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

Ocamlyacc Input

- File format:

%{
 <header>
%}
 <declarations>
%%
 <rules>
%%
 <trailer>

Ocamlyacc *<header>*

- Contains arbitrary Ocaml code
- Typically used to give types and functions needed for the semantic actions of rules and to give specialized error recovery
- May be omitted
- *<footer>* similar. Possibly used to call parser

Ocamlyacc <declarations>

- %token *symbol … symbol*
- Declare given symbols as tokens
- %token *<type> symbol … symbol*
- Declare given symbols as token constructors, taking an argument of type *<type>*
- %start *symbol … symbol*
- Declare given symbols as entry points; functions of same names in *<grammar>*.ml

Ocamlyacc *<declarations>*

- %type *<type> symbol … symbol*

  Specify type of attributes for given symbols. Mandatory for start symbols
- %left *symbol … symbol*
- %right *symbol … symbol*
- %nonassoc *symbol … symbol*

  Associate precedence and associativity to given symbols. Same line,same precedence; earlier line, lower precedence (broadest scope)

Ocamlyacc *<rules>*

- *nonterminal* :
  symbol ... symbol { *semantic_action* }
  | ...
  | *symbol ... symbol* { *semantic_action* }
  ;
- Semantic actions are arbitrary Ocaml expressions
- Must be of same type as declared (or inferred) for *nonterminal*
- Access semantic attributes (values) of symbols by position: $1 for first symbol, $2 to second …

Example - Base types

```
(* File: expr.ml *)
type expr =
    Term_as_Expr of term
  | Plus_Expr of (term * expr)
  | Minus_Expr of (term * expr)
and term =
    Factor_as_Term of factor
  | Mult_Term of (factor * term)
  | Div_Term of (factor * term)
and factor =
    Id_as_Factor of string
  | Parenthesized_Expr_as_Factor of expr
```


Example - Lexer (exprlex.mll)

```
{ (*open Exprparse*) }
let numeric = ['0' - '9']
let letter =['a' - 'z' 'A' - 'Z']
rule token = parse
  | "+" {Plus_token}
  | "-"  {Minus_token}
  | "*"  {Times_token}
  | "/"  {Divide_token}
  | "("  {Left_parenthesis}
  | ")"  {Right_parenthesis}
  | letter (letter|numeric|"_")* as id  {Id_token id}
  | [' ' '\t' '\n'] {token lexbuf}
  | eof {EOL}
```


Example - Parser (exprparse.mly)

```
%{ open Expr
%}
%token <string> Id_token
%token Left_parenthesis Right_parenthesis
%token Times_token Divide_token
%token Plus_token Minus_token
%token EOL
%start main
%type <expr> main
%%
```


Example - Parser (exprparse.mly)

```
expr:
   term
       { Term_as_Expr $1 }
 | term Plus_token expr
       { Plus_Expr ($1, $3) }
 | term Minus_token expr
       { Minus_Expr ($1, $3) }
```


Example - Parser (exprparse.mly)

```
term:
   factor
       { Factor_as_Term $1 }
 | factor Times_token term
       { Mult_Term ($1, $3) }
 | factor Divide_token term
       { Div_Term ($1, $3) }
```


Example - Parser (exprparse.mly)

```
factor:
   Id_token
       { Id_as_Factor $1 }
 | Left_parenthesis expr Right_parenthesis
       {Parenthesized_Expr_as_Factor $2 }
main:
 | expr EOL
       { $1 }
```

Example - Using Parser

```
# #use "expr.ml";;
…
# #use "exprparse.ml";;
…
# #use "exprlex.ml";;
…
# let test s =
  let lexbuf = Lexing.from_string (s^"\n") in
      main token lexbuf;;
```


Example - Using Parser

```
# test "a + b";;
- : expr =
Plus_Expr
 (Factor_as_Term (Id_as_Factor "a"),
  Term_as_Expr (Factor_as_Term
   (Id_as_Factor "b")))
```


Ambiguous Grammars and Languages

- A BNF grammar is *ambiguous* if its language contains strings for which there is more than one parse tree
- If all BNF's for a language are ambiguous then the language is *inherently ambiguous*
- Your job: *disambiguate given grammar*
  - Write a new grammar that is **not** ambiguous that generates the **same** language

