Section 4: CUP & LL

CSE 401/M501

Adapted from Autumn 2022

Administrivia

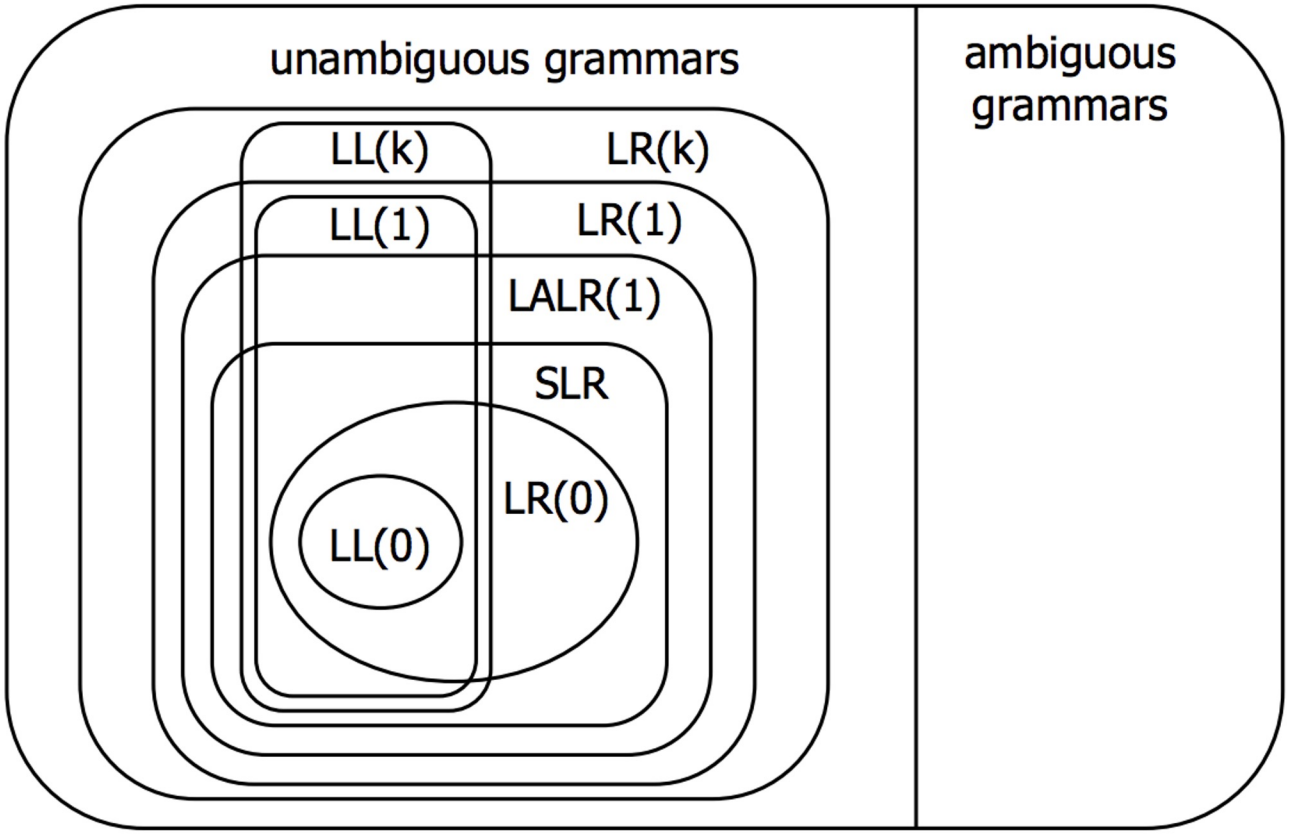
- Homework 2 is due tonight!
  - You have late days if you need them (2 max)
- Parser is due one week from today
  - Be sure to check your Scanner feedback – out later this week
- HW3 is out tomorrow, due in 1.5 weeks on ***Monday April 29th***
  - **Only one late day allowed** on this assignment so we can distribute solutions before the midterm at the end of that week.
  - More on hw3 in sections next week, but start before then if you can

15 12:00-13:00 OH (Connor) CSE2 150 14:30-15:20 Lecture CSE2 G10 *ASTs & visitors* slides 15:30-16:30 OH (Aragorn) CSE2 151	16 12:00-13:00 OH (Eric) CSE2 153 15:30-16:30 OH (Edward) CSE2 151	17 11:30-12:30 OH (Aragorn) CSE2 150 14:30-15:20 Lecture CSE2 G10 *LL Parsing & recursive descent (3.3)* 15:30-16:30 OH (Richard) CSE2 151	18 Section *CUP parser generator, ASTs; LL parsing* 10:30-11:30 OH (Richard) CSE2 151 16:30-18:00 OH (Edward) CSE2 150 23:59 hw2 due (LR grammars)	19 12:00-13:00 OH (Connor) CSE2 151 14:30-15:20 Lecture CSE2 G10 *Intro to semantics and type checking (4.1-4.2)* 15:30-16:30 OH (Eric) CSE2 153
22 12:00-13:00 OH (Connor) CSE2 150 14:30-15:20 Lecture CSE2 G10 *Symbol tables and representation of types* 15:30-16:30 OH (Aragorn) CSE2 151	23 12:00-13:00 OH (Eric) CSE2 153 15:30-16:30 OH (Edward) CSE2 151	24 11:30-12:30 OH (Aragorn) CSE2 150 14:30-15:20 Lecture CSE2 G10 *Type checking / semantics wrapup* 15:30-16:30 OH (Richard) CSE2 151	25 Section *LL parsing review; ASTs & semantics* 10:30-11:30 OH (Richard) CSE2 151 16:30-18:00 OH (Edward) CSE2 150 23:59 Project: parser+AST due	26 12:00-13:00 OH (Connor) CSE2 151 14:30-15:20 Lecture CSE2 G10 *x86-64 (everything you forgot from 351)* 15:30-16:30 OH (Eric) CSE2 153
29 12:00-13:00 OH (Connor) CSE2 150 14:30-15:20 Lecture CSE2 G10 *x86-64 function calls; Code shape I - basics (start)* 15:30-16:30 OH (Aragorn) CSE2 151 23:59 mini hw3 due (LL grammars & parsing) **Only one late day max so we can discuss solutions before the midterm**	30 12:00-13:00 OH (Eric) CSE2 153 15:30-16:30 OH (Edward) CSE2 151	01 11:30-12:30 OH (Aragorn) CSE2 150 14:30-15:20 Lecture CSE2 G10 *Code shape I (concl); Code shape II - objects and dynamic dispatch (start)* 15:30-16:30 OH (Richard) CSE2 151	02 Section *Midterm review* 10:30-11:30 OH (Richard) CSE2 151 16:30-18:00 OH (Edward) CSE2 150	03 12:00-13:00 OH (Connor) CSE2 151 14:30-15:20 Midterm exam 15:30-16:30 OH (Eric) CSE2 153

Parser Live Demo

A video recording of this demo will be posted on the website as a supplement

Language Hierarchies



The CUP parser generator

- Uses LALR(1)
  - A little weaker (less selective), but many fewer states than LR(1) parsers
  - Handles most realistic programming language grammars
  - More selective than SLR (or LR(0)) about when to do reductions, so works for more languages

The CUP parser generator

- LALR(1) parser generator based on YACC and Bison
- CUP can resolve some ambiguities itself
  - Precedence for reduce/reduce conflicts
  - Associativity for shift/reduce conflicts
  - Useful for our project for things like arithmetic expressions (use exp+exp, exp*exp, etc. for fewer non-terminals, then add precedence and associativity declarations). ***Read the CUP docs!***

MiniJava BNF with AST Nodes

Use this to check your work ***only after*** your team has examined the grammar and AST code first.

Program
MainClass
ClassDecl
VarDecl
MethodDecl
Type

```
Goal ::= MainClass ( ClassDeclaration )* <EOF>
MainClass ::= "class" Identifier "{" "public" "static" "void" "main" "(" "String" "[" "]" Identifier ")" "{" Statement "}" "}"
ClassDeclaration ::= "class" Identifier ( "extends" Identifier )? "{" ( VarDeclaration )* ( MethodDeclaration )* "}"
VarDeclaration ::= Type Identifier ";"
MethodDeclaration ::= "public" Type Identifier "(" ( Type Identifier ( "," Type Identifier )* )? ")" "{" ( VarDeclaration )* ( Statement )* "return" Expression ";" "}"
Type ::= "int" "[" "]"
       | "boolean"
       | "int"
       | Identifier
```

ClassDeclSimple
ClassDeclExtends (if there is "extends")
Formal
IntArrayType
BooleanType
IntegerType
IdentifierType

Statement

```
Statement ::= "{" ( Statement )* "}"
            | "if" "(" Expression ")" Statement "else" Statement
            | "while" "(" Expression ")" Statement
            | "System.out.println" "(" Expression ")" ";"
            | Identifier "=" Expression ";"
            | Identifier "[" Expression "]" "=" Expression ";"
```

