# CSE216
# Programming Abstraction


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# What is a program?

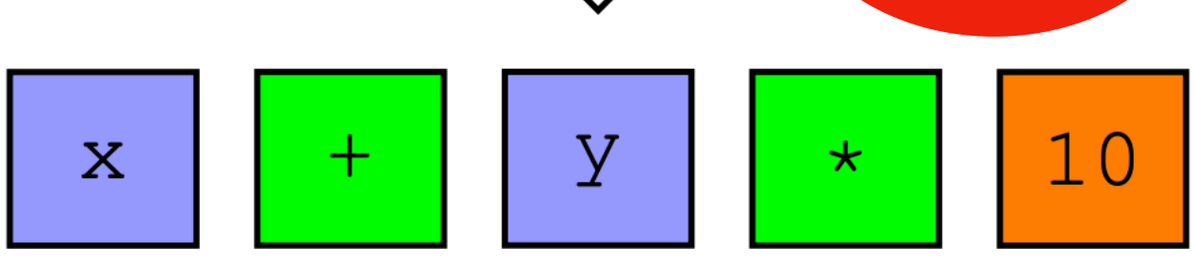

- Let us consider an expression x + y*10
- Think of this expression as a program in a programming language
- This is actually a program written in a programming language used by a calculator
- Today we will analyze the syntax of a general program — Syntax analysis
- Syntax analysis can take a whole semester to learn; we will touch only the surface

# Syntax analysis

"x +y*10"

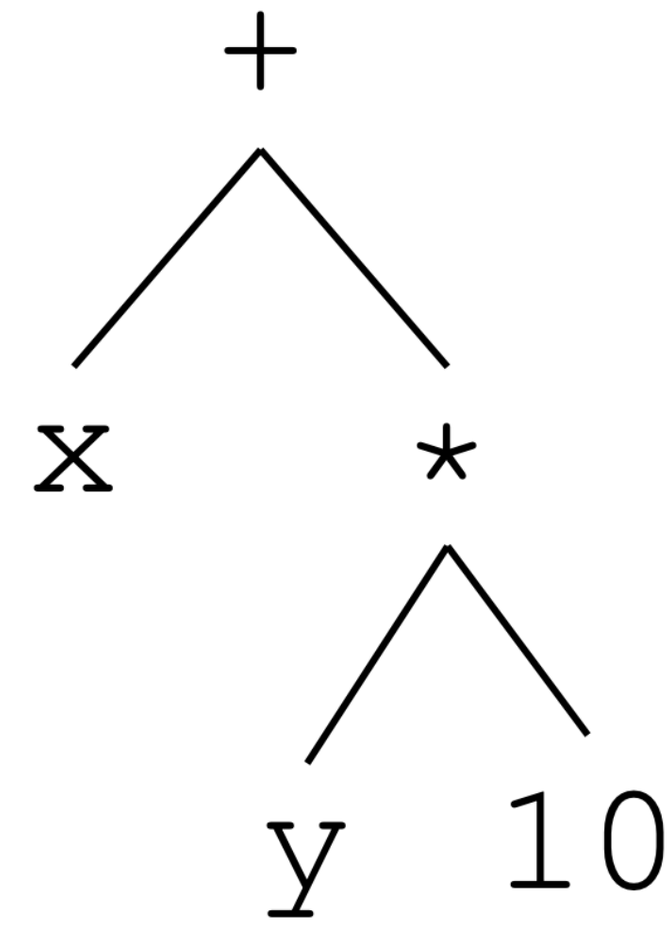
Lexer

Regular expression Specification




Parser

Context-free grammar specification



# Regular expression specification looks like this in Ocaml

```
rule Token = parse
  | [' ' '\t' '\n' '\r']  { Token lexbuf }
  | ['0'-'9']+            { CSTINT (...) }
  | ['a'-'z''A'-'Z']['a'-'z''A'-'Z''0'-'9']*
                          { keyword (...) }
  | '+'                   { PLUS  }
  | '-'                   { MINUS }
  | '*'                   { TIMES }
  | '('                   { LPAR  }
  | ')'                   { RPAR  }
  | eof                   { EOF   }
  | _                     { lexerError lexbuf "Bad char" }
```

# Context-free grammar specification looks like this in Ocaml

```
Main ::= Expr EOF
Expr ::= NAME
       | CSTINT
       | - CSTINT
       | ( Expr )
       | let NAME = Expr in Expr end
       | Expr *  Expr
       | Expr + Expr
       | Expr - Expr
```

# Menu for Today

- Regular expressions
- Finite State Automata
- Nondeterministic Finite Automaton (NFA)
- Deterministic Finite Automaton (DFA)
- Context-free Grammars
- Derivation and ambiguity
- Python basics for the recitation

# Regular expressions

| $r$ | Meaning | Language $\mathcal{L}(r)$ |
|---|---|---|
| `a` | Character `a` | $\{\text{"a"}\}$ |
| $\varepsilon$ | Empty string | $\{\text{""}\}$ |
| $r_1 r_2$ | $r_1$ followed by $r_2$ | $\{s_1 s_2 \mid s_1 \in \mathcal{L}(r_1), s_2 \in \mathcal{L}(r_2)\}$ |
| $r^*$ | Zero or more $r$ | $\{s_1 \ldots s_n \mid s_i \in \mathcal{L}(r), n \geq 0\}$ |
| $r_1 \mid r_2$ | Either $r_1$ or $r_2$ | $\mathcal{L}(r_1) \cup \mathcal{L}(r_2)$ |

## Examples

`ab`* represents {"a","ab","abb",...}

(`ab`)* represents {"","ab","abab",...}

(`a`|`b`)* represents {"","a","b","aa","ab","ba",...}

## Exercise

What does (`a`|`b`)`c`* represent?

