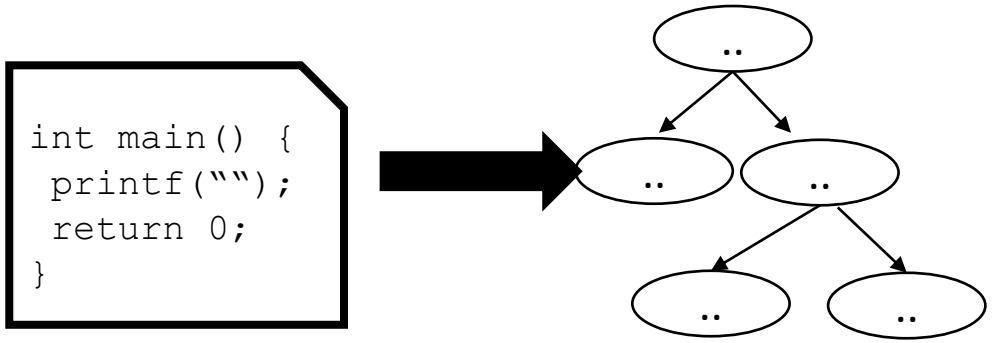
CSE110A: Compilers

April 19, 2024

Topics:

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



Announcements

- HW 1 is due by midnight
  - ***No guaranteed help off business hours***

- Thanks to those who are asking/answering questions on Piazza

Quiz

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
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simple_expr ::= NUM '+' NUM
            |   NUM '*' NUM
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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_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?

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

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1: Statement ::= "if" Expr "then" Statement "else" Statement
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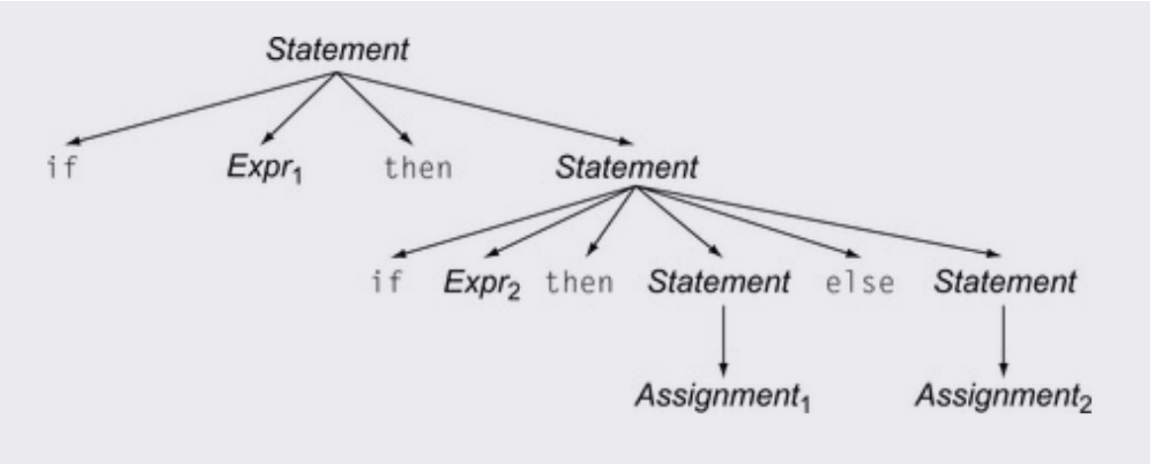

