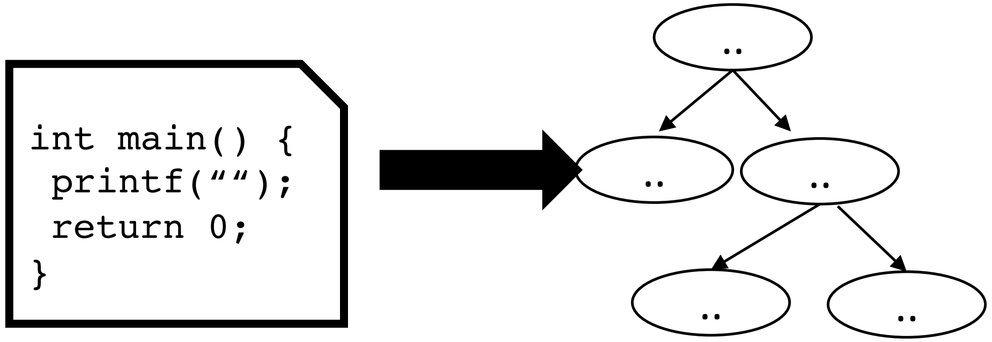
CSE110A: Compilers

April 13, 2022

Topics:

- *Syntactic Analysis continued*
  - *Derivations*
  - *Parse trees*
  - *Precedence and associativity*



```
int main() {
 printf("");
 return 0;
}
```

Announcements

- HW 1 is out
  - Due next Monday at Midnight

- Plenty of help available
  - I have office hours tomorrow
  - TAs and tutors have office hours on Friday
  - ***No guaranteed help over the weekend or off business hours***

- Thanks to those who are asking/answering questions on Piazza
  - And especially for finding bugs in the HW!

- Plan on HW2 assigned on Monday (Due 2 weeks later)

Announcements

- For part 3 and 4:
  - *Only use the “tokens” from tokens.py*
  - *We will use our own tokens.py to test. If you rely on anything else from that file it will break our grading*
  - *You should use token actions for keywords, even though first class functions can be a little strange at first*

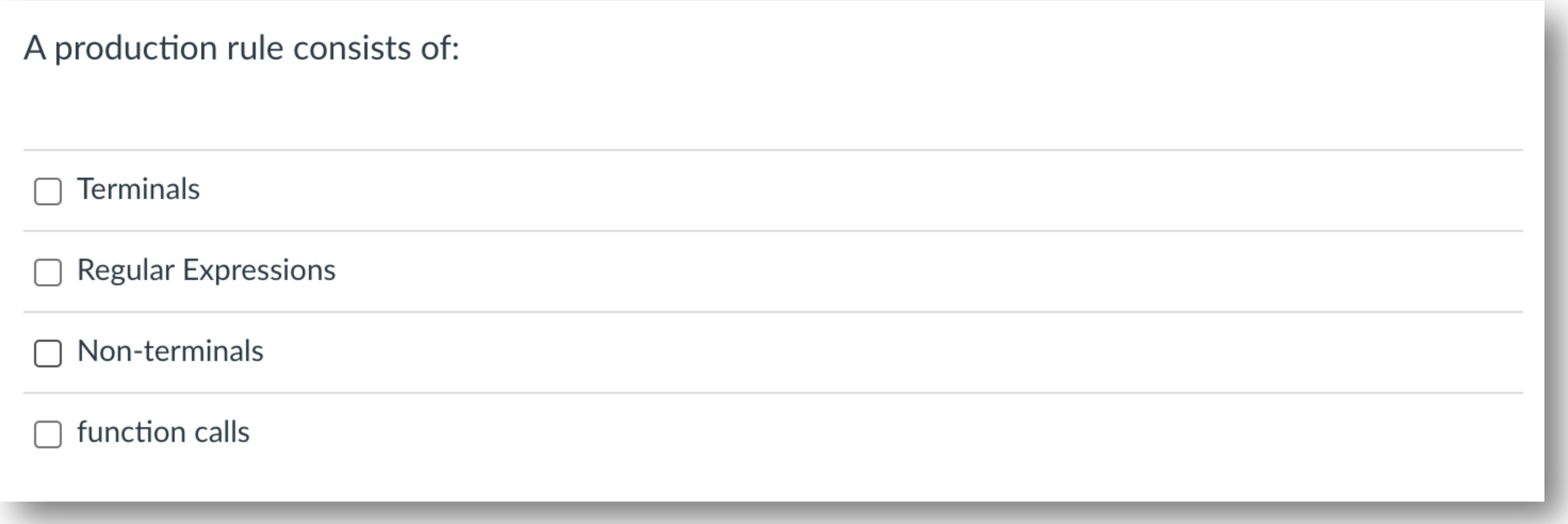
- Just to clarify: slides are all available on the website!

Quiz

With the technical issues we didn’t get through all the material to answer all the quiz questions, but we will today

Quiz

Start out-of-order



A production rule consists of:

- □ Terminals
- □ Regular Expressions
- □ Non-terminals
- □ function calls

Context-free grammar

We will use *Backus–Naur form* (BNF) form

- Production rules contain a sequence of either non-terminals or terminals
- In our class, terminals will either be string constants or tokens
- Traditionally tokens will be all caps.

```
Examples:

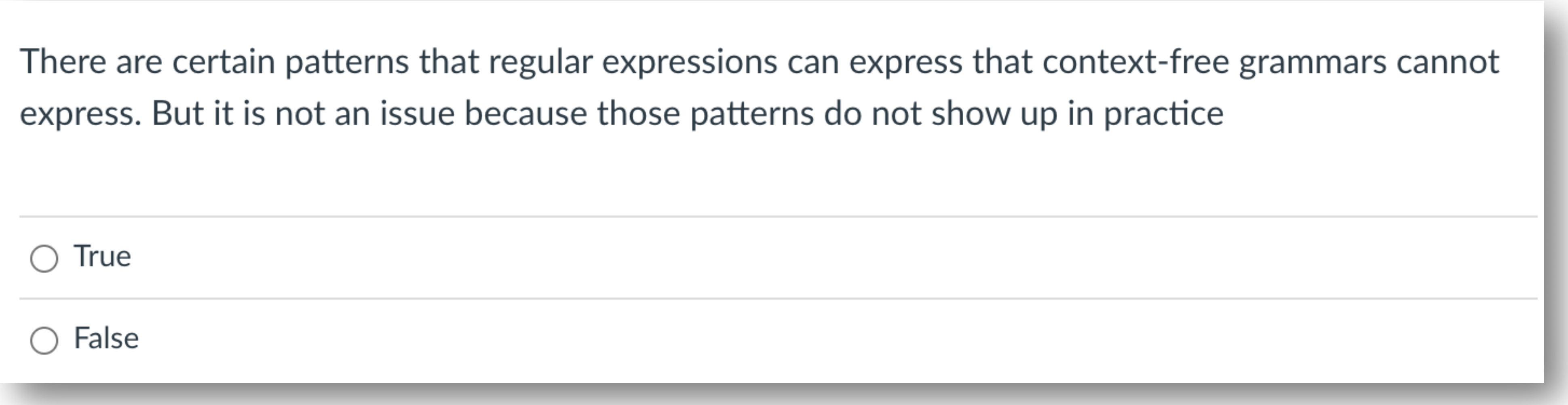
add_expr ::= NUM ‘+’ NUM

mult_expr ::= NUM ‘*’ NUM

joint_expr ::= add_expr ‘*’ add_expr

simple_expr ::= NUM ‘+’ NUM
            |   NUM ‘*’ NUM
```

Quiz



There are certain patterns that regular expressions can express that context-free grammars cannot express. But it is not an issue because those patterns do not show up in practice

○ True

○ False

Any RE can be expressed in BNF

- We just need to show fundamental operators
  - concat, choice, star

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```
add_expr ::= NUM ‘+’ NUM
```

Any RE can be expressed in BNF

- We just need to show fundamental operators
  - concat, choice, star

```
simple_expr ::= NUM ‘+’ NUM
              |    NUM ‘*’ NUM
```

Any RE can be expressed in BNF

- We just need to show fundamental operators
  - concat, choice, star

How to express “a” in BNF?*

```
a_star ::= ?
```

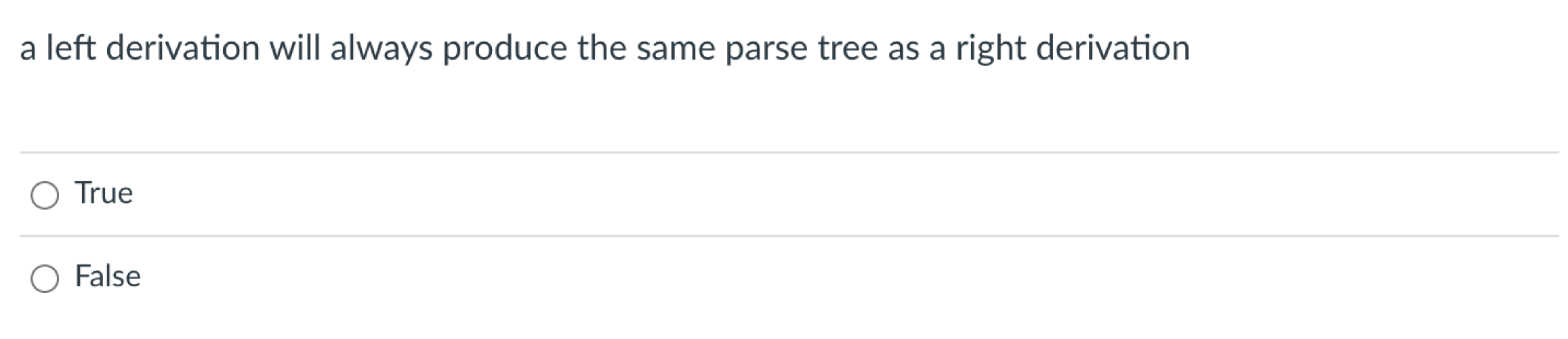
Any RE can be expressed in BNF

- We just need to show fundamental operators
  - concat, choice, star

How to express “a” in BNF?*

```
a_star ::= ""
        |   “a”
        |   “a” a_star
```

Quiz



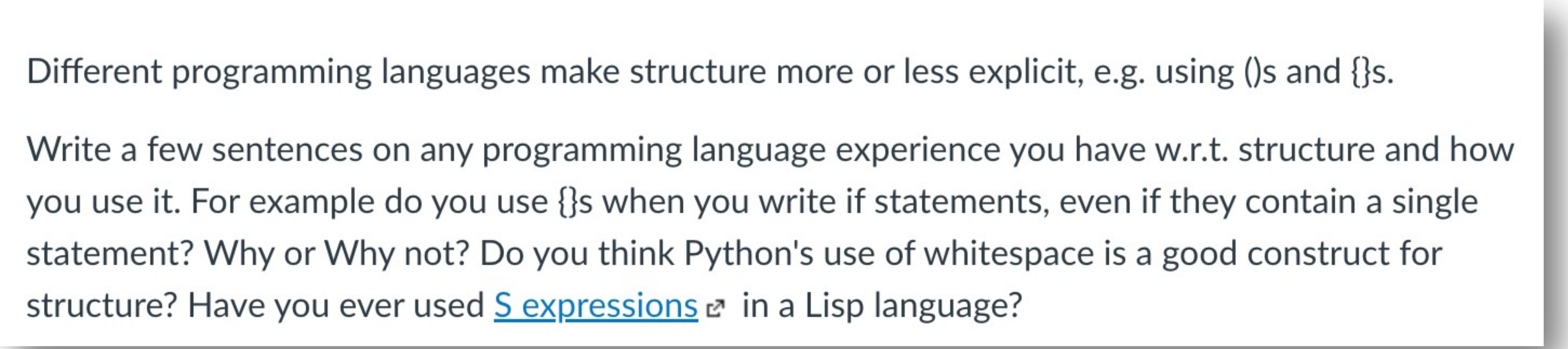
a left derivation will always produce the same parse tree as a right derivation

○ True

○ False

We didn’t get this far in the lecture

Quiz



Different programming languages make structure more or less explicit, e.g. using ()s and {}s.

Write a few sentences on any programming language experience you have w.r.t. structure and how you use it. For example do you use {}s when you write if statements, even if they contain a single statement? Why or Why not? Do you think Python's use of whitespace is a good construct for structure? Have you ever used S expressions in a Lisp language?

Programming language structure

```
if (x) {
  my_var++;
 }
```

vs.

```
if (x)
  my_var++;
```

Should conditionals require braces?

```
5 + 6 * 3
```

vs.

```
5 + (6 * 3)
```

should expressions require parenthesis?

```
(+ 5 (* 6 3))
```

vs.

```
(+ 5 (* 6 3))
```

S expressions (lisp) require explicit structure

What are pros and cons of each?

Programming language structure

```
int x = 1;
int y = 0;
int check0 = 0;


if (x)
if (y)
pass();
else
check0 = 1;
```

pop quiz: what is the value of check0 at the end?

Programming language structure

```
x = 1
y = 0
check0 = 0


if (x):
if (y):
pass
else:
check0 = 1


print(check0)
```

How does Python handle this?

Programming language structure

```
x = 1
y = 0
check0 = 0


if (x):
if (y):
pass
else:
check0 = 1


print(check0)
```

How does Python handle this?

```
x = 1
y = 0
check0 = 0


if (x):
  if (y):
    pass
  else:
    check0 = 1


print(check0)
```

Invalid syntax, you need to indent, which makes it clear

Review

- Regular expressions are insufficient for expressing the language grammar
  - Mostly because of ()s and {}s

Review: matching () with regex

```
\(? NUM ((PLUS | MULT) \(? NUM \)?)*
```

Test RE

```
5
```

```
5 + 6
```

```
5 + 6 * 3
```

But what does this one mean? What if we want different precedence?

```
(5 + 6) * 3
```

Can we do this one?

Review: matching () with regex

```
\(? NUM ((PLUS | MULT) \(? NUM \)?)*
```

Seems like it works! But what is the issue?

```
(5 + 6 * 3
```

What about this one?

()s are a key part of syntax. They are import for the structure we want to create and we need to reliably detect strings that are not syntactically valid!

Review

- How can a CFG handle ()’s

```
\(? NUM ((PLUS | MULT) \(? NUM \)?)*
```

As an exercise, how would we express this expression in BNF
- an expression with ()s +, *?

```
Expr ::=
```

Review

- How can a CFG handle ()'s

```
\(? NUM ((PLUS | MULT) \(? NUM \)?)*
```

As an exercise, how would we express this expression in BNF
- an expression with ()s +, *?

