Syntax Analysis – Part I

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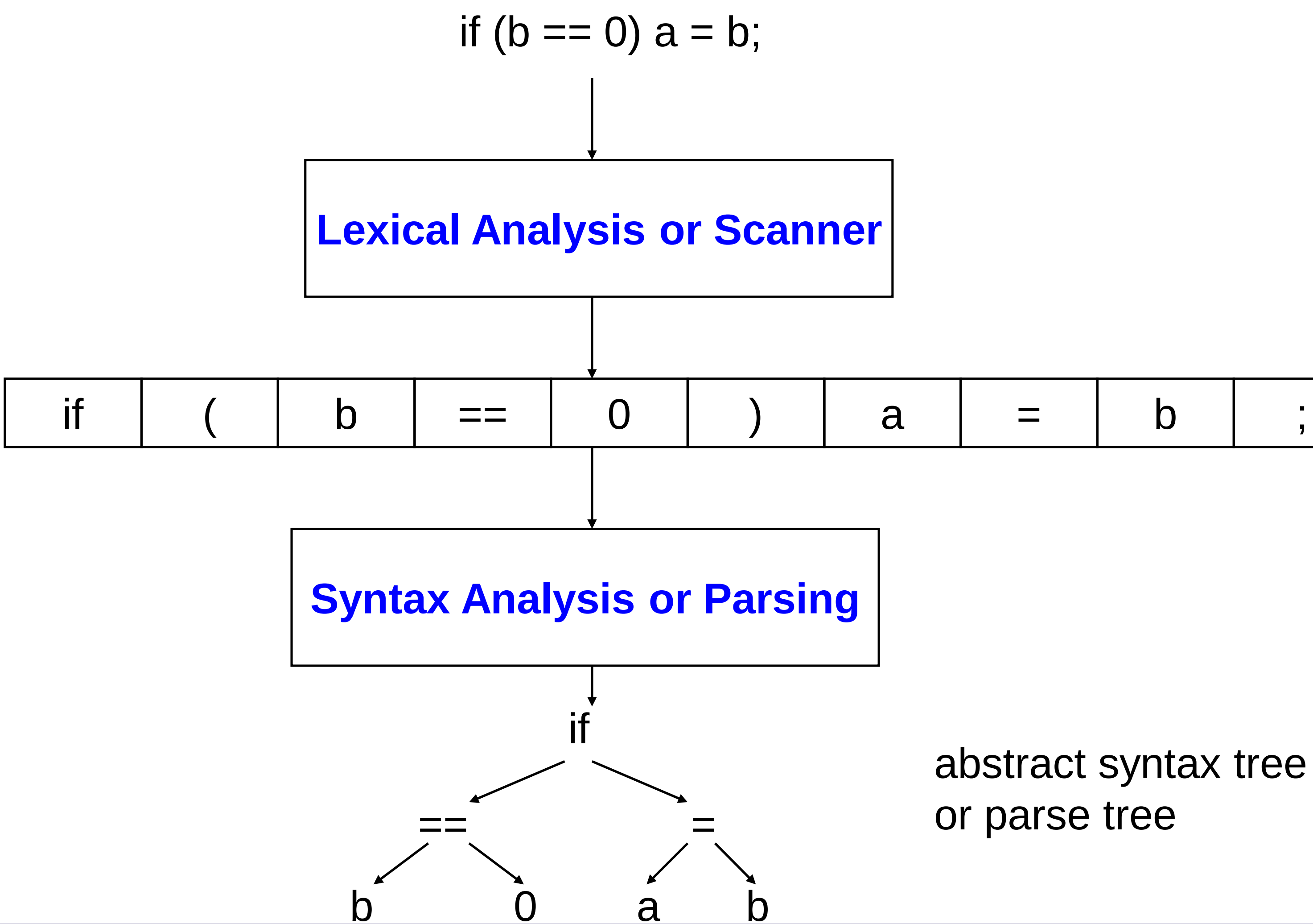
