Programming Languages and Compilers (CS 421)

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https://courses.grainger.illinois.edu/cs421/fa2023/

Based heavily on slides by Elsa Gunter, which were based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha

Objectives for Today

- We want to turn strings (code) into computer instructions
- Done in **phases**
  - Turn strings into abstract syntax trees (**parse**)
  - Translate abstract syntax trees into executable instructions (**interpret** or **compile**)
- Today we will learn the first step of parsing, which is **lexing** those raw input strings into **tokens**

Questions from last week?

Syntax

Meta-discourse

- Language **Syntax** and **Semantics**
- **Syntax**: form
  - Regular Expressions, DFSAs and NDFSAs
  - Grammars
- **Semantics**: meaning
  - Natural Semantics
  - Transition Semantics
- Compilers and interpreters (when correctly implemented) **map** from the **syntax** of programs (as written) to their **semantics** (as executed)

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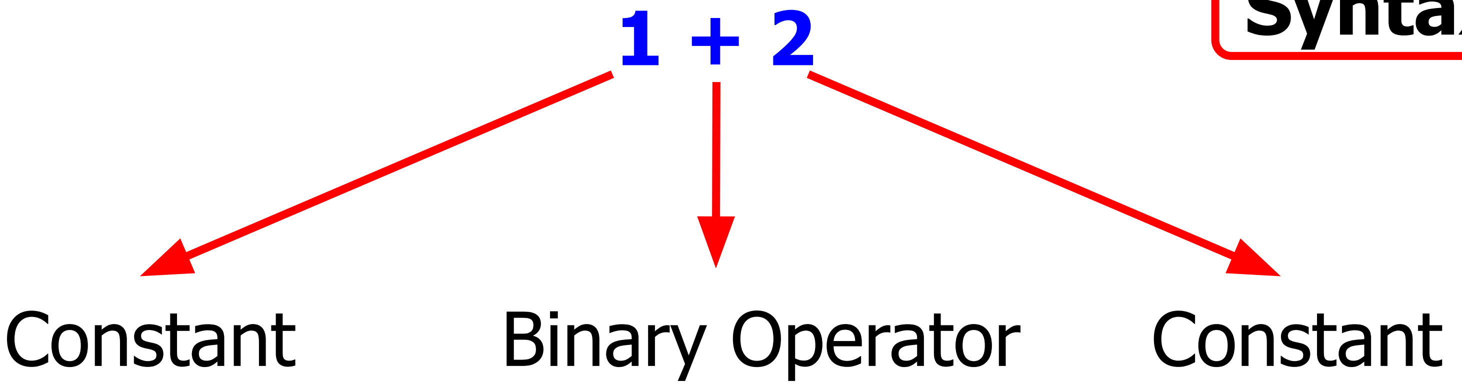
Meta-discourse