# Regular expression abbreviations

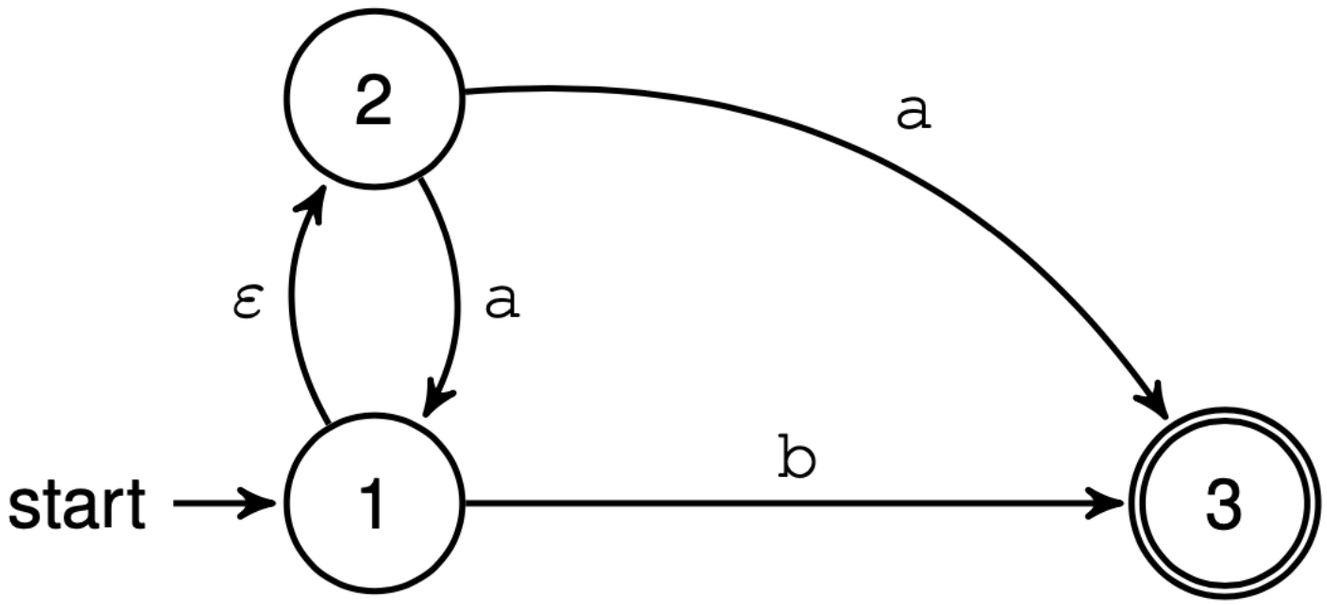
| Abbrev. | Meaning | Expansion |
|---|---|---|
| [aeiuo] | Set | a\|e\|i\|o\|u |
| [0–9] | Range | 0\|1\|...\|8\|9 |
| [0–9a–Z] | Ranges | 0\|1\|...\|8\|9\|a\|b\|...\|y\|z |
| *r*? | Zero or one *r* | *r*\|$\varepsilon$ |
| $r^+$ | One or more *r* | *r r*$^*$ |

# Exercises

Write regular expressions for:

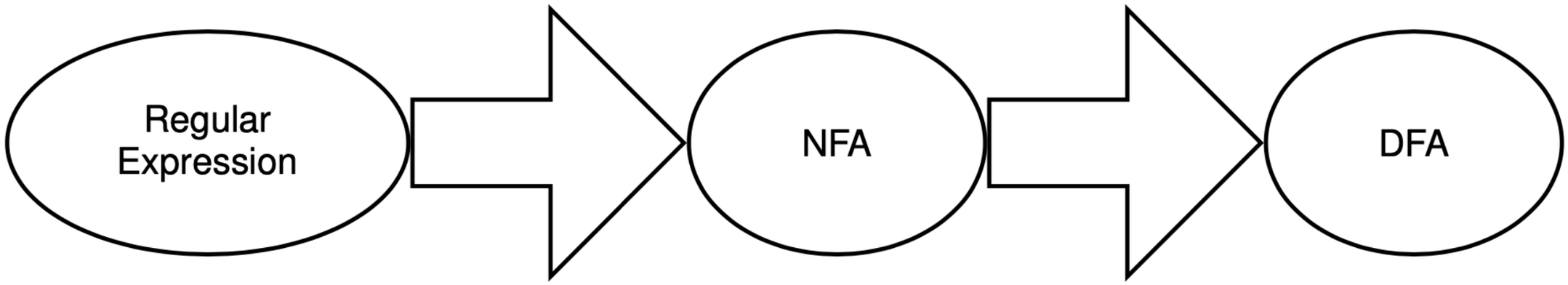
- Non-negative integer constants
- Integer constants
- Floating-point constants:
  - `3.14`
  - `3E8`
  - `+6.02E23`
- Java variable names:
  - `xy`
  - `x12`
  - `_x`
  - `$x12`

# Finite State Automata




- A finite automaton, FA, is a graph of states (nodes) and labelled transitions (edges)
- An FA accepts string s if there is a path from start to an accept state such that the labels make up s
- Epsilon (ε) does not contribute to the string
- This automaton is nondeterministic (NFA)
- It accepts string b
- Does it accept a or aa or ab or aba?

# Regular expression = finite automata



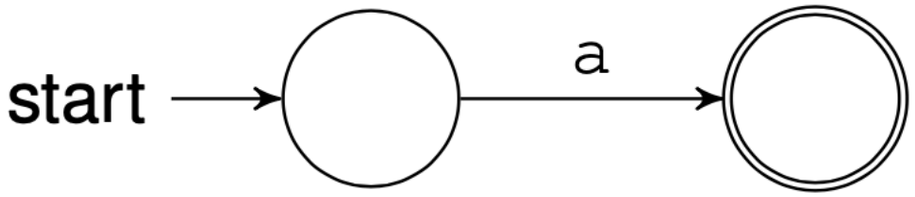

- For every regular expression r, there exists a deterministic finite automaton that recognizes precisely the strings described by r.
- The converse is also true.