Block
If
While
Print
Assign
ArrayAssign

Exp

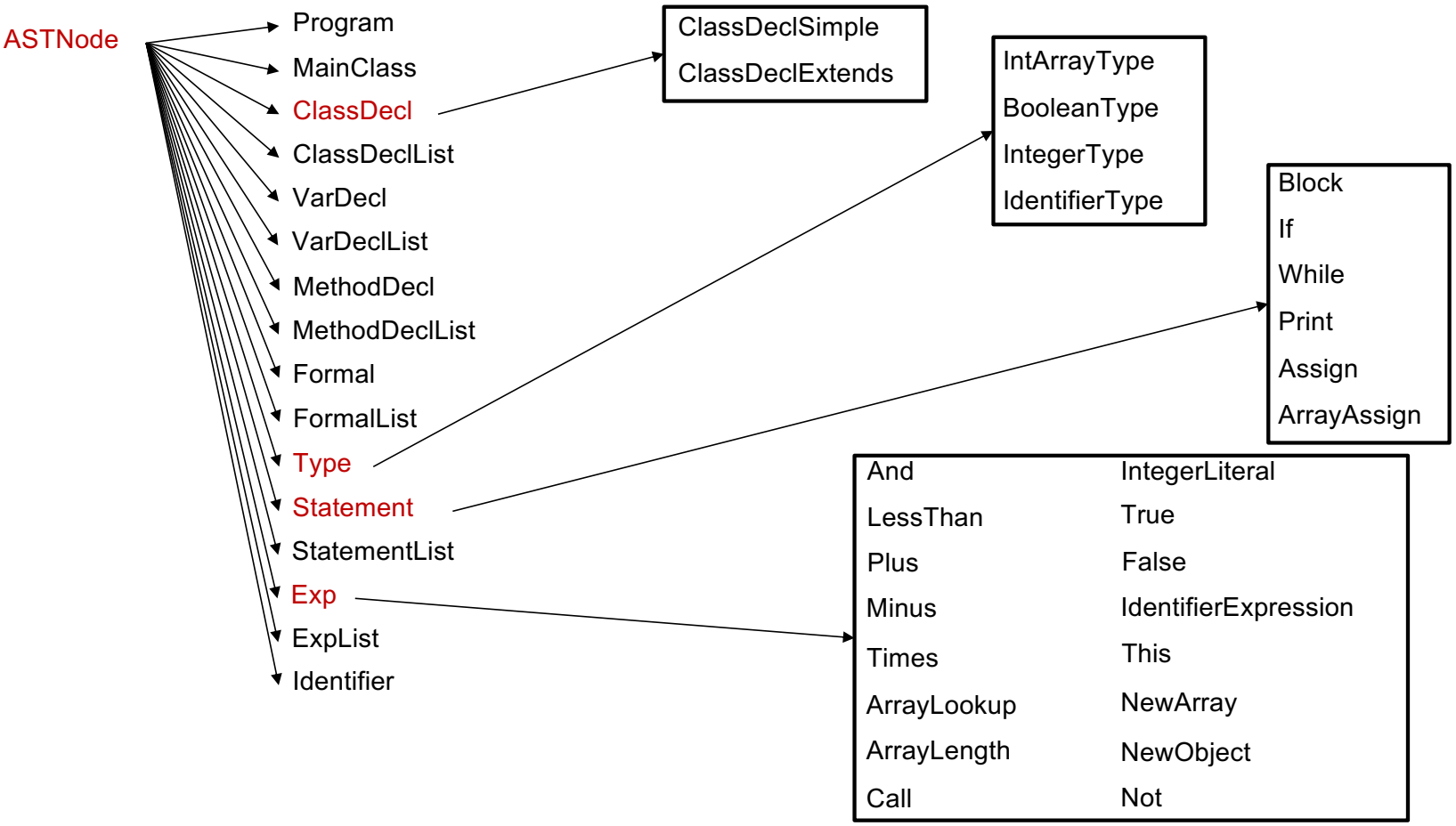
```
Expression ::= Expression ( "&&" | "<" | "+" | "-" | "*" ) Expression
             | Expression "[" Expression "]"
             | Expression "." "length"
             | Expression "." Identifier "(" ( Expression ( "," Expression )* )? ")"
             | <INTEGER_LITERAL>
             | "true"
             | "false"
             | Identifier
             | "this"
             | "new" "int" "[" Expression "]"
             | "new" Identifier "(" ")"
             | "!" Expression
             | "(" Expression ")"
```

And LessThan Plus Minus Times
ArrayLookup
ArrayLength
Call
IntegerLiteral
True
False
IdentifierExpression
This
NewArray
NewObject
Not

Identifier

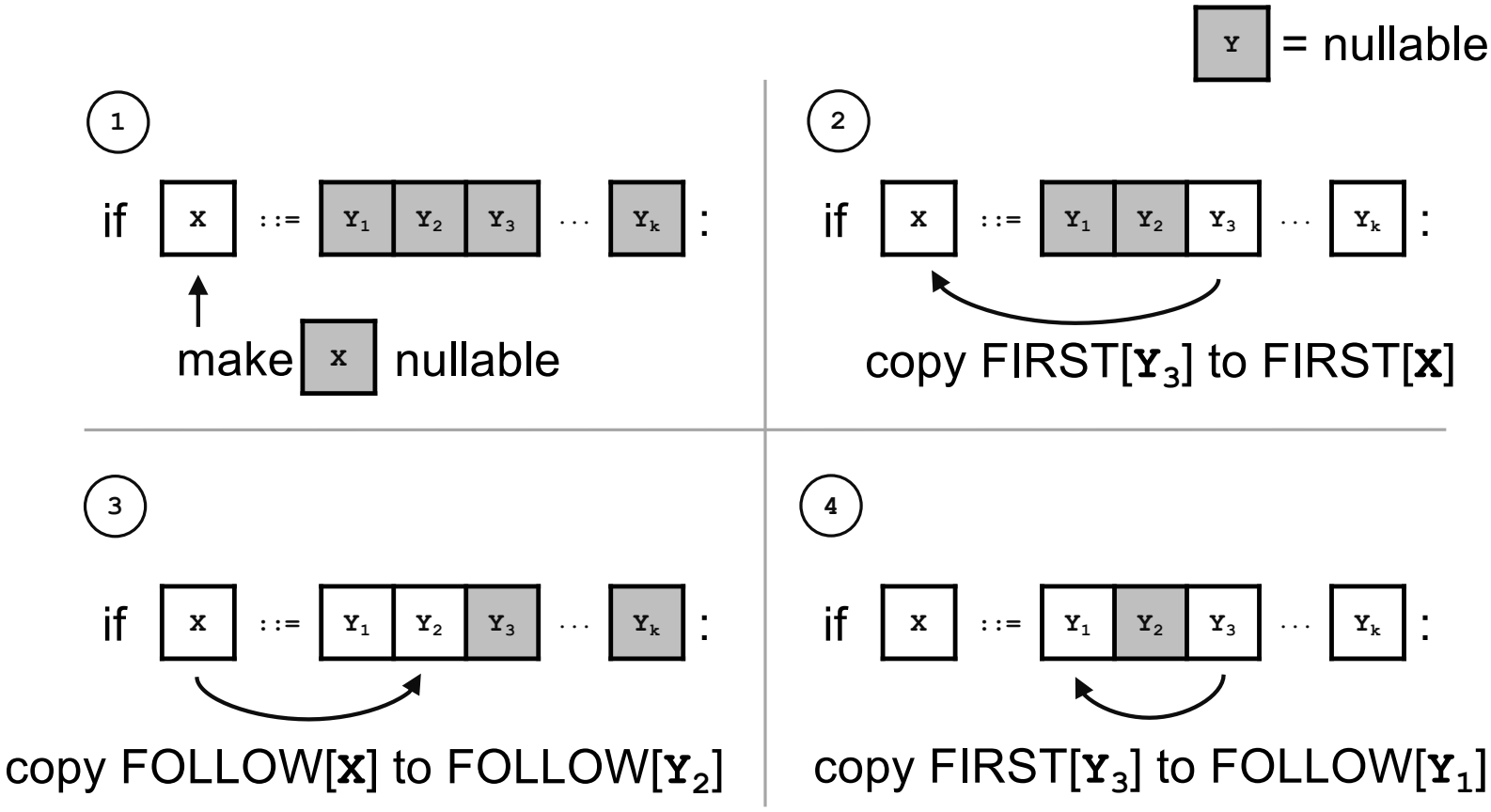
```
Identifier ::= <IDENTIFIER>
```

Abstract Syntax Tree Class Hierarchy



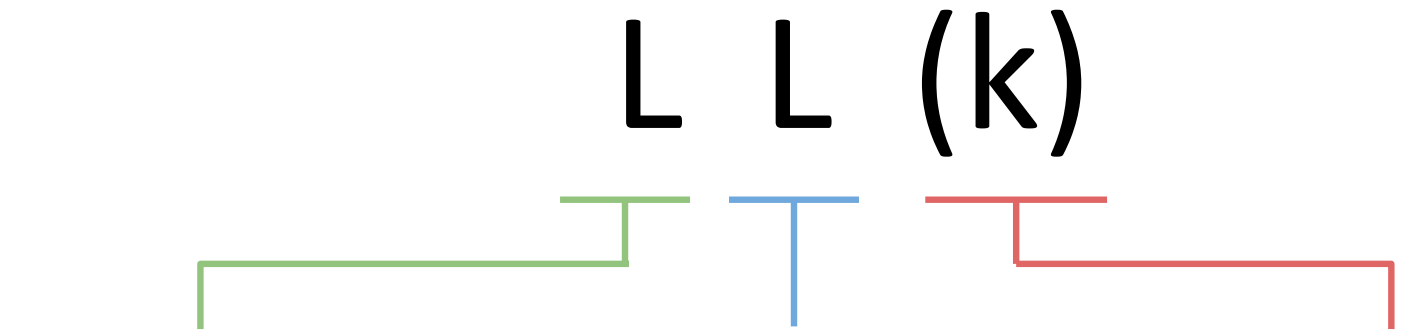
LL Parsing

Computing FIRST, FOLLOW, & nullable (3)



Computing FIRST, FOLLOW, and nullable

repeat
  for each production $X := Y_1\ Y_2 \ldots Y_k$
    if $Y_1 \ldots Y_k$ are all nullable (or if $k = 0$)
      set nullable[X] = true
    for each i from 1 to k and each j from $i+1$ to k
      if $Y_1 \ldots Y_{i-1}$ are all nullable (or if $i = 1$)
        add FIRST[Y_i] to FIRST[X]
      if $Y_{i+1} \ldots Y_k$ are all nullable (or if $i = k$)
        add FOLLOW[X] to FOLLOW[Y_i]
      if $Y_{i+1} \ldots Y_{j-1}$ are all nullable (or if i+1=j)
        add FIRST[Y_j] to FOLLOW[Y_i]
Until FIRST, FOLLOW, and nullable do not change



Left-to-Right

Only takes one pass, performed from the left

Leftmost

At each point, finds the derivation for the leftmost handle **(top-down)**

k Terminal Lookahead

Must determine derivation from the next unparsed terminal in the string
Typically $k = 1$, just like LR

LL(k) parsing

- LL(*k*) scans left-to-right, builds leftmost derivation, and looks ahead *k* symbols