Syntax



1 + 2

Constant

Binary Operator

Constant

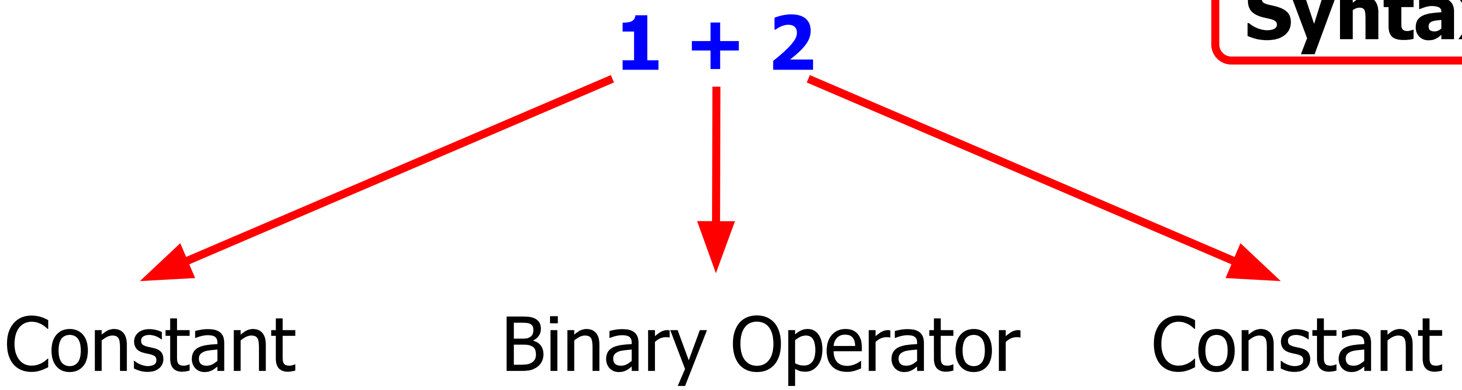
---

1 + 2 = 3

Semantics

Meta-discourse

Syntax



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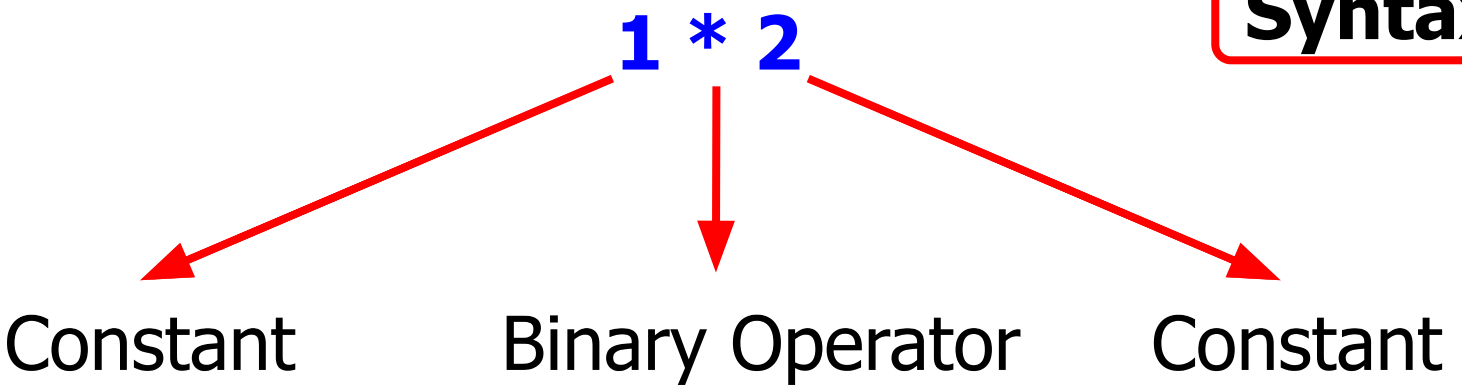

1 * 2

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(Bizarre) Semantics

Meta-discourse

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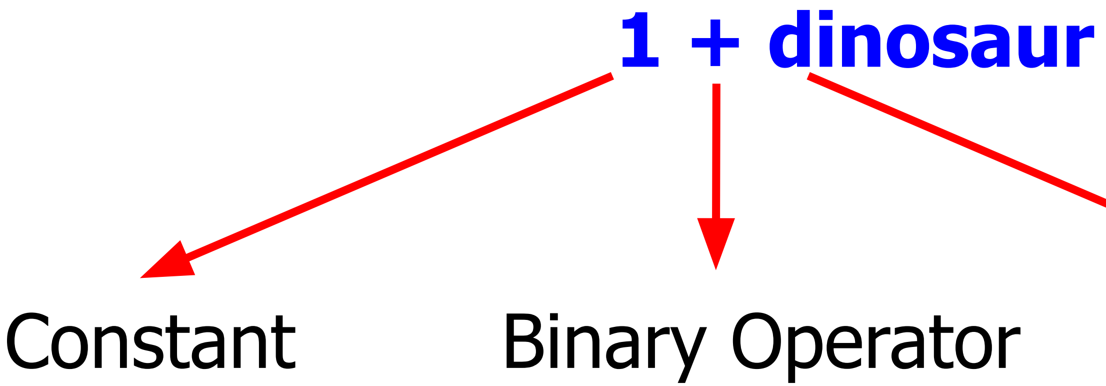

1 + dinosaur

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Binary Operator

Constant

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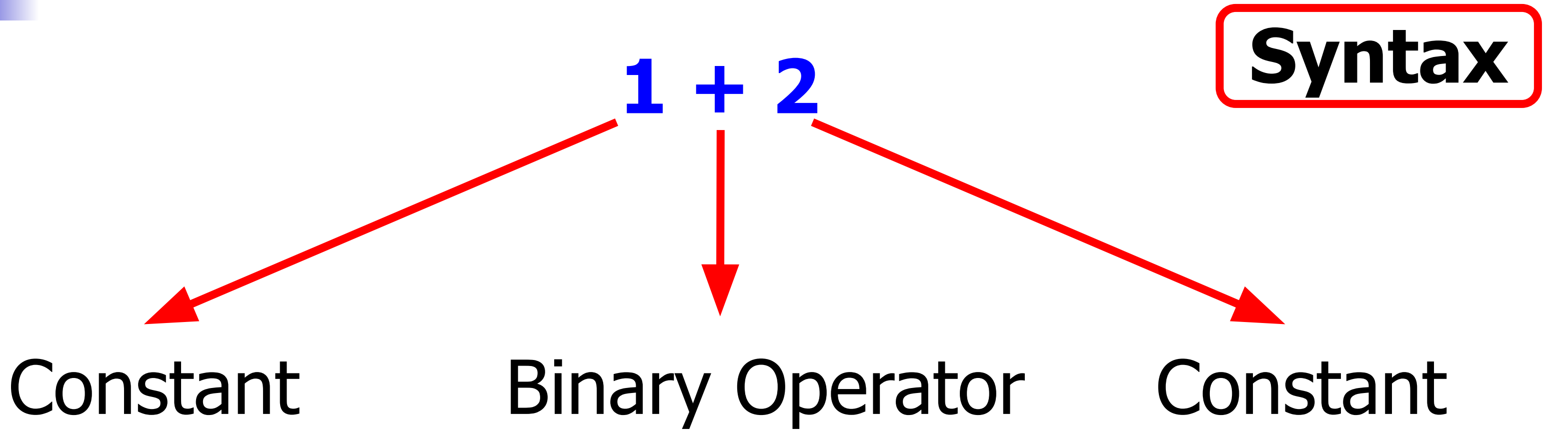
(Bizarre) Semantics