```
Expr ::= NUM
     |  EXPR PLUS EXPR
     |  EXPR MULT EXPR
     |  \( EXPR \)
```

Review

- How to derive strings from a context free grammar

Deriving strings

Give each production rule a numeric id

```
1: SheepNoise ::= ‘baa’ SheepNoise
2:            |    ‘baa’
```

RULE	Sentential Form
start	SheepNoise

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Deriving strings

Give each production rule a numeric id

```
1: SheepNoise ::= ‘baa’ SheepNoise
2:            |   ‘baa’
```

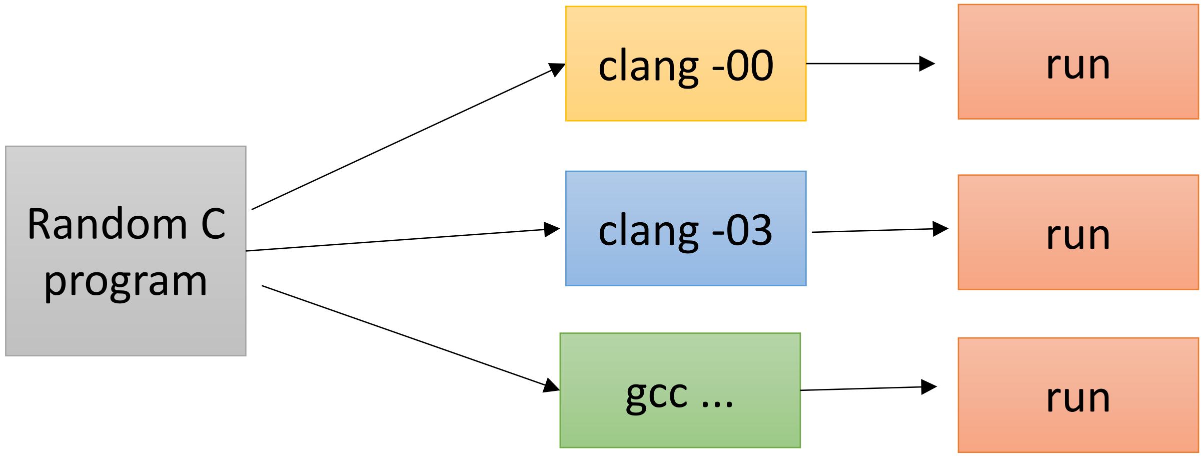
RULE	Sentential Form
start	SheepNoise
2	baa

RULE	Sentential Form
start	SheepNoise
1	baa SheepNoise
2	baa baa

Case study in string derivation: CSmith

Case study in string derivation: CSmith

- Using a CFG, you can derive random strings in a language
- C-Smith
  - Generates random C programs
  - Used to test compiler correctness

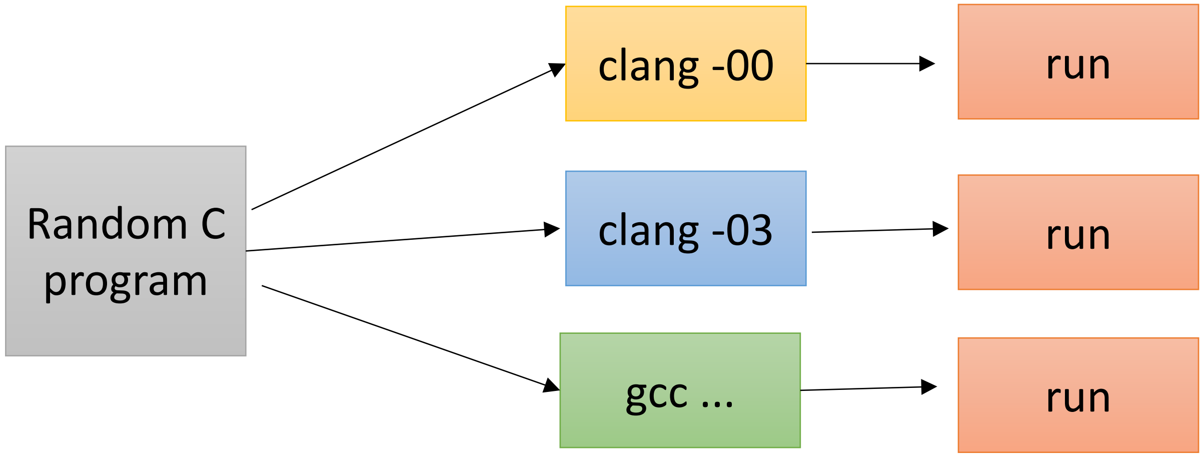


Check outcome. Is it the same? if not, then there is a bug in one of the compilers

Case study

- 400+ compiler bugs found

- Demo



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Case study

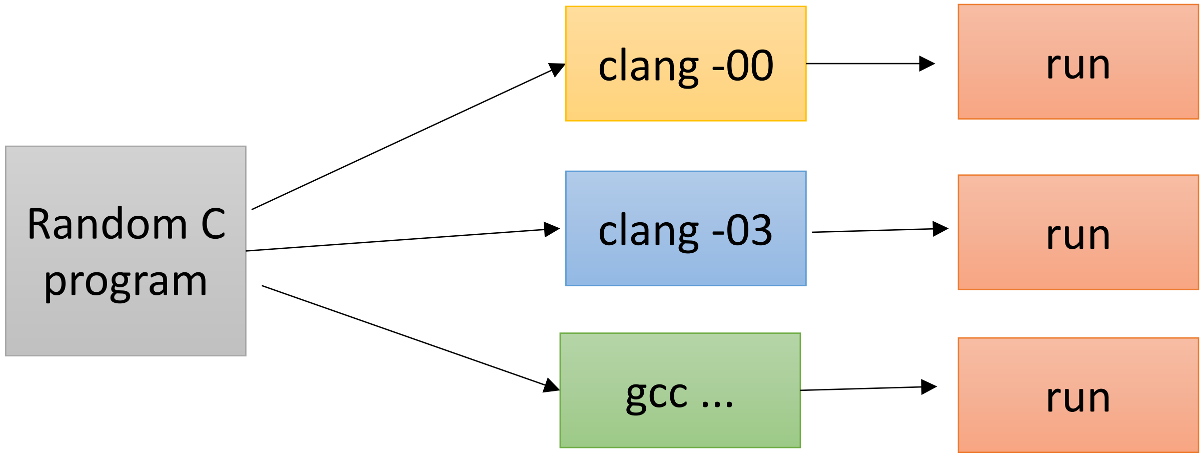
- Big challenge: Undefined behavior

- Even though the program is syntactically valid, the behavior may be undefined

```
int main() {
  int x;
  printf("%d\n", x);
  return 0;
}
```

Uninitialized variables can return anything!

Use advanced compiler analysis to catch these issues



Random C program

clang -O0

clang -O3

gcc ...

run

run

run

Check outcome. Is it the same? if not, then there is a bug in one of the compilers

Moving on to new material

- We are going to start with the derivation we did at the end of class last time

A more complicated derivation

```
1: Expr ::= ‘(’ Expr ‘)’
2:      |    Expr Op ID
3:      |    ID
4: Op   ::= ‘+’
5: Op   |   ‘*’
```

Can we derive the string `(a+b)*c`

RULE	Sentential Form
start	Expr

A more complicated derivation

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We can visualize this as a tree:

Expr

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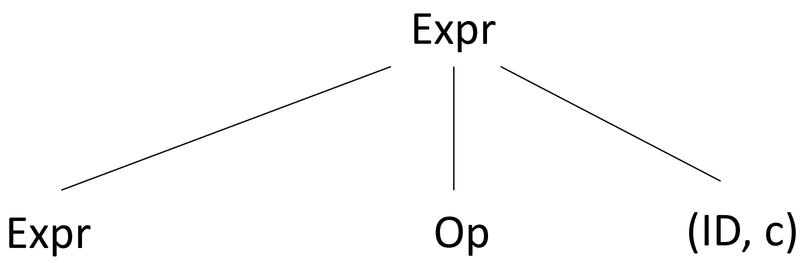

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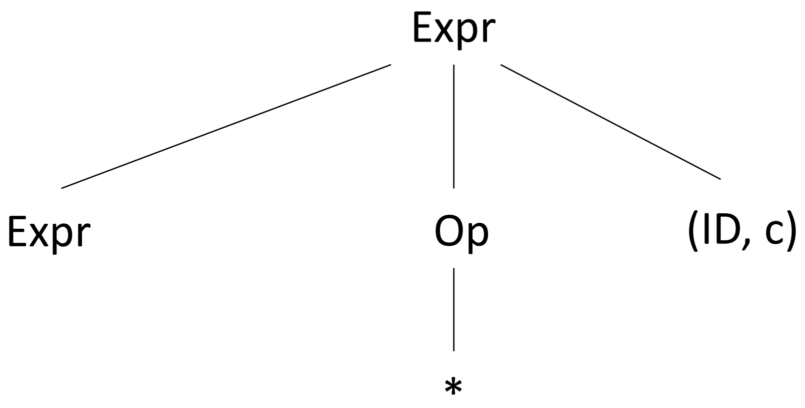

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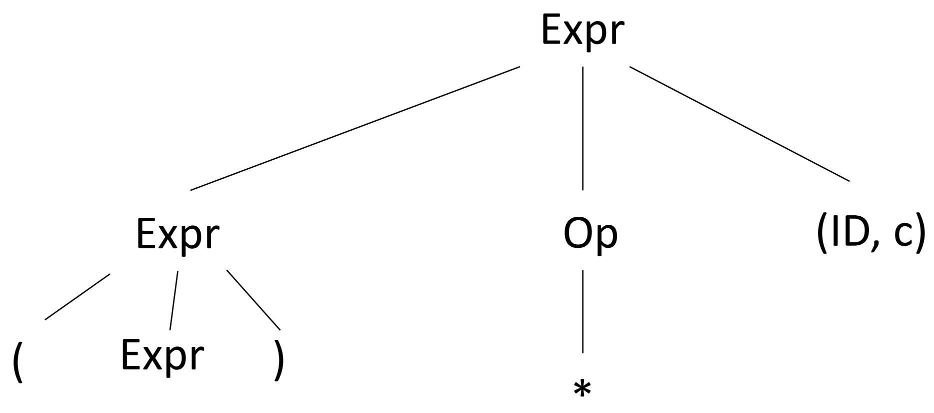

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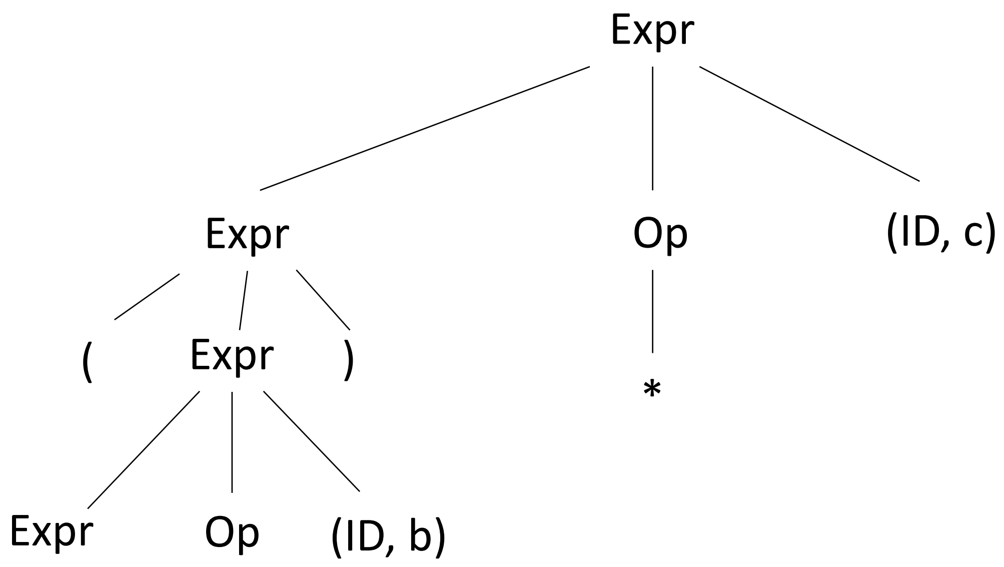

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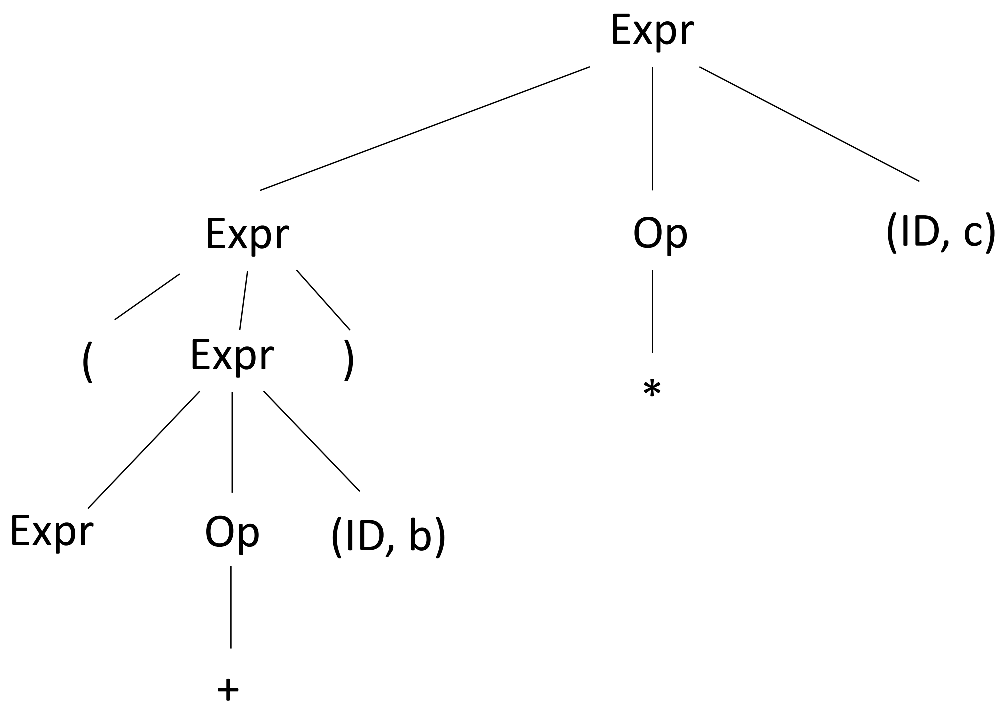

A more complicated derivation

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```

Are there other ways to derive `(a+b)*c`?

RULE	Sentential Form
start	Expr
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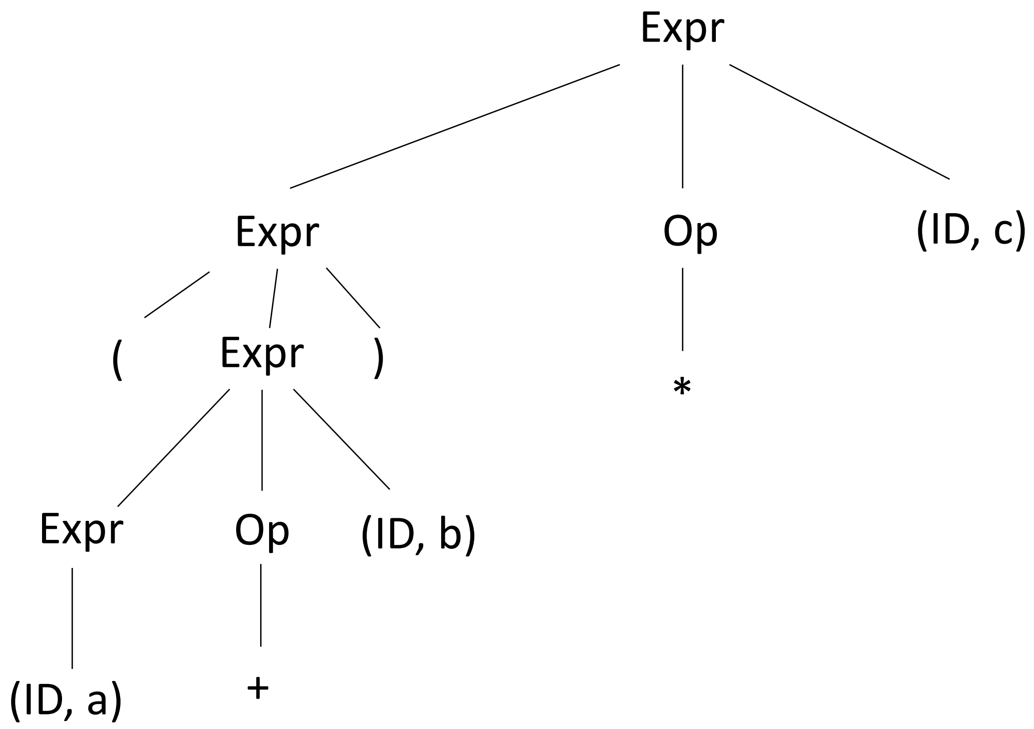
4	(Expr + ID) * ID
3	(ID + ID) * ID

We can visualize this as a tree:



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Are there other ways to derive `(a+b)*c`*?*

RULE	Sentential Form
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2	(Expr Op ID) * ID
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RULE	Sentential Form
start	Expr

A more complicated derivation

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Are there other ways to derive `(a+b)*c`?

RULE	Sentential Form
start	Expr
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4	(Expr + ID) * ID
3	(ID + ID) * ID

right derivation

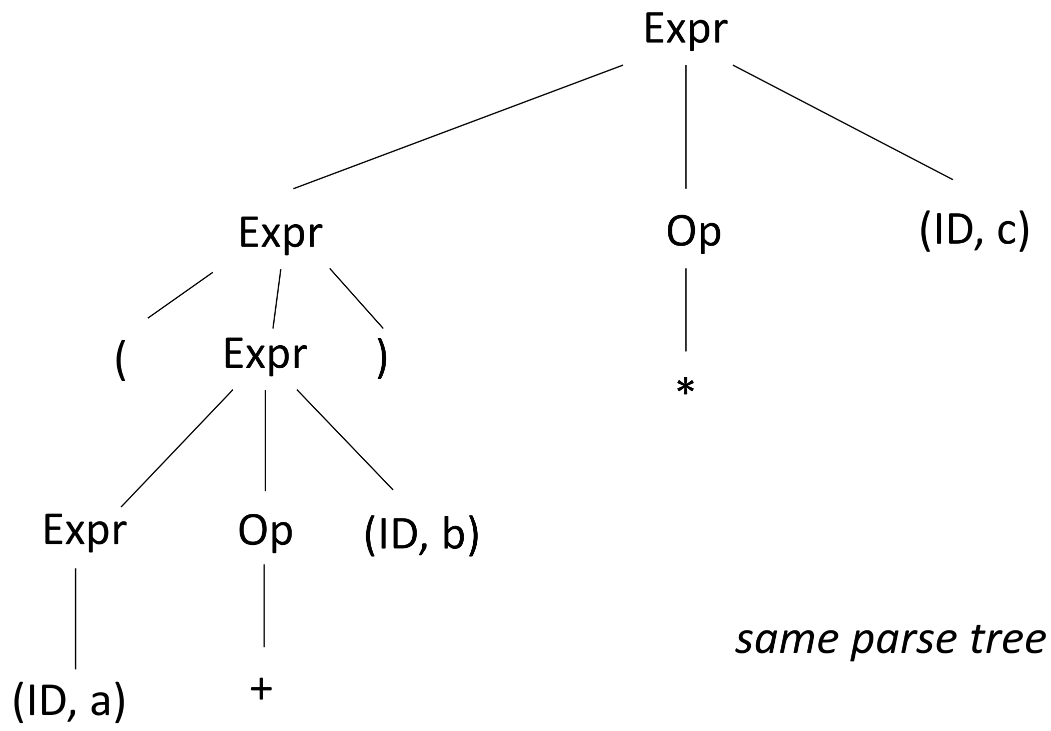
RULE	Sentential Form
start	Expr
2	Expr Op ID
1	(Expr) Op ID
2	(Expr Op ID) Op ID
3	(ID Op ID) Op ID
4	(ID + ID) Op ID
5	(ID + ID) + ID

left derivation

A more complicated derivation