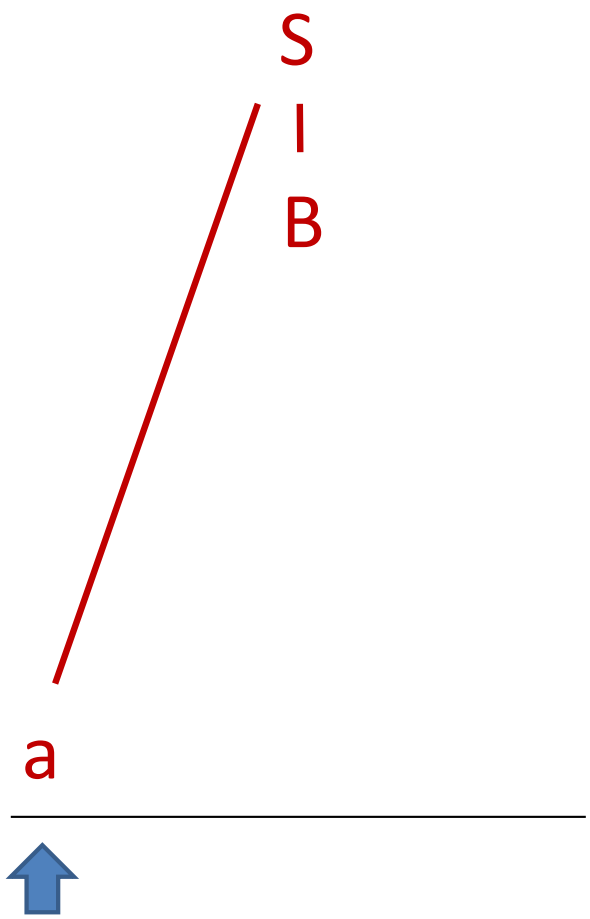
- The LL condition enable the parser to choose productions correctly with 1 symbol of look-ahead
- We can often transform a grammar to satisfy this if needed

LL(1) parsing: An example top-down derivation of “a z x”

```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | z
```

Lookahead	Remaining
a	z x

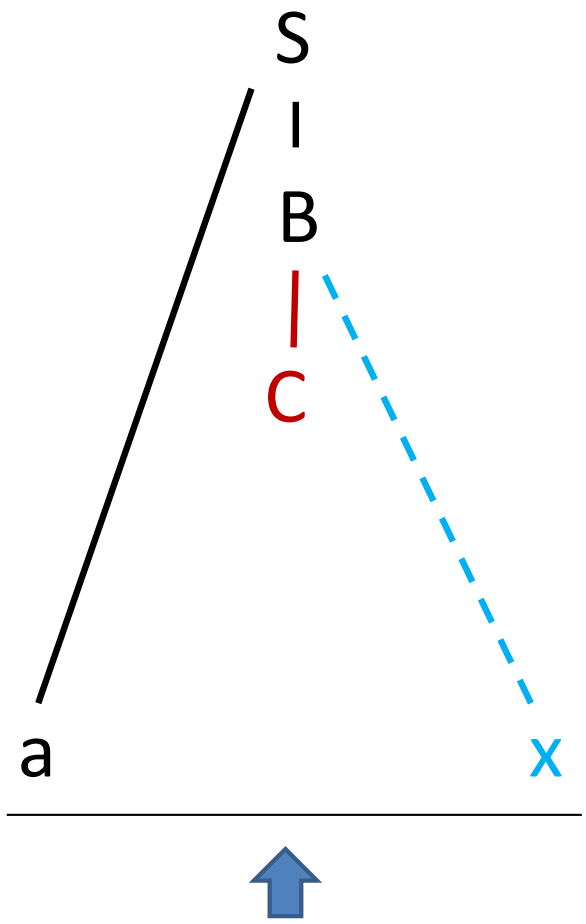
Top-Down Derivation of “a z x”




```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | z
```

Lookahead	Remaining
a	z x

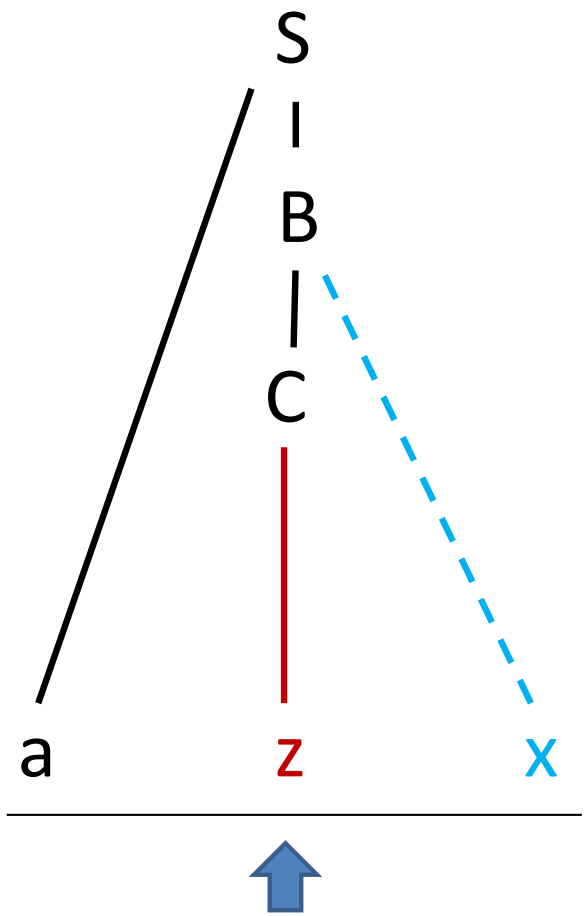
Top-Down Derivation of “a z x”




```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | z
```

Lookahead	Remaining
z	x

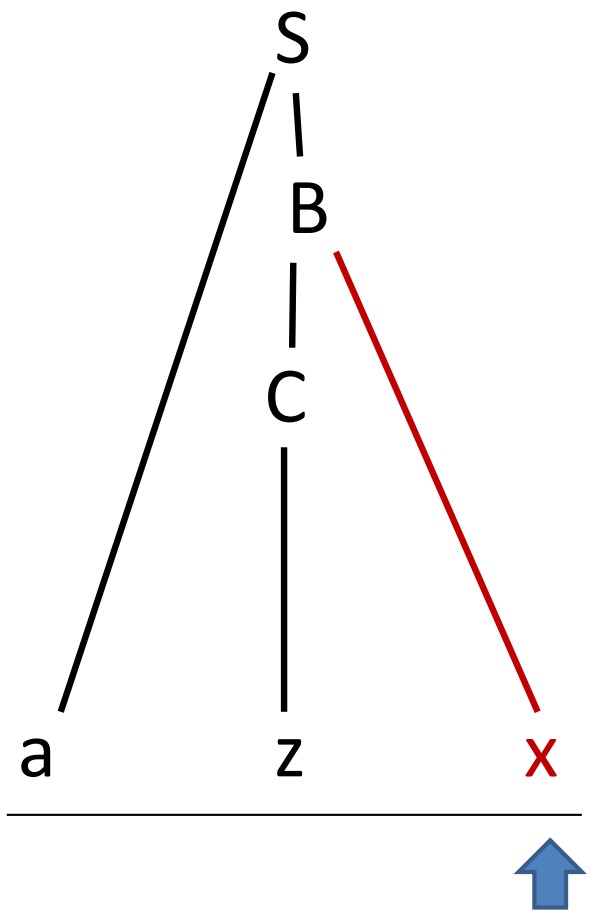
Top-Down Derivation of “a z x”




```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | z
```

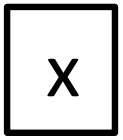
Lookahead	Remaining
z	x

Top-Down Derivation of “a z x”

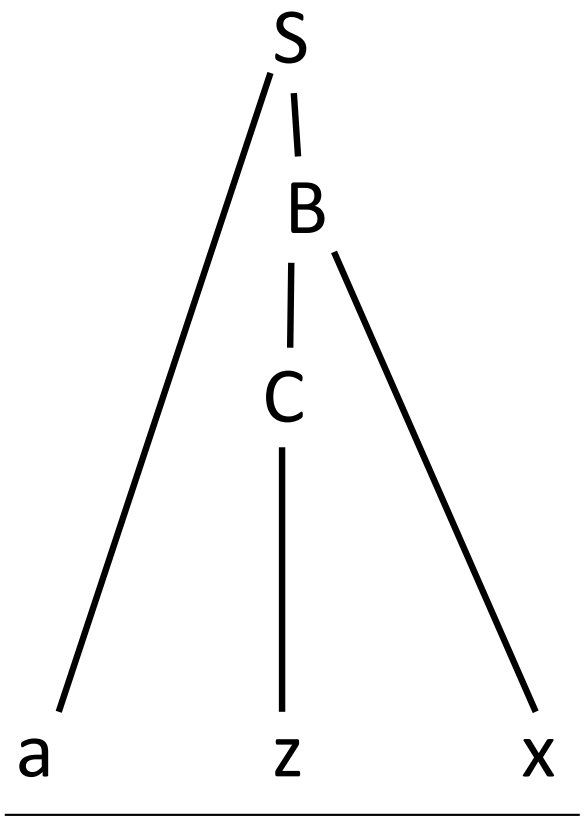



```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | z
```

Lookahead Remaining



Top-Down Derivation of “a z x”




```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | z
```

Successful parse!