Meta-discourse



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Semantics

Language Syntax

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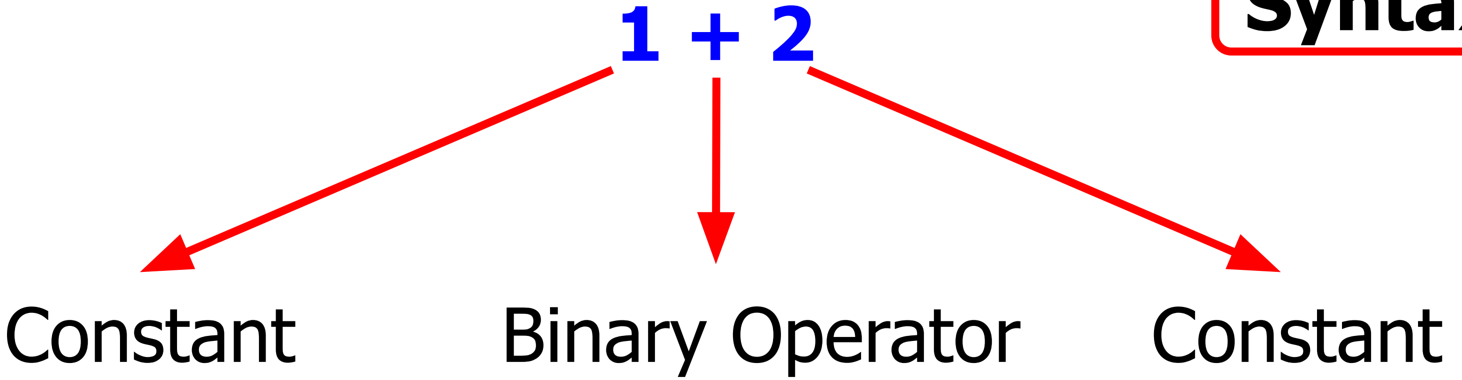

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Language Syntax

- **Syntax** describe which strings of **symbols** are meaningful **expressions** in a language
- It takes more than syntax to **understand** a language; need meaning (**semantics**) too
- **Syntax is the entry point**

Questions so far?

Lexing

Lexing and Parsing

- Converting strings (representing programs) to abstract syntax trees done in **two phases**:
  - **Lexing:** Converting **strings** (or streams of characters) into lists/streams of **tokens** (the "words" of the language)
    - Specification Technique: Regular Expressions
  - **Parsing:** Convert lists/streams of **tokens** into **abstract syntax trees**
    - Specification Technique: BNF Grammars

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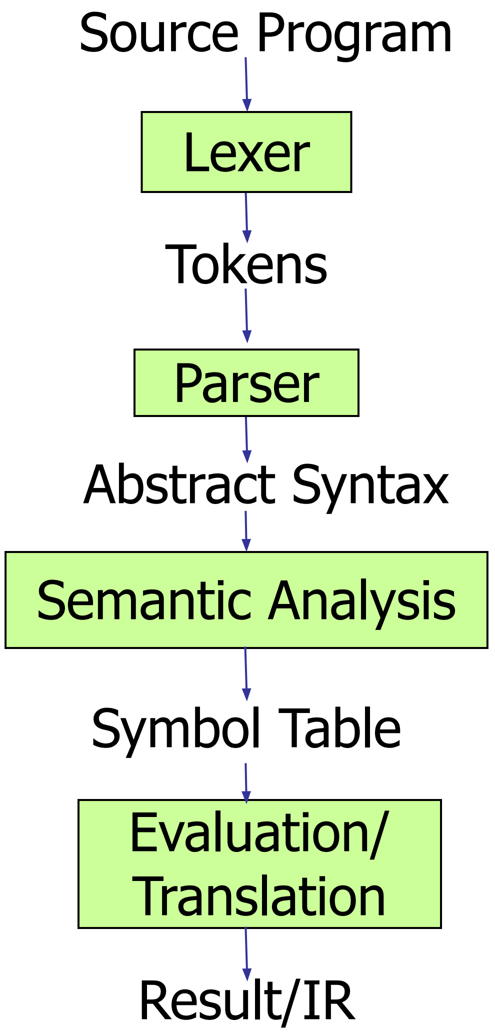
Lexing and Parsing



