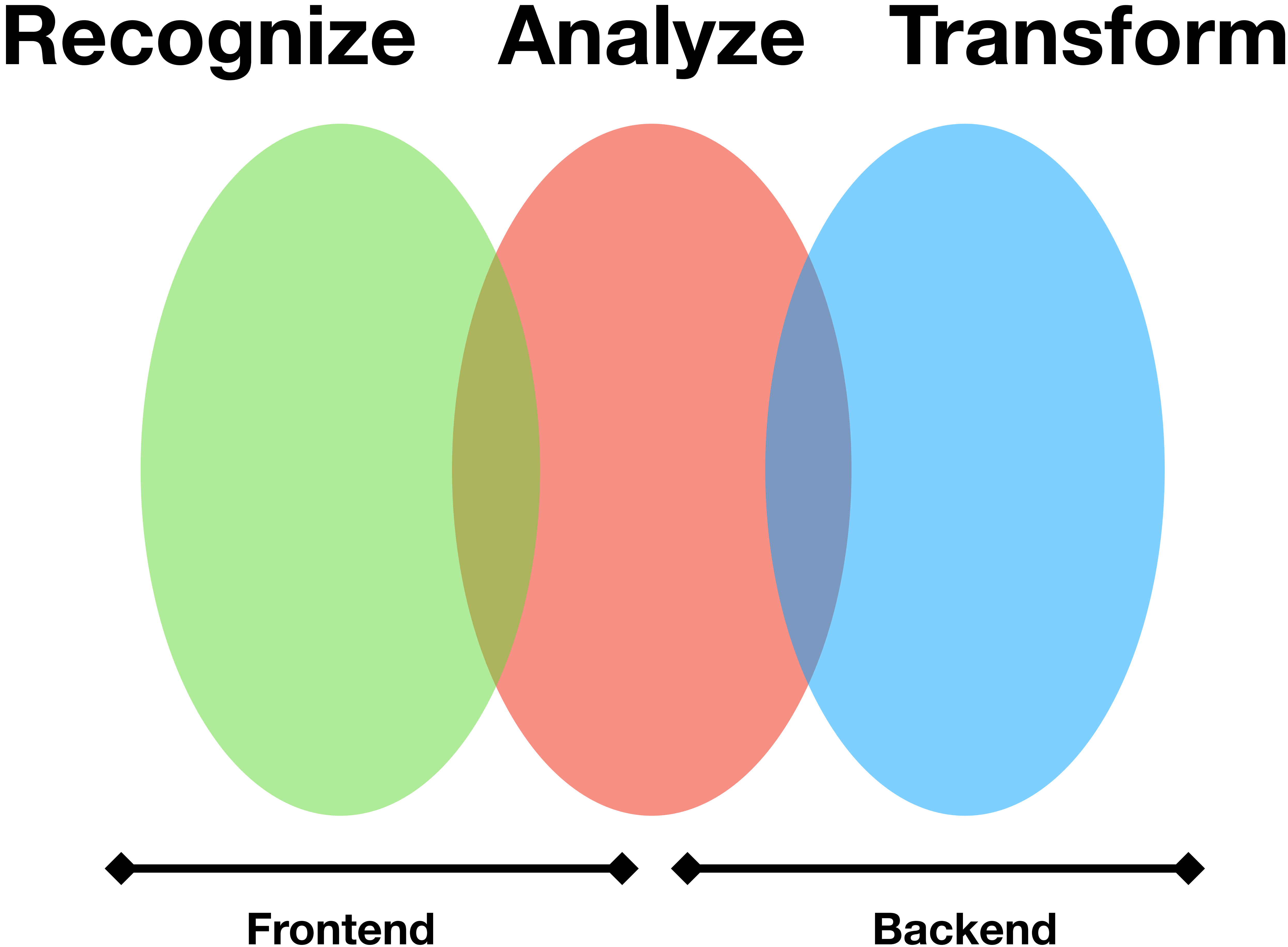
CSC488/2107 Winter 2019 — Compilers & Interpreters

https://www.cs.toronto.edu/~csc488h/

Peter McCormick
pdm@cs.toronto.edu

Agenda

- Recognize, Analyze, Transform
- Lexical analysis
- Building lexical analyzers


Recognize
Analyze
Transform
Frontend
Backend

Recognize

- Lexical structure
- Syntactic structure
- Highly language/syntax specific

- Data flow:
  Stream of *Characters*
  ➥ Stream of *Tokens*
  ➥ *Parse Tree* (Concrete Syntax)

Analyze

- Semantic meaning
- Less language specific
- Data flow:

