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

Parser Code

- <*grammar*>.ml defines one parsing function per entry point
- Parsing function takes a lexing function (lexer buffer to token) and a lexer buffer as arguments
- Returns semantic attribute of corresponding entry point

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")))
```


LR Parsing

- Read tokens left to right (L)
- Create a rightmost derivation (R)
- How is this possible?
- Start at the bottom (left) and work your way up
- Last step has only one non-terminal to be replaced so is right-most
- Working backwards, replace mixed strings by non-terminals
- Always proceed so that there are no non-terminals to the right of the string to be replaced

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

<Sum> =>

= ● (0 + 1) + 0 shift

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

<Sum> =>

= (● 0 + 1) + 0 shift

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

<Sum> =>

=>	(0 ● + 1) + 0	reduce
=	(● 0 + 1) + 0	shift
=	● (0 + 1) + 0	shift

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

<Sum> =>

=	(<Sum> ● + 1) + 0	shift
=>	(0 ● + 1) + 0	reduce
=	(● 0 + 1) + 0	shift
=	● (0 + 1) + 0	shift

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

<Sum> =>

=	(<Sum> + ● 1) + 0	shift
=	(<Sum> ● + 1) + 0	shift
=>	(0 ● + 1) + 0	reduce
=	(● 0 + 1) + 0	shift
=	● (0 + 1) + 0	shift

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

<Sum> =>

=>	(<Sum> + 1 ●) + 0	reduce
=	(<Sum> + ● 1) + 0	shift
=	(<Sum> ● + 1) + 0	shift
=>	(0 ● + 1) + 0	reduce
=	(● 0 + 1) + 0	shift
=	● (0 + 1) + 0	shift

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

<Sum> =>

=>	(<Sum> + <Sum> ●) + 0	reduce
=>	(<Sum> + 1 ●) + 0	reduce
=	(<Sum> + ● 1) + 0	shift
=	(<Sum> ● + 1) + 0	shift
=>	(0 ● + 1) + 0	reduce
=	(● 0 + 1) + 0	shift
=	● (0 + 1) + 0	shift

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

<Sum> =>

=	(<Sum> ●) + 0	shift
=>	(<Sum> + <Sum> ●) + 0	reduce
=>	(<Sum> + 1 ●) + 0	reduce
=	(<Sum> + ● 1) + 0	shift
=	(<Sum> ● + 1) + 0	shift
=>	(0 ● + 1) + 0	reduce
=	(● 0 + 1) + 0	shift
=	● (0 + 1) + 0	shift

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