Valid derivation

Ambiguous grammars

```
1: Statement ::= "if" Expr "then" Statement "else" Statement
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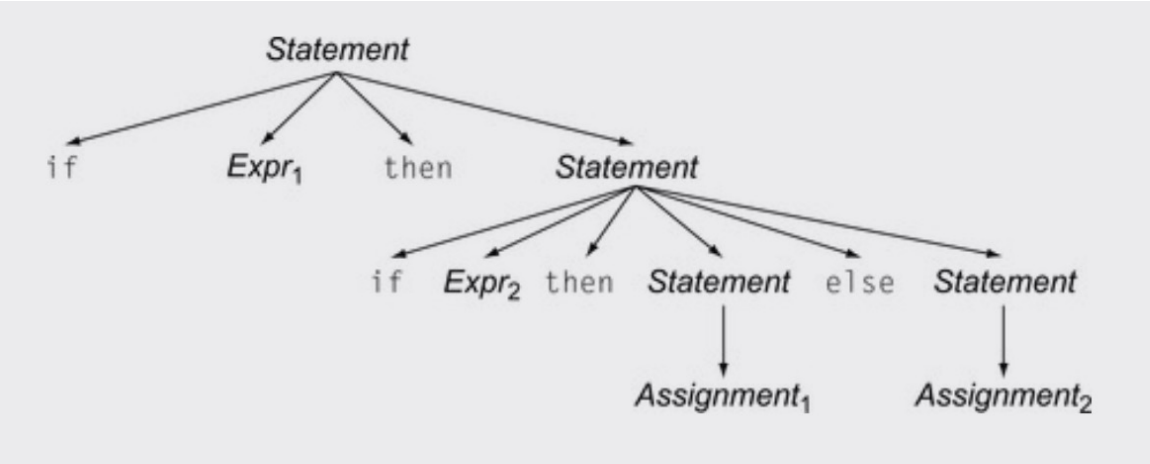

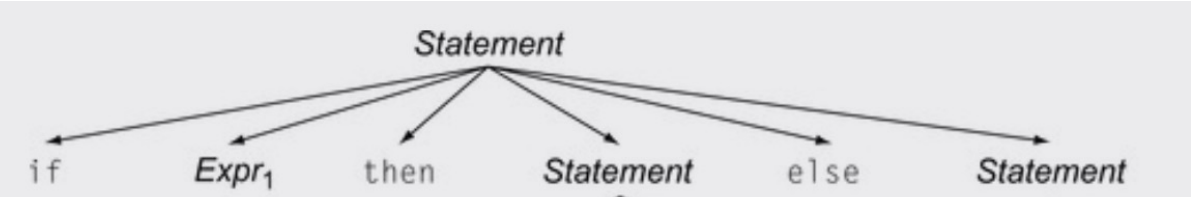

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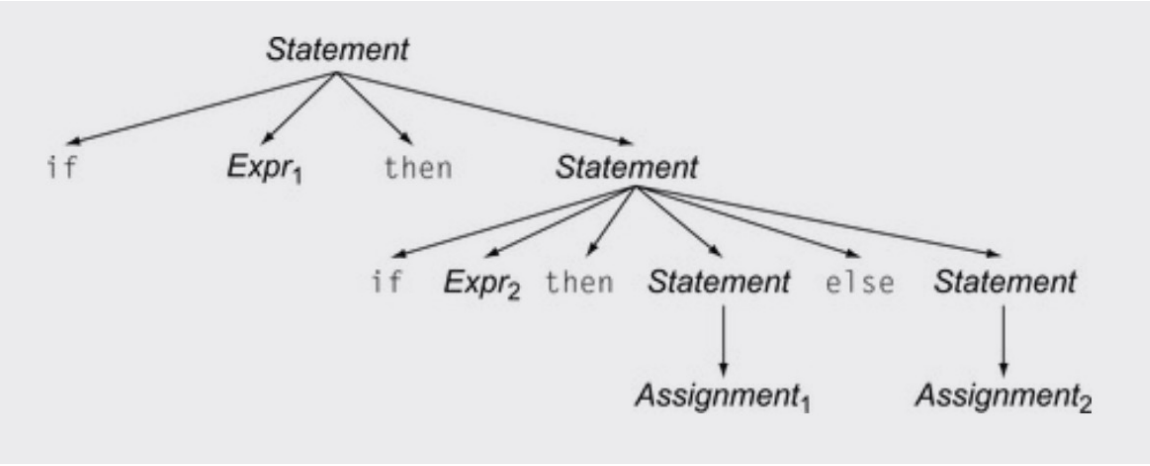
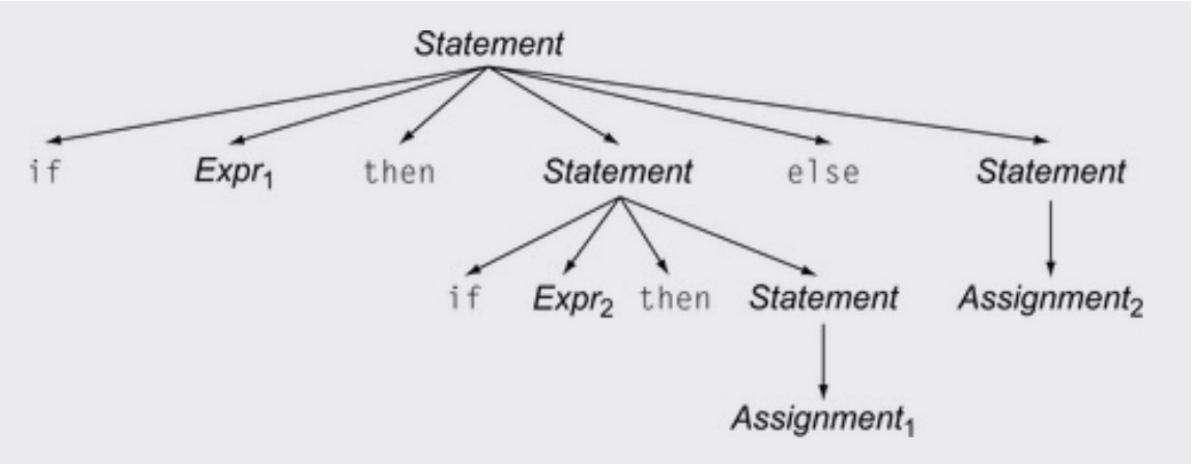


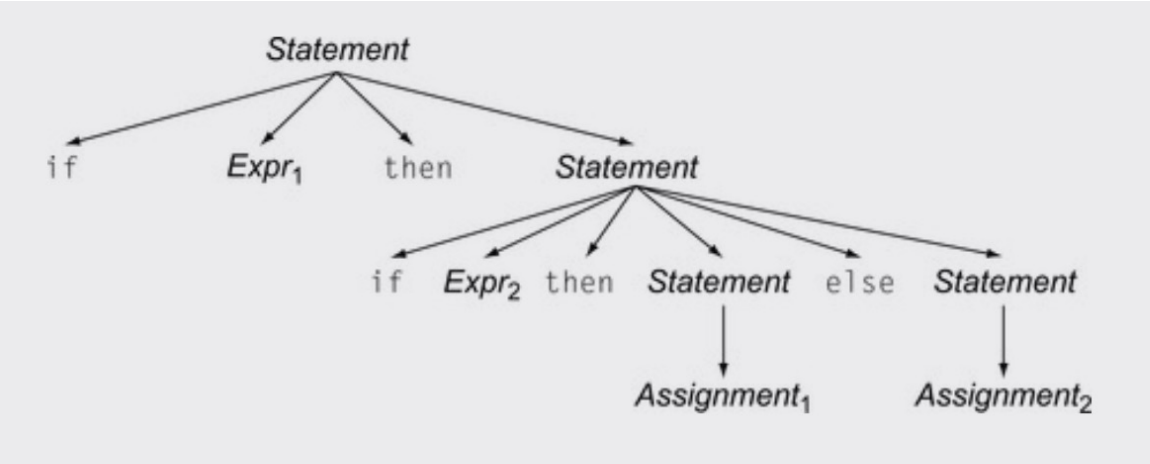
Valid derivation



Also a valid derivation

Ambiguous grammars

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



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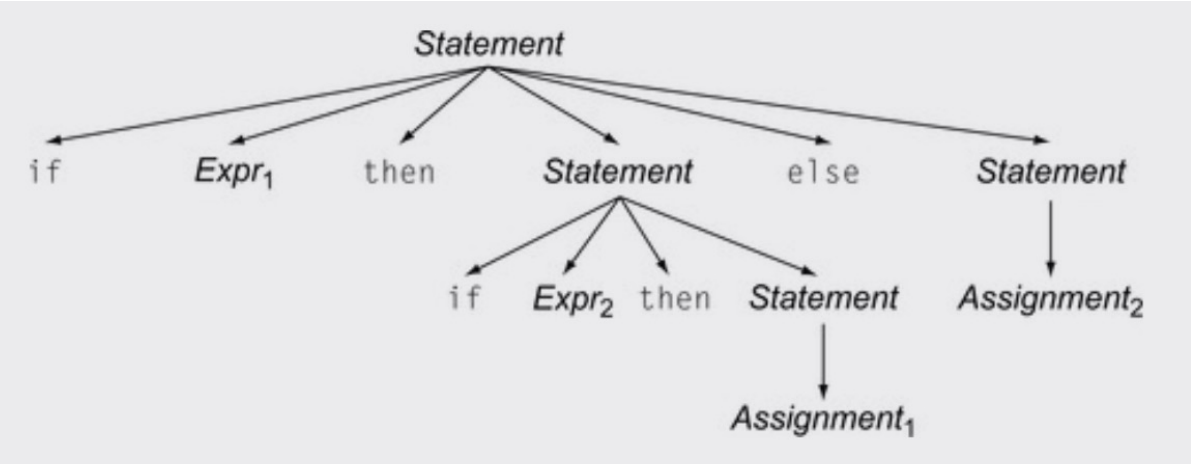


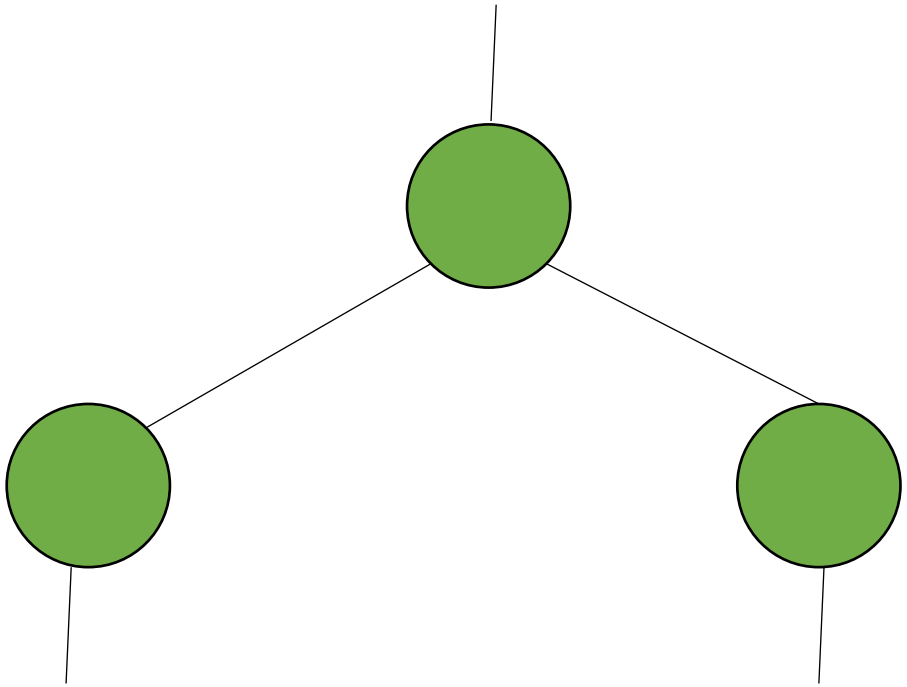
Also a valid derivation

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)

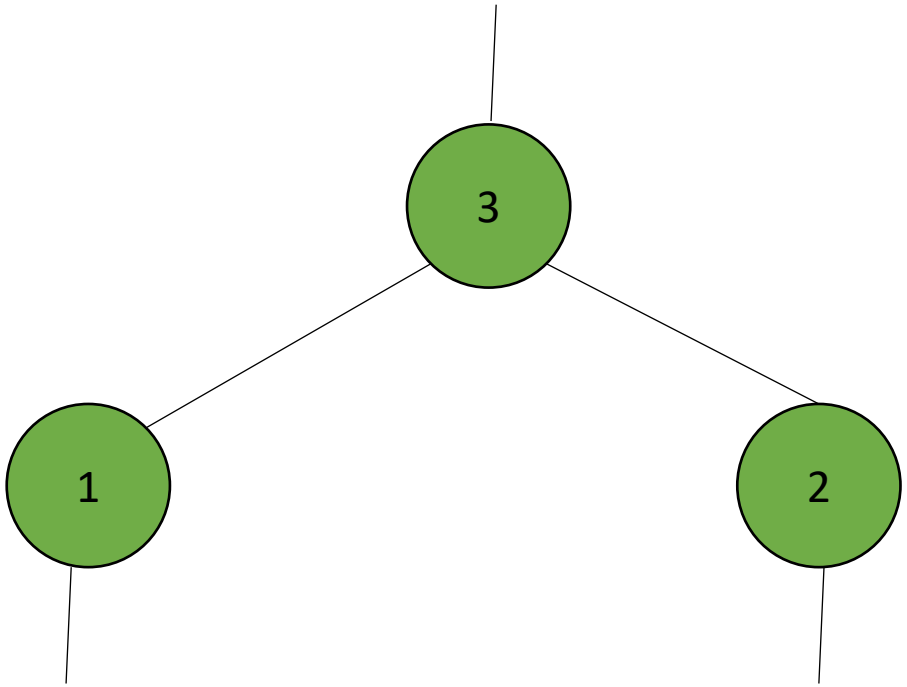
Post order traversal



visiting for for different types of traversals:

pre order?
in order?
post order?

Post order traversal

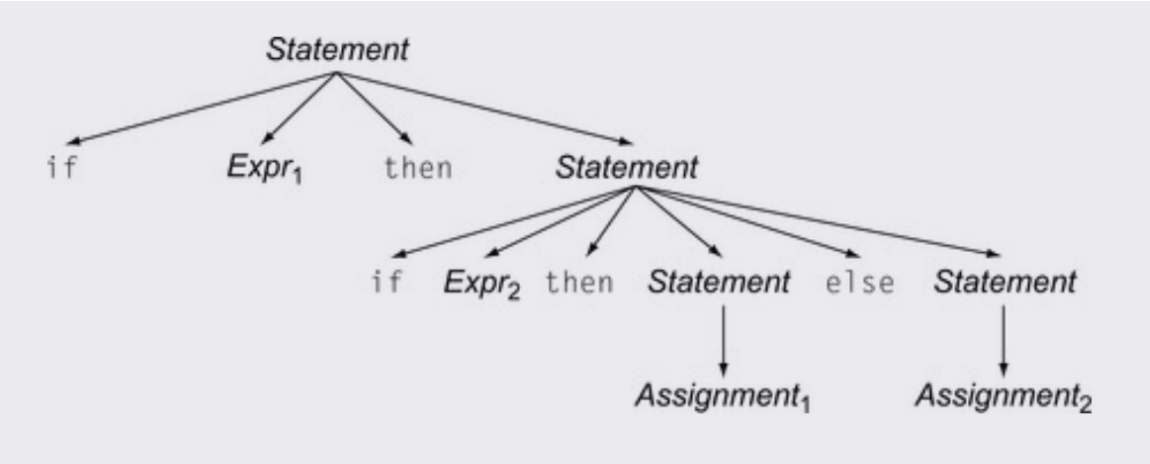


visiting for for different types of traversals:

post order

Ambiguous grammars

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



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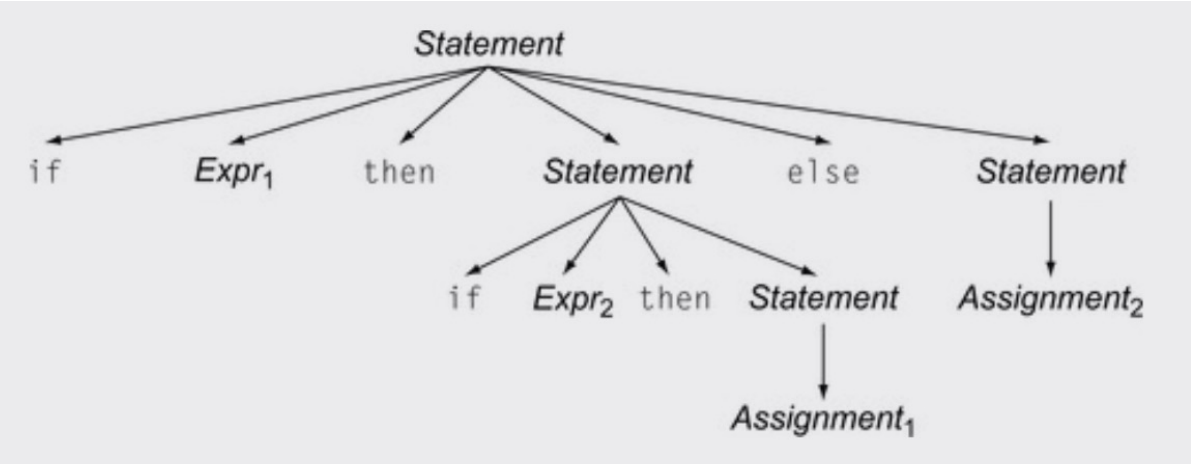

Also a valid derivation

Programming language structure

