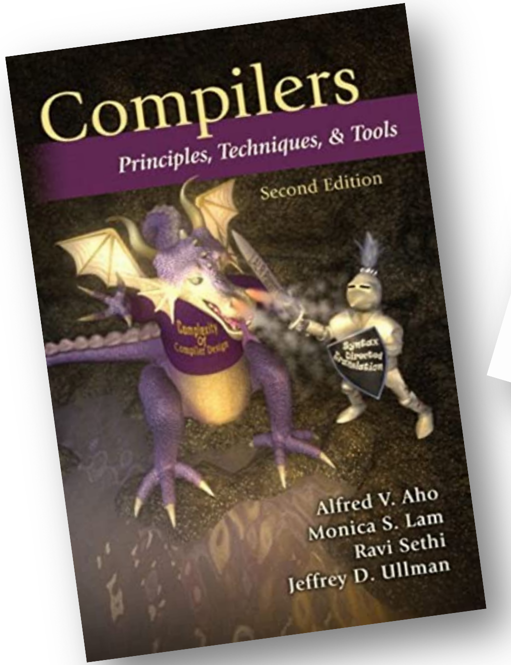
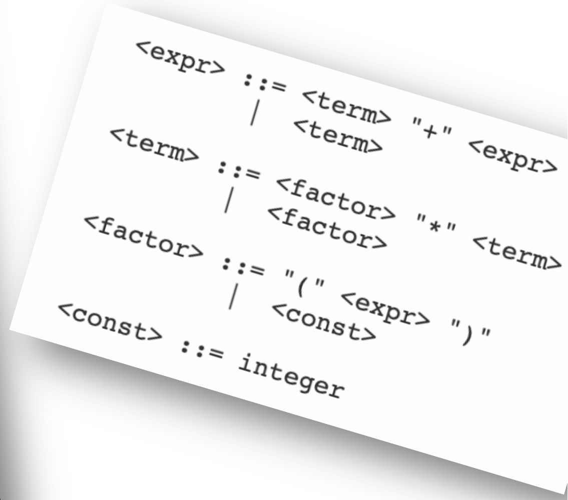
CSE211: Compiler Design

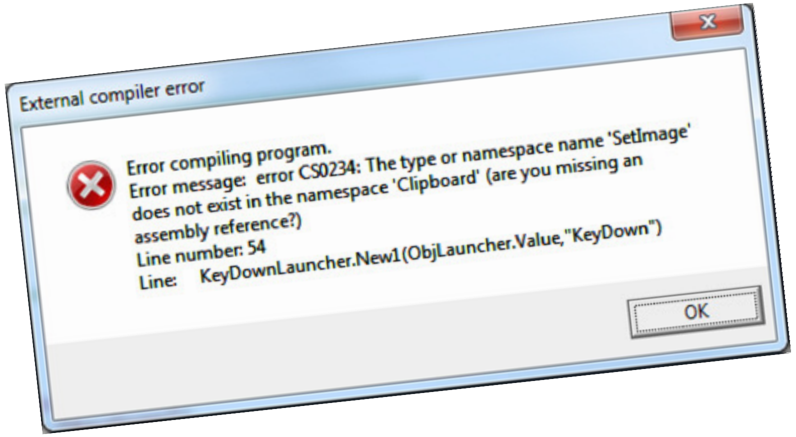
Oct. 2, 2023

- **Topic**: Intro to parsing

- **Previous Questions**:
    - *What is a compiler?*
    - *What are some of your favorite compilers?*
    - *Have you ever built a compiler?*







COMPILER INFRASTRUCTURE

Announcements

- Didn’t get a chance to:
  - Set up Piazza
  - Set office hours
  - Reply to people’s emails

- I will do it all today!

- As a reminder:
  - If you are an undergrad, you need to message me for a permission code!

Discussion from last time

What is a compiler?

What are some of your favorite compilers

```
---
title: "Graduate Compiler Design"
layout: single
---


### Welcome to **CSE211:** _Graduate Compiler Design_, Fall 2021 Quarter at UCSC!

- **Instructor:** [Tyler Sorensen](https://users.soe.ucsc.edu/~tsorensen/)
- **Time:** MWF 4:00 - 5:05 pm
- **Location:** Thimann Lab 101 (_in person!_)
- **Contact:** \<first name\>.\<last name\>@ucsc.edu


Hello! I'm Tyler  and welcome to the graduate compiler design course!

In this class you will learn about advanced topics in compiler design and implementation. In the abstract, compilers explore many of the [foundational problems in computer science](https://en.wikipedia.org/wiki/Halting_problem). In practice, compilers are [massive pieces of well-oiled software](https://www.phoronix.com/scan.php?page=news_item&px=MTg3OTQ), and are some of the engineering marvels of the modern world. Given the end of Dennard's scaling, compilers will play an increasingly important role to achieve further computational gains. _The main focus of this class is how compilers can make your code more efficient and safe on modern (and near-future) processors_.
```

CSE211, Fall 2021 — Home · Overview · Schedule · Homeworks · References

Graduate Compiler Design

Welcome to CSE211: *Graduate Compiler Design*, Fall 2021 Quarter at UCSC!

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- **Time:** MWF 4:00 - 5:05 pm
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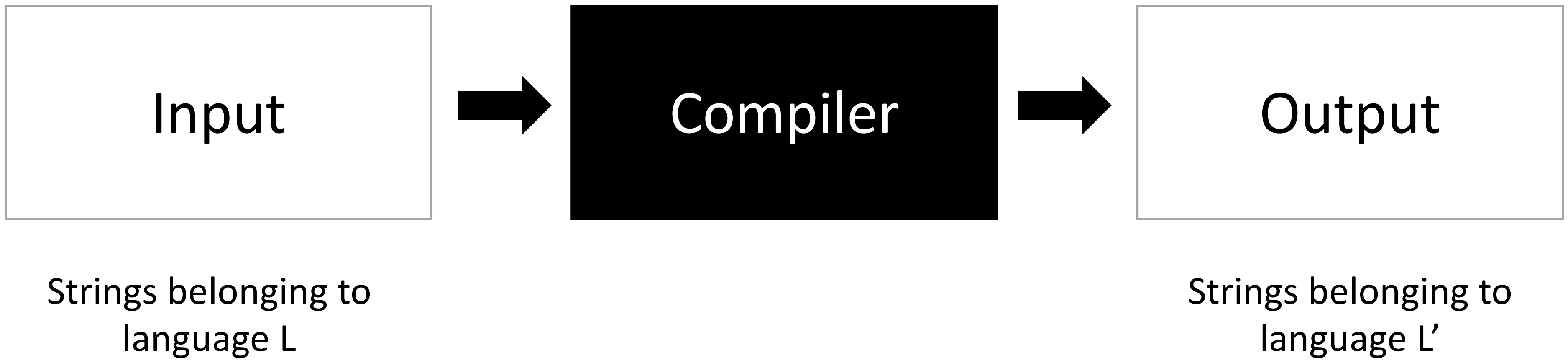
Building this website started with:

- Markdown to describe the page
- compiled with Jekyll to a static webpage
- static webpage is in HTML and javascript

Have you ever built a compiler?

What is a compiler?

What is a compiler?



What is a compiler?

Strings belonging to language L

A series of statements in programming language L

Strings belonging to language L’

An executable binary file in an ISA language

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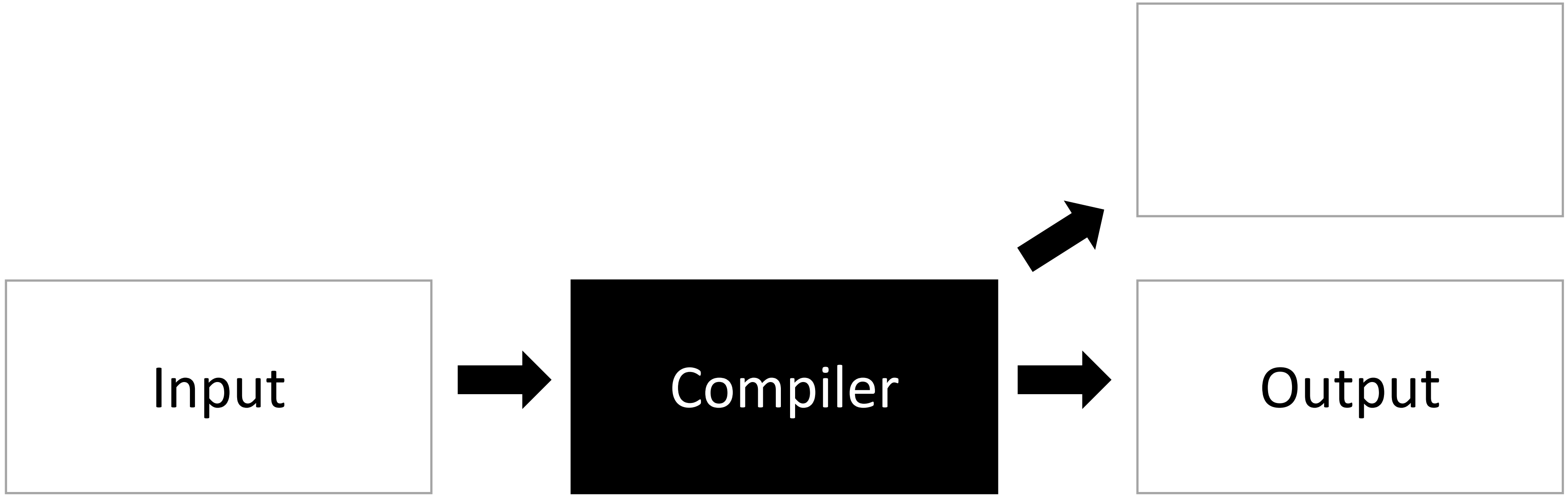

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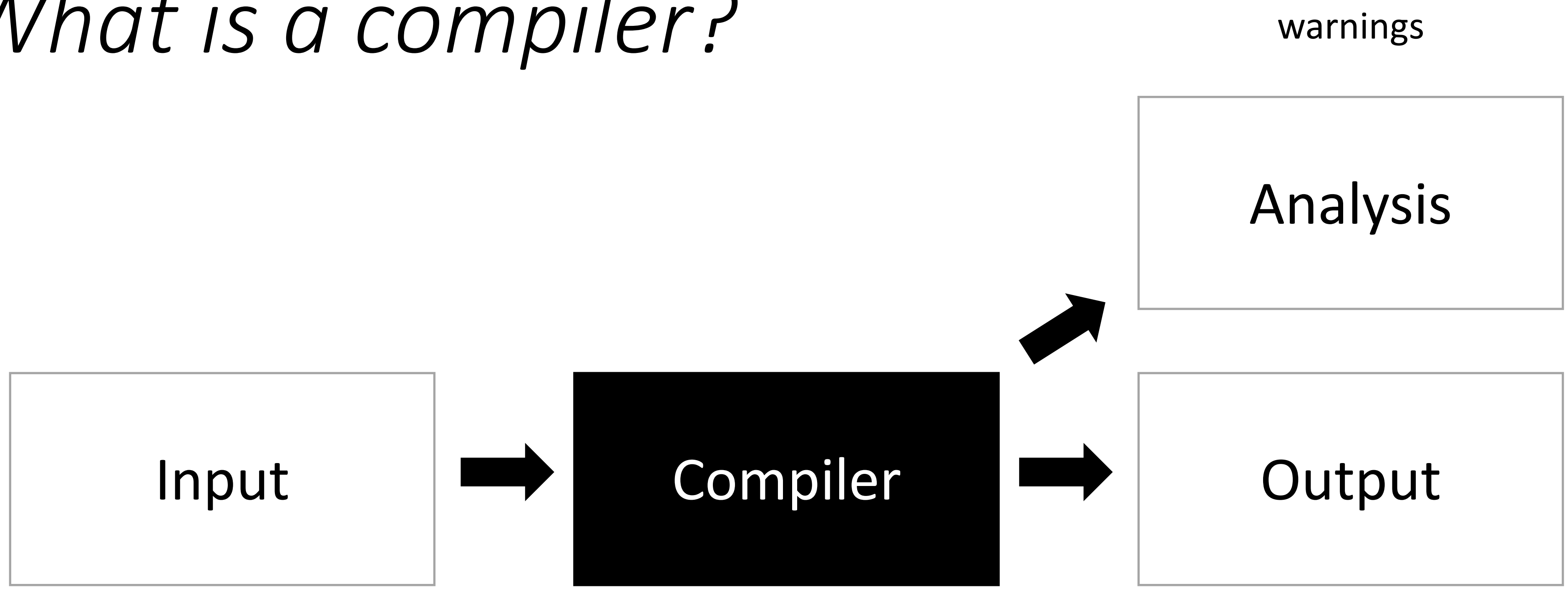

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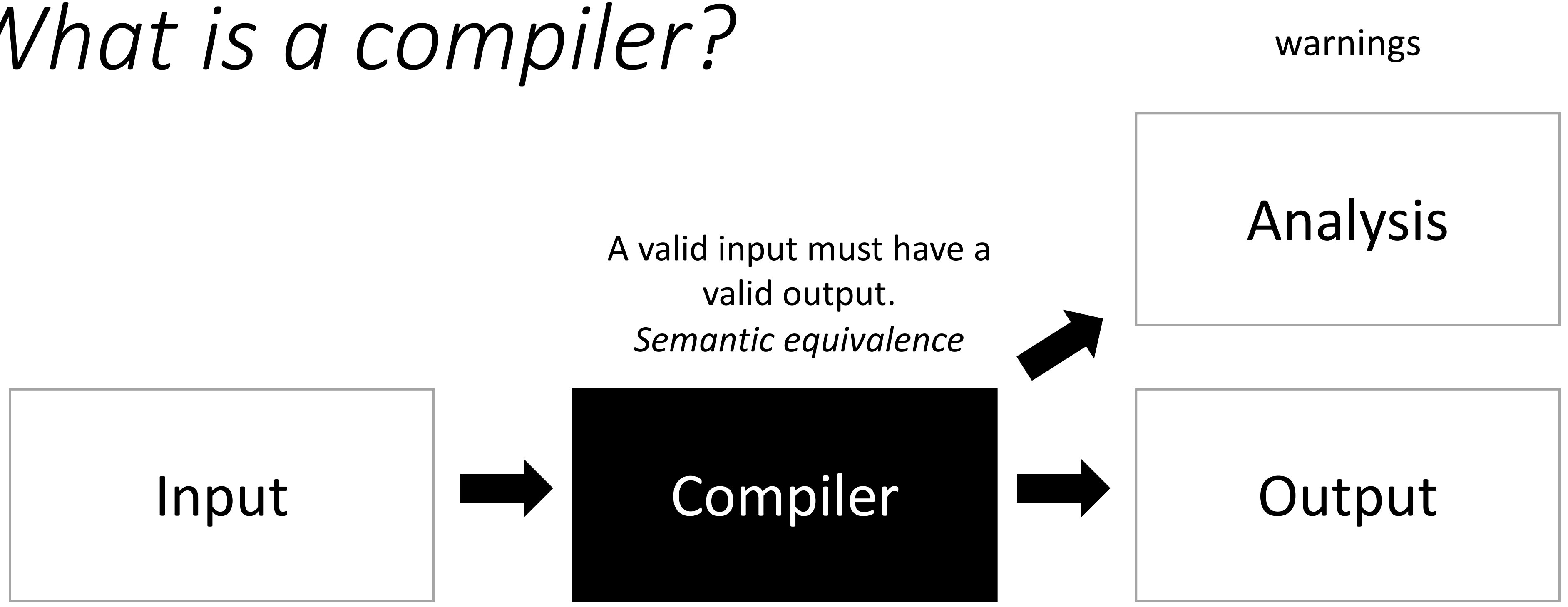

