Programming Language Concepts

Chapter 3

Describing Syntax and Semantics

Review

- Syntax is the description of which strings of symbols are meaningful expressions in a language
- It takes more than syntax to understand a language; need meaning (semantics) too
- Syntax is the entry point

Features of a Good Syntax

- Readable
- Writeable
- Lack of ambiguity
- Suggestive of correct meaning
- Ease of translation

Elements of Syntax

- Character set – typically ASCII
- Keywords – usually reserved
- Special constants – cannot be assigned to
- Identifiers – can be assigned to
- Operator symbols (+, -, *)
- Delimiters (parenthesis, braces, brackets,)
- Blanks (white space)

Elements of Syntax

- Expressions
- Type expressions
- Declarations
- Statements (in imperative languages)
- Subprograms (subroutines)

Elements of Syntax

- Modules
- Interfaces
- Classes (for object-oriented languages)
- Libraries

Grammars

- Grammars are formal descriptions of which strings over a given character set are in a particular language
- Language designers write grammar
- Language implementers use grammar to know what programs to accept
- Language users use grammar to know how to write legitimate programs

Sample Grammar

- Language: Parenthesized sums of 0’s and 1’s

- <Sum> ::= 0
- <Sum >::= 1
- <Sum> ::= <Sum> + <Sum>
- <Sum> ::= (<Sum>)

BNF Grammars

- Start with a set of characters, **a,b,c,…**
  - We call these *terminals*
- Add a set of different characters, **X,Y,Z,…**
  - We call these *non-terminals*
- One special non-terminal **S** called *start symbol*

BNF Grammars

- BNF rules (productions) have form

  X ::= *y*

  where **X** is any non-terminal and *y* is a string of terminals and non-terminals
- BNF grammar is a set of BNF rules such that every non-terminal appears on the left of some rule

Sample Grammar

- Terminals: 0 1 + ( )
- Non-terminals: <Sum>
- Start symbol = <Sum>

<Sum> ::= 0
<Sum >::= 1
<Sum> ::= <Sum> + <Sum>
<Sum> ::= (<Sum>)
Can be abbreviated as
<Sum> ::= 0 | 1 | <Sum> + <Sum> | (<Sum>)

BNF Derivations

- Given rules

$$\mathbf{X ::=}\ y\mathbf{Z}w \text{ and } \mathbf{Z}::=v$$

we may replace **Z** by *v* to say

$$\mathbf{X} \Rightarrow y\mathbf{Z}w \Rightarrow yvw$$

BNF Derivations

- Start with the start symbol:

<Sum> =>

BNF Derivations

- Pick a non-terminal

<Sum> =>

BNF Derivations

- Pick a rule and substitute:
  - <Sum> ::= <Sum> + <Sum>

<Sum> => <Sum> + <Sum >

BNF Derivations

- Pick a non-terminal:

<Sum> => <Sum> + <Sum >

BNF Derivations

- Pick a rule and substitute:
  - <Sum> ::= (<Sum>)

<Sum> => <Sum> + <Sum >

=> (<Sum>) + <Sum>

BNF Derivations

- Pick a non-terminal:

<Sum> => <Sum> + <Sum >

=> (<Sum>) + <Sum>

BNF Derivations

- Pick a rule and substitute:
  - <Sum> ::= <Sum> + <Sum>

<Sum> => <Sum> + <Sum >

=> (<Sum>) + <Sum>

=> (<Sum> + <Sum>) + <Sum>

BNF Derivations

- Pick a non-terminal:

<Sum> => <Sum> + <Sum >

=> (<Sum>) + <Sum>

=> (<Sum> + <Sum>) + <Sum>

BNF Derivations

- Pick a rule and substitute:
  - <Sum >::= 1

<Sum> => <Sum> + <Sum >

=> (<Sum>) + <Sum>

=> (<Sum> + <Sum>) + <Sum>

=> (<Sum> + 1) + <Sum>

BNF Derivations

- Pick a non-terminal:

<Sum> => <Sum> + <Sum >

=> (<Sum>) + <Sum>

=> (<Sum> + <Sum>) + <Sum>

=> (<Sum> + 1) + <Sum>

BNF Derivations

- Pick a rule and substitute:
  - <Sum >::= 0

<Sum> => <Sum> + <Sum >

=> (<Sum>) + <Sum>

=> (<Sum> + <Sum>) + <Sum>

=> (<Sum> + 1) + <Sum>

=> (<Sum> + 1) + 0

BNF Derivations

- Pick a non-terminal:

<Sum> => <Sum> + <Sum >

=> (<Sum>) + <Sum>

=> (<Sum> + <Sum>) + <Sum>

=> (<Sum> + 1) + <Sum>

=> (<Sum> + 1) + 0

BNF Derivations

- Pick a rule and substitute
  - <Sum> ::= 0

<Sum> => <Sum> + <Sum >

=> (<Sum>) + <Sum>

=> (<Sum> + <Sum>) + <Sum>

=> (<Sum> + 1) + <Sum>

=> (<Sum> + 1) 0

=> (0 + 1) + 0

BNF Derivations

- (0 + 1) + 0 is generated by grammar

<Sum> => <Sum> + <Sum >
=> (<Sum>) + <Sum>
=> (<Sum> + <Sum>) + <Sum>
=> (<Sum> + 1) + <Sum>
=> (<Sum> + 1) + 0
=> (0 + 1) + 0

BNF Semantics

- The meaning of a BNF grammar is the set of all strings consisting only of terminals that can be derived from the Start symbol

Remember Parse Trees

- Graphical representation of a derivation
- Each node labeled with either a non-terminal or a terminal
- If node is labeled with a terminal, then it is a leaf (no sub-trees)
- If node is labeled with a terminal, then it has one branch for each character in the right-hand side of rule used to substitute for it

Example

- Consider grammar:

  <exp> ::= <factor>

  | <factor> + <factor>

  <factor> ::= <bin>

  | <bin> * <exp>

  <bin> ::= 0 | 1

- Build parse tree for 1 * 1 + 0 as an <exp>

Example cont.

- 1 * 1 + 0:   <exp>

<exp> is the start symbol for this parse tree

Example cont.

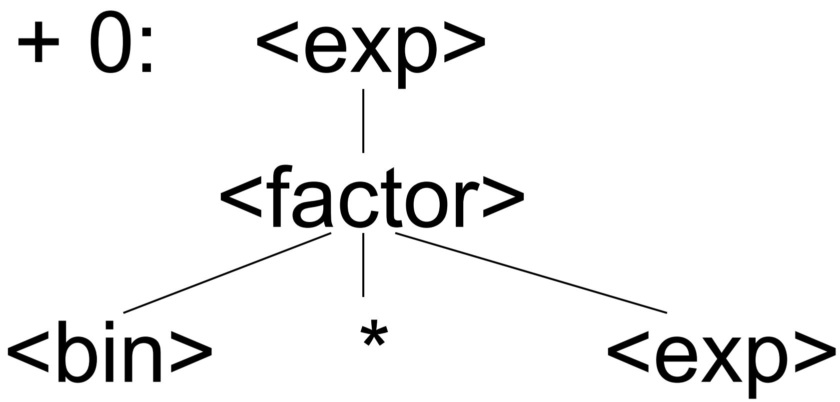
- 1 * 1 + 0: <exp>

<factor>

Use rule: <exp> ::= <factor>

Example cont.

