let letters = letter +  
```
Example: test.mll

rule main = parse
    (digits)'.digits as f { Float (float_of_string f) }
| digits as n { Int (int_of_string n) }
| letters as s { String s }
| _ { main lexbuf }
{ let newlexbuf = (Lexing.from_channel stdin) in
print_string "Ready to lex."
print_newline ()
main newlexbuf }
Example

```ocaml
# use "test.ml";;
...
val main : Lexing.lexbuf -> result = <fun>
val __ocaml_lex_main_rec : Lexing.lexbuf -> int ->
    result = <fun>

Ready to lex.

hi there 234 5.2
- : result = String "hi"

What happened to the rest?!?!
Example

# let b = Lexing.from_channel stdin;;
# main b;;
hi 673 there
- : result = String "hi"
# main b;;
- : result = Int 673
# main b;;
- : result = String "there"
Your Turn

- Work on MP4
  - Add a few keywords
  - Implement booleans and unit
  - Implement Ints and Floats
  - Implement identifiers
Problem

- How to get lexer to look at more than the first token at one time?

- **Answer**: *action* has to tell it to -- recursive calls

- Side Benefit: can add “state” into lexing

- Note: already used this with the `_` case
Example

rule main = parse
  (digits) '.' digits as f { Float
    (float_of_string f) :: main lexbuf}
| digits as n          { Int (int_of_string n) ::
  main lexbuf }
| letters as s         { String s :: main
  lexbuf}
| eof                   { [] }
| _                     { main lexbuf }
Example Results

Ready to lex.

hi there 234 5.2

- : result list = [String "hi"; String "there"; Int 234; Float 5.2]

#

Used Ctrl-d to send the end-of-file signal
Dealing with comments

First Attempt

let open_comment = "(*"
let close_comment = "*)"

rule main = parse
    (digits) '.' digits as f { Float (float_of_string f) :: main lexbuf}
| digits as n { Int (int_of_string n) :: main lexbuf }
| letters as s { String s :: main lexbuf}
Dealing with comments

| open_comment       | { comment lexbuf}
|--------------------|-------------------
| eof                | { [] }            |
| _                  | { main lexbuf }   |

and comment = parse

    close_comment   | { main lexbuf }
| _                 | { comment lexbuf } |
Dealing with nested comments

rule main = parse ...
| open_comment { comment 1 lexbuf}
| eof { [] }
| _ { main lexbuf }
and comment depth = parse
  open_comment { comment (depth+1) lexbuf }
| close_comment { if depth = 1
    then main lexbuf
    else comment (depth - 1) lexbuf }
| _ { comment depth lexbuf }
Dealing with nested comments

rule main = parse
  (digits) '!' digits as f { Float (float_of_string f) ::
  main lexbuf}
| digits as n       { Int (int_of_string n) :: main lexbuf }
| letters as s      { String s :: main lexbuf}
| open_comment      { (comment 1 lexbuf}
| eof                { [] } }
| _ { main lexbuf }}
Dealing with nested comments

and comment depth = parse

  open_comment      { comment (depth+1) lexbuf }

| close_comment     { if depth = 1
|                  then main lexbuf
                  else comment (depth - 1) lexbuf }

| _                  { comment depth lexbuf }
Types of Formal Language Descriptions

- Regular expressions, regular grammars
- Context-free grammars, BNF grammars, syntax diagrams
- Finite state automata

- Whole family more of grammars and automata – covered in automata theory
Sample Grammar

- Language: Parenthesized sums of 0’s and 1’s

- \(<\text{Sum}> ::= 0\)
- \(<\text{Sum}> ::= 1\)
- \(<\text{Sum}> ::= <\text{Sum}> + <\text{Sum}>\)
- \(<\text{Sum}> ::= (<\text{Sum}>))\)
BNF Grammars

- Start with a set of characters, $a, b, c, \ldots$
  - We call these *terminals*
- Add a set of different characters, $X, Y, Z, \ldots$
  - We call these *nonterminals*
- One special nonterminal $S$ called *start symbol*
BNF Grammars

- BNF rules (aka *productions*) have form
  \[ X ::= y \]
  where \( X \) is any nonterminal and \( y \) is a string of terminals and nonterminals

- BNF *grammar* is a set of BNF rules such that every nonterminal appears on the left of some rule
Sample Grammar

- Terminals: 0 1 + ( )
- Nonterminals: <Sum>
- Start symbol = <Sum>

- <Sum> ::= 0
- <Sum> ::= 1
- <Sum> ::= <Sum> + <Sum>
- <Sum> ::= (<Sum>)

Can be abbreviated as
- <Sum> ::= 0 | 1 | <Sum> + <Sum> | (<Sum>)
BNF Derivations

- Given rules
  \[ X ::= yZw \text{ and } Z ::= v \]
  we may replace \( Z \) by \( v \) to say
  \[ X \Rightarrow yZw \Rightarrow yvw \]

