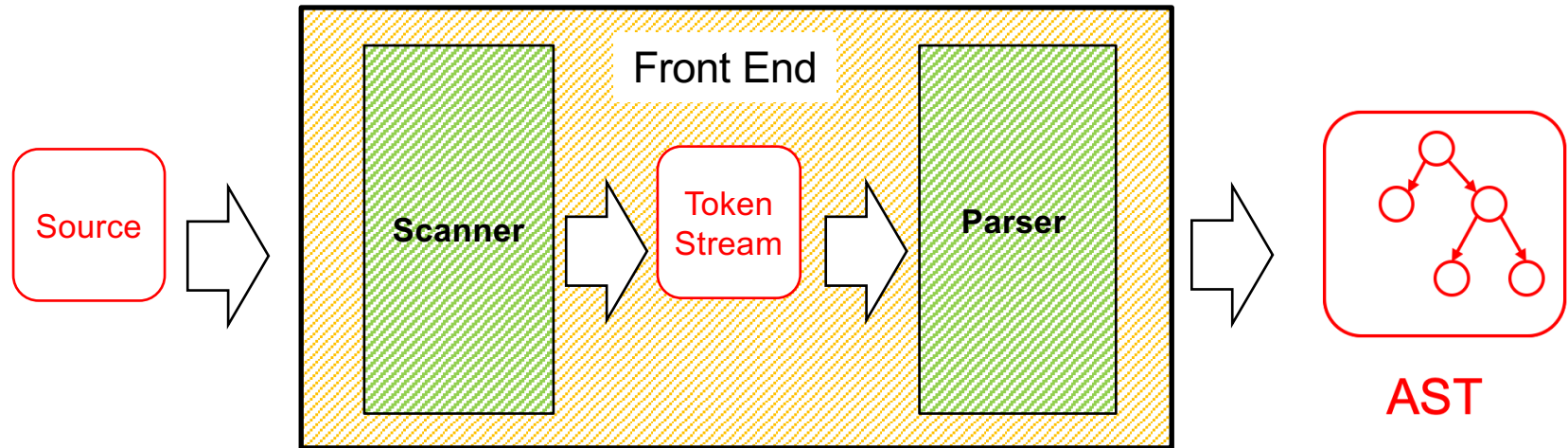# CMSC 330: Organization of Programming Languages

Parsing

Recall: Front End Scanner and Parser

- Scanner / lexer / tokenizer converts program source into tokens (keywords, variable names, operators, numbers, etc.) with regular expressions
- Parser converts tokens into an AST (abstract syntax tree) based on a context free grammar

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

Scanning ("tokenizing")

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

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

A Scanner in OCaml

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

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

```
let re_num = Str.regexp "[0-9]" (* single digit *)
let re_add = 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_Sum::(tok (pos+1) s)
     else
       raise (IllegalExpression "tokenize")
 in
 tok 0 str
```

Uses
Str
library
module
for
regexps

Parsing

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

```
let tokens = tokenize "1+2"
t = [Tok_Num '1'; Tok_Sum; Tok_Num '2'; Tok_END]
```
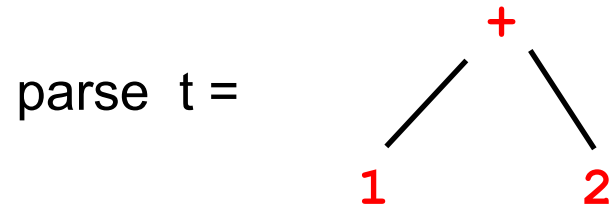
parse t =

Sum(Num 1, Num 2)

Implementing Parsers

- Many efficient techniques for parsing
  - LL(k), SLR(k), LR(k), LALR(k)…
  - Take CMSC 430 for more details

- One simple technique: recursive descent parsing
  - This is a top-down parsing algorithm

