Introduction to Parsing, Ambiguity, and Syntax Errors

Outline

- Regular languages revisited
- Parser overview
- Context-free grammars (CFG's)
- Derivations
- Ambiguity
- Syntax errors

Languages and Automata

- Formal languages are very important in CS.
  - Especially in programming languages and compilers.
- Regular languages:
  - The weakest formal languages widely used.
  - Sufficient for many applications.
- We will also study context-free languages.

Limitations of Regular Languages

Intuition: A finite automaton that runs long enough must repeat states.

- A finite automaton *cannot remember* number of times it has visited a particular state ...
- ... because a finite automaton has finite memory.
  - Only enough to store in which state it is.
  - Cannot count, except up to a finite limit.
- Many languages are not regular.
- E.g., the language of balanced parentheses is not regular: $\{ (^n)^n \mid n \geq 0\}$

The Functionality of the Parser

- **Input:** sequence of tokens from lexer.
- **Output:** parse tree of the program.

Example

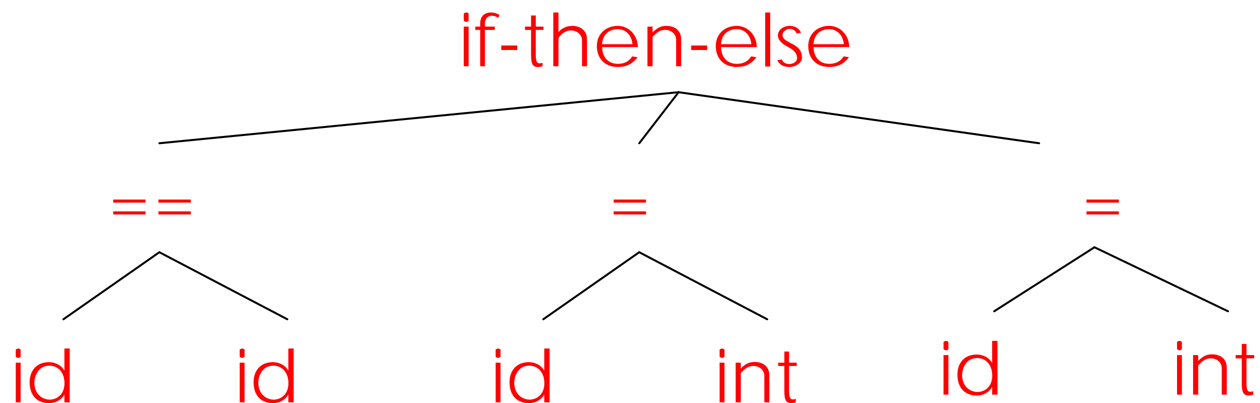
- If-then-else statement

```
if (x == y) then z = 1; else z = 2;
```

- Parser input (lexer output)

  if (id == id) then id = int; else id = int;

- Possible parser output



Comparison with Lexical Analysis

Phase	*Input*	*Output*
Lexer	Sequence of characters	Sequence of tokens
Parser	Sequence of tokens	Parse tree

The Role of the Parser

- Not all sequences of tokens are programs ...
- Parser must distinguish between valid and invalid sequences of tokens.

- We need:
  - A language for describing valid sequences of tokens.
  - A method for distinguishing valid from invalid sequences of tokens.

Context-Free Grammars

- Many programming language constructs have a recursive structure.

- E.g. A STMT is of the form:

  if COND then STMT else STMT , or

  while COND do STMT , or

  …

- Context-free grammars (CFGs) are a natural notation for this recursive structure.

CFGs (Cont.)

A CFG consists of

- A set of *terminals* T
- A set of *non-terminals* N
- A *start symbol* S (a non-terminal)
- A set of *productions*

Assuming $X \in N$ the productions are of the form

$X \to \varepsilon$, or

$X \to Y_1 \, Y_2 \, \ldots \, Y_n$ where $Y_i \in N \cup T$

Notational Conventions

- In these lecture notes:
  - Non-terminals are written upper-case.
  - Terminals are written lower-case.
  - The start symbol is the left-hand side of the first production.

Example: A small fragment of our language:

STMT → if COND then STMT else STMT
| while COND do STMT
| id = int

One More Example

Grammar for simple arithmetic expressions:

$$
\begin{aligned}
E \rightarrow\ & E * E \\
|\ & E + E \\
|\ & (E) \\
|\ & \text{int}
\end{aligned}
$$

The Language of a CFG

Read productions as replacement rules:

$X \rightarrow Y_1 \ldots Y_n$

Means X can be replaced by $Y_1 \ldots Y_n$ (in this order).

$X \rightarrow \varepsilon$

Means X can be erased (replaced with empty string).

Key Idea

(1) Begin with a string consisting of the start symbol "S"

(2) Replace any non-terminal X in the string by the right-hand side of some production

$$X \rightarrow Y_1 \ldots Y_n$$

(3) Repeat (2) until there are no non-terminals in the string

The Language of a CFG (Cont.)

More formally, we write

$$X_1 \cdots X_i \cdots X_n \to X_1 \cdots X_{i-1} Y_1 \cdots Y_m X_{i+1} \cdots X_n$$

if there is a production

$$X_i \to Y_1 \cdots Y_m$$

We write

$$X_1 \cdots X_n \overset{*}{\to} Y_1 \cdots Y_m$$

if

$$X_1 \cdots X_n \to \cdots \to \cdots \to Y_1 \cdots Y_m$$

in 0 or more steps.