```
1: Expr ::= ‘(’ Expr ‘)’
2:      |    Expr Op ID
3:      |    ID
4: Op   ::= ‘+’
5: Op   |   ‘*’
```

*Are there other ways to derive (a+b)*c?*



same parse tree

RULE	Sentential Form
start	Expr
2	Expr Op ID
1	(Expr) Op ID
2	(Expr Op ID) Op ID
3	(ID Op ID) Op ID
4	(ID + ID) Op ID
5	(ID + ID) + ID

left derivation

Ambiguous grammars

- What happens when different derivations have different parse trees?

```
1: Statement ::= ”if” Expr “then” Statement “else” Statement
2:             |  ”if” Expr “then” Statement
3:             |   Assignment
4:             |   ....
```

can we derive this string?

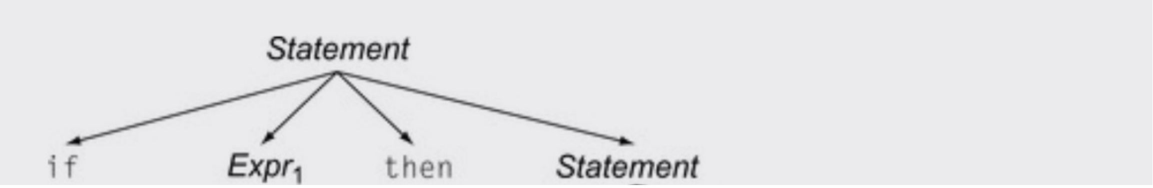
if $Expr_1$ **then** **if** $Expr_2$ **then** $Assignment_1$ **else** $Assignment_2$

Next few figures taken from the EAC book (Chapter 3.1)

Ambiguous grammars

```
1: Statement ::= ”if” Expr “then” Statement “else” Statement
2:             |   ”if” Expr “then” Statement
3:             |    Assignment
4:             |    ....
```

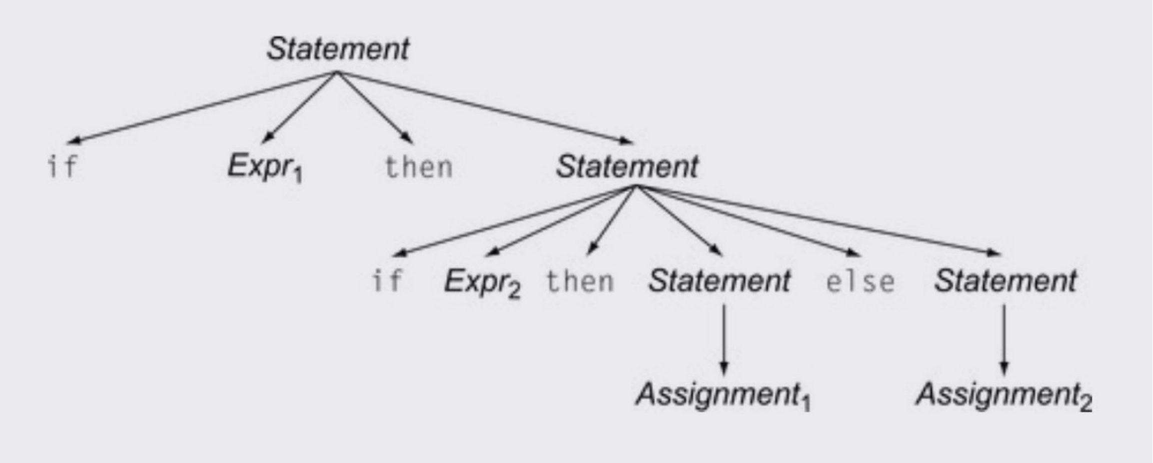
if *Expr*$_1$ **then** **if** *Expr*$_2$ **then** *Assignment*$_1$ **else** *Assignment*$_2$



Ambiguous grammars

```
1: Statement ::= ″if″ Expr “then” Statement “else” Statement
2:            |   ″if″ Expr “then” Statement
3:            |    Assignment
4:            |    ....
```

`if Expr₁ then if Expr₂ then Assignment₁ else Assignment₂`

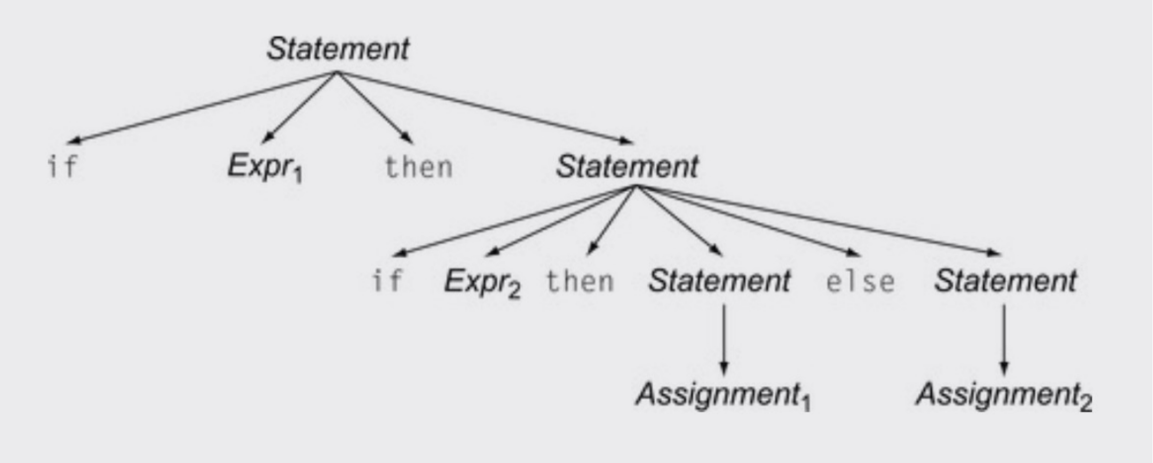


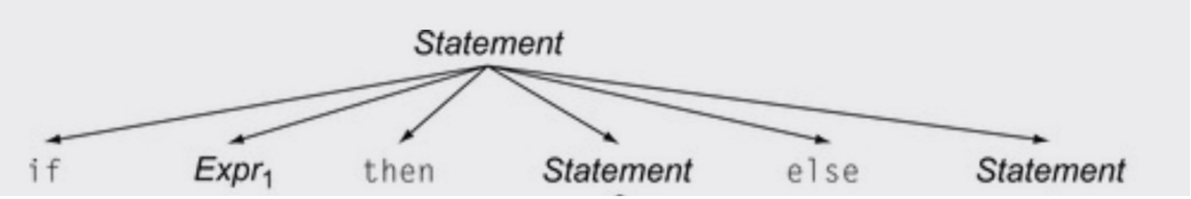
Valid derivation

Ambiguous grammars

```
1: Statement ::= ″if″ Expr “then” Statement “else” Statement
2:           |    ″if″ Expr “then” Statement
3:           |     Assignment
4:           |     ....
```

if *Expr₁* **then** **if** *Expr₂* **then** *Assignment₁* **else** *Assignment₂*



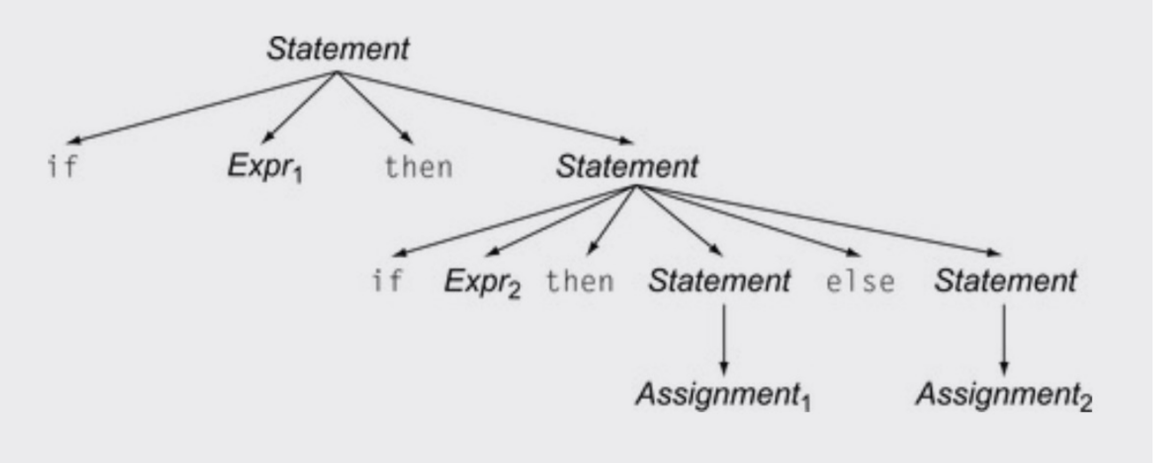


Valid derivation

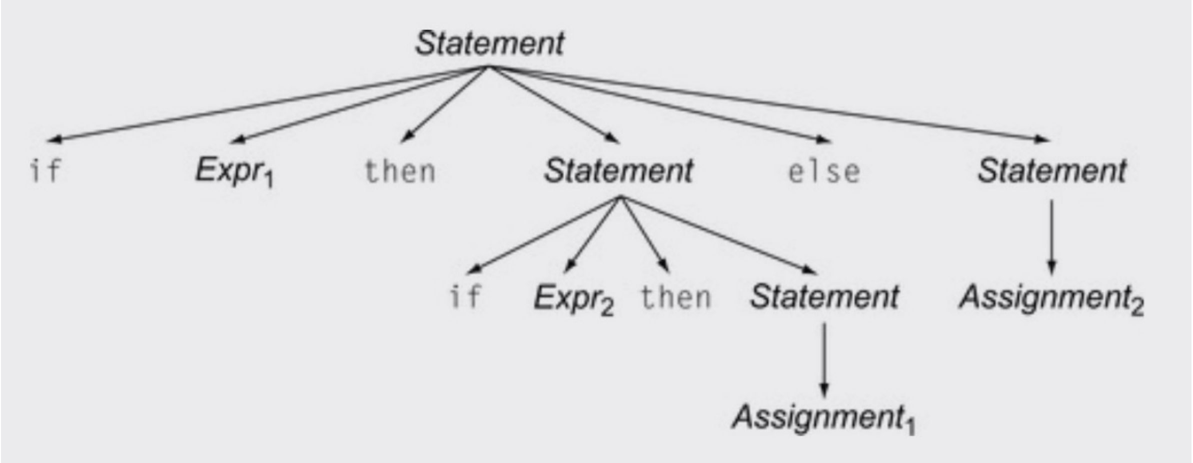
Ambiguous grammars

```
1: Statement ::= ″if″ Expr “then” Statement “else” Statement
2:             |   ″if″ Expr “then” Statement
3:             |    Assignment
4:             |    ....
```

