# Chapter 3
# Where Syntax Meets Semantics



1

## 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**

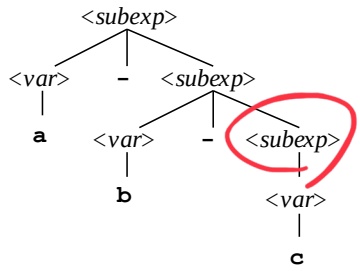
These grammars all define the same language: the language of strings that contain one or more **a**s, **b**s or **c**s separated by minus signs. But...



2

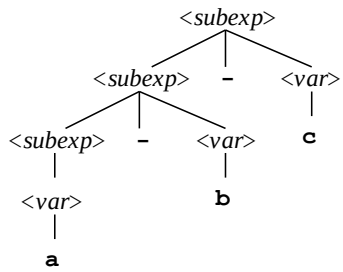
# Three "Equivalent" Grammars

G2 parse tree:




a-(b-c)

G3 parse tree:




(a-b)-c)





# 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

## 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

5

5

## 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`

单元运算符
二进制运算符
三元运算符

Unary
Binary
Ternary

6

6

## 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++**

7

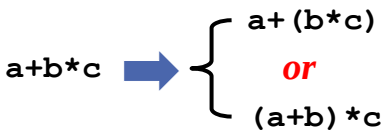
7

## Working Grammar

- Take a look at the following 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**

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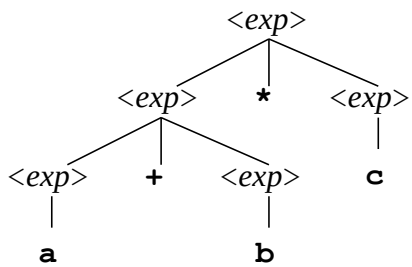
## Issue #1: Precedence

- 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*.

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## 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)**