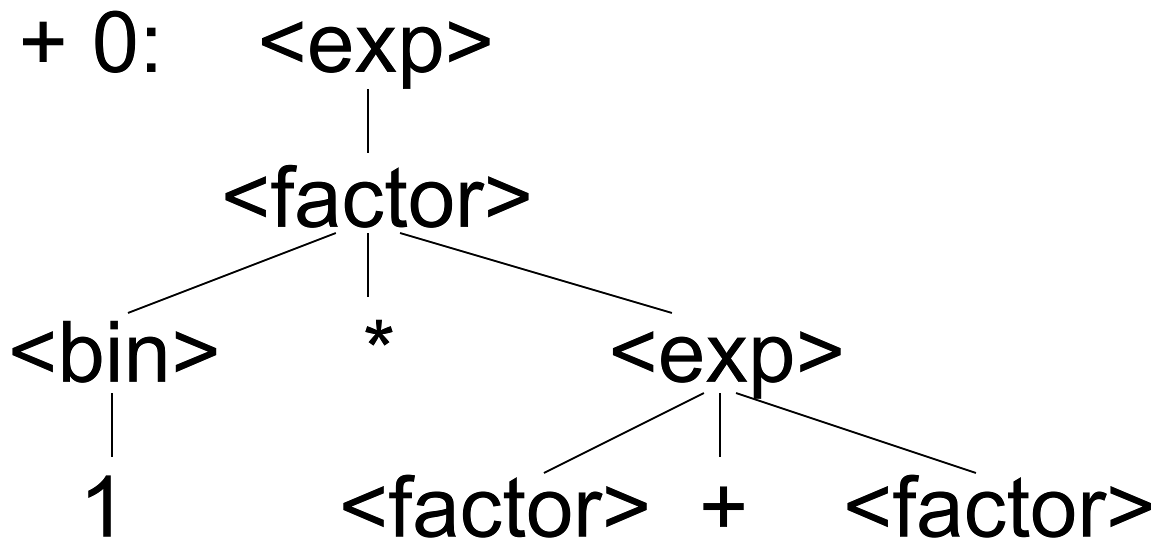
- 1 * 1 + 0:



Use rule: <factor> ::= <bin> * <exp>

Example cont.

- 1 * 1 + 0:

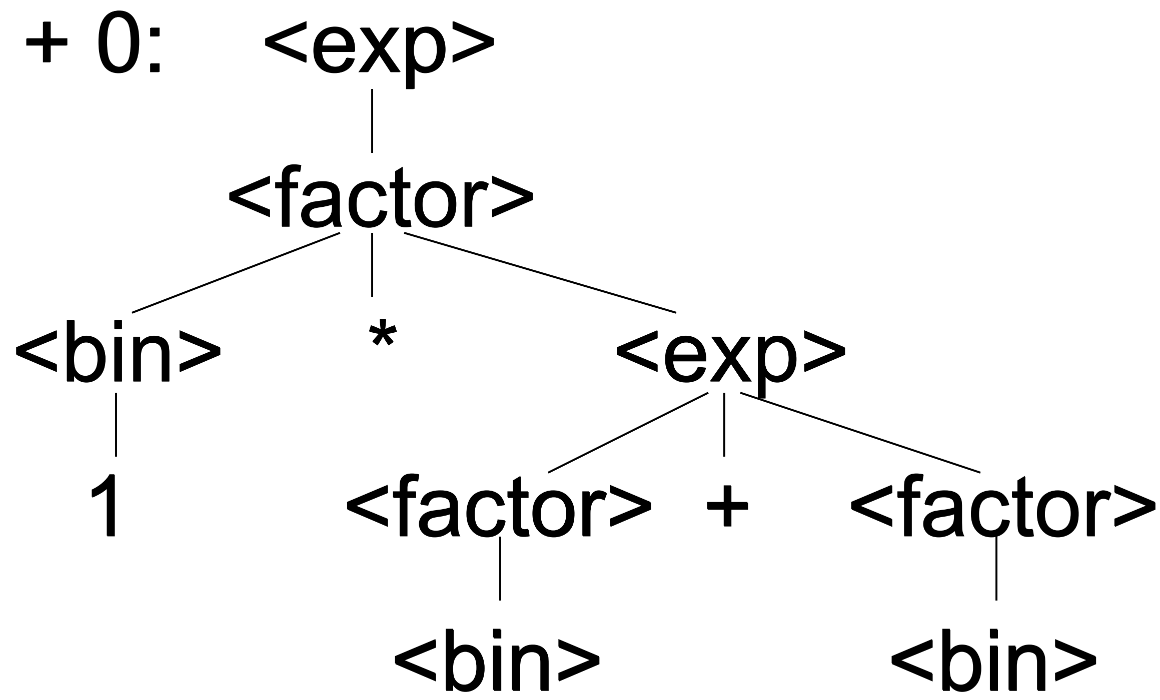


Use rules: <bin> ::= 1 and

<exp> ::= <factor> + <factor>

Example cont.

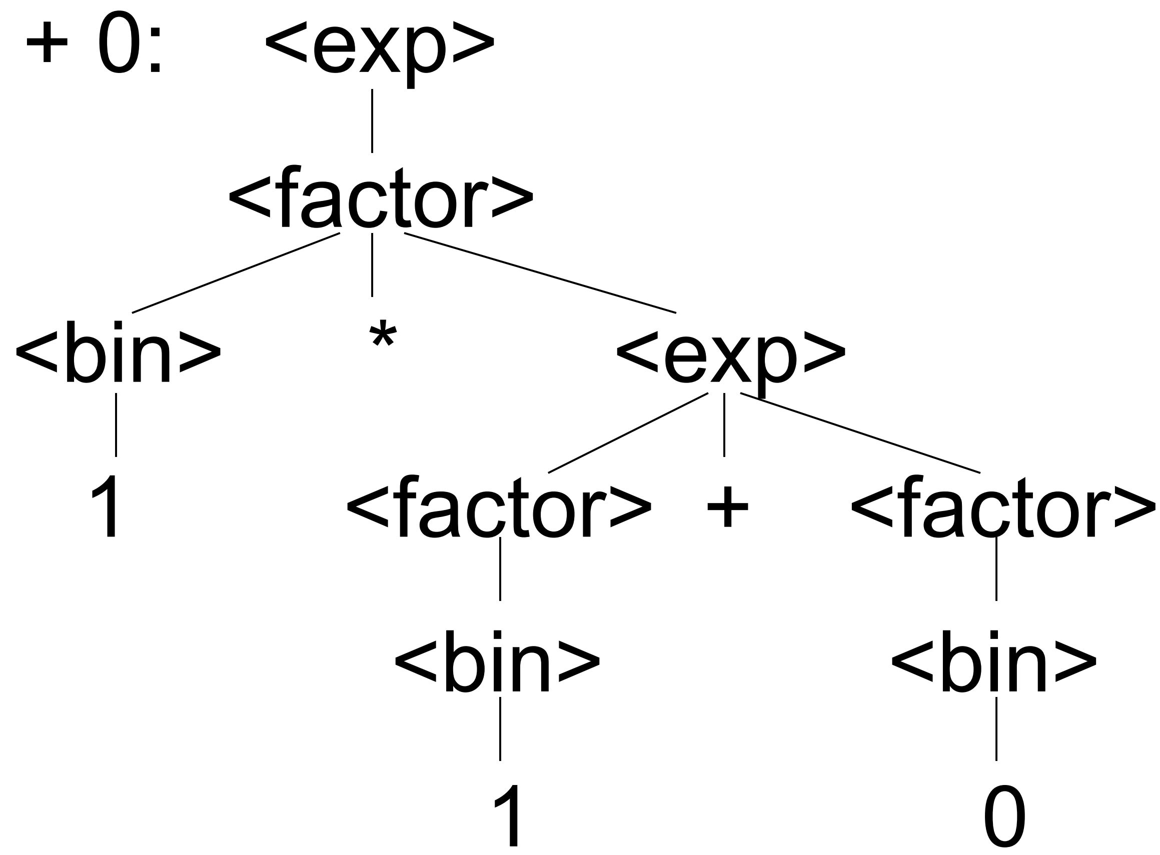
- 1 * 1 + 0:



Use rule: <factor> ::= <bin>

Example cont.

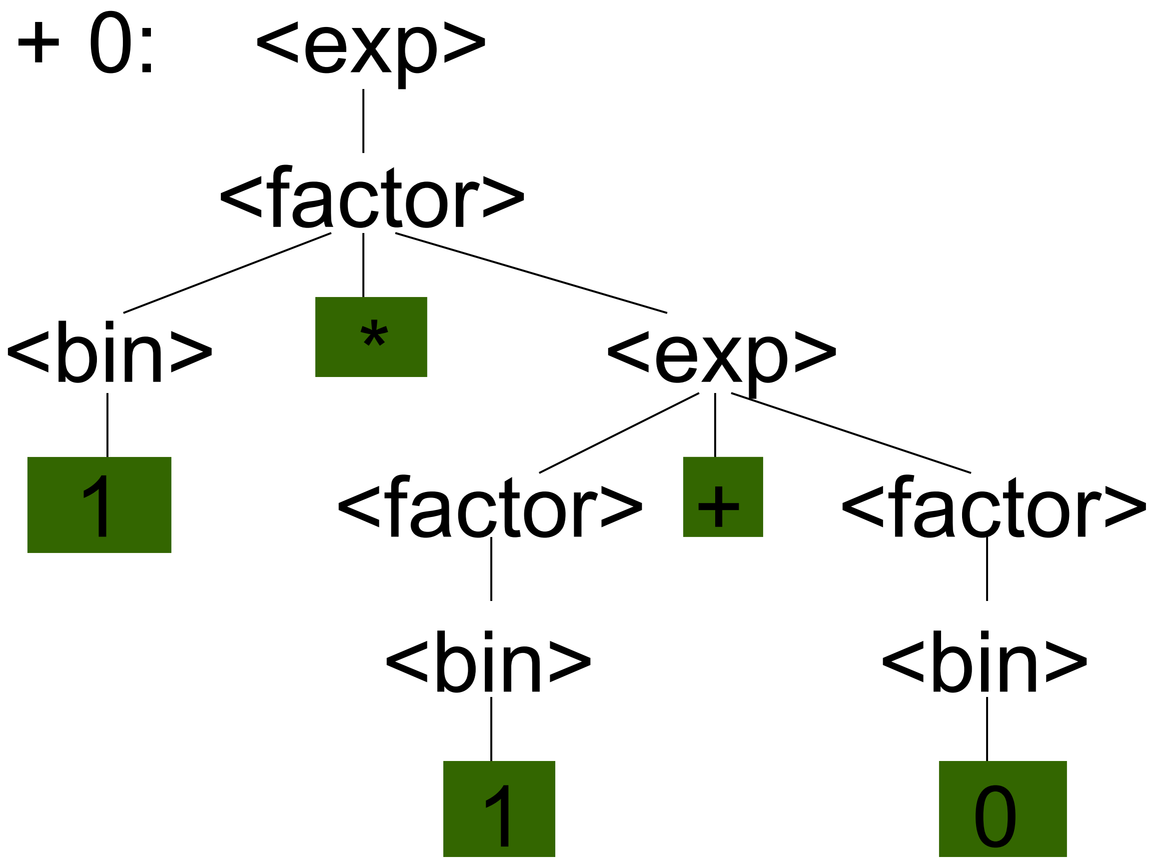
- 1 * 1 + 0:



Use rules: <bin> ::= 1 | 0

Example cont.

- 1 * 1 + 0:



Fringe of tree is string generated by grammar

Where Syntax Meets Semantics

Three “Equivalent” Grammars

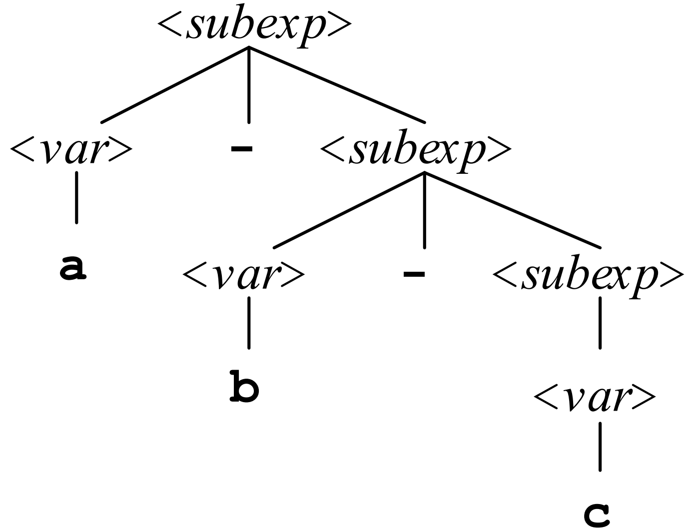
G1: <*subexp*> `::=` **`a`** | **`b`** | **`c`** | <*subexp*> **`-`** <*subexp*>

G2: <*subexp*> `::=` <*var*> **`-`** <*subexp*> | <*var*>
<*var*> `::=` **`a`** | **`b`** | **`c`**