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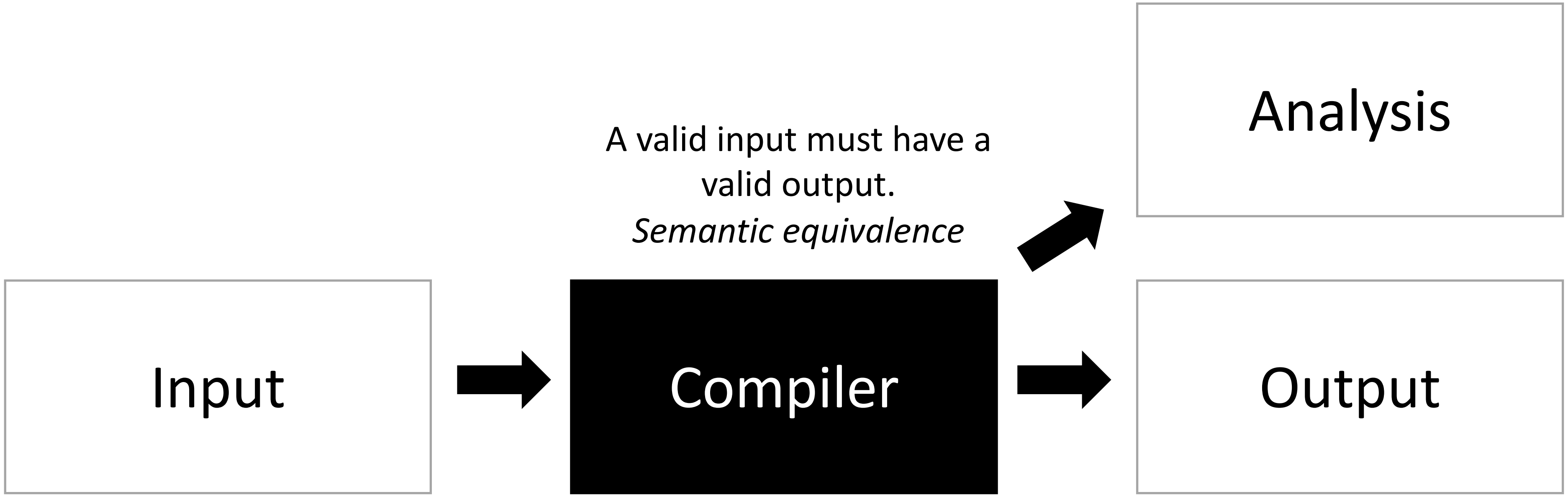
What is a compiler?

warnings

A valid input must have a valid output.
Semantic equivalence



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What can happen when the Input isn't valid?

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What can happen when the Input isn't valid?

```
int main() {
    int my_var = 5;
    my_var = my_car + 5;
    return 0;
}
```

Try running this through clang. What happens?

What can happen when the Input isn’t valid?

```c
int main() {
    int my_var = 5;
    my_var = my_car + 5;
    return 0;
}
```

```c
#include <stdlib.h>

int foo() {
   int *x = (int *) malloc(100*sizeof(int));
   return x[100];
}
```

What about this one?

Can the compiler make your code go faster?

```
int foo() {
    int my_var = 0;
    for (int i = 0; i < 128; i++) {
        my_var++;
    }
    return my_var;
}
```

Try running this on https://godbolt.org/
change the optimization level to -O3 and see what happens!

What is the compiler allowed to do?

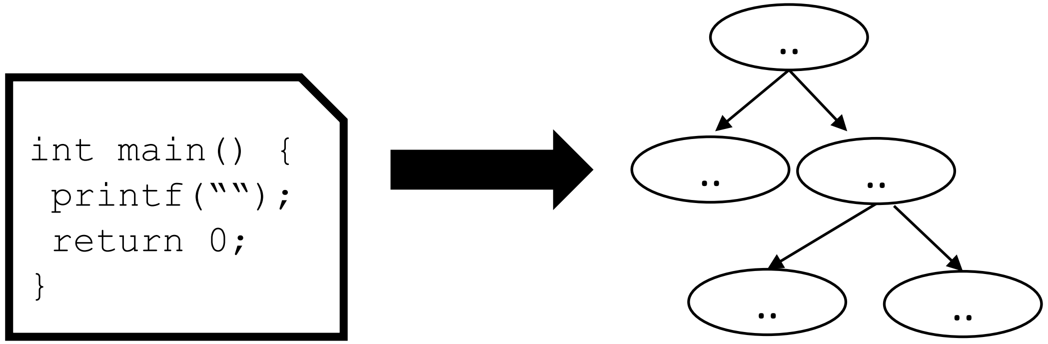
```c
void add_arrays(int *a, int *b) {
    for (int i = 0; i < 128; i++) {
        a[i] += b[i];
    }
}
```

Try running this on https://godbolt.org/
change the optimization level to -O3 and see what happens!
Look for instructions like `paddd`. what does it do?

Moving to Module 1

Starting Module 1

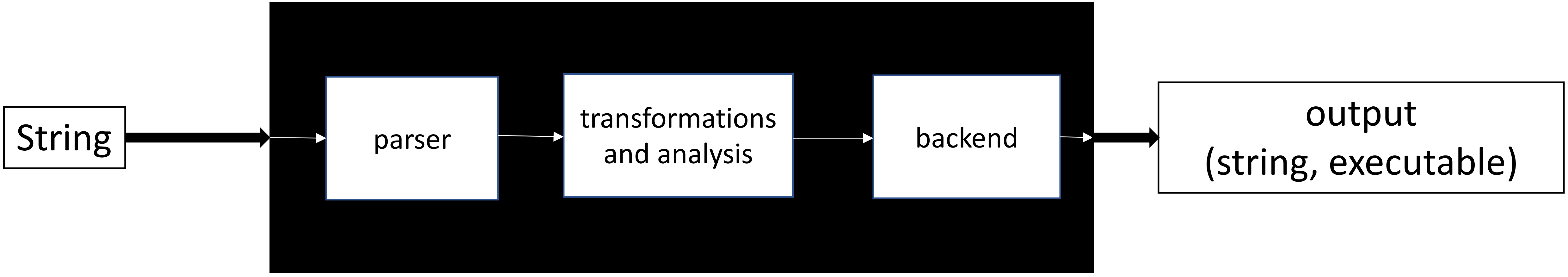
- **Topic**: Parsing



- **Questions**:
  - *What is parsing?*
  - *Have you used Regular Expressions before?*
  - *How do you parse Regular Expressions? What about Context-free Grammars?*

Compiler architecture overview

Compiler architecture overview



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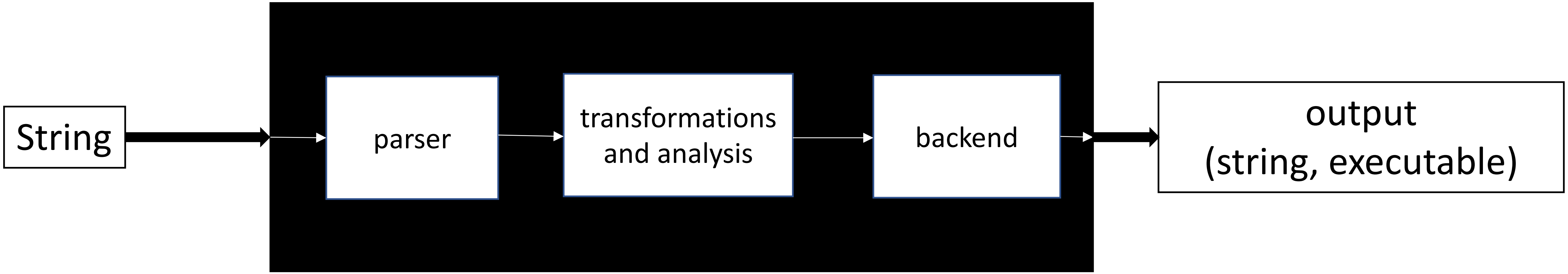
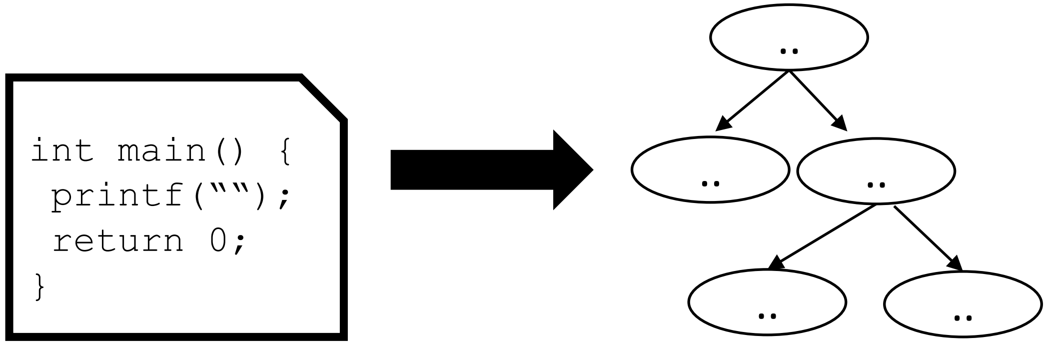


Parsing is the first step in the compiler

Creates structure



Parsing is the first step in a compiler

- How do we parse a sentence in English?

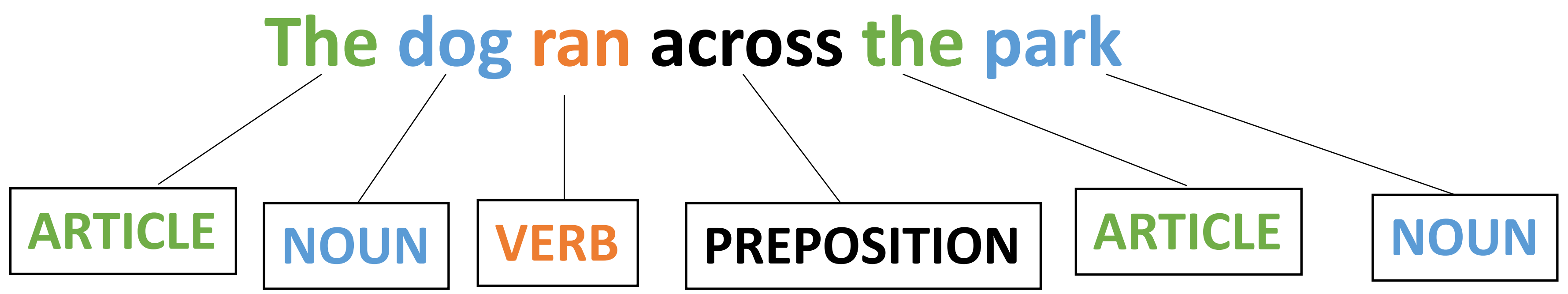
Parsing is the first step in a compiler

- How do we parse a sentence in English?

The dog ran across the park

Parsing is the first step in a compiler

- How do we parse a sentence in English?



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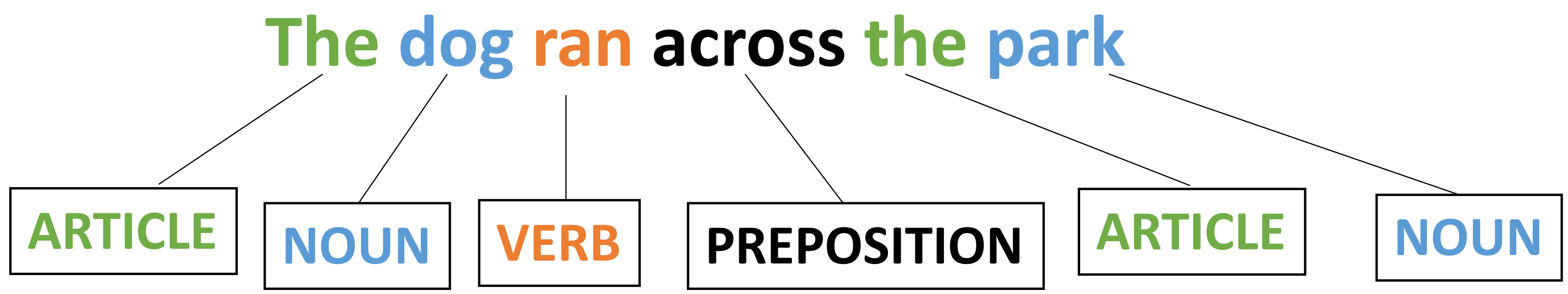
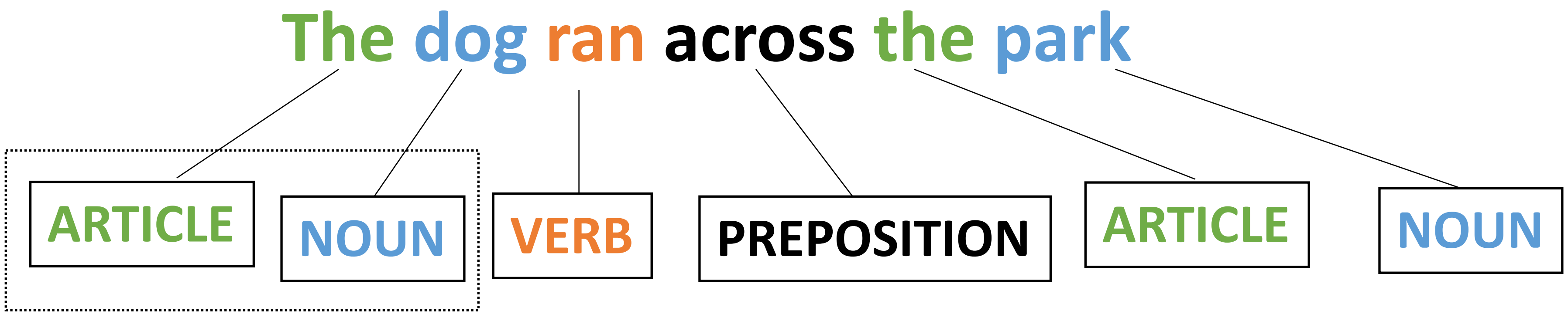


Grammar and Syntax

What about semantics?