```
int x = 1; //true
int y = 0; //false
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

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

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

input: 5

expr

Parse trees examples

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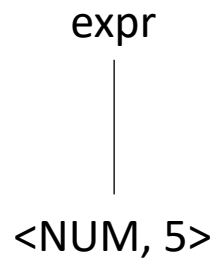

```
input: 5
```



Parse trees examples

input: 5*6

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expr ::= NUM
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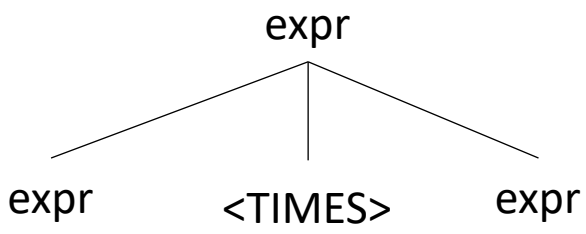

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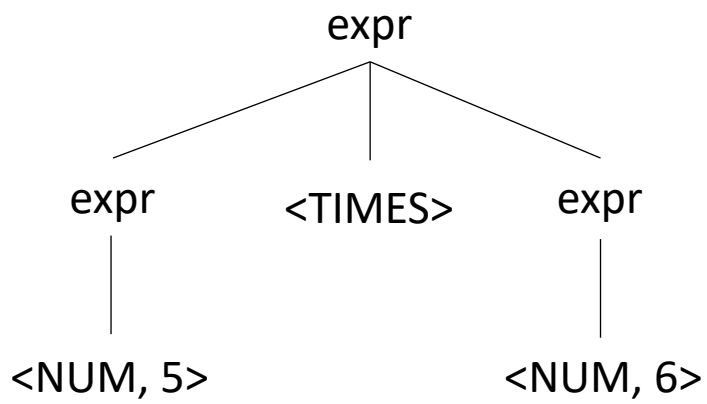

Parse trees examples

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

expr

What happens in an error?

Parse trees examples

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expr ::= NUM
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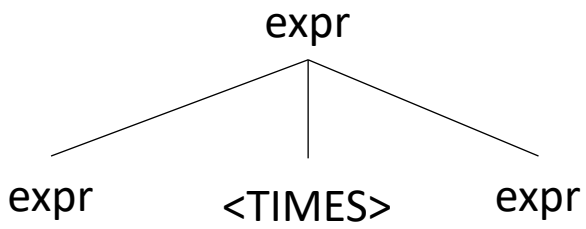

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Parse trees examples

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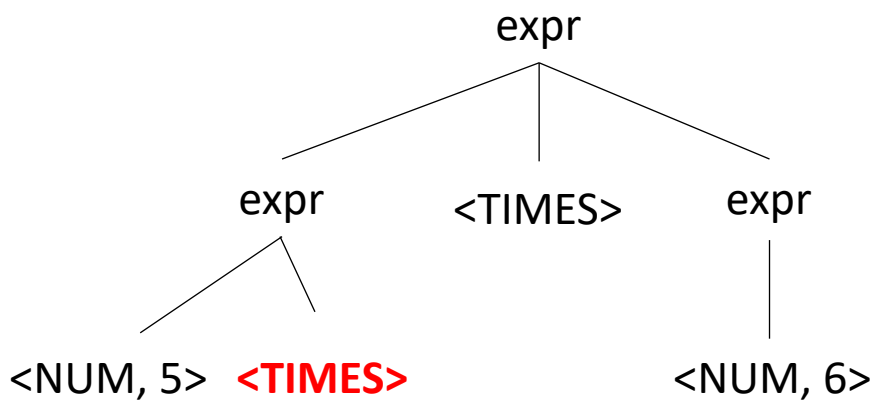

Not possible!

Parse trees examples

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

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

Parse trees examples

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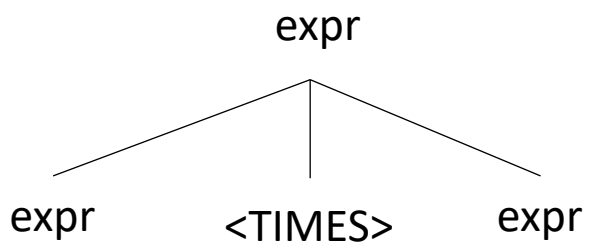

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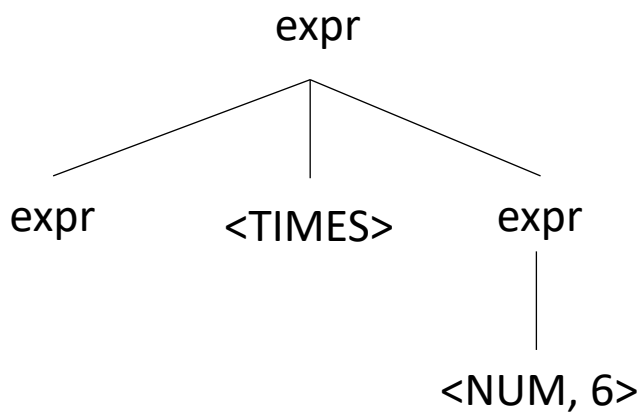

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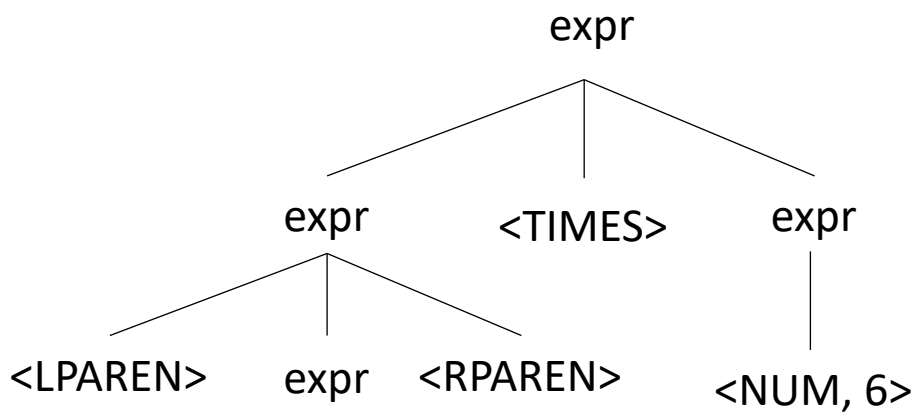

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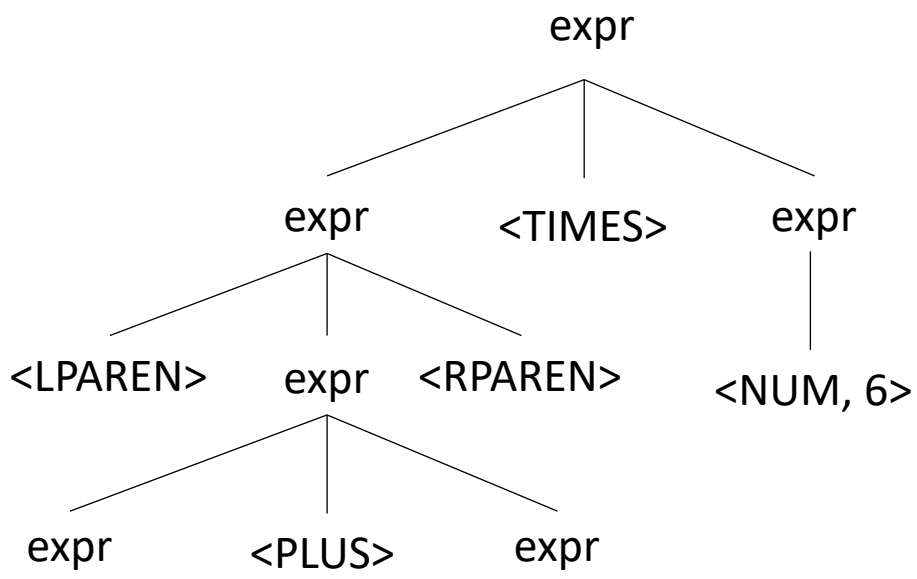

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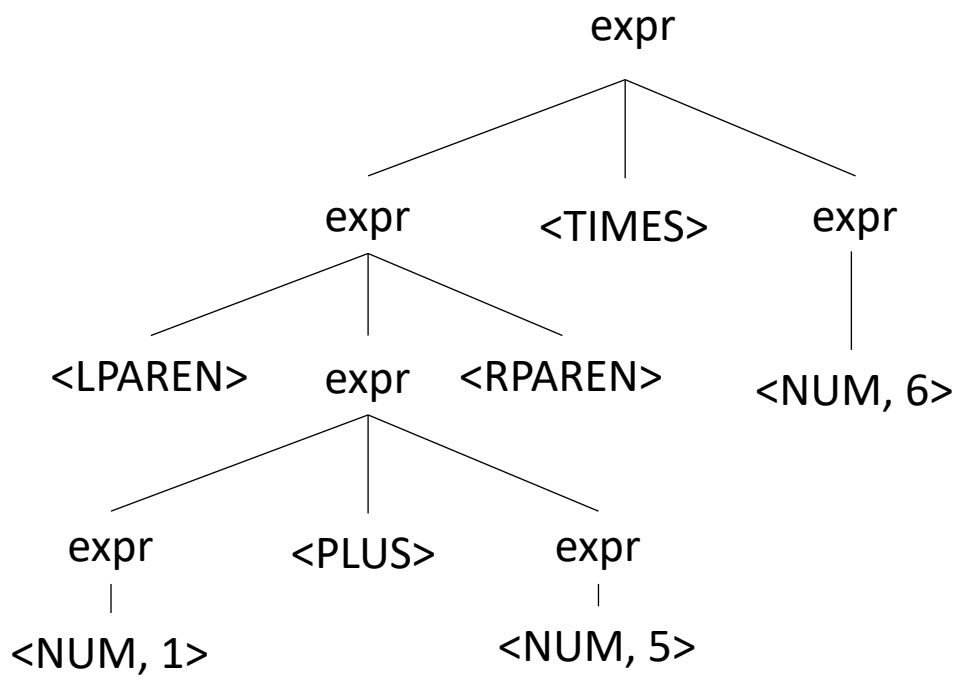

Parse trees examples

Does this parse tree capture the structure we want?