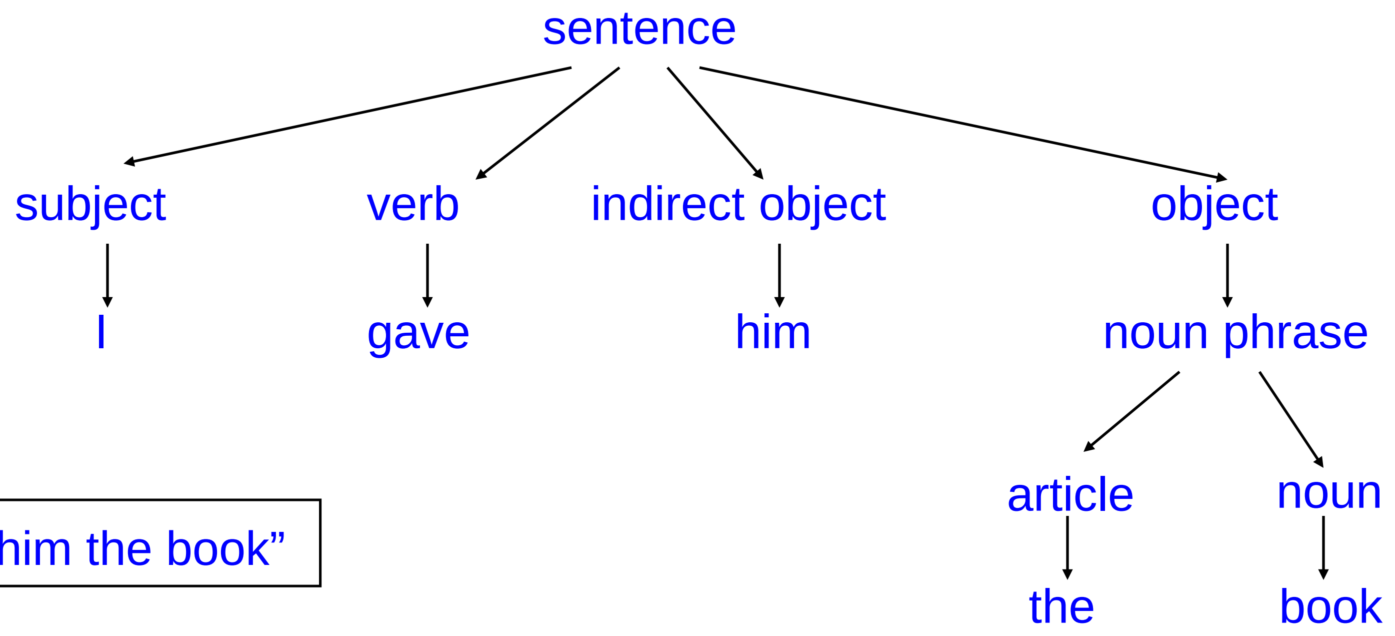
Where is Syntax Analysis Performed?