```
if Expr₁ then if Expr₂ then Assignment₁ else Assignment₂
```



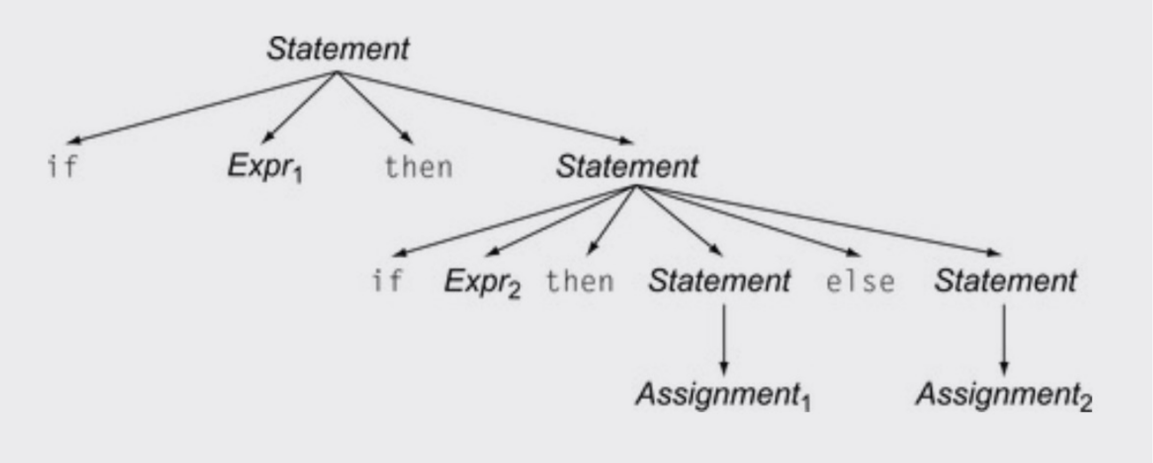
Valid derivation



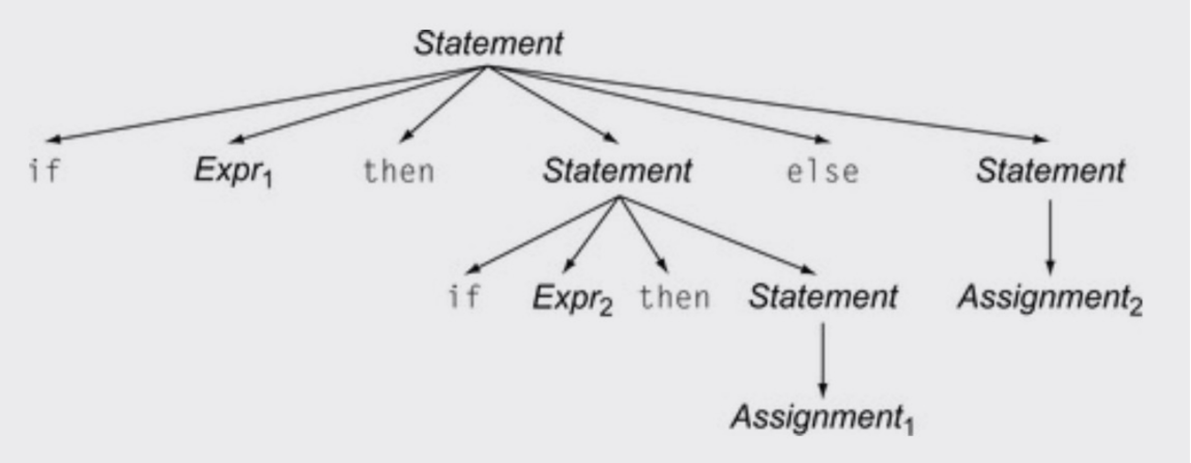
Also a valid derivation

Ambiguous grammars

Is this an issue? Don’t we only care if a grammar can derive a string?



Valid derivation



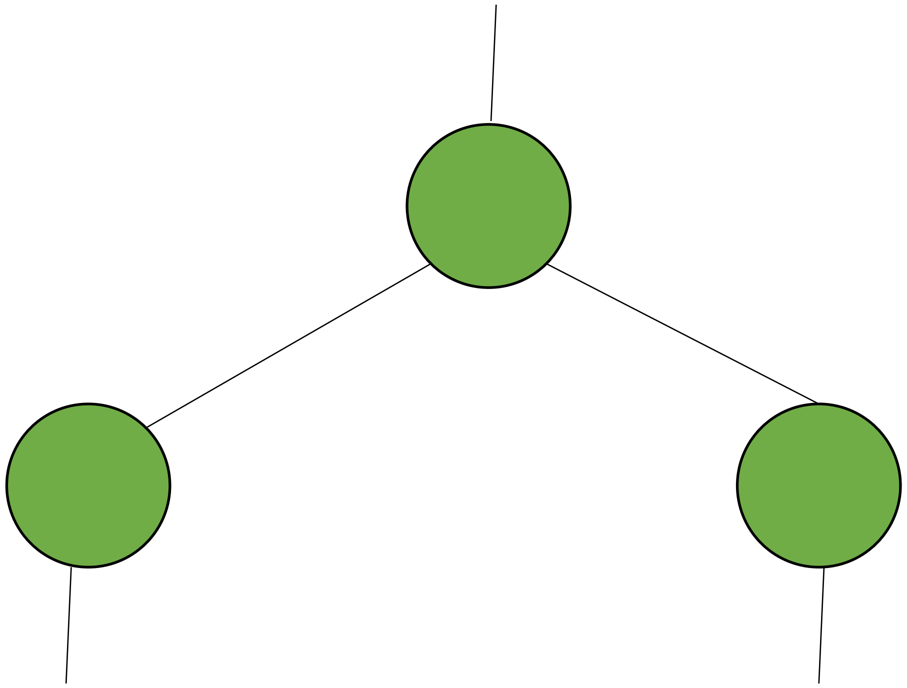
Also a valid derivation

Meaning into structure

- We want to start encoding meaning into the parse structure. We will want as much structure as possible as we continue through the compiler

- The structure is that we want evaluation of program to correspond to a post order traversal of the parse tree (also called the natural traversal)

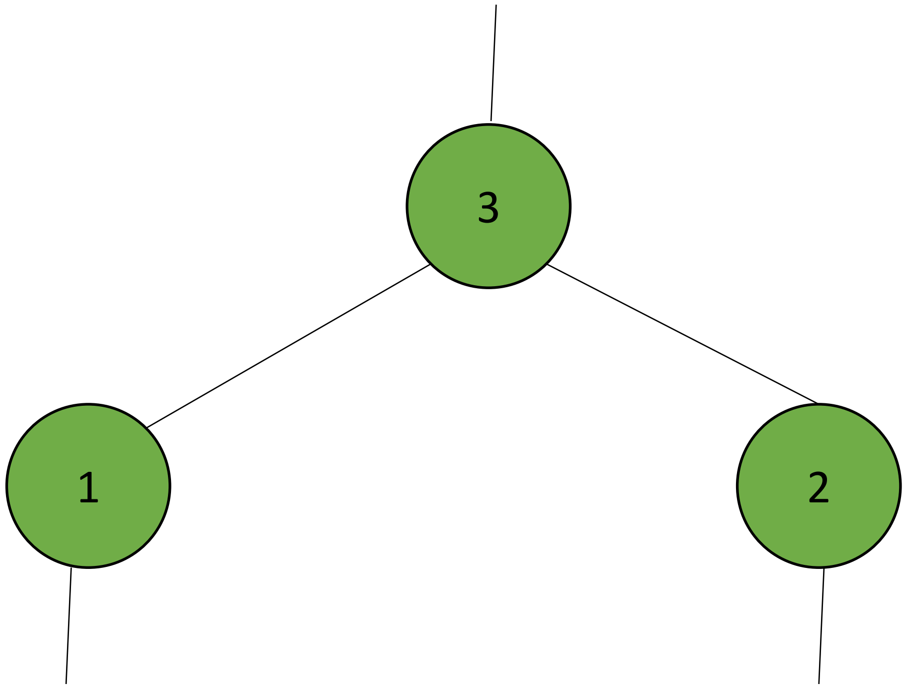
Post order traversal



visiting for for different types
of traversals:

pre order?
in order?
post order?

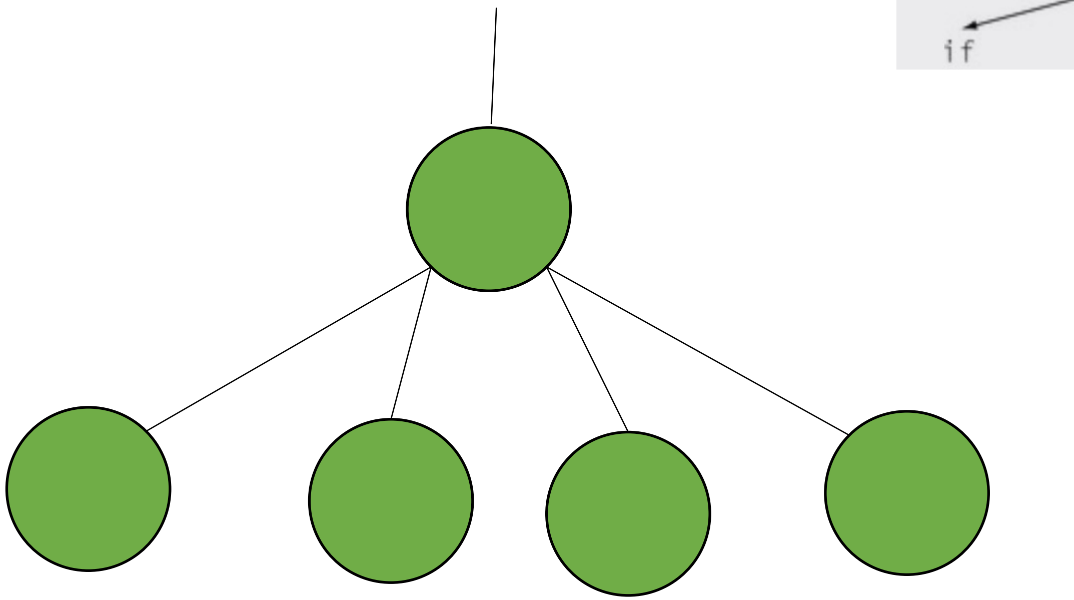
Post order traversal

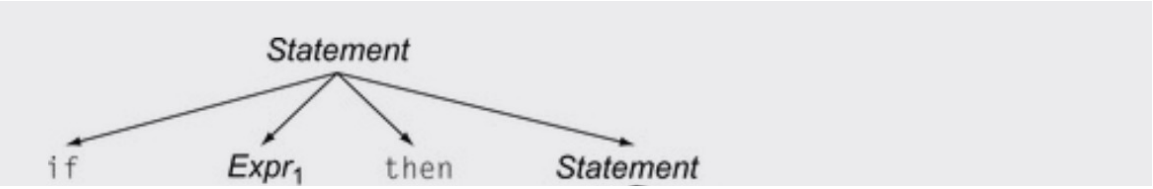


visiting for for different types of traversals:

post order

Post order traversal

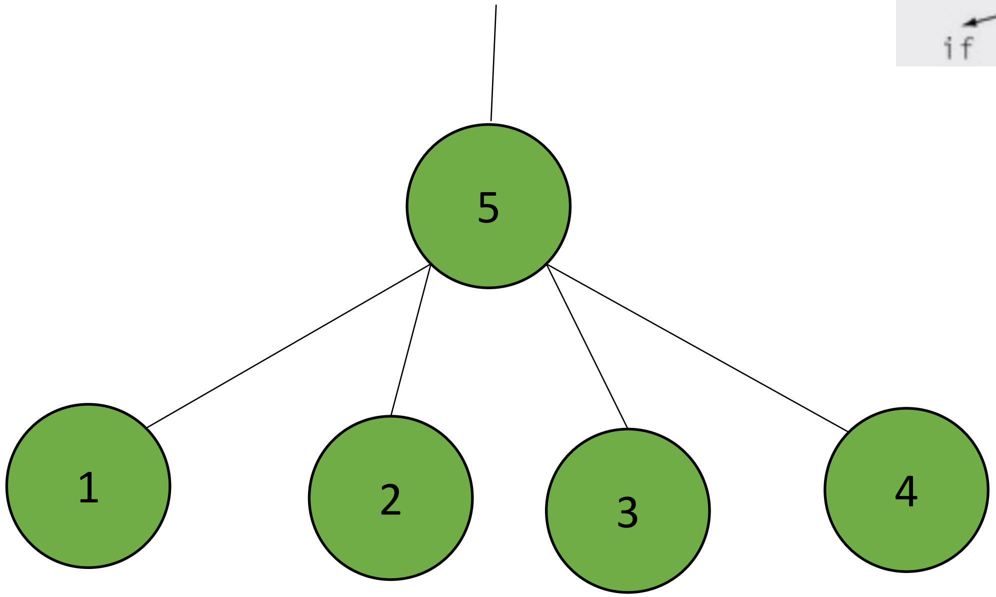


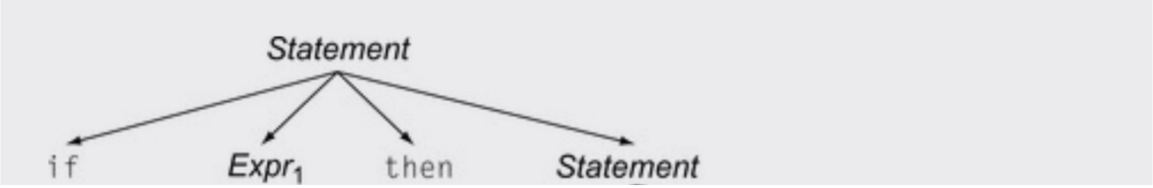


What if you have more children?

post order

Post order traversal



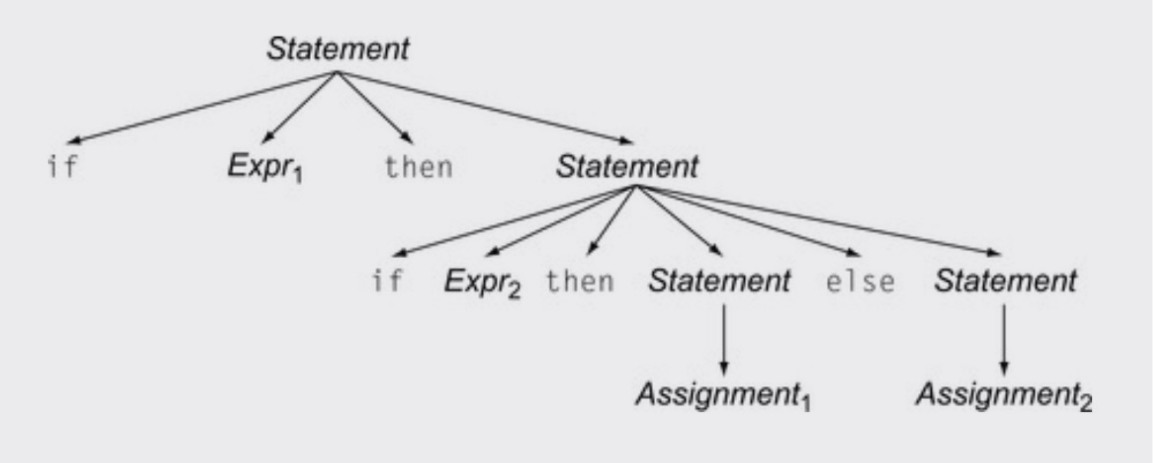


What if you have more children?

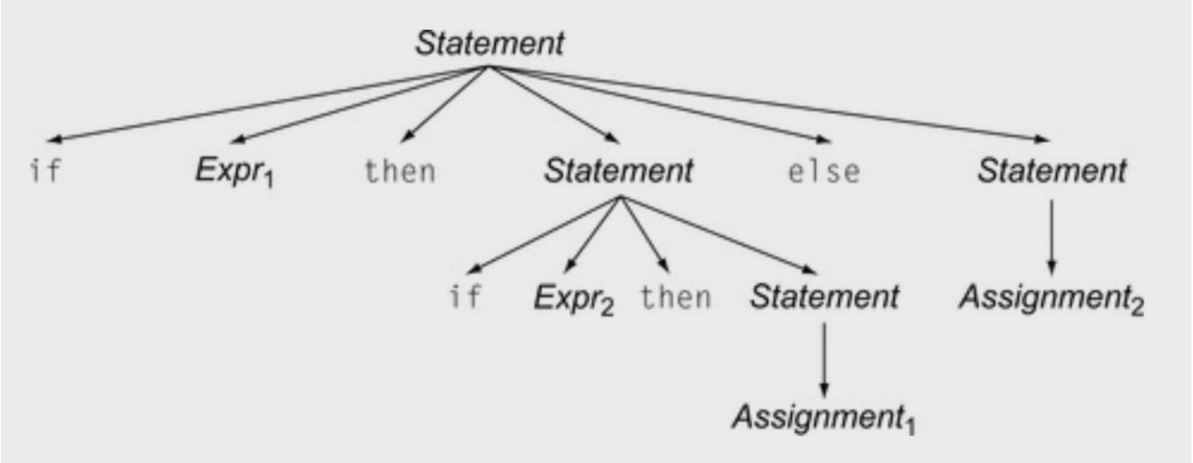
post order

Ambiguous grammars

When we encode meaning into structure, these are very different programs



Valid derivation



Also a valid derivation

Ambiguous expressions

- First lets define tokens:
  - `NUM = ”[0-9]+”`
  - `PLUS = ‘\+’`
  - `TIMES = ’\*’`
  - `LP = ‘\(’`
  - `RP = \)’`

Lets define a simple expression language

```
Expr :== NUM
       | Expr PLUS Expr
       | Expr TIMES Expr
       | LP Expr RP
```

Parse trees examples

```
input: 5
```

```
expr ::= NUM
     | expr PLUS expr
     | expr TIMES expr
     | LPAREN expr RPAREN
```

expr

Parse trees examples

```
expr ::= NUM
      | expr PLUS expr
      | expr TIMES expr
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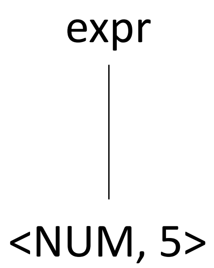
```

```
input: 5
```



expr

<NUM, 5>

Parse trees examples

```
input: 5*6
```

```
expr ::= NUM
     | expr PLUS expr
     | expr TIMES expr
     | LPAREN expr RPAREN
```

Parse trees examples

```
expr ::= NUM
      | expr PLUS expr
      | expr TIMES expr
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input: 5*6
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expr

Parse trees examples

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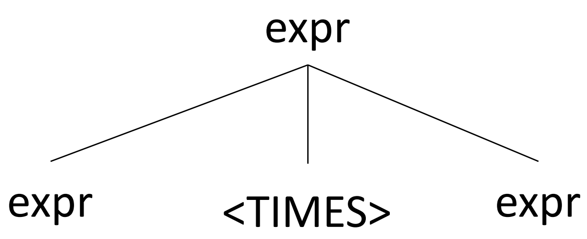
`input: 5*6`



