### Scanner

Ronghui Gu Fall 2022

Columbia University

\* Course website: https://verigu.github.io/4115Fall2022/

\*\* These slides are borrowed from Prof. Edwards.

# **The Big Picture**

#### How do we describe/construct a program?

#### Use continuously varying values?



#### Very efficient, but has serious noise issues

Edison Model B Home Cylinder phonograph, 1906

### The ENIAC: Programming with Spaghetti



#### Have one symbol per program?



#### Not so good when there are many, many things

Nippon Typewriter SH-280, 2268 keys

#### Solution: Use a Discrete Combinatorial System

Use combinations of a small number of things to represent (exponentially) many different things.











#### **Every Human Writing System Does This**



Hieroglyphics (24+)



Cuneiform (1000 - 300)



Sanskrit (36)



Chinese (214 - 4000)



IBM Selectric (88-96)



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# How do we describe the combinations of a small number of things.

#### Just List Them?



Gets annoying for large numbers of combinations

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A A A A A A A A CBS Moving 130 Lansdowne , 533-7139 A A A A A A A A A A Big Apple Escort Service . 465-2767 AAAAAAAAA Accident And Accompanying Injuries&Criminal Practice 1018 FinchW . 663-2211 A A A A A A A A A A A Accident Accompanying Injuries&Criminal Practice 1018 FinchW . 663-2211 AAAAAAAAA China Blue Escort Service, 323-9522 A A A A A A A A A A A AAABCO Door Co 1860 BonhillRd Mississauga, 748-3667 A A A A A A A A A A A A Action Law 5233 DundasStW . 253-0888 A A A A A A A A A A A Alert Auto Glass, 398-4585 ..... 599-3410 AAAAAAAAAA AMJ Campbell Van Lines Inc 1190 MeyersideDr. 213-5660 A A A A A A A A A A A A Auto Glass Hotline \_ 283-0042 A A A A A A A A A A A Collins&Greig Cartage Ltd 33 Coronet, 239-2991 A A A A A A A A A A A Competition Auto Glass, 223-1292 A A A A A A A A A A A Competition Auto Glass \_ 283-0042 A A A A A A A A A A A Competition Auto Glass 410-7693 A A A A A A A A A A A International Escorts 929-6848 A A A A A A A A A A A Jewel Dating&Escort Service . 461-0629 A A A A A A A Marketing Services . 413-0444 A A A A A A A A A A A Nothing But Class 595,1884 A A A A A A A A A A A On The Wild Side Sensational Female Escort Service, 255-1320 A A A A A A A A A A A The Good Life Clubs 21 McCaul, 979-1422 If Busy Call 667-0470 A A A A A A A A A A A A A A Affordable And Aggressive Defence 4950 YongeSt. 221-7108 A A A A A A A A A A A Campbell Moving Systems 265-4433 Go 159 Dynevor, 787-8039 A A A A A A A A A A A A Sunset Escorts , 622-1177 A A A A A A A A A A A A Best Of The Best, 929-3039 A A A A A A A A A A A A A Bill&Son Towin 286 RoyalYork . 255-8518

#### A A A A A A A A A A A A A Class Above Limousine 173 DanforthAv : 465-5643 Towing 18 Canso \_ 245-7676 AAAAAAAAAAAAA Cross Movers 1232-B Woodbine, 423-0239 **AAAAAAAAAAAA** Miss Victoria . 967-7176 A A A A A A A A A A A A A Pavless Escorts . 485-5333 A A A A A A A 700 LawrenceAvW . 256-1600 AAAAAA 699-6700 Mannie Zeller 255 DuncanMilRd, 441-9500 A Cohen& Associates 1 StClairE, 323-0907 AAAAAAAAAAAAAAAA A A A A A A A A A A A A A Aabaco Transmissions 285 OldKingston, 287-0000 Movers&Storage 17 Canso . 242-6662 AAAAAAAAAAAAAAAAAAAAAAAAAAAAA A A A A A A A A Abba Movers& Storage . 366-0237 \*\*\*\*\* 14-A Hazelton, 964-0138 ............. A A A A A A A A A A A A A Adrian The Mover 64 StClairW, 944-2018 **AAAAAAAAAAAAAAAAAAAAA** A A A A A Abba Auto Collision& Glass . 777-9595 AAAAAAAAAAAAAAAAA A A A A A A A A A A A A Armor Lock And Safe 6083 Yonge . 225-5589 AAAAAAAAAAAAAAAAAA A A A A A A A A A A Basement Systems Canada 38 Garnforth , 285-6002 AAAAAAAAAAAAAAAA AAAAAAAAAA A A A A A A A A Ad 3420 FinchE . 499-2144 AAAAAAAAAAAAAA A A A A A A A Law 305 Milner . 299-6688 Action Law 5233 DundasStW\_ 253-0888 **AAAAAAAAAAAAAAAAAAAAA** Allan&Associates 401 Bay, 363-5431 \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\* W Auto Glass 821 Kipling, 233-4773 A A A A A A A A A A A A A A A A A A Eagle Alarms 557 DixonRd , 247-0000 AAAAAAAAAAAAAAAAAAAAA Towing 18 Canso , 245-7676