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```
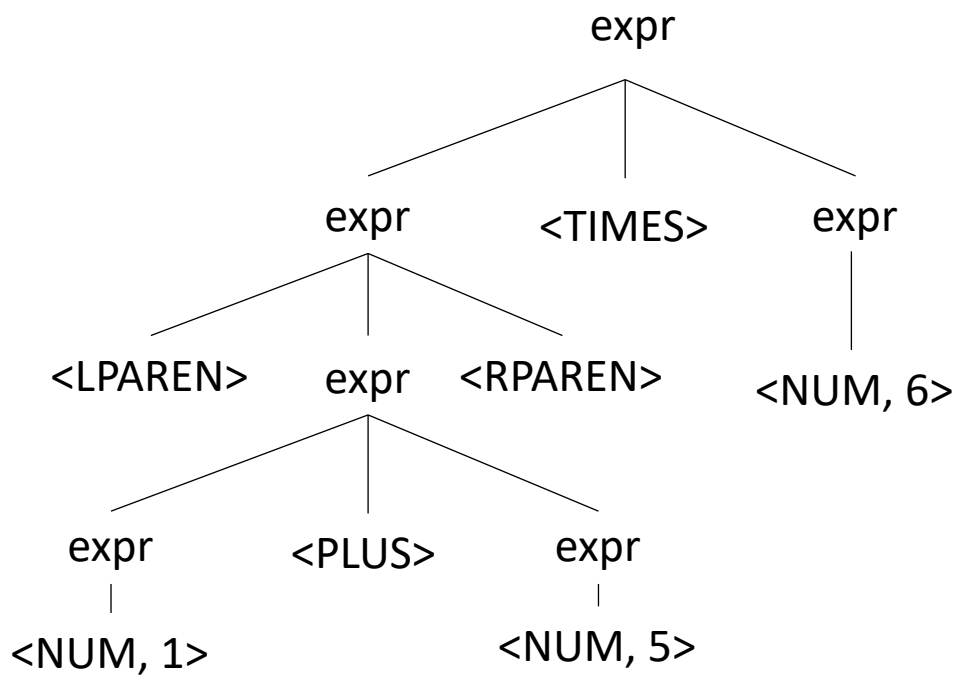

`input: (1+5)*6`



Parse trees

- How about: `1 + 5 * 6`

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Parse trees

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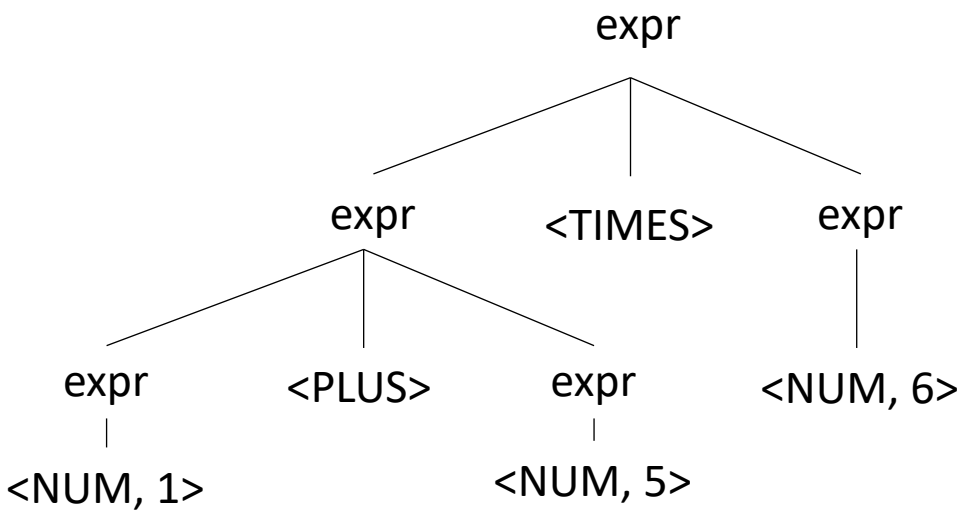

Ambiguous grammars

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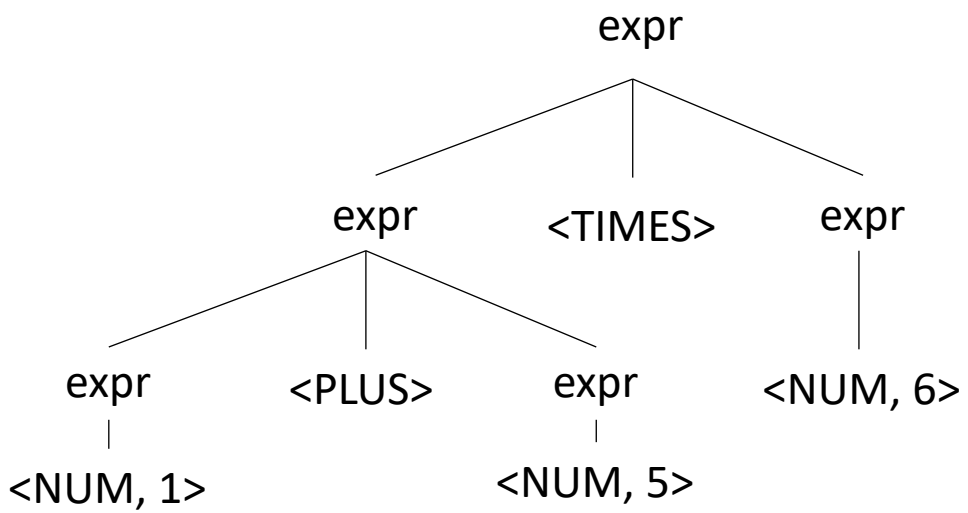

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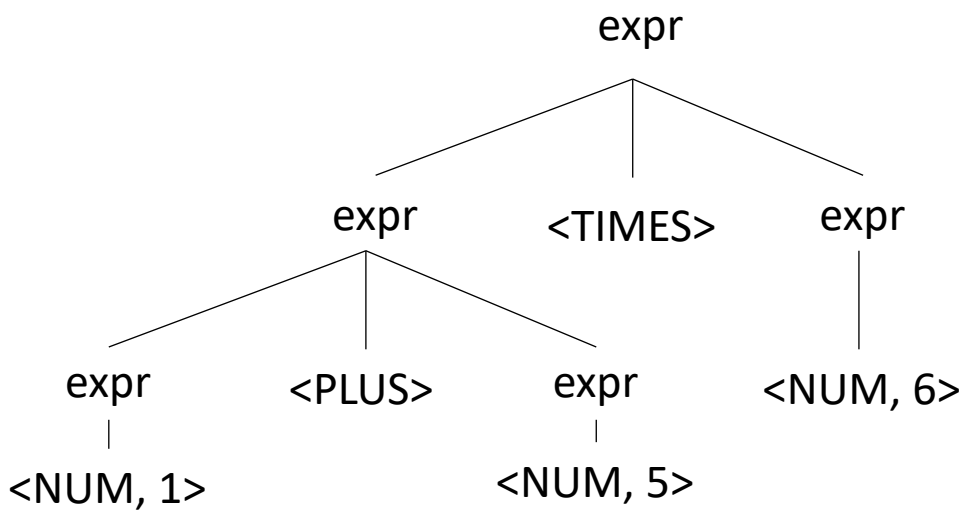

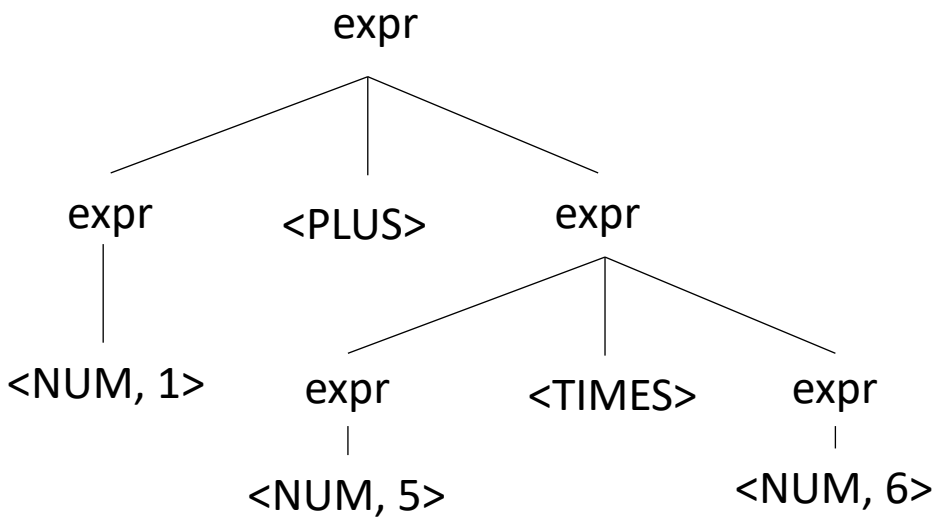

Avoiding Ambiguity

- 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
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expr

