



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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Syntax

Meta-discourse

Syntax

1 + 2

Constant

Binary Operator

Constant

1 + 2 = 3

Semantics

Syntax

Meta-discourse

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1 + 2

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Semantics

Syntax

Meta-discourse

Syntax

1 * 2

Constant

Binary Operator

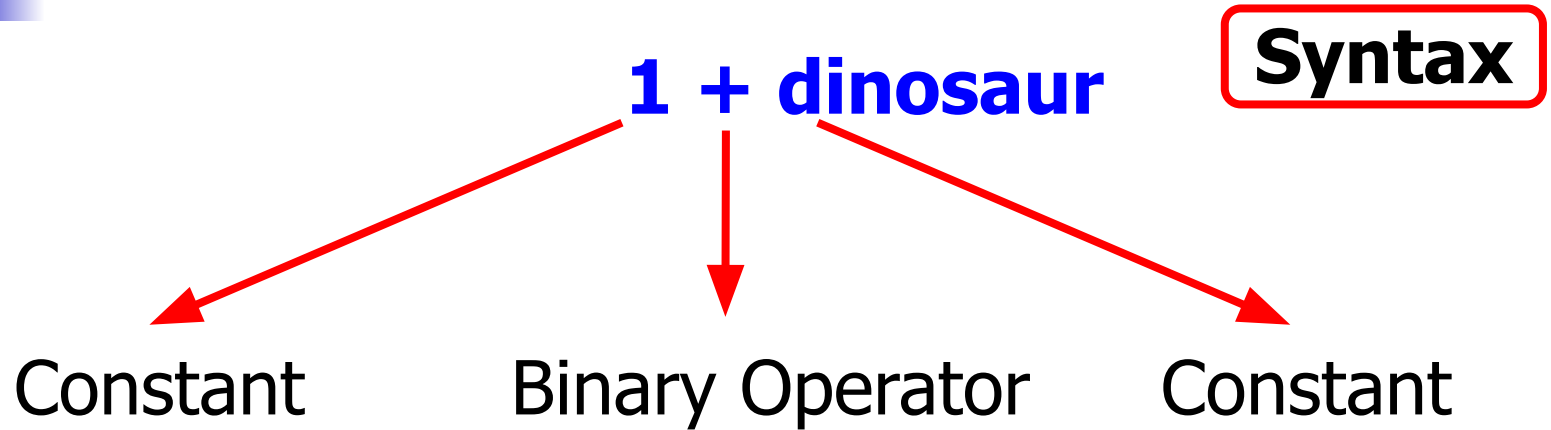
Constant

1 * 2 = 3

**(Bizarre)
Semantics**

Syntax

Meta-discourse



1 + dinosaur = 3

**(Bizarre)
Semantics**

Syntax

Meta-discourse

Syntax

1 + 2

Constant

Binary Operator

Constant

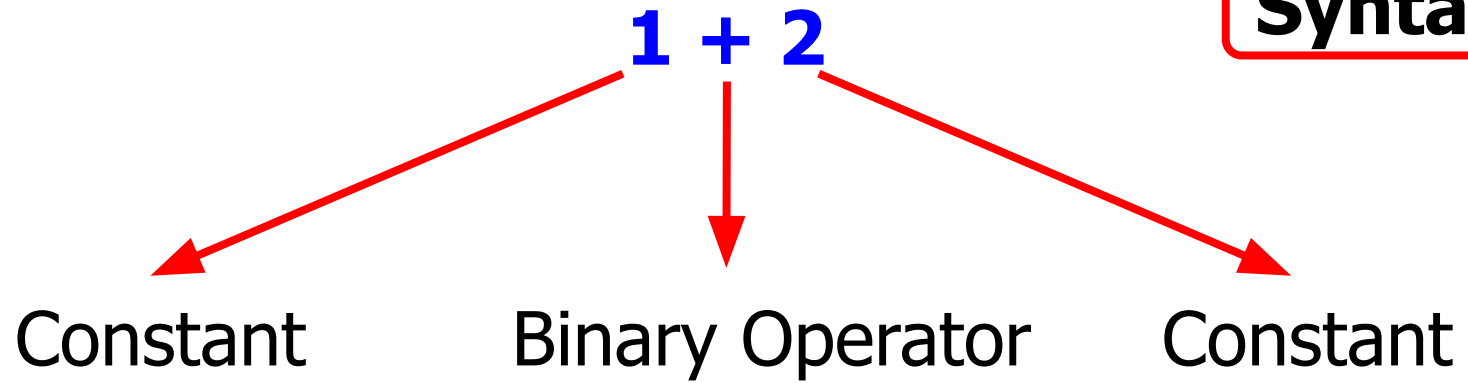
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Semantics