LL Condition

For each nonterminal in the grammar:

- Its *productions* must have disjoint FIRST sets

✗
```
A ::= x | B
B ::= x
```

✓
```
A ::= x | B
B ::= y
```

- If it is *nullable*, the FIRST sets of its productions must be disjoint from its FOLLOW set

✗
```
S ::= A x
A ::= ε | x
```

✓
```
S ::= A y
A ::= ε | x
```

**We can often transform a grammar to satisfy this if needed

Canonical FIRST Conflict

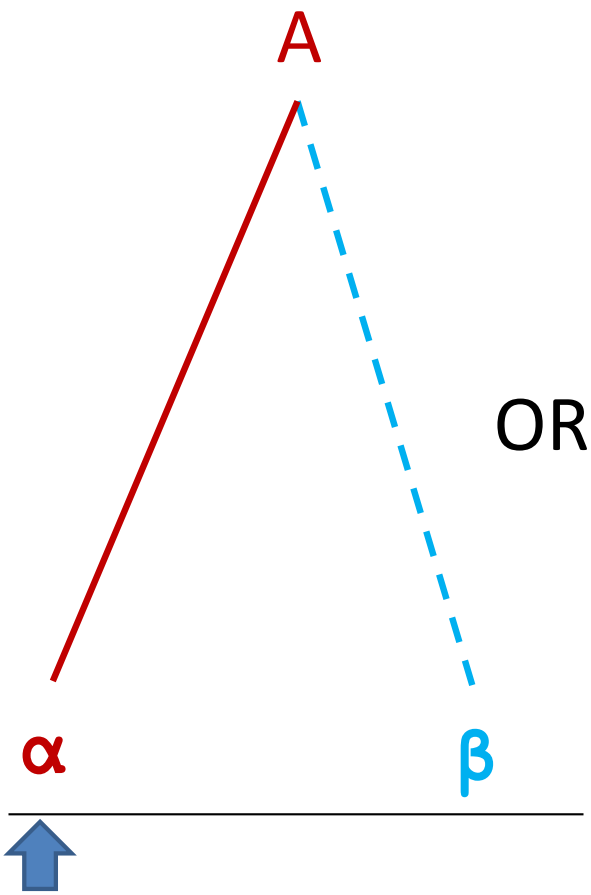
Problem

0. **A** ::= αβ | αγ

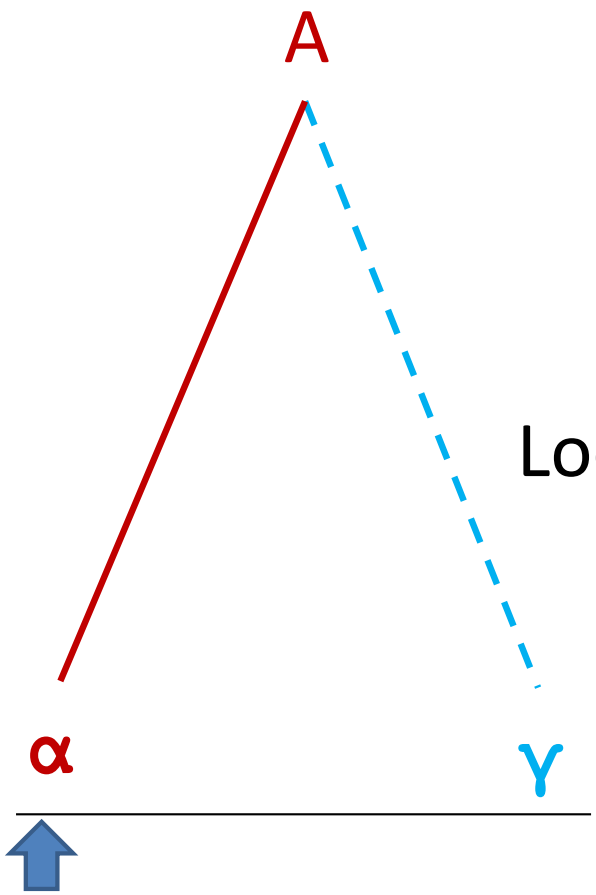
The FIRST sets of the right-hand sides for the SAME NON-TERMINAL must be disjoint!

Let's try a top-down derivation of αβ

0. A ::= αβ | αγ



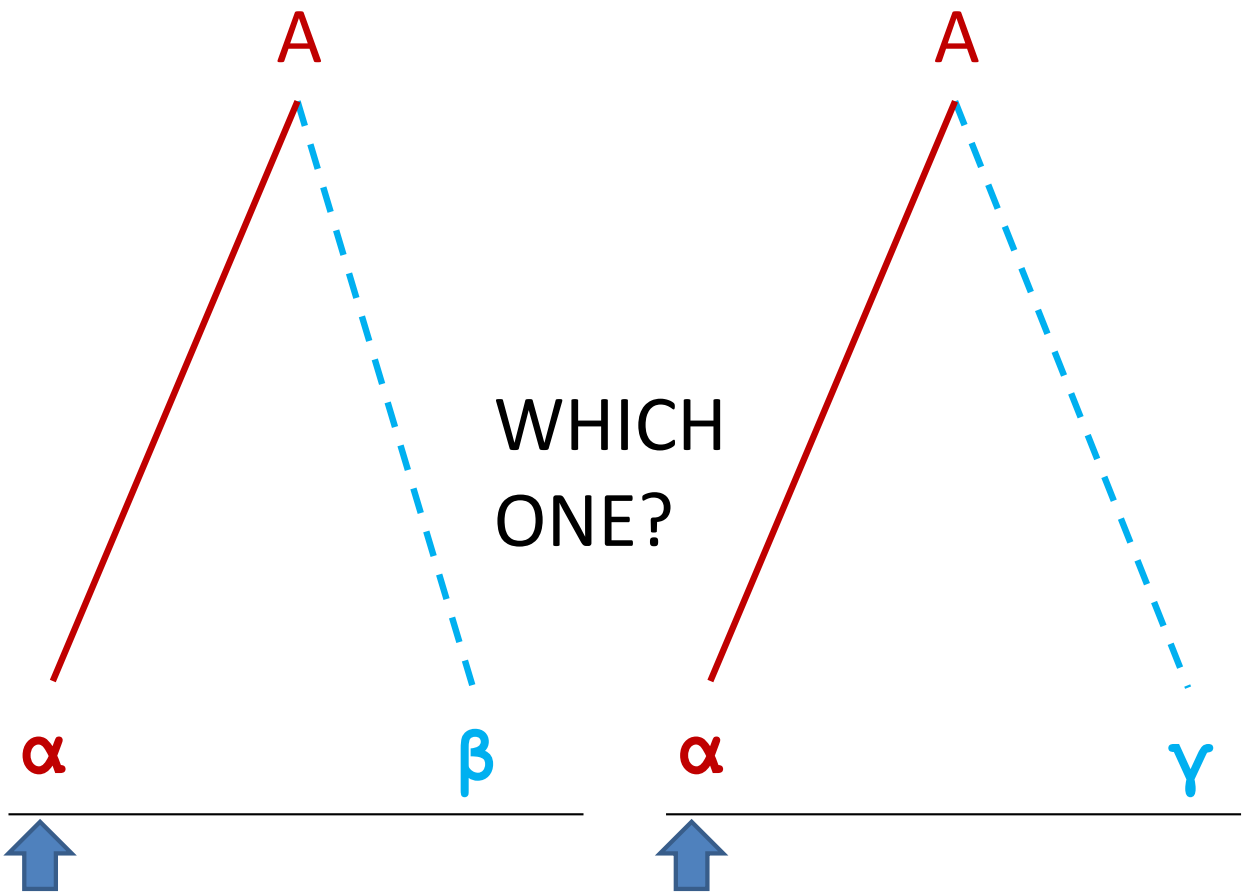
OR



Lookahead Remaining

α β

Let's try a top-down derivation of αβ



0. **A ::= αβ | αγ**

We don't know!

We are using an LL(1) parser, we can't see more than **α**!

Canonical FIRST Conflict Solution

Solution

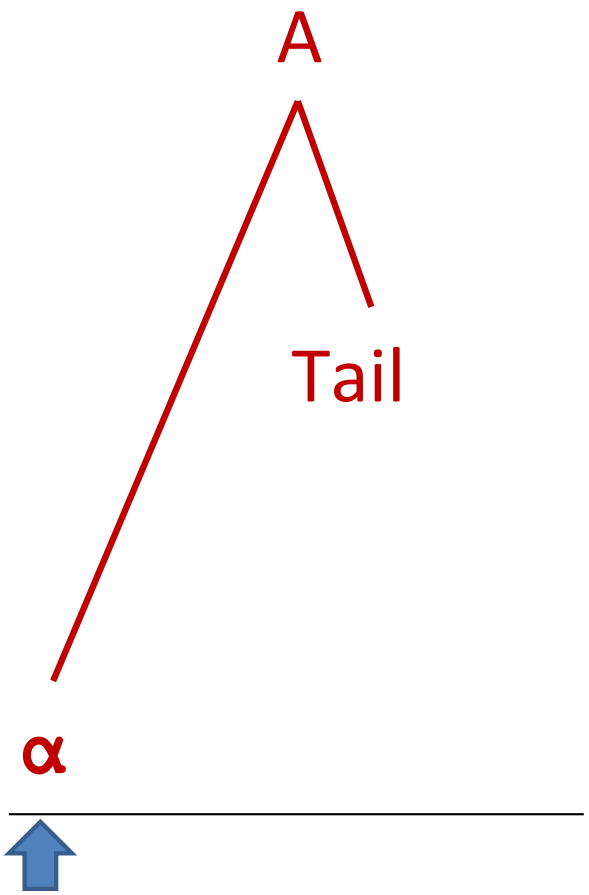
```
0. A ::= αβ | αγ
```

```
0. A ::= α Tail
1. Tail ::= β | γ
```

Factor out the common prefix

When multiple productions of a nonterminal share a common prefix, turn the different suffixes into a new nonterminal.

