CMSC 330: Organization of Programming Languages

Parsing

Scanning ("tokenizing")

- Converts textual input into a stream of tokens
  - These are the terminals in the parser's CFG
  - Example tokens are keywords, identifiers, numbers, punctuation, etc.
- Scanner typically ignores/eliminates whitespace

```
type token =
   Tok_Num of char
 | Tok_Add
 | Tok_END
```

```
tokenize "1 + 2" =
  [Tok_Num '1'; Tok_Add; Tok_Num '2'; Tok_END]
```

A Scanner in OCaml

```
type token = Tok_Num of char | Tok_Add | Tok_Mul |Tok_END

let tokenize (s:string) = (* returns token list *)
```

```
let re_num = Str.regexp "[0-9]" (* single digit *)
let re_add = Str.regexp "+"
let re_mul = Str.regexp "*"

let tokenize str =
 let rec tok pos s =
   if pos >= String.length s then
     [Tok_END]
   else
     if (Str.string_match re_num s pos) then
       let token = Str.matched_string s in
         (Tok_Num token.[0])::(tok (pos+1) s)
     else if (Str.string_match re_add s pos) then
       Tok_Add::(tok (pos+1) s)
     else
       raise (IllegalExpression "tokenize")
 in
 tok 0 str
```

Uses **Str** library module for regexps

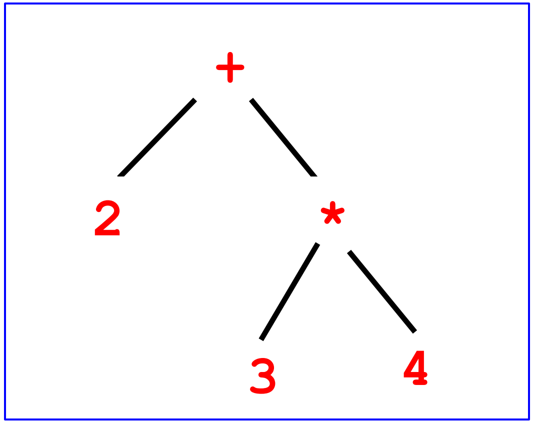
Parsing (to an AST)

```
type token =
    Tok_Num of char
  | Tok_Add
  | Tok_Mul
  | Tok_END
```

```
let tokens= tokenize "2+3*4";;

tokens = [Tok_Num '2'; Tok_Add;
Tok_Num '3'; Tok_Mul; Tok_Num '4';
Tok_END]
```

```
type expr =
   Num of int
 | Add of expr * expr
 | Mult of expr * expr
```




```
parse tokens = Add (Num 2, Mul(Num 3, Num 4)
```

Top-Down Parsing (Intuition)

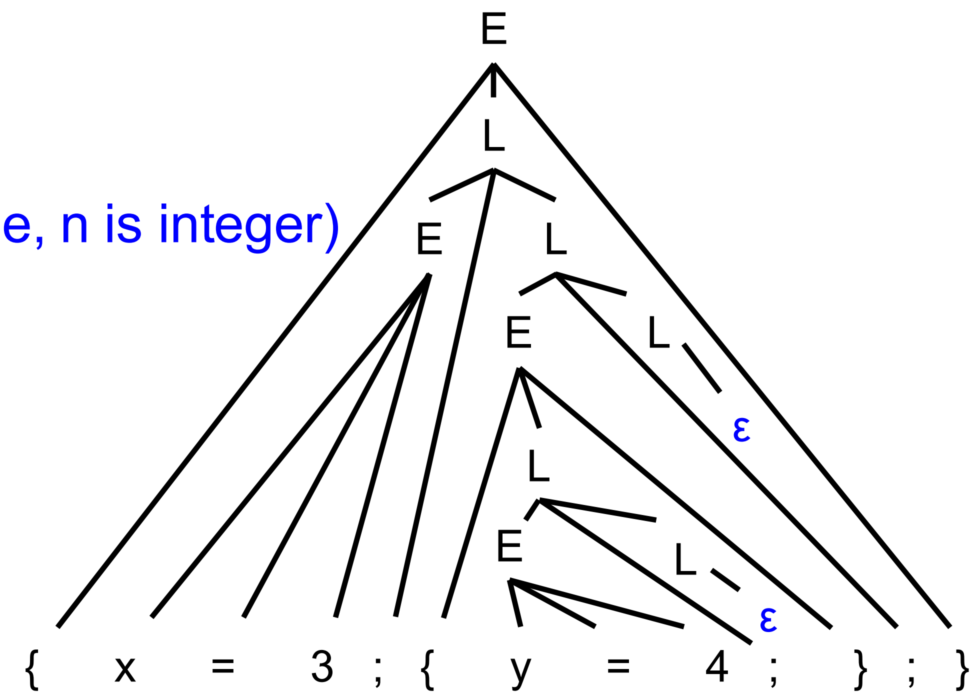
$E \rightarrow id = n \mid \{ L \}$

$L \rightarrow E \; ; L \mid \varepsilon$

(Assume: id is variable name, n is integer)