- Other algorithms are bottom-up
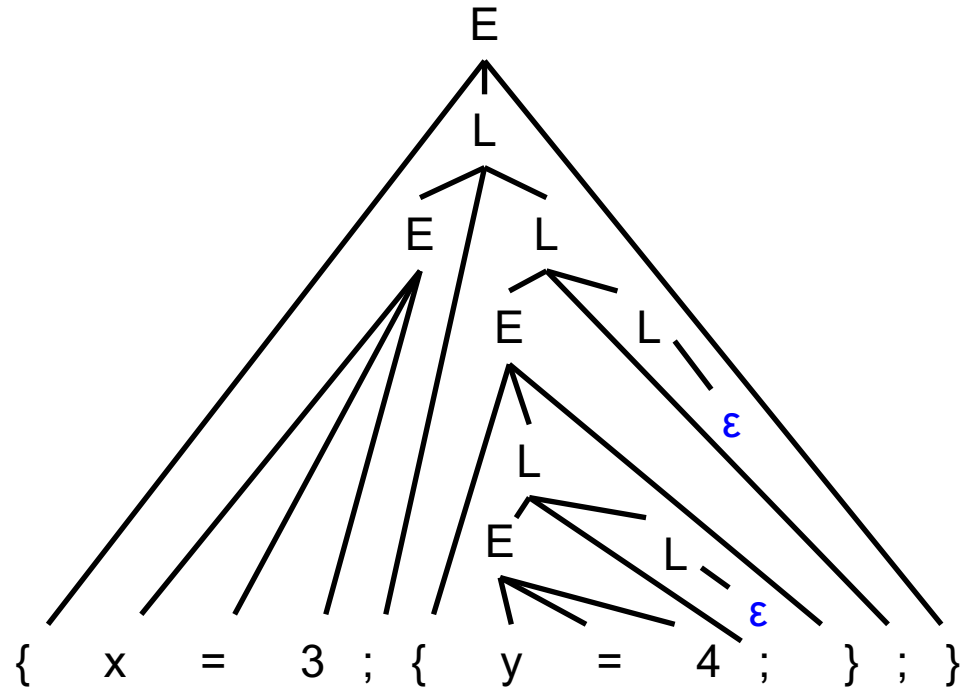
Top-Down Parsing (Intuition)

E → id = n | { L }

L → E ; L | ε

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

Show parse tree for
{ x = 3 ; { y = 4 ; } ; }

Recursive Descent Parsing

▸ **Goal**

- Can we "parse" a string – does it match our grammar?
  - ➢ We will talk about constructing an AST later

▸ **Approach: Perform parse**

- Replace each non-terminal A by the *rhs* of a production A→ *rhs*

- And/or match each terminal against token in input

- Repeat until input consumed, or failure

Recursive Descent Parsing (cont.)

▸ At each step, we'll keep track of two facts

- What grammar element are we trying to match/expand?
- What is the lookahead (next token of the input string)?

▸ At each step, apply one of three possible cases

- If we're trying to match a terminal
  - ➢ If the lookahead is that token, then succeed, advance the lookahead, and continue
- If we're trying to match a nonterminal
  - ➢ Pick which production to apply based on the lookahead
- Otherwise fail with a parsing error

Parsing Example

E → id = n | { L }

L → E ; L | ε

- Here n is an integer and id is an identifier

▶ One input might be

- { x = 3; { y = 4; }; }
- This would get turned into a list of tokens

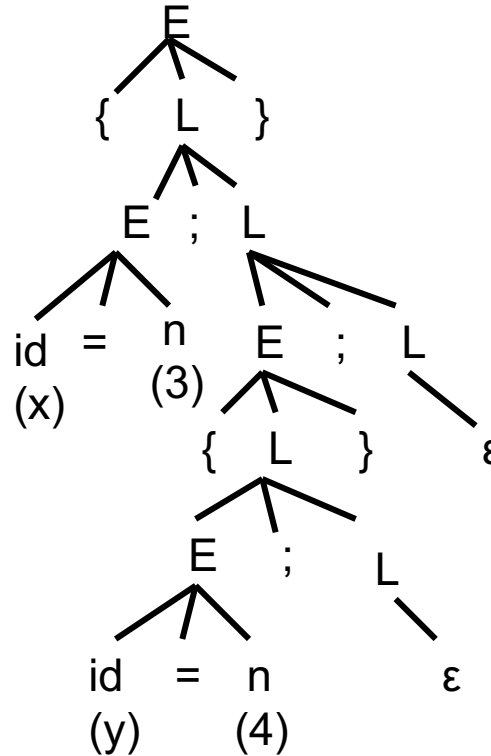   { x = 3 ; { y = 4 ; } ; }

- And we want to turn it into a parse tree

Parsing Example (cont.)

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

$L \to E ; L \mid \varepsilon$

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

lookahead

Recursive Descent Parsing (cont.)