Parsing Analogy

- Syntax analysis for natural languages
  - Recognize whether a sentence is grammatically correct
  - Identify the function of each word



"I gave him the book"

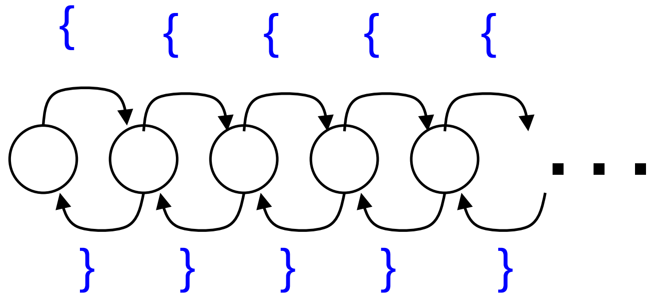
Syntax Analysis Overview

- **Goal – Determine if the input token stream satisfies the syntax of the program**
- **What do we need to do this?**
  - An expressive way to describe the syntax
  - A mechanism that determines if the input token stream satisfies the syntax description
- **For lexical analysis**
  - Regular expressions describe tokens
  - Finite automata = mechanisms to generate tokens from input stream

Just Use Regular Expressions?

- **REs can expressively describe tokens**
  – Easy to implement via DFAs
- **So just use them to describe the syntax of a programming language??**
  – NO! – They don't have enough power to express any non-trivial syntax
  – Example – Nested constructs (blocks, expressions, statements) – Detect balanced braces:

{{} {} {{} { }}}



- We need unbounded counting!
- FSAs cannot count except in a strictly modulo fashion

Context-Free Grammars

- **Consist of 4 components:**
  - Terminal symbols = token or ε
  - Non-terminal symbols = syntactic variables
  - Start symbol S = special non-terminal
  - Productions of the form LHS→RHS
    - LHS = single non-terminal
    - RHS = string of terminals and non-terminals
    - Specify how non-terminals may be expanded

S → a S a
S → T
T → b T b
T → ε

- **Language generated by a grammar is the set of strings of terminals derived from the start symbol by repeatedly applying the productions**
  - L(G) = language generated by grammar G

CFG - Example

- **Grammar for balanced-parentheses language**
  - $S \rightarrow (S) S$
  - $S \rightarrow \varepsilon$
    - 1 non-terminal: S
    - 2 terminals: "(", ")"
    - Start symbol: S
    - 2 productions

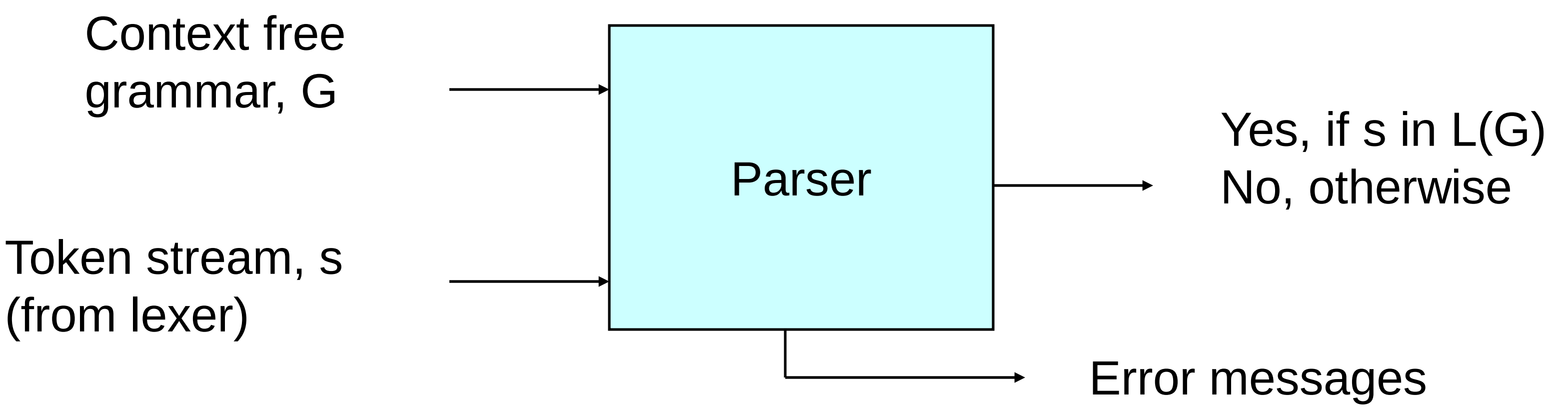
? Why is the final S required?

- **If grammar accepts a string, there is a derivation of that string using the productions**
  - "(())"
  - $S = (S)\ \varepsilon = ((S)\ S)\ \varepsilon = ((\varepsilon)\ \varepsilon\ )\ \varepsilon = (())$

More on CFGs

- Shorthand notation – vertical bar for multiple productions
  - $S \rightarrow a\ S\ a \mid T$
  - $T \rightarrow b\ T\ b \mid \varepsilon$
- CFGs powerful enough to expression the syntax in most programming languages
- Derivation = successive application of productions starting from S
- Acceptance? = Determine if there is a derivation for an input token stream

A Parser



Syntax analyzers (parsers) = CFG acceptors which also output the corresponding derivation when the token stream is accepted

Various kinds: LL(k), LR(k), SLR, LALR

RE is a Subset of CFG

Can inductively build a grammar for each RE

ε	$S \rightarrow \varepsilon$
a	$S \rightarrow a$
R1 R2	$S \rightarrow S1\ S2$
R1 | R2	$S \rightarrow S1 \mid S2$
R1*	$S \rightarrow S1\ S1 \mid \varepsilon$

Where

G1 = grammar for R1, with start symbol S1

G2 = grammar for R2, with start symbol S2

Grammar for Sum Expression

- **Grammar**
  - S → E + S | E
  - E → number | (S)
- **Expanded**
  - S → E + S
  - S → E
  - E → number
  - E → (S)