Source Program

Lexer

Tokens

Parser

Abstract Syntax

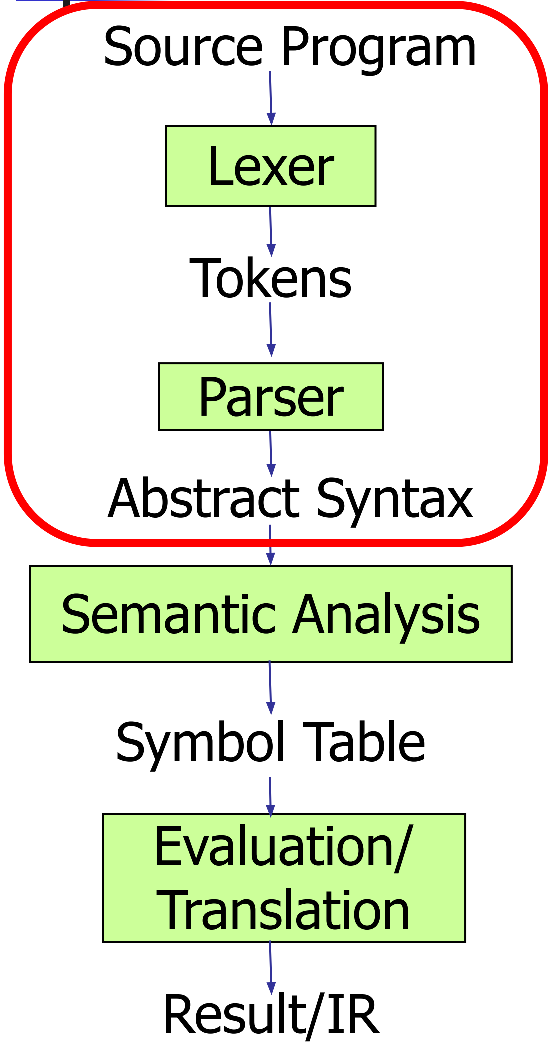
Semantic Analysis

Symbol Table

Evaluation/
Translation

Result/IR

Lexing and Parsing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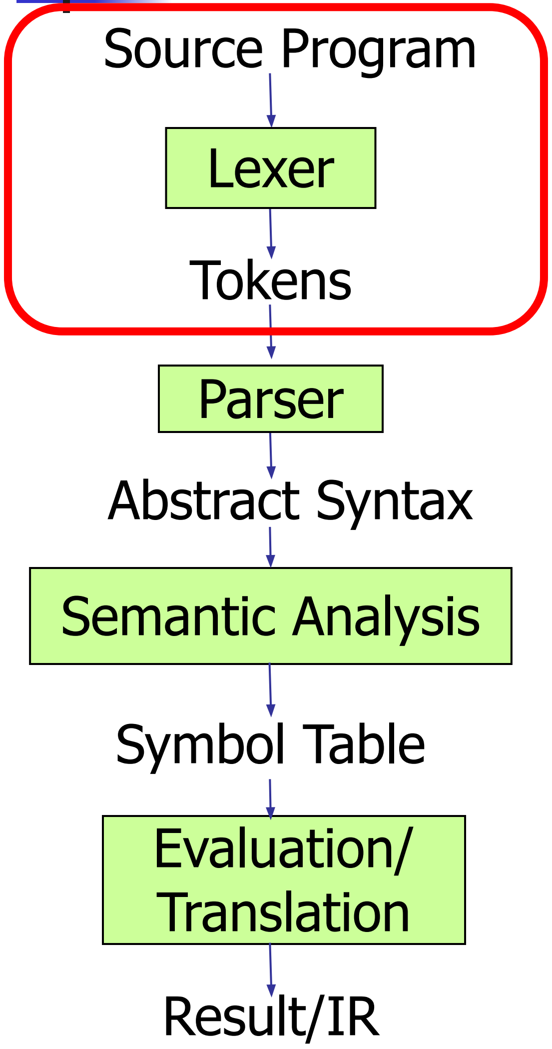

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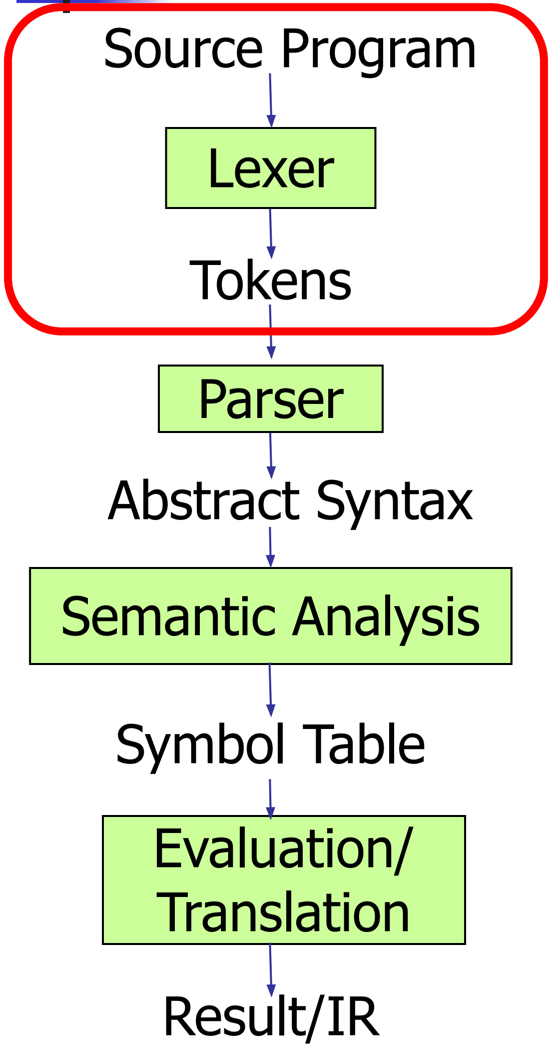

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Tokens just tell us what category each part of the input falls into.

Lexing

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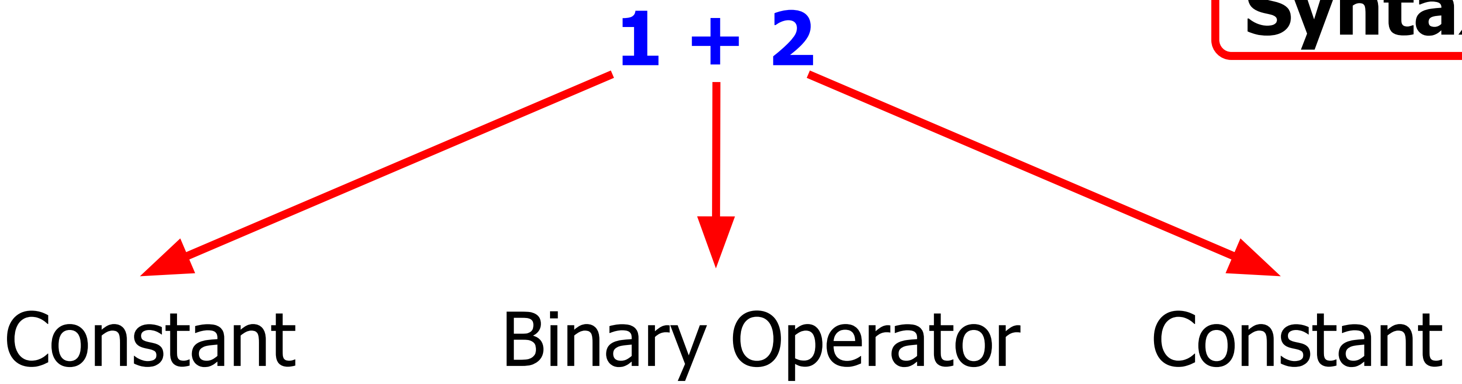