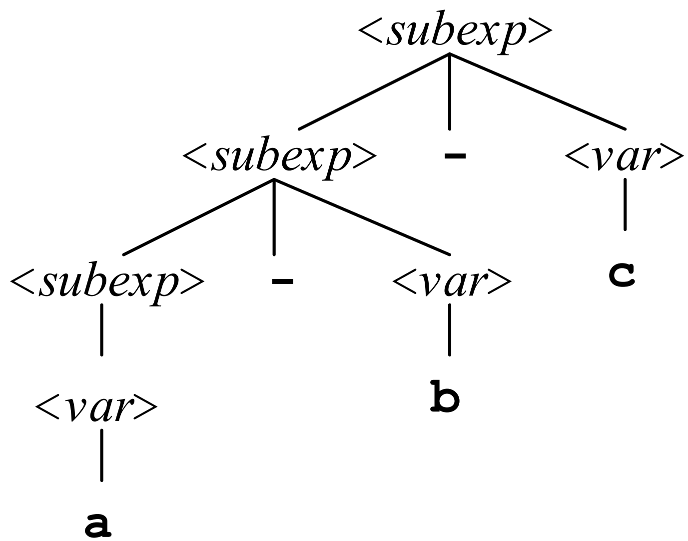
G3: <*subexp*> `::=` <*subexp*> **`-`** <*var*> | <*var*>
<*var*> `::=` **`a`** | **`b`** | **`c`**

These grammars all define the same language: the language of strings that contain one or more **a**s, **b**s or **c**s separated by minus signs.

G2 parse tree:



G3 parse tree:



Why Parse Trees Matter

- We want the structure of the parse tree to correspond to the semantics of the string it generates
- This makes grammar design much harder: we're interested in the structure of each parse tree, not just in the generated string
- Parse trees are where syntax meets semantics

Outline

- Operators
- Precedence
- Associativity
- Ambiguities
- Cluttered grammars
- Parse trees and EBNF
- Abstract syntax trees

Operators

- Special syntax for frequently-used simple operations like addition, subtraction, multiplication and division
- The word *operator* refers both to the token used to specify the operation (like **+** and *****) and to the operation itself
- Usually predefined, but not always
- Usually a single token, but not always

Operator Terminology

- *Operands* are the inputs to an operator, like **`1`** and **`2`** in the expression **`1+2`**
- *Unary* operators take one operand: **`-1`**
- *Binary* operators take two: **`1+2`**
- *Ternary* operators take three: **`a?b:c`**

More Operator Terminology

- In most programming languages, binary operators use an *infix* notation: **`a + b`**
- Sometimes you see *prefix* notation: **`+ a b`**
- Sometimes *postfix* notation: **`a b +`**
- Unary operators, similarly:
  - (Can’t be infix, of course)
  - Can be prefix, as in **`–1`**
  - Can be postfix, as in **`a++`**

Outline

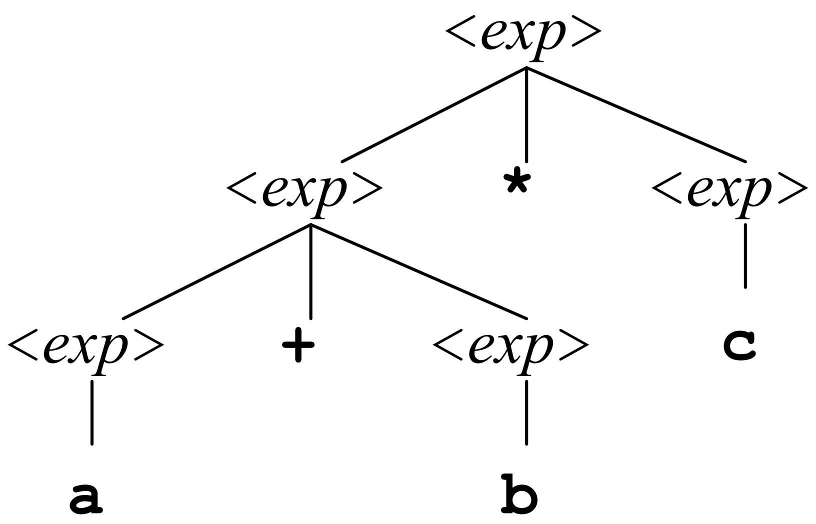
- Operators
- Precedence
- Associativity
- Ambiguities
- Cluttered grammars
- Parse trees and EBNF
- Abstract syntax trees

Working Grammar

G4: *<exp>* **::=** *<exp>* **+** *<exp>*
| *<exp>* ***** *<exp>*
| **(***<exp>***)**
| **a** | **b** | **c**

This generates a language of arithmetic expressions using parentheses, the operators **+** and *****, and the variables **a**, **b** and **c**

Issue #1: Precedence



Our grammar generates this tree for **a+b*c**. In this tree, the addition is performed before the multiplication, which is not the usual convention for operator *precedence*.

Operator Precedence

- Applies when the order of evaluation is not completely decided by parentheses
- Each operator has a *precedence level*, and those with higher precedence are performed before those with lower precedence, as if parenthesized
- Most languages put `*` at a higher precedence level than `+`, so that

```
a+b*c = a+(b*c)
```

Precedence Examples

- C (15 levels of precedence—too many?)

```
a = b < c ? * p + b * c : 1 << d ()
```

- Pascal (5 levels—not enough?)

```
a <= 0 or 100 <= a
```

Error!

- Smalltalk (1 level for all binary operators)

```
a + b * c
```

Precedence In The Grammar

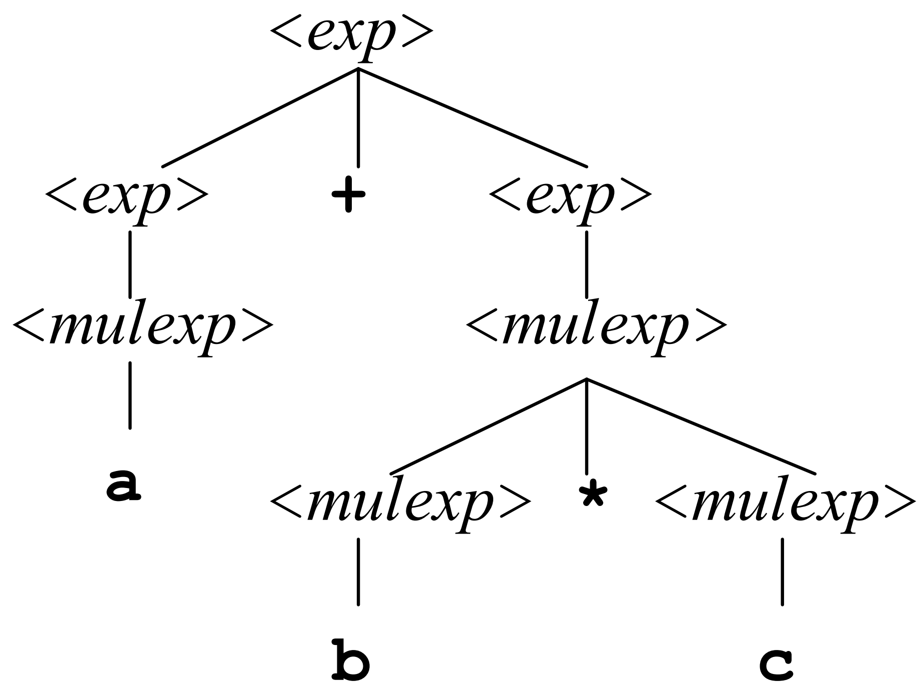
```
G4:   <exp> ::= <exp> + <exp>
              | <exp> * <exp>
              | (<exp>)
              | a | b | c
```