Syntax

Language Syntax

Syntax





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



Lexing and Parsing

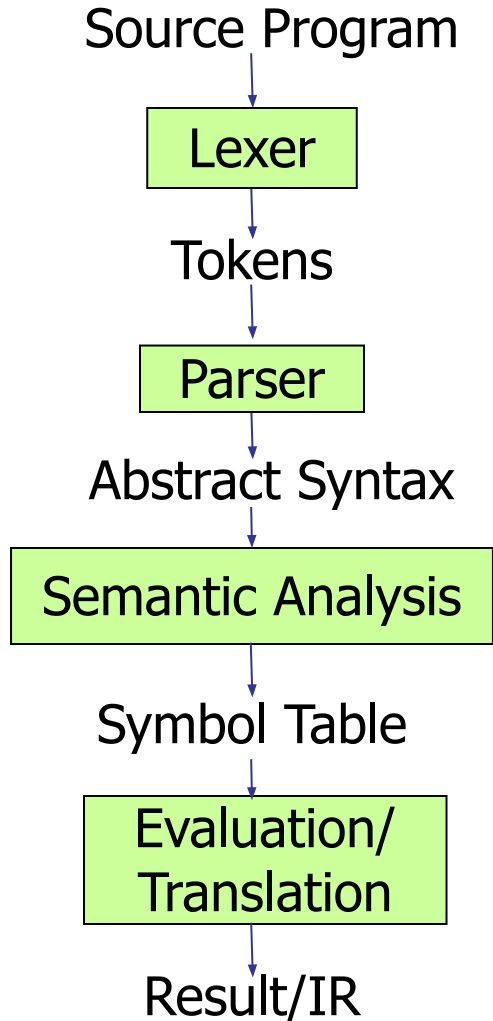
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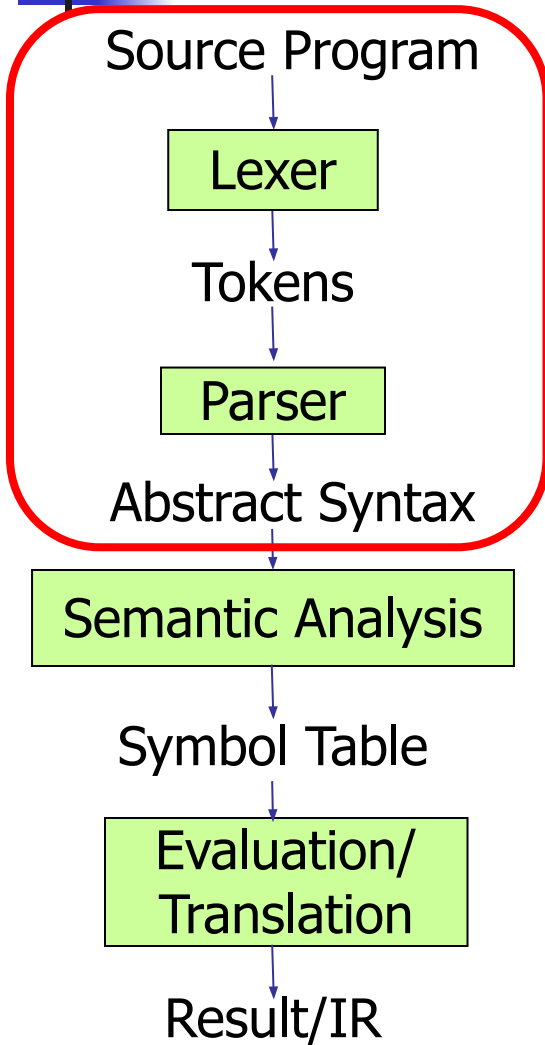
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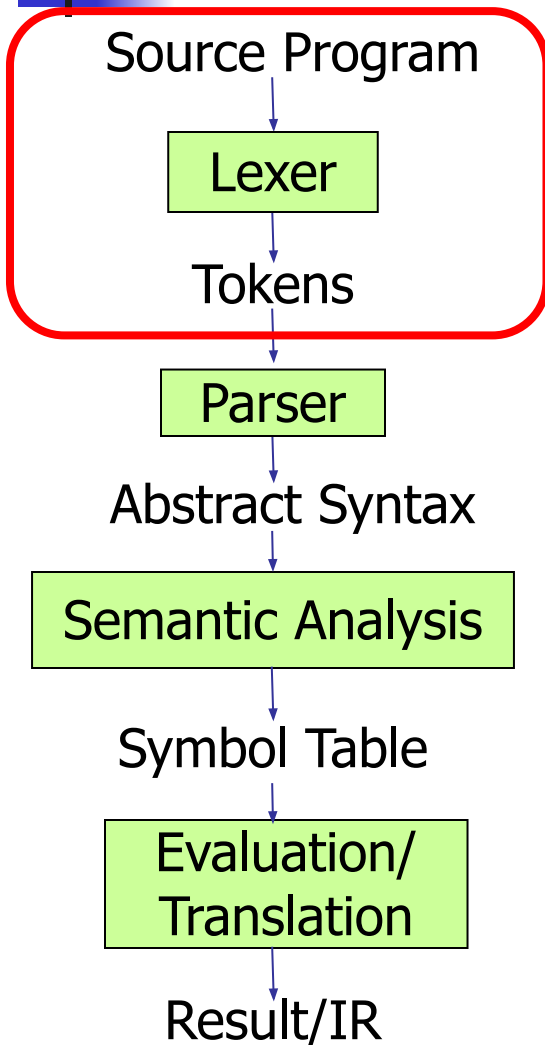
Lexing and Parsing