Parsing is the first step in a compiler

- How do we parse a sentence in English?



Grammar and Syntax

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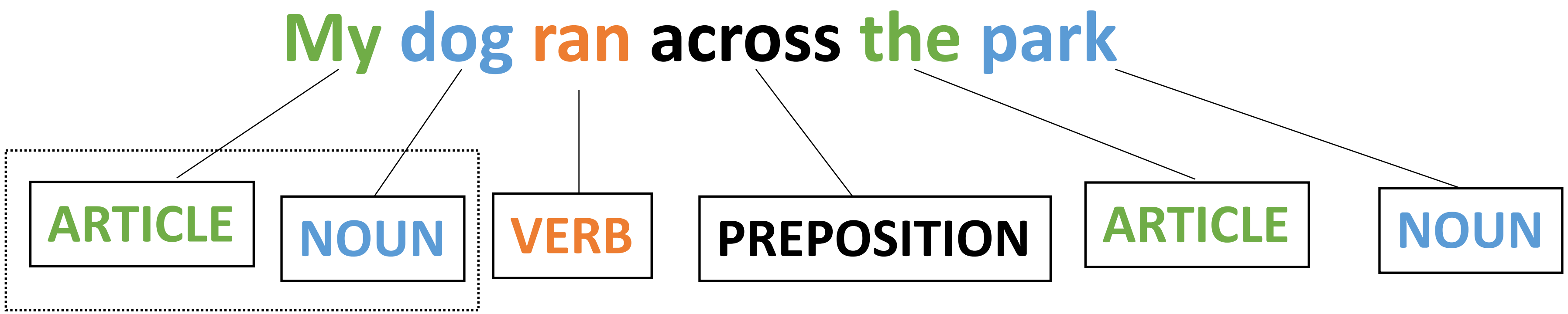

Grammar and Syntax

What about semantics?

New Question

Can we define a simple language using these building blocks?

- ARTICLE
- NOUN
- VERB
- ADJECTIVE

A Simple Language

- ARTICLE = {The, A, My, Your}
- NOUN = {Dog, Car, Computer}
- VERB = {Ran, Crashed, Accelerated}
- ADJECTIVE = {Purple, Spotted, Old}

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ARTICLE NOUN VERB

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ARTICLE ADJECTIVE NOUN VERB

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Question mark means optional

ARTICLE ADJECTIVE? NOUN VERB

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ARTICLE	ADJECTIVE?	NOUN	VERB
My	Old	Computer	Crashed

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Syntactically correct,
logically correct?

ARTICLE	ADJECTIVE?	NOUN	VERB
The	Purple	Dog	Crashed

A Simple Language

- ARTICLE = {The, A, My, Your}
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What other languages can you specify?

ARTICLE ADJECTIVE NOUN VERB

Goals in this module

- **Understand** the architecture of a modern parser (*tokenizing and parsing*)
- **Understand** the language of tokens (*regular expressions*) and parsers (*context-free grammars*)
- How to **design** CFG production rules to avoid **ambiguity**
- **Utilize** a classic parser generator (*Lex and Yacc*) for a simple language

Goals in this module

- We will **NOT** discuss parsing algorithms for CFGs. If you are interested, you can do this for a paper assignment.
- This module should provide you with the background to implement parsers, which are **USEFUL** in many different projects.
- These topics are typically covered in more depth in an undergrad course.

High-level parser

Parser

High-level parser

A parser needs to know about the language:

- What forms can these take?

Parser

High-level parser

A parser needs to know about the language:

- 1800 page C++ specification,
  - English language
- Formal specification, mathematical
  - Mostly used in academics
  - X86, ARM, Functional languages

Parser

High-level parser

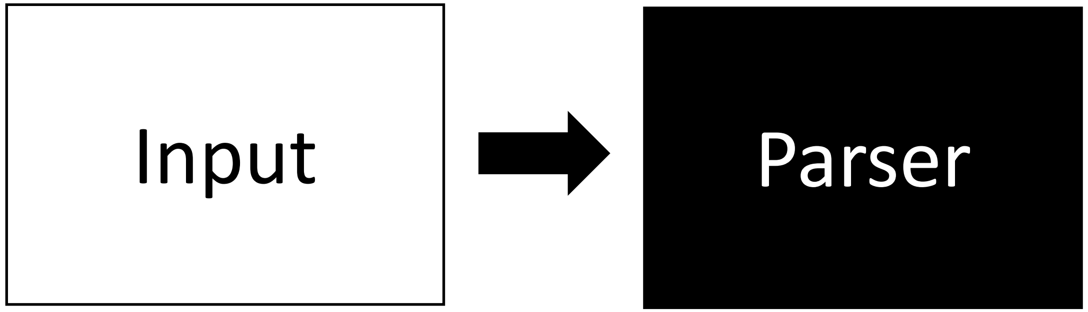
A parser needs to know about the language:

- 1800 page C++ specification,
  - English language
- Formal specification, mathematical
  - Mostly used in academics
  - X86, ARM, Functional languages

Parser

Parser needs only a small part of the specification!
*The **Grammar!***

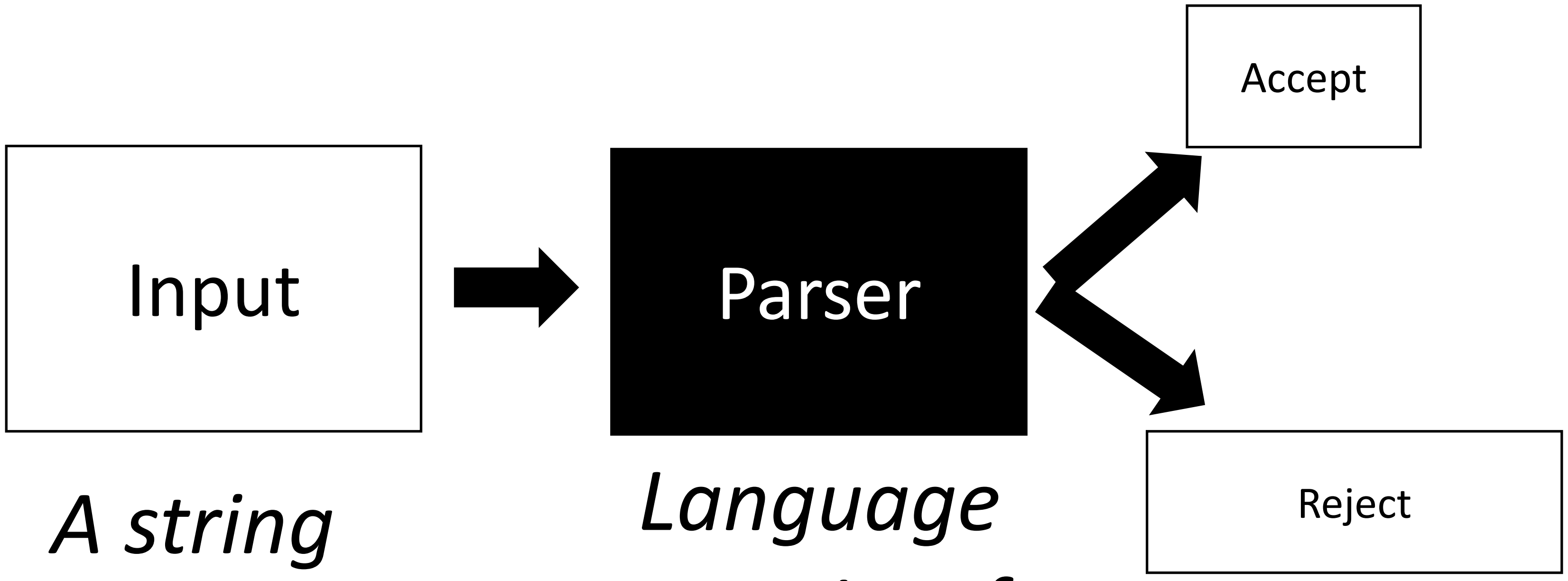
High-level parser



A string

Language Recognizer for L’s Grammar

High-level parser



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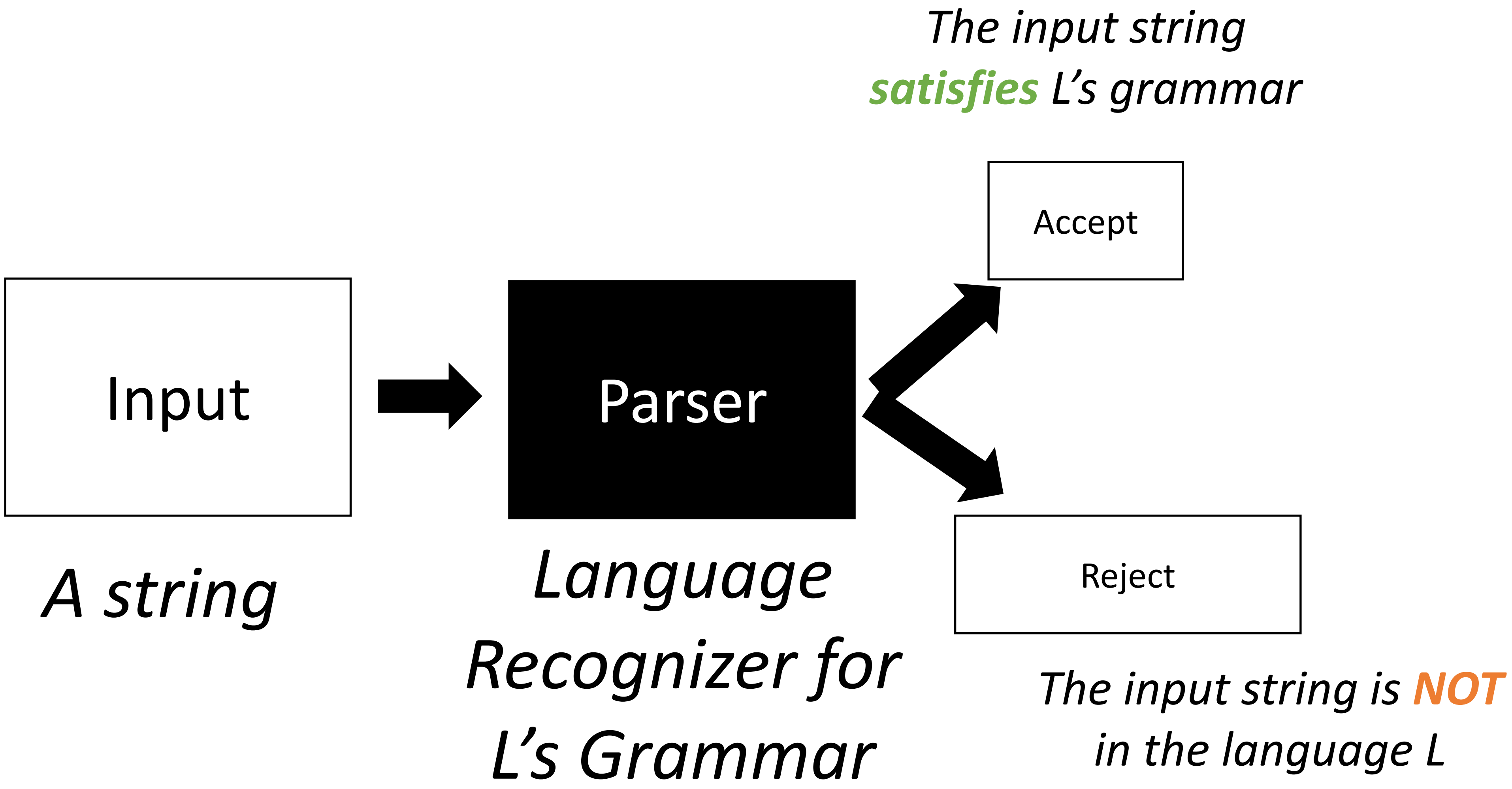
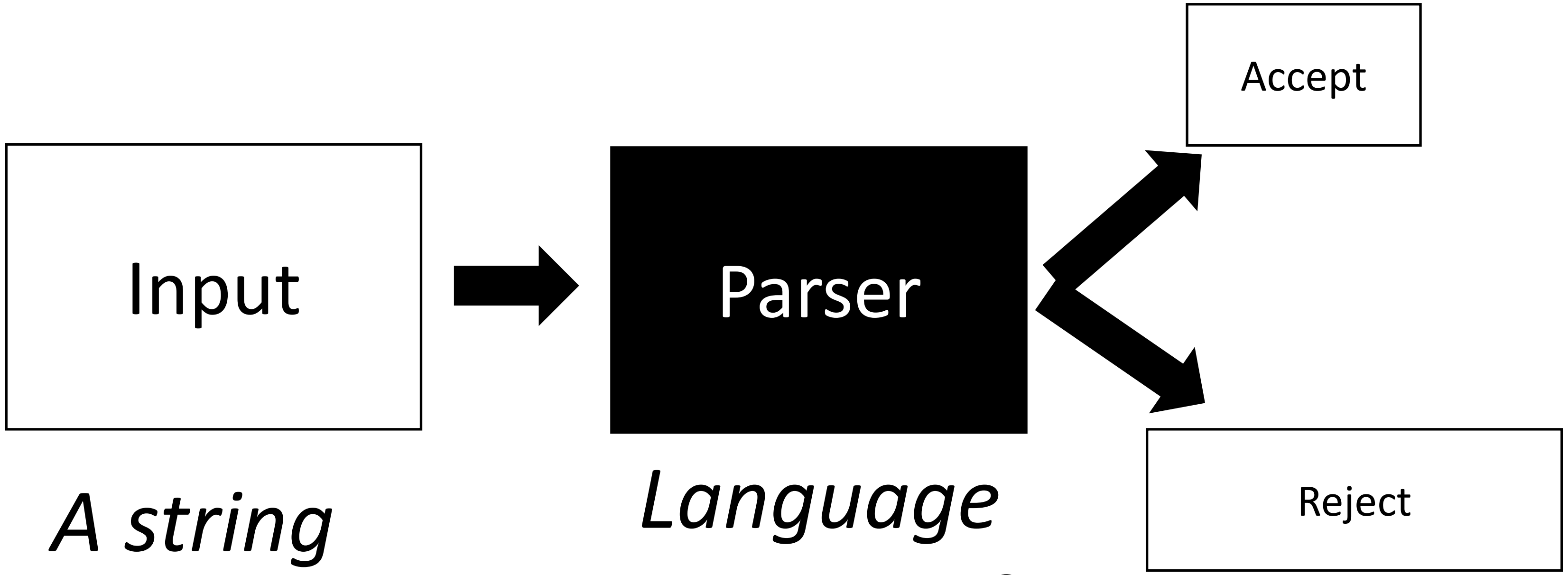


High-level parser

what other types of errors might happen up here?