To fix the precedence problem, we modify the grammar so that it is forced to put ***** below **+** in the parse tree.

```
G5:   <exp> ::= <exp> + <exp> | <mulexp>
      <mulexp> ::= <mulexp> * <mulexp>
                 | (<exp>)
                 | a | b | c
```

Correct Precedence

G5 parse tree:

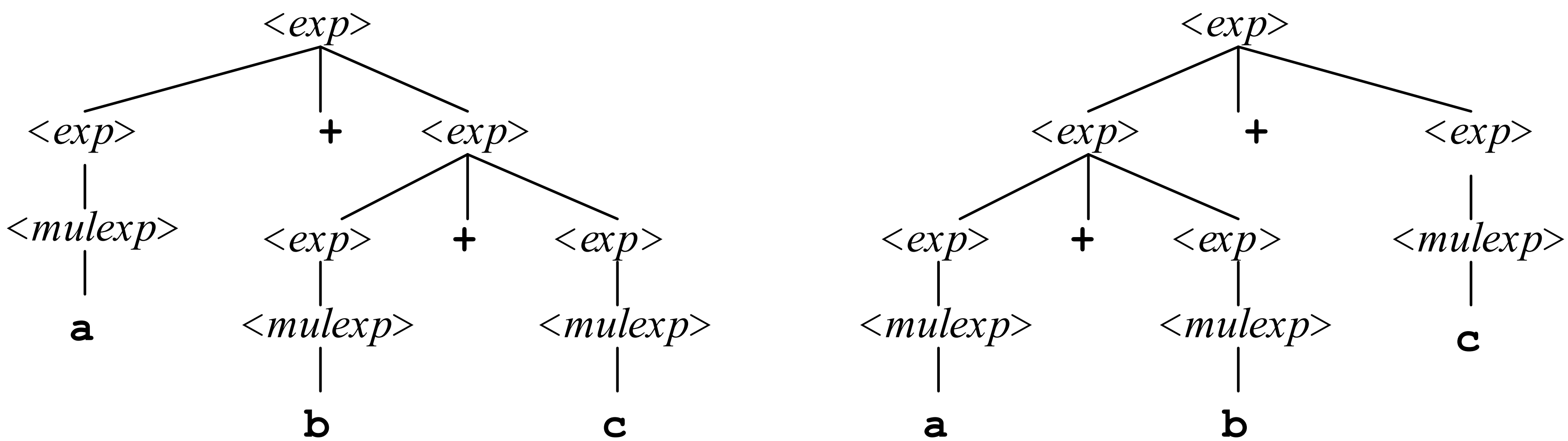


Our new grammar generates this tree for **a+b*c**. It generates the same language as before, but no longer generates parse trees with incorrect precedence.

Outline

- Operators
- Precedence
- Associativity
- Ambiguities
- Cluttered grammars
- Parse trees and EBNF
- Abstract syntax trees

Issue #2: Associativity



Our grammar G5 generates both these trees for **a+b+c**. The first one is not the usual convention for operator *associativity*.

Operator Associativity

- Applies when the order of evaluation is not decided by parentheses or by precedence
- *Left-associative* operators group left to right: `a+b+c+d = ((a+b)+c)+d`
- *Right-associative* operators group right to left: `a+b+c+d = a+(b+(c+d))`
- Most operators in most languages are left-associative, but there are exceptions

Associativity Examples

- C
- ML
- Fortran

`a<<b<<c` — most operators are left-associative
`a=b=0` — right-associative (assignment)

`3-2-1` — most operators are left-associative
`1::2::nil` — right-associative (list builder)

`a/b*c` — most operators are left-associative
`a**b**c` — right-associative (exponentiation)

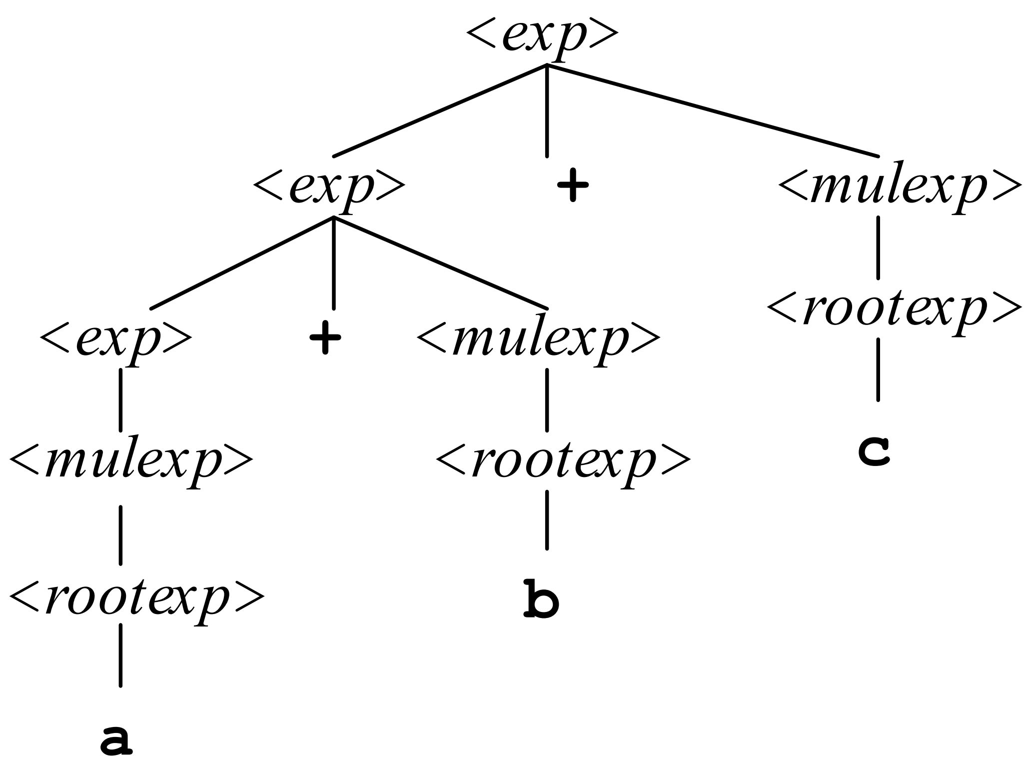
Associativity In The Grammar

G5: *<exp>* **::=** *<exp>* **+** *<exp>* | *<mulexp>*
<mulexp> **::=** *<mulexp>* ***** *<mulexp>*
| **(***<exp>***)**
| **a** | **b** | **c**

To fix the associativity problem, we modify the grammar to make trees of **+**s grow down to the left (and likewise for *****s)

G6: *<exp>* **::=** *<exp>* **+** *<mulexp>* | *<mulexp>*
<mulexp> **::=** *<mulexp>* ***** *<rootexp>* | *<rootexp>*
<rootexp> **::=** **(***<exp>***)**
| **a** | **b** | **c**

Correct Associativity



Our new grammar generates this tree for **a+b+c**. It generates the same language as before, but no longer generates trees with incorrect associativity.

