Programming Languages and Compilers (CS 421)

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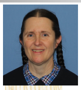

https://courses.engr.illinois.edu/cs421/sp2023

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

EOH!

- Engineering Open House is Friday and Saturday
- They are taking this room

- On Friday only, we will meet in Zoom only:
- **Zoom Info:**Meeting Id: 838 6324 1301
  Passcode: cs421
  URL: https://illinois.zoom.us/j/83863241301?pwd=U2dtRm9RUmhVQUw4d3dFOVJxNHY4UT09

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"
```

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

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*

Sample Grammar

- Language: Parenthesized sums of 0's and 1's
- <Sum> ::= 0
- <Sum >::= 1
- <Sum> ::= <Sum> + <Sum>
- <Sum> ::= (<Sum>)

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 ::= *y* **Z** *w* and **Z** ::= *v*

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

X => *y* **Z** *w* => *y v w*

- Sequence of such replacements called *derivation*
- Derivation called *right-most* if always replace the right-most non-terminal

BNF Semantics

- The meaning of a BNF grammar is the set of all strings consisting only of terminals that can be derived from the Start symbol

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

Extended BNF Grammars

- Alternatives: allow rules of from $X::=y \mid z$
  - Abbreviates $X::= y$, $X::= z$
- Options: $X::=y\,[v]\,z$
  - Abbreviates $X::=y\,v\,z$, $X::=y\,z$
- Repetition: $X::=y\,\{v\}^*\,z$
  - Can be eliminated by adding new nonterminal V and rules $X::=y\,z$, $X::=y\,V\,z$, $V::=v$, $V::=v\,V$

Parse Trees

- Graphical representation of derivation
- Each node labeled with either non-terminal or terminal
- If node is labeled with a terminal, then it is a leaf (no sub-trees)
- If node is labeled with a non-terminal, then it has one branch for each character in the right-hand side of rule used to substitute for it

Example

- Consider grammar:

  <exp> ::= <factor>
  | <factor> + <factor>
  <factor> ::= <bin>
  | <bin> * <exp>
  <bin> ::= 0 | 1

- Problem: Build parse tree for 1 * 1 + 0 as an <exp>

Example cont.

- 1 * 1 + 0: <exp>

<exp> is the start symbol for this parse tree

Example cont.

- 1 * 1 + 0: <exp>
  <factor>

Use rule: <exp> ::= <factor>

Example cont.

- 1 * 1 + 0: <exp>
  <factor>
  <bin> * <exp>

Use rule: <factor> ::= <bin> * <exp>

Example cont.

- 1 * 1 + 0: <exp>
  <factor>
  <bin> * <exp>
  1 <factor> + <factor>

Use rules: <bin> ::= 1 and
<exp> ::= <factor> + <factor>

Example cont.

- 1 * 1 + 0: <exp>

```
            <exp>
              |
           <factor>
         /    |     \
    <bin>     *      <exp>
      |            /   |   \
      1     <factor>   +   <factor>
                |             |
              <bin>         <bin>
```

Use rule: <factor> ::= <bin>

Example cont.

- 1 * 1 + 0: <exp>

```
            <exp>
              |
           <factor>
         /    |     \
    <bin>     *      <exp>
      |            /   |   \
      1     <factor>   +   <factor>
                |             |
              <bin>         <bin>
                |             |
                1             0
```

Use rules: <bin> ::= 1 | 0

Example cont.

- 1 * 1 + 0: <exp>

```
            <exp>
              |
           <factor>
         /    |     \
    <bin>     *      <exp>
      |            /   |   \
      1     <factor>   +   <factor>
                |             |
              <bin>         <bin>
                |             |
                1             0
```

Fringe of tree is string generated by grammar

Your Turn: 1 * 0 + 0 * 1

```
              <exp>
            /   |   \
      <fact>    +    <fact>
     /  |  \        /  |  \
  <b>   *  <e>   <b>   *  <e>
```