- 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)
    - Analyze grammar to find FIRST sets for productions
    - Compare with lookahead to decide which production to select
    - Parse fails if lookahead does not match FIRST

S->A|B
A->0A| ε
B->1B| ε

Parser Demo

S->A|B
A->0A| ε
B->1B| ε

```
let rec parse_S tokens =
  let t = lookahead tokens in
  match t with
    '0' -> parse_A tokens
   |'1' -> parse_B tokens
   |_->tokens

and parse_A tokens =
  let t = lookahead tokens in
  match t with
    '0' ->
     let tokens = match_tok '0' tokens in
     let tokens = parse_A tokens in
    tokens
   |_-> let _= tokens
and parse_B tokens =
  let t = lookahead tokens in
  match t with
    '1' ->
     let tokens = match_tok '1' tokens in
    let tokens = parse_B tokens in
    tokens
   |_-> let _=  tokens
```

Selecting a Production

- **Motivating example**
  - If grammar S → xyz | abc and lookahead is x
    - ➢ Select S → xyz since 1st terminal in RHS matches x
  - If grammar S → A | B   A → x | y B → z
    - ➢ If lookahead is x, select S → A, since A can derive string beginning with x

- **In general**
  - Choose a production that can derive a sentential form beginning with the lookahead
  - Need to know what terminal may be first in any sentential form derived from a nonterminal / production

First Sets

- ▸ Definition
  - First(γ), for any terminal or nonterminal γ, is the set of initial terminals of all strings that γ may expand to
  - We'll use this to decide which production to apply
- ▸ Example: Given grammar

    S → A | B

    A → x | y

    B → z

  - First(A) = { x, y } since First(x) = { x }, First(y) = { y }
  - First(B) = { z } since First(z) = { z }
- ▸ So: If we are parsing S and see x or y, we choose S → A; if we see z we choose S → B

Calculating First(γ)

- For a terminal a
  - First(a) = { a }
- For a nonterminal N
  - If $N \rightarrow \varepsilon$, then add ε to First(N)
  - If $N \rightarrow \alpha_1 \alpha_2 \ldots \alpha_n$, then (note the α_i are all the symbols on the right side of one single production):
    - Add First($\alpha_1 \alpha_2 \ldots \alpha_n$) to First(N), where First($\alpha_1 \alpha_2 \ldots \alpha_n$) is defined as
      - First(α_1) if $\varepsilon \notin$ First(α_1)
      - Otherwise (First(α_1) − ε) ∪ First($\alpha_2 \ldots \alpha_n$)
    - If $\varepsilon \in$ First(α_i) for all i, $1 \leq i \leq k$, then add ε to First(N)

First( ) Examples

E → id = n | { L }
L → E ; L | ε

First(id) = { id }
First("=") = { "=" }
First(n) = { n }
First("{")= { "{" }
First("}")= { "}" }
First(";")= { ";" }
First(E) = { id, "{" }
First(L) = { id, "{", ε }

E → id = n | { L } | ε
L → E ; L

First(id) = { id }
First("=") = { "=" }
First(n) = { n }
First("{")= { "{" }
First("}")= { "}" }
First(";")= { ";" }
First(E) = { id, "{", ε }
First(L) = { id, "{", ";" }

Quiz #1

Given the following grammar:

```
S -> aAB |B
A -> CBC
B -> b
C -> cC | ε
```

What is First(S)?

```
A. {b,c}
B. {b}
C. {a,b}
D. {c}
```

Quiz #1

Given the following grammar:

```
S -> aAB |B
A -> CBC
B -> b
C -> cC | ε
```

What is First(S)?

A. {b,c}

B. {b}

C. {a,b}

D. {c}

Quiz #2

Given the following grammar:

```
S -> aAB
A -> CBC
B -> b
C -> cC | ε
```

What is First(B)?

A. {a}

B. {b,c}

C. {b}

D. {c}

Quiz #2

Given the following grammar:

```
S -> aAB
A -> CBC
B -> b
C -> cC | ε
```

What is First(B)?

A. {a}
B. {b,c}
C. {b}
D. {c}

Quiz #3

Given the following grammar:

```
S -> aAB
A -> CBC
B -> b
C -> cC | ε
```

What is First(A)?

A. {a}

B. {b,c}

C. {b}

D. {c}

Quiz #3

Given the following grammar:

```
S -> aAB
A -> CBC
B -> b
C -> cC | ε
```

What is First(A)?