Outline

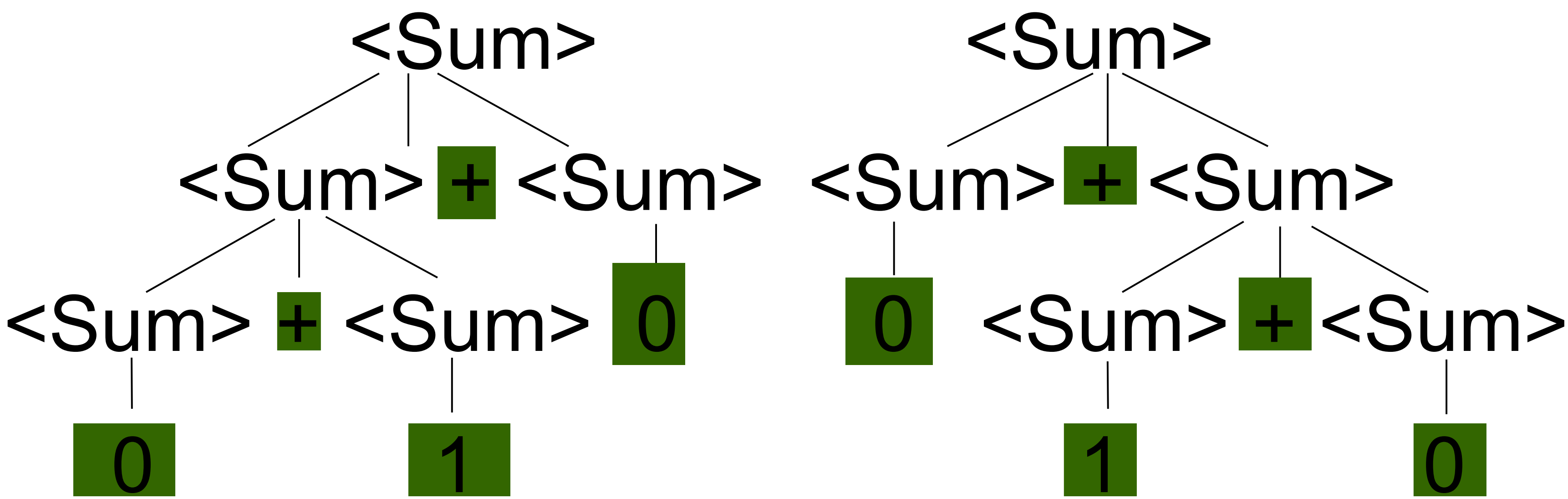
- Operators
- Precedence
- Associativity
- Ambiguities
- Cluttered grammars
- Parse trees and EBNF
- Abstract syntax trees

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*

Example: Ambiguous Grammar

- 0 + 1 + 0



Example

- What is the result for:

$$3 + 4 * 5 + 6$$

Example

- What is the result for:

  3 + 4 * 5 + 6

- Possible answers:
  - 41 = ((3 + 4) * 5) + 6
  - 47 = 3 + (4 * (5 + 6))
  - 29 = (3 + (4 * 5)) + 6 = 3 + ((4 * 5) + 6)
  - 77 = (3 + 4) * (5 + 6)

Example

- What is the value of:

$$7 - 5 - 2$$

Example

- What is the value of:

$$7 - 5 - 2$$

- Possible answers:
  - In Pascal, C++, SML assoc. left

    $7 - 5 - 2 = (7 - 5) - 2 = 0$
  - In APL, associate to right

    $7 - 5 - 2 = 7 - (5 - 2) = 4$

Two Major Sources of Ambiguity

- Lack of determination of operator precedence
- Lack of determination of operator associatively

- Not the only sources of ambiguity

Issue #3: Ambiguity

- G4 was *ambiguous*: it generated more than one parse tree for the same string
- Fixing the associativity and precedence problems eliminated all the ambiguity
- This is usually a good thing: the parse tree corresponds to the meaning of the program, and we don't want ambiguity about that
- Not all ambiguity stems from confusion about precedence and associativity...