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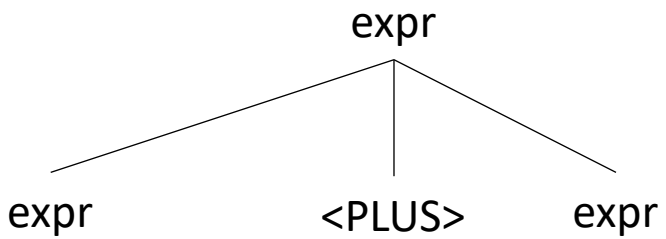
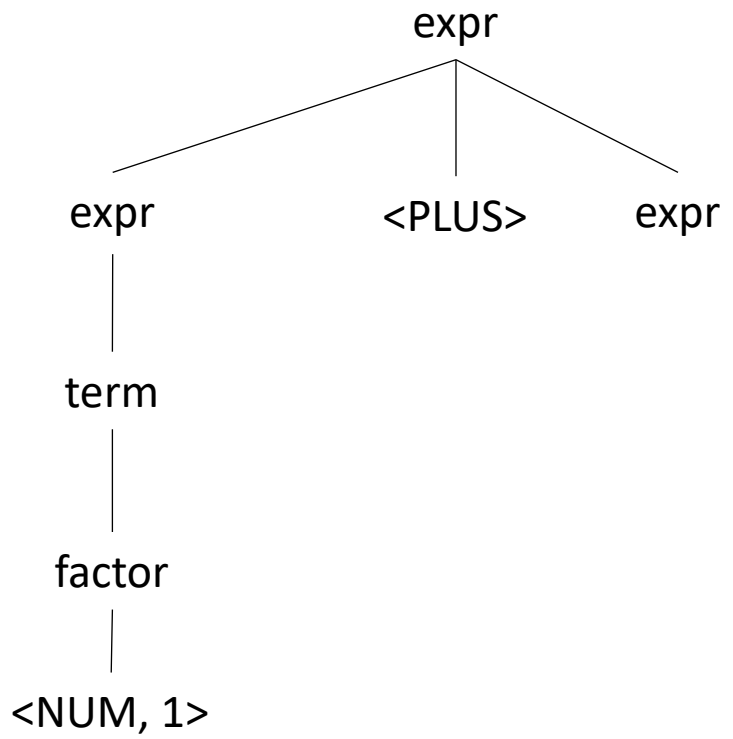
()	`factor`	`: LPAREN expr RPAREN` `| NUM`



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`



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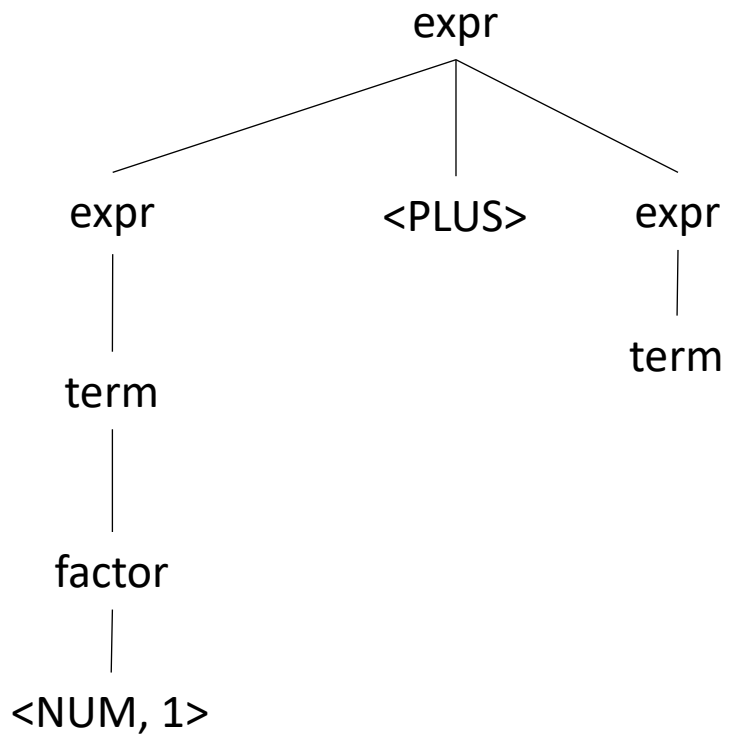

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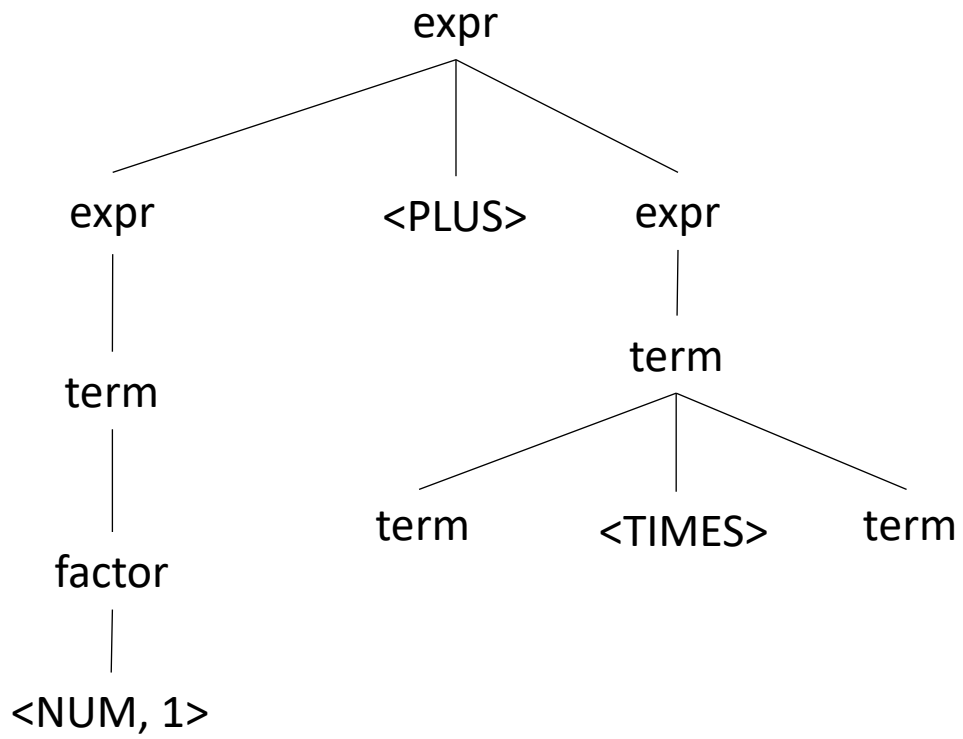

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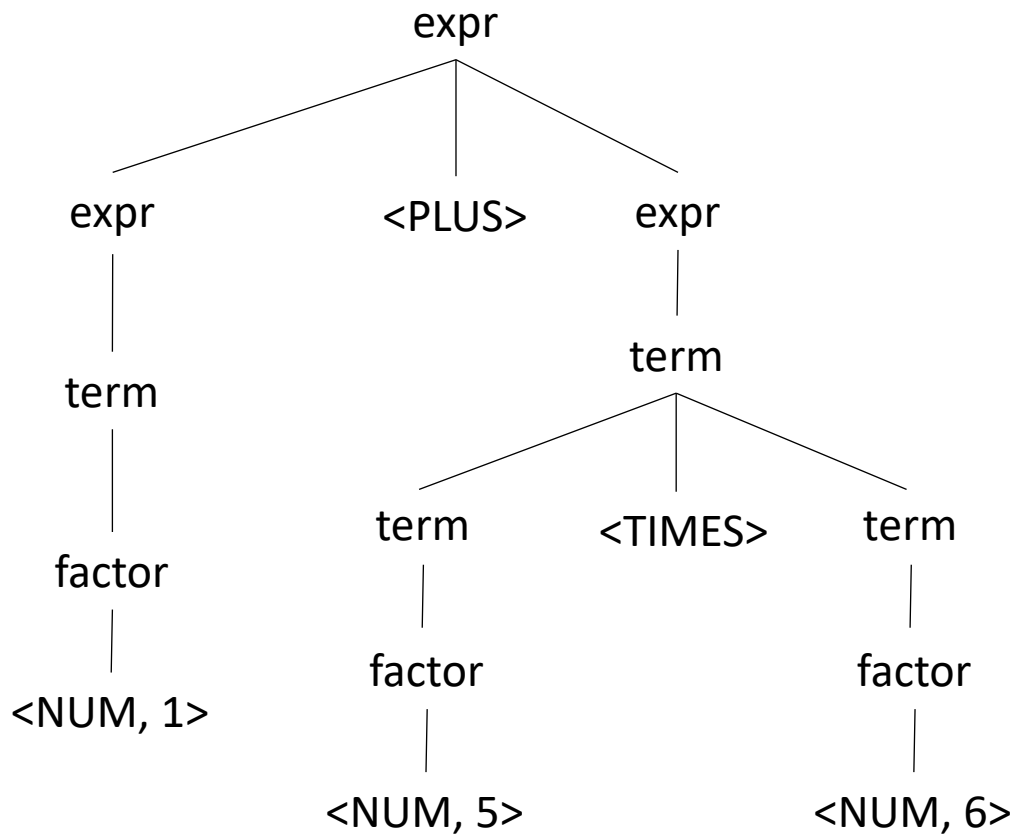