- Construction: Regular expression ⇒ Nondeterministic finite automaton (NFA) ⇒ Deterministic finite automaton (DFA)
- Results in an efficient way of determining whether a given string is described by a regular expression

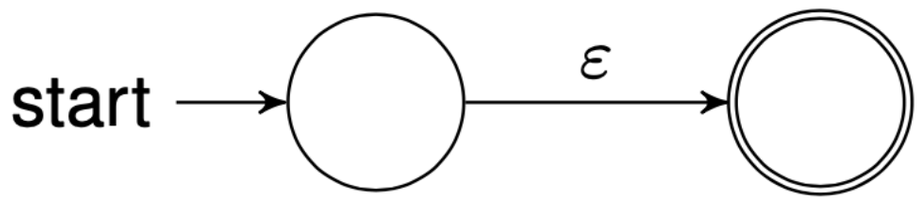
# From regular expression to NFA

Build NFA recursively by the case of the regular expression.

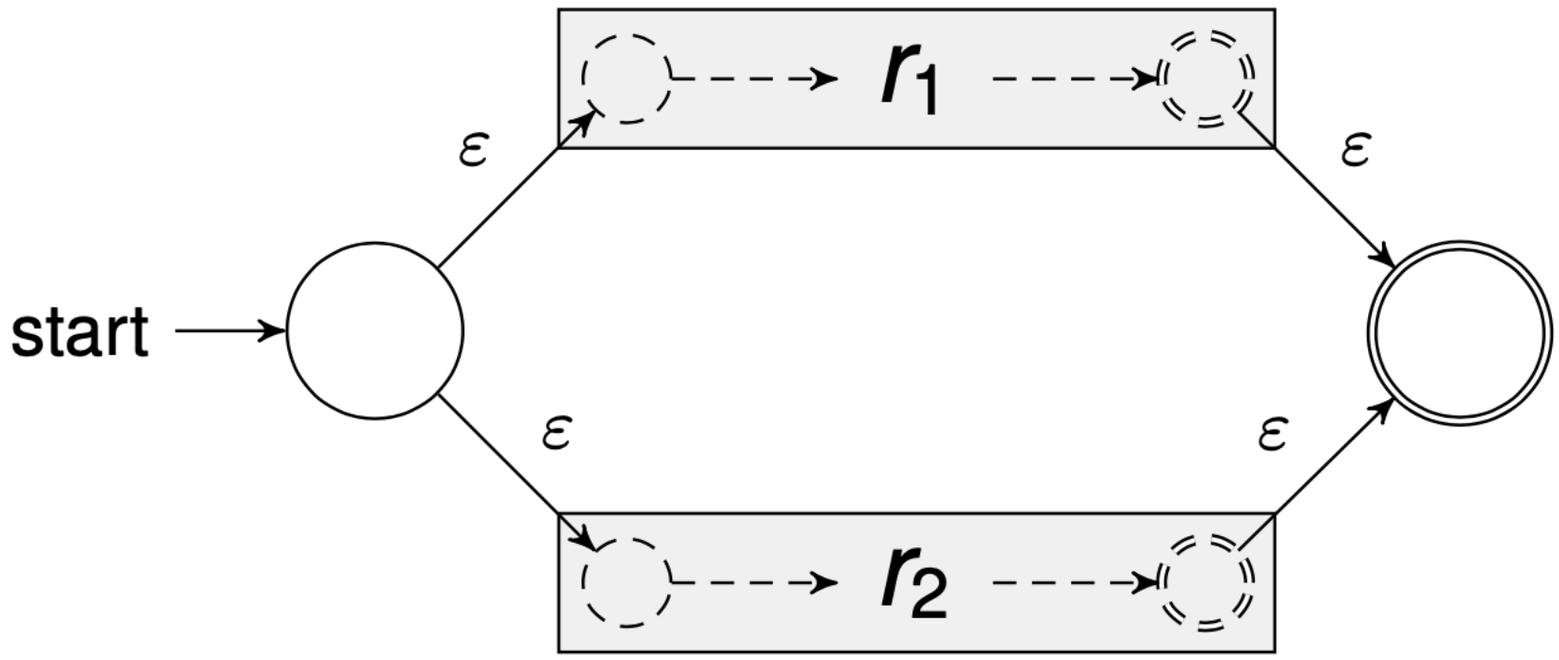
a