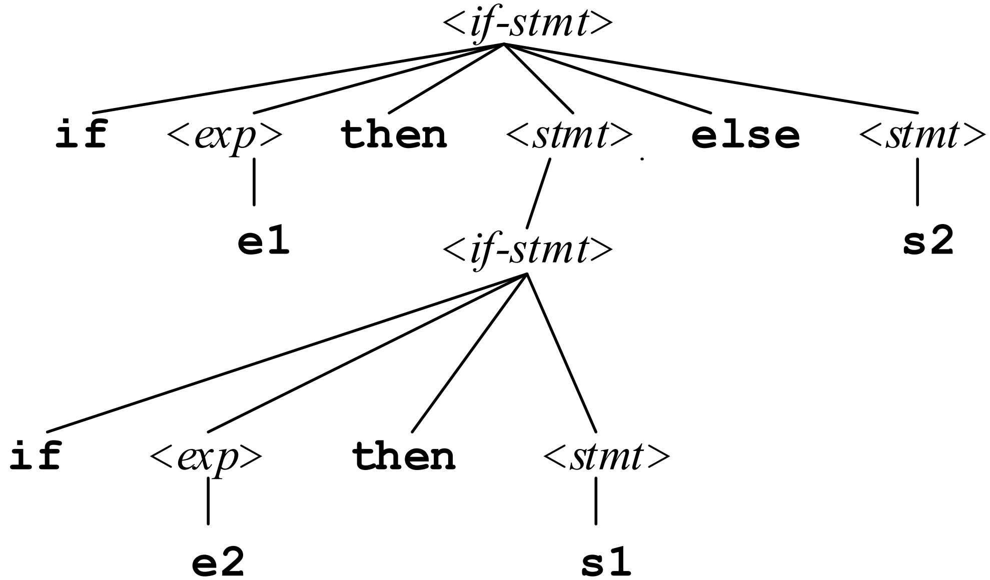
Dangling Else In Grammars

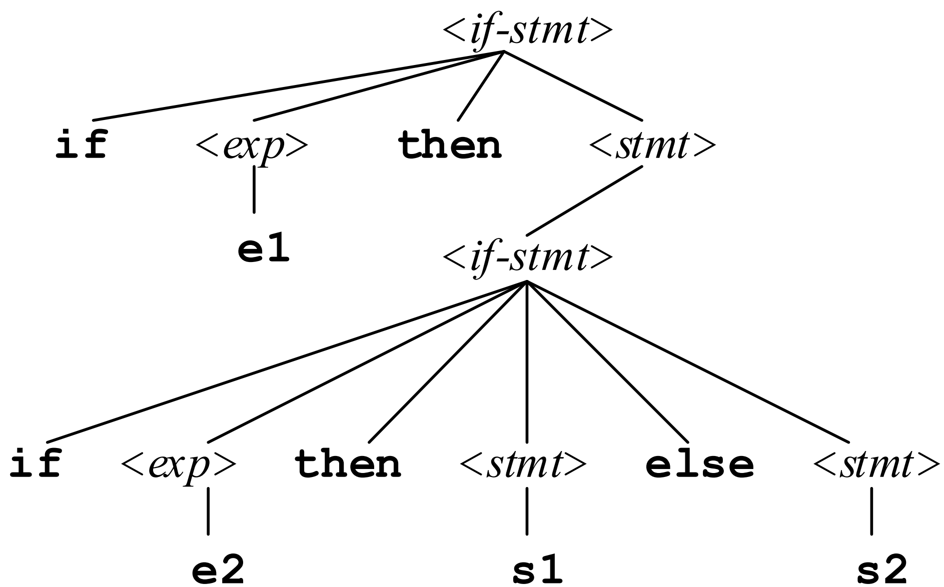
<stmt> `::=` *<if-stmt>* | **`s1`** | **`s2`**
<if-stmt> `::=` **`if`** *<expr>* **`then`** *<stmt>* **`else`** *<stmt>*
| **`if`** *<expr>* **`then`** *<stmt>*
<expr> `::=` **`e1`** | **`e2`**

This grammar has a classic “dangling-else ambiguity.” The statement we want derived is

`if e1 then if e2 then s1 else s2`

and the next slide shows two different parse trees for it...





Most languages that have this problem choose this parse tree: **`else`** goes with nearest unmatched **`then`**

Eliminating The Ambiguity

<stmt> **`::=`** *<if-stmt>* | **`s1`** | **`s2`**
<if-stmt> **`::=`** **`if`** *<expr>* **`then`** *<stmt>* **`else`** *<stmt>*
| **`if`** *<expr>* **`then`** *<stmt>*
<expr> **`::=`** **`e1`** | **`e2`**

We want to insist that if this expands into an **`if`**, that **`if`** must already have its own **`else`**. First, we make a new non-terminal *<full-stmt>* that generates everything *<stmt>* generates, except that it can't generate **`if`** statements with no **`else`**:

<full-stmt> **`::=`** *<full-if>* | **`s1`** | **`s2`**
<full-if> **`::=`** **`if`** *<expr>* **`then`** *<full-stmt>* **`else`** *<full-stmt>*

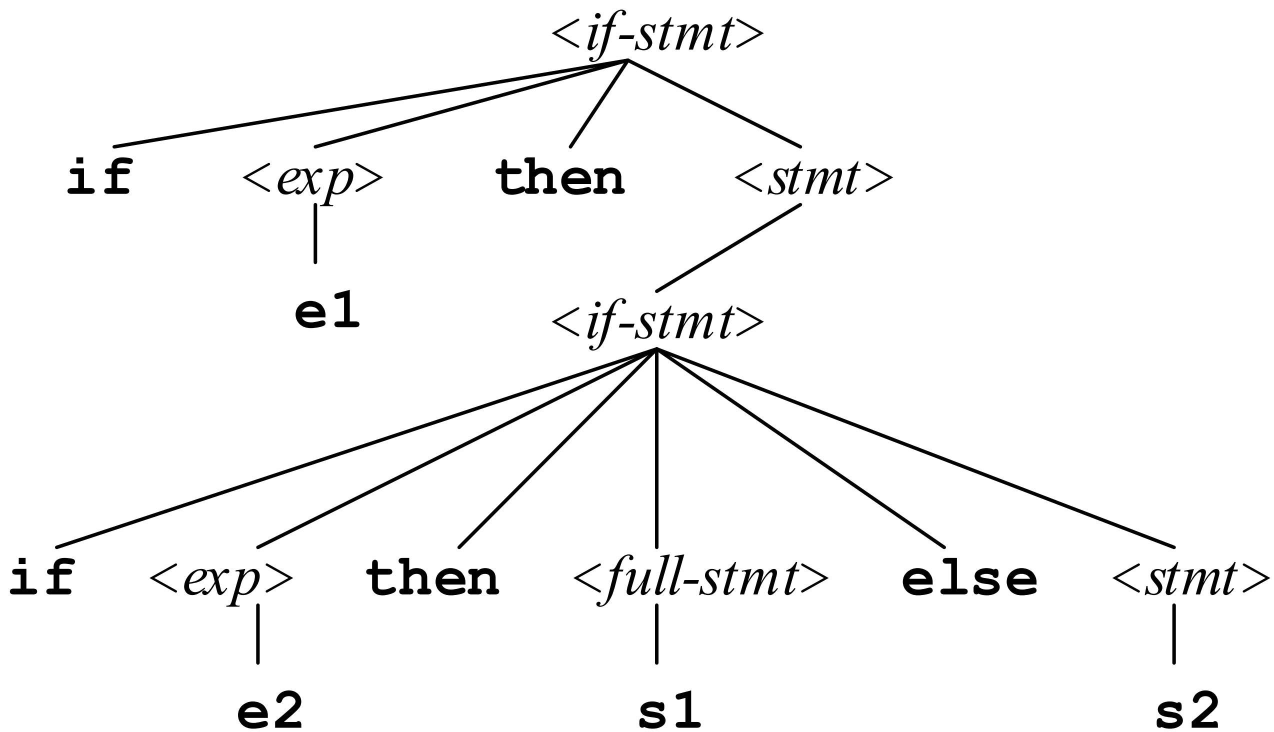
Eliminating The Ambiguity

<stmt> `::=` *<if-stmt>* | **`s1`** | **`s2`**
<if-stmt> `::=` **`if`** *<expr>* **`then`** *<full-stmt>* **`else`** *<stmt>*
  | **`if`** *<expr>* **`then`** *<stmt>*
<expr> `::=` **`e1`** | **`e2`**

Then we use the new non-terminal here.

The effect is that the new grammar can match an **`else`** part with an **`if`** part only if all the nearer **`if`** parts are already matched.

Correct Parse Tree



Dangling Else

- The grammar trouble reflects a problem with the language, which we did not change
- A chain of if-then-else constructs can be very hard for people to read
- Especially true if some but not all of the else parts are present

For Example

```
int a=0;
if (0==0)
  if (0==1) a=1;
else a=2;
```

What is the value of **a** after this fragment executes?