10

10

## 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
```

11

11

## Precedence In The Grammar

语法中的优先级

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**

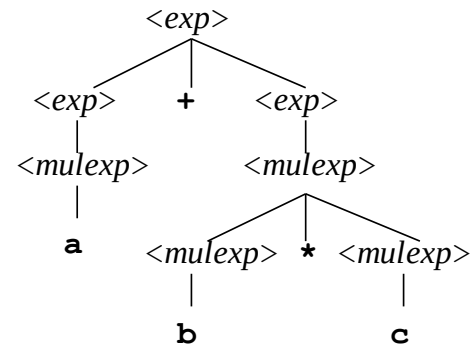
去进中的内层嵌.

12

12

# 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.

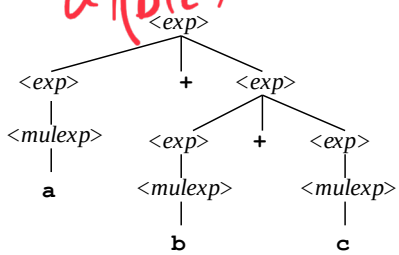
13

13

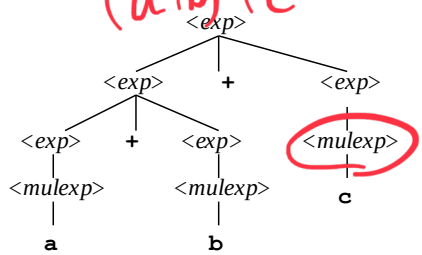
# Issue #2: Associativity 结合型

G5

a+(b+c)




(a+b)+c




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

G5 比 G4 增加了优先级

14

14

## 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

15

15

## Associativity Examples

- C

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

- ML

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

- Fortran

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

16

16

# Associativity in the Grammar

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

增加优先级

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

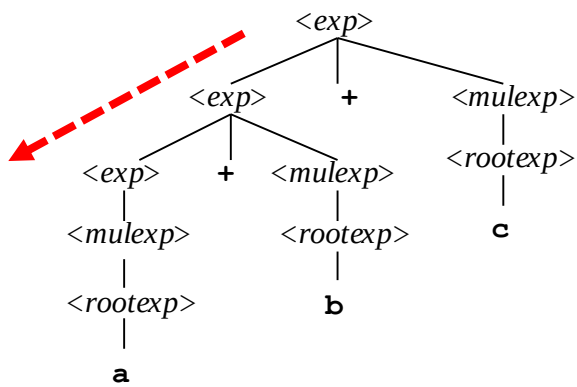
G6: <exp> ::= <exp> + <mulexp> | <mulexp>
<mulexp> ::= <mulexp> * <rootexp> | <rootexp>
<rootexp> ::= (<exp>)
| a | b | c

17

17

# Correct Associativity

The tree grows down to the right.




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.

18

18

# Practice

Starting with this grammar:

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

1.) Add a left-associative & operator, at lower precedence than any of the others
2.) Then add a right-associative ** operator, at higher precedence than any of the others

19

19

# 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...

21

21

# 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 to derive is

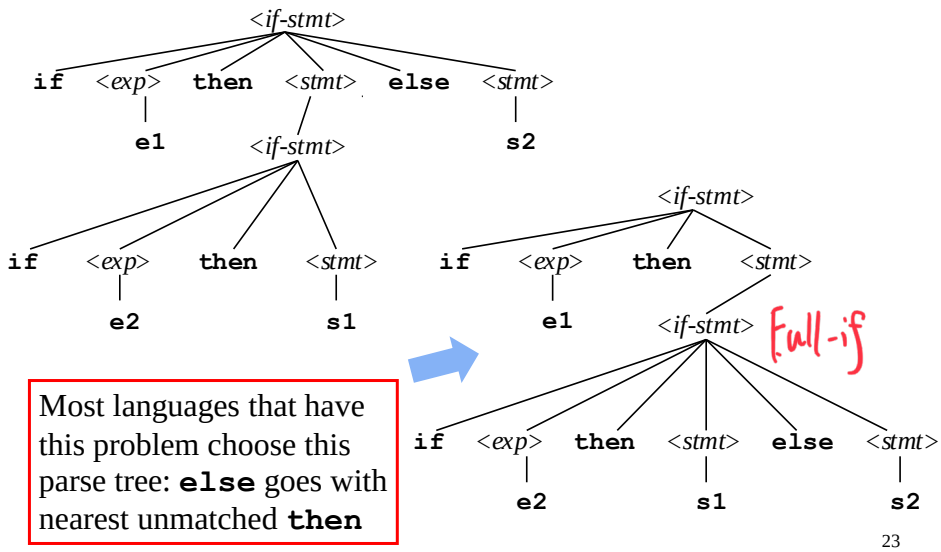
**if e1 then if e2 then s1 else s2**

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

22

22

# Dangling *else* in Grammars




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

23

23

# 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 not generate **`if`** statements with no **`else`**:

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





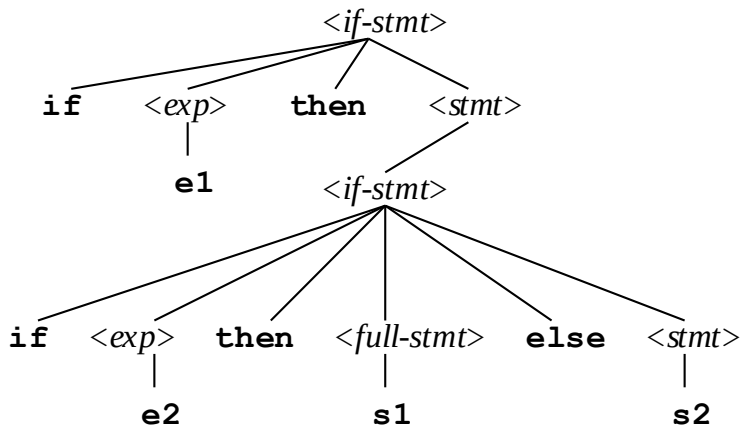
# Eliminating The Ambiguity

```
<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








# Practice

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

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

a=2

## Dangling *else*

- We fixed the grammar, but 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
- Some languages handle the conditional execution with a different syntax that does not suffer the dangling-*else* problem.