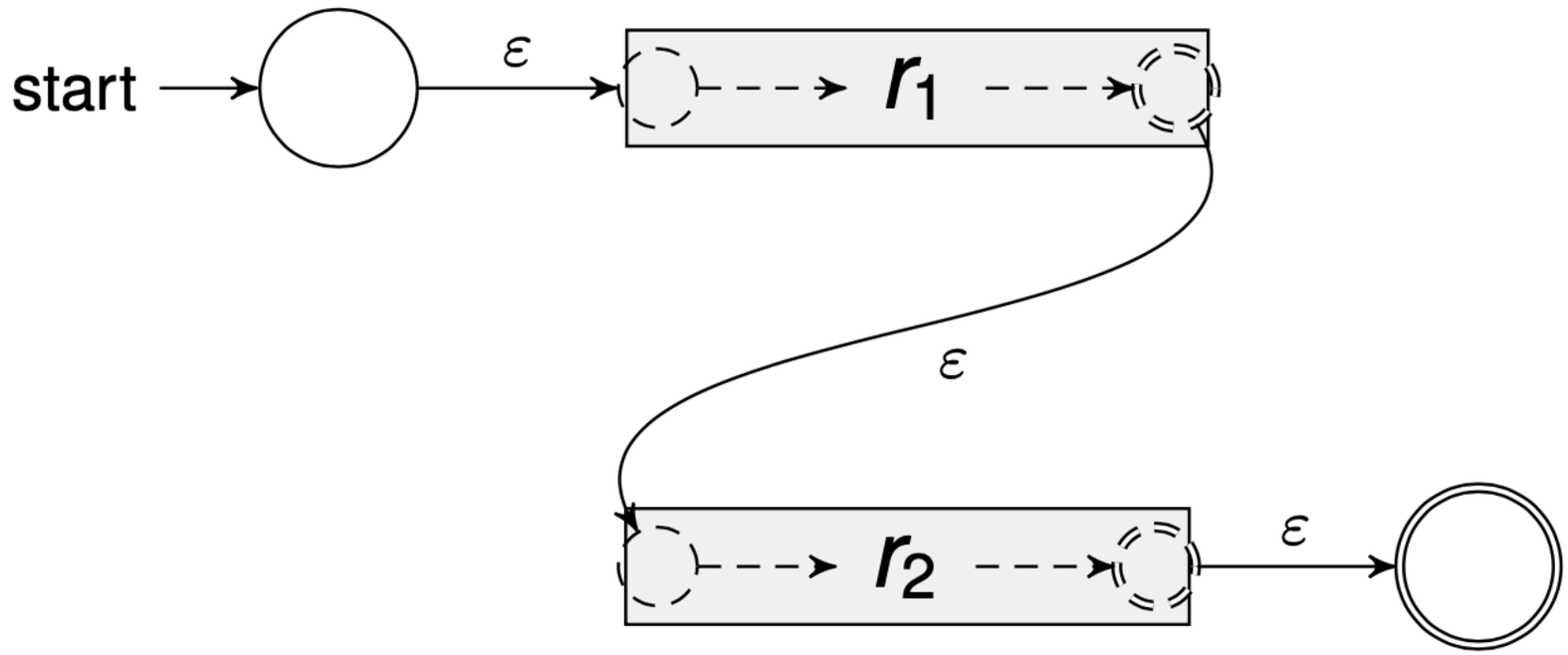

ε



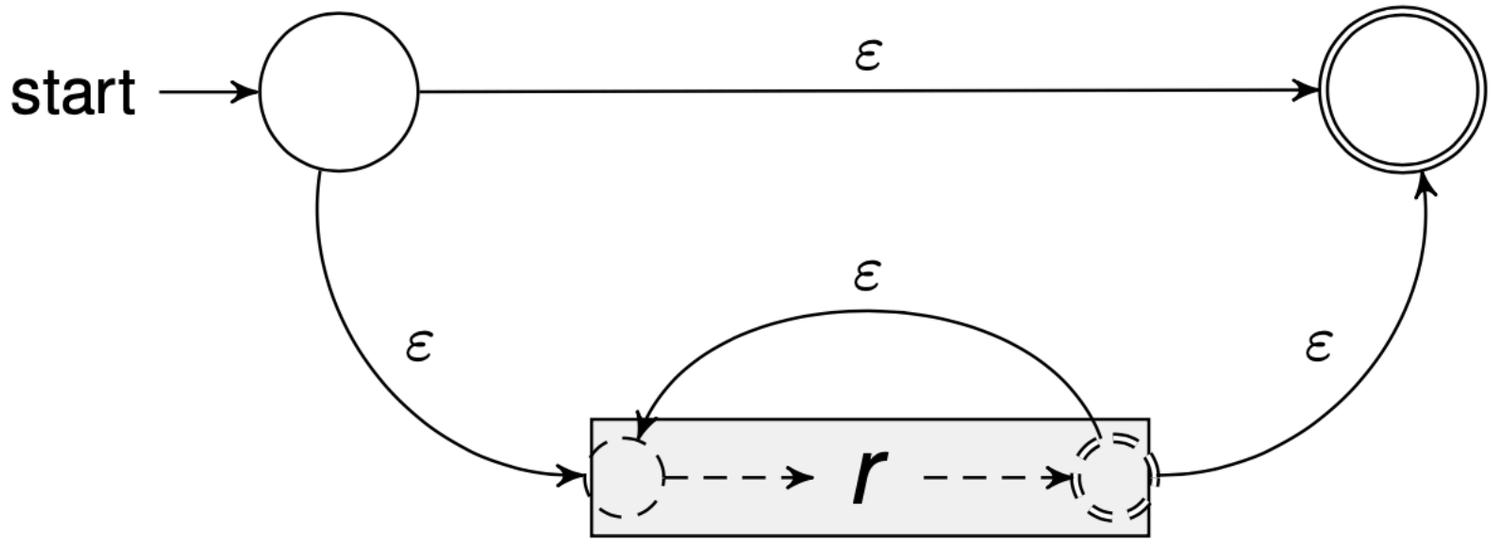
$r_1 | r_2$



$r_1 r_2$



# *r**

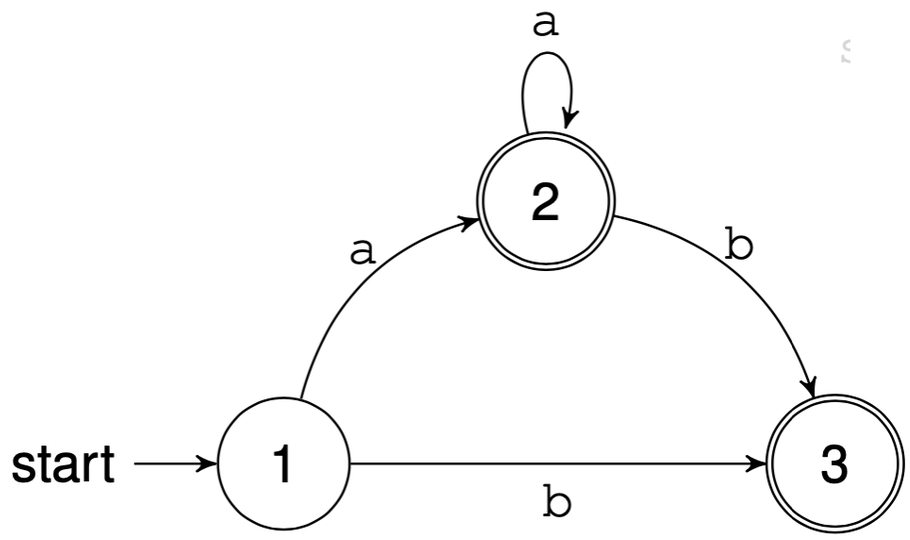



*Exercise:*

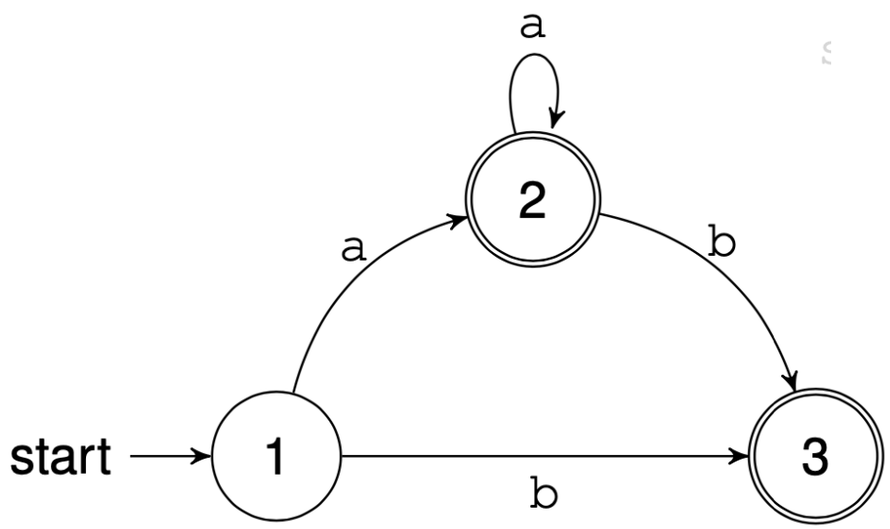
- *Make NFA for* `(ab)*`
- *Make NFA for* `(a|b)*`

# Deterministic Finite Automata

- No ε-transitions
- Distinct transitions from each state
- Multiple accepting states OK