Parse trees examples

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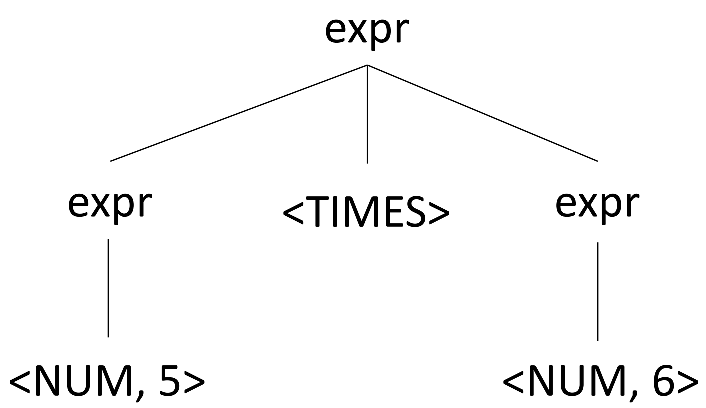
      | LPAREN expr RPAREN
```

```
input: 5*6
```



Parse trees examples

```
expr ::= NUM
      | expr PLUS expr
      | expr TIMES expr
      | LPAREN expr RPAREN
```

```
input: 5**6
```

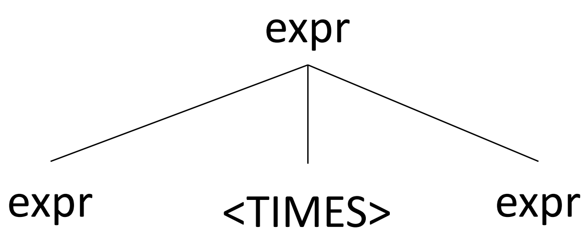
expr

What happens in an error?

Parse trees examples

```
expr ::= NUM
      | expr PLUS expr
      | expr TIMES expr
      | LPAREN expr RPAREN
```

`input: 5**6`



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Parse trees examples

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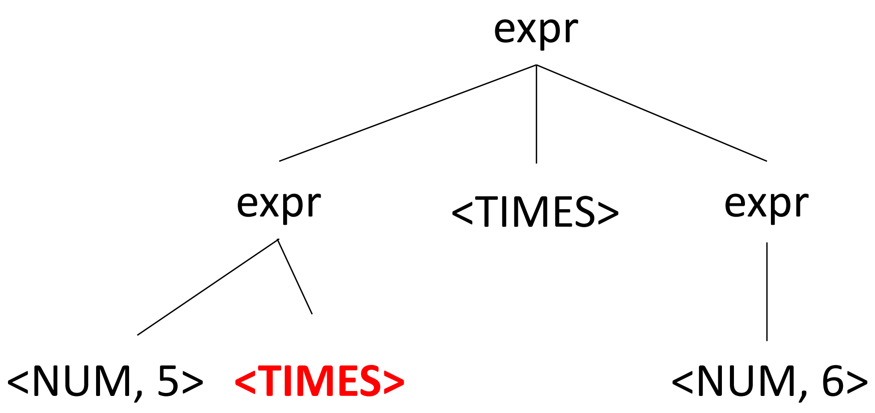

Not possible!

Parse trees examples

```
input: (1+5)*6
```

```
expr ::= NUM
      | expr PLUS expr
      | expr TIMES expr
      | LPAREN expr RPAREN
```

Parse trees examples

input: (1+5)*6

```
expr ::= NUM
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expr

Parse trees examples

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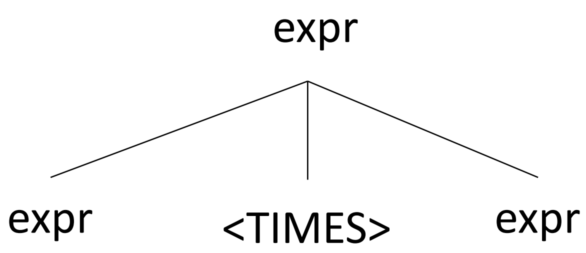

Parse trees examples

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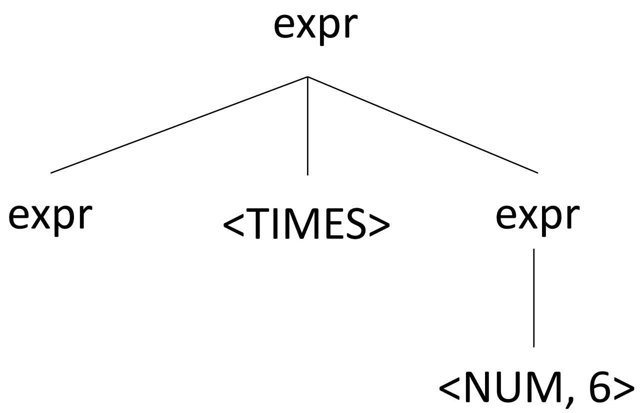

Parse trees examples

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```
input: (1+5)*6
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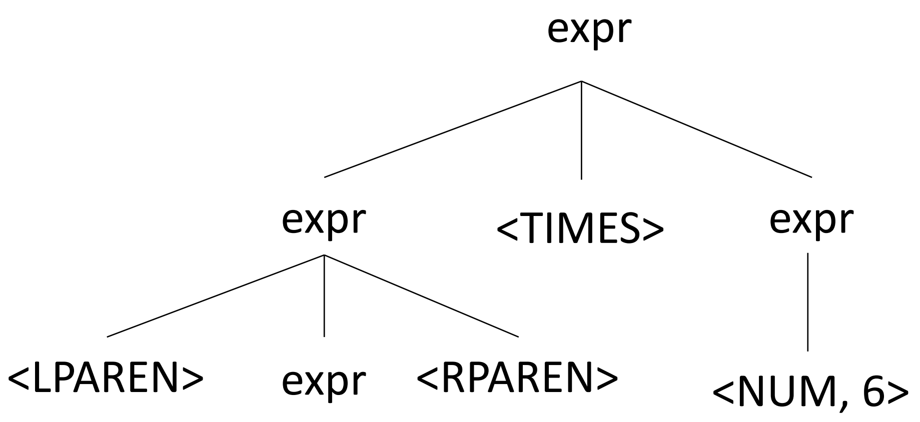

Parse trees examples

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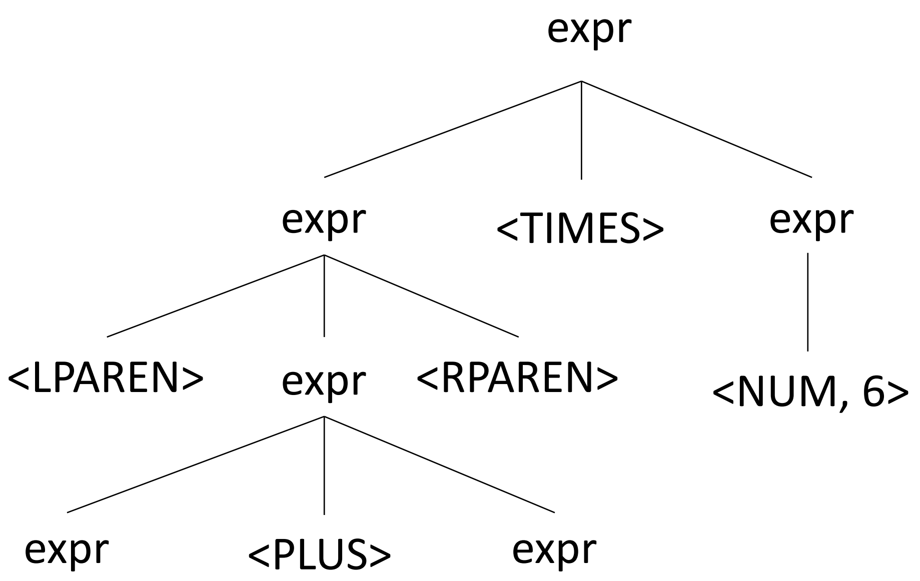
input: (1+5)*6



Parse trees examples

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```

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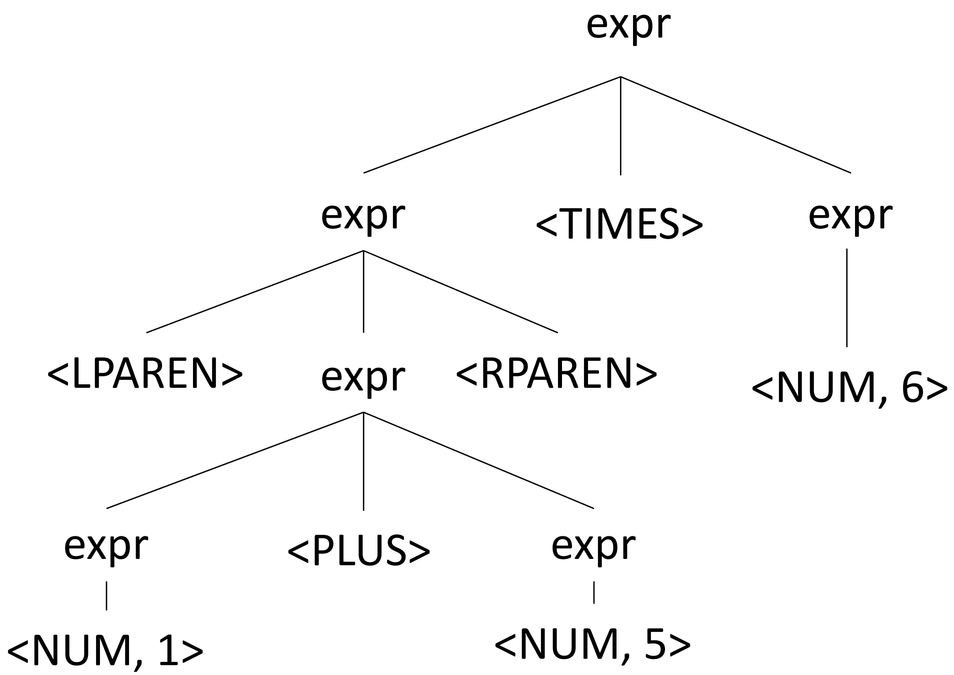
input: (1+5)*6
```

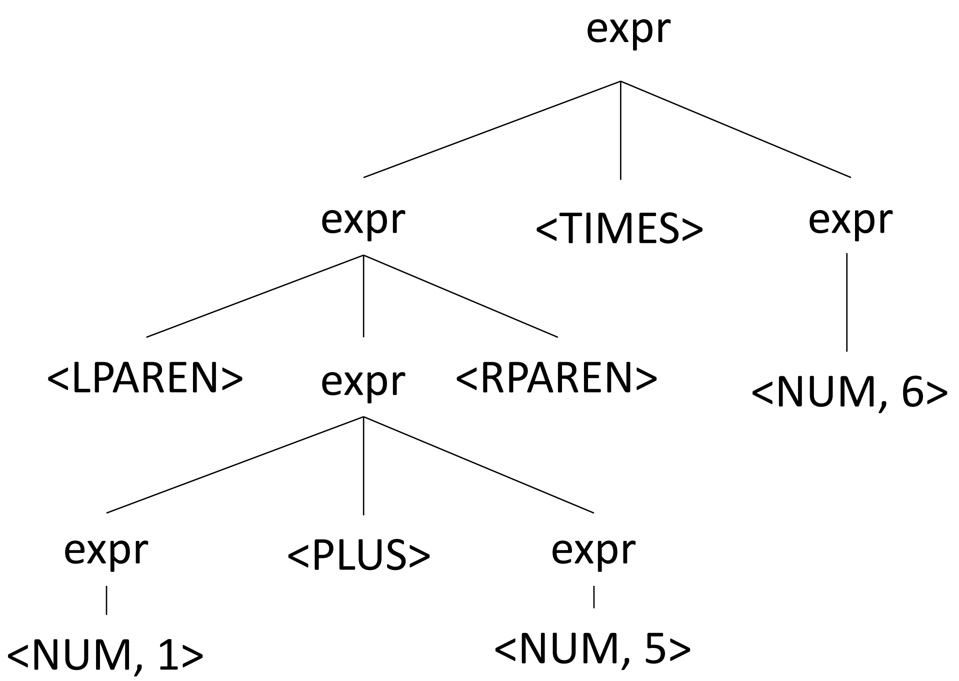


Parse trees examples

Does this parse tree capture the structure we want?

```
input: (1+5)*6
```

```
expr ::= NUM
      | expr PLUS expr
      | expr TIMES expr
      | LPAREN expr RPAREN
```



Parse trees

- How about: `1 + 5 * 6`

```
expr ::= NUM
       | expr PLUS expr
       | expr TIMES expr
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Parse trees

- How about: `1 + 5 * 6`

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expr ::= NUM
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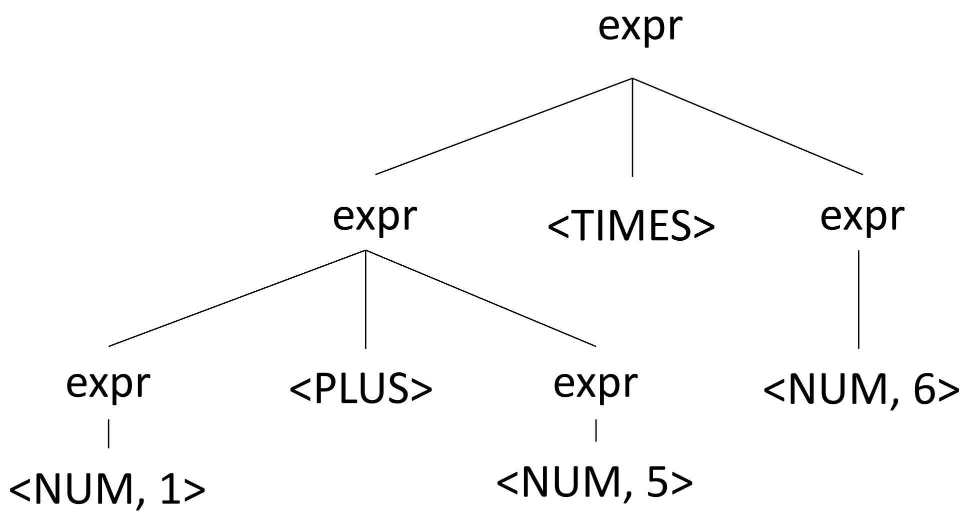

Ambiguous grammars

- `input: 1 + 5 * 6`

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expr ::= NUM
       | expr PLUS expr
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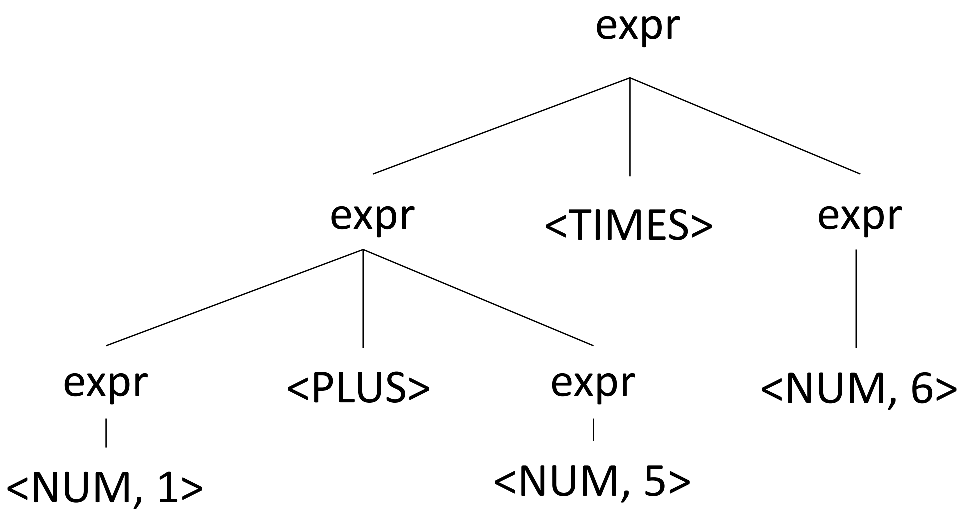