Show parse tree for

{ x = 3 ; { y = 4 ; } ; }



Source code of this example:
https://github.com/anwarmamat/cmsc330spring2024/tree/main/examples/parser_class_example

Recursive Descent Parsing

- Approach: Try to produce leftmost derivation
  - Begin with start symbol S, and input tokens t
  - Repeat:
    - Rewrite S and consume tokens in t via a production in the grammar
  - Until all tokens matched, or failure

Grammar:

```
S -> A + S | A
A -> B * A | B
B -> 0 | 1 … | 9
```

Σ={0-9,*,+}

```
Input: 2 + 3 * 4
```

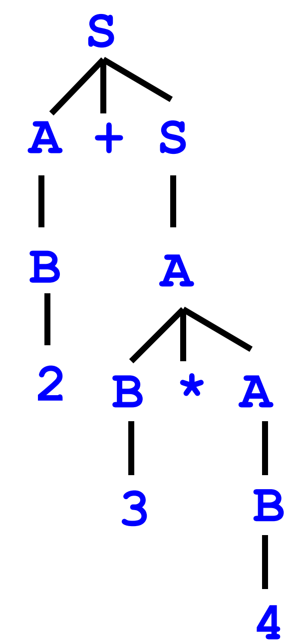
Recursive Descent Parsing: Example

Grammar:

```
S -> A + S | A
A -> B * A | B
B -> 0 | 1 … | 9
```

Parsing

Input: 2+3*4



Example

```
let lookahead tokens =
  match tokens with
   [] -> raise (ParseError "no tokens")
| (h::t) -> h


let match_token tokens  token =
   match tokens with
    | [] -> raise Exception
    | h :: t when h = token -> t
    | h :: _ -> raise Exception
```

Quiz 1

- What is the value of x?

```
let tokens =
    [Tok_Num '2'; Tok_Add; Tok_Num '3'; Tok_END]
let x = lookahead tokens
```

A. 2
B. Tok_Num
C. Tok_Num '2'
D. [Tok_Add; Tok_Num '3'; Tok_END]

Quiz 1

- What is the value of x?

```
let tokens =
   [Tok_Num '2'; Tok_Add; Tok_Num '3'; Tok_END]
let x = lookahead tokens
```

A. 2
B. Tok_Num
C. Tok_Num '2'
D. [Tok_Add; Tok_Num '3'; Tok_END]

Quiz 2

- What is the value of x?

```
let tokens =
   [Tok_Num '2'; Tok_Add; Tok_Num '3'; Tok_END]
let x = match_token tokens Tok_Add
```

A. 2
B. raise Exception
C. Tok_Num '2'
D. [Tok_Add; Tok_Num '3'; Tok_END]

Quiz 2

- What is the value of x?

```
let tokens =
    [Tok_Num '2'; Tok_Add; Tok_Num '3'; Tok_END]
let x = match_token tokens Tok_Add
```

A. `2`
B. `raise Exception`
C. `Tok_Num '2'`
D. `[Tok_Add; Tok_Num '3'; Tok_END]`

Quiz 3

- What is the value of x?

```
let tokens =
    [Tok_Num '2'; Tok_Add; Tok_Num '3'; Tok_END]
let x = match_token tokens (Tok_Num '2')
```

```
A.  2
B.  raise Exception
C.  Tok_Num '2'
D.  [Tok_Add; Tok_Num '3'; Tok_END]
```

Quiz 3

- What is the value of x?

```
let tokens =
   [Tok_Num '2'; Tok_Add; Tok_Num '3'; Tok_END]
let x = match_token tokens (Tok_Num '2')
```