- Sequence of such replacements called *derivation*

- Derivation called *right-most* if always replace the right-most non-terminal
BNF Derivations

Start with the start symbol:

<Sum> =>
BNF Derivations

- Pick a non-terminal

<Sum> =>
BNF Derivations

- Pick a rule and substitute:
  - <Sum> ::= <Sum> + <Sum>

  <Sum> => <Sum> + <Sum>
  <Sum> => <Sum> + <Sum>
BNF Derivations

- Pick a non-terminal:

\[ \langle \text{Sum} \rangle \implies \langle \text{Sum} \rangle + \langle \text{Sum} \rangle \]
BNF Derivations

- Pick a rule and substitute:
  - `<Sum> ::= ( <Sum> )`

  `<Sum> => <Sum> + <Sum>`

  `=> ( <Sum> ) + <Sum>`
Pick a non-terminal:

<Sum> => <Sum> + <Sum>
=> ( <Sum> ) + <Sum>
BNF Derivations

- Pick a rule and substitute:
  - `<Sum> ::= <Sum> + <Sum>`
  - `<Sum> => <Sum> + <Sum>`
  - `=> ( <Sum> ) + <Sum>`
  - `=> ( <Sum> + <Sum> ) + <Sum>`
BNF Derivations

- Pick a non-terminal:

\[ <\text{Sum}> \Rightarrow <\text{Sum}> + <\text{Sum}> \]
\[ \Rightarrow ( <\text{Sum}> ) + <\text{Sum}> \]
\[ \Rightarrow ( <\text{Sum}> + <\text{Sum}> ) + <\text{Sum}> \]
BNF Derivations

- Pick a rule and substitute:
  - `<Sum>` ::= 1

`<Sum>` => `<Sum>` + `<Sum>`

=> ( `<Sum>` ) + `<Sum>`

=> ( `<Sum>` + `<Sum>` ) + `<Sum>`

=> ( `<Sum>` + 1 ) + `<Sum>`
BNF Derivations

- Pick a non-terminal:

\[ <\text{Sum}> \Rightarrow <\text{Sum}> + <\text{Sum}> \]
\[ \Rightarrow ( <\text{Sum}> ) + <\text{Sum}> \]
\[ \Rightarrow ( <\text{Sum}> + <\text{Sum}> ) + <\text{Sum}> \]
\[ \Rightarrow ( <\text{Sum}> + 1 ) + <\text{Sum}> \]
BNF Derivations

- Pick a rule and substitute:
  - \(<\text{Sum} \>): ::= 0

\(<\text{Sum} \> \) => \(<\text{Sum} \> + \,<\text{Sum} \>

=> ( \(<\text{Sum} \> \) ) + \,<\text{Sum} \>

=> ( \(<\text{Sum} \> + \,<\text{Sum} \>) \) + \,<\text{Sum} \>

=> ( \(<\text{Sum} \> + 1 \) ) + \,<\text{Sum} \>

=> ( \(<\text{Sum} \> + 1 \) ) + 0
BNF Derivations

- Pick a non-terminal:

\[ \text{<Sum>} \Rightarrow \text{<Sum>} + \text{<Sum>} \]
\[ \Rightarrow ( \text{<Sum>} ) + \text{<Sum>} \]
\[ \Rightarrow ( \text{<Sum>} + \text{<Sum>} ) + \text{<Sum>} \]
\[ \Rightarrow ( \text{<Sum>} + 1 ) + \text{<Sum>} \]
\[ \Rightarrow ( \text{<Sum>} + 1 ) + 0 \]
BNF Derivations

- Pick a rule and substitute
  - \(<\text{Sum}\> \ ::= \ 0\)

\(<\text{Sum}\> \Rightarrow \ <\text{Sum}\> \ + \ <\text{Sum}\> \\
= \Rightarrow (\ <\text{Sum}\> ) \ + \ <\text{Sum}\> \\
= \Rightarrow (\ <\text{Sum}\> + <\text{Sum}\> ) \ + \ <\text{Sum}\> \\
= \Rightarrow (\ <\text{Sum}\> + 1 ) \ + \ <\text{Sum}\> \\
= \Rightarrow (\ <\text{Sum}\> + 1 )\ 0 \\
= \Rightarrow (\ 0 + 1 ) \ + \ 0 \)
BNF Derivations

(0 + 1) + 0 is generated by grammar

<Sum> => <Sum> + <Sum>
=> ( <Sum> ) + <Sum>
=> ( ( <Sum> + <Sum> ) ) + <Sum>
=> ( <Sum> + 1 ) + <Sum>
=> ( <Sum> + 1 ) + 0
=> ( 0 + 1 ) + 0
<Sum> ::= 0 | 1 | <Sum> + <Sum> | (<Sum>)