Top-Down Derivation of "αβ"

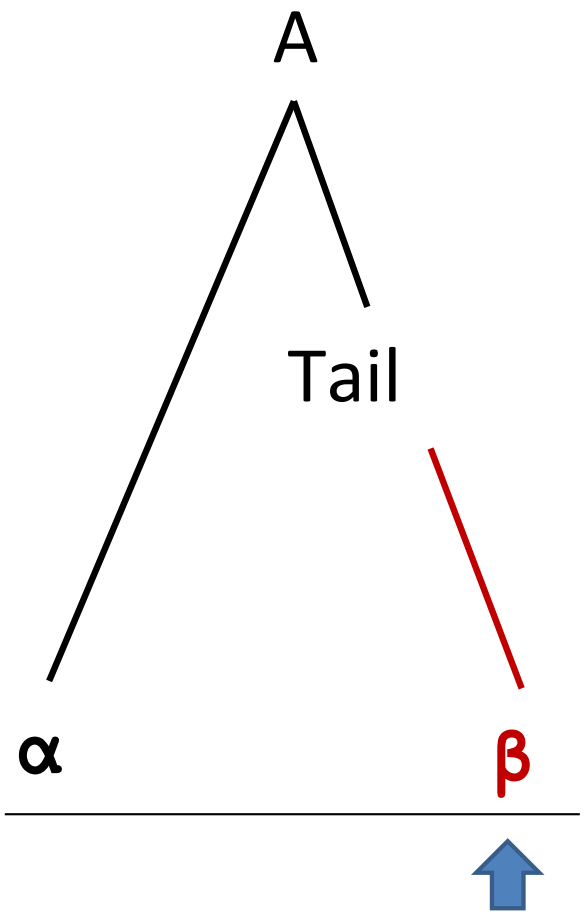



```
0. A ::= α Tail
1. Tail ::= β | γ
```

Lookahead Remaining

α β

Top-Down Derivation of "αβ"

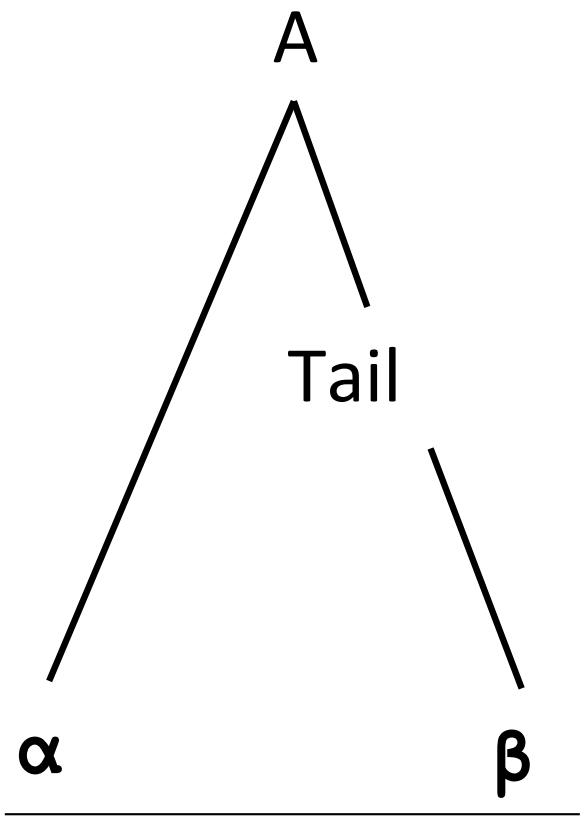



```
0. A ::= α Tail
1. Tail ::= β | γ
```

Lookahead Remaining

β

Top-Down Derivation of "αβ"




```
0. A ::= α Tail
1. Tail ::= β | γ
```

Successful parse!

Changing original grammar a little (Grammar 1)

```
0. S ::= a B | a w
1. B ::= C x | y
2. C ::= ε | z
```

Lookahead	Remaining
a	z x

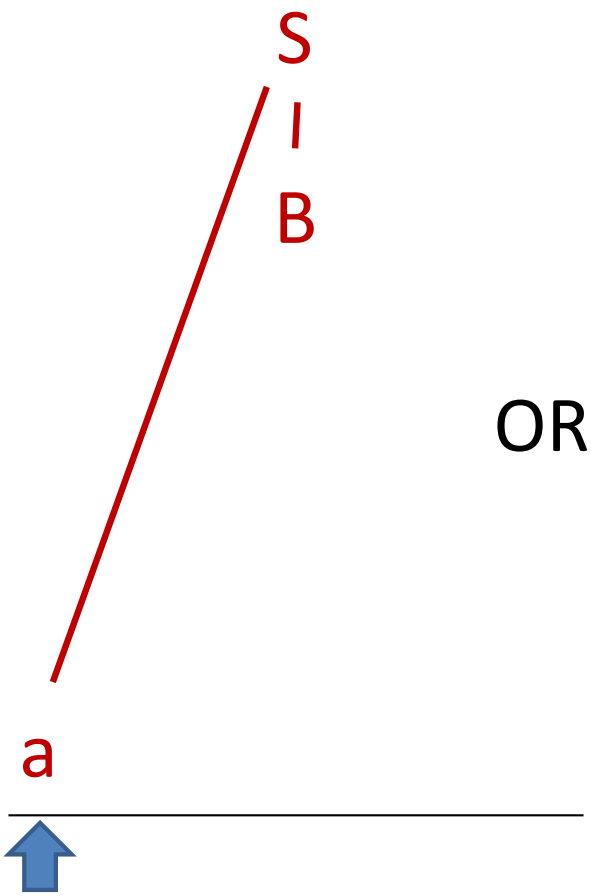
What's the issue?

```
0. S ::= a B | a w
1. B ::= C x | y
2. C ::= ε | z
```

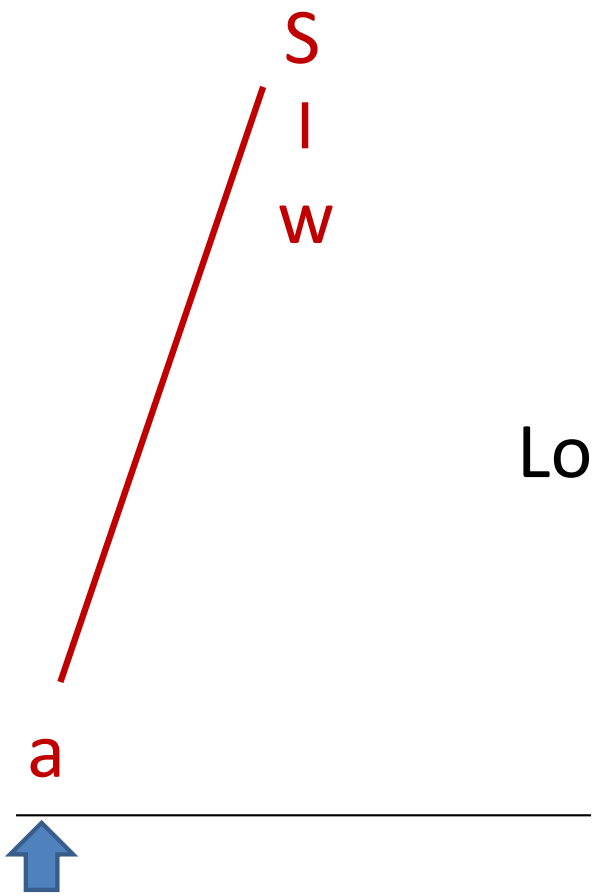
There's a FIRST Conflict!

Top-Down Derivation of “a z x”: LL(1) can’t parse

```
0. S ::= a B | a w
1. B ::= C x | y
2. C ::= ε | z
```

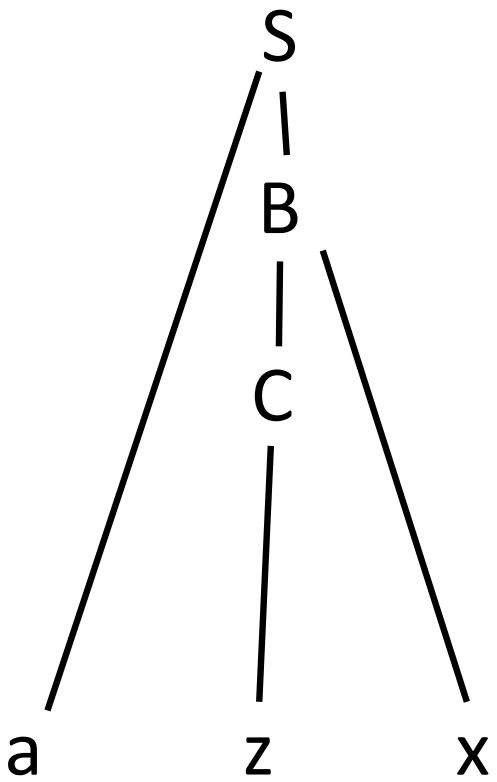


OR



Lookahead	Remaining
a	z x

Parse Tree without changing Grammar

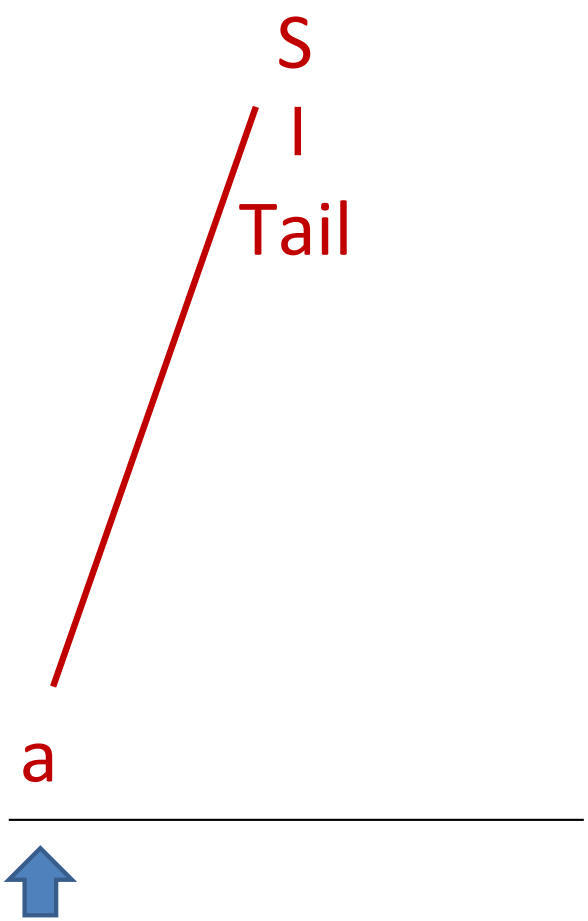



```
0. S ::= a B | a w
1. B ::= C x | y
2. C ::= ε | z
```