Two Major Sources of Ambiguity

- Lack of determination of operator precedence
- Lack of determination of operator assoicativity
- Not the only sources of ambiguity

How to Enforce Associativity

- Have at most one recursive call per production
- When two or more recursive calls would be natural leave right-most one for right assoicativity, left-most one for left assoiciativity

Example

- <Sum> ::= 0 | 1 | <Sum> + <Sum>
| (<Sum>)
- Becomes
  - <Sum> ::= <Num> | <Num> + <Sum>
  - <Num> ::= 0 | 1 | (<Sum>)

Operator Precedence

- Operators of highest precedence evaluated first (bind more tightly).
- Precedence for infix binary operators given in following table
- Needs to be reflected in grammar

Predence in Grammar

- Higher precedence translates to longer derivation chain
- Example:

<exp> ::= <id> | <exp> + <exp>
| <exp> * <exp>

- Becomes

<exp> ::= <mult_exp>
| <exp> + <mult_exp>
<mult_exp> ::= <id> | <mult_exp> * <id>

Recursive Descent Parsing

- Recursive descent parsers are a class of parsers derived fairly directly from BNF grammars
- A recursive descent parser traces out a parse tree in top-down order, corresponding to a left-most derivation (LL - left-to-right scanning, leftmost derivation)

Recursive Descent Parsing

- Each nonterminal in the grammar has a subprogram associated with it; the subprogram parses all phrases that the nonterminal can generate
- Each nonterminal in right-hand side of a rule corresponds to a recursive call to the associated subprogram

Recursive Descent Parsing

- Each subprogram must be able to decide how to begin parsing by looking at the left-most character in the string to be parsed
  - May do so directly, or indirectly by calling another parsing subprogram
- Recursive descent parsers, like other top-down parsers, cannot be built from left-recursive grammars
  - Sometimes can modify grammar to suit

Sample Grammar

<expr> ::= <term> | <term> + <expr>
| <term> - <expr>

<term> ::= <factor> | <factor> * <term>
| <factor> / <term>

<factor> ::= <id> | (<expr>)

Tokens as OCaml Types

- <+ - * / ( ) <id>
- Becomes an OCaml datatype

```
type token =
    Id_token of string
  | Left_parenthesis | Right_parenthesis
  | Times_token | Divide_token
  | Plus_token | Minus_token
```


Parse Trees as Datatypes

<expr> ::= <term> | <term> + <expr>
| <term> - <expr>

```
type expr =
    Term_as_Expr of term
  | Plus_Expr of (term * expr)
  | Minus_Expr of (term * expr)
```


Parse Trees as Datatypes

<term> ::= <factor> | <factor> * <term>
| <factor> / <term>

```
and term =
    Factor_as_Term of factor
  | Mult_Term of (factor * term)
  | Div_Term of (factor * term)
```


Parse Trees as Datatypes

<factor> ::= <id> | (<expr>)

```
and factor =
    Id_as_Factor of string
  | Parenthesized_Expr_as_Factor of expr
```


Parsing Lists of Tokens

- Will create three mutually recursive functions:
  - expr : token list -> (expr * token list)
  - term : token list -> (term * token list)
  - factor : token list -> (factor * token list)
- Each parses what it can and gives back parse and remaining tokens

Parsing an Expression

<expr> ::= <term> [(+ | -) <expr>]

```
let rec expr tokens =
  (match term tokens
   with ( term_parse , tokens_after_term) ->
    (match tokens_after_term
     with( Plus_token  :: tokens_after_plus) ->
```

Parsing an Expression

<expr> ::= <term> [(+ | -) <expr>]

let rec expr tokens =
  (match term tokens
    with (term_parse , tokens_after_term) ->
      (match tokens_after_term
        with (Plus_token :: tokens_after_plus) ->

Parsing a Plus Expression

<expr> ::= <term> [(+ | -) <expr>]

let rec expr tokens =
  (match term tokens
    with (term_parse , tokens_after_term) ->
      (match tokens_after_term
        with (Plus_token :: tokens_after_plus) ->

Parsing a Plus Expression

<expr> ::= <term> [(+ | -) <expr>]

let rec expr tokens =
  (match term tokens
    with (term_parse , tokens_after_term) ->
      (match tokens_after_term
        with (Plus_token :: tokens_after_plus) ->