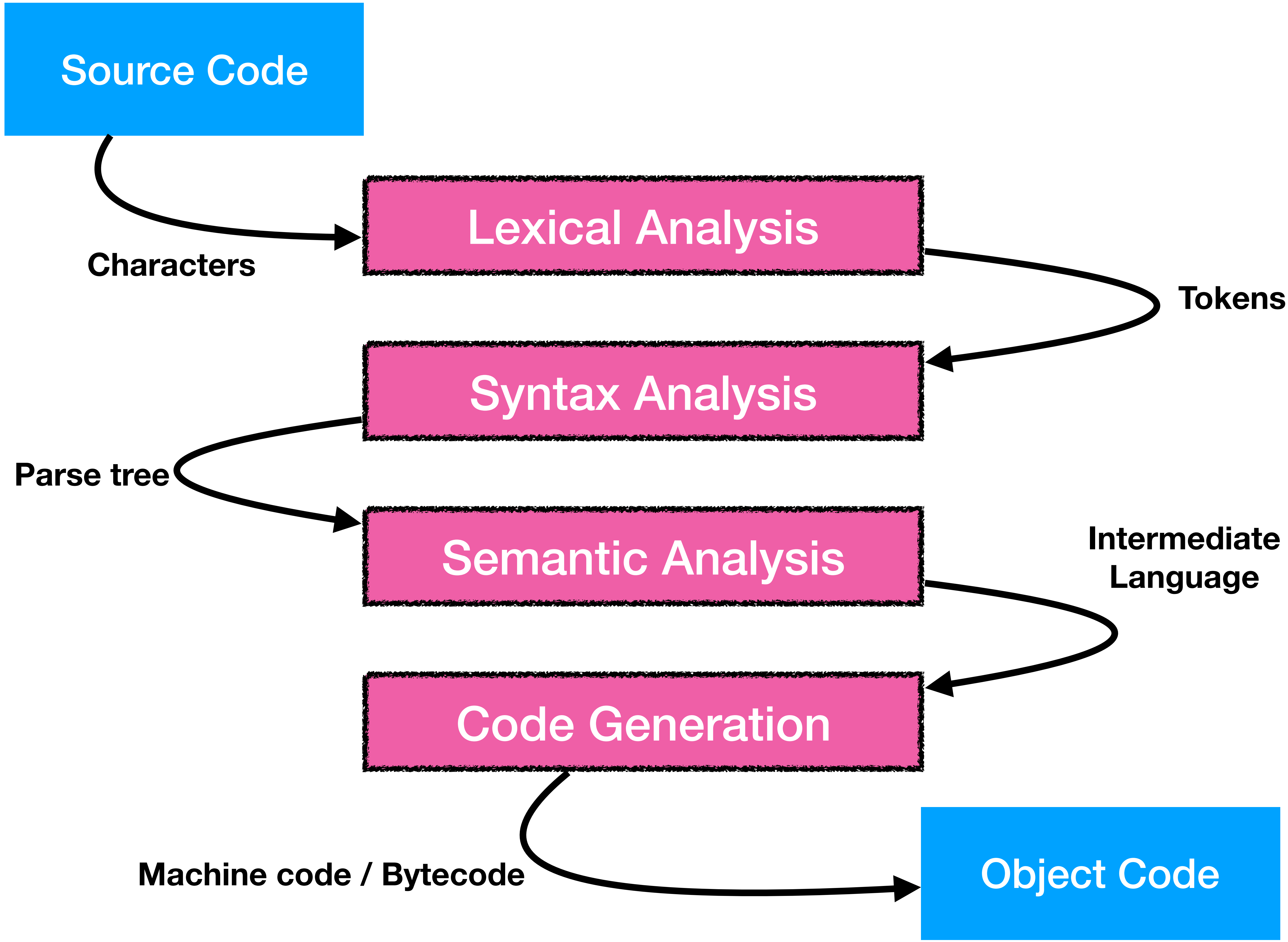
    Parse Tree

    ➥ *Abstract Syntax Tree* (possibly with annotations and/or associated symbol tables)

Transform (Lower)

- Memory layout
- Optimization (optional)
- Code generation
- Very target specific

- Data flow:
  Abstract Syntax Tree
  ➥ *Intermediate Languages/Representations* (optional)
  ➥ *Target Machine Code*


Source Code
Characters
Lexical Analysis
Tokens
Syntax Analysis
Parse tree
Semantic Analysis
Intermediate
Language
Code Generation
Machine code / Bytecode
Object Code

C pre-processor

Pre-processed:

```
#include <stdio.h>
```

Post-processed:

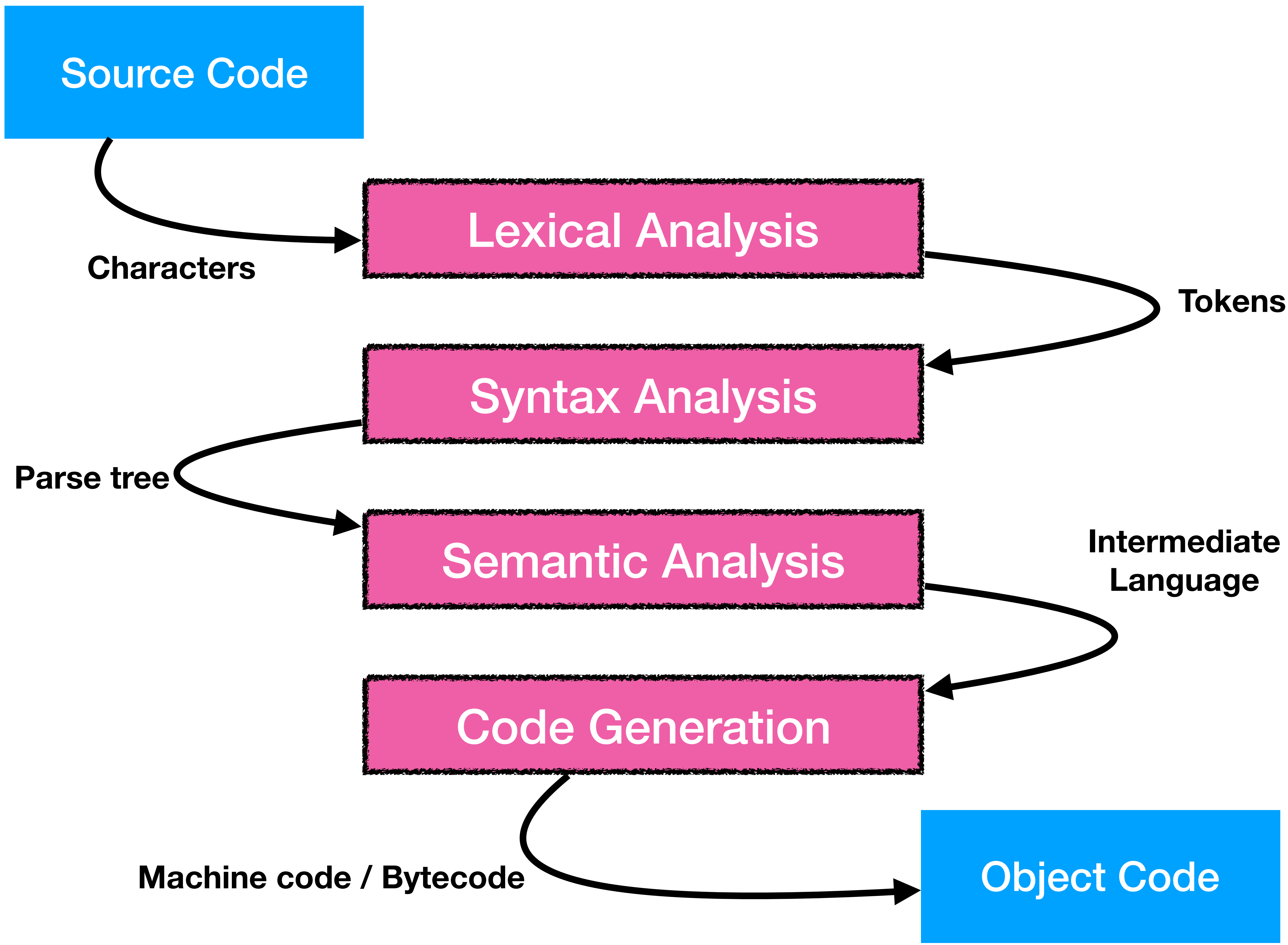
```
/* complete contents of stdio.h */
```