The Language of a CFG (Cont.)

Let G be a context-free grammar with start symbol S. Then the language of G is:

$$\left\{ a_1 \ldots a_n \mid S \xrightarrow{*} a_1 \ldots a_n \text{ and every } a_i \text{ is a terminal} \right\}$$

Terminals

- Terminals are called so because there are no rules for replacing them.
- Once generated, terminals are permanent.
- Terminals ought to be tokens of the language.

Examples

L(G) is the language of the CFG G

Strings of balanced parentheses $\left\{ (^i)^i \mid i \geq 0 \right\}$

Two equivalent ways of writing the grammar G:

$$\begin{array}{lll} S & \rightarrow & (S) \\ S & \rightarrow & \varepsilon \end{array}$$

or

$$\begin{array}{lll} S & \rightarrow & (S) \\ & \mid & \varepsilon \end{array}$$

Example

A fragment of our example language (simplified):

```
STMT → if COND then STMT
     | if COND then STMT else STMT
     | while COND do STMT
     | id = int
COND → (id == id)
     | (id != id)
```

Example (Cont.)

Some elements of our example language:

id = int

if (id == id) then id = int else id = int

while (id != id) do id = int

while (id == id) do while (id != id) do id = int

if (id != id) then if (id == id) then id = int else id = int

Arithmetic Expressions Example

Grammar for simple arithmetic expressions:

$$E \rightarrow E + E \mid E * E \mid (E) \mid \text{int}$$

Some elements of the language:

int	int + int
(int)	int * int
(int) * int	int * (int)

Notes

The idea of a CFG is a big step.

But:

- Membership in a language is just "yes" or "no"; we also need the parse tree of the input.
- Must handle errors gracefully.
- Need an implementation of CFG's
  - e.g., yacc/bison/ML-yacc/...

Derivations and Parse Trees

A *derivation* is a sequence of productions:

$$S \to \cdots \to \cdots \to \cdots$$

A derivation can be drawn as a tree.

- Start symbol is the tree's root.
- For a production $X \to Y_1 \cdots Y_n$ add children $Y_1 \cdots Y_n$ to node X

Derivation Example

- Grammar

$$E \rightarrow E + E \mid E * E \mid (E) \mid \text{int}$$

- String

int * int + int

Derivation Example (Cont.)

$E \rightarrow E{+}E \mid E{*}E \mid (E) \mid$ int

E

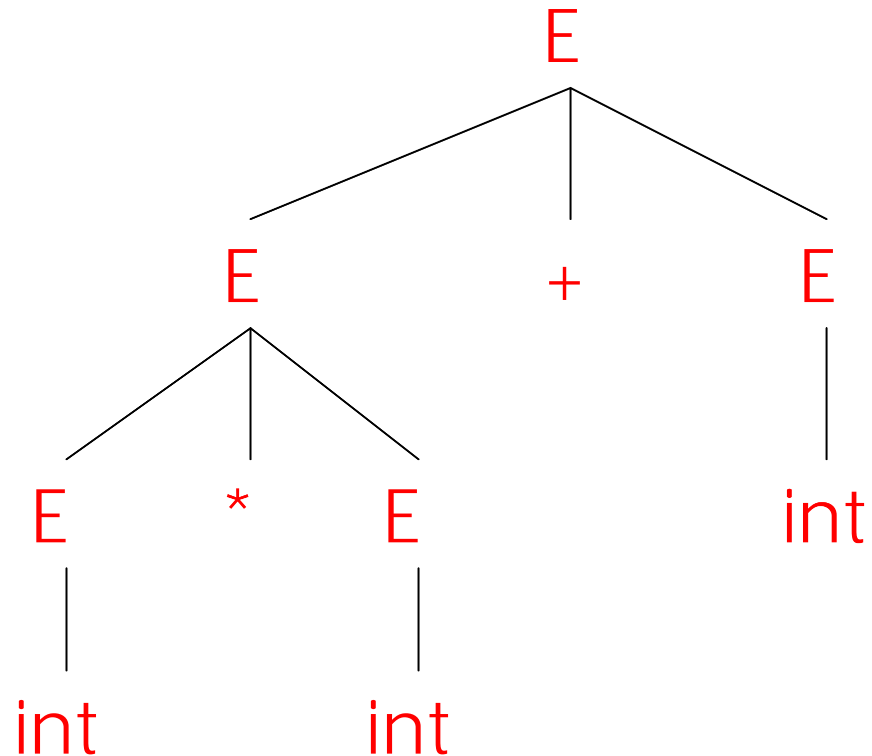
→ E + E

→ E * E + E

→ int * E + E

→ int * int + E

→ int * int + int



Derivation in Detail (1)

$E \rightarrow E+E \mid E*E \mid (E) \mid$ **int**

E

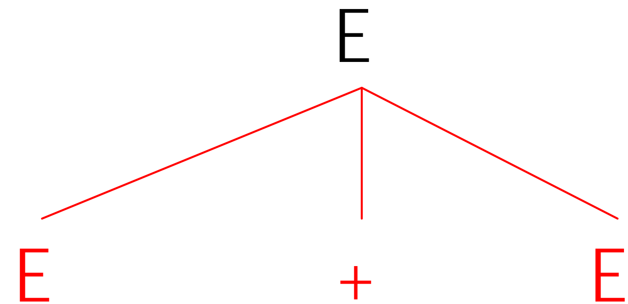
E

Derivation in Detail (2)