Applying the Fix: Factor out the Common Prefix

0. **S ::= a Tail**
1. **Tail ::= B | w**
2. B ::= C x | y
3. C ::= ε | z

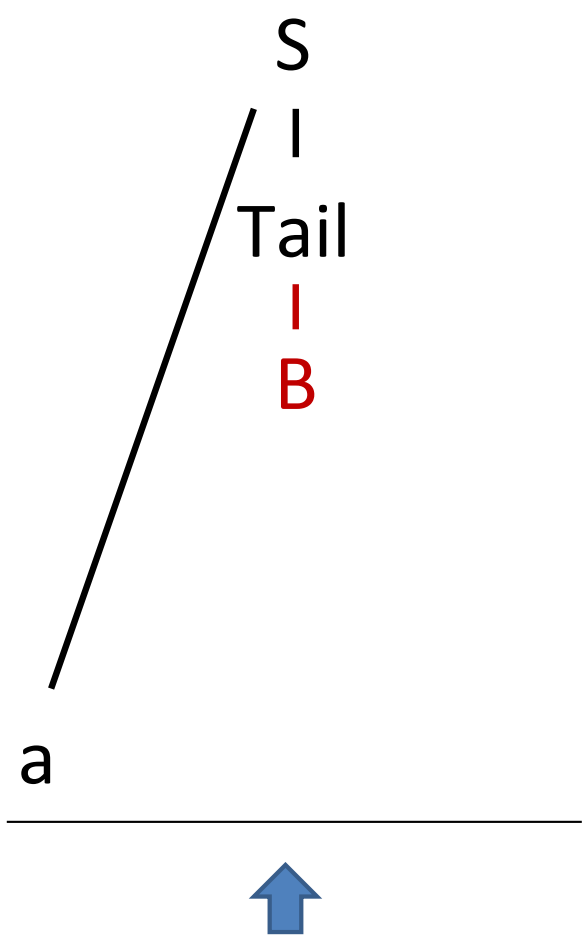
Top-Down Derivation of “a z x”




```
0. S ::= a Tail
1. Tail ::= B | w
2. B ::= C x | y
3. C ::= ε | z
```

Lookahead	Remaining
a	z x

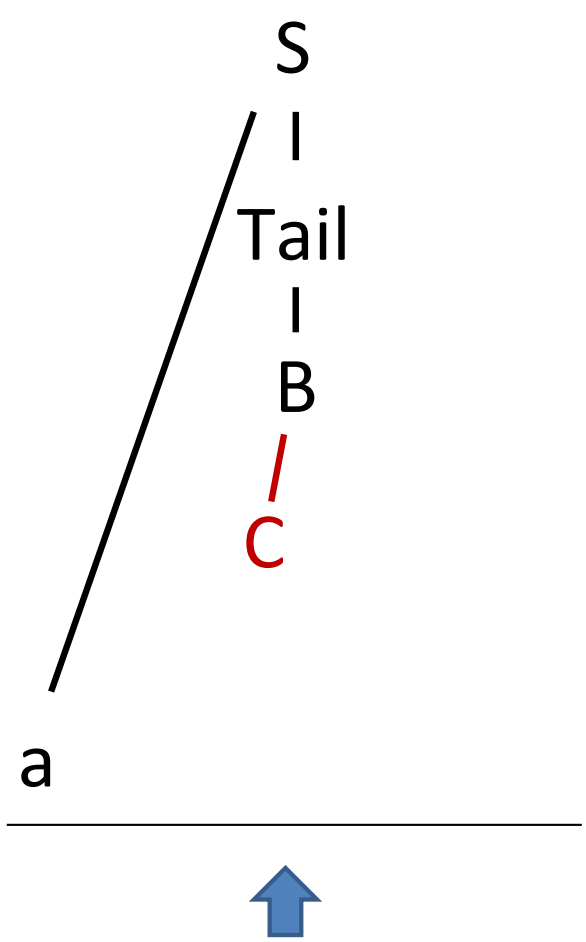
Top-Down Derivation of “a z x”




```
0. S ::= a Tail
1. Tail ::= B | w
2. B ::= C x | y
3. C ::= ε | z
```

Lookahead	Remaining
z	x

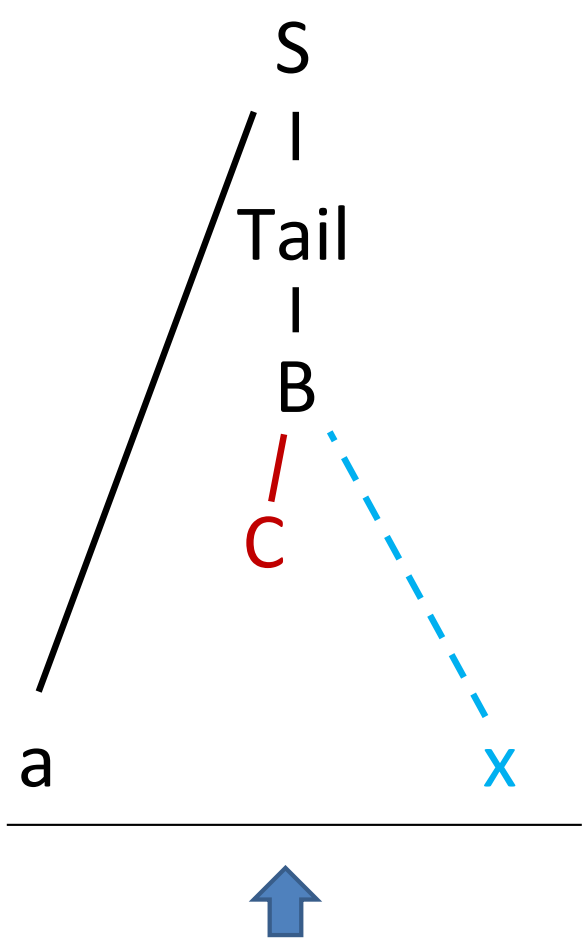
Top-Down Derivation of “a z x”




```
0. S ::= a Tail
1. Tail ::= B | w
2. B ::= C x | y
3. C ::= ε | z
```

Lookahead	Remaining
z	x

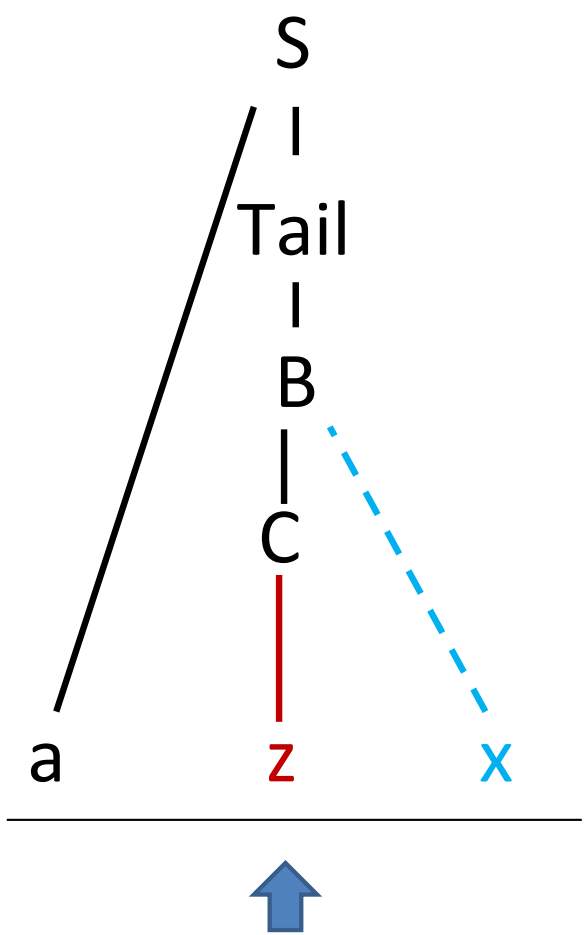
Top-Down Derivation of “a z x”




```
0. S ::= a Tail
1. Tail ::= B | w
2. B ::= C x | y
3. C ::= ε | z
```

Lookahead	Remaining
z	x

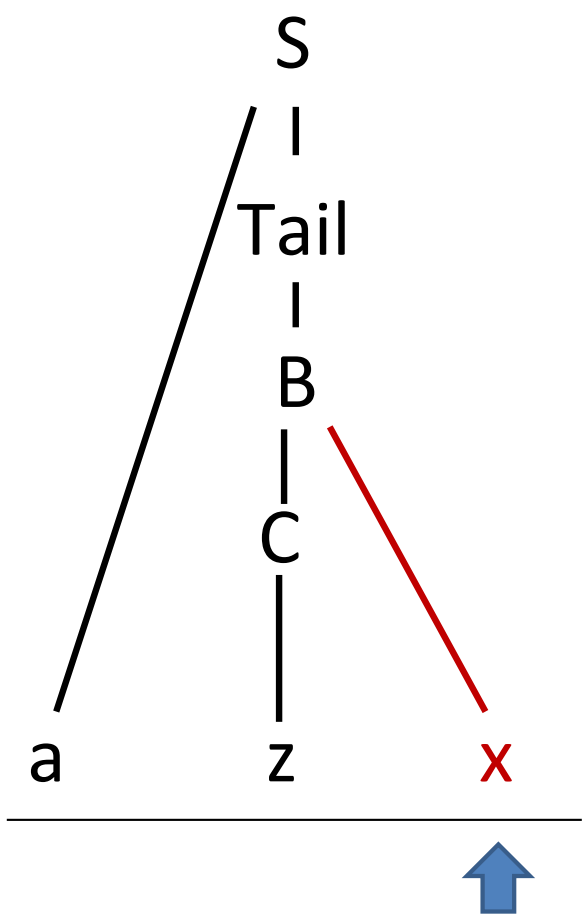
Top-Down Derivation of “a z x”




```
0. S ::= a Tail
1. Tail ::= B | w
2. B ::= C x | y
3. C ::= ε | z
```

Lookahead	Remaining
z	x

Top-Down Derivation of “a z x”