<Sum> =>

=> (<Sum>) ● + 0 reduce
= (<Sum> ●) + 0 shift
=> (<Sum> + <Sum> ●) + 0 reduce
=> (<Sum> + 1 ●) + 0 reduce
= (<Sum> + ● 1) + 0 shift
= (<Sum> ● + 1) + 0 shift
=> (0 ● + 1) + 0 reduce
= (● 0 + 1) + 0 shift
= ● (0 + 1) + 0 shift

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

<Sum> =>

= <Sum> ● + 0 shift
=> (<Sum>) ● + 0 reduce
= (<Sum> ●) + 0 shift
=> (<Sum> + <Sum> ●) + 0 reduce
=> (<Sum> + 1 ●) + 0 reduce
= (<Sum> + ● 1) + 0 shift
= (<Sum> ● + 1) + 0 shift
=> (0 ● + 1) + 0 reduce
= (● 0 + 1) + 0 shift
= ● (0 + 1) + 0 shift

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

<Sum> =>

= <Sum> + ● 0 shift
= <Sum> ● + 0 shift
=> (<Sum>) ● + 0 reduce
= (<Sum> ●) + 0 shift
=> (<Sum> + <Sum> ●) + 0 reduce
=> (<Sum> + 1 ●) + 0 reduce
= (<Sum> + ● 1) + 0 shift
= (<Sum> ● + 1) + 0 shift
=> (0 ● + 1) + 0 reduce
= (● 0 + 1) + 0 shift
= ● (0 + 1) + 0 shift

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

<Sum> =>

=> <Sum> + 0 ● reduce
= <Sum> + ● 0 shift
= <Sum> ● + 0 shift
=> (<Sum>) ● + 0 reduce
= (<Sum> ●) + 0 shift
=> (<Sum> + <Sum> ●) + 0 reduce
=> (<Sum> + 1 ●) + 0 reduce
= (<Sum> + ● 1) + 0 shift
= (<Sum> ● + 1) + 0 shift
=> (0 ● + 1) + 0 reduce
= (● 0 + 1) + 0 shift
= ● (0 + 1) + 0 shift

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

<Sum> => <Sum> + <Sum > ● reduce
=> <Sum> + 0 ● reduce
= <Sum> + ● 0 shift
= <Sum> ● + 0 shift
=> (<Sum>) ● + 0 reduce
= (<Sum> ●) + 0 shift
=> (<Sum> + <Sum> ●) + 0 reduce
=> (<Sum> + 1 ●) + 0 reduce
= (<Sum> + ● 1) + 0 shift
= (<Sum> ● + 1) + 0 shift
=> (0 ● + 1) + 0 reduce
= (● 0 + 1) + 0 shift
= ● (0 + 1) + 0 shift

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

<Sum> ● => <Sum> + <Sum > ● reduce
=> <Sum> + 0 ● reduce
= <Sum> + ● 0 shift
= <Sum> ● + 0 shift
=> (<Sum>) ● + 0 reduce
= (<Sum> ●) + 0 shift
=> (<Sum> + <Sum> ●) + 0 reduce
=> (<Sum> + 1 ●) + 0 reduce
= (<Sum> + ● 1) + 0 shift
= (<Sum> ● + 1) + 0 shift
=> (0 ● + 1) + 0 reduce
= (● 0 + 1) + 0 shift
= ● (0 + 1) + 0 shift

Example

(0 + 1) + 0

Example

(0 + 1) + 0

Example

(0 + 1) + 0

Example

<Sum>

(0 + 1) + 0

Example

<Sum>