29

29

## Clearer Styles

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

正确的缩进

Better: correct indentation

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

使用块强化结构.

Even better: use of a block reinforces the structure

30

30

不会悬停的语言

# Languages That don't Dangle

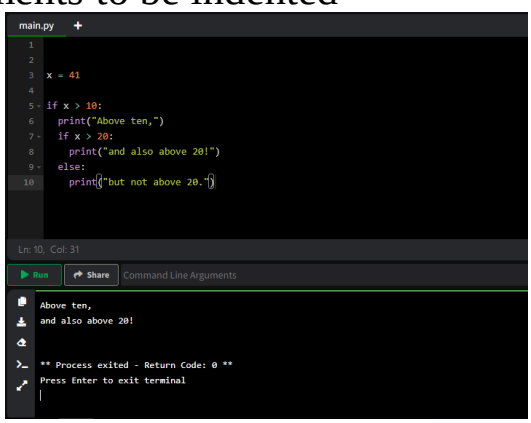
- Some languages define if-then-else in a way that forces the programmer to be more clear
  - Algol does not allow the **`then`** part to be another **`if`** statement – though it can be a block containing an **`if`** statement
  - Ada requires each **`if`** statement to be terminated with an **`end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

31

31

# Languages That don't Dangle

- For example: Python requires nested *if* statements to be indented




32

32

## Cluttered Grammars

- 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 the cost to remove ambiguity, but is not always the right trade-off

33

33

## Reminder: Multiple Audiences

- In Chapter 2 we saw that 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

34

34

## 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
  - One cluttered grammar for parsing tools
  - One simple grammar for people to read

一条计算机看
一条人看

35

35

## 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 is the associativity of that `+` operator? What kind of parse tree would be generated for `a+a+a`?

36

36

## EBNF and Associativity

- One approach:
  - Use {} anywhere it helps
  - Add a paragraph of text dealing with ambiguities, associativity of operators, etc.
- Another approach:
  - Define a convention: for example, that the form <*exp*> ::= <*mulexp*> {**+** <*mulexp*>} will be used only for left-associative operators
  - Use explicitly recursive rules for anything unconventional:

    <*expa*> ::= <*expb*> [ **=** <*expa*> ]
- E.g. G6 → G7

37

37

## About Syntax Diagrams

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

添加一段备注

38

38

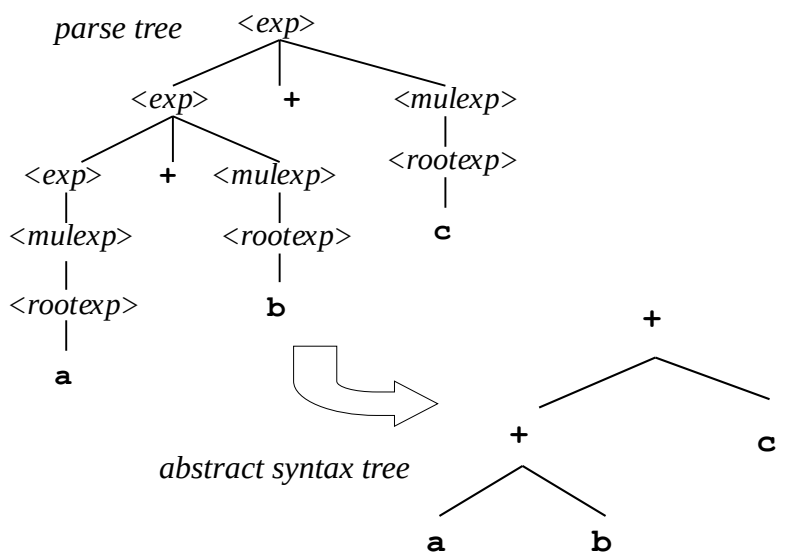
# Abstract Syntax Tree

- 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

39

39

# Abstract Syntax Tree

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## Abstract Syntax Tree

- 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 AST instead
- More info about ASTs is in Chapter 23





## Questions?