Programming Languages and Compilers (CS 421)

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Based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha

Programming Languages & Compilers

Three Main Topics of the Course

I

New Programming Paradigm

II

Language Translation

III

Language Semantics

Programming Languages & Compilers

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

Subject	Verb
David	*sings*
The dog	*barked*
Susan	*yawned*

- Pattern 2

Subject	Verb	Direct Object
David	*sings*	*ballads*
The professor	*wants*	*to retire*
The jury	*found*	*the defendant guilty*

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

  if ... then begin ... ; ... end else begin ... ; ... end

- Type expressions

  $typexpr_1$ -> $typexpr_2$

- Declarations (in functional languages)

  let *pattern* = *expr*

- Statements (in imperative languages)

  a = b + c

- Subprograms

  let $pattern_1$ = $expr_1$ 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**…
- $L(\boldsymbol{\varepsilon}) = \{\text{“”}\}$
- Each character is a regular expression
  - It represents the set of one string containing just that character
  - $L(\mathbf{a}) = \{a\}$

Regular Expressions

- 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 $L(x)$={a,ab} and $L(y)$={c,d}

then $L(xy)$ ={ac,ad,abc,abd}

Regular Expressions

- If **x** and **y** are regular expressions, then **x∨y** is a regular expression
  - It represents the set of strings described by either **x** or **y**

    If $\mathcal{L}(x)=\{a,ab\}$ and $\mathcal{L}(y)=\{c,d\}$

    then $\mathcal{L}(x \vee y)=\{a,ab,c,d\}$

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 L(x) = {a,ab} then L(x*) ={“”,a,ab,aa,aab,abab,…}
- ε
  - It represents {“”}, set containing the empty string
- Φ
  - It represents { }, the empty set

Example Regular Expressions

- **(0$\vee$1)*1**
  - The set of all strings of **0**'s and **1**'s ending in 1, **{1, 01, 11,…}**
- **a*b(a*)**
  - The set of all strings of a's and b's with exactly one b
- **((01) $\vee$(10))***
  - You tell me
- Regular expressions (equivalently, regular grammars) important for lexing, breaking strings into recognized words

Right Regular Grammars

- Subclass of BNF (covered in detail sool)
- Only rules of form
  <nonterminal>::=<terminal><nonterminal> or
  <nonterminal>::=<terminal> or
  <nonterminal>::=ε
- 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 $\cong$ states; rule $\cong$ edge

Example

- Right regular grammar:
  <Balanced> ::= ε
  <Balanced> ::= 0<OneAndMore>
  <Balanced> ::= 1<ZeroAndMore>
  <OneAndMore> ::= 1<Balanced>
  <ZeroAndMore> ::= 0<Balanced>
- Generates even length strings where every initial substring of even length has same number of 0's as 1's

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

Example: Lexing

- Regular expressions good for describing lexemes (words) in a programming language
  - Identifier = (a $\vee$ b $\vee$ … $\vee$ z $\vee$ A $\vee$ B $\vee$ … $\vee$ Z) (a $\vee$ b $\vee$ … $\vee$ z $\vee$ A $\vee$ B $\vee$ … $\vee$ Z $\vee$ 0 $\vee$ 1 $\vee$ … $\vee$ 9)*
  - Digit = (0 $\vee$ 1 $\vee$ … $\vee$ 9)
  - Number = 0 $\vee$ (1 $\vee$ … $\vee$ 9)(0 $\vee$ … $\vee$ 9)* $\vee$ ~ (1 $\vee$ … $\vee$ 9)(0 $\vee$ … $\vee$ 9)*
  - Keywords: if = if, while = while,…

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
 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 an bottom of *<filename>*.ml

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

Ocamllex 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*... a*rgn* 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 $e_1 \vee e_2$

Ocamllex Regular Expression

- $[c_1 - c_2]$: choice of any character between first and second inclusive, as determined by character codes
- $[\wedge c_1 - c_2]$: choice of any character NOT in set
- $e*$: same as before
- $e+$: same as $e\ e*$
- $e?$: option - was $e \vee \varepsilon$

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*

Ocamllex Manual

- More details can be found at

Version for ocaml 4.07:

https://v2.ocaml.org/releases/4.07/htmlman/lexyacc.html

Current version (ocaml 4.14)

https://v2.ocaml.org/releases/4.14/htmlman/lexyacc.html

(same, except formatting, I think)

Example : test.mll

```
{ 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_newline ();
 main newlexbuf  }
```

Example

#use "test.ml";;

…

val main : Lexing.lexbuf -> result = <fun>

val __ocaml_lex_main_rec : Lexing.lexbuf -> int -> result = <fun>

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 MP8
  - 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
  - Not what you want to sew this together with ocamlyacc
- 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

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

Sample Grammar

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

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

BNF Grammars

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

BNF Grammars

- BNF rules (aka *productions*) have form

$$\mathbf{X} ::= y$$

  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 Deriviations

- Given rules

$$\mathbf{X}::= y\mathbf{Z}w \text{ and } \mathbf{Z}::=v$$

we may replace **Z** by *v* to say

$$\mathbf{X} => y\mathbf{Z}w => yvw$$

- 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 >

BNF Derivations

- Pick a non-terminal:

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

BNF Derivations

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

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

=> (<Sum>) + <Sum>

BNF Derivations

- 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:

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

=> (<Sum>) + <Sum>

=> (<Sum> + <Sum>) + <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:

<Sum> => <Sum> + <Sum >
=> (<Sum>) + <Sum>
=> (<Sum> + <Sum>) + <Sum>
=> (<Sum> + 1) + <Sum>

BNF Derivations

- Pick a rule and substitute:
  - <Sum >::= 0

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

=> (<Sum>) + <Sum>

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

=> (<Sum> + 1) + <Sum>

=> (<Sum> + 1) + 0

BNF Derivations

- Pick a non-terminal:

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

BNF Derivations

- Pick a rule and substitute
  - <Sum> ::= 0

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

BNF Derivations

- Pick a non-terminal:

<Sum> => <Sum> + <Sum >
=> (<Sum>) + <Sum>
=> (<Sum> + <Sum>) + <Sum>
=> (<Sum> + 1) + <Sum>