Lexing and Parsing

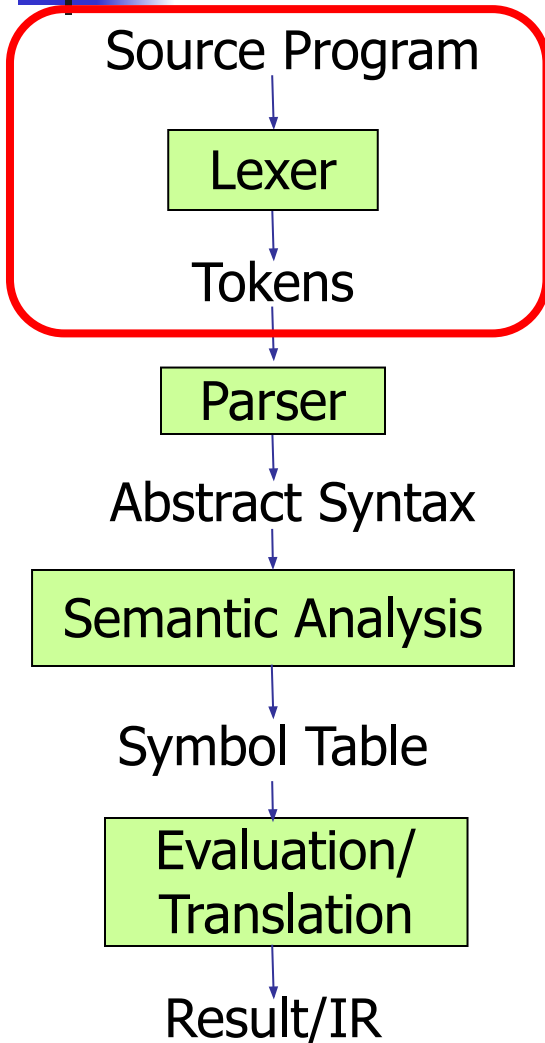


Lexing and Parsing



To **lex** our source program and get **tokens**, we need **regular expressions**, **automata**, and a specific kind of **grammar**.