$E \rightarrow E+E \mid E*E \mid (E) \mid int$

E

$\rightarrow$ E + E



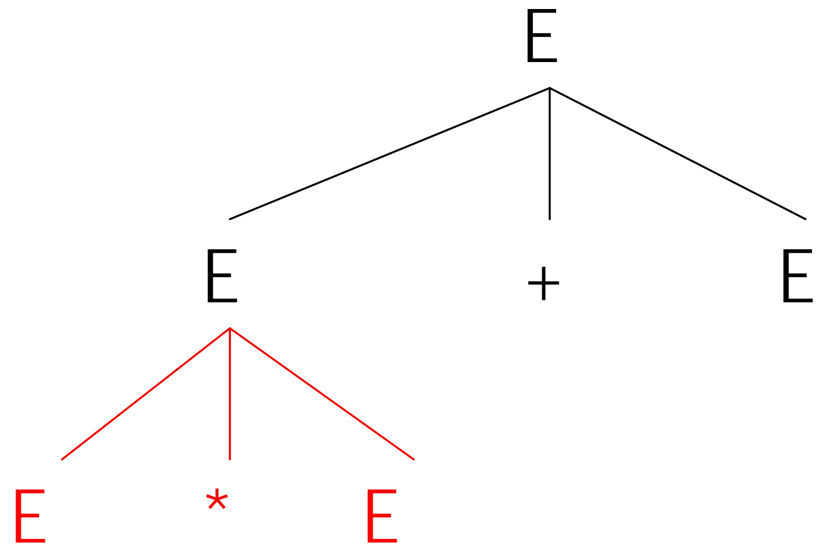
Derivation in Detail (3)

$E \rightarrow E+E \mid E^*E \mid (E) \mid$ int

E

$\rightarrow$ E + E

$\rightarrow$ E * E + E



Derivation in Detail (4)

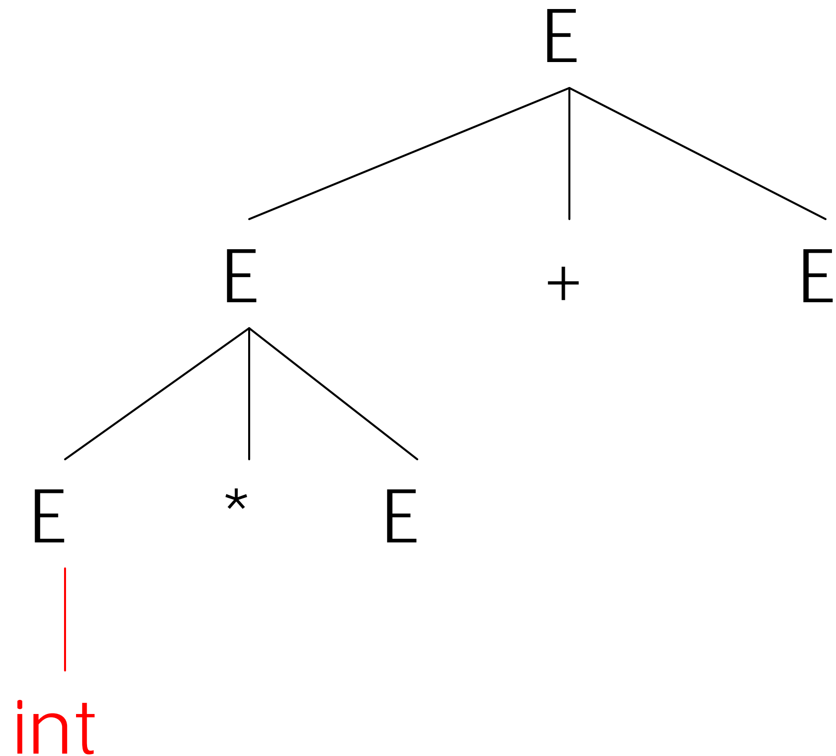
$E \rightarrow E+E \mid E{*}E \mid (E) \mid$ int

E

→ E + E

→ E * E + E

→ int * E + E



Derivation in Detail (5)

E → E+E | E*E | (E) | int

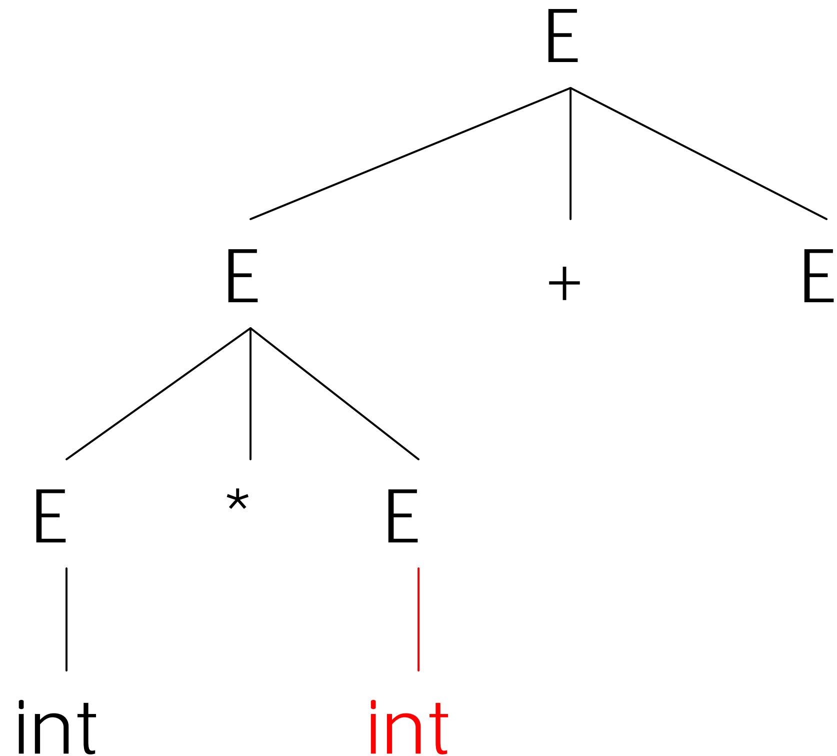
E

→ E + E

→ E * E + E

→ int * E + E

→ int * int + E



Derivation in Detail (6)