Parsing REs

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

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

- *Assume . is concat*

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

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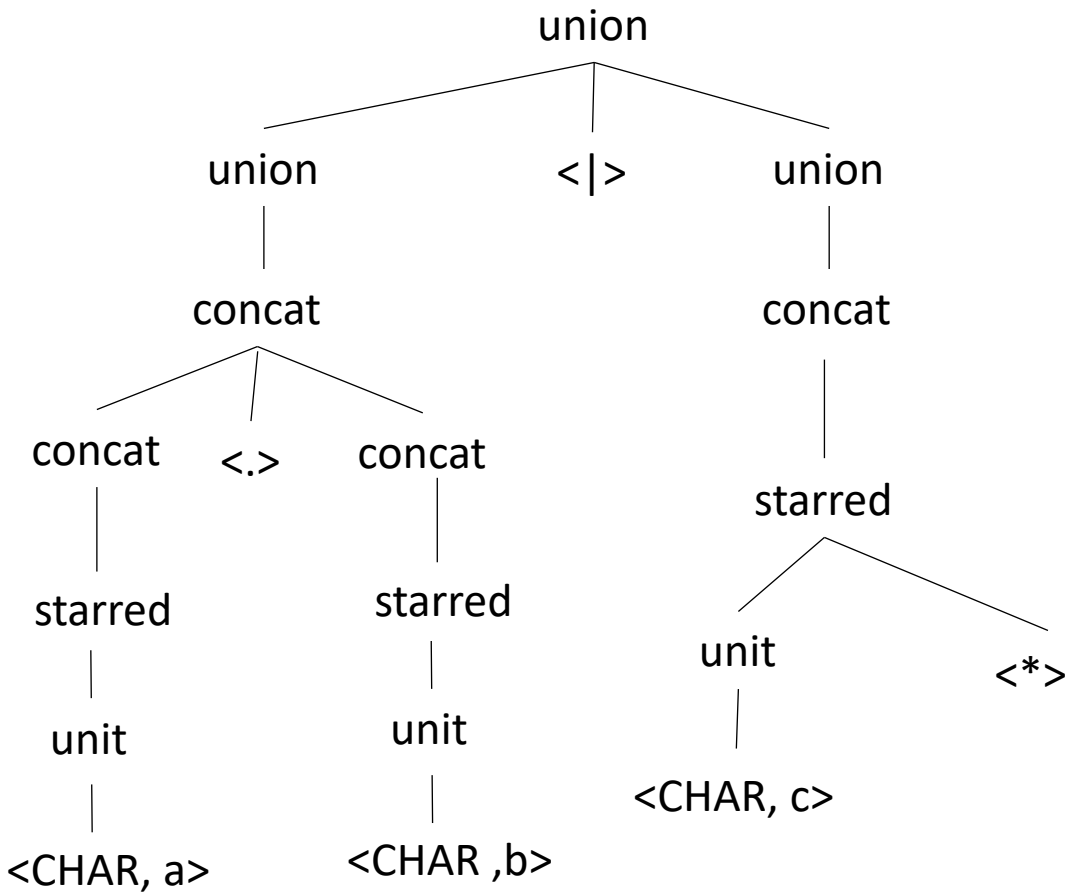

How many levels of precedence does C have?

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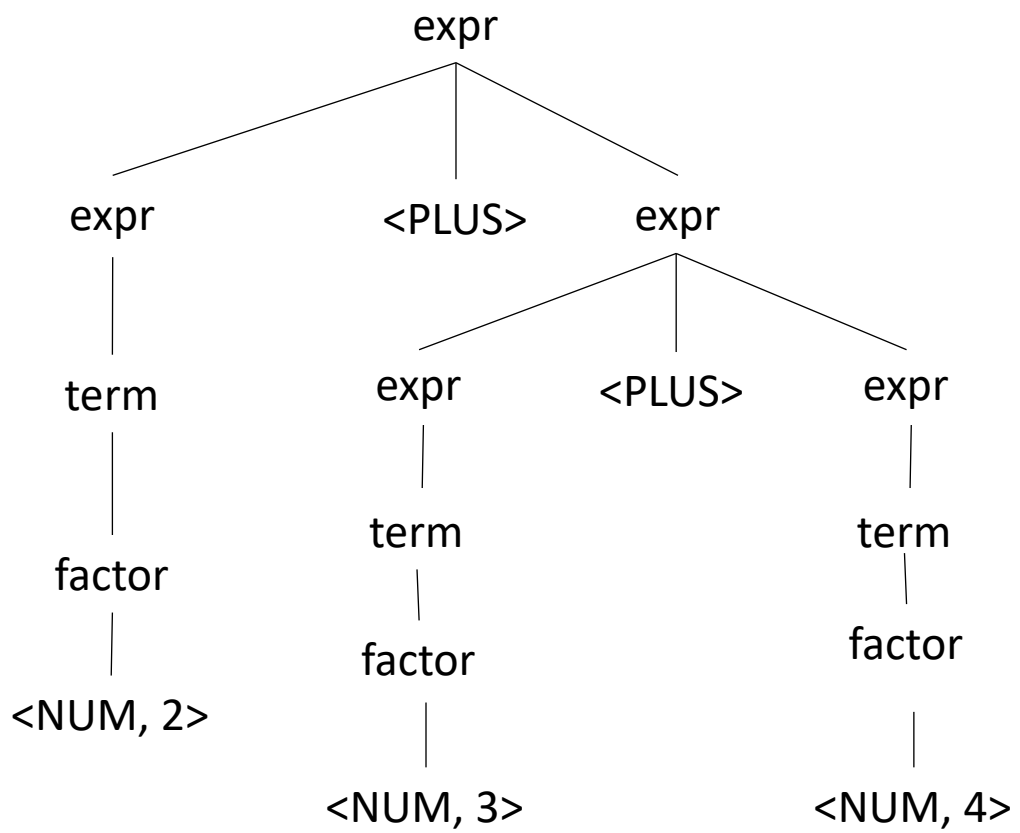
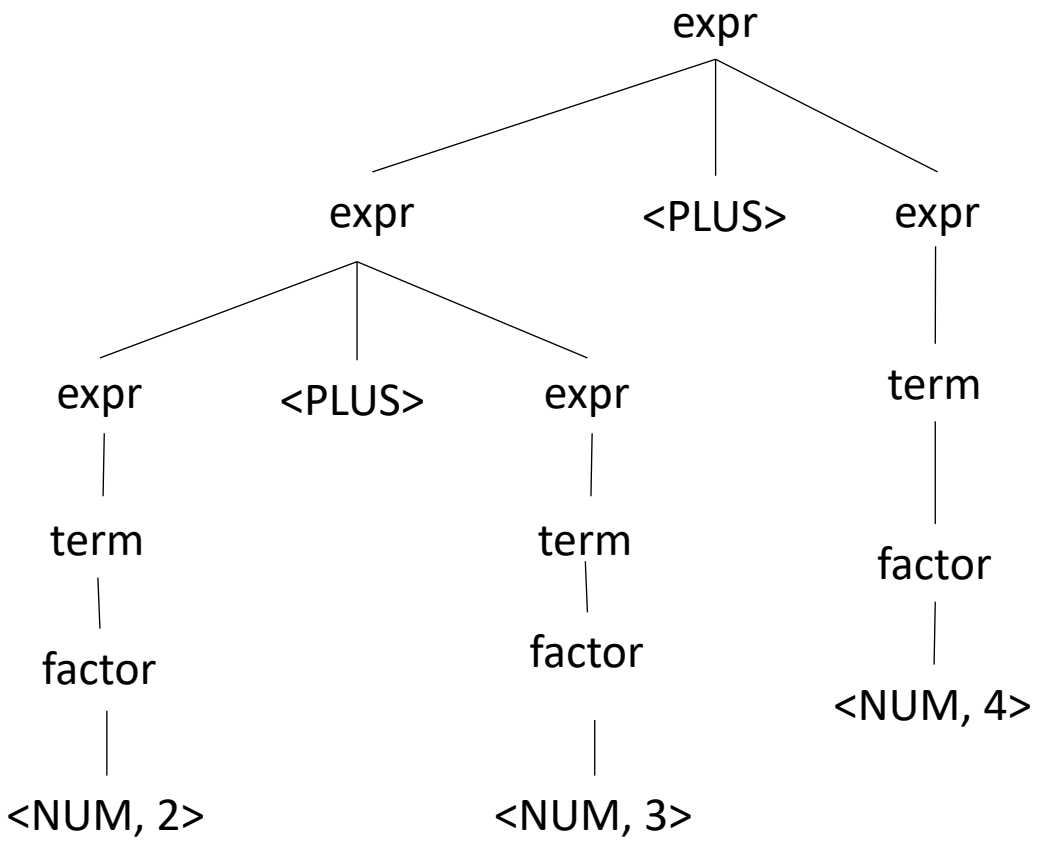
()	`factor`	`: LP expr RP` `| NUM`

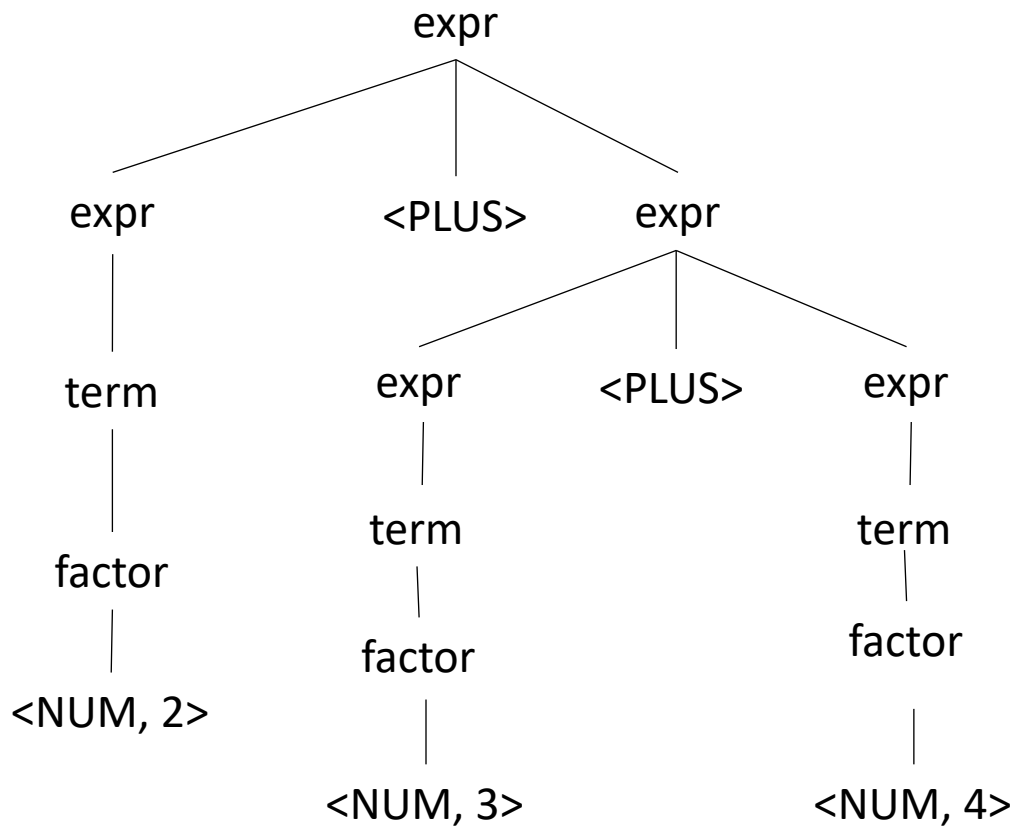
`input: 2+3+4`



This is ambiguous, is it an issue?