Parsing a Plus Expression

<expr> ::= <term> [(+ | -) <expr>]

let rec expr tokens =
  (match term tokens
    with (term_parse , tokens_after_term) ->
      (match tokens_after_term
        with (Plus_token :: tokens_after_plus) ->

Parsing a Plus Expression

<expr> ::= <term> + <expr>

  (match expr tokens_after_plus
    with (expr_parse , tokens_after_expr) ->
    (Plus_Expr (term_parse , expr_parse),
    tokens_after_expr))

Parsing a Plus Expression

<expr> ::= <term> + <expr>

(match expr tokens_after_plus
    with (expr_parse , tokens_after_expr) ->
    (Plus_Expr (term_parse , expr_parse),
    tokens_after_expr))

Building Plus Expression Parse Tree

<expr> ::= <term> + <expr>

```
(match expr tokens_after_plus
   with ( expr_parse , tokens_after_expr) ->
  ( Plus_Expr ( term_parse , expr_parse ),
   tokens_after_expr))
```


Parsing a Minus Expression

<expr> ::= <term> - <expr>

```
| ( Minus_token :: tokens_after_minus) ->
   (match expr tokens_after_minus
   with ( expr_parse , tokens_after_expr) ->
  ( Minus_Expr ( term_parse , expr_parse ),
   tokens_after_expr))
```


Parsing a Minus Expression

<expr> ::= <term> - <expr>

```
| ( Minus_token :: tokens_after_minus) ->
   (match expr tokens_after_minus
   with ( expr_parse , tokens_after_expr) ->
  ( Minus_Expr ( term_parse , expr_parse ),
   tokens_after_expr))
```


Parsing an Expression as a Term

<expr> ::= <term>

```
| _ -> (Term_as_Expr term_parse ,
  tokens_after_term)))
```

- Code for **term** is same except for replacing addition with multiplication and subtraction with division

Parsing Factor as Id

<factor> ::= <id>

```
and factor tokens =
 (match tokens
  with (Id_token id_name :: tokens_after_id) =
  ( Id_as_Factor id_name, tokens_after_id)
```


Parsing Factor as Parenthesized Expression

<factor> ::= (<expr>)

```
| factor ( Left_parenthesis :: tokens) =
   (match expr tokens
    with ( expr_parse , tokens_after_expr) ->
```

Parsing Factor as Parenthesized Expression

<factor> ::= (<expr>)

(match tokens_after_expr

with Right_parenthesis :: tokens_after_rparen ->

(Parenthesized_Expr_as_Factor expr_parse ,
tokens_after_rparen)

Error Cases

- What if no matching right parenthesis?

  | _ -> raise (Failure "No matching rparen")))

- What if no leading id or left parenthesis?

  | _ -> raise (Failure "No id or lparen"));;

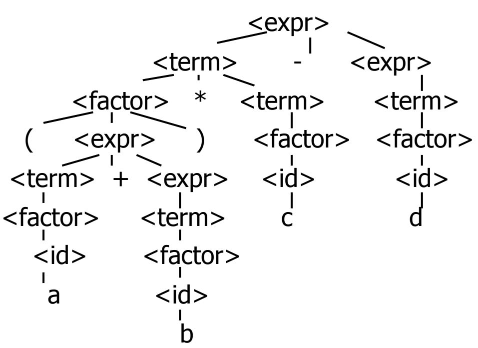
(a + b) * c - d

expr [Left_parenthesis; Id_token "a”;
Plus_token; Id_token "b”;
Right_parenthesis; Times_token;
Id_token "c”; Minus_token;
Id_token "d"];;

(a + b) * c - d

```
- : expr * token list =
(Minus_Expr
 (Mult_Term
  (Parenthesized_Expr_as_Factor
   (Plus_Expr
    (Factor_as_Term (Id_as_Factor "a"),
     Term_as_Expr (Factor_as_Term
 (Id_as_Factor "b")))),
   Factor_as_Term (Id_as_Factor "c")),
  Term_as_Expr (Factor_as_Term (Id_as_Factor
  "d"))),
 [])
```