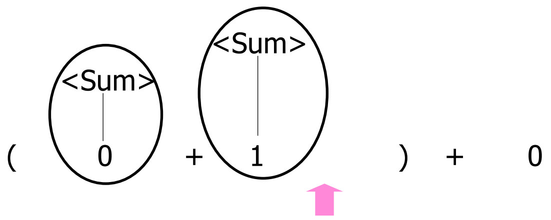
(0 + 1) + 0

Example

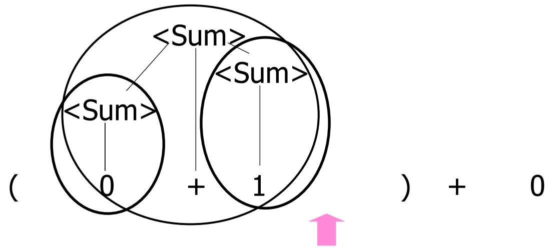
<Sum>

(0 + 1) + 0

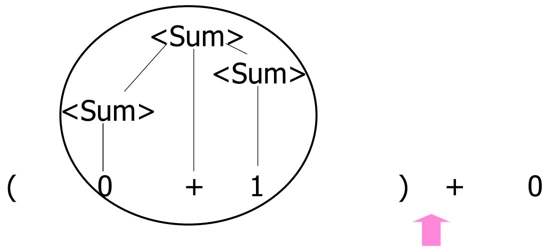
Example



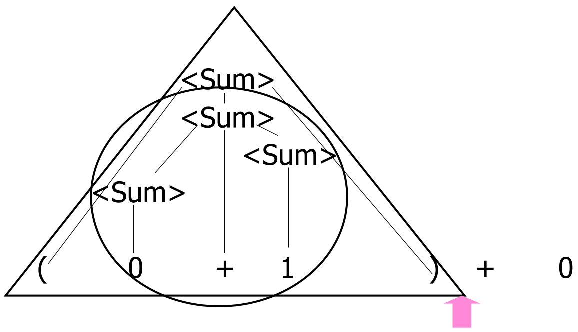
Example



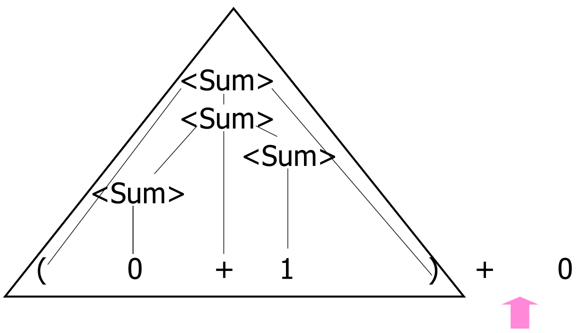
Example



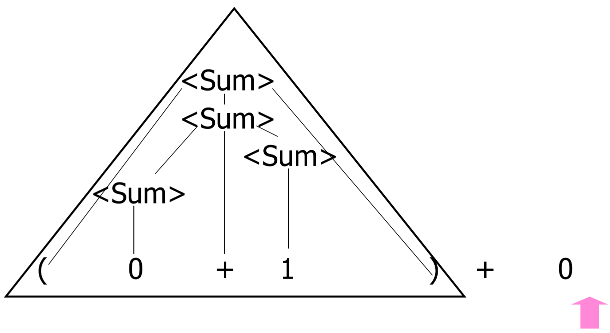
Example



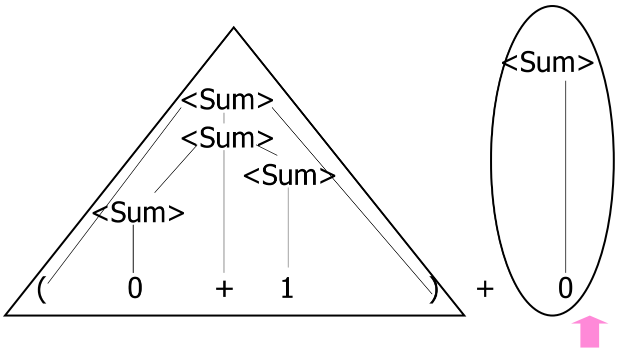
Example



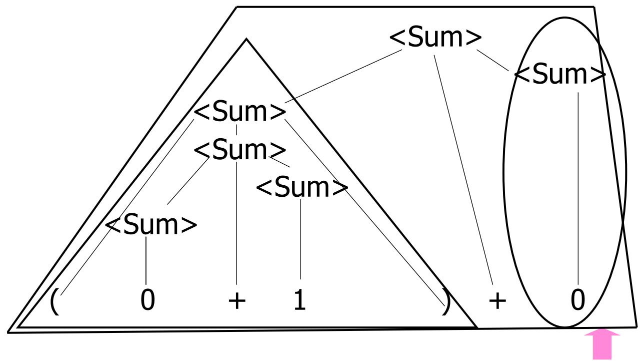
Example



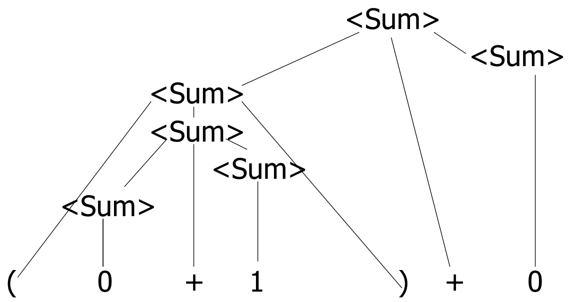
Example



Example



Example



LR Parsing Tables

- Build a pair of tables, Action and Goto, from the grammar
  - This is the hardest part, we omit here
  - Rows labeled by states
  - For Action, columns labeled by terminals and "end-of-tokens" marker
    - (more generally strings of terminals of fixed length)
  - For Goto, columns labeled by non-terminals

Action and Goto Tables

- Given a state and the next input, Action table says either
  - **shift** and go to state *n*, or
  - **reduce** by production *k* (explained in a bit)
  - **accept** or **error**
- Given a state and a non-terminal, Goto table says
  - go to state *m*

LR(i) Parsing Algorithm

- Based on push-down automata
- Uses states and transitions (as recorded in Action and Goto tables)
- Uses a stack containing states, terminals and non-terminals

LR(i) Parsing Algorithm

0. Insure token stream ends in special “end-of-tokens” symbol
1. Start in state 1 with an empty stack
2. Push **state**(1) onto stack
3. Look at next *i* tokens from token stream (*toks*) (don’t remove yet)
4. If top symbol on stack is **state**(*n*), look up action in Action table at (*n*, *toks*)

LR(i) Parsing Algorithm

5. If action = **shift** *m*,
   a) Remove the top token from token stream and push it onto the stack
   b) Push **state**(*m*) onto stack
   c) Go to step 3

LR(i) Parsing Algorithm

6. If action = **reduce** *k* where production *k* is E ::= u
   a) Remove 2 * length(u) symbols from stack (u and all the interleaved states)
   b) If new top symbol on stack is **state**(*m*), look up new state *p* in Goto(*m*,E)
   c) Push E onto the stack, then push **state**(*p*) onto the stack
   d) Go to step 3