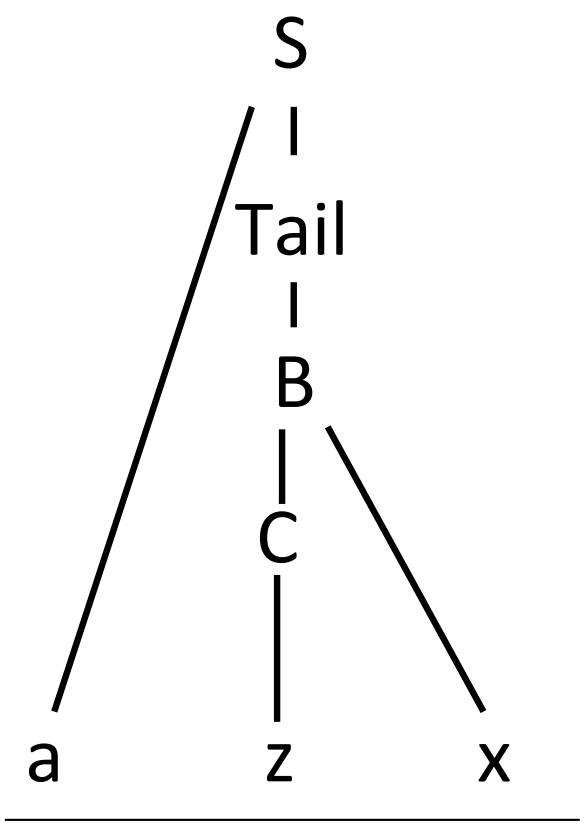


0. **S ::= a Tail**
1. **Tail ::= B | w**
2. B ::= C x | y
3. C ::= ε | z

Lookahead Remaining

x

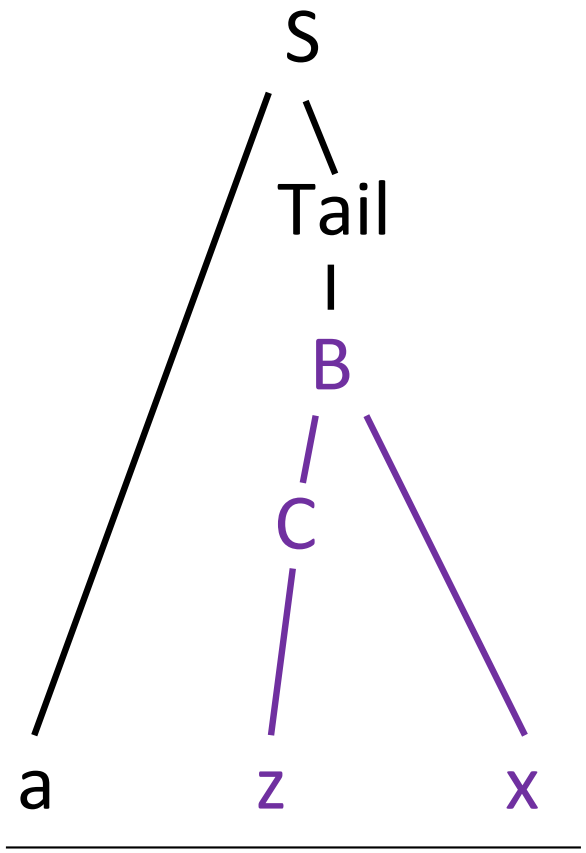
Top-Down Derivation of “a z x”



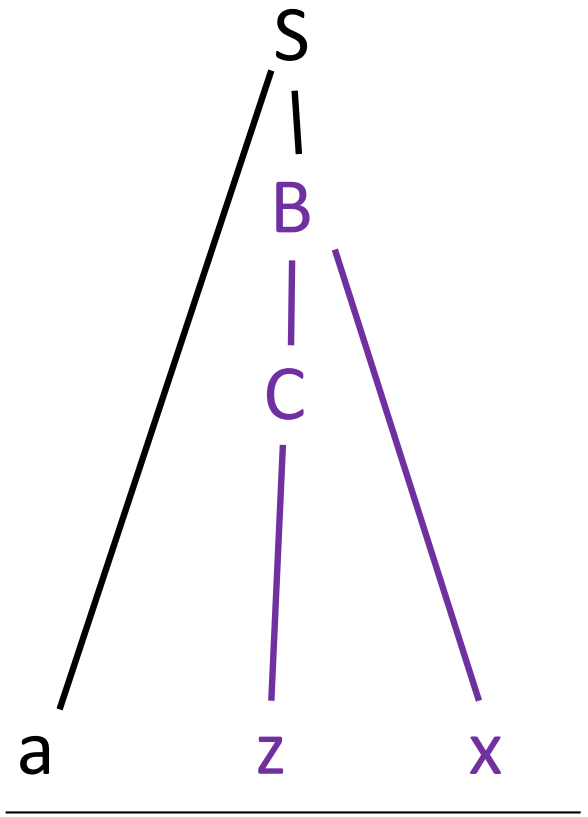
0. **S ::= a Tail**
1. **Tail ::= B | w**
2. B ::= C x | y
3. C ::= ε | z

Success!

Comparing Parse Trees



Purple trees are the same!



LL Condition

For each nonterminal in the grammar:

- Its *productions* must have disjoint FIRST sets

✗
```
A ::= x | B
B ::= x
```

✓
```
A ::= x | B
B ::= y
```

- If it is *nullable*, the FIRST sets of its productions must be disjoint from its FOLLOW set

✗
```
S ::= A x
A ::= ε | x
```

✓
```
S ::= A y
A ::= ε | x
```

**We can often transform a grammar to satisfy this if needed

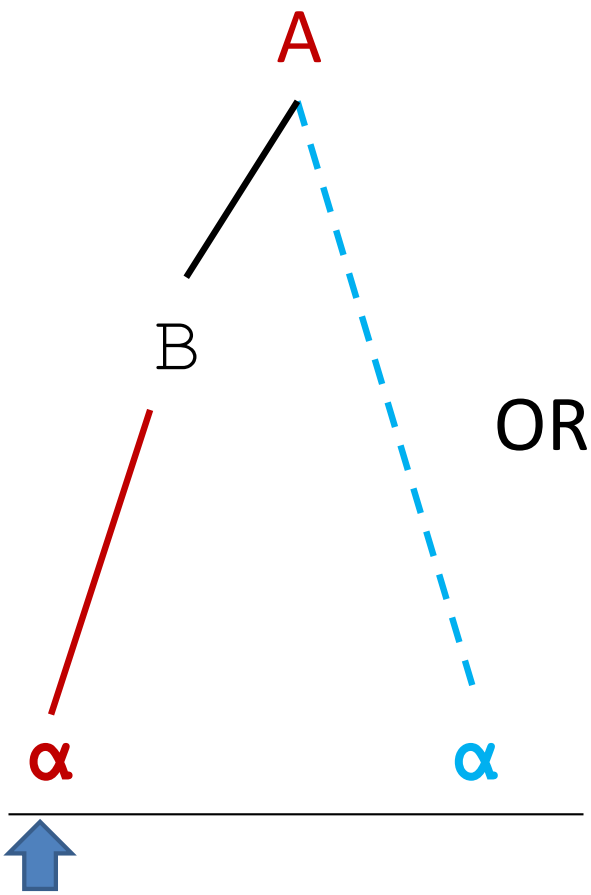
Canonical FIRST FOLLOW Conflict

Problem

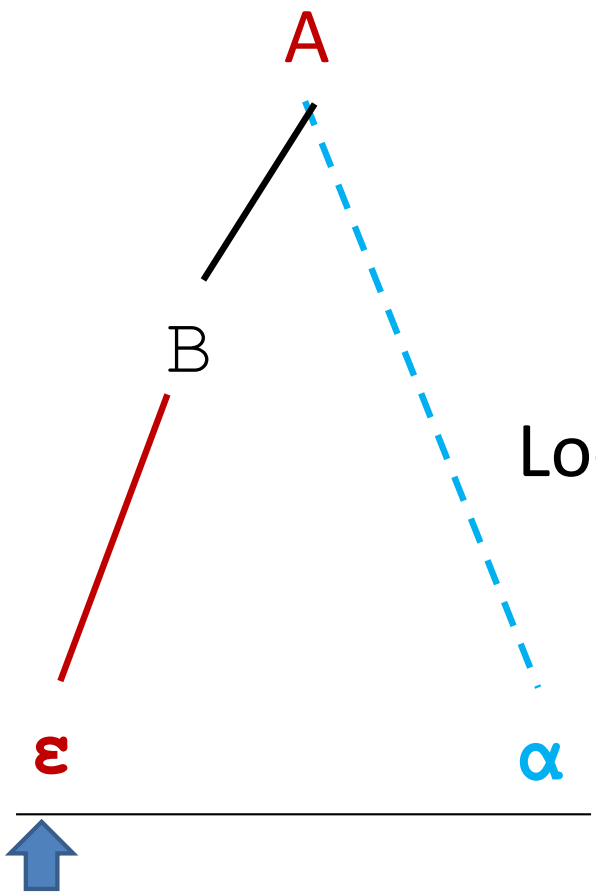
```
0. A ::= B α
1. B ::= α | ε
```

Because B is nullable, its FOLLOW set must be disjoint from the FIRST sets of its right-hand sides!

Let's try a top-down derivation of "α"