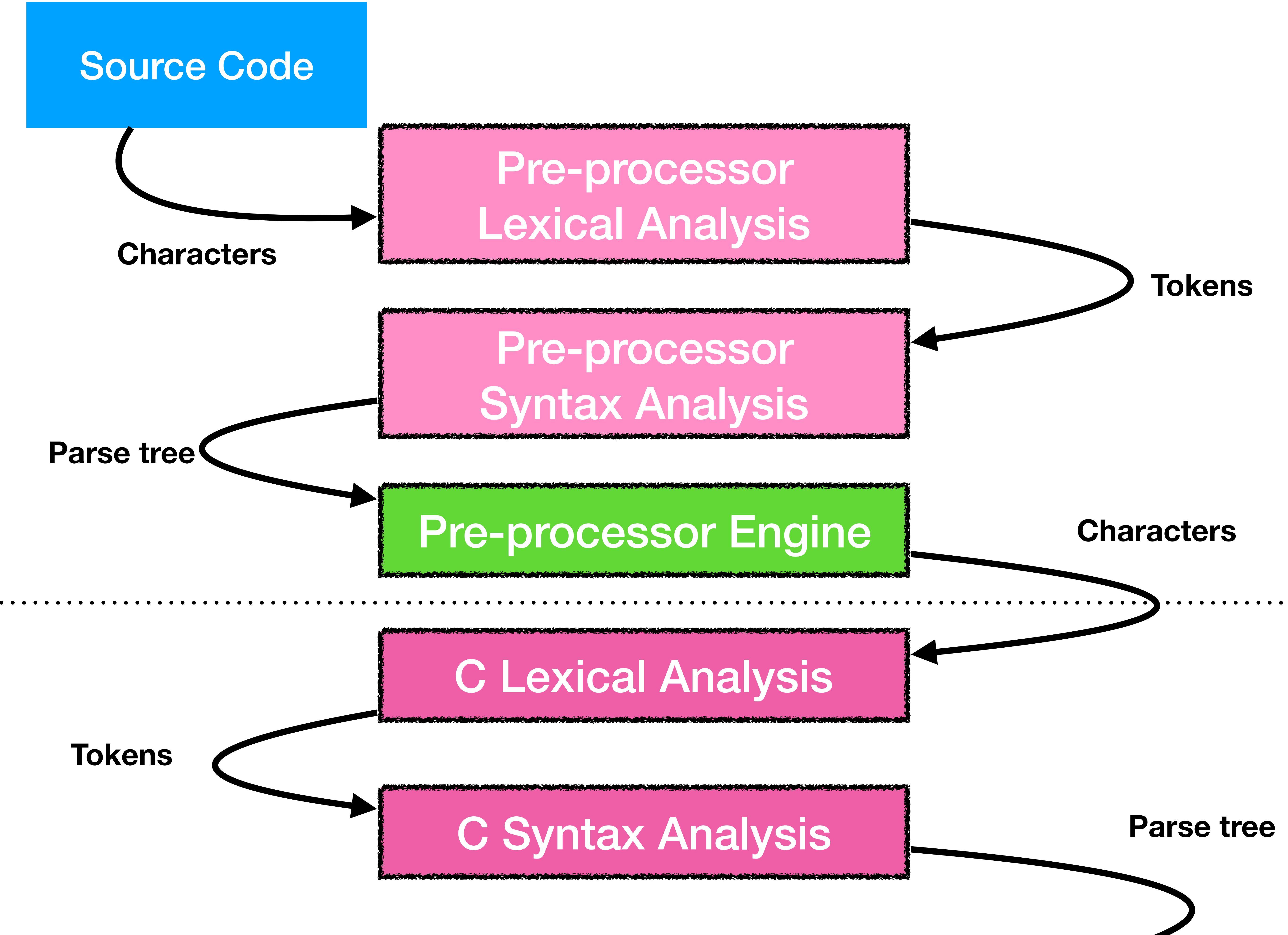
Pre-processed:

```
#define PI 3.1415
float pi = PI;
```