The input string ***satisfies*** *L's grammar*



A string

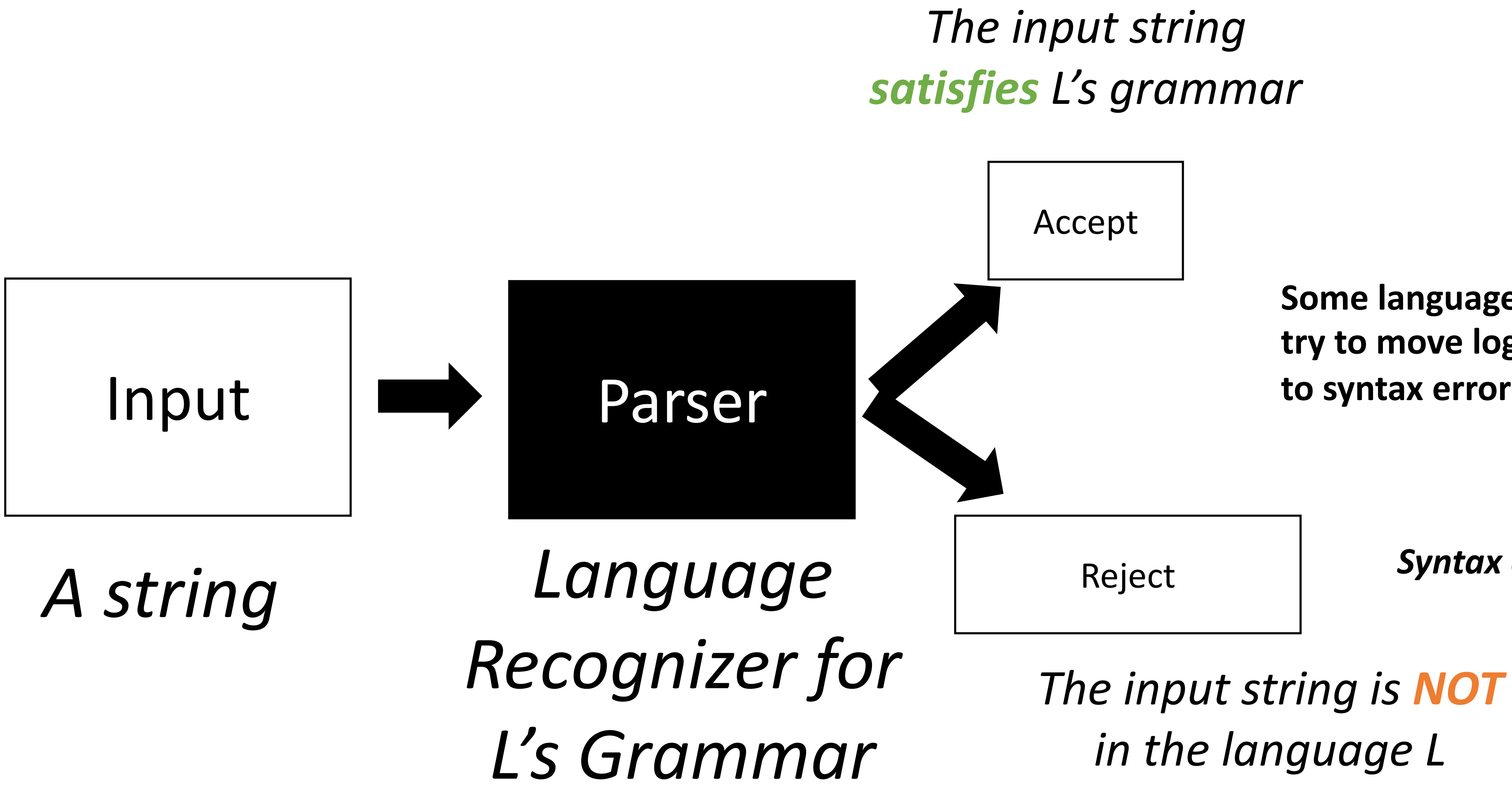
Language Recognizer for L's Grammar

Syntax error

The input string is ***NOT*** *in the language L*

High-level parser

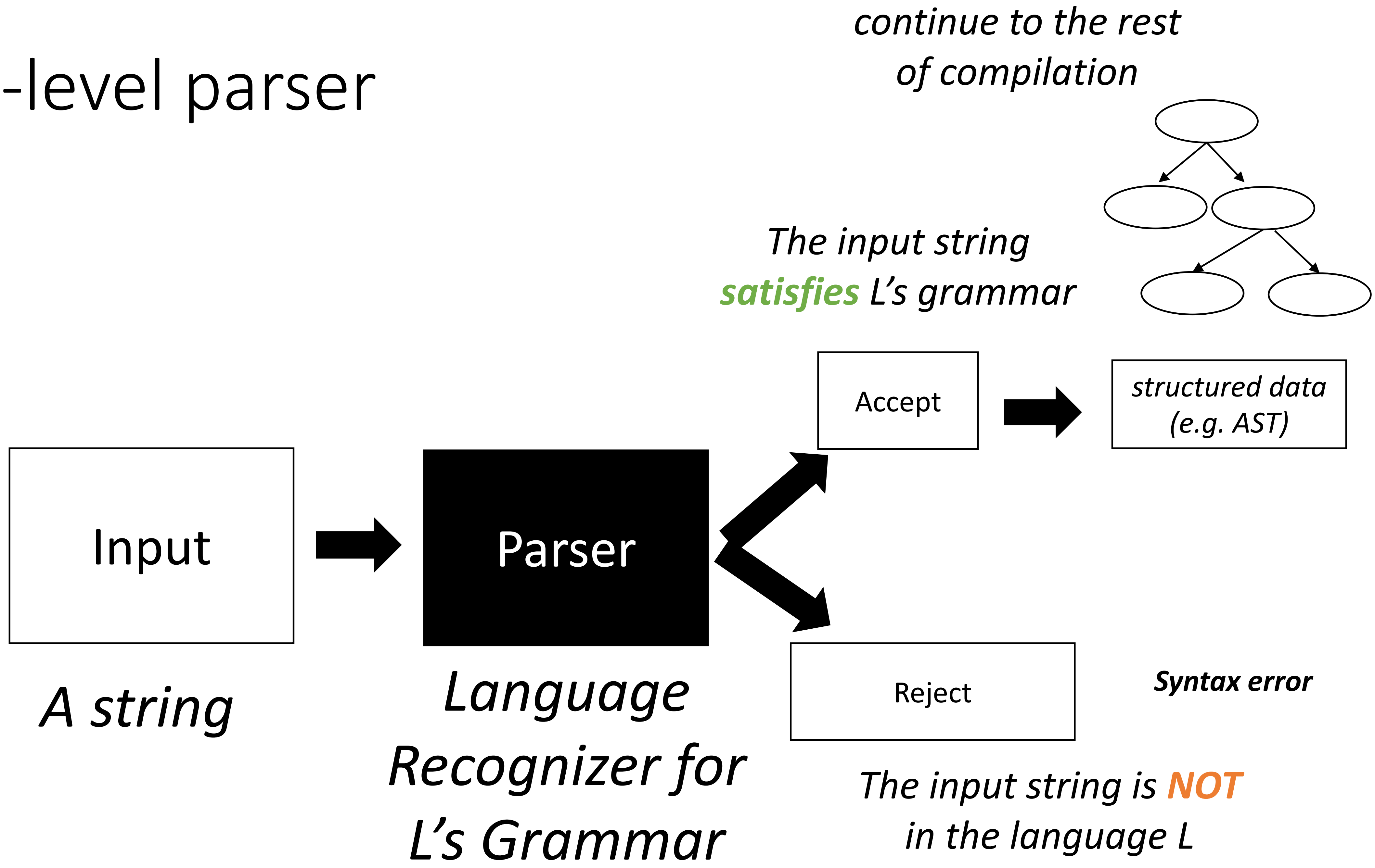
what other types of errors might happen up here?



Some languages try to move logic errors to syntax errors!

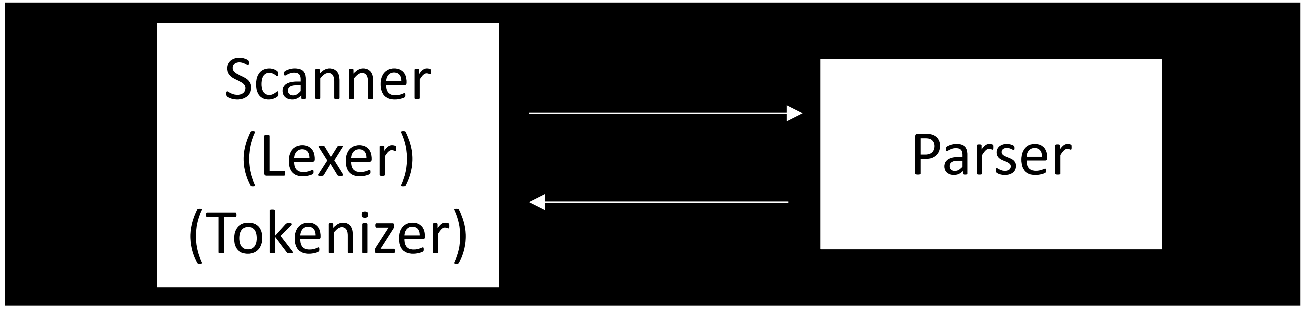
Syntax error

High-level parser



Parser architecture

Parser



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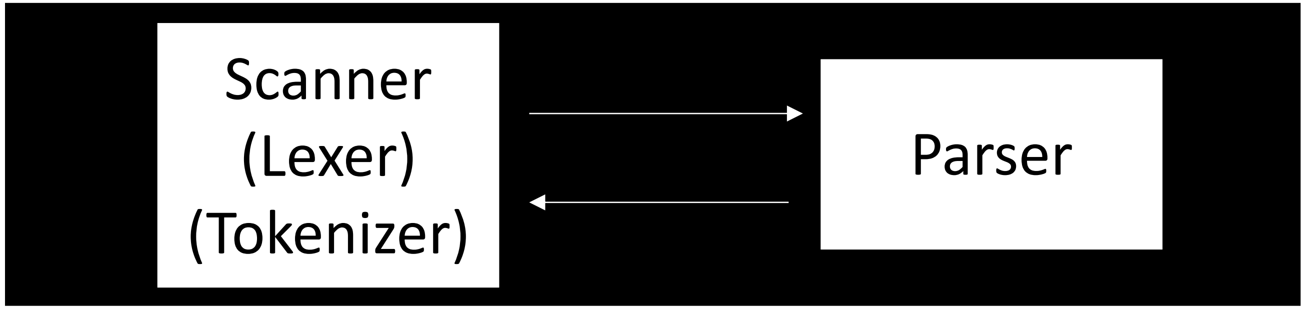
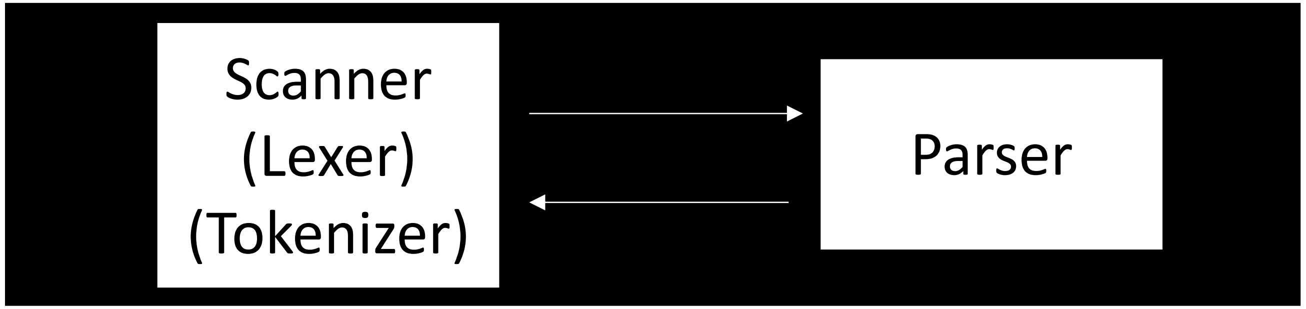


First level of abstraction. Transforms a string of characters into a string of tokens

Second level: transforms a string of tokens in a tree of tokens.

Parser architecture

Parser



First level of abstraction. Transforms a string of characters into a string of tokens

Second level: transforms a string of tokens in a tree of tokens.

***Language**: Regular Expressions (REs)*

***Language**: Context-Free Grammars (CFGs)*

Scanner

- List of tokens:
- e.g. {NOUN, ARTICLE, ADJECTIVE, VERB}

Scanner

My Old Computer Crashed

Scanner

My Old Computer Crashed

↓ Scanner

```
[(ARTICLE, "my") (ADJECTIVE, "old") (NOUN, "Computer") (VERB, "Crashed")]
```

Scanner

My Old Computer Crashed

[(ARTICLE, “my”) (ADJECTIVE, “old”) (NOUN, “Computer”) (VERB, “Crashed”)]

Lexeme: *(TOKEN, value)*

Scanner

- Lets write tokens for arithmetic expression:

$$(5 + 4) * 3$$

ideas?

Scanner

- Lets write tokens for arithmetic expression:

LPAREN = ‘(‘
NUMBER = {‘5’,’4’,’3’, ..}
PLUS = ‘+’
RPAREN = ‘)’
TIMES = ‘*’

(5 + 4) * 3

Scanner

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TIMES = ‘*’

(5 + 4) * 3

LPAREN = ‘(‘
NUMBER = {‘5’,’4’,’3’, ..}
OP = {‘+’, “*”}
RPAREN = ‘)’

You can generalize tokens

Scanner

- Lets write tokens for arithmetic expression:

LPAREN = ‘(‘
NUMBER = {‘5’,’4’,’3’, ..}
PLUS = ‘+’
RPAREN = ‘)’
TIMES = ‘*’

(5 + 4) * 3

LPAREN = ‘(‘
ONE = ‘1’
TWO = ‘2’
THREE = ‘3’
...
PLUS = ‘+’
RPAREN = ‘)’
TIMES = ‘*’

You can make tokens more specific

Scanner

- Lets write tokens for arithmetic expression:

LPAREN = ‘(‘
NUMBER = {‘5’,’4’,’3’, ..}
PLUS = ‘+’
RPAREN = ‘)’
TIMES = ‘*’

(5 + 4) * 3

PAREN = {‘(‘, ‘)’}
NUMBER = {‘5’,’4’,’3’, ..}
PLUS = ‘+’
TIMES = ‘*’

What about this one?