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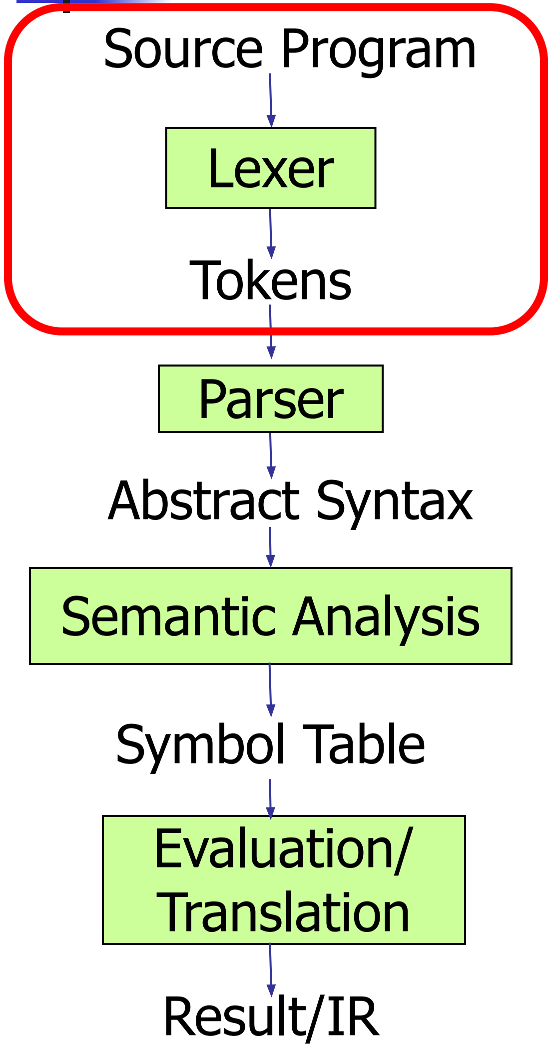

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Regular Expressions

Regular Expressions - Review

- Start with given character set (**alphabet**):
  - For example, {a, b, c, … }
- **Empty Set:**
  - $L(\Phi) = \{ \}$
- **Empty String:**
  - $L(\boldsymbol{\varepsilon}) = \{\text{“”}\}$
- **Literals:** Each **character** is a regular expression
  - Represents the set of one string containing just that character
  - $L(\mathbf{a}) = \{a\}$

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Regular Expressions - Review

- If **x** and **y** are regular expressions, then their **concatenation xy** is a regular expression
  - Represents the set of strings made from first a string described by **x** then a string described by **y**
  - $L(xy) = L(x) \times L(y)$. e.g., if $L(x) = \{a, ab\}$ and $L(y) = \{c, d\}$, then $L(xy) = \{ac, ad, abc, abd\}$
- If **x** and **y** are regular expressions, then their **alternation x** $\vee$ **y** (sometimes **x | y**) is too
  - Represents the set of strings described by **x** or **y**
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Regular Expressions - Review

- **Grouping:** If **x** is a regular expression, so is **(x)**
  - Represents the same thing as **x**
- **Repeat:** If **x** is a regular expression, then so is **x***
  - It represents strings made from concatenating zero or more strings from **x**
  - $L(x^*) = L(\varepsilon) \cup L(x) \cup (L(x) \times L(x)) \cup \ldots$ e.g., if $L(x) = \{a, ab\}$, then $L(x^*) = \{\text{“”}, a, ab, aa, aab, abab, \ldots\}$

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Aside for Math Nerds

- On a given alphabet, these form a **semiring**:
  - Φ is 0 **(additive identity)**
  - ε is 1 **(multiplicative identity)**
  - x ∨ y is x + y **(addition)**
  - xy is x · y **(multiplication)**
  - If curious, try proving the semiring laws :)
- Special kind—a (star-continuous) **Kleene algebra**:
  - The Kleene star x* can be viewed as the infinite sum of powers of x (the **closure**)
  - Furthermore, we have x + x = x **(idempotence)**
  - Imposes a partial ordering and other goodies!

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Example Regular Expressions

- **$(0 \vee 1)^*1$**
  - Set of all strings of **0**s and **1**s ending in **1**
  - **{1, 01, 11,…}**
- **a*b(a*)**
  - Set of all strings of **a**s and **b**s with exactly one **b**
- **$((01) \vee (10))^*$**
  - You tell me
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Questions so far?