Post-processed:

```
float pi = 3.1415;
```


Source Code
Characters
Lexical Analysis
Tokens
Syntax Analysis
Parse tree
Semantic Analysis
Intermediate Language
Code Generation
Machine code / Bytecode
Object Code



Source Code
Characters
Pre-processor
Lexical Analysis
Tokens
Pre-processor
Syntax Analysis
Parse tree
Pre-processor Engine
Characters
C Lexical Analysis
Tokens
C Syntax Analysis
Parse tree

Lexical Analysis

Recognizing the textual building blocks of source code

A *scanner* or *lexer* converts
a stream of **characters**
into
a stream of **lexical tokens**

Characters

- Visual representation (human):
  - ASCII characters or Unicode code points
- Physical byte representation:
  - Fixed length: 7 bit ASCII, UCS-4
  - Variable length: UTF-8/16/32
- Integers to the compiler

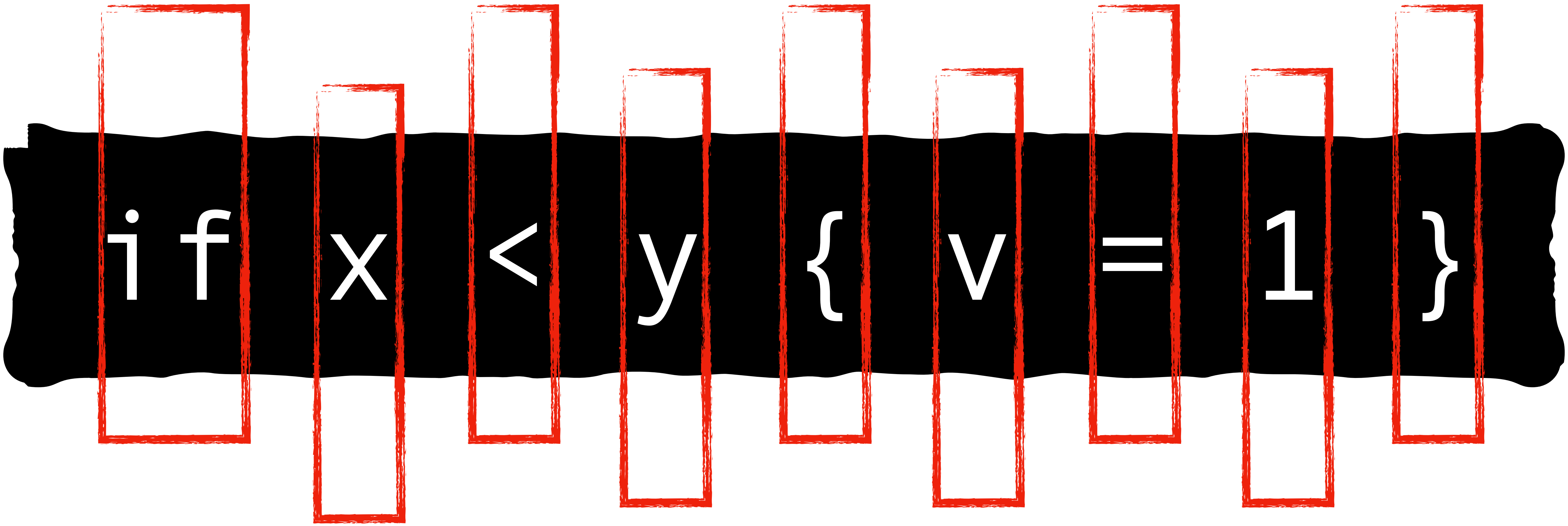
Lexical Token

- One of a fixed set of distinguishing categories:
  - Identifiers
    - Reserved identifiers / keywords
  - Literal constants: numeric, string
  - Special punctuaction (braces, symbols, etc.)
  - Comments
- Language specific

Scanner/Lexer

- Consumes character input
- Identifies lexical boundaries
- Emits a stream of tokens
- Identifies malformed input and emits errors
- Chooses what to ignore (comments, whitespace)
- Manages additional bookkeeping like source coordinates (input filenames, line and column numbers)

```
if x < y { v = 1 }
```


if x < y { v = 1 }

```
if x<y {v=1}
```

```
if x < y { v = 1 }
```

IF

IDENT x

LT

IDENT y

LBRACE

IDENT v

EQ

INTEGER 1

RBRACE

Careful language design choices can enable fast scanners

Building lexical analyzers

```
struct Token {
  enum {
    IF, LT, IDENT, LITERAL, …
  } type;
  union {
    char *ident;
    int literal;
  };
  // more bookkeeping
};
```

```
data Token
  = If
  | Lt
  | Ident String
  | Literal Integer
  | …
```

Idea: Use finite automata (state machines) to recognize tokens out of a stream of characters