Defining tokens

Defining tokens

- Literal – single character:
  - PLUS = ‘+’, TIMES = ‘*’

Defining tokens

- Literal – single character:
  - PLUS = ‘+’, TIMES = ‘*’

- Keyword – single string:
  - IF = “if”, INT = “int”

Defining tokens

- Literal – single character:
  - PLUS = ‘+’, TIMES = ‘*’
- Keyword – single string:
  - IF = “if”, INT = “int”
- Sets of words:
  - NOUN = {“Cat”, “Dog”, “Car”}

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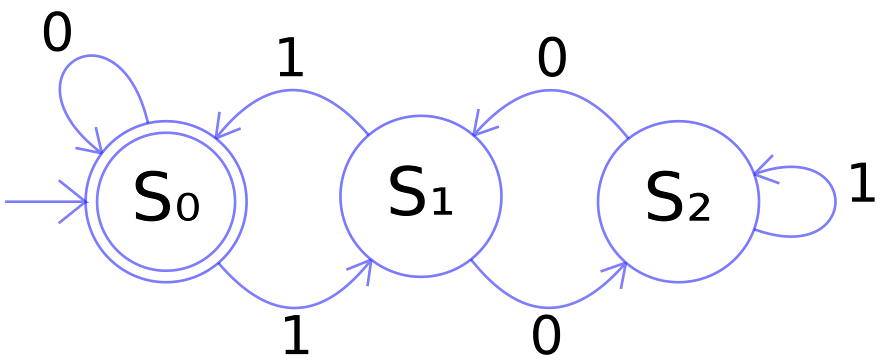
- Numbers
  - NUM = {“0”, “1” …}

Defining tokens

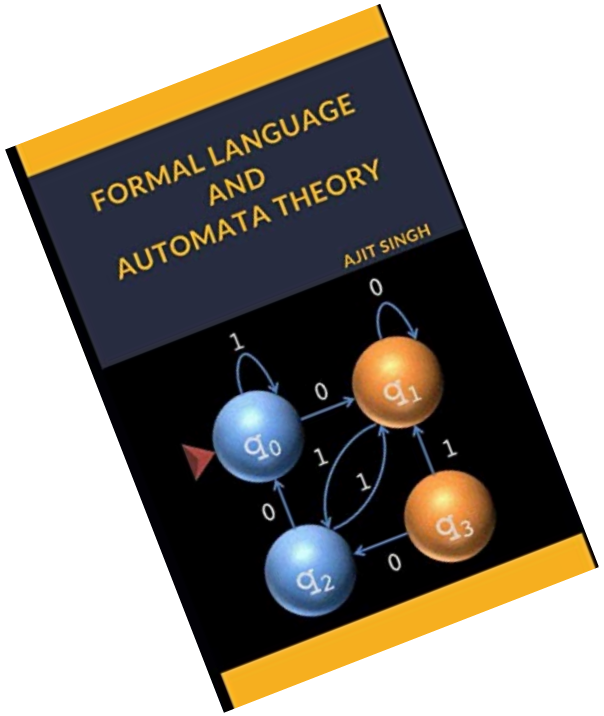
- ~~Literal – single character:~~
  - ~~PLUS = ‘+’, TIMES = ‘*’~~
  - ~~–~~
- ~~Keyword – single string:~~
  - ~~IF = “if”, INT = “int”~~
  - ~~–~~
- ~~Sets of words:~~
  - ~~NOUN = {“Cat”, “Dog”, “Car”}~~
  - ~~–~~
- ~~Numbers~~
  - ~~NUM = {“0”, “1” …}~~

- Regular expressions!

Regular Expressions



- Lots of literature!
  - Simplest grammar in the Chomsky language hierarchy
  - abstract machine definition (finite automata)
  - Many implementations (e.g. Python standard library)



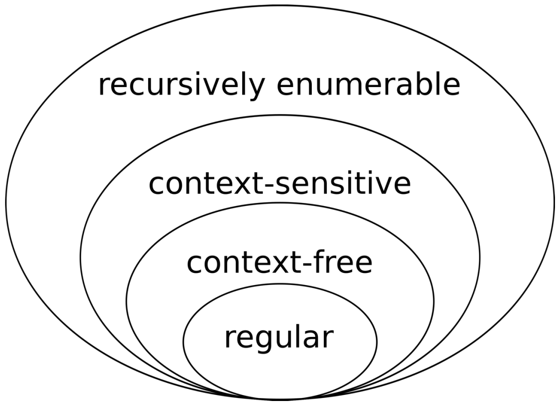


image source: wikipedia

Regular Expressions

We will define RE’s recursively:

Input:

- Regular Expression *R*
- String *S*

Output:

- Does the Regular Expression *R* match the string *S*

Regular Expressions

We will define RE’s recursively:

The base case: a character literal

- The RE for a character ‘x’ is given by ‘x’. It matches only the character ‘x’

Regular Expressions

We will define RE's recursively:

Regular expressions are closed under concatenation:

- The concatenation of two REs x and y is given by xy and matches the strings of RE x concatenated with the strings of RE y

Regular Expressions

We will define RE’s recursively:

Regular expressions are closed under union:

- The union of two REs x and y is given by x|y and matches the strings of RE x **OR** the strings of RE y

Regular Expressions

We will define RE’s recursively:

Regular expressions are closed under Kleene star:

- The Kleene star of an RE x is given by x* and matches the strings of RE x **REPEATED** 0 or more times

Regular Expressions

Examples

Regular Expressions

- Use ()'s to force precedence!
- Just like in math:
  - 3 + 4 * 5
- what is the precedence of concatenation, union, and star?
  - "x | yw"
    - Is it "(x | y)w" or "x | (yw)"
  - "xy*"
    - is it (xy)* or x(y*)

Regular Expressions

- Use ()’s to force precedence!

- Just like in math:
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  - “x | yw”
    - Is it “(x | y)w” or “x | (yw)”
  - “xy*”
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How can we determine precedence?

Regular Expressions

- Use ()’s to force precedence!

- Just like in math:
  - 3 + 4 * 5

- what is the precedence of concatenation, union, and star?
  - Star > Concat > Union
  - use () to avoid mistakes!

Regular Expressions

Most RE implementations provide syntactic sugar:

- Ranges:
  - [0-9]: any number between 0 and 9
  - [a-z]: any lower case character
  - [A-Z]: any upper case character
- Optional(?)
  - Matches 0 or 1 instances:
  - ab?c matches ”abc” or ”ac”
  - can be implemented as: (abc | ac)

Defining tokens using REs

- Literal – single character:
  - PLUS = ‘\+’, TIMES = ‘*’
- Keyword – single string:
  - IF = “if”, INT = “int”
- Sets of words:
  - NOUN = “(Cat)|(Dog)|(Car)”
- Numbers
  - SINGLE_NUM = [0-9]
  - how to do INT = [0-9]*
  - how to do FLOAT?

Defining tokens using REs

- Literal – single character:
  - PLUS = ‘+’, TIMES = ‘*’
- Keyword – single string:
  - IF = “if”, INT = “int”
- Sets of words:
  - NOUN = “(Cat)|(Dog)|(Car)”
- Numbers
  - SINGLE_NUM = [0-9]
  - INT = -?([1-9][0-9]*) | 0
  - FLOAT =?

Scanner

- Takes in a list of tokens and a string and tokenizes the input

Scanner

Tokens

- ARTICLE = ”The|A|My|Your”
- NOUN = “Dog|Car|Computer”
- VERB = ”Ran|Crashed|Accelerated”
- ADJECTIVE = “Purple|Spotted|Old”

Input

“My Old Computer Crashed”

Scanner

```
[(ARTICLE, "my") (ADJECTIVE, "old") (NOUN, "Computer") (VERB, "Crashed")]
```

Tokens are defined with Regular expressions, which are used to split up the input stream into lexemes

Scanner

LPAREN = ‘(‘
NUMBER = ‘[0-9]+’
PLUS = ‘+’
RPAREN = ‘)’
TIMES = ‘*’

“(5 + 4) * 3”

Scanner

`re.match`

- A streaming API supported by most RE libraries
  - Only has to match part the beginning part of the string, not the entire string

re.match

- A streaming API supported by most RE libraries
  - Only has to match part the beginning part of the string, not the entire string
- CLASS_TOKEN = {“cse |211|cse211”}
- What would get matched here?: “cse211”
- (CLASS_TOKEN, ?)

Scanners should provide the longest possible match

- Important for operators, e.g. in C
- ++, +=,

how would we parse "x++;"

```
(ID, "x") (ADD, "+") (ADD, "+") (SEMI, ";")

(ID, "x") (INCREMENT, "++") (SEMI, ";")
```

We can experiment in Godbolt using the clang args:: -fsyntax-only -Xclang -dump-tokens

Subtle differences here

- RE definitions are not guaranteed to give you the longest possible match
  - OP = “+|++”, ID = ”[a-z]”
  - What will this return for “x++”

- Scanners will tokenize the string according to the token with the longest match
  - PLUS = “+”, PP = “++”, ID = ”[a-z]”
  - What will this return for “x++”

- What does this mean for you?
  - If you are implementing a scanner?
  - If you are writing tokens?

Scanner Summary

- Tokens are defined using regular expressions
- A scanner uses tokens to split a string into lexemes
- Regular expressions are good for splitting up a program into numbers, variables, operators, and structure (e.g. parenthesis and braces)
- You will get more practice using them in the homework
- Chapter 2 in EAC goes into detail on regular expression parsing
  - Finite automata etc.

Define a full language using tokens?

limited to non-negative integers
and just using + and *

- What about a mathematical sentence (expression)?

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- First let’s define tokens:

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- What about a mathematical sentence (expression)?

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    - NUM = [0-9]+
    - PLUS = ‘\+’
    - TIMES = ’*’

- What should our language look like?

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- What about a mathematical sentence (expression)?

- First let’s define tokens:
  - NUM = [0-9]+
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- What should our language look like?
  - NUM

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- What about a mathematical sentence (expression)?

- First let’s define tokens:
  - NUM = [0-9]+
  - PLUS = ‘\+’
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- What should our language look like?
  - NUM
  - NUM PLUS NUM

Define a full language using tokens?

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- What about a mathematical sentence (expression)?

- First let’s define tokens:
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  - TIMES = ’*’

- What should our language look like?
  - NUM
  - NUM PLUS NUM
  - …

Define a full language using tokens?

limited to non-negative integers
and just using + and *

- What about a mathematical sentence (expression)?

- First let's define tokens:
  - NUM = [0-9]+
  - PLUS = '\+'
  - TIMES = '*'

Why not just use regular expressions?

What would the expression look like?

- What should our language look like?
  - NUM
  - NUM PLUS NUM
  - …

Define a full language using tokens?

- Where are we going to run into issues?

What about ()’s

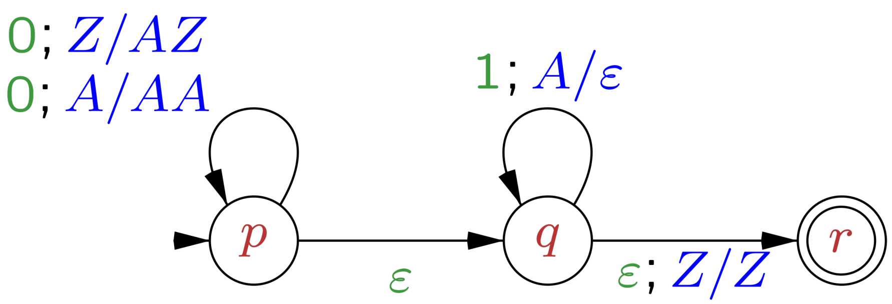
- there is a formal proof available that regex CANNOT match ()’s: pumping lemma

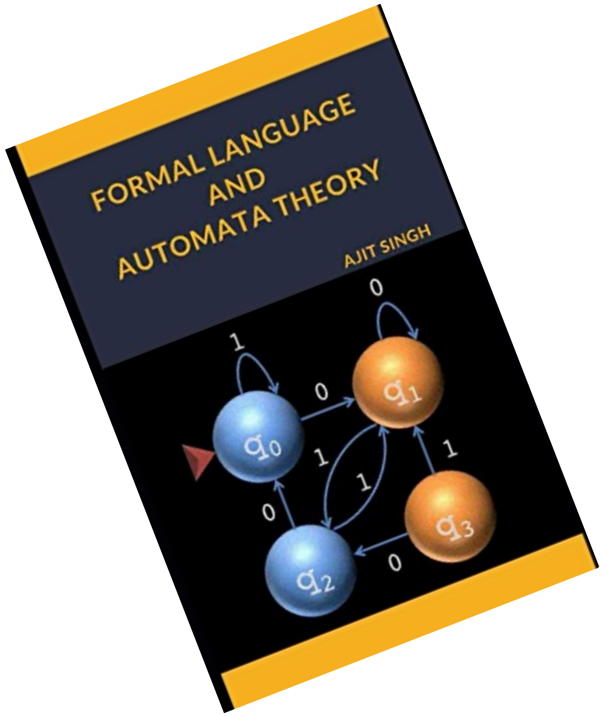
- Informal argument:
  - Try matching $(^n)^n$using Kleene star
  - Impossible!

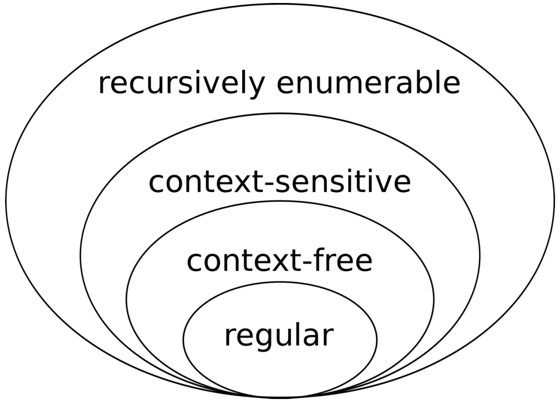
- We are going to need a more powerful language description framework!