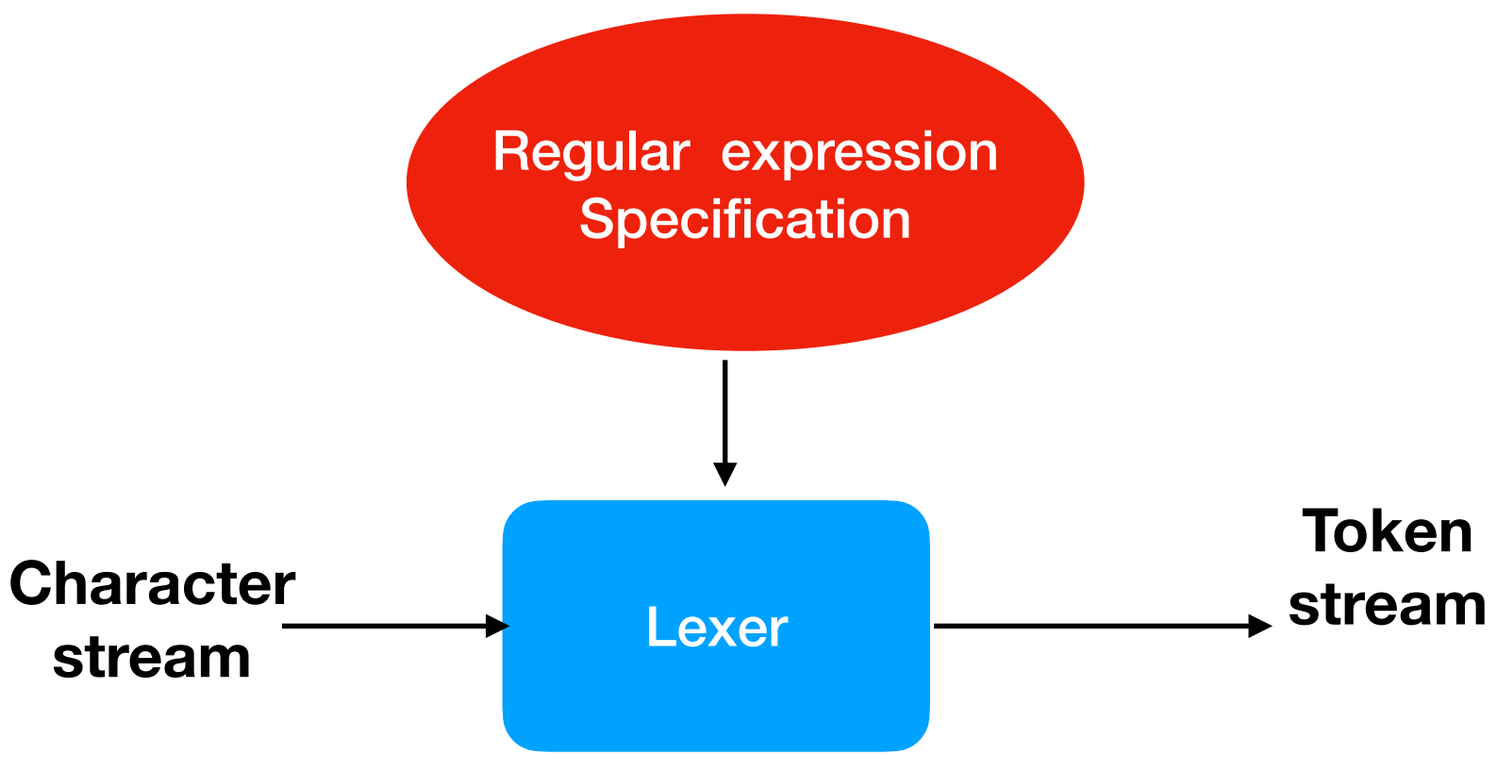
# Why DFA




| State | Input | Go to |
|---|---|---|
| 1 | a | 2 |
| 1 | b | 3 |
| 2 | a | 2 |
| 2 | b | 3 |
| 3 | a | fail |
| 3 | b | fail |

- A DFA is easy to implement with table lookup:
  - next_state = table[current_state][next_symbol]
- Decides in linear time whether it accepts a string s
- For every NFA there is a corresponding DFA that accepts the same set of strings.