Answer: `a=2`, (read both ways)

Clearer Styles

```
int a=0;
if (0==0)
  if (0==1) a=1;
  else a=2;
```

Better: correct indentation

```
int a=0;
if (0==0) {
  if (0==1) a=1;
  else a=2;
}
```

Even better: use of a block reinforces the structure

Languages That Don't Dangle

- Some languages define if-then-else in a way that forces the programmer to be more clear
- Algol does not allow the `then` part to be another `if` statement – though it can be a block containing an `if` statement
- Ada requires each `if` statement to be terminated with an `end if`

Outline

- Operators
- Precedence
- Associativity
- Ambiguities
- Cluttered grammars
- Parse trees and EBNF
- Abstract syntax trees

Clutter

- The new if-then-else grammar is harder for people to read than the old one
- It has a lot of clutter: more productions and more non-terminals
- Same with G4, G5 and G6: we eliminated the ambiguity but made the grammar harder for people to read
- This is not always the right trade-off

Reminder: Multiple Audiences

- Grammars have multiple audiences:
  - Novices want to find out what legal programs look like
  - Experts—advanced users and language system implementers—want an exact, detailed definition
  - Tools—parser and scanner generators—want an exact, detailed definition in a particular, machine-readable form
- Tools often need ambiguity eliminated, while people often prefer a more readable grammar

Options

- Rewrite grammar to eliminate ambiguity
- Leave ambiguity but explain in accompanying text how things like associativity, precedence, and the dangling else should be parsed
- Do both in separate grammars

Outline

- Operators
- Precedence
- Associativity
- Ambiguities
- Cluttered grammars
- Parse trees and EBNF
- Abstract syntax trees

EBNF and Parse Trees

- You know that {x} means "zero or more repetitions of x" in EBNF
- So <*exp*> ::= <*mulexp*> {+ <*mulexp*>} should mean a <*mulexp*> followed by zero or more repetitions of "+ <*mulexp*>"
- But what then is the associativity of that + operator? What kind of parse tree would be generated for **a+a+a**?

Two Camps

- Some people use EBNF loosely:
  - Use {} anywhere it helps

- Other people use EBNF strictly:
  - Use <*exp*> ::= <*mulexp*> {+ <*mulexp*>} only for left-associative operators
  - Use recursive rules for right-associative operators: <*expa*> ::= <*expb*> [= <*expa*>]

About Syntax Diagrams

- Similar problem: what parse tree is generated?
- As in loose EBNF applications, add a paragraph of text dealing with ambiguities, associativity, precedence, and so on

Outline

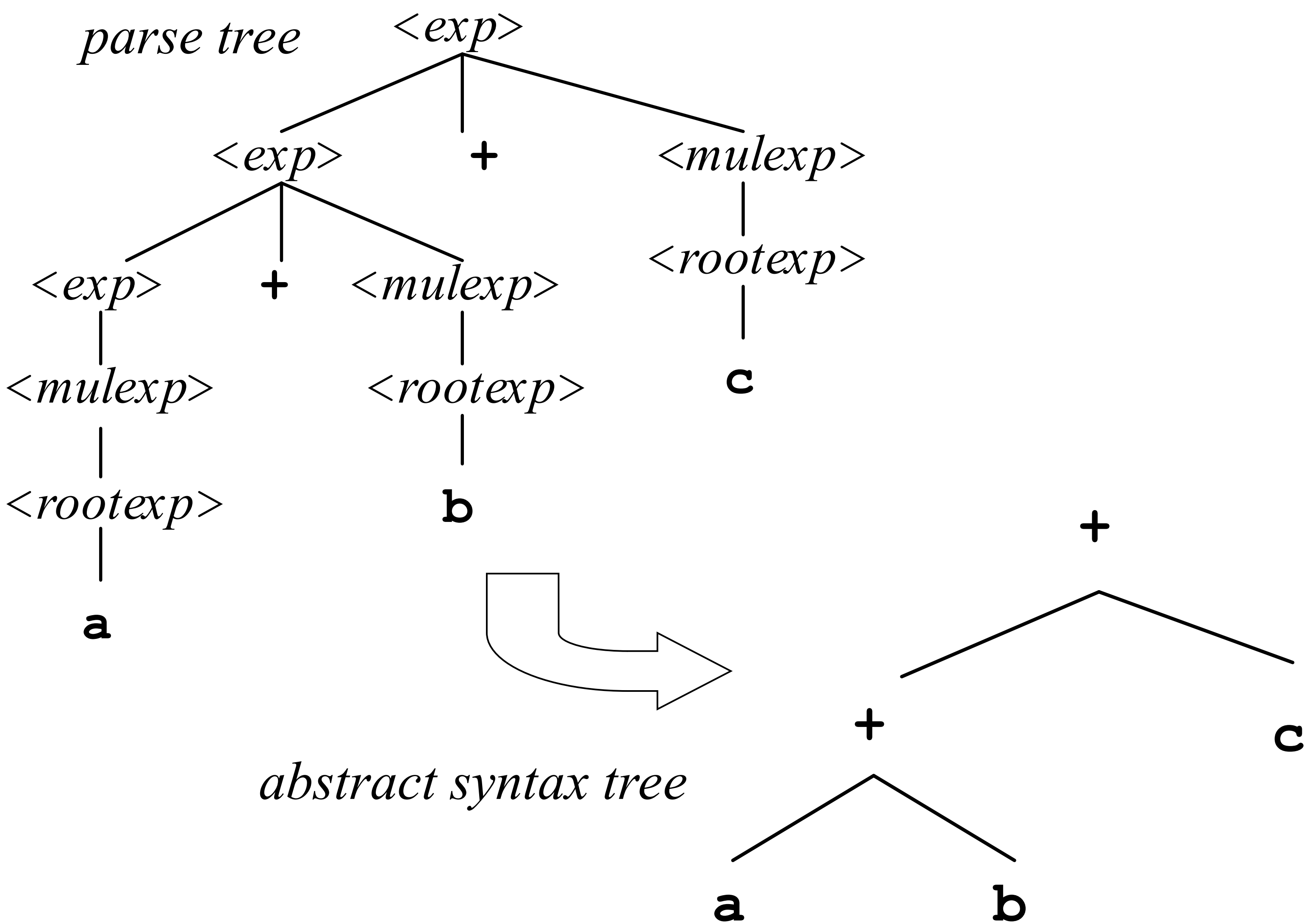
- Operators
- Precedence
- Associativity
- Ambiguities
- Cluttered grammars
- Parse trees and EBNF
- Abstract syntax trees

Full-Size Grammars

- In any realistically large language, there are many non-terminals
- Especially true when in the cluttered but unambiguous form needed by parsing tools
- Extra non-terminals guide construction of unique parse tree
- Once parse tree is found, such non-terminals are no longer of interest

Abstract Syntax Tree

- Language systems usually store an abbreviated version of the parse tree called the *abstract syntax tree*
- Details are implementation-dependent
- Usually, there is a node for every operation, with a subtree for every operand


parse tree
<exp>
<exp>
+
<mulexp>
<exp>
+
<mulexp>
<rootexp>
c
<mulexp>
<rootexp>
<rootexp>
b
a
abstract syntax tree
+
+
c
a
b

Parsing, Revisited

- When a language system parses a program, it goes through all the steps necessary to find the parse tree
- But it usually does not construct an explicit representation of the parse tree in memory
- Most systems construct an *abstract syntax tree* (AST) instead

Conclusion

- Grammars define syntax, *and more*
- They define not just a set of legal programs, but a parse tree for each program
- The structure of a parse tree corresponds to the order in which different parts of the program are to be executed
- Therefore, grammars contribute to the definition of semantics

End of Syntax and Semantics