Context Free Grammars

- Backus–Naur form (BNF)
  - A syntax for representing context free grammars
  - Naturally creates tree-like structures
- More powerful than regular expressions







BNF Production Rules

- <production name> : <token list>
  - Example:
    sentence: ARTICLE NOUN VERB

- <production name> : <token list> | <token list>
  - Example:

sentence: ARTICLE ADJECTIVE NOUN VERB
| ARTICLE NOUN VERB

Convention: Tokens in all caps, production rules in lower case

BNF Production Rules

- Production rules can reference other production rules

sentence: non_adjective_sentence
| adjective_sentence

non_adjective_sentence: ARTICLE NOUN VERB

adjective_sentence: ARTICLE ADJECTIVE NOUN VERB

BNF Production Rules

sentence: ARTICLE ADJECTIVE NOUN VERB*

BNF Production Rules

sentence: ARTICLE ADJECTIVE NOUN VERB*

We cannot do the star in production rules

BNF Production Rules

- Production rules can be recursive
  - Imagine a list of adjectives:
    “The small brown energetic dog barked”

sentence: ARTICLE adjective_list NOUN VERB

adjective_list: ADJECTIVE adjective_list
| <empty>

Let’s go back to mathematical sentences (expressions)

- First lets define tokens:
  - NUM = [0-9]+
  - PLUS = ‘\+’
  - TIMES = ’*’

How can we make BNF production rules for this?

Let’s go back to mathematical sentences (expressions)

- First lets define tokens:
  - NUM = [0-9]+
  - PLUS = ‘\+’
  - TIMES = ’*’

```
expression : NUM
           | expression PLUS expression
           | expression TIMES expression
```

Let’s go back to mathematical sentences (expressions)

- First lets define tokens:
  - NUM = [0-9]+
  - PLUS = ‘\+’
  - TIMES = ’*’

Let’s add () to the language!

expression : NUM

| expression PLUS expression

| expression TIMES expression

Let’s go back to mathematical sentences (expressions)

- First lets define tokens:
  - NUM = [0-9]+
  - PLUS = ‘\+’
  - TIMES = ’*’
  - LPAREN = ‘\(‘
  - RPAREN = ‘\)’

What other syntax like () are used in programming languages?

```
expression : NUM
           | expression PLUS expression
           | expression TIMES expression
           | LPAREN expression RPAREN
```

Let’s go back to mathematical sentences (expressions)

- First lets define tokens:
  - NUM = [0-9]+
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What other syntax like () are used in programming languages?

expression : NUM
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| LPAREN expression RPAREN

https://stackoverflow.com/questions/1732348/regex-match-open-tags-except-xhtml-self-contained-tags

(previously) 2nd most upvoted post on stackoverflow

How to determine if a string matches a CFG?

Parse trees

- A string is accepted by a BNF form if and only if there exists a parse tree.

```
input: 5
```

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

Parse trees

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```

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| expr PLUS expr

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expr

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`input: 5`

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

expr

root of the tree is the entry production

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     | expr PLUS expr
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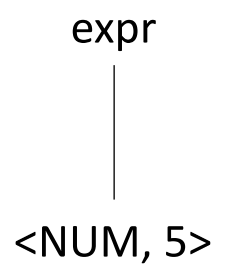

leafs are lexemes

Parse trees

- A string is accepted by a BNF form if and only if there exists a parse tree.

`input: 5*6`

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

Parse trees

- A string is accepted by a BNF form if and only if there exists a parse tree.

```
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| expr TIMES expr

| LPAREN expr RPAREN

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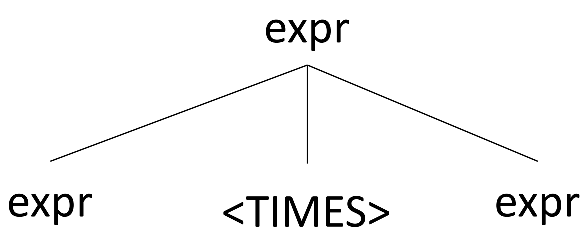

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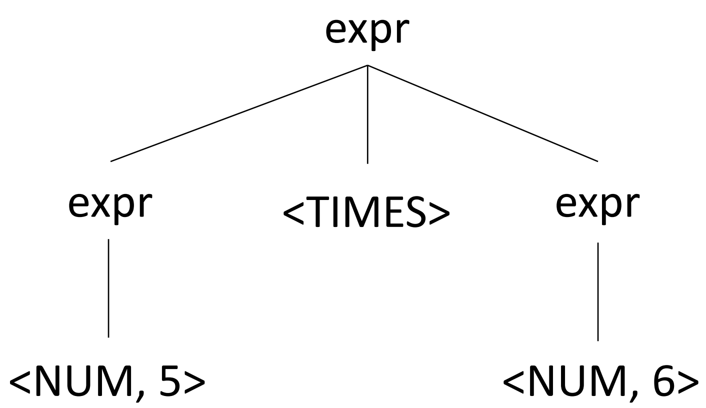

Parse trees

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

expr : NUM

| expr PLUS expr

| expr TIMES expr

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expr

What happens in an error?

Parse trees

- A string is accepted by a BNF form if and only if there exists a parse tree.

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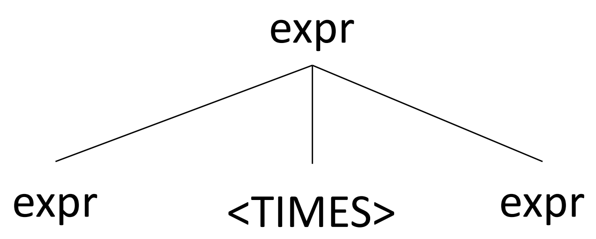

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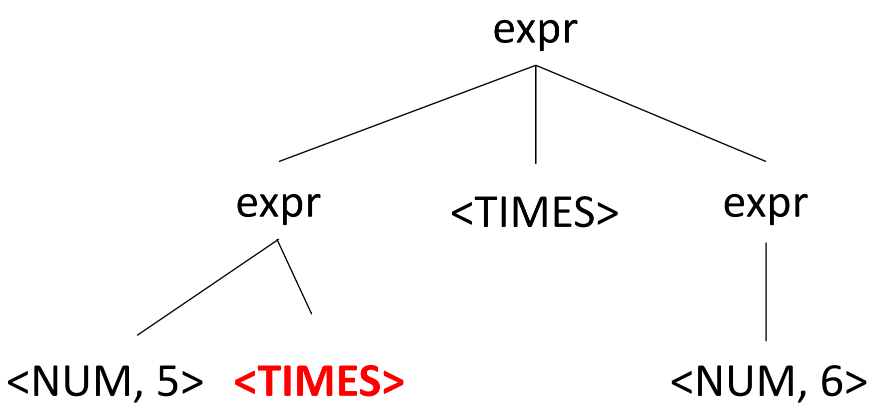

Not possible!

Parse trees

- A string is accepted by a BNF form if and only if there exists a parse tree.

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

expr : NUM

| expr PLUS expr

| expr TIMES expr

| LPAREN expr RPAREN

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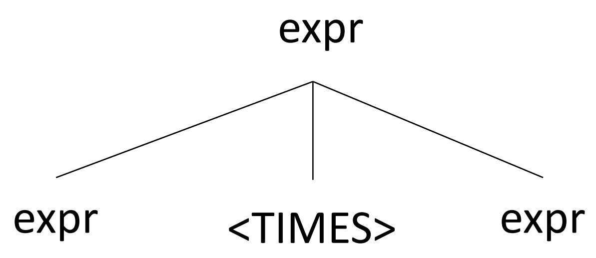

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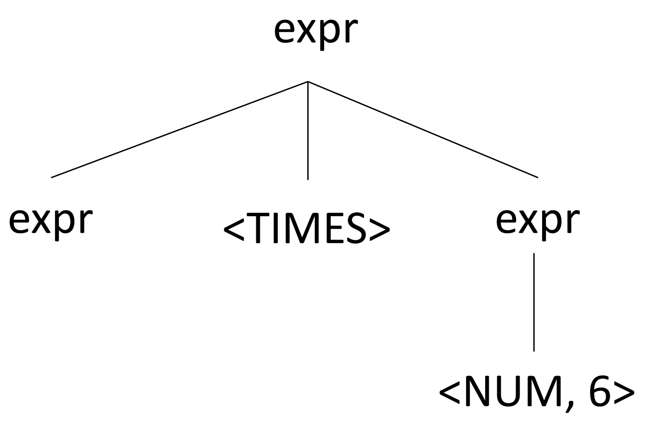

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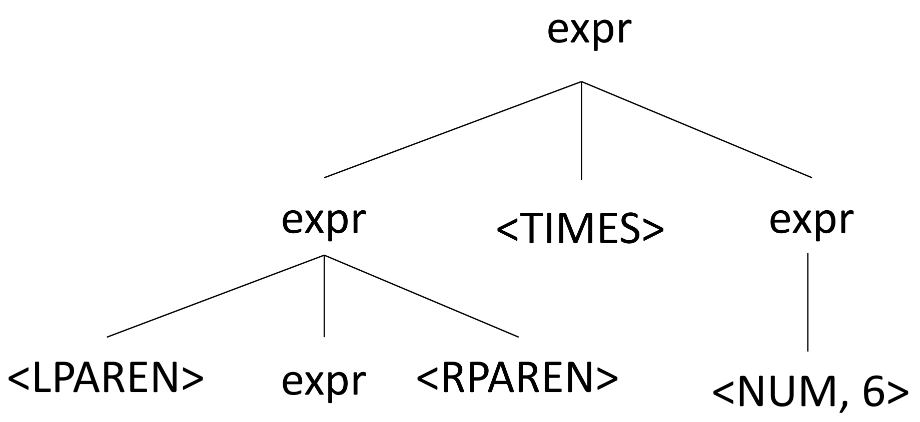

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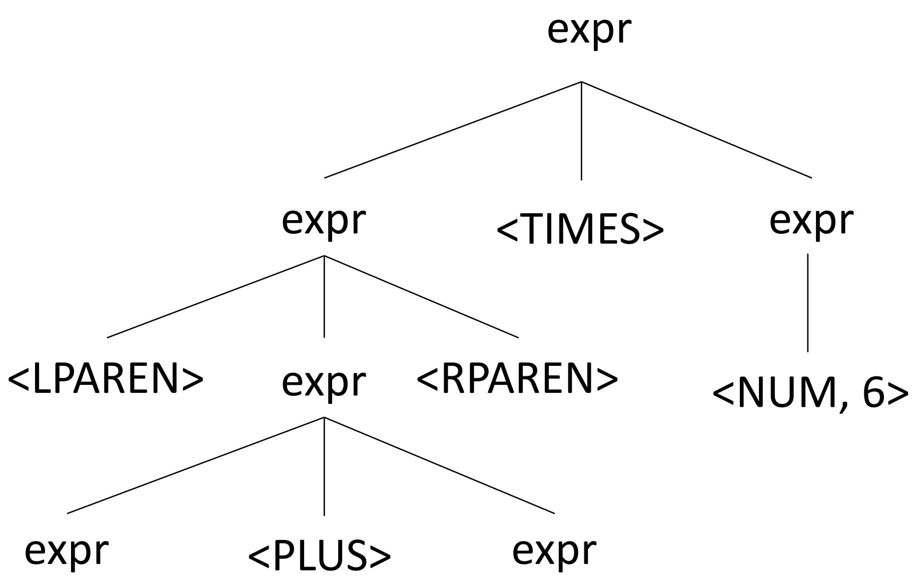

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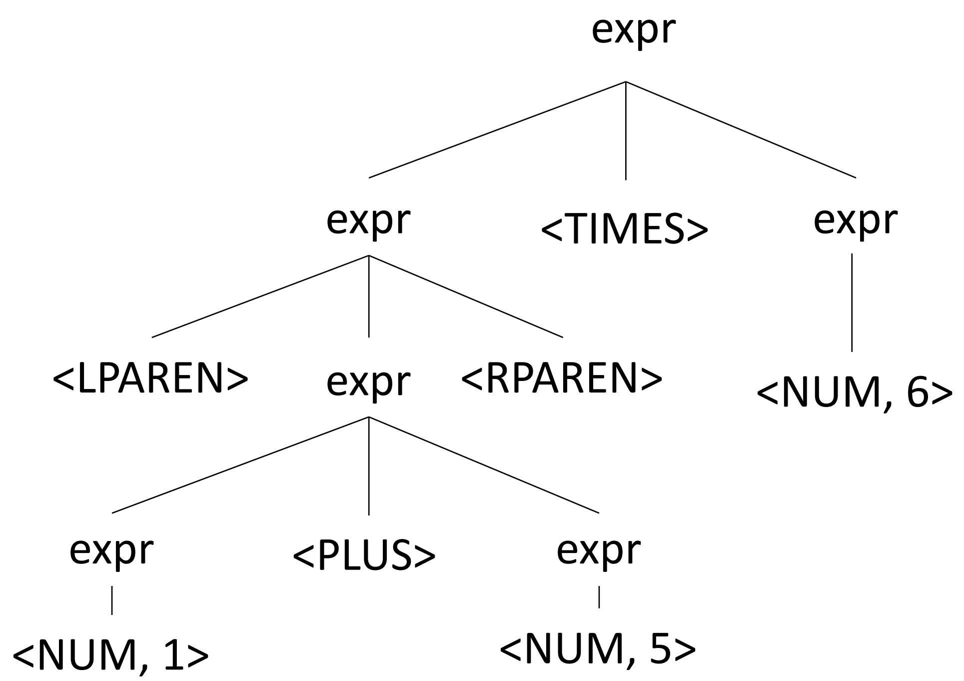


Parse trees

- Reverse question: given a parse tree: how do you create a string?

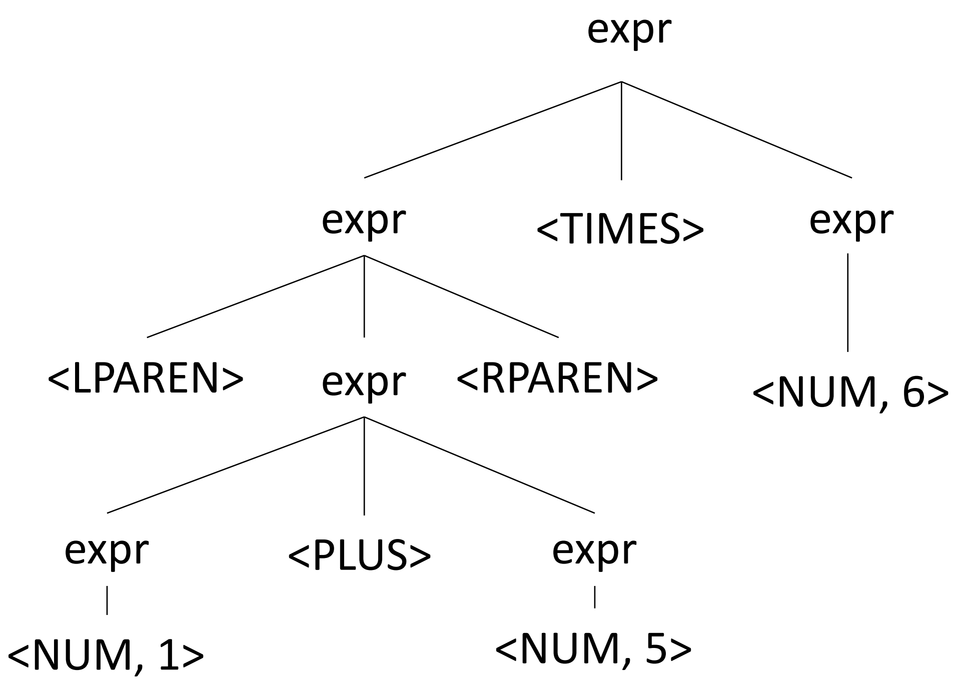
`input: ?`

expr : NUM

| expr PLUS expr

| expr TIMES expr

| LPAREN expr RPAREN



Ambiguous grammars

“I saw a person on a hill with a telescope.”

What does it mean??

https://www.quora.com/What-are-some-examples-of-ambiguous-sentences

Parse trees

- Try making a parse tree from : `1 + 5 * 6`