4 productions
2 non-terminals (S,E)
4 terminals: "(", ")", "+", number
start symbol: S

Constructing a Derivation

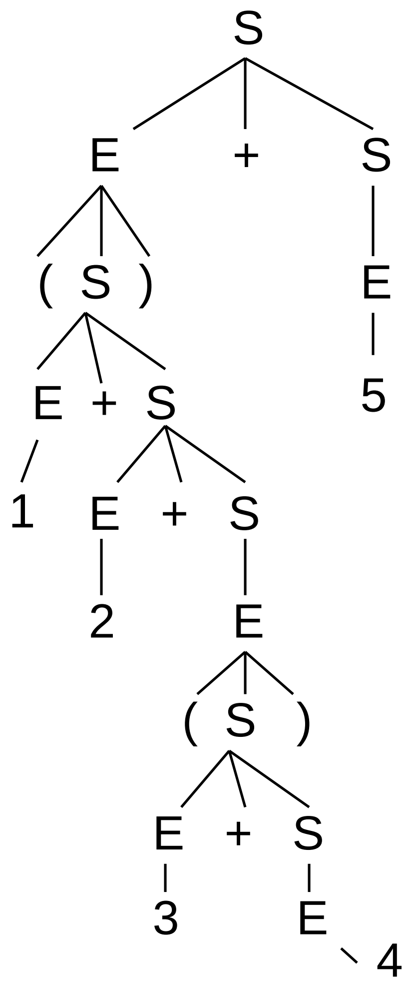
- **Start from S (the start symbol)**
- **Use productions to derive a sequence of tokens**
- **For arbitrary strings α, β, γ and for a production: A → β**
  - A single step of the derivation is
  - $\alpha\ A\ \gamma \Rightarrow \alpha\ \beta\ \gamma$ (substitute β for A)

- **Example**
  - S → E + S
  - $(\underline{S} + E) + E \rightarrow (\underline{E + S} + E) + E$

Class Problem

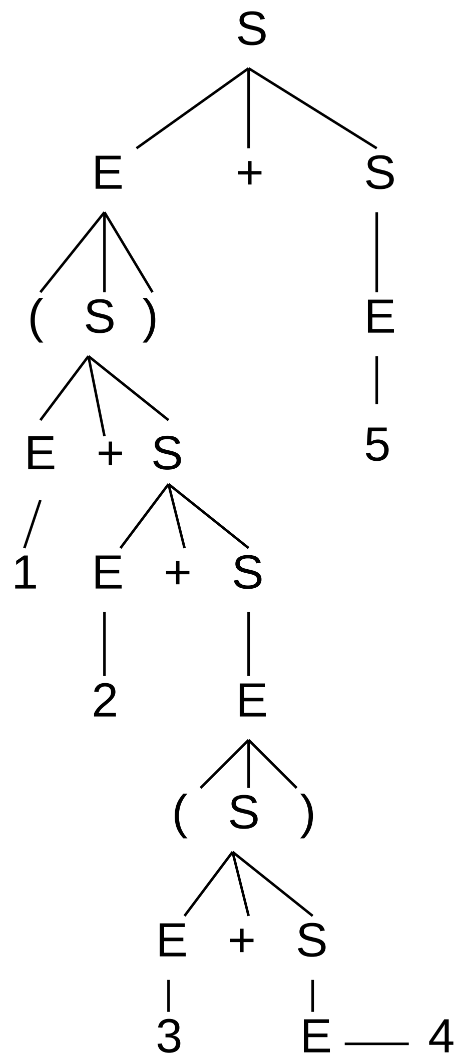
  - S → E + S | E
  - E → number | (S)
- **Derive: (1 + 2 + (3 + 4)) + 5**

Parse Tree

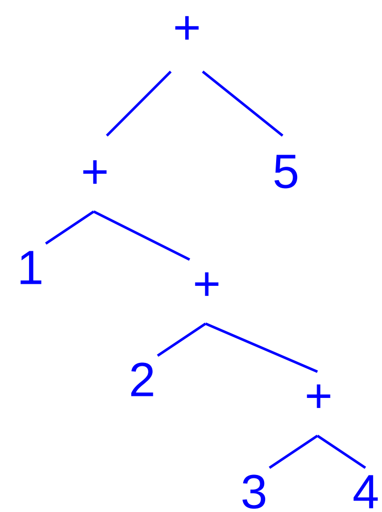


- Parse tree = tree representation of the derivation
- Leaves of the tree are terminals
- Internal nodes are non-terminals
- No information about the order of the derivation steps