**A A A A A A A A A A A** 

Claims 2 StClairW, 944-2313 Automatic Garage Doors Ftobicoke **AAAAAAAAAAAAAA**AAAAA Professional Express System Apple Auto Glass A A A AAABCO Door Co 1860 BonhillRid Mississauga A A A A A A B S Movers A AA AABBCCDEF Locksmith A A A A A B C Movers Inc AAAAA M O I Moving Systems 1860 BonhillRd Mississauga

\*\*\*\*\*\*

236 NorthQueen . 620-1212

Access

Practice 1000 FinchW, 663-2211

Rezz. 652-5252

Law: 784-2020

Robertson Moving&Storage

Accompanying Injuries&Criminal

AAAAAAAAAAAAA

Ability 2 SheppardAvE, 224-0750 A A A A A A A A A A A A A A A A A Advant Edge Door Systems 222-8322 Executive's Choice . 929-9390 64 Clarkson \_ 785-7820 252-5686 AAAAAAAAAAAAAAAAAAAAAAAA Cross Alarms 280 Consumers , 494-9777 A A A A A A A A A A A A A A A A Elegant Mature Escorts, 923-3333 475 AdelaideW 504,9111 **AAAAAAAAAAAAAAAAA** Escorts&You, 259-3940 A AAAA AAAA AAAA AAAA AAAA Anthony De Marco 1205 StClairW, 651-2295 A AAAA AAAA AAAA AAAA Domenic Tagliola 1205 StClairW, 651-2299 AAAAAAAAAAAAAAAAAAAA A Always Available 465-919 Class Escort Service . 461-8110 Toronto 748-3667 643 LansdowneAv 588-1499 80 StClairE . 922-2255 955 Middlefield, 299-4239 A A A A&B Moving 900 CaledoniaRd, 787-4964 A A A ABC Glass Supply 11 Concord. 531-1548 AAAABCO Door&Window Co Toronto 748-3667

Can be really redundant

#### **Scanning and Parsing**



# **Lexical Analysis**

### Lexical Analysis (Scanning)

#### Translate a stream of characters to a stream of tokens





Token	Lexemes	Pattern
EQUALS	=	an equals sign
PLUS	+	a plus sign
ID	a foo bar	letter followed by letters or digits
NUM	0 42	one or more digits



is not a C program<sup>†</sup>



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Scanners are usually much faster than parsers.



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Discard as many irrelevant details as possible (e.g., whitespace, comments).



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Scanners are usually much faster than parsers.

Discard as many irrelevant details as possible (e.g., whitespace, comments).

Parser does not care that the identifer is "supercalifragilisticexpialidocious."

Parser rules are only concerned with tokens.

 $^{\dagger}$  It is what you type when your head hits the keyboard

#### Alphabet: A finite set of symbols

Examples:  $\{ 0, 1 \}, \{ A, B, C, ..., Z \}, ASCII, Unicode$ 

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**String**: A finite sequence of symbols from an alphabet Examples:  $\epsilon$  (the empty string), Ronghui,  $\alpha\beta\gamma$  **Alphabet**: A finite set of symbols Examples: { 0, 1 }, { A, B, C, ..., Z }, ASCII, Unicode

**String**: A finite sequence of symbols from an alphabet Examples:  $\epsilon$  (the empty string), Ronghui,  $\alpha\beta\gamma$ 

#### Language: A set of strings over an alphabet

Examples:  $\emptyset$  (the empty language), { 1, 11, 111, 1111 }, all English words, strings that start with a letter followed by any sequence of letters and digits

Let  $L = \{ \epsilon, wo \}, M = \{ man, men \}$ 

#### Concatenation: Strings from one followed by the other

 $LM = \{ man, men, woman, women \}$ 

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**Union**: All strings from each language  $L \cup M = \{\epsilon, wo, man, men \}$ 

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#### Concatenation: Strings from one followed by the other

 $LM = \{ \text{ man, men, woman, women } \}$ 

#### Union: All strings from each language

 $L \cup M = \{\epsilon, \text{ wo, man, men }\}$ 

#### Kleene Closure: Zero or more concatenations

 $M^* = \{\epsilon\} \cup M \cup MM \cup MMM \dots = \{\epsilon, \text{ man, men, manman, manmen, menman, menmen, manmanman, } \dots\}$ 

- 1.  $\epsilon$  is a regular expression that denotes  $\{\epsilon\}$
- 2. If  $a \in \Sigma$ , a is an RE that denotes  $\{a\}$
- 3. If r and s denote languages L(r) and L(s),

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 $(r) \mid (s)$  denotes  $L(r) \cup L(s)$ 

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- 3. If r and s denote languages L(r) and L(s),

 $\begin{array}{ll} (r) \mid (s) & {\rm denotes} & L(r) \cup L(s) \\ \\ (r)(s) & & \{tu: t \in L(r), u \in L(s)\} \end{array}$ 