Example:
Addition expressions

Example expressions

1

123+456

1+2+3+456

Lexical structure

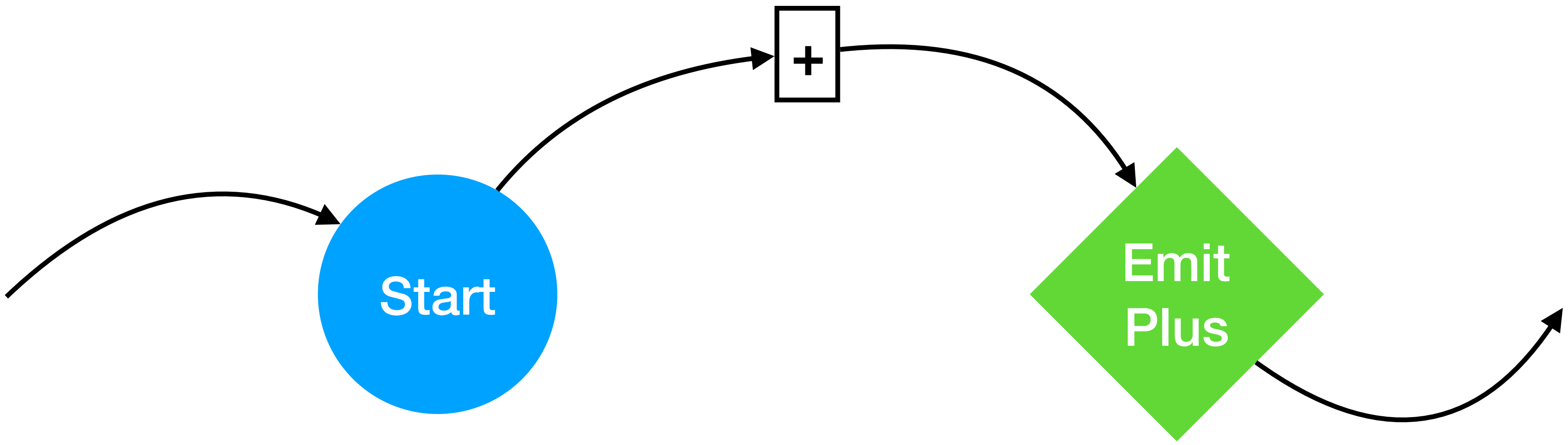
- 2 token types
  - Plus
  - Positive integer literal
- No whitespace handling

Σ — Vocabulary

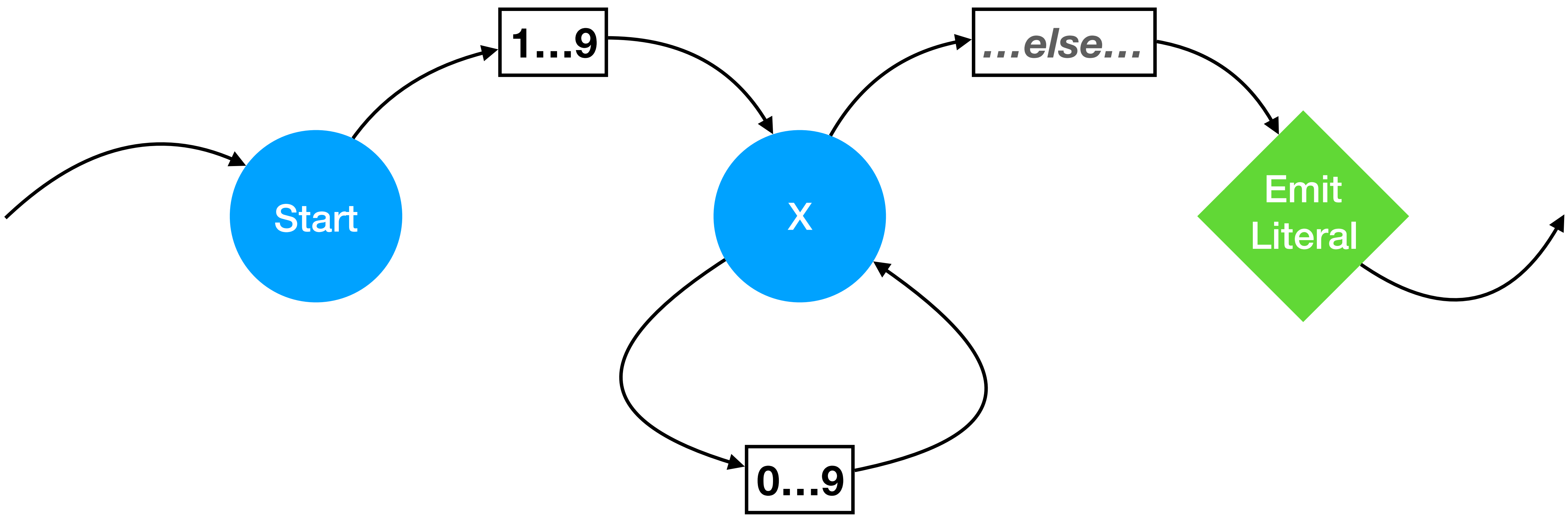
Σ = { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, + }