$E \rightarrow E+E \mid E*E \mid (E) \mid int$

E

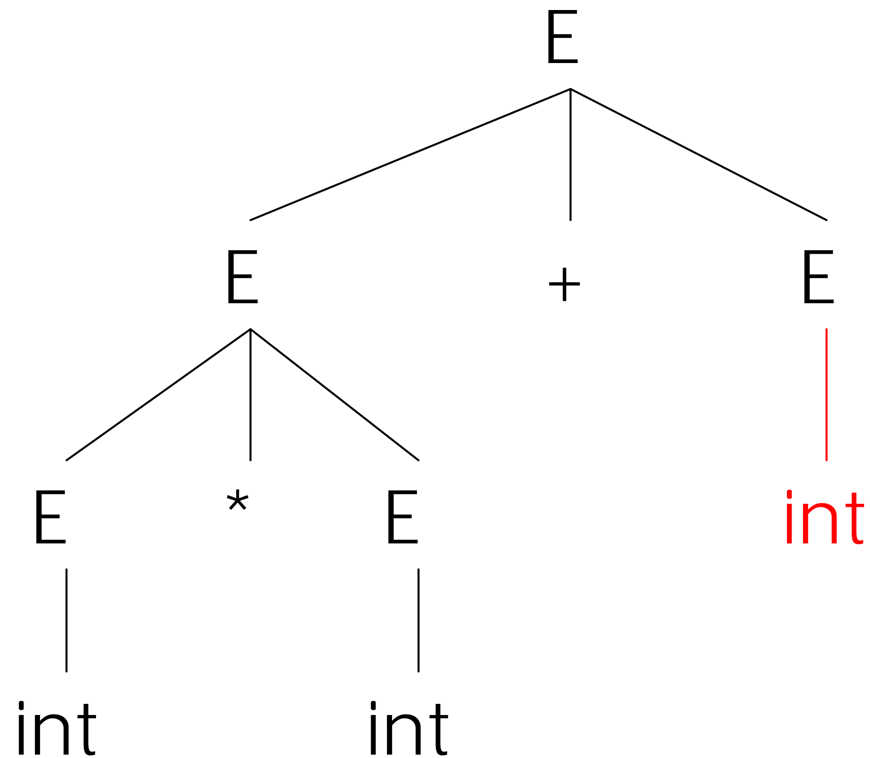
→ E + E

→ E * E + E

→ int * E + E

→ int * int + E

→ int * int + int



Notes on Derivations

- A parse tree has:
  - terminals at the leaves;
  - non-terminals at the interior nodes.
- An in-order traversal of the leaves is the original input.
- The parse tree shows the association of operations; the input string does not !

Left-most and Right-most Derivations

- What was shown before was a *left-most derivation*.
  - At each step, we replaced the left-most non-terminal.
- There is an equivalent notion of a *right-most derivation*.
  - Shown on the right.

E → E+E | E*E | (E) | int

E
→ E + E
→ E + int
→ E * E + int
→ E * int + int
→ int * int + int

Right-most Derivation in Detail (1)

E → E+E | E*E | (E) | int

E

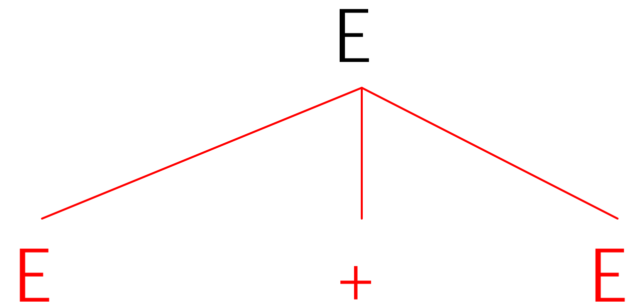
E

Right-most Derivation in Detail (2)

$E \rightarrow E+E \mid E*E \mid (E) \mid \textbf{int}$

E

$\rightarrow$ E + E



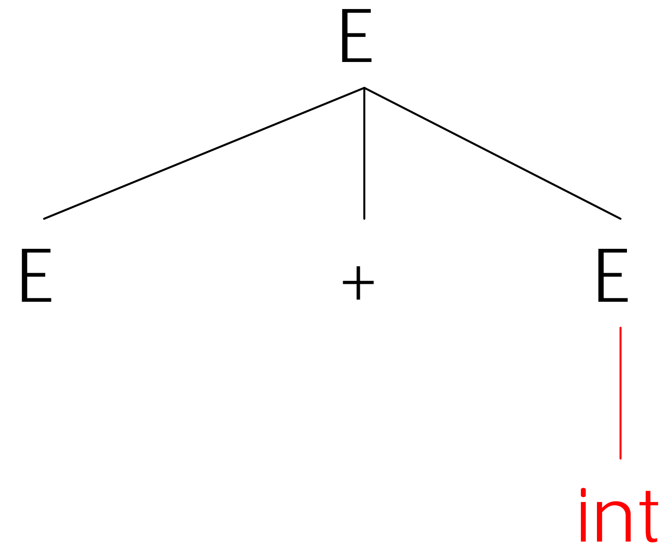
Right-most Derivation in Detail (3)