# Summary so far



# Formal grammar

- Formal grammar is a set of rules **for generating the structure of a language** or a formal language. It is a mathematical framework used to describe the syntax of a language, where syntax refers to the set of rules governing how words and phrases are combined to form sentences.

- Formal grammars are typically expressed using a set of **symbols and production rules** that define how those symbols can be combined to form valid sentences or expressions.

- There are **different types of formal grammars, including context-free grammars, regular grammars, and context-sensitive grammars**, each with its own set of rules and restrictions. Formal grammar is an essential tool for analyzing and understanding the structure of languages, both natural and artificial, and it has applications in fields such as computational linguistics, natural language processing, and artificial intelligence.

# Context-free grammar, a first example

1. $S \to aSb$
2. $S \to ba$

- We start with S, and can choose a rule to apply to it.

- If we choose rule 1, we obtain the string aSb. If we then choose rule 1 again, we replace S with aSb and obtain the string aaSbb. If we now choose rule 2, we replace S with ba and obtain the string aababb, and are done.

- We can write this series of choices more briefly, using symbols: S => aSb => aaSbb => aababb

- The language of the grammar is the infinite set {a^n ba b^n | n>0} where  n is  is  repeated  times.

- This grammar is *context-free* (only single nonterminals appear as left-hand sides) and *unambiguous*.

# Definition of Formal Grammar

$G = < V, \Sigma, P, \sigma >$

V – set of *terminal* symbols

Σ – set of *nonterminal* symbols with the restriction that V and Σ are disjoint

σ – start symbol

P – set of production rules in a form:

A –> B

where:

A – is a sequence of symbols having at least one *nonterminal*,

B – is the result of replacing some *nonterminal* symbol A with a sequence of symbols (possibly empty) from V and Σ

# Example 2: A small set of English

V = {“the”, ”a”, ”cat”, ”dog”, ”saw”, “chased“}

Σ = {S, NP, VP, D, N, V }

S – sentence D – determiner

NP – noun phrase N – noun

VP – verb phrase V – verb

σ = S

P = {

S –> NP VP,

NP –> D N,

VP –> V NP,

D –> ”the”, D –> “a”,

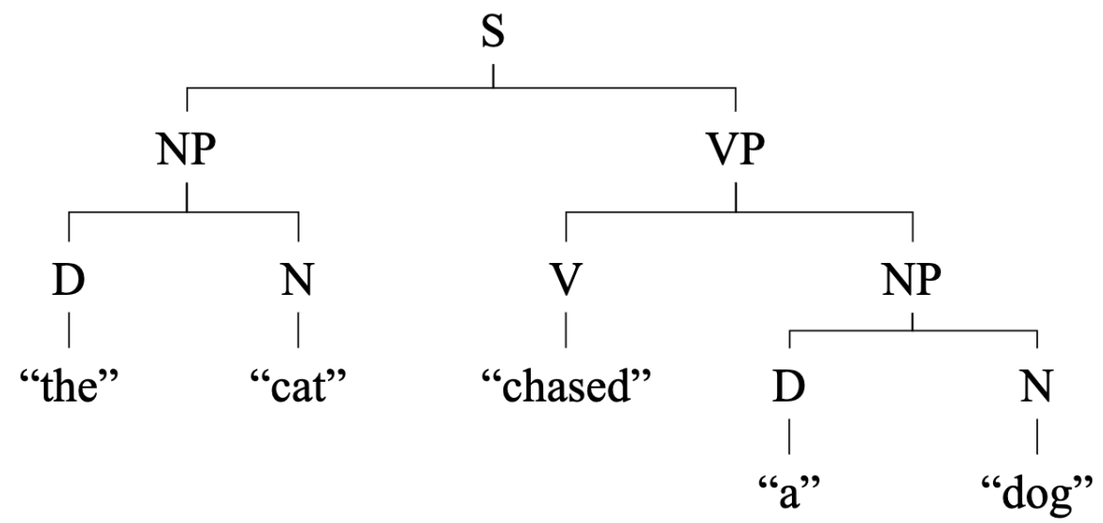
N –> ”cat”, N –> ”dog”,

V –> “saw”, V –> “chased”

}

# Cont.

**Abstract syntax tree (parsing tree)**




S –> NP VP
–> D N VP
–> “the” N VP
–> “the” “cat” VP
–> “the” “cat” V NP
–> “the” “cat” “chased” NP
–> “the” “cat” “chased” D N
–> “the” “cat” “chased” “a” N
–> “the” “cat” “chased” “a” “dog”