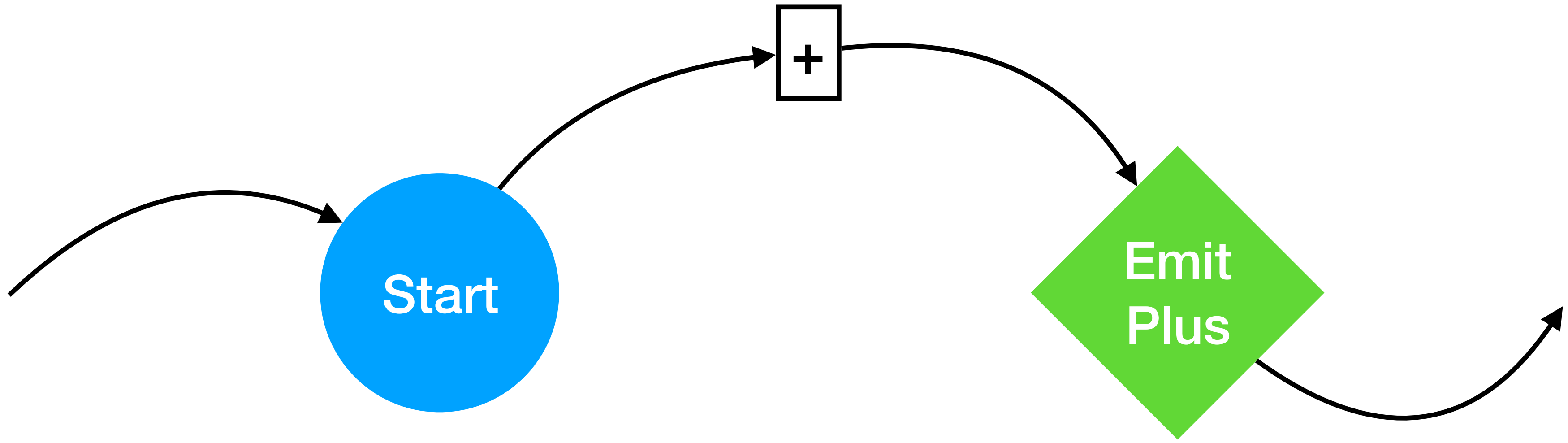
Represent finite automata (state machines) using a state transition diagrams