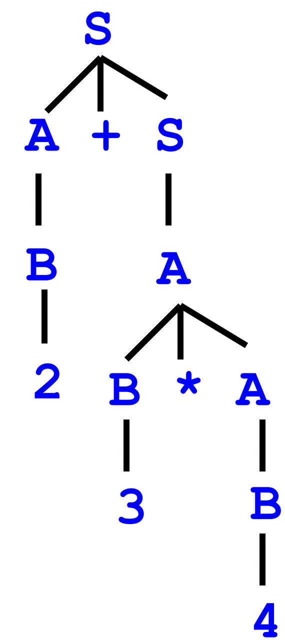
```
A.  2
B.  raise Exception
C.  Tok_Num '2'
D.  [Tok_Add; Tok_Num '3'; Tok_END]
```

Example

Grammar:

```
S -> A + S | A
A -> B * A | B
B -> 0 | 1 … | 9
```

Input: 2+3*4




```
let rec parse_S tokens =
  let e1, t1 = parse_A tokens in
    match lookahead t1 with
    | Tok_Add -> (* S -> A Tok_Add E *)
       let t2 = match_token t1 Tok_Add in
       let e2, t3 = parse_S t2 in
       (Add (e1, e2), t3)
    | _ -> (e1, t1) (* S -> A *)
```

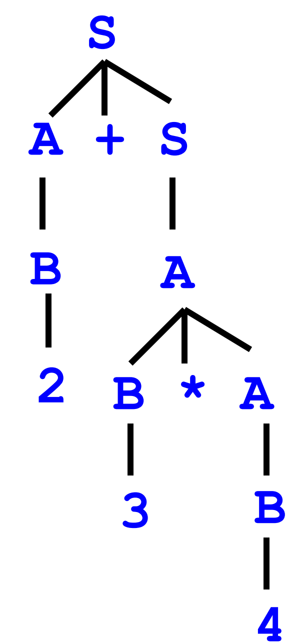
Example

Grammar:

S -> A + S | A
A -> B * A | B
B -> 0 | 1 … | 9

```
let rec parse_A tokens =
  let e1, tokens = parse_B tokens in
   match lookahead tokens with
    | Tok_Mult -> (* A -> B Tok_Mult A *)
      let t2 = match_token tokens Tok_Mult in
      let e2, t3 = parse_A t2 in
      (Mult (e1, e2), t3)
    | _ -> (e1, tokens)
```

Input: 2+3*4

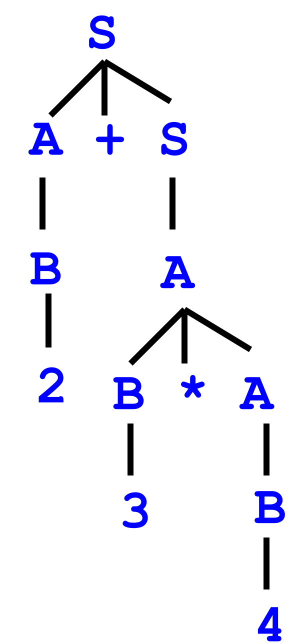


Example

Grammar:

```
S -> A + S | A
A -> B * A | B
B -> 0 | 1 … | 9
```

Input: 2+3*4




```
let rec parse_B tokens =
  match lookahead tokens with
  | Tok_Num c -> (* B -> Tok_Num *)
    let t = match_token tokens (Tok_Num c) in
     (Num (int_of_string c), t)
  | _ -> raise (ParseError "parse_B")
```

Recursive Descent Parsing: Key Step

- Key step: Choosing the right production
- Two approaches
  - Backtracking
    - Choose some production
    - If fails, try different production
    - Parse fails if all choices fail
  - Predictive parsing (what we will do)
    - Compare with lookahead to decide which production to select
    - Parse fails if lookahead does not match any production

Recursive Descent Parser Implementation

- For all terminals, use function match_tok a
  - If lookahead is a it consumes the lookahead by advancing the lookahead to the next token, and returns
  - Fails with a parse error if lookahead is not a

- For each nonterminal N, create a function parse_N
  - Called when we're trying to parse a part of the input which corresponds to (or can be derived from) N
  - parse_S for the start symbol S begins the parse

Example Parser

- Given grammar S → xyz | abc
- Parser

```
let parse_S () =
  if lookahead () = "x" then (* S → xyz *)
    (match_tok "x";
     match_tok "y";
     match_tok "z")
   else if lookahead () = "a" then (* S → abc *)
     (match_tok "a";
     match_tok "b";
     match_tok "c")
   else raise (ParseError "parse_S")
```