Parse Tree vs Abstract Syntax Tree



Parse tree also called “concrete syntax”



AST discards (abstracts) unneeded information – more compact format

Summary so far

- Representing lexical structures
  - Regular expressions
- Representing syntactic structures
  - Context-free grammars
- A context-free grammar is a set of grammar rules.
- Major difference between regular expressions and the rules of a context-free grammar
  - recursion
- Derivation = successive application of productions starting from S
- Acceptance? = Determine if there is a derivation for an input token stream

Derivation Order

- Can choose to apply productions in any order, select non-terminal and substitute RHS of production
- Two standard orders: left and right-most
- Leftmost derivation
  - In the string, find the leftmost non-terminal and apply a production to it
  - E + S → 1 + S
- Rightmost derivation
  - Same, but find rightmost non-terminal
  - E + S → E + E + S

Leftmost/Rightmost Derivation Examples

» S → E + S | E

» E → number | (S)

» Leftmost derive: (1 + 2 + (3 + 4)) + 5

S → E + S → (S)+S → (E+S) + S → (1+S)+S → (1+E+S)+S → (1+2+S)+S → (1+2+E)+S → (1+2+(S))+S → (1+2+(E+S))+S → (1+2+(3+S))+S → (1+2+(3+E))+S → (1+2+(3+4))+S → (1+2+(3+4))+E → (1+2+(3+4))+5

»Now, rightmost derive the same input string

S → E+S → E+E → E+5 → (S)+5 → (E+S)+5 → (E+E+S)+5 → (E+E+E)+5 → (E+E+(S))+5 → (E+E+(E+S))+5 → (E+E+(E+E))+5 → (E+E+(E+4))+5 → (E+E+(3+4))+5 → (E+2+(3+4))+5 → (1+2+(3+4))+5

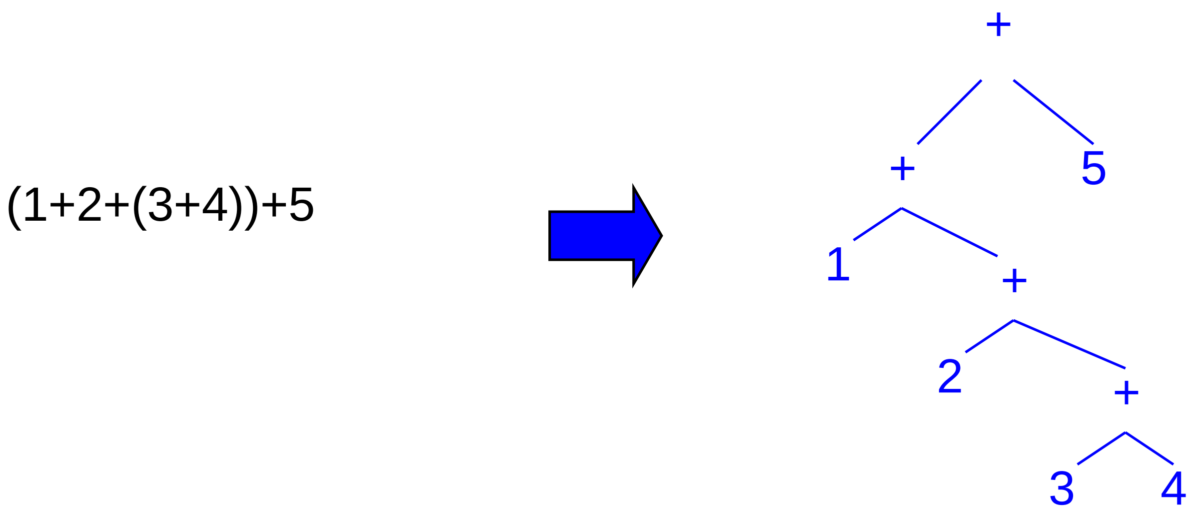
Result: Same parse tree: same productions chosen, but in diff order

Class Problem

  - S → E + S | E
  - E → number | (S) | -S
- **Do the rightmost derivation of : 1 + (2 + -(3 + 4)) + 5**