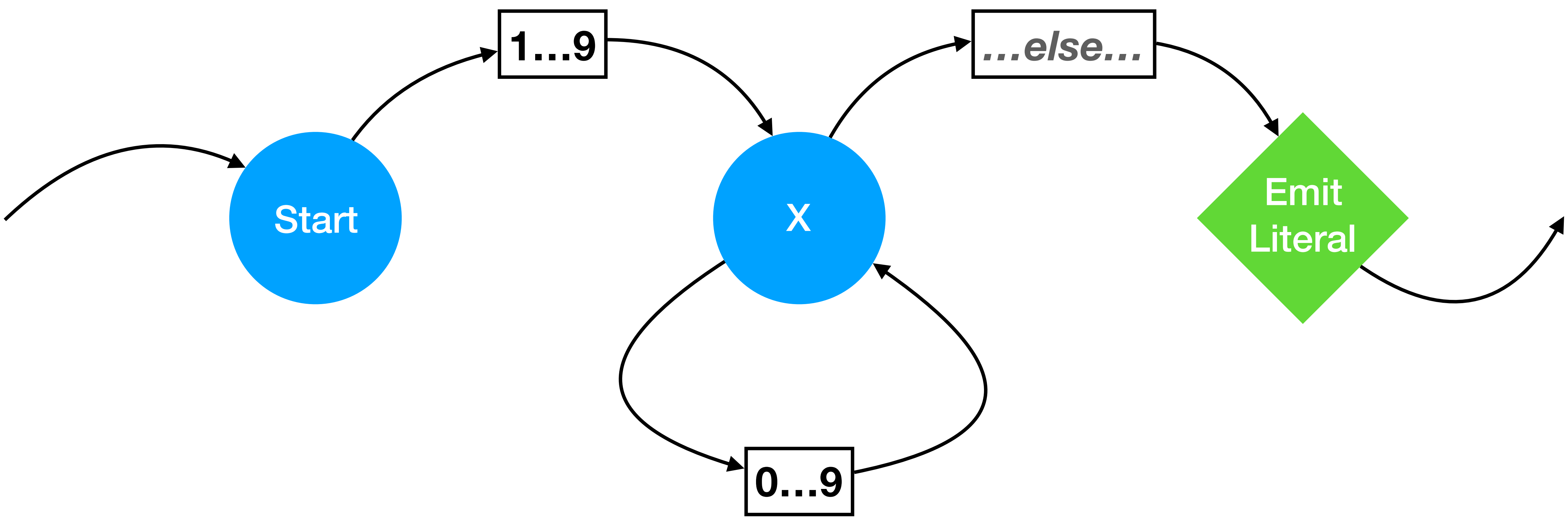
State transition diagram: Plus



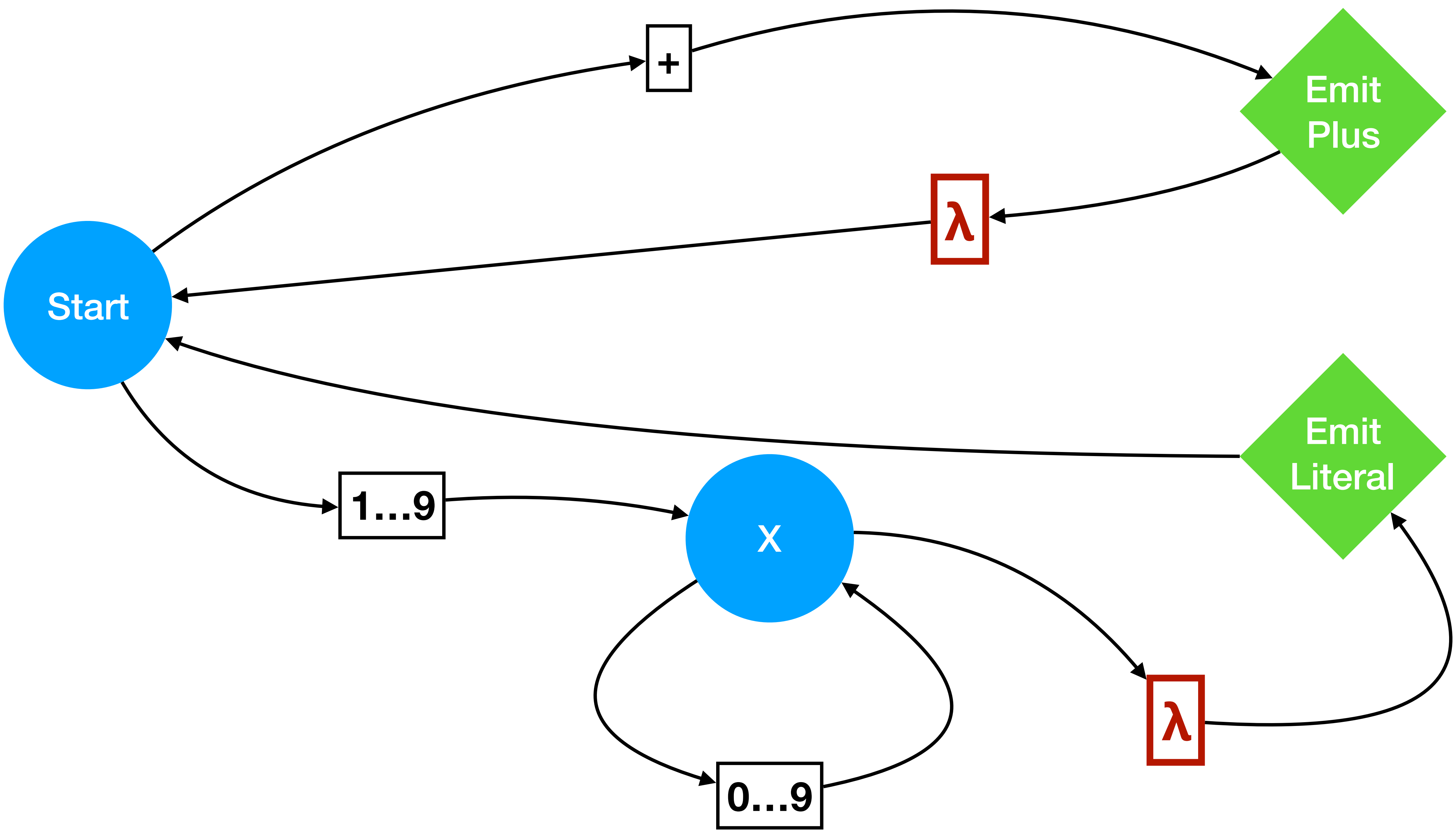
State transition diagram: Positive integer literals




+
Start
Emit
Plus


1...9
...else...
Start
X
Emit
Literal
0...9

Non-deterministic finite automata (NFA)



Deterministic finite automata (DFA)