$E \rightarrow E+E \mid E*E \mid (E) \mid$ int

E

$\rightarrow$ E + E

$\rightarrow$ E + int



Right-most Derivation in Detail (4)

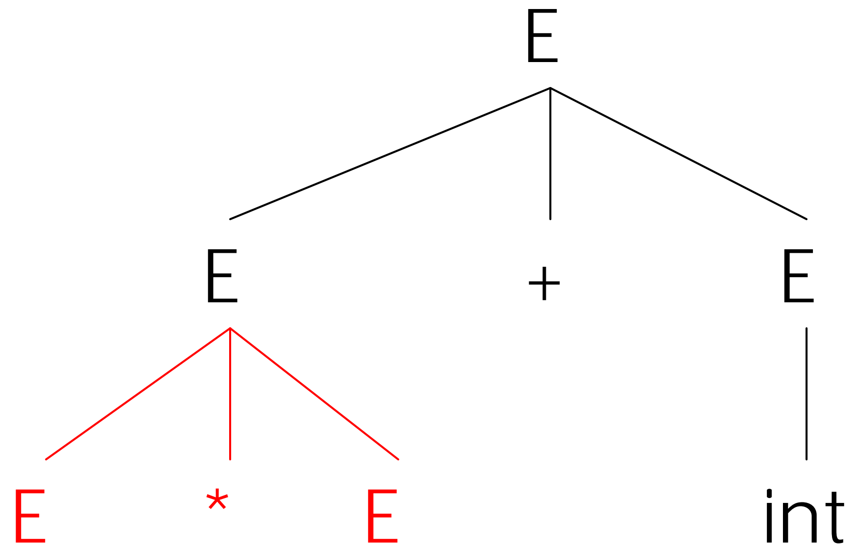
$E \rightarrow E+E \mid E*E \mid (E) \mid \text{int}$

E

→ E + E

→ E + int

→ E * E + int



Right-most Derivation in Detail (5)

$E \to E+E \mid E*E \mid (E) \mid int$

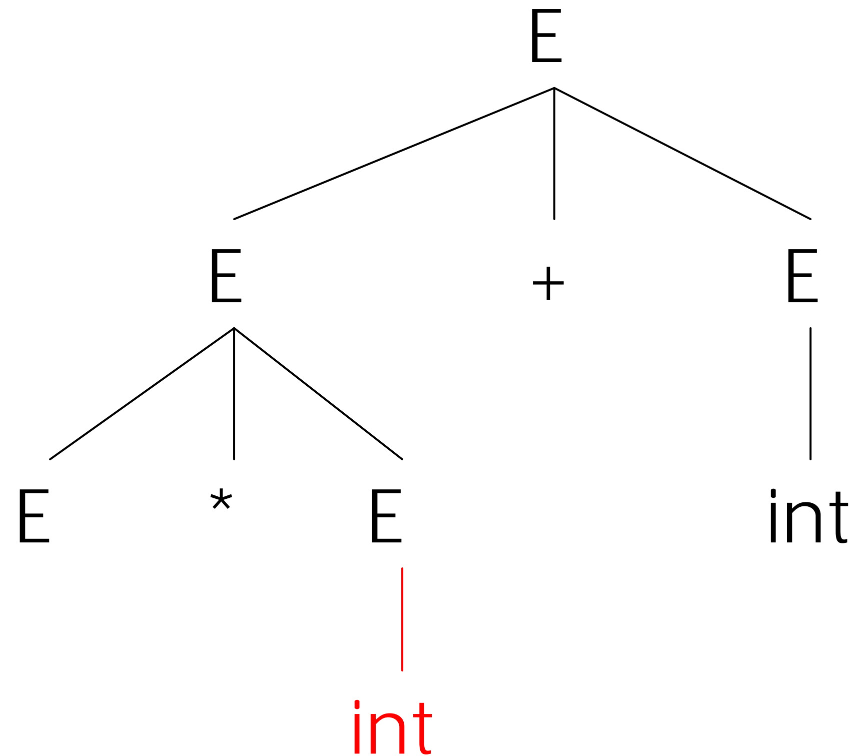
E

→ E + E

→ E + int

→ E * E + int

→ E * int + int



Right-most Derivation in Detail (6)