A. {a}

B. {b,c}

C. {b}

D. {c}

Note:
First(B) = **{b}**
First(C) = **{c,ε}**

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

match_tok in OCaml

```
let tok_list = ref [] (* list of parsed tokens *)

exception ParseError of string

let match_tok a =
  match !tok_list with
    (* checks lookahead; advances on match *)
    | (h::t) when a = h -> tok_list := t
    | _ -> raise (ParseError "bad match")

(* used by parse_X *)
let lookahead () =
  match !tok_list with
    [] -> raise (ParseError "no tokens")
  | (h::t) -> h
```

Parsing Nonterminals

- The body of parse_N for a nonterminal N does the following
  - Let $N \rightarrow \beta_1 \mid ... \mid \beta_k$ be the productions of N
    - Here β_i is the entire right side of a production- a sequence of terminals and nonterminals
  - Pick the production $N \rightarrow \beta_i$ such that the lookahead is in First(β_i)
    - It must be that First(β_i) $\cap$ First(β_j) = $\varnothing$ for i ≠ j
    - If there is no such production, but $N \rightarrow \varepsilon$ then return
    - Otherwise fail with a parse error
  - Suppose $\beta_i = \alpha_1 \alpha_2 ... \alpha_n$. Then call parse_$\alpha_1$(); ... ; parse_$\alpha_n$() to match the expected right-hand side, and return

Example Parser

- Given grammar S → xyz | abc
  - First(xyz) = { x }, First(abc) = { a }

- 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 $S \rightarrow A \mid B \quad A \rightarrow x \mid y \quad B \rightarrow z$
  - First(A) = { x, y }, First(B) = { z }

- Parser:
```
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 () = …
```

Syntax for *mutually recursive* functions in OCaml – **parse_S** and **parse_A** and **parse_B** can each call the other

Example

$E \rightarrow id = n \mid \{ L \}$ First(E) = { id, "{" }

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

Parser:

```
let rec parse_E () =

  if lookahead () = "id" then
    (* E → id = n *)
    (match_tok "id";
     match_tok "=";
     match_tok "n")

   else if lookahead () = "{" then
    (* E → { L } *)
    (match_tok "{";
     parse_L ();
     match_tok "}")

  else raise (ParseError "parse_A")
```

```
and parse_L () =

  if lookahead () = "id"
  || lookahead () = "{" then
    (* L → E ; L *)
    (parse_E ();
     match_tok ";";
     parse_L ())

  else
    (* L → ε *)
    ()
```

Things to Notice

- If you draw the execution trace of the parser
  - You get the parse tree (we'll consider ASTs later)
- 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
```

Things to Notice (cont.)

- This is a predictive parser
  - Because the lookahead determines exactly which production to use
- This parsing strategy may fail on some grammars
  - Production First sets overlap
  - Production First sets contain ε
  - Possible infinite recursion
- Does not mean grammar is not usable
  - Just means this parsing method not powerful enough
  - May be able to change grammar

Conflicting First Sets

- Consider parsing the grammar $E \rightarrow ab \mid ac$

  - First(ab) = a
  - First(ac) = a

  Parser cannot choose between RHS based on lookahead!

- Parser fails whenever $A \rightarrow \alpha_1 \mid \alpha_2$ and

  - First(α_1) ∩ First(α_2) != ε or ∅

- Solution

  - Rewrite grammar using left factoring

Left Factoring Algorithm

- Given grammar
  - $A \rightarrow x\alpha_1 \mid x\alpha_2 \mid \ldots \mid x\alpha_n \mid \beta$
- Rewrite grammar as
  - $A \rightarrow xL \mid \beta$
  - $L \rightarrow \alpha_1 \mid \alpha_2 \mid \ldots \mid \alpha_n$
- Repeat as necessary
- Examples
  - $S \rightarrow ab \mid ac$ $\Rightarrow S \rightarrow aL$ $L \rightarrow b \mid c$
  - $S \rightarrow abcA \mid abB \mid a$ $\Rightarrow S \rightarrow aL$ $L \rightarrow bcA \mid bB \mid \varepsilon$
  - $L \rightarrow bcA \mid bB \mid \varepsilon$ $\Rightarrow L \rightarrow bL' \mid \varepsilon$ $L' \rightarrow cA \mid B$

Alternative Approach

- Change structure of parser
  - First match common prefix of productions
  - Then use lookahead to chose between productions
- Example
  - Consider parsing the grammar E → a+b | a*b | a