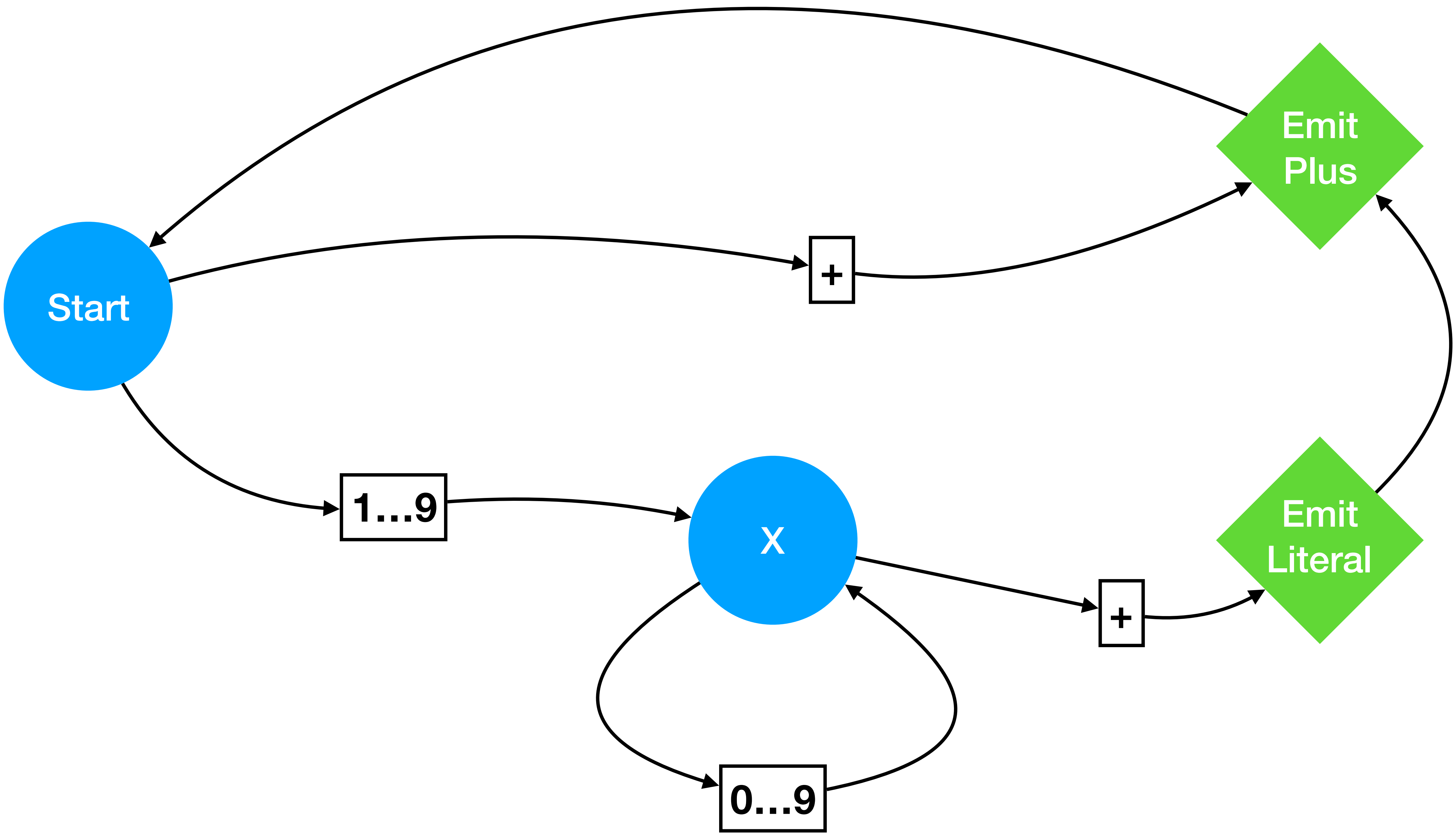


Table driven DFA

Input \ State	+	0	1	2	3	4	5	6	7	8	9	Action
S	T	*error*	U	U	U	U	U	U	U	U	U	
T	S+											Emit Plus
U	T	U+	U+	U+	U+	U+	U+	U+	U+	U+	U+	Emit Literal

Notation: V to change state, V+ to change while consuming 1 input character

```
while True:
    c = curInput()
    if state is START:
        if c == '+':
            emitPlus()
            nextInput()
        elif c in digits19:
            save(c)
            state = LITERAL
            nextInput()
        else:
            error()
    elif state is LITERAL:
        if c in digits09:
            save(c)
            nextInput()
        else:
            emitLiteral(getSaved())
            resetSaved()
            state = START
    if c is EOF: break
```

Regular Expressions

- A *regular expression* is a rigorous mathematic statement defining the members of a *regular set*
- Very compact means of specifying the structure of lexical tokens

Notation & Definitions

Let Ø be the *empty* set

Let Σ be a finite set of distinguished characters (the *vocabulary*)

May use quote marks to avoid confusion:

$$\Sigma = \{ \text{‘\{’}, \text{‘\}’}, \text{‘,’} \}$$

A *string* is defined inductively by cases:

1. The *empty* or *null* string, denoted λ
   - $\emptyset \neq \lambda$
2. A character from Σ is itself a string
3. The *concatenation* of two strings is a string
   - For any strings S and T, both S T and T S are strings
   - For any string S, λ S = S λ = S

Ø is also a *regular expression* denoting the empty set

Any string S is a regular expression, denoting the set containing that string

Forming regular expressions

For any two regular expressions A and B, the following are also regular expressions:

1. **Alternation**: A | B
    - Set union
2. **Concatenation**: A B
    - Set of all strings formed by the concatenation of any string from A and any string from B
3. **Kleene Closure**: A*
    - Zero or more concatenations of A
4. **Parenthesis**: (A)
    - Disambiguation

Useful shorthands

1. **Positive Closure**: A^+
    - A A* (one or more concatenations)
2. **Optional**: A?
    - A | λ (zero or one A)
3. **Complement**: Not(A)
    - Match anything from Σ that does *not* match A
4. **Character ranges**: ["A" … "Z"]
    - "A" | "B" | … | "Y" | "Z"
    - When it's clear what the "…" ranges over

Examples

Addition expressions tokens as regular expressions

Σ = { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, + }

Digits19 = (1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9)
Digits = (0 | Digits19)
Plus = (+)
Literal = (Digits19 Digits*)

Token = Plus | Literal

More examples (1)

Digit = “0” … “9”
Letter = “a” … “z” | “A” … “Z”
<u>**Identifier**</u> = (Letter | “_”) (Letter | Digit | “_”)*

More examples (2)

Digit1 = “1” … “9”
Digit = “0” | Digit1
HexDigit = Digit | “a” … “f” | “A” … “F”
DecLiteral = Digit1 Digit*
HexLiteral = “0” (“x” | “X”) HexDigit^{+}
<u>Literal</u> = (“-“)? DecLiteral | HexLiteral

More examples (3)

EOL = ‘\r’ | ‘\n’ | ‘\r’ ‘\n’
PythonComment = ‘#’ Not(EOL)* EOL
CComment = ‘/‘ ‘*’ Not(‘*’ ‘/‘)* ‘*’ ‘/‘

Great… but can we use them in a lexer?

By Thompson’s construction, a regular expression can always be converted into an NFA

NFA's are equivalent to DFA's

It's always possible to convert an NFA into a DFA

DFA scanners can be implemented extremely efficiently

See <u>re2c</u> for an even faster, code generation approach

Scanner development options

- Write by hand
- Use *scanner generator* tools
  - Provide a specially formatted definition file containing regular expressions and code fragments
  - Generates source code implementing the scanner
  - GNU Flex, ANTLR, PLY (Python Lex-Yacc), Ragel, re2c
- Use built-in language support for regular expressions

scanner.py

```
if x < y { v = 1 }
```

IF

IDENT x

LT

IDENT y

LBRACE

IDENT v

EQ

INTEGER 1

RBRACE

```python
import re

SPEC = r'''
    (?P<IDENT>  [_a-zA-Z] [_a-zA-Z0-9]* ) |
    (?P<NUMBER> [-]? [1-9] [0-9]*       ) |
    (?P<LT>     <                       ) |
    (?P<EQ>     =                       ) |
    (?P<LBRACE> {                       ) |
    (?P<RBRACE> }                       ) |
    (?P<WS>     \s+                     )
    '''

lex = re.compile(SPEC, re.VERBOSE).match
```

Next Week

- Syntax analysis & parsing

No tutorial on Tuesday Jan 22