Another Example Parser

- Given grammar S → A | B   A → x | y   B → z

```
let rec parse_S () =
  if lookahead () = "x" ||
     lookahead () = "y" then
     parse_A () (* S → A *)
  else if lookahead () = "z" then
     parse_B () (* S → B *)
  else raise (ParseError "parse_S")

and parse_A () =
   if lookahead () = "x" then
     match_tok "x" (* A → x *)
   else if lookahead () = "y" then
     match_tok "y" (* A → y *)
   else raise (ParseError "parse_A")

and parse_B () = …
```

Execution Trace = Parse Tree

- If you draw the execution trace of the parser
  - You get the parse tree
- Examples
  - Grammar

    S → xyz

    S → abc
  - String “xyz”

    parse_S ()

      match_tok “x”

      match_tok “y”

      match_tok “z”

```
  S
 /|\
x y z
```

  - Grammar

    S → A | B

    A → x | y

    B → z
  - String “x”

    parse_S ()

      parse_A ()

        match_tok “x”

```
S
|
A
|
x
```

Left Recursion

- Consider grammar $S \rightarrow Sa \mid \varepsilon$
  - Try writing parser

```
let rec parse_S () =
    if lookahead () = "a" then
      (parse_S ();
      match_tok "a") (* S → Sa *)
    else ()
```

  - Body of parse_S () has an infinite loop!
    - Infinite loop occurs in grammar with left recursion

Right Recursion

- Consider grammar $S \rightarrow aS \mid \varepsilon$ Again, First(aS) = a
  - Try writing parser

```
let rec parse_S () =
    if lookahead () = "a" then
      (match_tok "a";
      parse_S ())  (* S → aS *)
    else ()
```

  - Will parse_S( ) infinite loop?
    - Invoking match_tok will advance lookahead, eventually stop
  - Top-down parsers handles grammar w/ right recursion

Algorithm To Eliminate Left Recursion

- Given grammar
  - $A \rightarrow A\alpha_1 \mid A\alpha_2 \mid \ldots \mid A\alpha_n \mid \beta$
    - β must exist or no derivation will yield a string
- Rewrite grammar as (repeat as needed)
  - $A \rightarrow \beta L$
  - $L \rightarrow \alpha_1 L \mid \alpha_2 L \mid \ldots \mid \alpha_n L \mid \varepsilon$
- Replaces left recursion with right recursion
- Examples
  - $S \rightarrow Sa \mid \varepsilon$ ⇨ $S \rightarrow L$ $\quad L \rightarrow aL \mid \varepsilon$
  - $S \rightarrow Sa \mid Sb \mid c$ ⇨ $S \rightarrow cL$ $\quad L \rightarrow aL \mid bL \mid \varepsilon$

Quiz 4

- What does the following code parse?

```
let parse_S () =
  if lookahead () = "a" then
    (match_tok "a";
     match_tok "x";
     match_tok "y";
     match_tok "q")
  else
    raise (ParseError "parse_S")
```

A. S → axyq
B. S → a | q
C. S → aaxy | qq
D. S → axy | q

Quiz 4

- What does the following code parse?

```
let parse_S () =
  if lookahead () = “a” then
    (match_tok "a";
     match_tok "x";
     match_tok "y”;
     match_tok "q”)
  else
    raise (ParseError "parse_S")
```

A. S → axyq
B. S → a | q
C. S → aaxy | qq
D. S → axy | q

Quiz 5

- What Does the following code parse?

```
let rec parse_S () =
  if lookahead () = “a” then
    (match_tok "a";
     parse_S ())
  else if lookahead () = “q” then
    (match_tok "q”;
     match_tok ”p”)
  else
    raise (ParseError "parse_S")
```

A. $S \rightarrow aS \mid qp$
B. $S \rightarrow a \mid S \mid qp$
C. $S \rightarrow aqSp$
D. $S \rightarrow a \mid q$

Quiz 5

- What Does the following code parse?

```
let rec parse_S () =
  if lookahead () = “a” then
    (match_tok "a";
     parse_S ())
  else if lookahead () = “q” then
    (match_tok "q”;
     match_tok ”p”)
  else
    raise (ParseError "parse_S")
```

A. **$S \rightarrow aS \mid qp$**
B. $S \rightarrow a \mid S \mid qp$
C. $S \rightarrow aqSp$
D. $S \rightarrow a \mid q$

Quiz 6

Can recursive descent parse this grammar?

$$S \rightarrow aBa$$
$$B \rightarrow bC$$
$$C \rightarrow \varepsilon \mid Cc$$

A. Yes
B. No

Quiz 6

Can recursive descent parse this grammar?