Equivalently…

Right Regular Grammars

- Subclass of BNF (covered in detail soon)
- Only rules of form
  <nonterminal> ::= <terminal><nonterminal> or
  <nonterminal> ::= <terminal> or
  <nonterminal> ::= ε
- Defines **same class of languages** as **regular expressions**
- Important for writing **lexers** (programs that convert strings of characters into strings of tokens)
- Connection to **nondeterministic finite state automata**: nonterminals ≅ states; rule ≅ edge

Example

- Right regular grammar:

  <Balanced> ::= ε

  <Balanced> ::= 0<OneAndMore>

  <Balanced> ::= 1<ZeroAndMore>

  <OneAndMore> ::= 1<Balanced>

  <ZeroAndMore> ::= 0<Balanced>

- Generates **even length strings** where **every initial substring of even length** has **same number** of **0**s as **1**s

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Implementing Regular Expressions

- Regular expressions can be **good** for **generating** strings in language
- They are **not so good** for **recognizing** when a string is in language
- **Problems**:
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- **Answer**: finite state automata
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Example: Lexing

- Regular expressions good for **describing lexemes (words)** in a programming language
  - **Identifier** = $(a \vee \ldots \vee z \vee A \vee \ldots \vee Z)$ $(a \vee \ldots \vee z \vee A \vee \ldots \vee Z \vee 0 \vee \ldots \vee 9)^*$
  - **Digit** = $(0 \vee 1 \vee \ldots \vee 9)$
  - **Number** = $0 \vee (1 \vee \ldots \vee 9)(0 \vee \ldots \vee 9)^* \vee$ $\sim (1 \vee \ldots \vee 9)(0 \vee \ldots \vee 9)^*$
  - **Keywords**: if = if, while = while,…

Lexing

- Different syntactic categories of “words”: **tokens**
- **Example**:
  - Convert sequence of characters into sequence of strings, integers, and floating point numbers
  - "asd 123 jkl 3.14" will become: [String "asd"; Int 123; String "jkl"; Float 3.14]
- Could write the regular expression, then translate to DFA by hand, but this is a lot of work
- Better: Write **program** to translate automatically
- **Lex** is such a program (**ocamllex** for ocaml)

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Lex

How to Lex

- To lex, we need:
  - A way to identify input strings (a **lexing buffer**)
  - A set of **regular expressions** to match against
  - A corresponding **set of actions** to take

Regexes

Lexing Buffer

Actions

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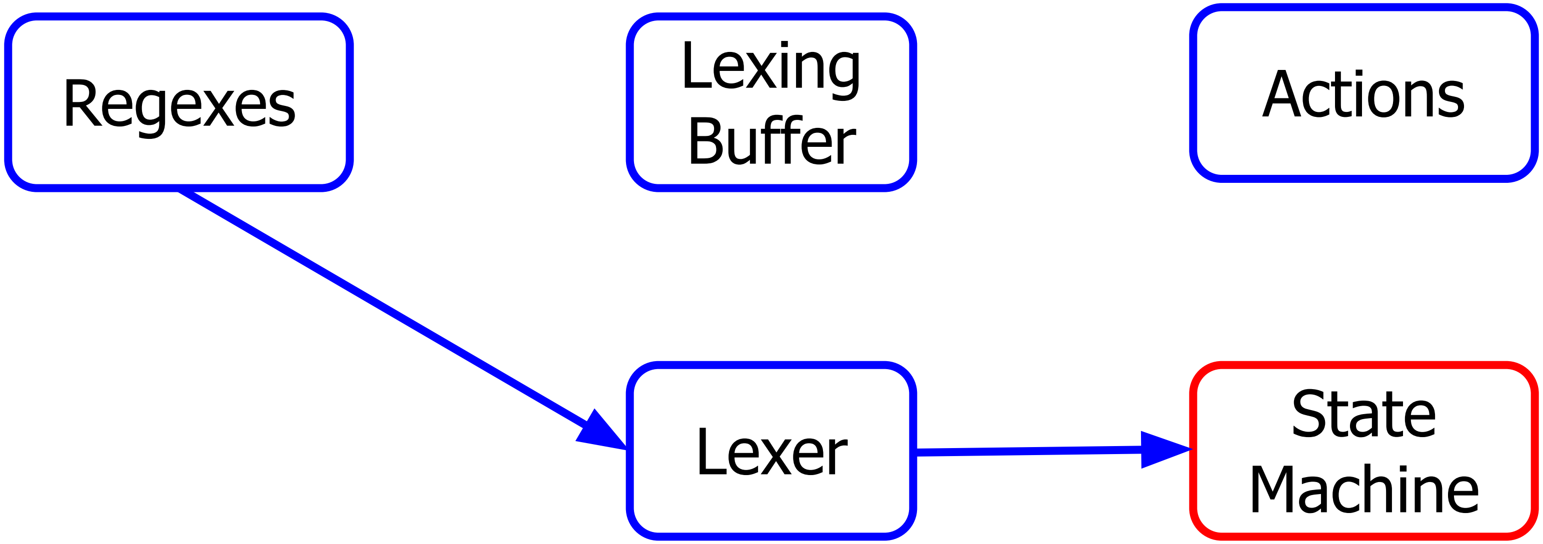