OR

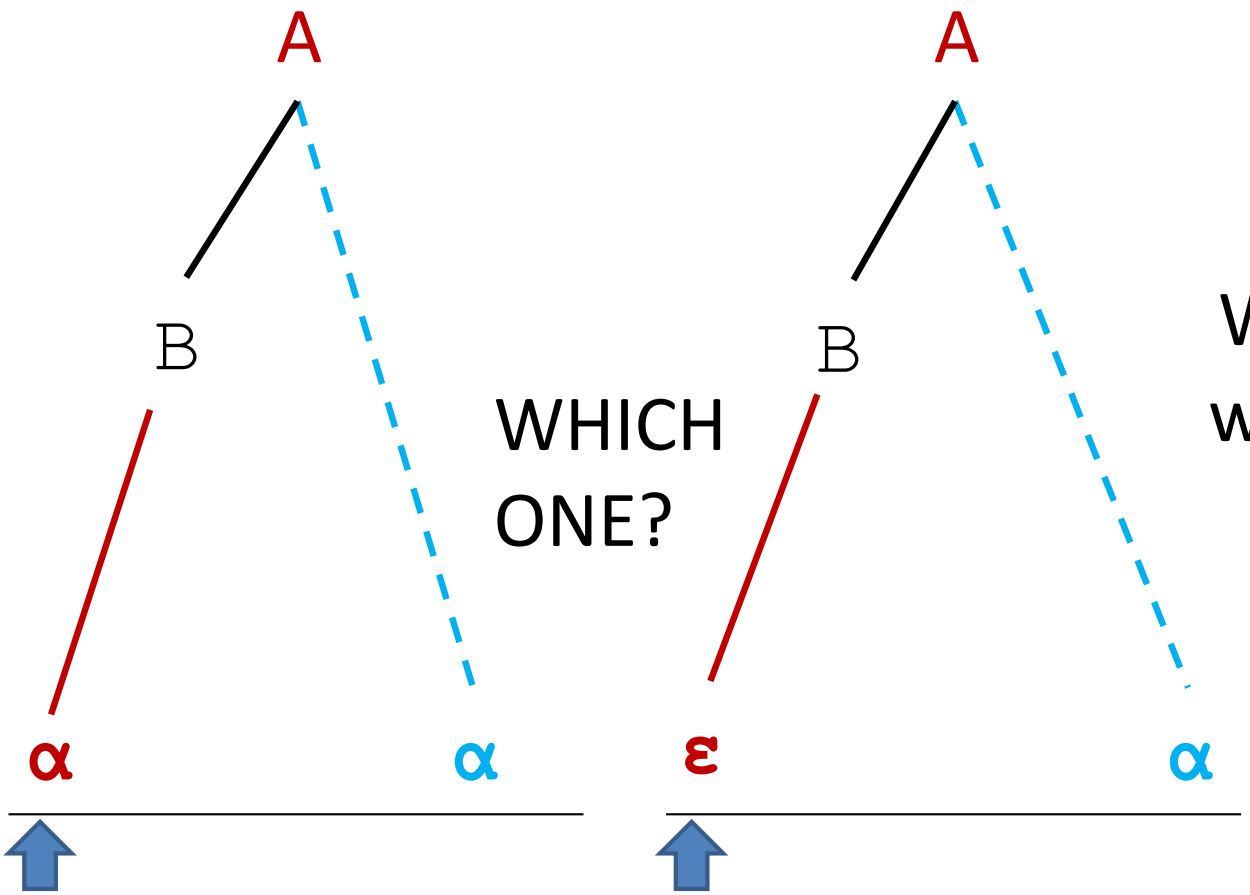



```
0. A ::= B α
1. B ::= α | ε
```

Lookahead Remaining

α

Let's try a top-down derivation of "α"




```
0. A ::= B α
1. B ::= α | ε
```

We don't know! Again, we can't see more than **α**!

Canonical FIRST FOLLOW Conflict Solution

Solution

```
0. A ::= B α
1. B ::= α | ε
```

Substitute the common prefix

```
0. A ::= αα | α
```

Factor out the tail

```
0. A ::= α Tail
1. Tail ::= α | ε
```

Watch out for Nullability! (Grammar 2)

Changing the grammar again…

```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | x
```

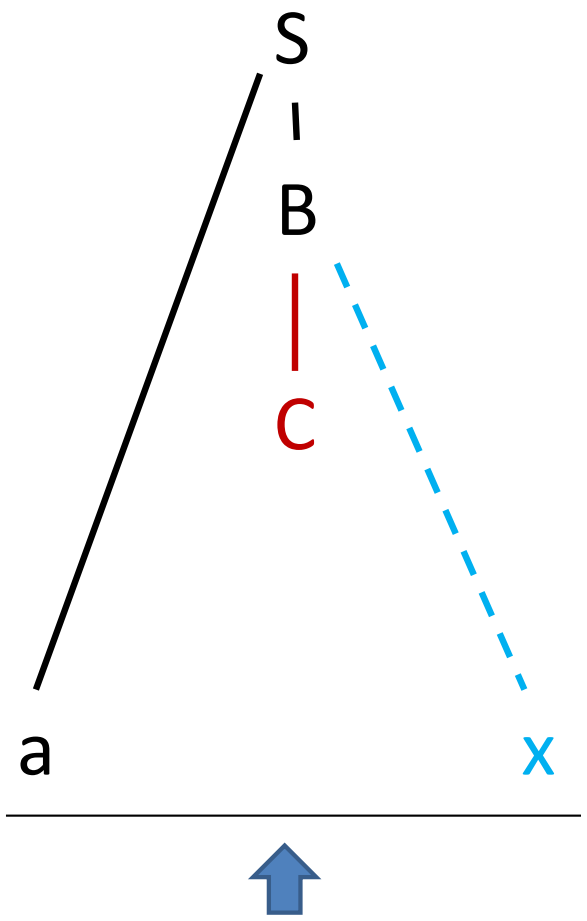
Lookahead	Remaining
a	x

What's the issue?

```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | x
```

FIRST FOLLOW Conflict

Top down derivation of “ax”



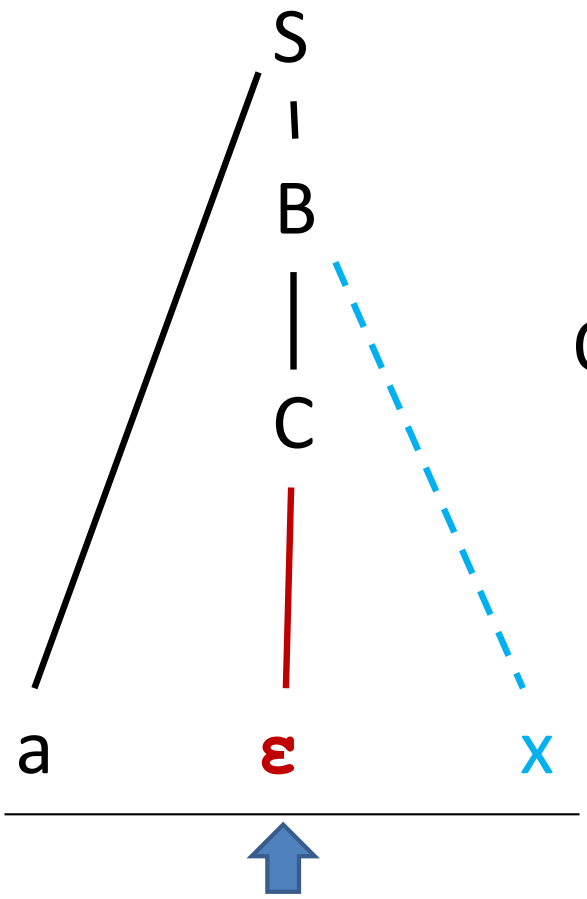

```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | x
```

Lookahead Remaining

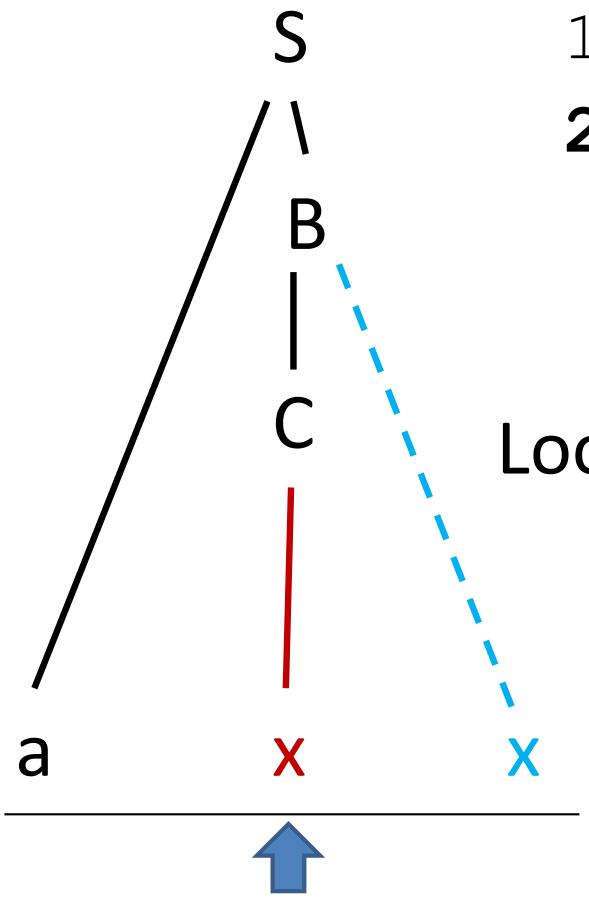
x

Top down derivation of “ax”

```
0. S ::= a B
1. B ::= C x | y
2. C ::= ε | x
```



OR



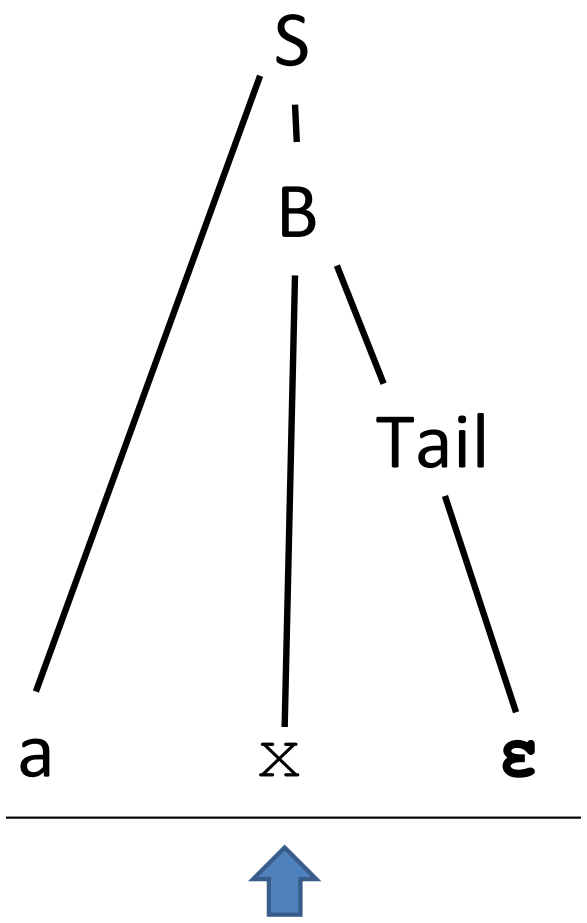
Lookahead	Remaining
x	

Applying the Fix: Substitute the Common Prefix,

```
                0. S ::= a B
1               1. B ::= x | xx | y
                2. C ::= ε | x

                0. S ::= a B
2               1. B ::= x Tail | y
                2. Tail ::= x | ε
```

Top down derivation of “ax”




```
0. S ::= a B
1. B ::= x Tail | y
2. Tail ::= x | ε
```

Lookahead Remaining

x