$E \rightarrow E+E \mid E*E \mid (E) \mid int$

E

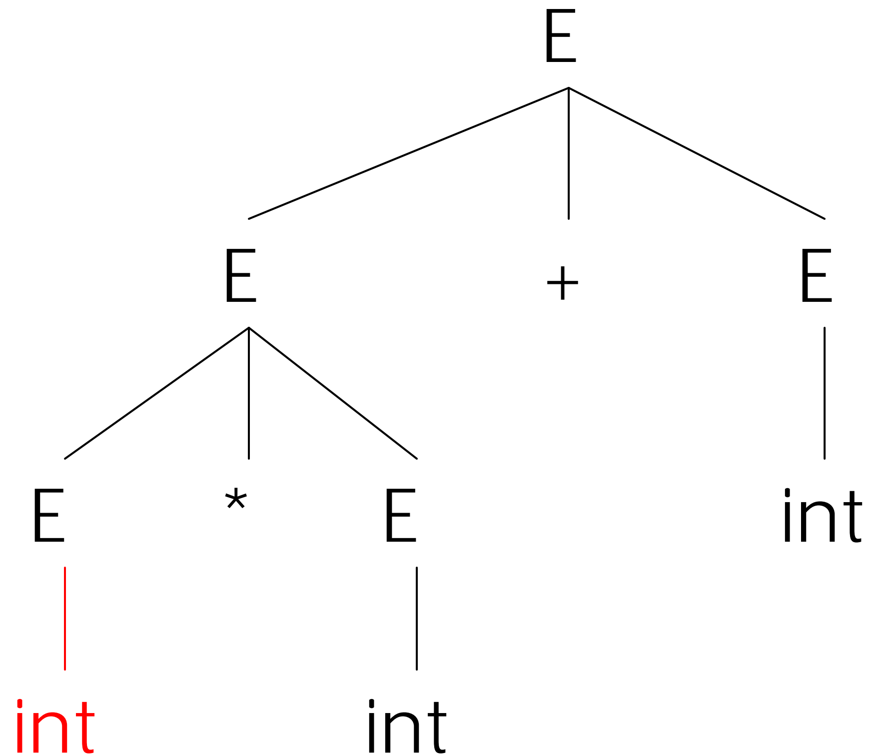
→ E + E

→ E + int

→ E * E + int

→ E * int + int

→ int * int + int



Derivations and Parse Trees

- Note that:
  - Right-most and left-most derivations have the same parse tree.
  - For each parse tree, there is a right-most and a left-most derivation.

- The difference *is just in the order* in which branches are added.

Summary of Derivations

- We are not just interested in whether

$$s \in L(G)$$

  - We also need a parse tree for s.

- A derivation defines a parse tree.
  - But one parse tree may have many derivations.

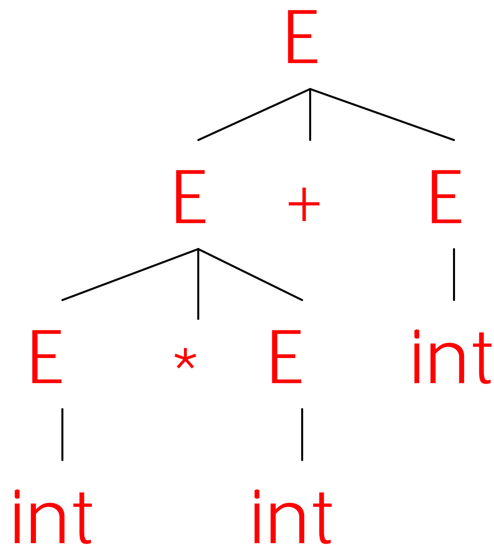
- Left-most and right-most derivations are important in parser implementation.

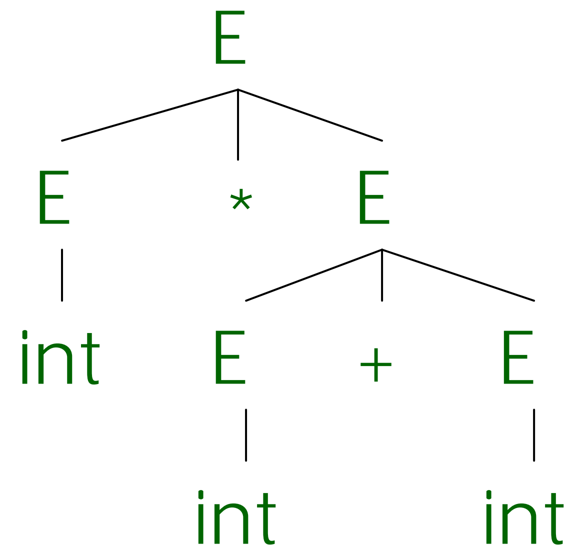
Ambiguity

- Grammar:

  E → E + E | E * E | (E) | int

- The string int * int + int has two parse trees





Ambiguity (Cont.)

- A grammar is *ambiguous* if it has more than one parse tree for some string.
  - Equivalently, if there is more than one right-most or left-most derivation for some string.
- Ambiguity is <u>bad</u> in programming languages.
  - Leaves meaning of some programs ill-defined.
- Ambiguity is <u>common</u> in programming languages:
  - Arithmetic expressions
  - IF-THEN-ELSE

Dealing with Ambiguity

- There are several ways to handle ambiguity.
- Most direct method is to rewrite the grammar unambiguously:

$$E \rightarrow T + E \mid T$$
$$T \rightarrow \text{int} * T \mid \text{int} \mid (E)$$

- This grammar enforces precedence of * over +.

Ambiguity: The Dangling Else

- Consider the following grammar:

$$
\begin{aligned}
S \rightarrow\ & \text{if } C \text{ then } S \\
\mid\ & \text{if } C \text{ then } S \text{ else } S \\
\mid\ & \text{OTHER}
\end{aligned}
$$

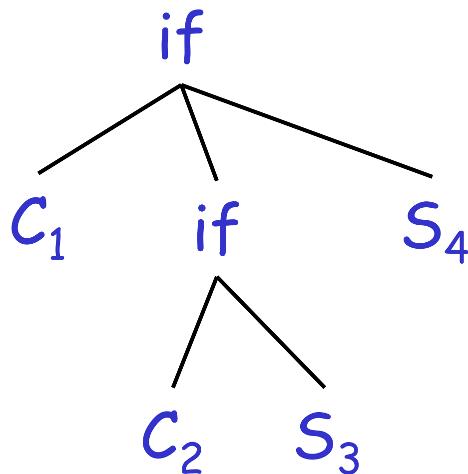
- This grammar is also ambiguous.