Ambiguous grammars

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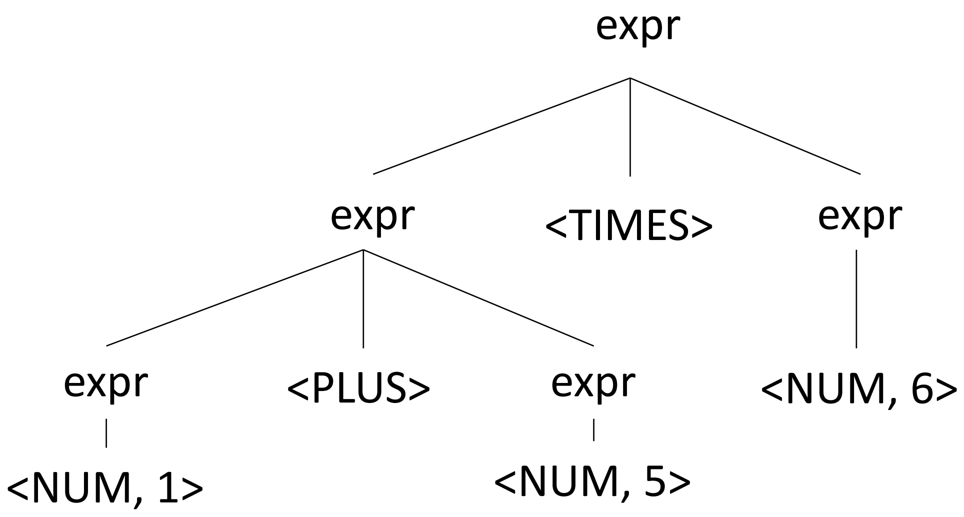

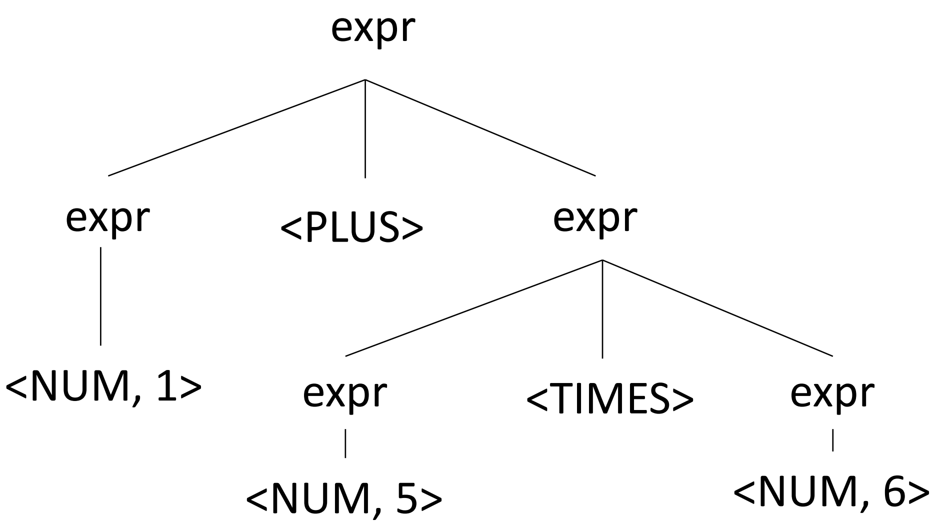

Avoiding Ambiguity

- How to avoid ambiguity related to precedence?

- Define precedence: ambiguity comes from conflicts. Explicitly define how to deal with conflicts, e.g. write* has higher precedence than +

- Some parser generators support this, e.g. Yacc

Avoiding Ambiguity

- How to avoid ambiguity related to precedence?

- **Second way**: new production rules
  - One non-terminal for each level of precedence
  - lowest precedence at the top
  - highest precedence at the bottom

- Lets try with expressions and the following:
  - + * ()

Avoiding Ambiguity

- How to avoid ambiguity related to precedence?

- **Second way**: new production rules
  - One non-terminal for each level of precedence
  - lowest precedence at the top
  - highest precedence at the bottom

- Lets try with expressions and the following:
  - + * ()

Precedence increases going down

Operator	Name	Productions

+	`expr`	`: expr PLUS expr`
		`| term`

*	`term`	`: term TIMES term`
		`| factor`

()	`factor`	`: LPAREN expr RPAREN`
		`| NUM`

Now lets create a parse tree

`input: 1+5*6`

Operator	Name	Productions

+	`expr`	`: expr PLUS expr`
		`| term`

*	`term`	`: term TIMES term`
		`| factor`

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expr

Now lets create a parse tree

`input: 1+5*6`

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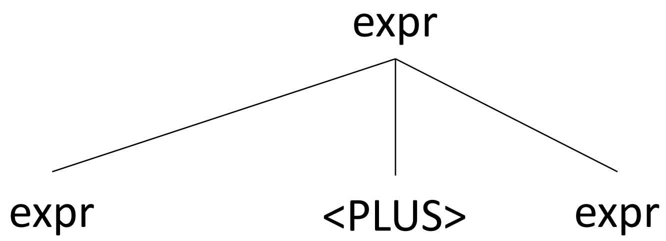
+	`expr`	`: expr PLUS expr`
		`| term`

*	`term`	`: term TIMES term`
		`| factor`

()	`factor`	`: LPAREN expr RPAREN`
		`| NUM`



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`input: 1+5*6`

Operator	Name	Productions

+	`expr`	`: expr PLUS expr`
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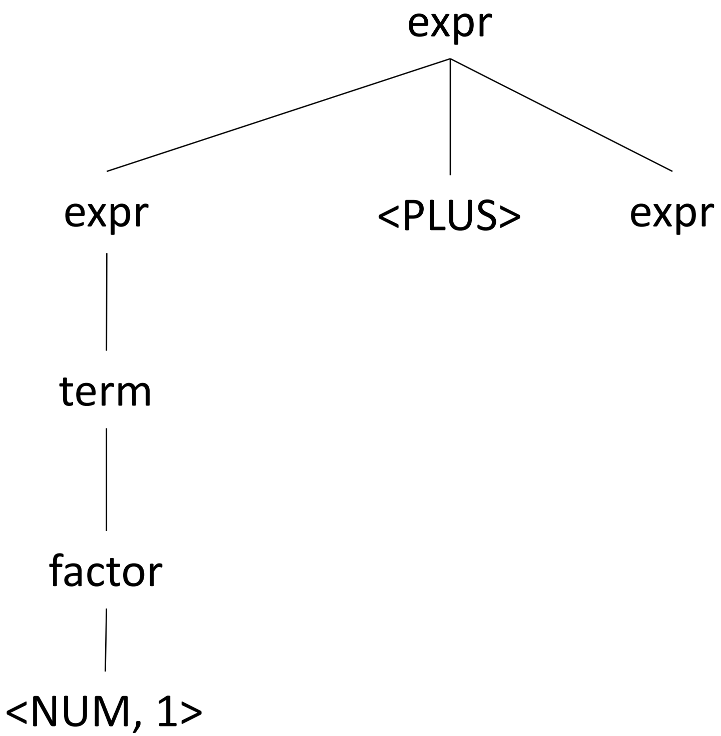
		`| factor`

()	`factor`	`: LPAREN expr RPAREN`
		`| NUM`



Now lets create a parse tree

`input: 1+5*6`

Operator	Name	Productions

+	`expr`	`: expr PLUS expr`
		`│ term`

*	`term`	`: term TIMES term`
		`│ factor`

()	`factor`	`: LPAREN expr RPAREN`
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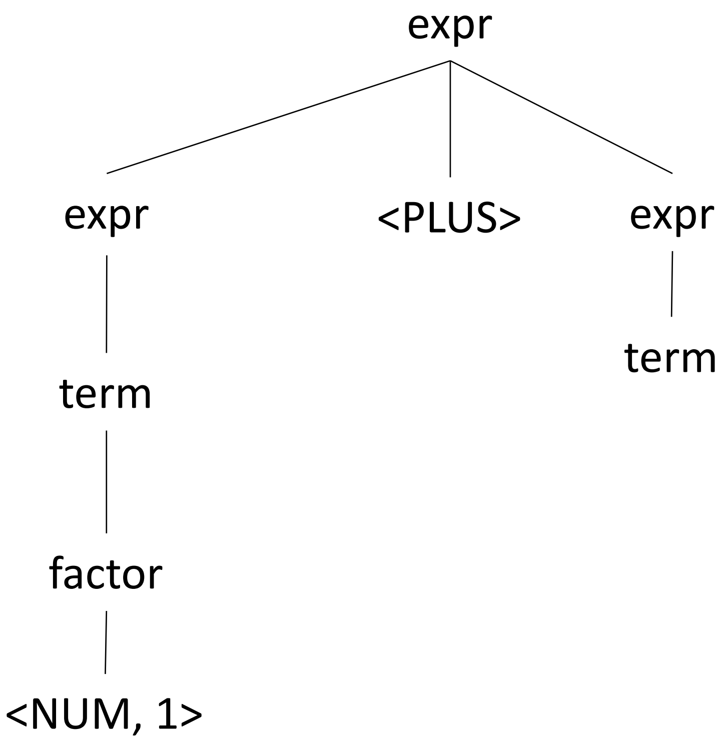

Now lets create a parse tree

`input: 1+5*6`

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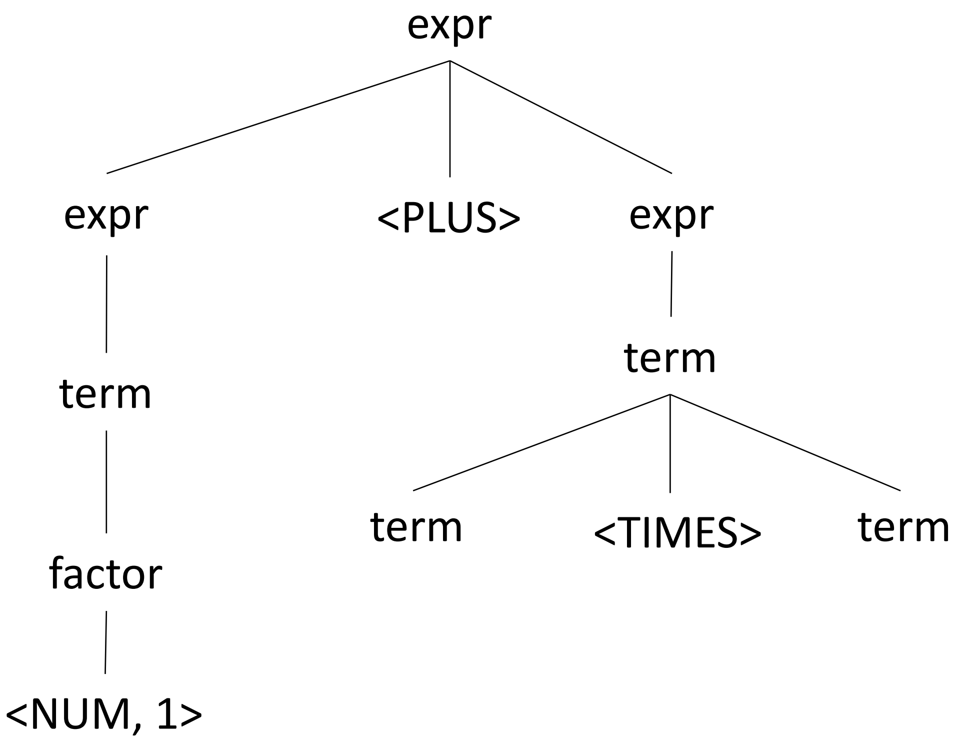
		`│ term`

*	`term`	`: term TIMES term`
		`│ factor`

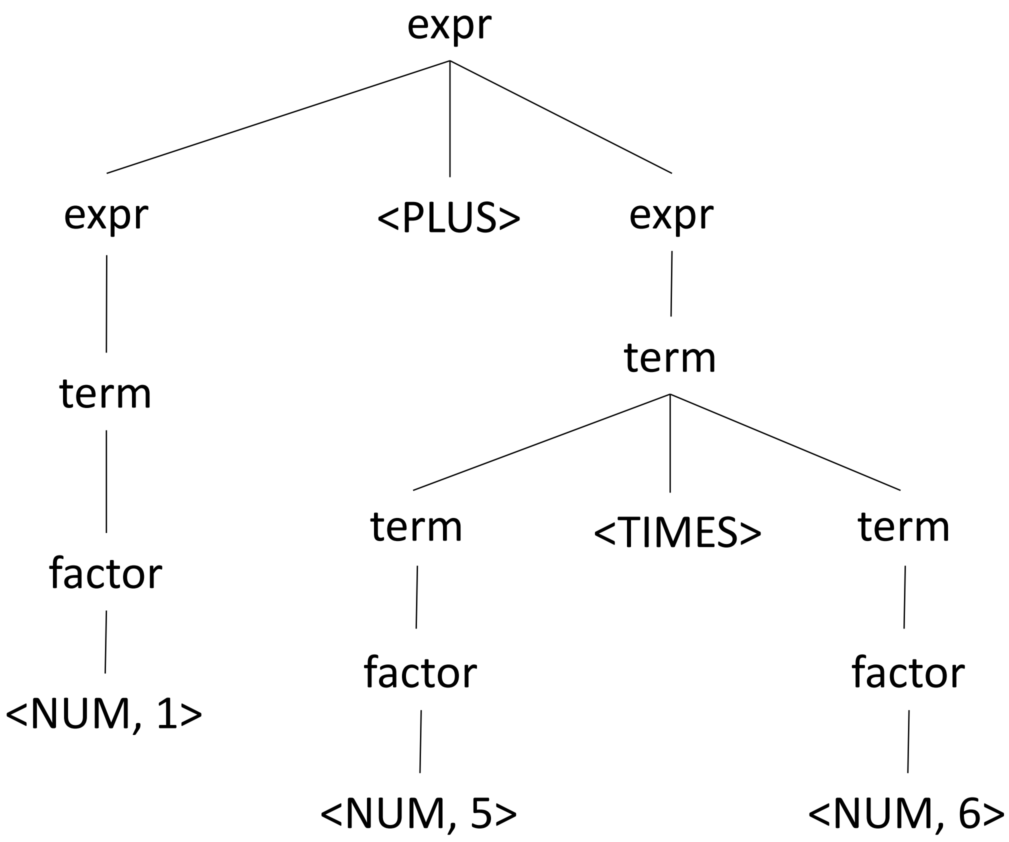
()	`factor`	`: LPAREN expr RPAREN`
		`│ NUM`



Now lets create a parse tree

input: 1+5*6

Operator	Name	Productions
+	expr	: expr PLUS expr | term
*	term	: term TIMES term | factor
()	factor	: LPAREN expr RPAREN | NUM



Parsing REs

Let’s try it for regular expressions, {| . * ()}

- *Assume . is concat*

Operator	Name	Productions

Parsing REs

Let’s try it for regular expressions, {| . * ()}

- *Assume . is concat*

Operator	Name	Productions
|	choice	: choice PIPE choice | concat
.	concat	: concat DOT concat | starred
*	starred	: starred STAR | unit
()	unit	: LPAREN choice RPAREN | CHAR

Parsing REs

```
input: a.b | c*
```

Let’s try it for regular expressions, {| . * ()}

- *Assume . is concat*

Operator	Name	Productions
|	choice	: choice PIPE choice | concat
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Parsing REs

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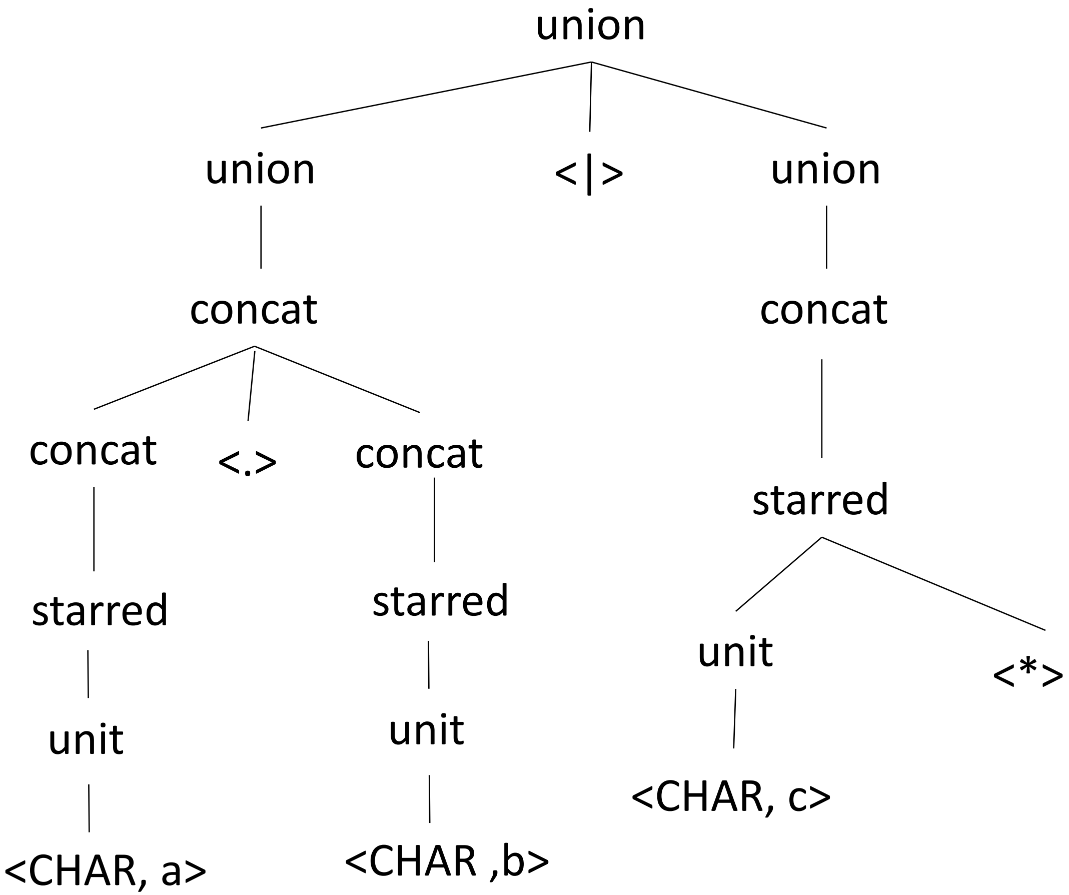
```
input: a.b | c*
```



How many levels of precedence does C have?