```
expr : NUM
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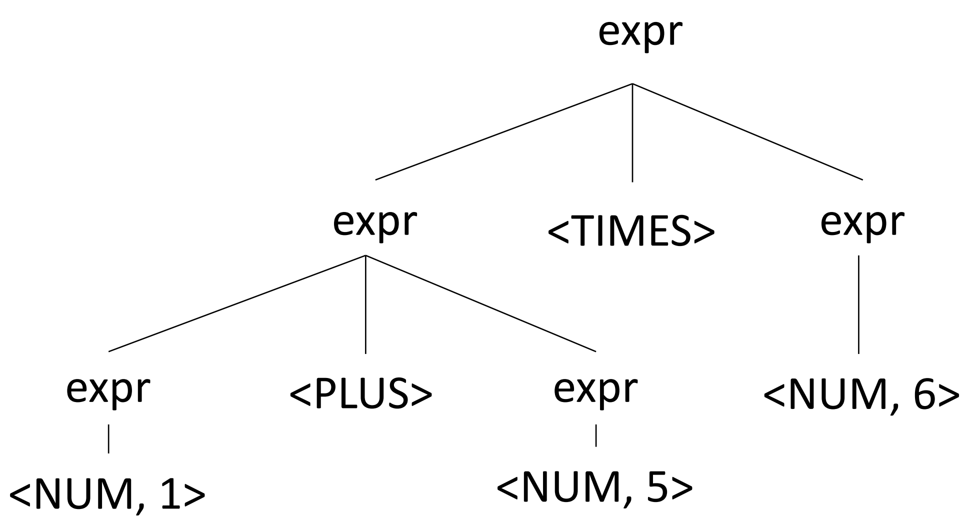

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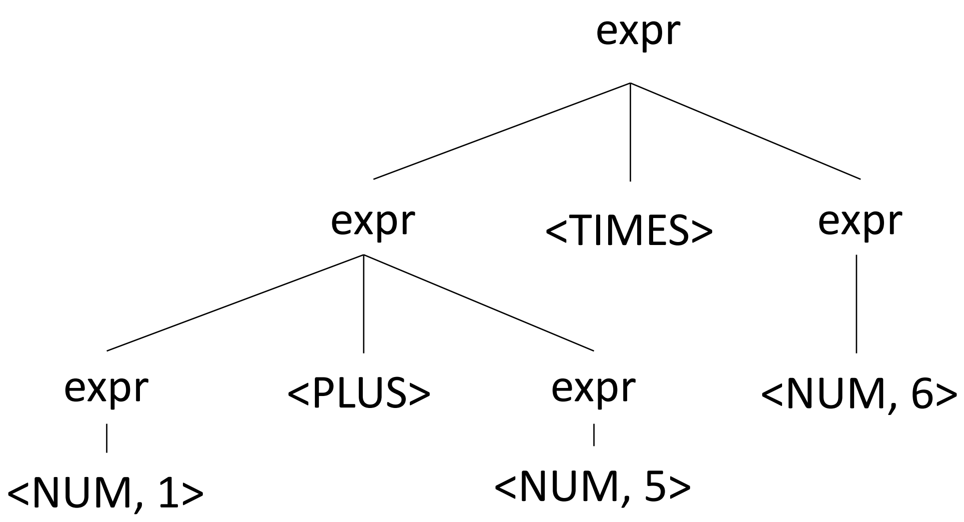

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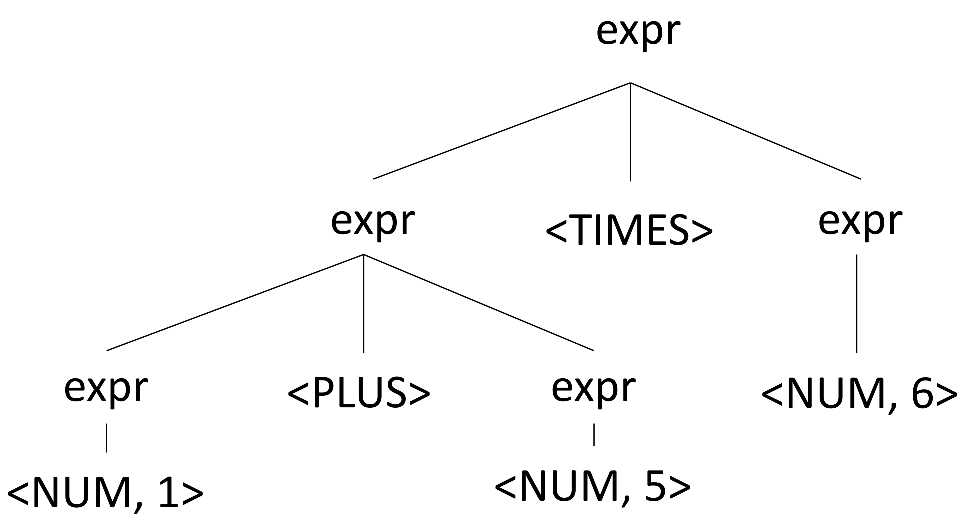
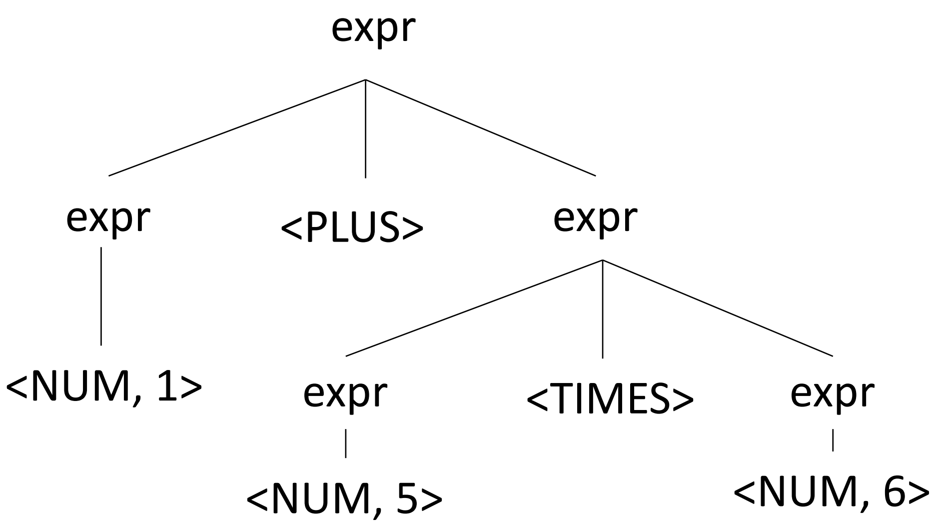
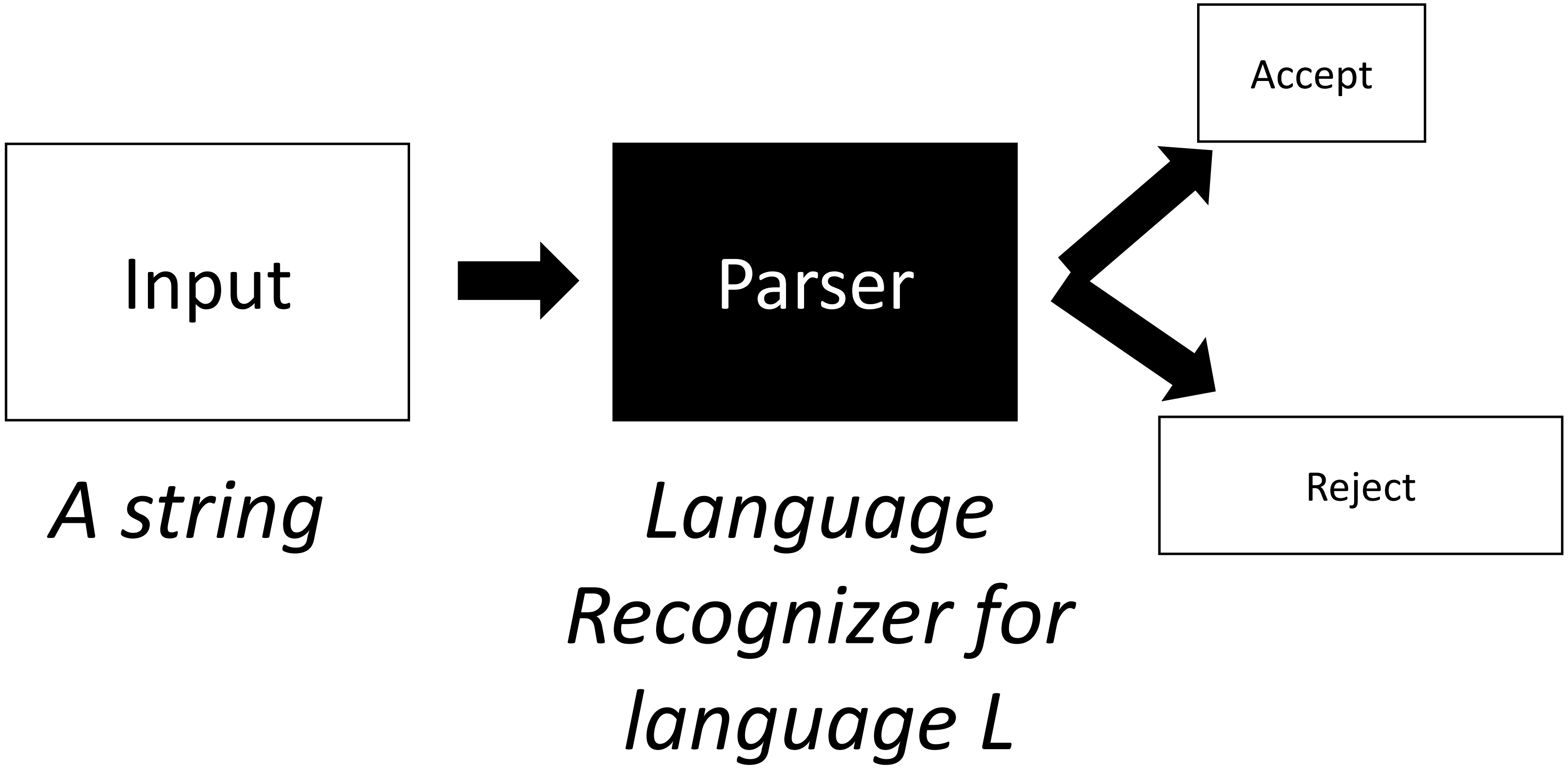




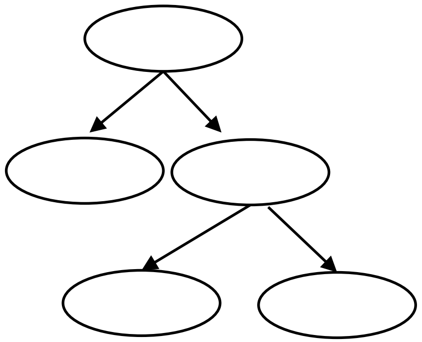
Ambiguous grammars

- What's the issue?



Ambiguous grammars

continue to the rest of compilation



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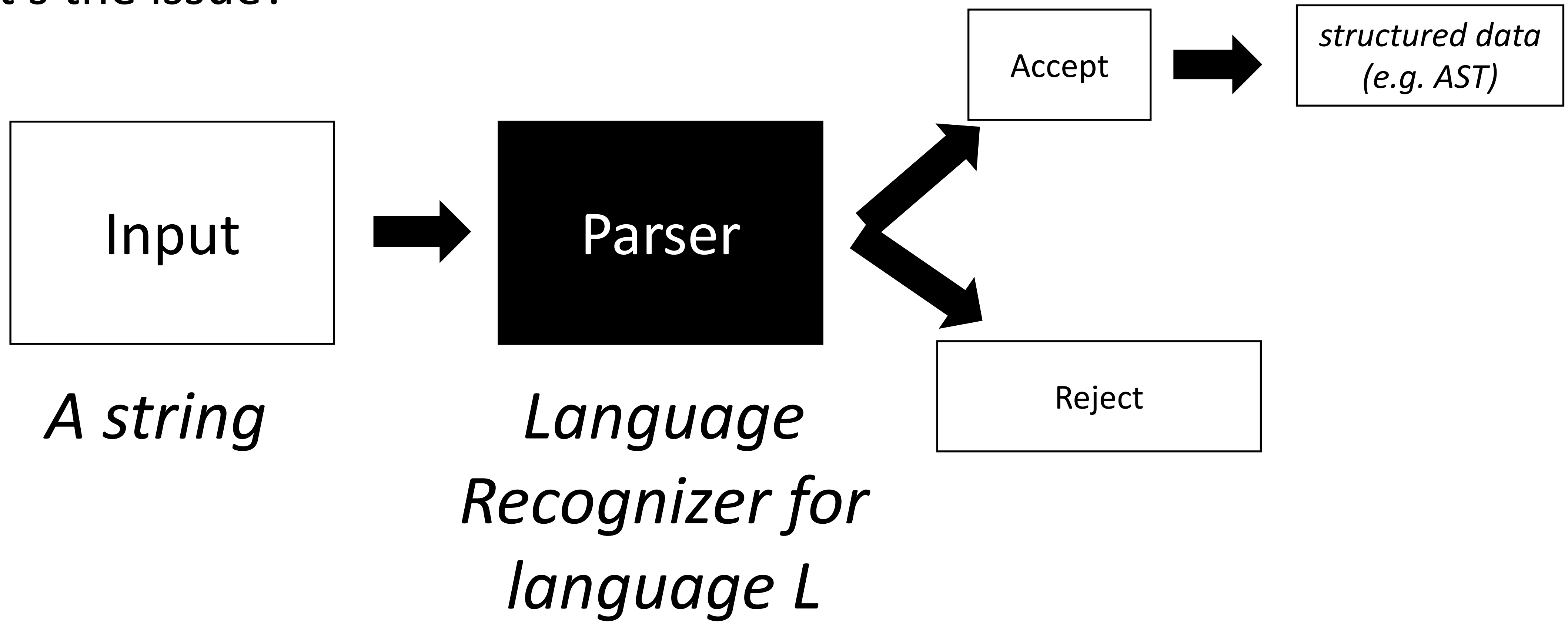