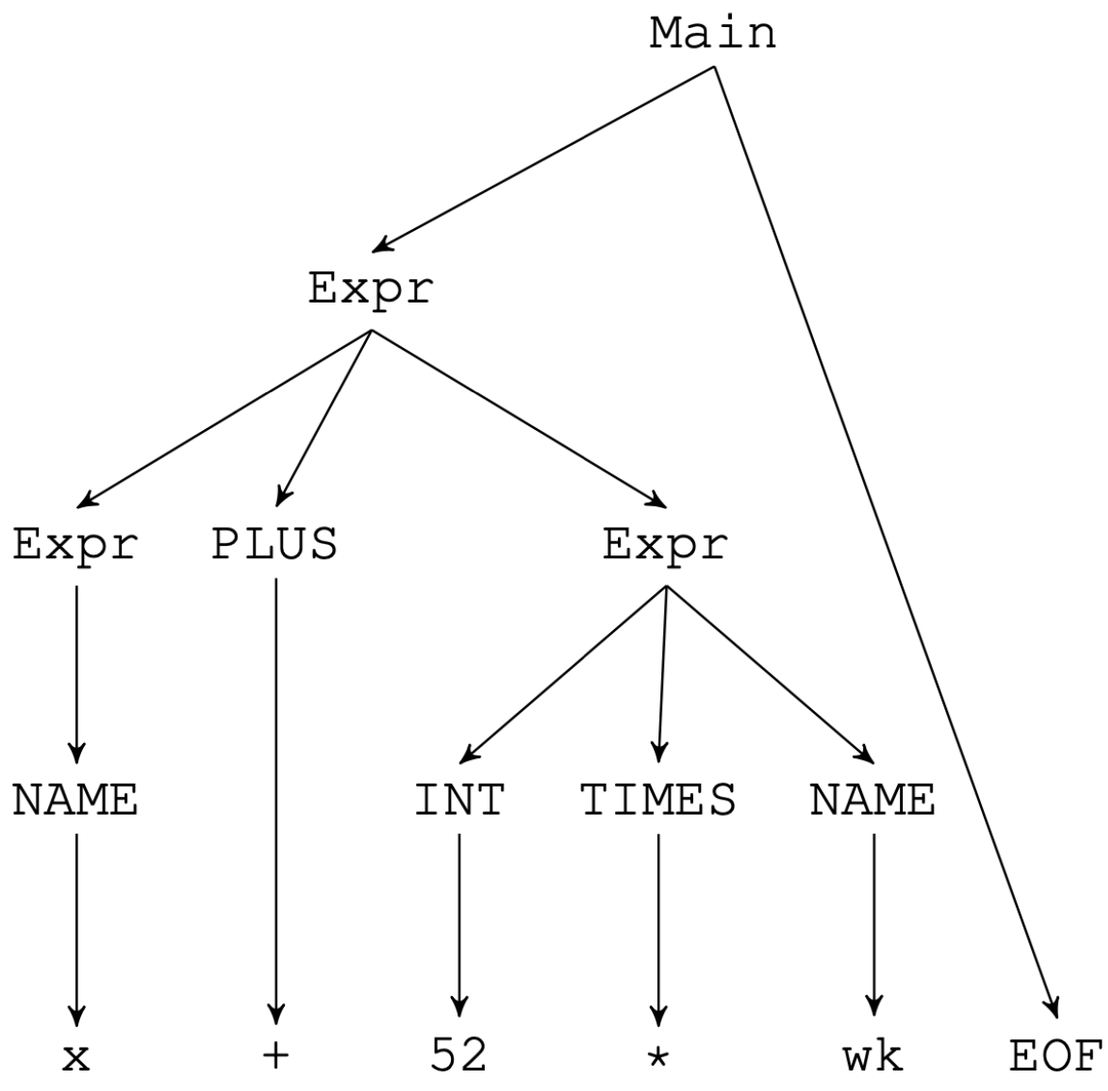
# Example 3: An Ocaml expression (to be parsed together with a lexer)

```
Main ::= Expr EOF                              (rule A)
Expr ::= NAME                                  (rule B)
       | CSTINT                                (rule C)
       | - CSTINT                              (rule D)
       | ( Expr )                              (rule E)
       | let NAME = Expr in Expr end           (rule F)
       | Expr *  Expr                          (rule G)
       | Expr + Expr                           (rule H)
       | Expr - Expr                           (rule I)
```

- • Nonterminal symbols
- Terminal symbols (from lexer): EOF, CSTINT, NAME, ‘let’, ‘in’
- Grammar rules, or Productions (called A–I)
- Start symbol (the nonterminal Main)

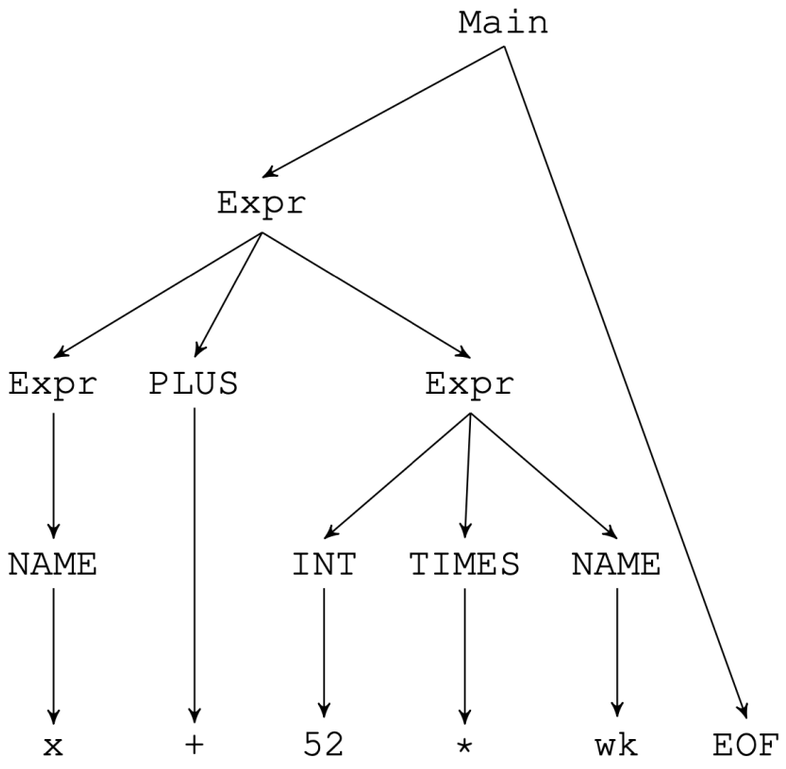
# Generating a syntax tree using a context-free grammar