- https://en.cppreference.com/w/c/language/operator_precedence

Have we removed all ambiguity?

Let’s make some more parse trees

`input: 2+3+4`

Operator	Name	Productions

+	`expr`	`: expr PLUS expr`
		`| term`

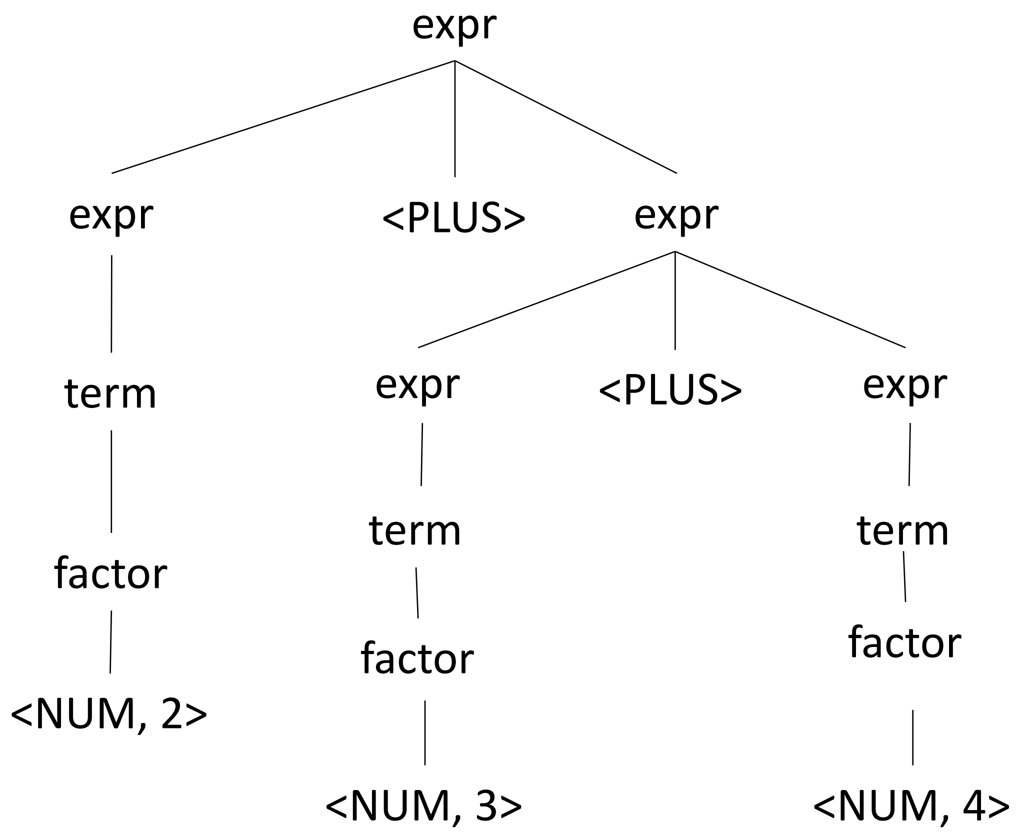
*	`term`	`: term TIMES term`
		`| factor`

()	`factor`	`: LP expr RP`
		`| NUM`

Let’s make some more parse trees

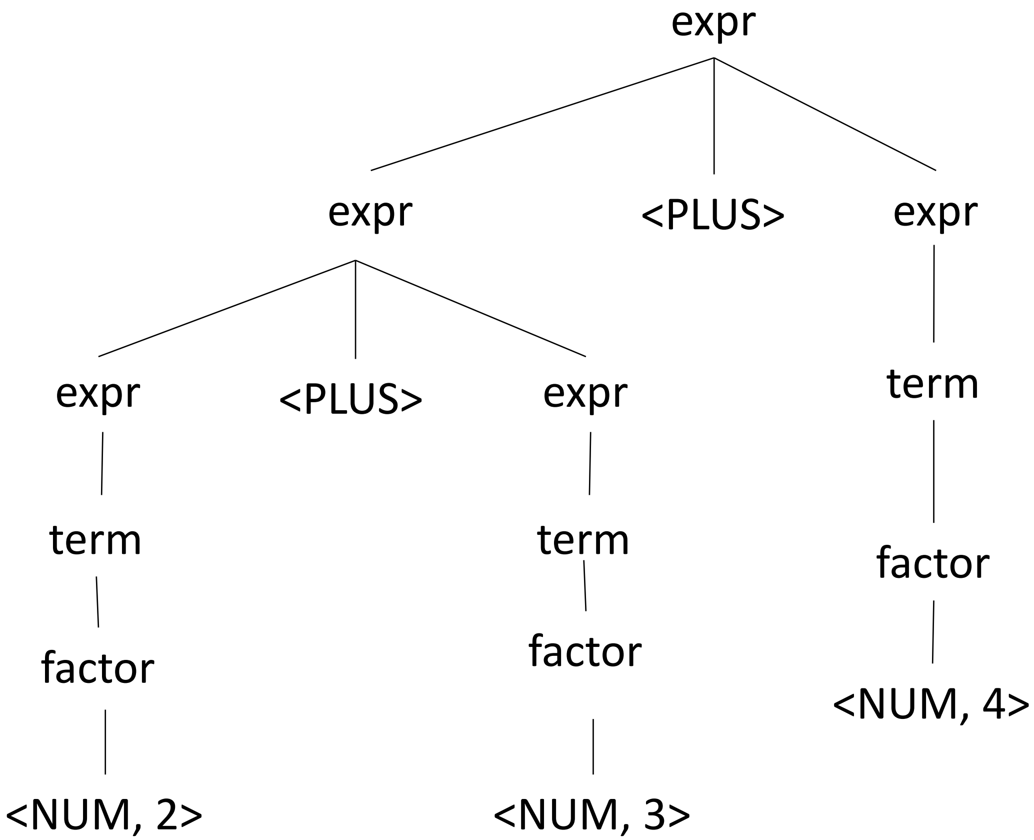
Operator	Name	Productions
+	expr	: expr PLUS expr | term
*	term	: term TIMES term | factor
()	factor	: LP expr RP | NUM

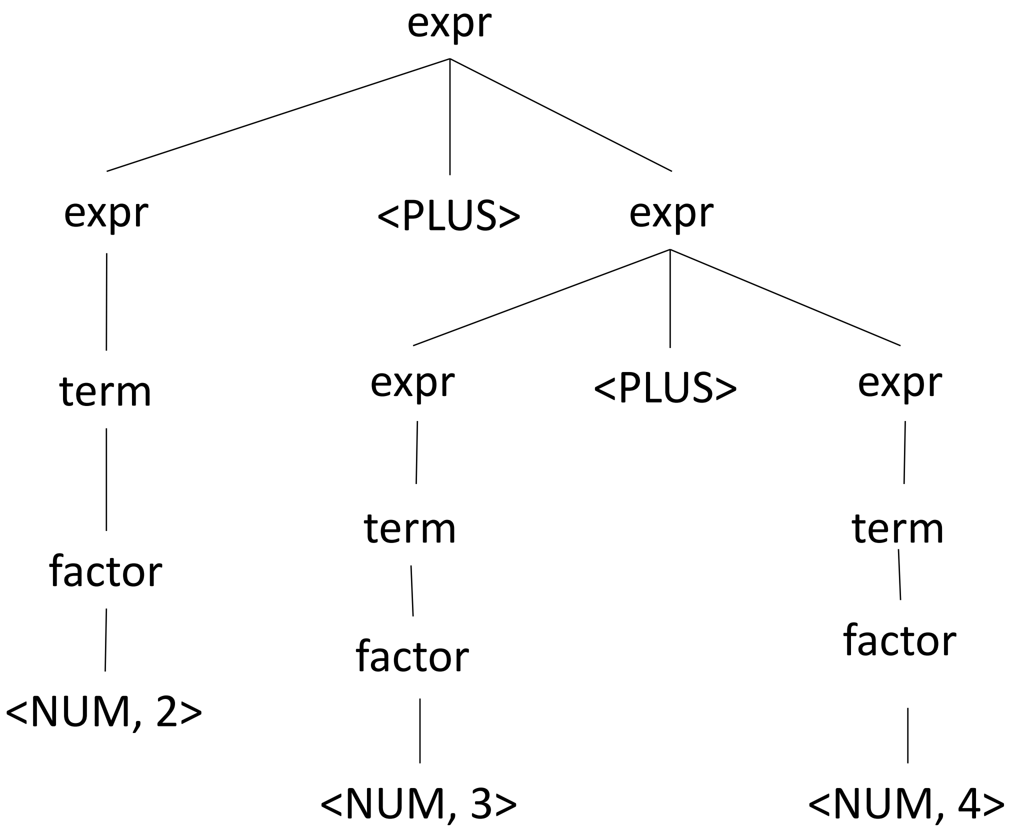
`input: 2+3+4`



This is ambiguous, is it an issue?