`input: 2+3+4`





What about for a different operator?

```
input: 2-3-4
```

What about for a different operator?

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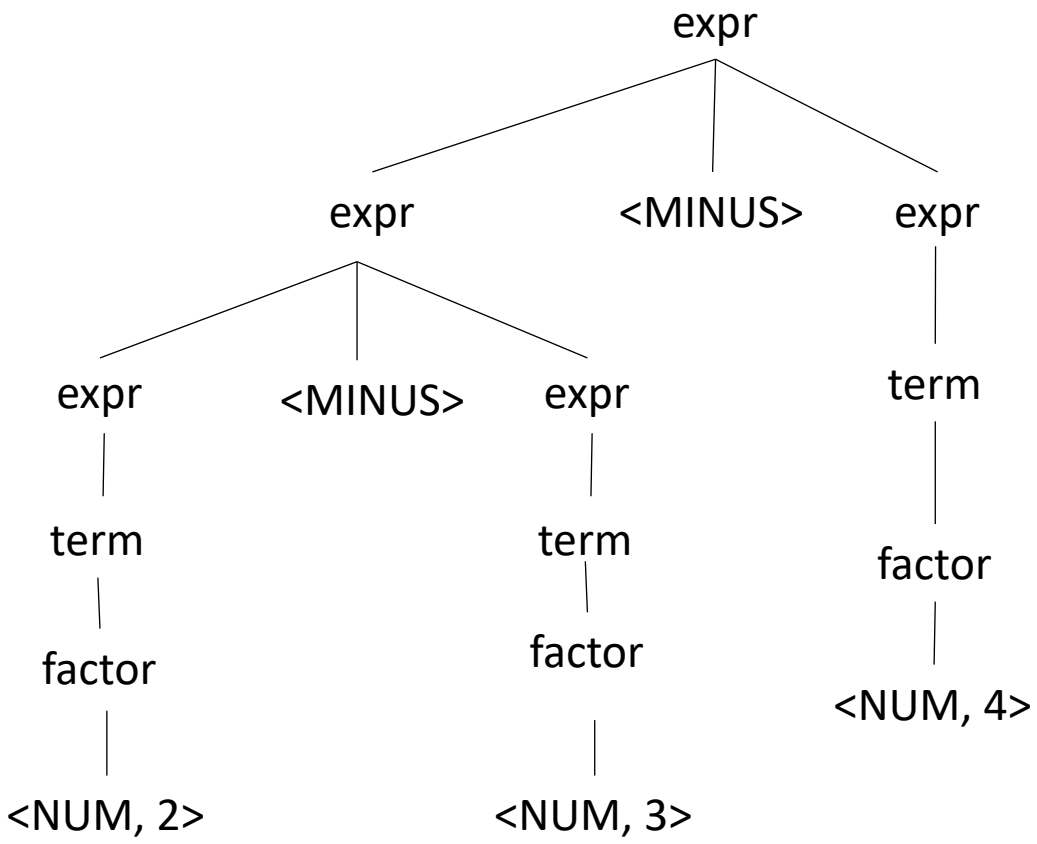
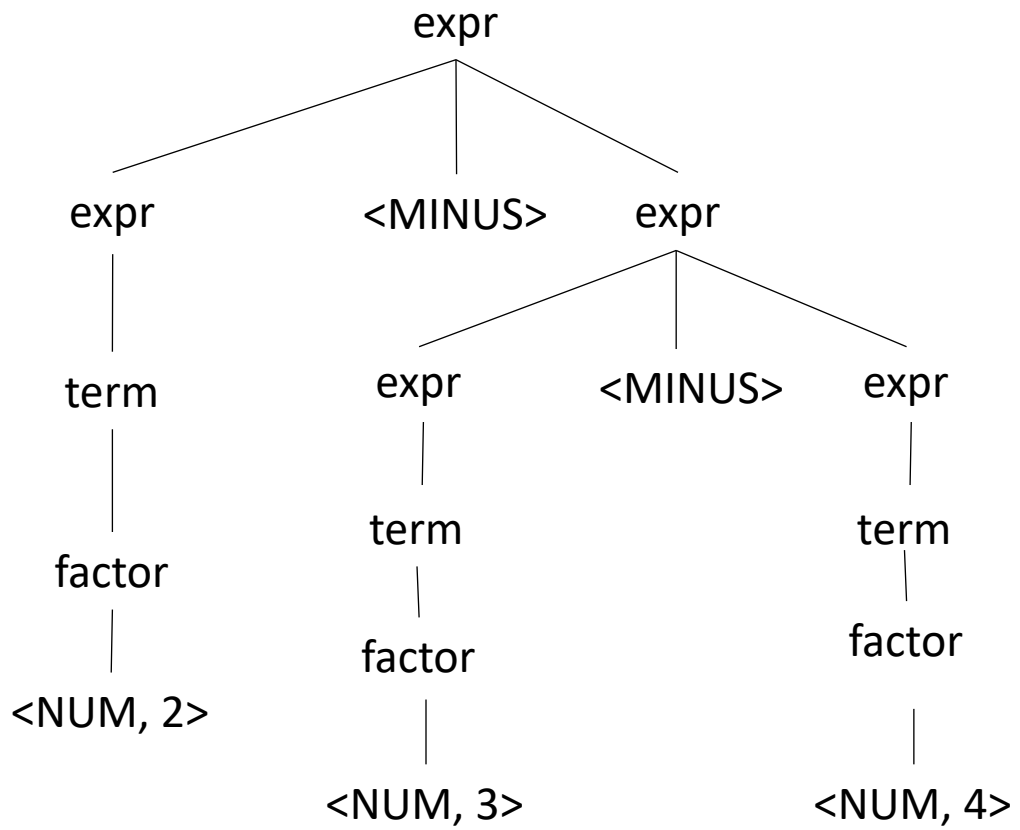




Which one is right?

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?

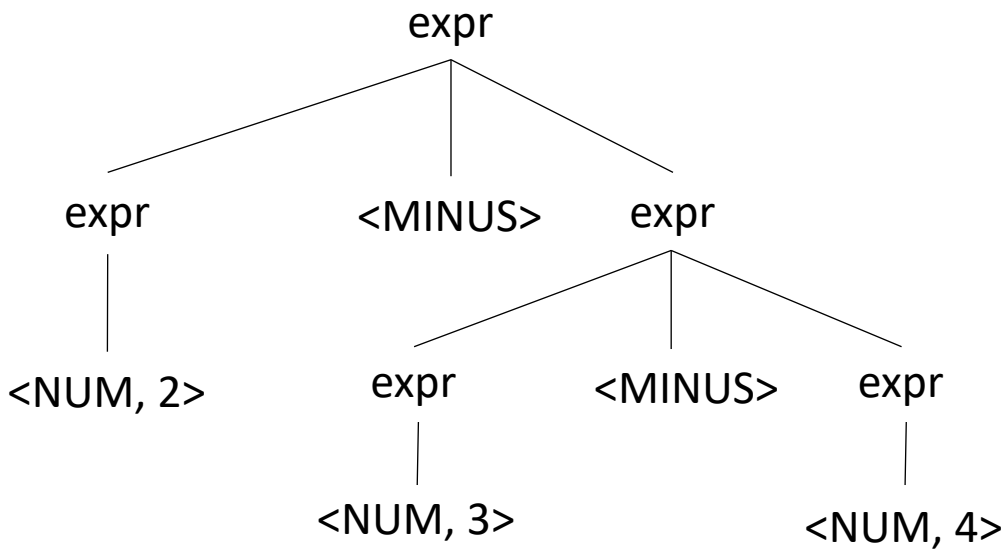
- Like precedence, some tools (e.g. YACC) allow associativity specification through keywords:
  - “+”: left, “^”: right