Ambiguous Grammars

- In the sum expression grammar, leftmost and rightmost derivations produced identical parse trees
- \+ operator associates to the right in parse tree regardless of derivation order



An Ambiguous Grammar

- **+ associates to the right because of the right-recursive production: S → E + S**

- **Consider another grammar**
  - S → S + S | S * S | number

- **Ambiguous grammar = different derivations produce different parse trees**
  - More specifically, G is ambiguous if there are 2 distinct leftmost (rightmost) derivations for some sentence

Ambiguous Grammar - Example

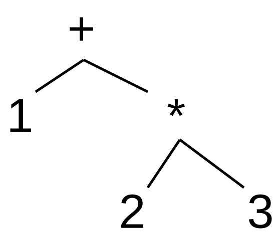
S → S + S | S * S | number

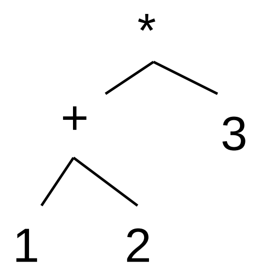
Consider the expression: 1 + 2 * 3

Derivation 1: S → S+S → 1+S → 1+S*S → 1+2*S → 1+2*3

Derivation 2: S → S*S → S+S*S → 1+S*S → 1+2*S → 1+2*3

2 leftmost derivations

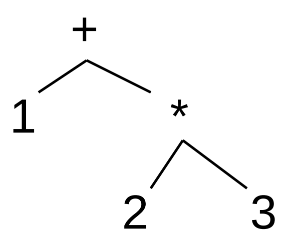




But, obviously not equal!

Impact of Ambiguity

- **Different parse trees correspond to different evaluations!**
- **Thus, program meaning is not defined!!**



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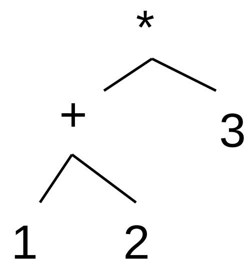

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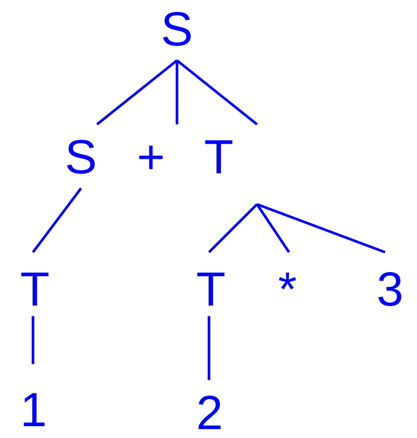
Can We Get Rid of Ambiguity?

- **<u>Ambiguity is a function of the grammar, not the language!</u>**
- **A context-free language L is inherently ambiguous if all grammars for L are ambiguous**
- **Every deterministic CFL has an unambiguous grammar**
  - So, no deterministic CFL is inherently ambiguous
  - No inherently ambiguous programming languages have been invented
- **To construct a useful parser, must devise an unambiguous grammar**

Eliminating Ambiguity

- **Often can eliminate ambiguity by adding nonterminals and allowing recursion only on right or left**
  - S → S + T | T
  - T → T * num | num



  - T non-terminal enforces precedence
  - Left-recursion; left associativity

A Closer Look at Eliminating Ambiguity

- **Precedence enforced by**
  - Introduce distinct non-terminals for each precedence level
  - Operators for a given precedence level are specified as RHS for the production
  - Higher precedence operators are accessed by referencing the next-higher precedence non-terminal

Associativity

- **An operator is either left, right or non associative**
  - Left: $a + b + c = (a + b) + c$
  - Right: $a \wedge b \wedge c = a \wedge (b \wedge c)$
  - Non: $a < b < c$ is illegal (thus undefined)
- **Position of the recursion relative to the operator dictates the associativity**
  - Left (right) recursion → left (right) associativity
  - Non: Don't be recursive, simply reference next higher precedence non-terminal on both sides of operator

Class Problem

$S \rightarrow S + S \mid S - S \mid S * S \mid S / S \mid (S) \mid -S \mid S \wedge S \mid num$

Enforce the standard arithmetic precedence rules and remove all ambiguity from the above grammar

Precedence (high to low)
(), unary –
^
*, /
+, -
Associativity
^ = right
rest are left