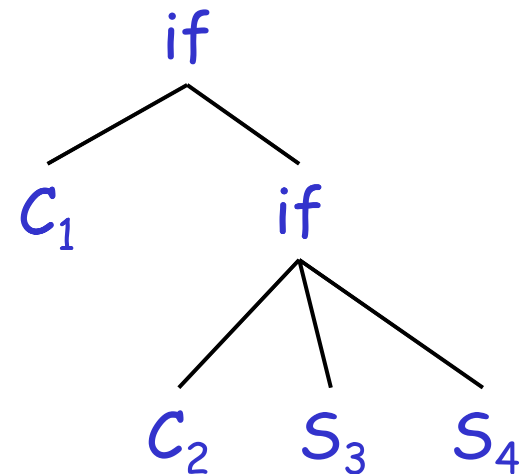
The Dangling Else: Example

- The expression

  if C_1 then if C_2 then S_3 else S_4

  has two parse trees.





- Typically we want the second form.

The Dangling Else: A Fix

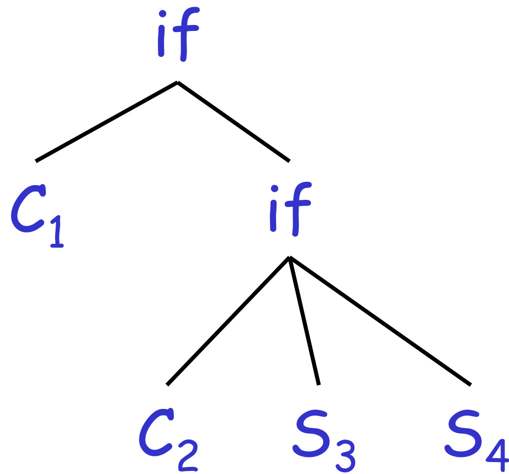
- else should match the closest unmatched then
- We can describe this in the grammar:

```
S → MIF                    /* all then are matched */
  | UIF                    /* some then are unmatched */
MIF → if C then MIF else MIF
    | OTHER
UIF → if C then S
    | if C then MIF else UIF
```

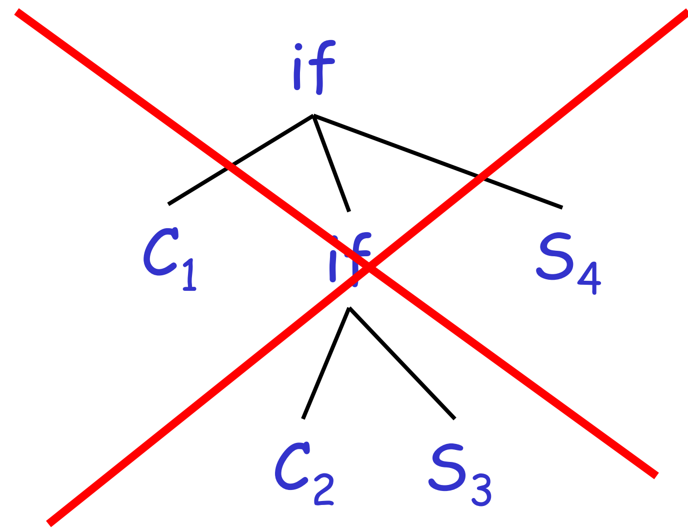
- Describes the same set of strings.

The Dangling Else: Example Revisited

The expression if C_1 then if C_2 then S_3 else S_4



A valid parse tree (for a UIF).



Not valid because the then expression is not a MIF.

Ambiguity

- No general techniques for handling ambiguity.
- In general, impossible to convert automatically an ambiguous grammar to an unambiguous one.
- Used with care, ambiguity can simplify the grammar.
  - Sometimes allows more natural definitions.
  - However, we need disambiguation mechanisms.

Precedence and Associativity Declarations

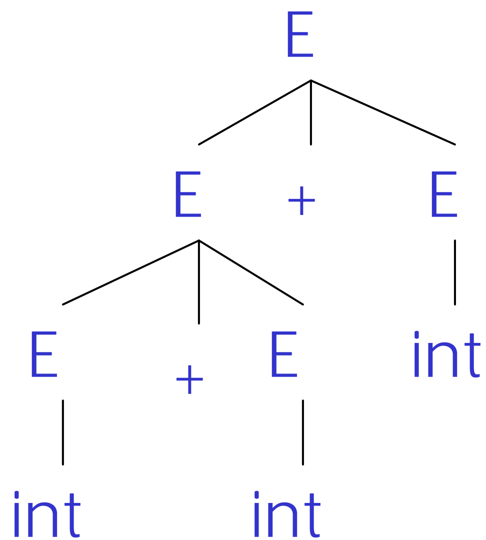
- Instead of rewriting the grammar:
  - use the more natural (ambiguous) grammar,
  - along with disambiguating declarations.