`input: 2+3+4`





What about for a different operator?

```
input: 2-3-4
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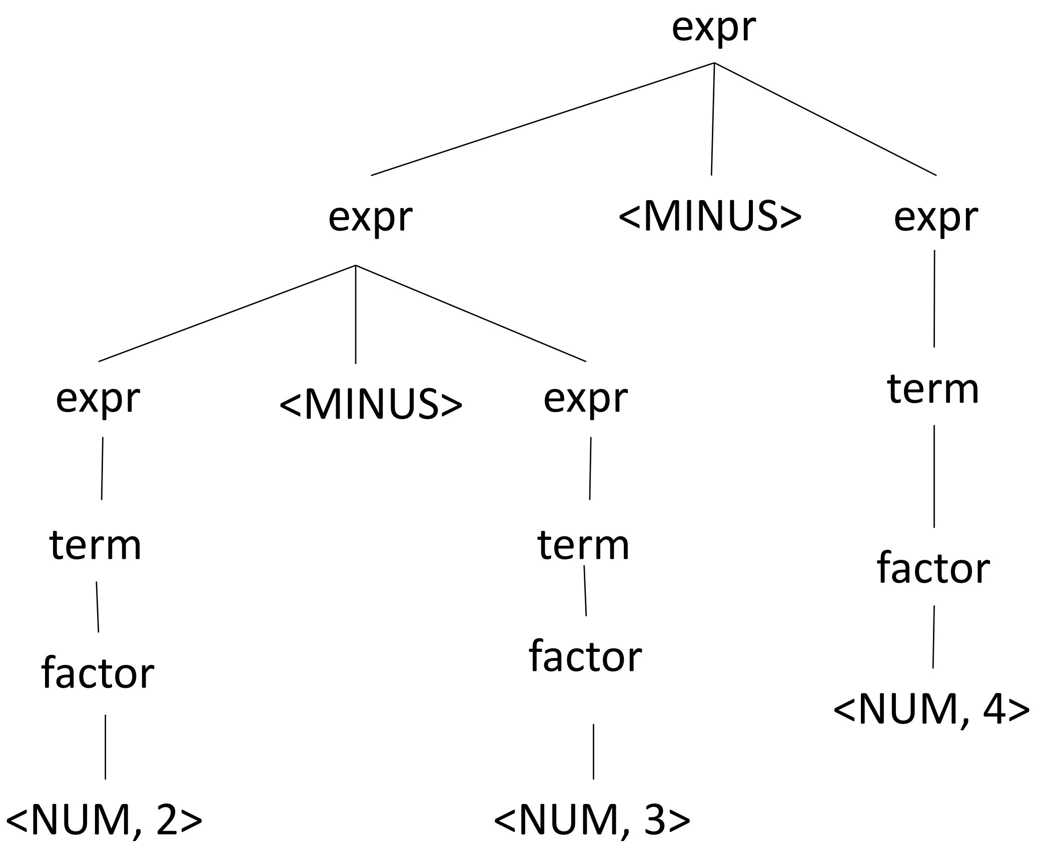
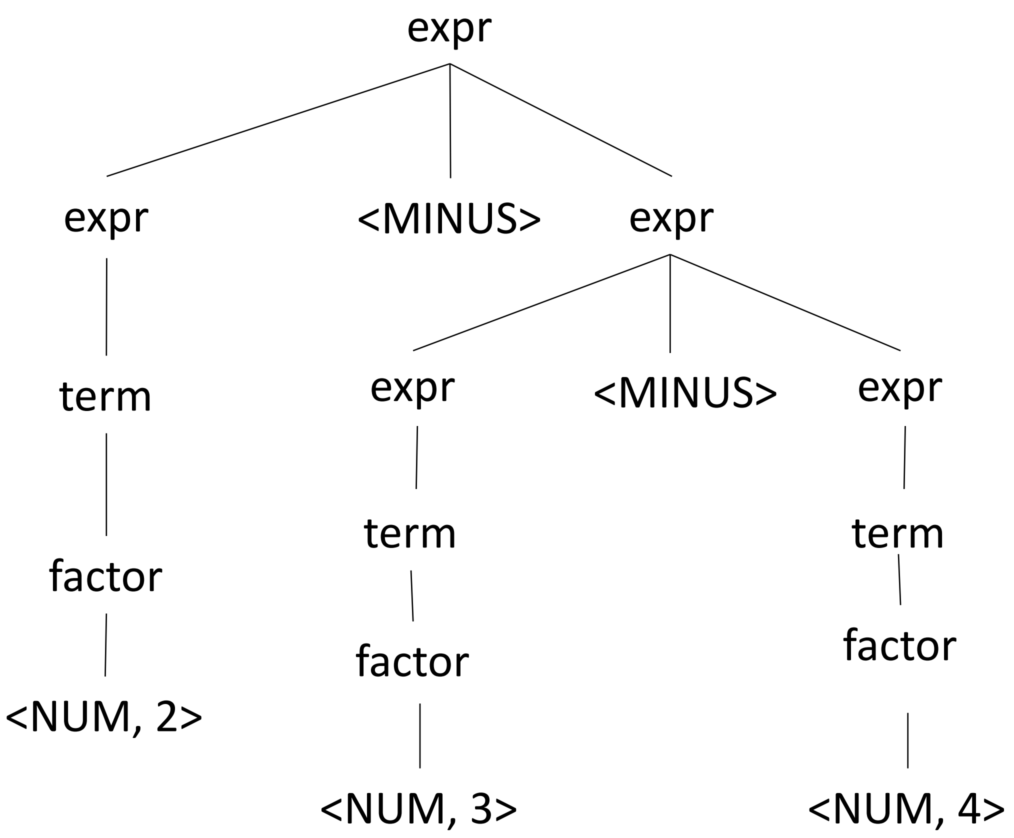




Which one is right?

Associativity

Describes the order in which apply the same operator

Sometimes it doesn’t matter:

- When?

Associativity

Describes the order in which apply the same operator

Sometimes it doesn’t matter:

- Integer arithmetic
- Integer multiplication

These operators are said to be associative

Good test:

- ((a OP b) OP c) == (a OP (b OP c))

What about floating point arithmetic?

Associativity

If an operator is not associative then we define

- left to right (left-associative)
  - `2–3–4` is evaluated as ((2-3) - 4)
  - What other operators are left-associative
- right-to-left (right-associative)
  - Any operators you can think of?

Associativity

If an operator is not associative then we define

- left to right (left-associative)
  - `2–3–4` is evaluated as ((2-3) - 4)
  - What other operators are left-associative

- right-to-left (right-associative)
  - Assignment, power operator

How to encode associativity?

- Like precedence, some tools (e.g. YACC) allow associativity specification through keywords:
  - “+”: left, “^”: right

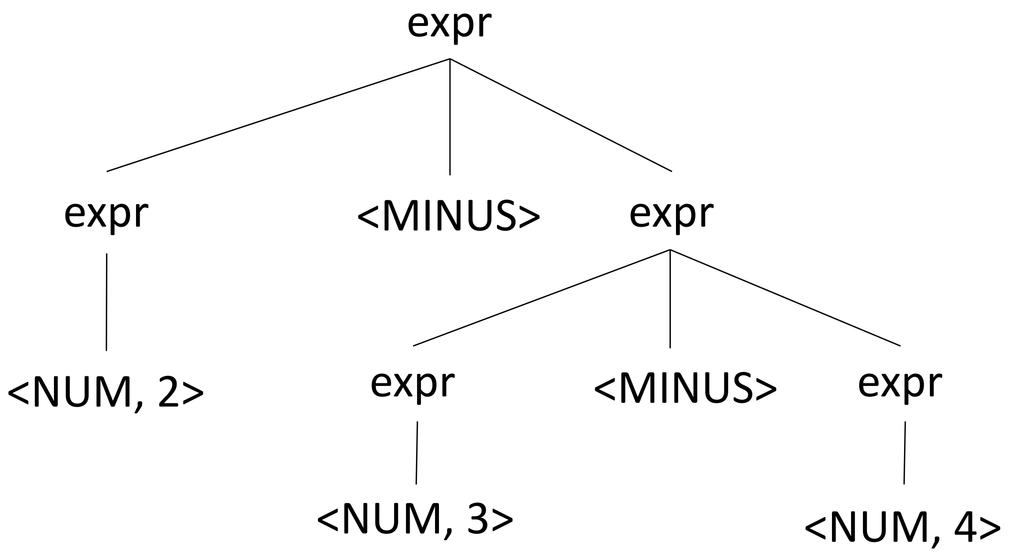
- Like precedence, we can also encode it into the production rules

Associativity for a single operator

Operator	Name	Productions

-	`expr`	`: expr MINUS expr`
		`| NUM`

`input: 2-3-4`



Associativity for a single operator

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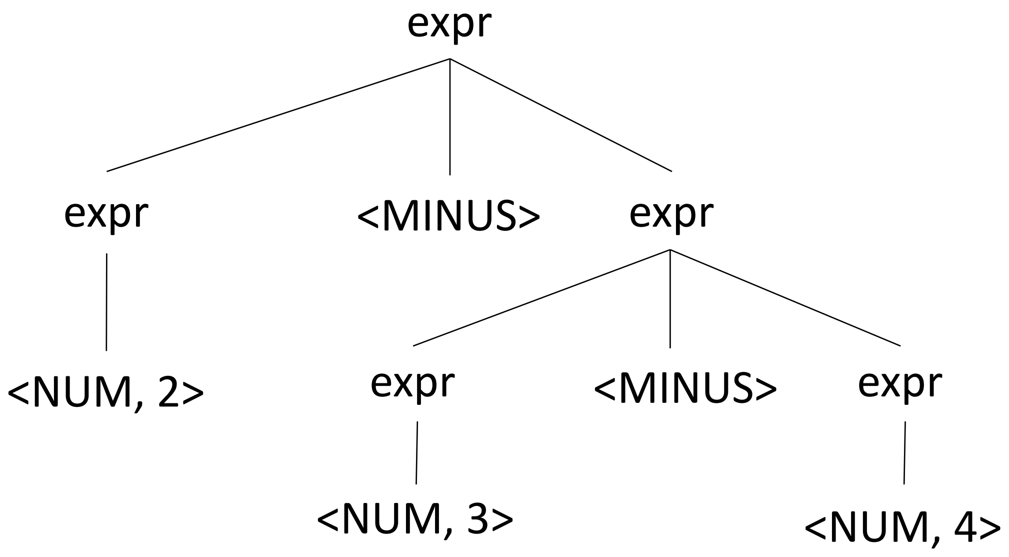
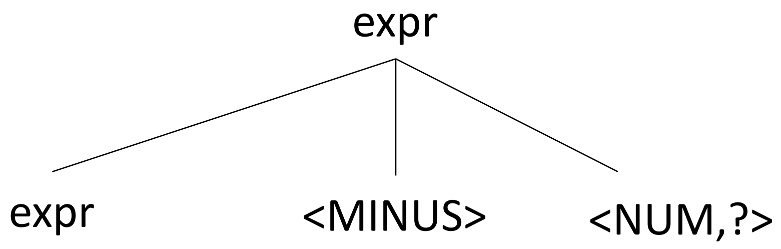


No longer allowed

Associativity for a single operator

`input: 2-3-4`



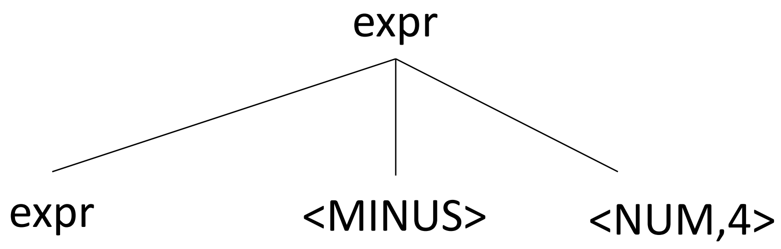
Operator	Name	Productions

-	`expr`	`: expr MINUS NUM`
		`| NUM`

Lets start over

Associativity for a single operator

`input: 2-3-4`



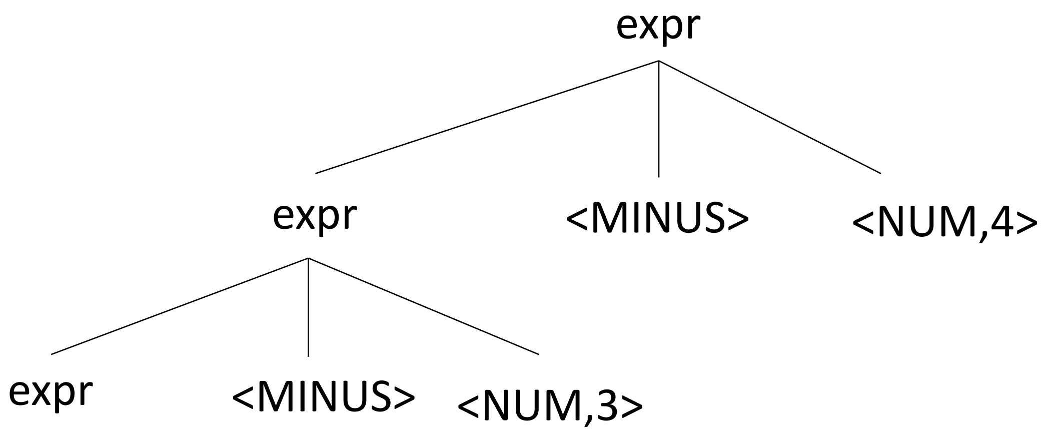
Operator	Name	Productions

-	`expr`	`: expr MINUS NUM`
		`| NUM`

Associativity for a single operator

Operator	Name	Productions
-	expr	: expr MINUS NUM | NUM

`input: 2-3-4`



Associativity for a single operator

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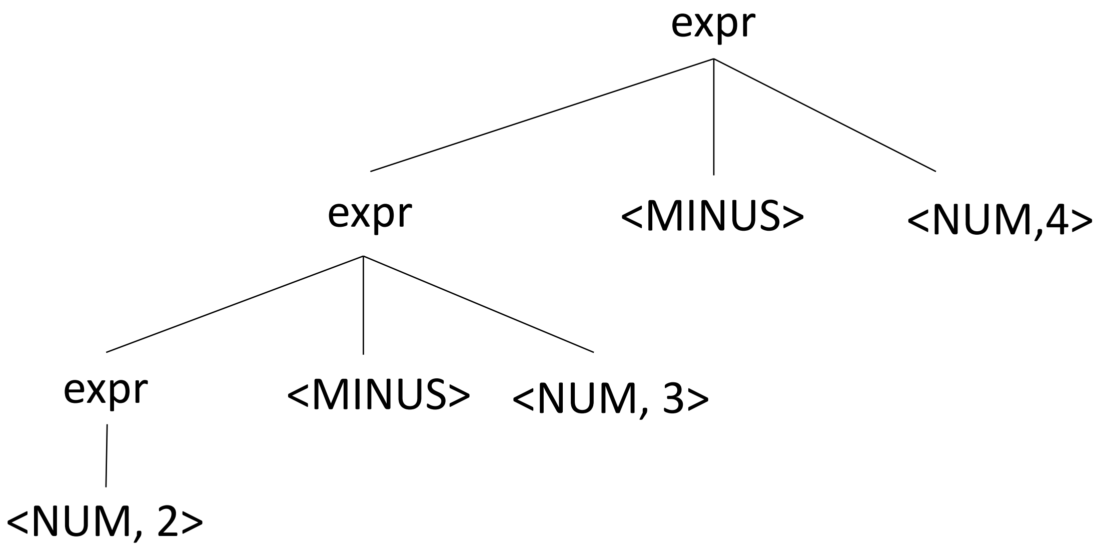
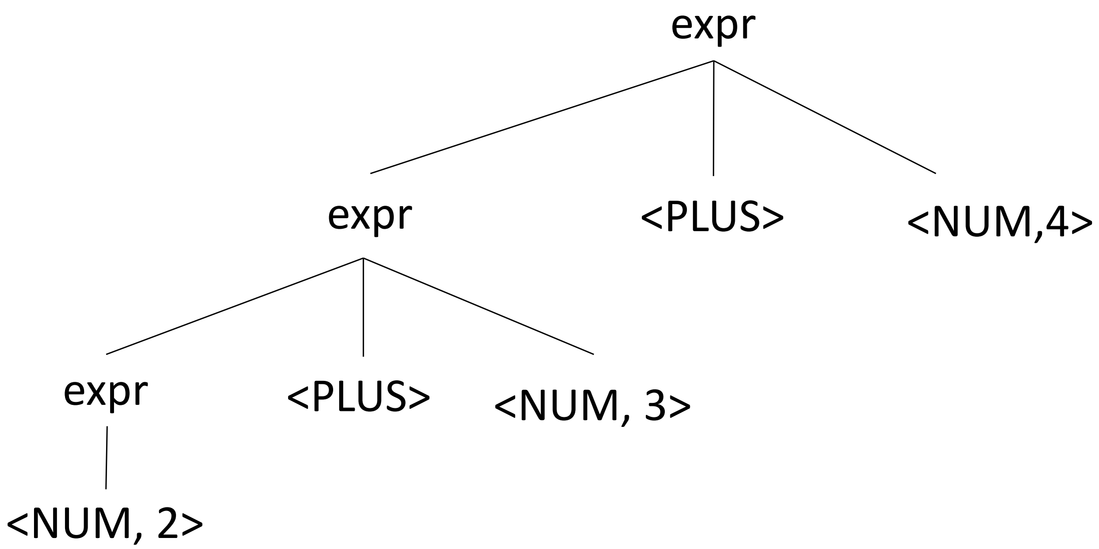


Should you have associativity when its not required?

`input: 2+3+4`

Benefits?
Drawbacks?



Operator	Name	Productions

+	`expr`	`: expr PLUS expr`
		`| NUM`

Should you have associativity when its not required?

Benefits?
Drawbacks?

Operator	Name	Productions

+	expr	`: expr PLUS expr`
		`| NUM`

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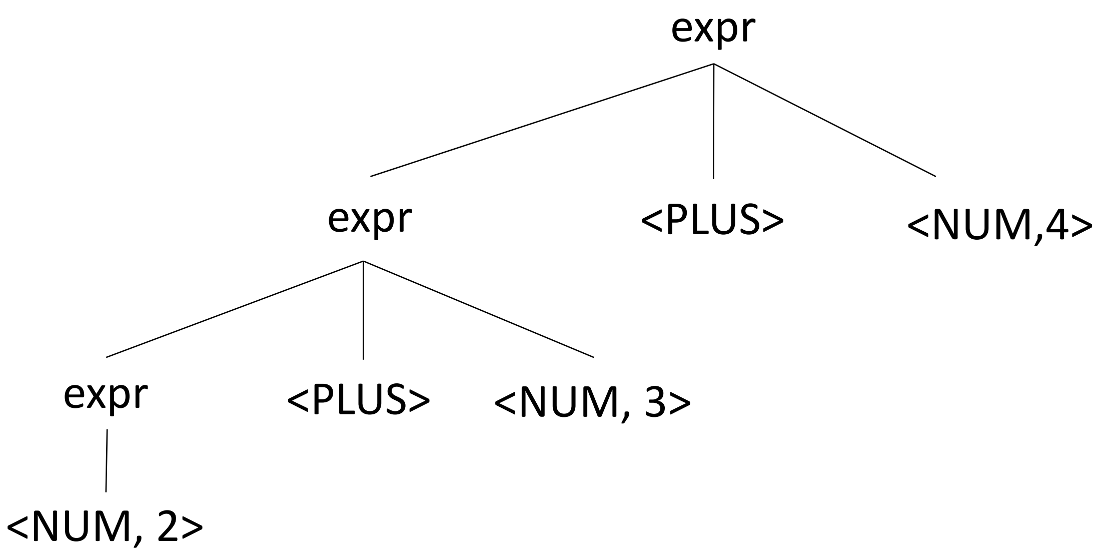

Good design principle to avoid ambiguous grammars, even when strictly not required too.

Helps with debugging, etc. etc.

Many tools will warn if it detects ambiguity

Let’s make a richer expression grammar

Let’s do operators `[+,*,-,/,^]` *and* `()`

Operator	Name	Productions

```
Tokens:
    NUM    = “[0-9]+”
    PLUS   = ‘\+’
    TIMES  = ’\*’
    LP     = ‘\(’
    RP     = \)’
    MINUS  = ‘-’
    DIV    = ‘/’
    CARROT =’ \^’
```

Let’s make a richer expression grammar

Let’s do operators `[+,*,-,/,^]` *and* `()`

Operator	Name	Productions

+,-	expr	`: expr PLUS term`
		`| expr MINUS term`
		`| term`

*,/	term	`: term TIMES pow`
		`| term DIV pow`
		`| pow`

^	pow	`: factor CARROT pow`
		`| factor`

()	factor	`: LPAR expr RPAR`
		`| NUM`

```
Tokens:
    NUM    = “[0-9]+”
    PLUS   = ‘\+’
    TIMES  = ’\*’
    LP     = ‘\(’
    RP     = \)’
    MINUS  = ‘-’
    DIV    = ‘/’
    CARROT =’ \^’
```

What associativities does C have?

- https://en.cppreference.com/w/c/language/operator_precedence

Next time: algorithms for syntactic analysis

- Top down parsing
  - oracle parsing
  - removing left recursion
  - constructing lookahead sets