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

Associativity for a single operator

Operator	Name	Productions
-	`expr`	`: expr MINUS expr` `| NUM`

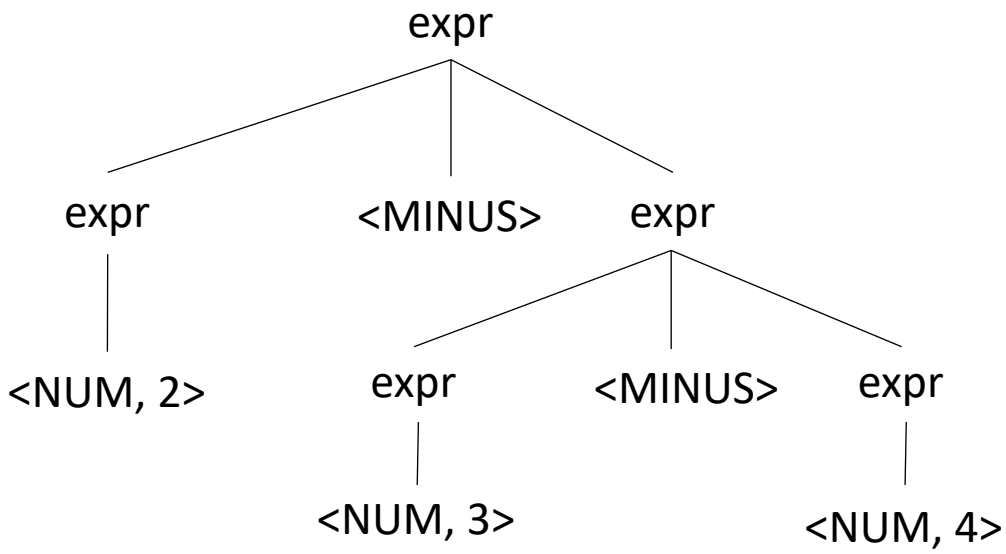
`input: 2-3-4`



Associativity for a single operator

Operator	Name	Productions
-	expr	: expr MINUS NUM | NUM

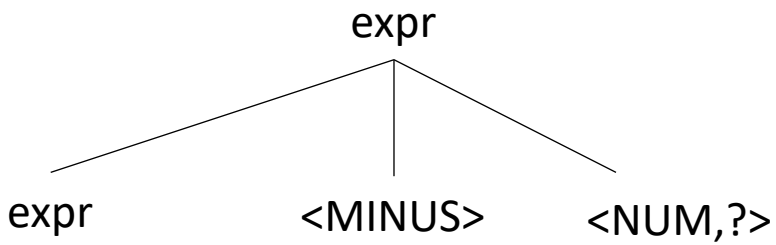
```
input: 2-3-4
```



No longer allowed

Associativity for a single operator

```
input: 2-3-4
```

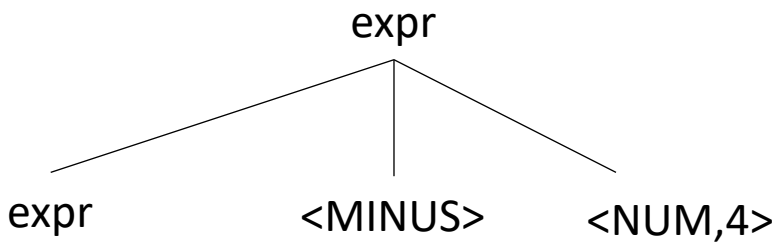


Operator	Name	Productions
-	expr	: expr MINUS NUM | NUM

Lets start over

Associativity for a single operator

```
input: 2-3-4
```



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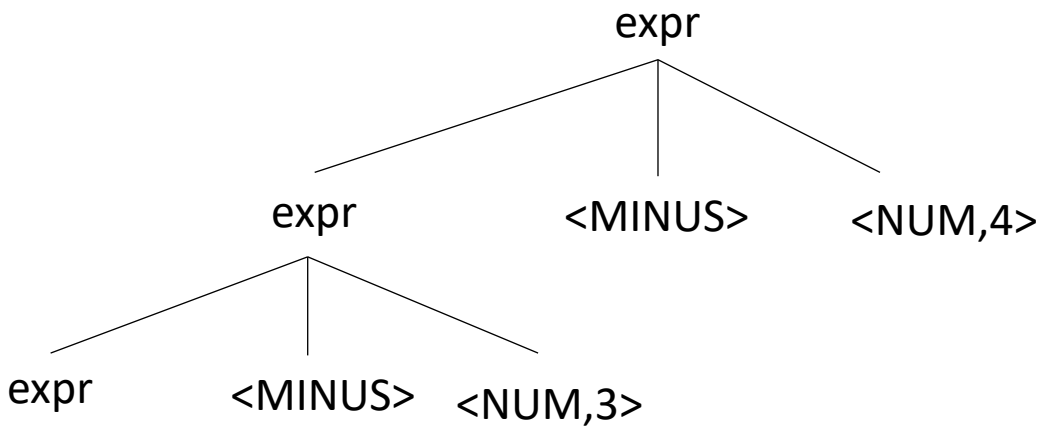
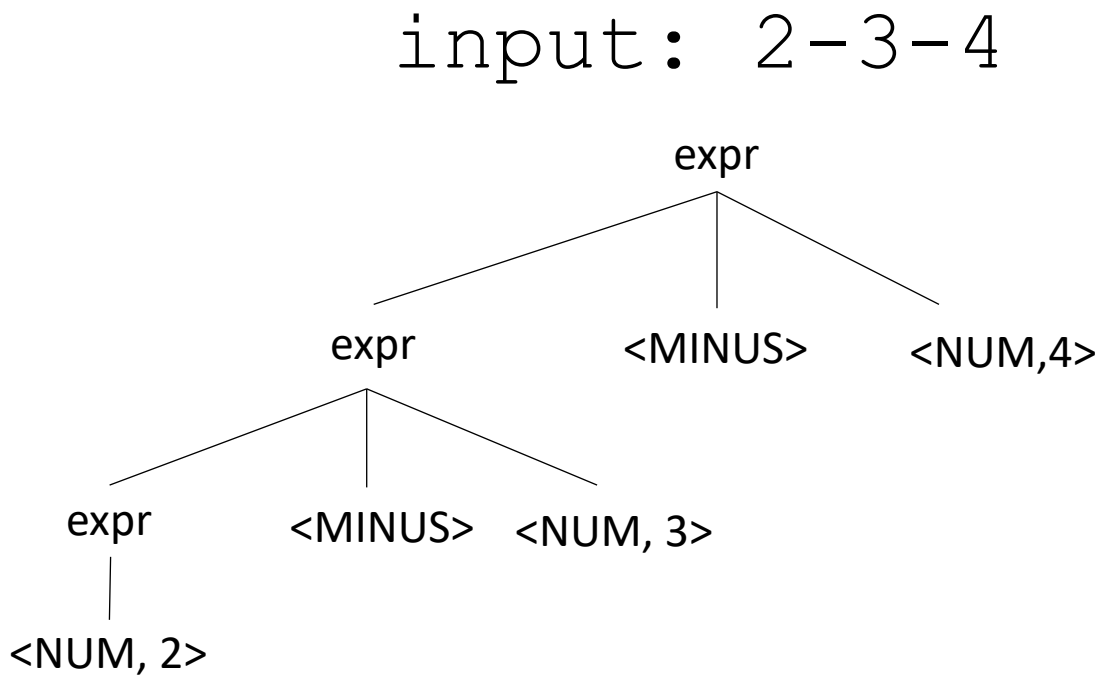


Associativity for a single operator

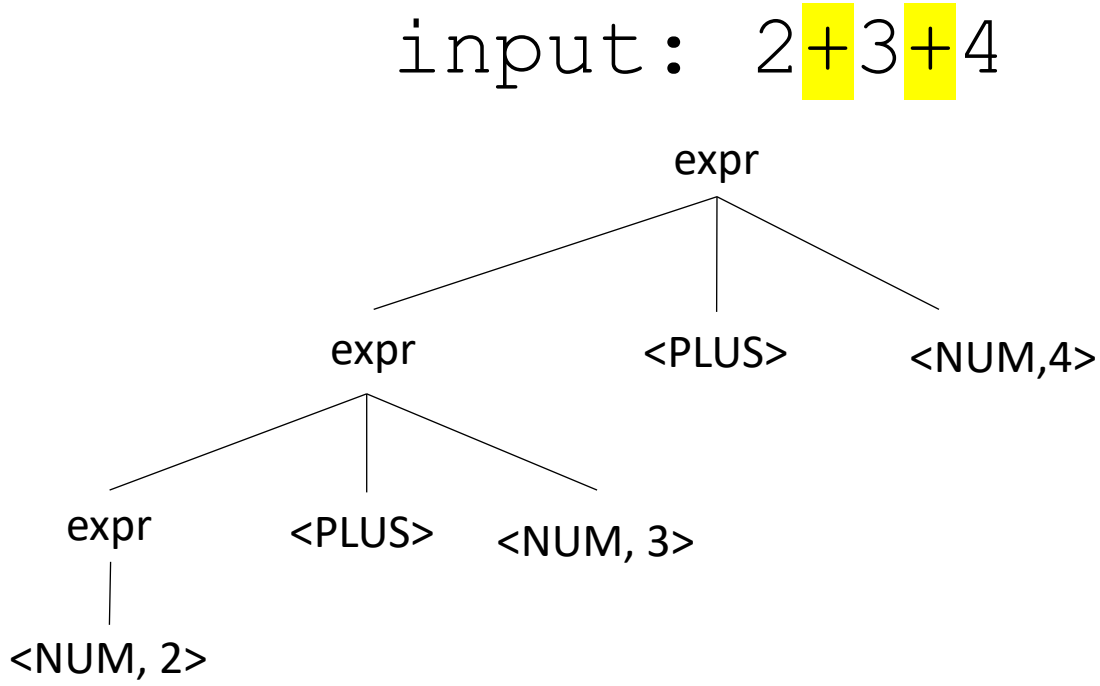
Operator	Name	Productions
-	expr	: expr MINUS NUM | NUM



Should you have associativity when its not required?

Benefits?
Drawbacks?

Operator	Name	Productions
+	`expr`	`: expr PLUS NUM` `| NUM`



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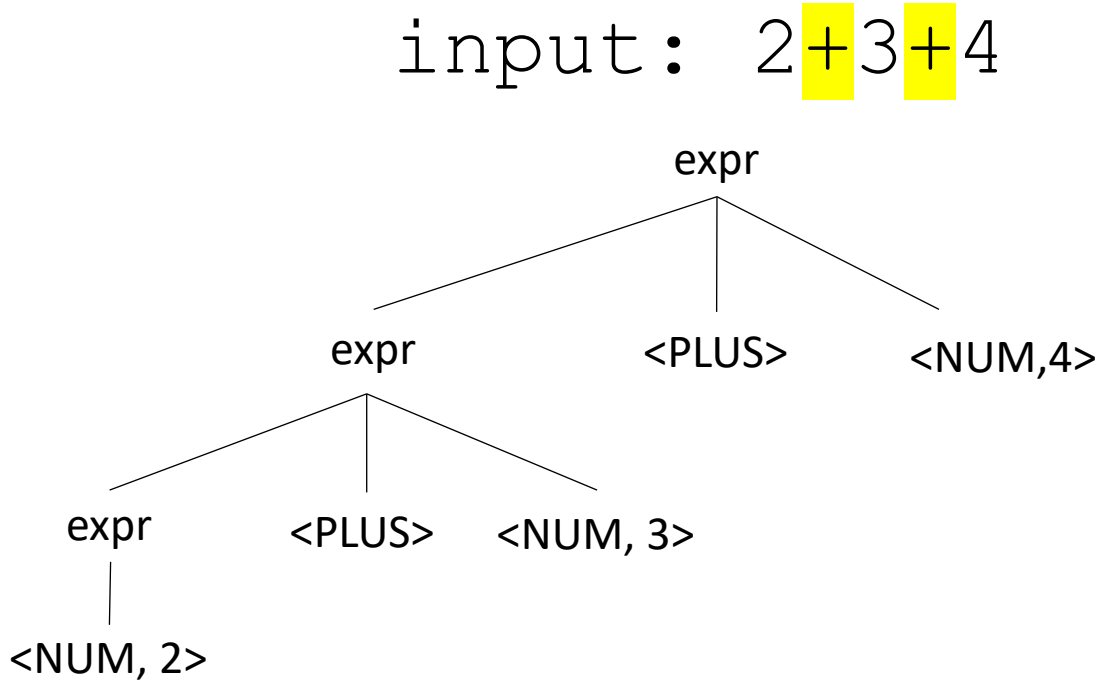

Good design principle to avoid ambiguous grammars, even when strictly not required too.

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