Lexing and Parsing

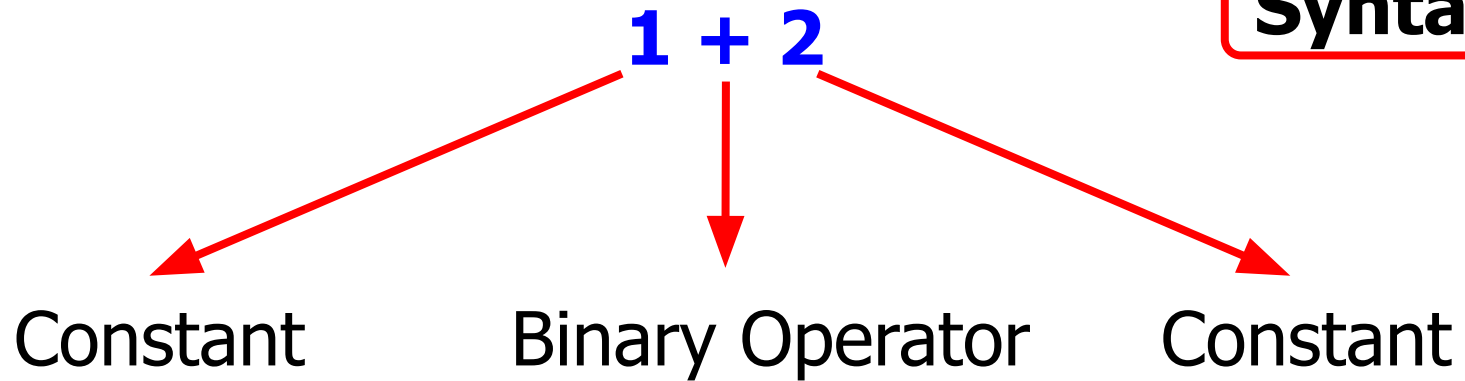


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Tokens just tell us what category each part of the input falls into.

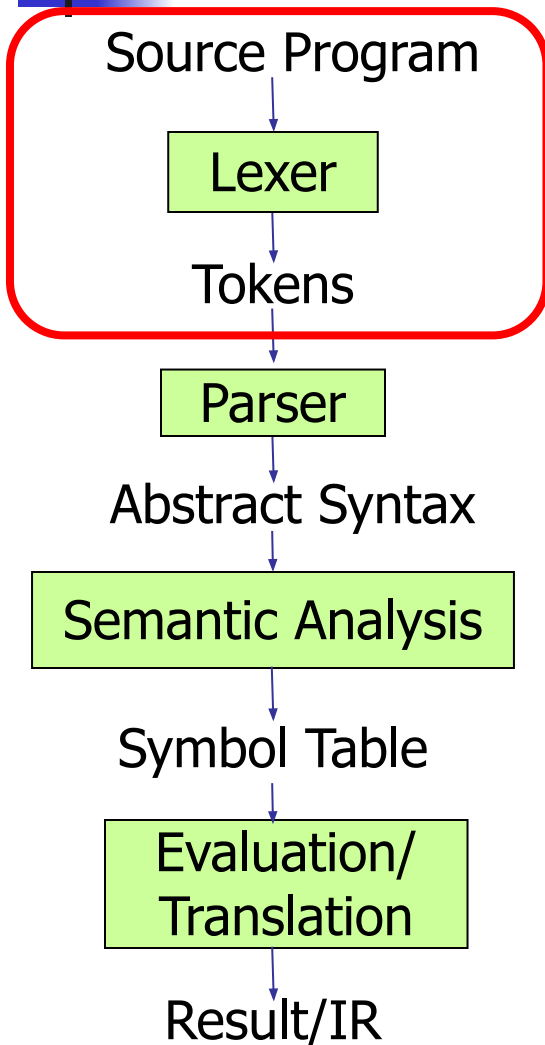
Lexing and Parsing

Syntax



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Lexing and Parsing



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Regular Expressions



Regular Expressions - Review

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



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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**
 - $L(x \vee y) = L(x) \cup L(y)$. e.g., if $L(x) = \{a, ab\}$ and $L(y) = \{c, d\}$, then $L(x \vee y) = \{a, ab, c, d\}$