LR(i) Parsing Algorithm

7. If action = **accept**
   - Stop parsing, return success
8. If action = **error**,
   - Stop parsing, return failure

Adding Synthesized Attributes

- Add to each **reduce** a rule for calculating the new synthesized attribute from the component attributes
- Add to each non-terminal pushed onto the stack, the attribute calculated for it
- When performing a **reduce**,
  - gather the recorded attributes from each non-terminal popped from stack
  - Compute new attribute for non-terminal pushed onto stack

Shift-Reduce Conflicts

- **Problem**: can’t decide whether the action for a state and input character should be **shift** or **reduce**
- Caused by ambiguity in grammar
- Usually caused by lack of associativity or precedence information in grammar

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

● 0 + 1 + 0	shift
-> 0 ● + 1 + 0	reduce
-> <Sum> ● + 1 + 0	shift
-> <Sum> + ● 1 + 0	shift
-> <Sum> + 1 ● + 0	reduce
-> <Sum> + <Sum> ● + 0	

Example - cont

- **Problem:** shift or reduce?
- You can shift-shift-reduce-reduce or reduce-shift-shift-reduce
- Shift first - right associative
- Reduce first- left associative

Reduce - Reduce Conflicts

- **Problem:** can't decide between two different rules to reduce by
- Again caused by ambiguity in grammar
- **Symptom:** RHS of one production suffix of another
- Requires examining grammar and rewriting it
- Harder to solve than shift-reduce errors

Example

- S ::= A | aB   A ::= abc   B ::= bc

● abc	shift
a ● bc	shift
ab ● c	shift
abc ●	

- Problem: reduce by B ::= bc then by S ::= aB, or by A::= abc then S::A?

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"));;

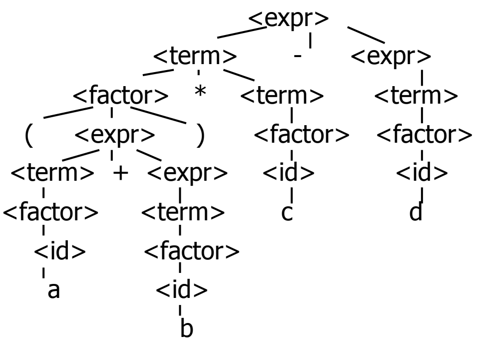
(a + b) * c - d

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"))),
 [])
```

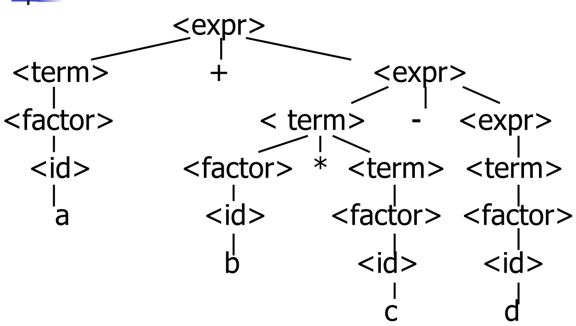
(a + b) * c – d



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:

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

Transform grammar to:

<S> ::= <A> a <B> b
<A> ::-= b<A1>
<A1> :: b<A1> | ε
<B> ::= a<B1>
<B1> ::= a<B1> | ε

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")))
```