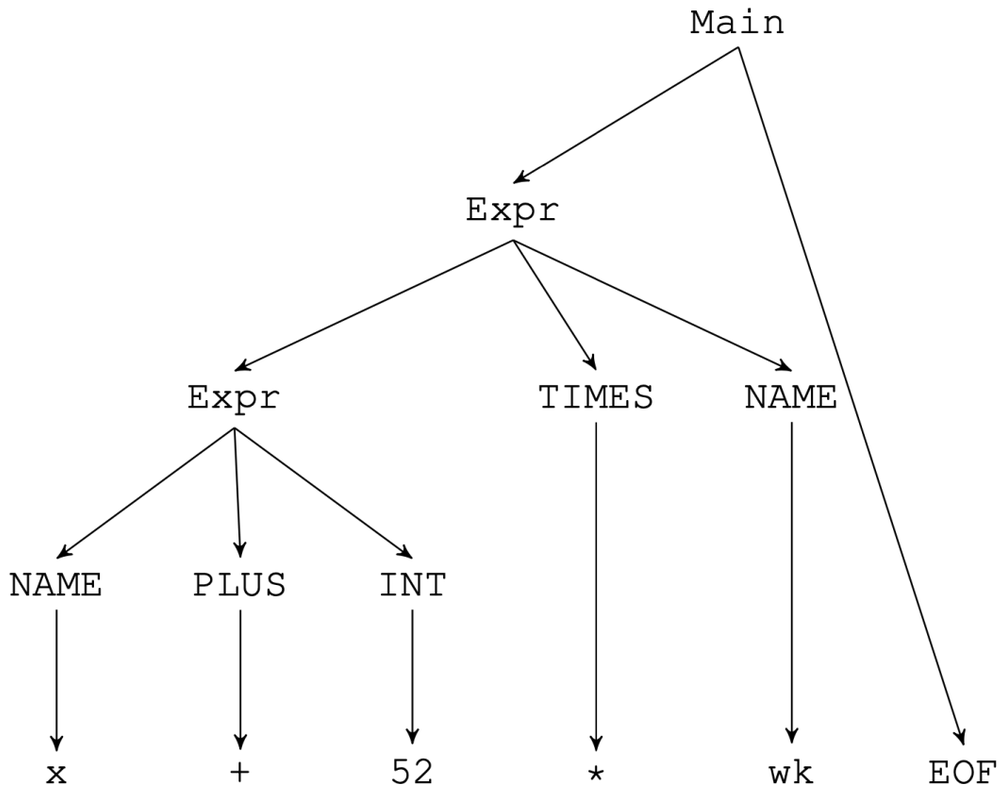
```
Main ::= Expr EOF                          (rule A
Expr ::= NAME                              (rule B
       | CSTINT                            (rule C
       | - CSTINT                          (rule D
       | ( Expr )                          (rule E
       | let NAME = Expr in Expr end       (rule F
       | Expr *  Expr                      (rule G
       | Expr + Expr                       (rule H
       | Expr - Expr                       (rule I
```



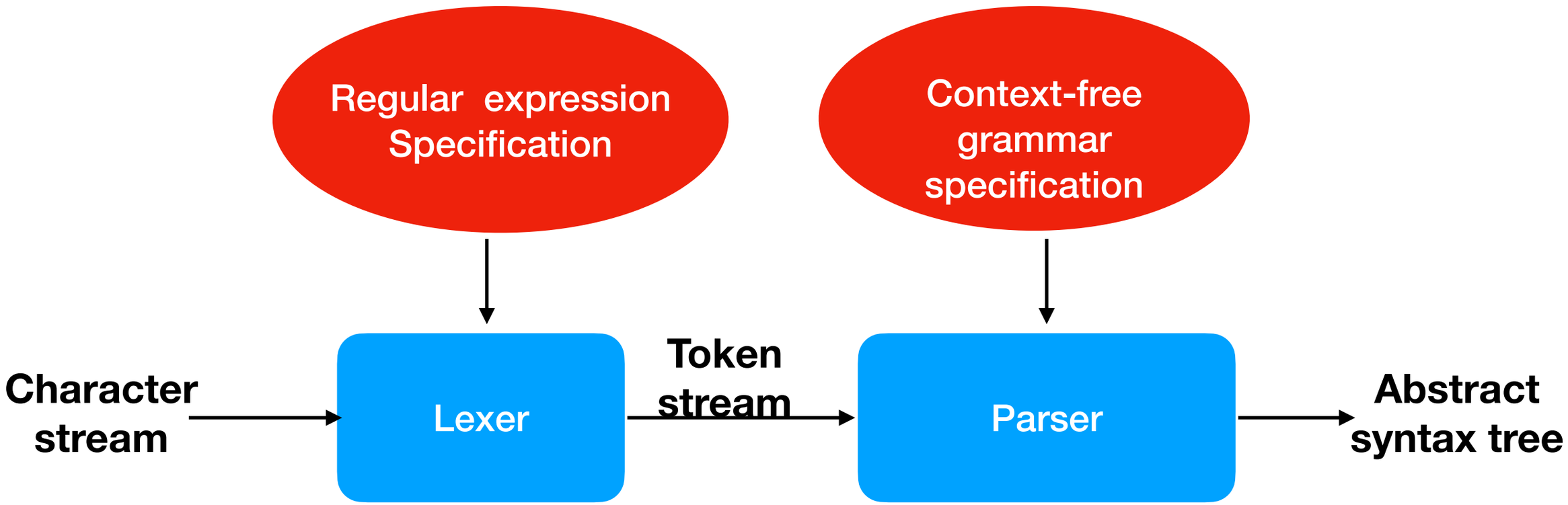
# Grammar ambiguity

- A grammar is ambiguous if there exists a string with more than one derivation tree.



# Summary




- A lexer converts a character stream to a token stream, using specification of regular expressions
- A parser converts a token stream to an abstract syntax tree, using specification of context-free grammar

# Basic Python (for recitation 1)

- Basic Python:
  - https://colab.research.google.com/drive/15eilquB2QVacfZWadm_jlw5Xv2ihl60J#scrollTo=UhcbBQUiStHG