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Regular Expressions



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**
 - $L(x^*) = L(\epsilon) \cup L(x) \cup (L(x) \times L(x)) \cup \dots$ e.g.,
if $L(x) = \{a, ab\}$, then $L(x^*) = \{\epsilon, a, ab, aa, aab, abab, \dots\}$

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Aside for Math Nerds

- On a given alphabet, these form a **semiring**:
 - \emptyset is **0 (additive identity)**
 - ε is **1 (multiplicative identity)**
 - $x \vee y$ is **$x + y$ (addition)**
 - xy is **$x \cdot y$ (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!

Regular Expressions



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Regular Expressions



Example Regular Expressions

- **$(0 \vee 1)^*1$**

- Set of all strings of **0**s and **1**s ending in **1**

- **$\{1, 01, 11, \dots\}$**

- **$a^*b(a^*)$**

- 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 \cong states; rule \cong edge
- Regular Expressions



Example

- Right regular grammar:

$\langle \text{Balanced} \rangle ::= \varepsilon$

$\langle \text{Balanced} \rangle ::= 0 \langle \text{OneAndMore} \rangle$

$\langle \text{Balanced} \rangle ::= 1 \langle \text{ZeroAndMore} \rangle$

$\langle \text{OneAndMore} \rangle ::= 1 \langle \text{Balanced} \rangle$

$\langle \text{ZeroAndMore} \rangle ::= 0 \langle \text{Balanced} \rangle$

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



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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:**
 - Which option to choose?
 - How many repetitions to make?
- **Answer:** finite state automata
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Example: Lexing

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

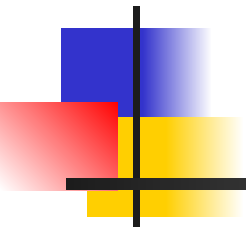


Lexing

- 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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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