Meaning into structure

- Structural meaning defined to be a post-order traversal

Meaning into structure

- Structural meaning defined to be a post-order traversal
  - Children return values to their parent
  - Nodes are only evaluated once all their children have been evaluated
  - Evaluated from left to right
  - Also called “Natural Order”

Meaning into structure

- Structural meaning defined to be a post-order traversal
  - Children return values to their parent
  - Nodes are only evaluated once all their children have been evaluated
  - Evaluated from left to right

- Can also encode the order of operation

Ambiguous grammars

- `input: 1 + 5 * 6`

expr : NUM

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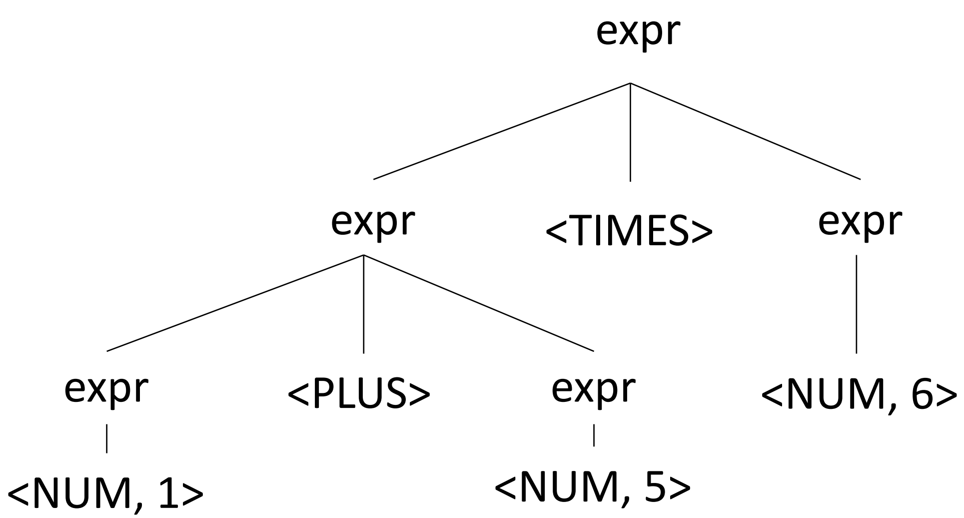
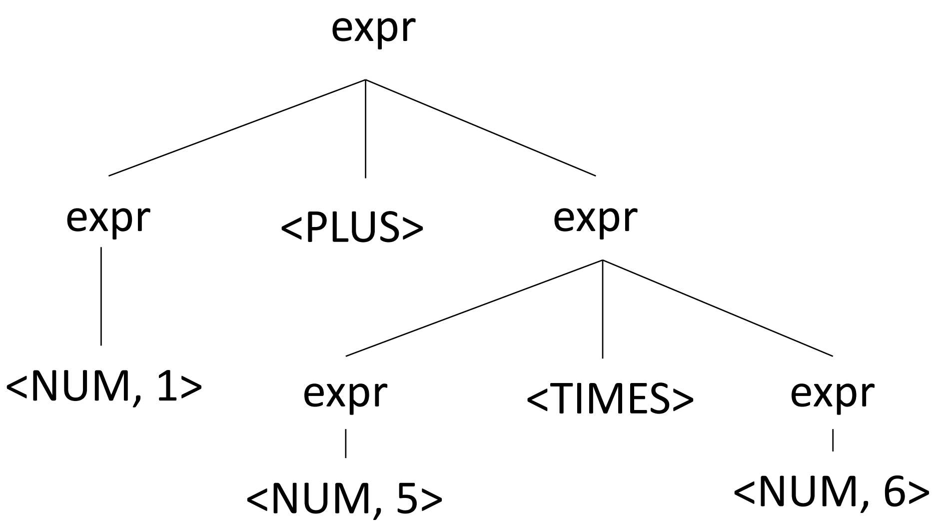
| expr TIMES expr

| LPAREN expr RPAREN





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 rule for each level of precedence
  - lowest precedence at the top
  - highest precedence at the bottom

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

Avoiding Ambiguity

Precedence increases going down

- How to avoid ambiguity related to precedence?
- **Second way**: new production rules
  - One rule for each level of precedence
  - lowest precedence at the top
  - highest precedence at the bottom
- Lets try with expressions and the following:
  - + * ()

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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Now lets create a parse tree

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expr

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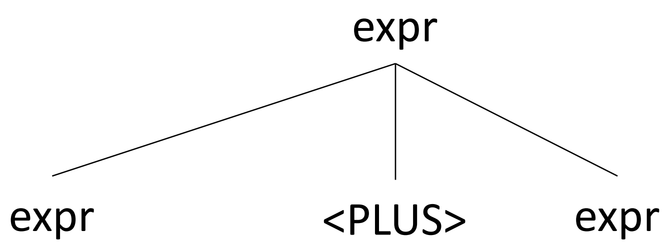

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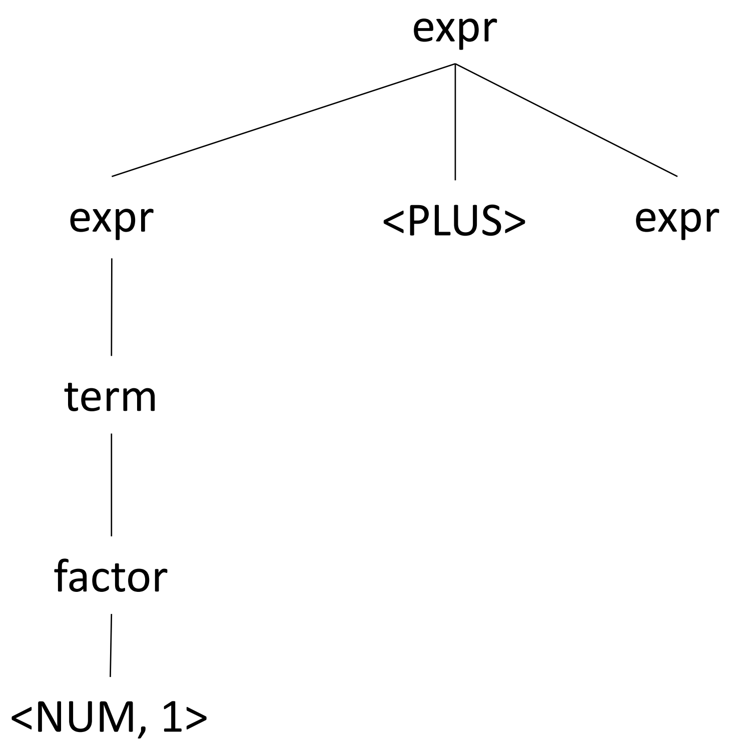

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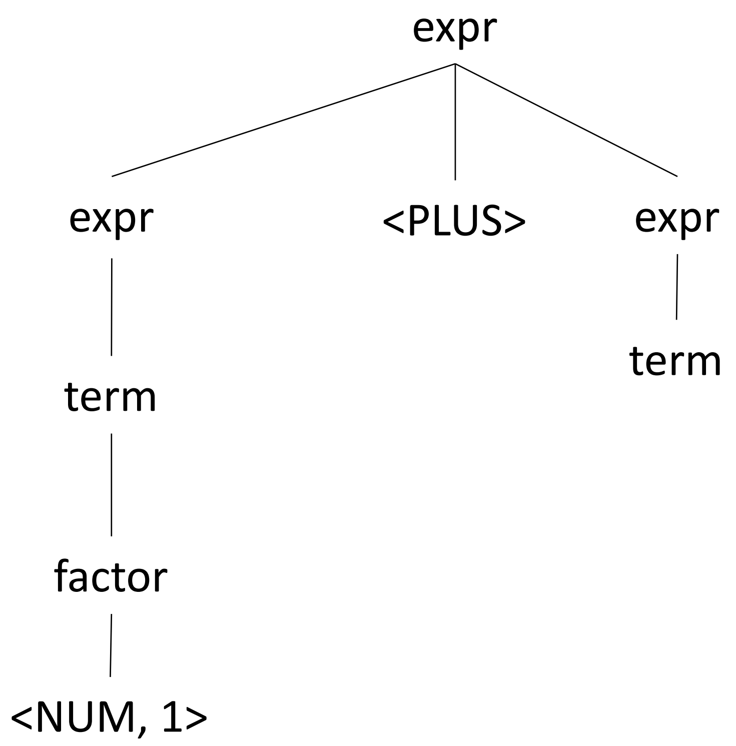

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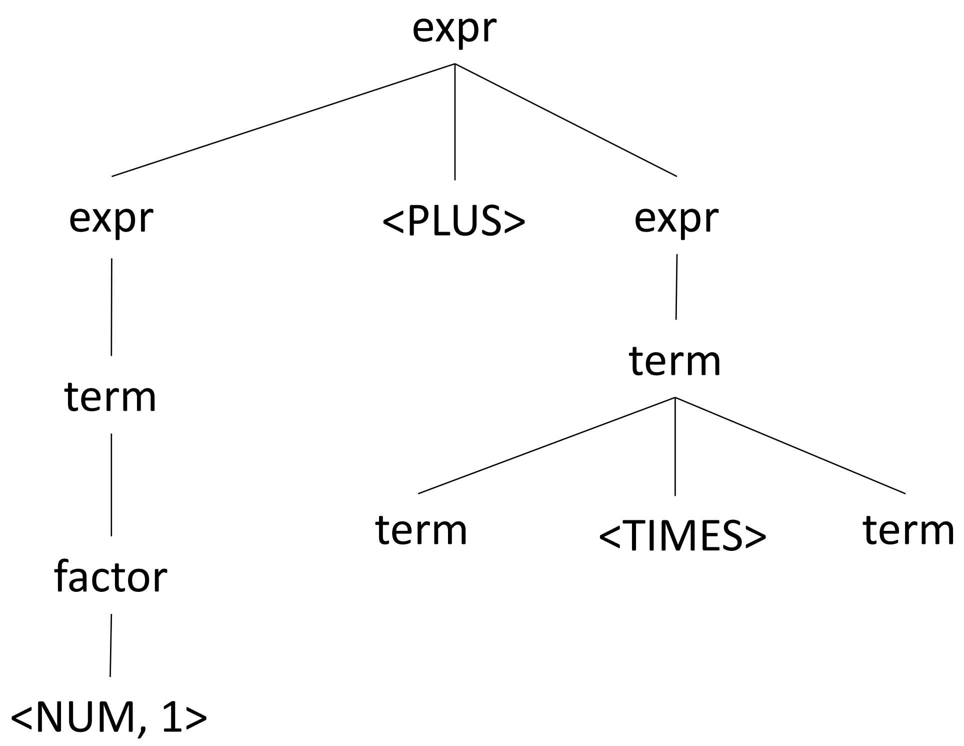

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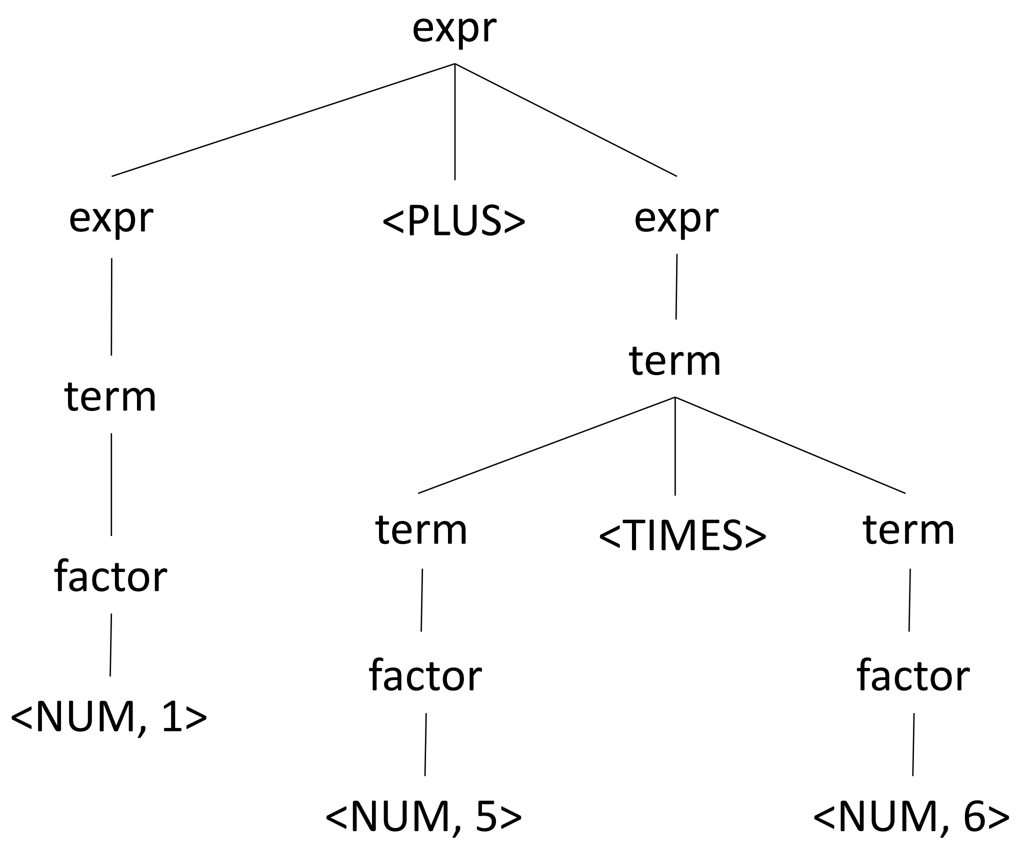

Parsing REs

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

<table>
<tr><th>Operator</th><th>Name</th><th>Productions</th></tr>
<tr><td>|</td><td></td><td></td></tr>
<tr><td>.</td><td></td><td></td></tr>
<tr><td>*</td><td></td><td></td></tr>
<tr><td>()</td><td></td><td></td></tr>
</table>

Parsing REs

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<table>
<tr><th>Operator</th><th>Name</th><th>Productions</th></tr>
<tr><td>|</td><td>union</td><td>: union PIPE union
| concat</td></tr>
<tr><td>.</td><td>concat</td><td>: concat DOT concat
| starred</td></tr>
<tr><td>*</td><td>starred</td><td>: starred STAR
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Parsing REs

`input: a.b | c*`

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

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

Operator	Name	Productions
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`input: a.b | c*`