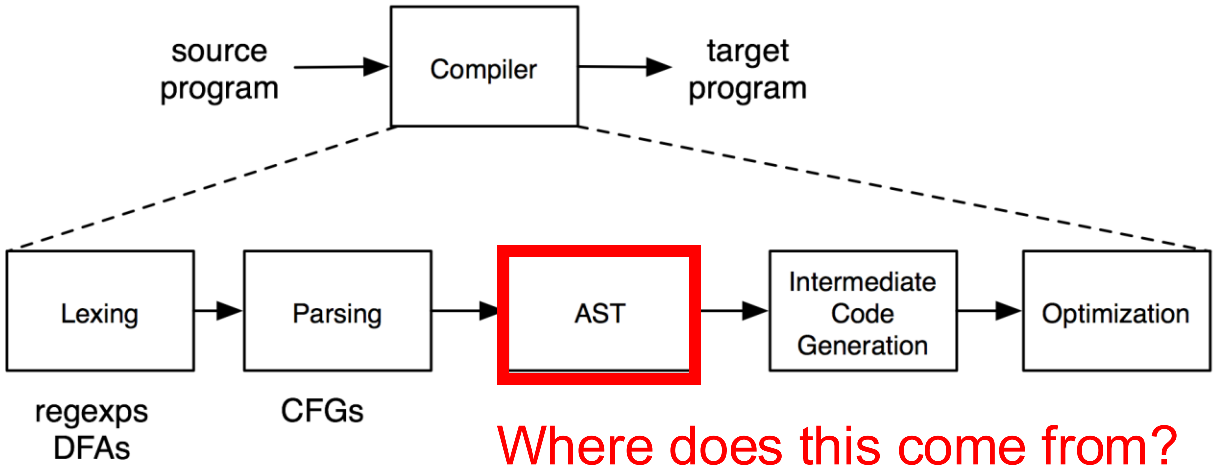
$$
\begin{array}{l}
S \rightarrow aBa \\
B \rightarrow bC \\
C \rightarrow \varepsilon \mid Cc
\end{array}
$$

A. Yes

B. No

(due to left recursion)

Recall: The Compilation Process

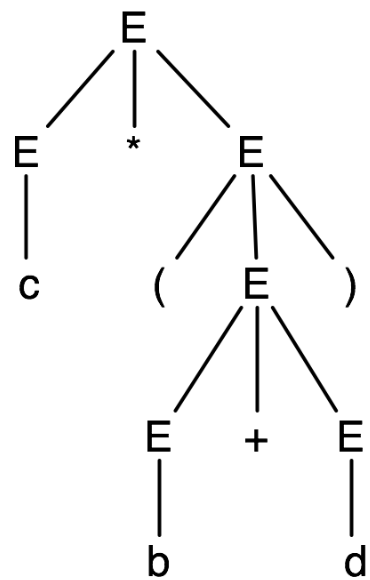


Parse Trees to ASTs

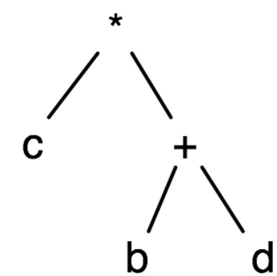
- Parse trees are a representation of a parse, with all of the syntactic elements present
  - Parentheses
  - Extra nonterminals for precedence
- This extra stuff is needed for parsing
- Lots of that stuff is not needed to actually implement a compiler or interpreter
  - So in the abstract syntax tree we get rid of it

Abstract Syntax Trees (ASTs)

- An abstract syntax tree is a more compact, abstract representation of a parse tree, with only the essential parts



parse tree



AST

Parser Examples:

- Top-Down Parsing example on slide 5
  - https://github.com/anwarmamat/cmsc330spring2024/tree/main/examples/parser_class_example

- Expression (addition and multiplication) parser Dune project
  - https://github.com/anwarmamat/cmsc330spring2024/tree/main/examples/parser

- Expression (addition and multiplication) parser
  - https://github.com/anwarmamat/cmsc330spring2024/blob/main/examples/parse_add_mult.ml

- Postfix expression parser:
  - https://github.com/anwarmamat/cmsc330spring2024/blob/main/examples/parser_postfix_exp.ml