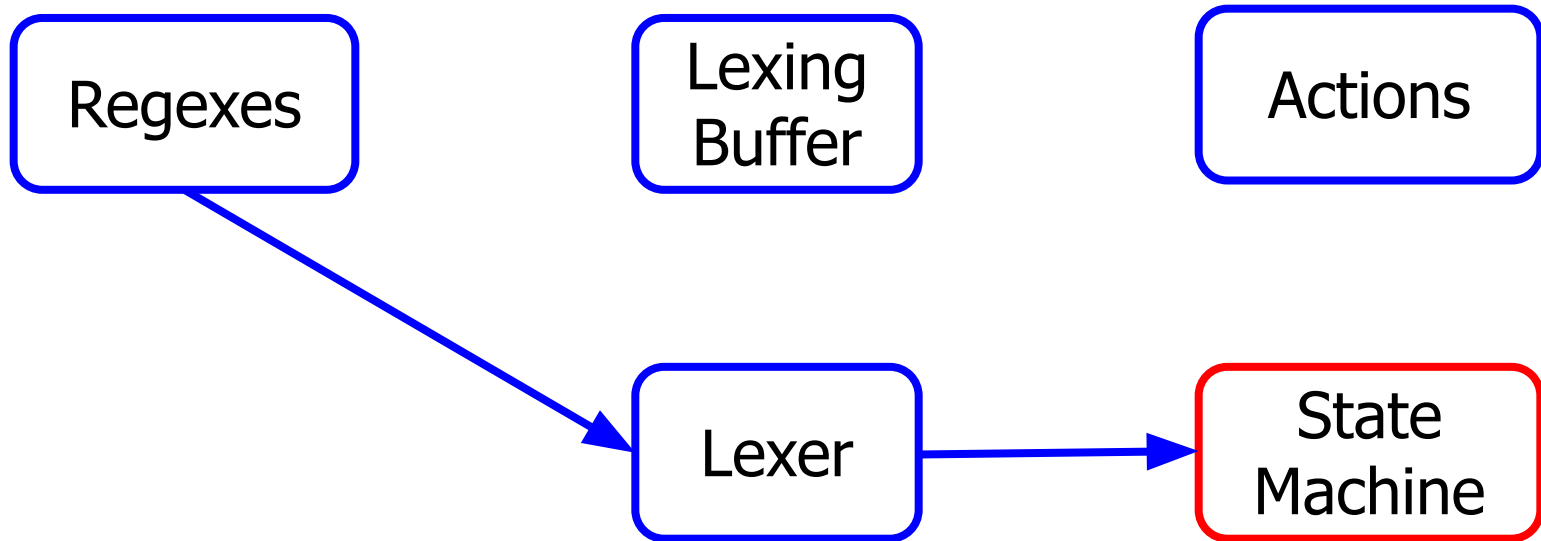
Regexes

Lexing
Buffer

Actions

How to Lex

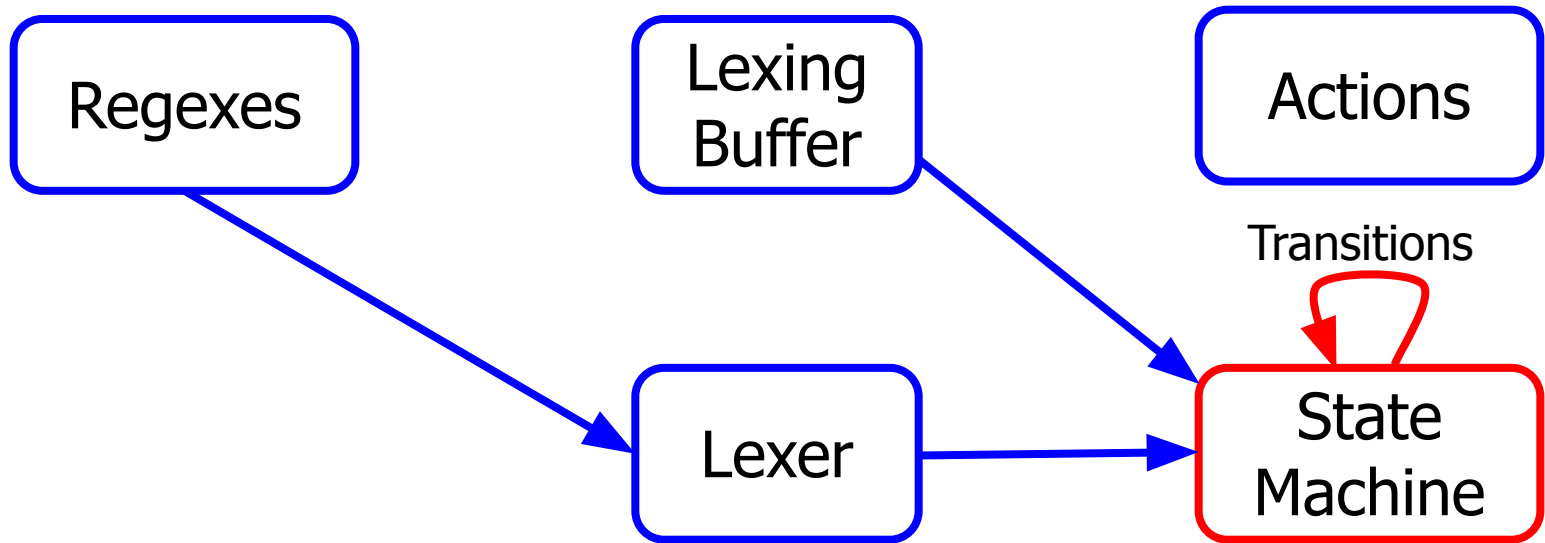
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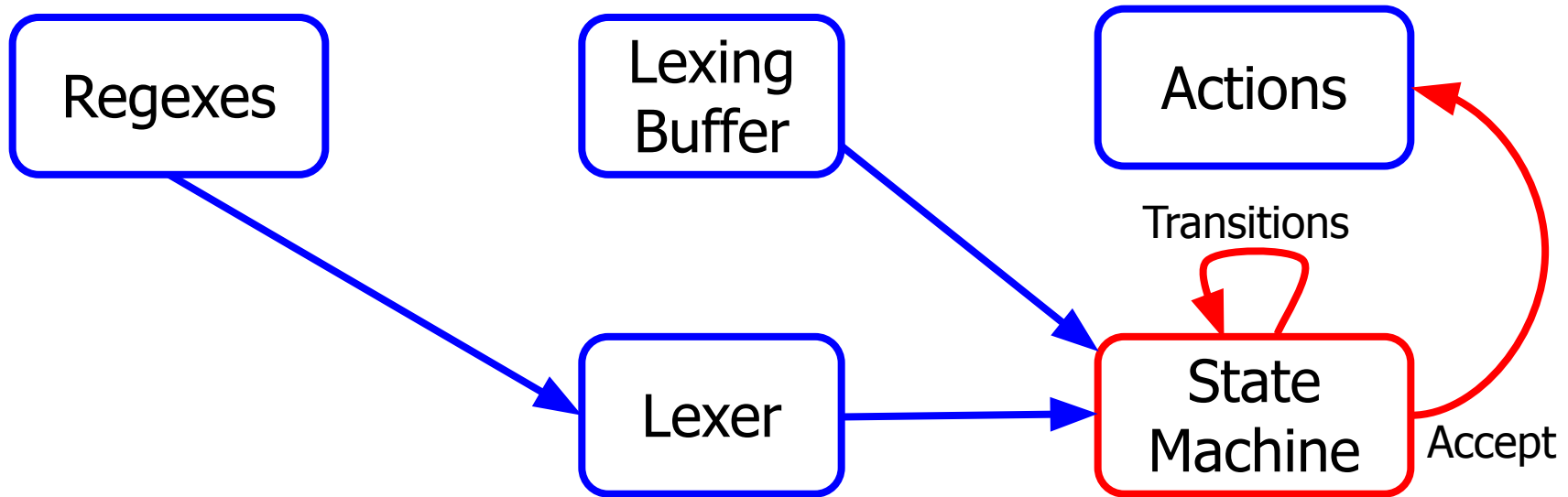
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Lex