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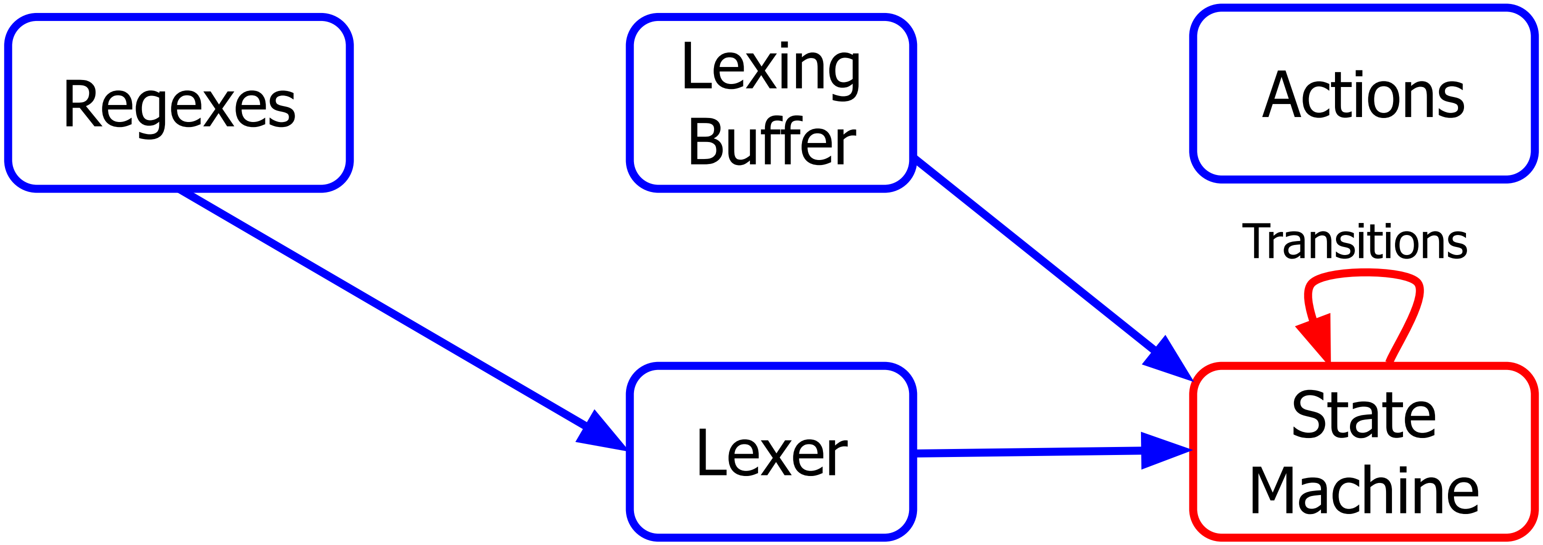

Regexes

Lexing Buffer

Actions

Transitions

Lexer

State Machine

How to Lex

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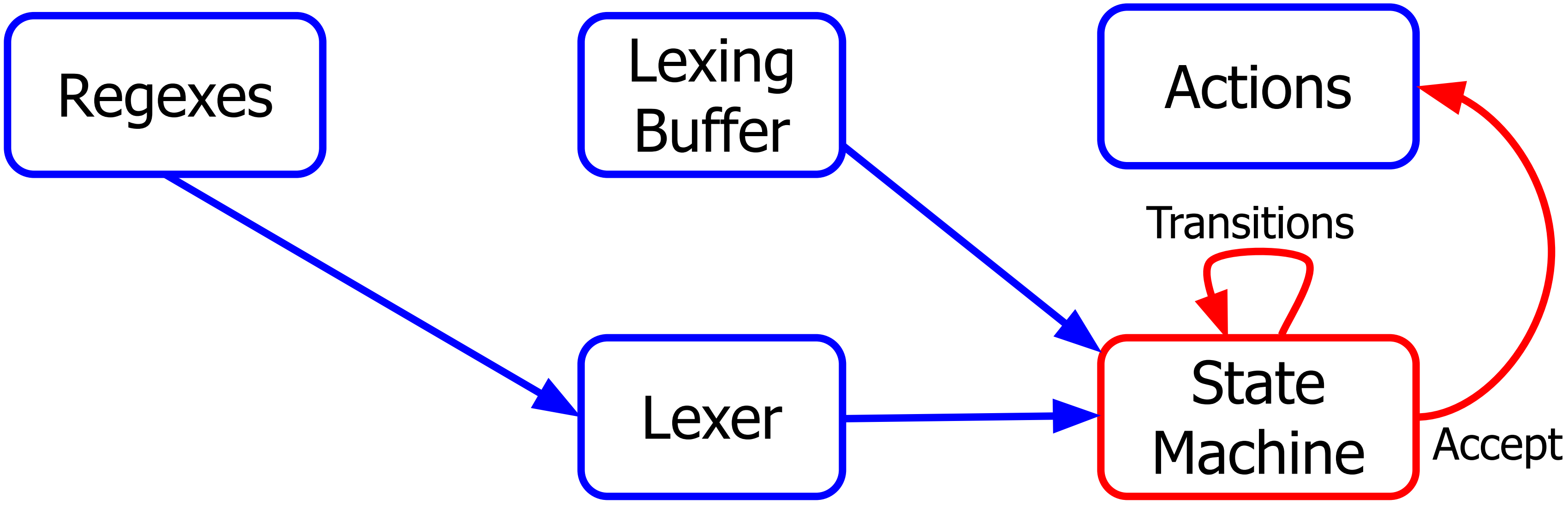

Ocamllex Mechanics

- Put **table** of **regular expressions** and corresponding **actions** (in OCaml) into a file:
  <*filename*>.mll
- **Call**:
  ocamllex <*filename*>.mll
- Produces **OCaml code** for a **lexical analyzer** in
  <*filename*>.ml

Sample Input

```
rule main = parse
| ['0'-'9']+ { print_string "Int\n"}
| ['0'-'9']+'.'['0'-'9']+ { print_string "Float\n"}
| ['a'-'z']+ { print_string "String\n"}
| _ { main lexbuf }
{
  let newlexbuf = Lexing.from_channel stdin in
  main newlexbuf
}
```