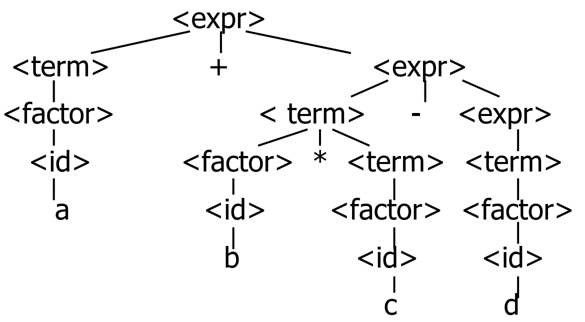

(a + b) * c – d



a + b * c – d

```
# expr [Id_token "a”; Plus_token; Id_token "b”;
  Times_token; Id_token "c”; Minus_token;
     Id_token "d"];;
- : expr * token list =
(Plus_Expr
 (Factor_as_Term (Id_as_Factor "a"),
  Minus_Expr
   (Mult_Term (Id_as_Factor "b", Factor_as_Term
 (Id_as_Factor "c")),
    Term_as_Expr (Factor_as_Term (Id_as_Factor
 "d")))),
 [])
```

a + b * c – d



(a + b * c - d

expr [Left_parenthesis; Id_token "a"; Plus_token; Id_token "b"; Times_token; Id_token "c"; Minus_token; Id_token "d"];;

Exception: Failure "No matching rparen".

Can't parse because it was expecting a right parenthesis but it got to the end without finding one

a + b) * c - d *)

expr [Id_token "a"; Plus_token; Id_token "b"; Right_parenthesis; Times_token; Id_token "c"; Minus_token; Id_token "d"];;

- : expr * token list =

(Plus_Expr

(Factor_as_Term (Id_as_Factor "a"),

Term_as_Expr (Factor_as_Term (Id_as_Factor "b"))),

[Right_parenthesis; Times_token; Id_token "c"; Minus_token; Id_token "d"])

Parsing Whole String

- Q: How to guarantee whole string parses?
- A: Check returned tokens empty

```
let parse tokens =
   match expr tokens
    with (expr_parse, []) -> expr_parse
    | _ -> raise (Failure "No parse");;
```

- Fixes <expr> as start symbol

Streams in Place of Lists

- More realistically, we don't want to create the entire list of tokens before we can start parsing
- We want to generate one token at a time and use it to make one step in parsing
- Will use (token * (unit -> token)) or (token * (unit -> token option))

  in place of token list

Problems for Recursive-Descent Parsing

- Left Recursion:

  A ::= Aw

  translates to a subroutine that loops forever
- Indirect Left Recursion:

  A ::= Bw

  B ::= Av

  causes the same problem

Problems for Recursive-Descent Parsing

- Parser must always be able to choose the next action based only only the very next token
- Pairwise Disjointedness Test: Can we always determine which rule (in the non-extended BNF) to choose based on just the first token

Pairwise Disjointedness Test

- For each rule
  A ::= *y*

Calculate

FIRST (*y*) =

{a | *y* =>* a*w*} ∪ {ε | if y =>* ε}

- For each pair of rules A ::= *y* and A ::= *z*, require FIRST(*y*) ∩ FIRST(*z*) = { }

Example

Grammar:

<S> ::= <A> a <B> b

<A> ::= <A> b | b

<B> ::= a <B> | a

FIRST (<A> b) = {b}

FIRST (b) = {b}

Rules for <A> not pairwise disjoint

Eliminating Left Recursion

- Rewrite grammar to shift left recursion to right recursion
  - Changes associativity
- Given

<expr> ::= <expr> + <term> and

<expr> ::= <term>

- Add new non-terminal <e> and replace above rules with

<expr> ::= <term><e>

<e> ::= + <term><e> | ε

Factoring Grammar

- Test too strong: Can't handle
  <expr> ::= <term> [(+ | -) <expr>]
- Answer: Add new non-terminal and replace above rules by
  <expr> ::= <term><e>
  <e> ::= + <term><e>
  <e> ::= - <term><e>
  <e> ::= ε
- You are delaying the decision point

Example

Both <A> and <B> have problems:	Transform grammar to:
<S> ::= <A> a <B> b	<S> ::= <A> a <B> b
<A> ::= <A> b | b	<A> ::-= b<A1>
<B> ::= a <B> | a	<A1> :: b<A1> | ε
	<B> ::= a<B1>
	<B1> ::= a<B1> | ε