Ocamlex 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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Sample Input

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



General Input

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rule *entrypoint* [*arg1*... *argn*] = parse

| *regex* { *action* }

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



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

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| *regexp* { *action* }

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

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

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rule *entrypoint* [*arg1*... *argn*] = parse

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

General Input

{ *header* }

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rule *entrypoint* [*arg1*... *argn*] = parse

| *regex* { *action* }

| ...

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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* }

| ...

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and *entrypoint* [*arg1*... *argn*] = parse

| ...

and ...

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The extra implicit last argument
has type `Lexing.lexbuf`

Ocamlex 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 / 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
- $[^c_1 - c_2]$: choice of any character NOT in set

Ocamlex Regular Expression

- e^* : same as before
- $e+$: same as $e e^*$
- $e?$: option - was $e \vee \epsilon$
- $e_1 \# e_2$: 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.ml

```
{  
  (* 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

```
{
  (* header *)
  type result = Int of int | Float of float | String of string
}
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let lower_case = ['a'-'z']
let upper_case = ['A'-'Z']
let letter = upper_case | lower_case
let letters = letter +
```



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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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

```
# #use "test.ml";;
```

```
...
```

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val main : Lexing.lexbuf -> result = <fun>
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```
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```

```
Lexing.lexbuf -> int -> result = <fun>
```

```
hi there 234 5.2
```

```
- : result = String "hi"
```

Example : using generated file

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# #use "test.ml";;
```

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```
val main : Lexing.lexbuf -> result = <fun>
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```
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