```
let parse_E () =
  match_tok "a"; (* common prefix *)

  if lookahead () = "+" then (* E → a+b *)
    (match_tok "+";
     match_tok "b")

  else if lookahead () = "*" then (* E → a*b *)
    (match_tok "*";
     match_tok "b")

  else () (* E → a *)
```

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** $S \to aS \mid \varepsilon$ 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
  - $S \rightarrow Sa \mid \varepsilon$ $\qquad\qquad\qquad \Rightarrow S \rightarrow L \qquad L \rightarrow aL \mid \varepsilon$
  - $S \rightarrow Sa \mid Sb \mid c \qquad \Rightarrow S \rightarrow cL \qquad L \rightarrow aL \mid bL \mid \varepsilon$

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 -> aS | qp
B. S -> a | S | qp
C. S -> aqSp
D. S -> a | 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 -> aS | qp**
B. S -> a | S | qp
C. S -> aqSp
D. S -> a | q

Quiz #6

Can recursive descent parse this grammar?

S -> aBa
B -> bC
C -> ε | Cc

A. Yes
B. No

Quiz #6

Can recursive descent parse this grammar?

> S -> aBa
> B -> bC
> C -> ε | Cc

A. Yes
B. No
   (due to left recursion)

What's Wrong With Parse Trees?

- Parse trees contain too much information
  - Example
    - Parentheses
    - Extra nonterminals for precedence
  - This extra stuff is needed for parsing

- But when we want to reason about languages
  - Extra information gets in the way (too much detail)

Abstract Syntax Trees (ASTs)
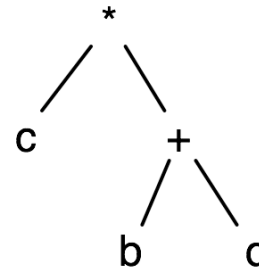
▶ An abstract syntax tree is a more compact, abstract representation of a parse tree, with only the essential parts

parse tree
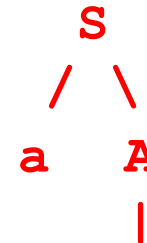
AST
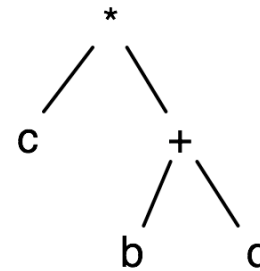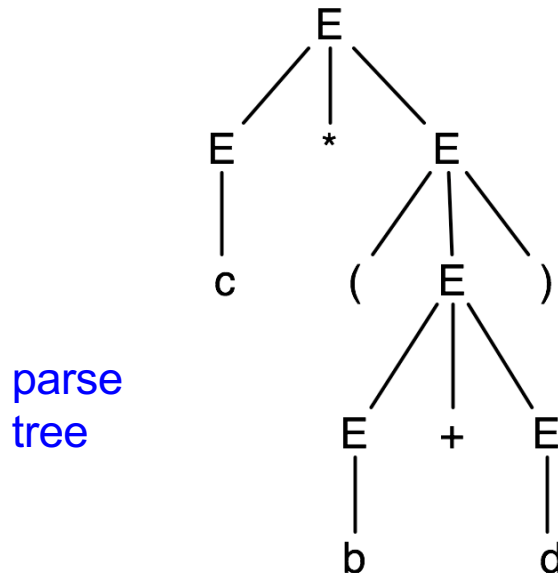
Abstract Syntax Trees (cont.)

▶ **Intuitively, ASTs correspond to the data structure you'd use to represent strings in the language**
- Note that grammars describe trees
  - ➤ So do OCaml datatypes, as we have seen already
- E → a | b | c | E+E | E-E | E*E | (E)

```
      *
     / \
    c   +
       / \
      b   d
```

Producing an AST

- To produce an AST, we can modify the parse() functions to construct the AST along the way
  - match_tok a returns an AST node (leaf) for a
  - parse_A returns an AST node for A
    - AST nodes for RHS of production become children of LHS node
- Example
  - S → aA

```
let rec parse_S () =
    if lookahead () = "a" then
        let n1 = match_tok "a" in
        let n2 = parse_A () in
        Node(n1,n2)
    else raise ParseError
        "parse_S"
```

```
     S
    / \
   a   A
       |
```

The Compilation Process