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let digits = ['0'-'9']+
let chars = ['a'-'z']+
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| _ { main lexbuf }
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General Input

{ *header* }
let *ident* = *regexp* …
rule *entrypoint* [*arg1*… *argn*] = parse
| *regexp* { *action* }
| …
| *regexp* { *action* }
and *entrypoint* [*arg1*… *argn*] = parse
| …
and …
{ *trailer* }

These contain **arbitrary ocaml code** put at top and bottom of <*filename*>.ml

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This **introduces a variable** *ident* for use in later regular expressions

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and …

{ *trailer* }

Each *entrypoint* corresponds to **one lexing function** in <*filename*>.ml

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| *regexp* { *action* }

| …

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| …

and …

{ *trailer* }

The **name** of that lexing function is the name given for *entrypoint*

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and …

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Each becomes an OCaml function that takes *n+1* **arguments** …

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The first *n* arguments are those defined here explicitly.

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and …
{ *trailer* }

Each argument *arg1* … *argn* is available for use in *action*

General Input

{ *header* }
let *ident* = *regexp* …
rule *entrypoint* [*arg1*… *argn*] = parse
| *regexp* { *action* }
| …
| *regexp* { *action* }
and *entrypoint* [*arg1*… *argn*] = parse
| …
and …
{ *trailer* }

The extra implicit last argument has type Lexing.lexbuf

Ocamllex Regular Expression

- Single quoted characters for letters: ‘a’
- _: (underscore) matches any letter
- Eof: special “end_of_file” marker
- Concatenation same as usual
- “*string*”: concatenation of sequence of characters
- $e_1 \mid e_2$: choice - what was $e_1 \vee e_2$
- $[c_1 - c_2]$: choice of any character between first and second inclusive, as determined by character codes
- $[\hat{}c_1 - c_2]$: choice of any character NOT in set

Ocamllex Regular Expression

- e*: same as before
- $e+$: same as $e\ e^*$
- $e?$: option - was $e \vee \varepsilon$
- e_1 # e_2: the characters in e_1 but not in e_2; e_1 and e_2 must describe just sets of characters
- *ident*: abbreviation for earlier reg exp in let *ident* = *regexp*
- e_1 as *id*: binds the result of e_1 to *id* to be used in the associated *action*

Ocamllex Manual

More details can be found at:
https://v2.ocaml.org/releases/4.14/htmlman/lexyacc.html

Example : test.mll

```
{
  (* header *)
  type result = Int of int | Float of float | String of string
}
(* variables for reference in later regular expressions *)
let digit = ['0'-'9']
let digits = digit +
let lower_case = ['a'-'z']
let upper_case = ['A'-'Z']
let letter = upper_case | lower_case
let letters = letter +
```

Example : test.mll

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  (* header *)
  type result = Int of int | Float of float | String of string
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```

Example : test.mll

```
rule main = parse    (* entrypoint called “main” *)
 | (digits)'.'digits as f  { Float (float_of_string f) }
 | digits as n              { Int (int_of_string n) }
 | letters as s             { String s}
 | _                         { main lexbuf }
 {
   (* trailer *)
   let newlexbuf = (Lexing.from_channel stdin) in
   print_newline ();
   main newlexbuf
 }
```

Example : test.mll

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rule main = parse     (* entrypoint called “main” *)
 | (digits)'.'digits as f  { Float (float_of_string f) }
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```

Example : using generated file

```
# #use "test.ml";;
…
val main : Lexing.lexbuf -> result = <fun>
val __ocaml_lex_main_rec :
  Lexing.lexbuf -> int -> result = <fun>
hi
- : result = String "hi”
```

Example : using generated file

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# #use "test.ml";;
…
val main : Lexing.lexbuf -> result = <fun>
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Example : using generated file

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# #use "test.ml";;
…
val main : Lexing.lexbuf -> result = <fun>
val __ocaml_lex_main_rec :
  Lexing.lexbuf -> int -> result = <fun>
hi there 234 5.2
- : result = String "hi”
```

Example : using generated file

```
# #use "test.ml";;
…
val main : Lexing.lexbuf -> result = <fun>
val __ocaml_lex_main_rec :
  Lexing.lexbuf -> int -> result = <fun>
hi there 234 5.2
- : result = String "hi”
```

What happened to the rest?

Example : using generated file

```
# let b = Lexing.from_channel stdin;;
# main b;;
hi 673 there
- : result = String "hi"
# main b;;
- : result = Int 673
# main b;;
- : result = String "there"
```

Recall the hidden argument of type lexbuf

Example : using generated file

```
# let b = Lexing.from_channel stdin;;
# main b;;
hi 673 there
- : result = String "hi"
# main b;;
- : result = Int 673
# main b;;
- : result = String "there"
```

Recall the hidden argument of type lexbuf

Example : using generated file

```
# let b = Lexing.from_channel stdin;;
# main b;;
hi 673 there
- : result = String "hi"
# main b;;
- : result = Int 673
# main b;;
- : result = String "there"
```

Recall the hidden argument of type lexbuf

Questions so far?

Your Turn

- Work on MP8
  - Add a few keywords
  - Implement booleans and unit
  - Implement Ints and Floats
  - Implement identifiers

Questions?

Next Class

- **EC2 is up**
- **Quiz 4** on **MP7** is **Tuesday**
  - **Please show up!**
  - **Extra chance for ADT midterm question!**
- **WA7** due next **Thursday**
- All deadlines can be found on **course website**
- Use **office hours** and **class forums** for help