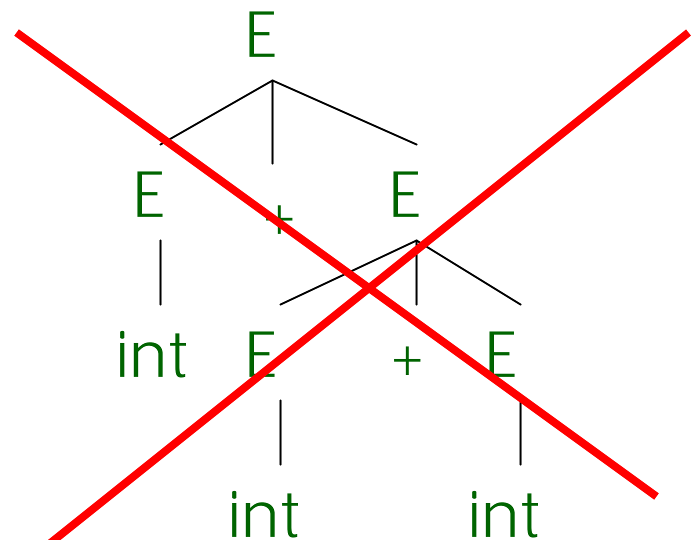
- Most tools allow precedence and associativity declarations to disambiguate grammars.

- Examples …

Associativity Declarations

- Consider the grammar $E \to E + E \mid \text{int}$
- Ambiguous: two parse trees of int + int + int

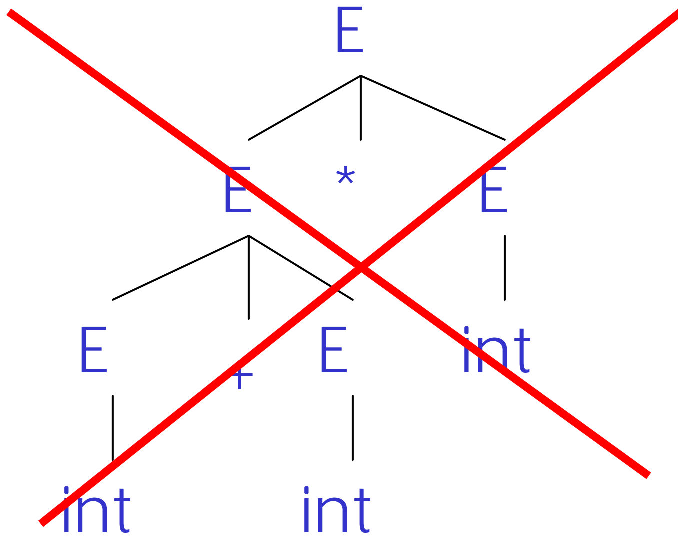


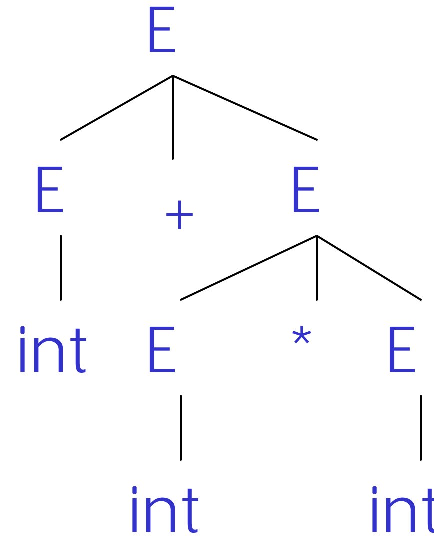


- Left associativity declaration: `%left +`

Precedence Declarations

- Consider the grammar $E \rightarrow E + E \mid E * E \mid$ int and the string int + int * int





- Precedence declarations: **%left +**

  %left *

Error Handling

- Purpose of the compiler is:
  - To detect non-valid programs.
  - To translate the valid ones.
- Many kinds of possible errors (e.g. in C)

Error kind	Example	Detected by ...
Lexical	... $ ...	Lexer
Syntax	... x *% ...	Parser
Semantic	... int x; y = x(3); ...	Type checker
Correctness	your favorite program	Tester/User

Syntax Error Handling

- Error handler should:
  - Report errors accurately and clearly.
  - Recover from an error quickly.
  - Not slow down compilation of valid code.

- Good error handling is not easy to achieve.

Approaches to Syntax Error Recovery

- From simple to complex:
  - Panic mode.
  - Error productions.
  - Automatic local or global correction.

- Not all are supported by all parser generators.

Error Recovery: Panic Mode

- Simplest, most popular method.
- When an error is detected:
  - Discard tokens until one with a clear role is found.
  - Continue from there.
- Such tokens are called synchronizing tokens.
  - Typically the statement or expression terminators.

Syntax Error Recovery: Panic Mode (Cont.)

- Consider the erroneous expression:

  (1 + + 2) + 3

- Panic-mode recovery:
  - Skip ahead to next integer and then continue.

- (ML)-Yacc: use the special terminal **error** to describe how much input to skip:

  $E \rightarrow$ int | E + E | (E) | **error** int | (**error**)

Syntax Error Recovery: Error Productions

- Idea: specify some recovery rules in the grammar based on known common mistakes.
- Essentially promotes common errors to alternative syntax.
- Example:
  - Write 5 x instead of 5 * x
  - Add the production $E \to \ldots \mid E\ E$
- Disadvantage:
  - Complicates the grammar.

Syntax Error Recovery: Past and Present

- (Distant) Past
  - Slow recompilation cycle (even once a day!).
  - Goal: find as many errors in one cycle as possible.
  - Researchers could not let go of the topic.

- Present
  - Quick recompilation cycle.
  - Users tend to correct one error/cycle.
  - Complex error recovery is needed less.
  - Panic-mode seems enough.