- 1.  $\epsilon$  is a regular expression that denotes  $\{\epsilon\}$
- 2. If  $a \in \Sigma$ , a is an RE that denotes  $\{a\}$
- 3. If r and s denote languages L(r) and L(s),

$\Sigma =$	$\{a,b\}$
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Regexp.	Language
$a \mid b$	$\{a, b\}$
$(a \mid b)(a \mid b)$	

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Regexp.	Language	
$a \mid b$	$\{a, b\}$	
$(a \mid b)(a \mid b)$	$\{aa, ab, ba, bb\}$	
$(a \mid b)^*$		

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Regexp.	Language
$a \mid b$	$\{a, b\}$
$(a \mid b)(a \mid b)$	$\{aa, ab, ba, bb\}$
$(a \mid b)^*$	$\{\epsilon, a, b, aa, ab, ba, bb, aaa, aab, aba, abb, \ldots\}$
$a \mid a^*b$	$\{a, b, ab, aab, aaab, aaaab, \ldots\}$

ID: letter followed by letters or digits

Typical choice:  $\Sigma = \text{ASCII characters, i.e.,}$ { $\cup$ ,!, ", #, \$, ..., 0, 1, ..., 9, ..., A, ..., Z, ..., ~} **letters:** A | B | ··· | Z | a | ··· | z **digits:** 0 | 1 | ··· | 9 **identifier:**  ID: letter followed by letters or digits

Typical choice:  $\Sigma = ASCII$  characters, i.e.,  $\{ , !, ", \#, \$, \dots, 0, 1, \dots, 9, \dots, A, \dots, Z, \dots, ~\}$ letters:  $A \mid B \mid \cdots \mid Z \mid a \mid \cdots \mid z$ **digits**:  $0 | 1 | \cdots | 9$ 

identifier: letter ( letter | digit )\*



"All strings containing an even number of o's and 1's"

#### Nondeterministic Finite Automata

"All strings containing an even number of O's and 1's"



1. Set of states CS:DB2. Set of input symbols  $\Sigma : \{0, 1\}$ 3. Transition function  $\sigma: S \times \Sigma_{\epsilon} \to 2^S$ state  $\epsilon = 0$  $\emptyset \{B\} \{C\}$ AØ B  $\{A\}$  $\{D\}$ Ø C $\{D\}$  $\{A\}$ Ø D  $\{B\}$ 4. Start state  $s_0$  : 5. Set of accepting states

F
An NFA accepts an input string x iff there is a path from the start state to an accepting state that "spells out" x.



Show that the string "010010" is accepted.

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Show that the string "010010" is accepted.

C

a



Symbol







#### Why So Many Extra States and Transitions?

Invariant: Single start state; single end state; at most two outgoing arcs from any state: helpful for simulation.

What if we used this simpler rule for Kleene Closure?



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Invariant: Single start state; single end state; at most two outgoing arcs from any state: helpful for simulation.

What if we used this simpler rule for Kleene Closure?



Now consider  $a^*b^*$  with this rule:



Is this right?

Example: Translate  $(a \mid b)^*abb$  into an NFA. Answer:

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Show that the string "*aabb*" is accepted. Answer:

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Problem: you must follow the "right" arcs to show that a string is accepted. How do you know which arc is right?

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Solution: follow them all and sort it out later.

"Two-stack" NFA simulation algorithm:

- 1. Initial states: the  $\epsilon$ -closure of the start state
- 2. For each character c,
  - New states: follow all transitions labeled  $\boldsymbol{c}$
  - Form the  $\epsilon\text{-closure}$  of the current states
- 3. Accept if any final state is accepting

#### Simulating an NFA: *·aabb*, Start



#### Simulating an NFA: $\cdot aabb$ , $\epsilon$ -closure



#### Simulating an NFA: $a \cdot abb$



#### Simulating an NFA: $a \cdot abb$ , $\epsilon$ -closure



#### Simulating an NFA: $aa \cdot bb$



#### Simulating an NFA: $aa \cdot bb$ , $\epsilon$ -closure



#### Simulating an NFA: $aab \cdot b$



#### Simulating an NFA: $aab \cdot b$ , $\epsilon$ -closure



#### Simulating an NFA: aabb.



#### Simulating an NFA: *aabb*., Done



Restricted form of NFAs:

- No state has a transition on  $\epsilon$
- For each state *s* and symbol *a*, there is at most one edge labeled *a* leaving *s*.

Very easy to check acceptance: simulate by maintaining current state. Accept if you end up on an accepting state. Reject if you end on a non-accepting state or if there is no transition from the current state for the next symbol.





#### **Deterministic Finite Automata**



#### Subset construction algorithm

Simulate the NFA for all possible inputs and track the states that appear.

Each unique state during simulation becomes a state in the DFA.

#### The Subset Construction Algorithm

- 1. Create the start state of the DFA by taking the  $\varepsilon$ -closure of the start state of the NFA.
- 2. Perform the following for the new DFA state: For each possible input symbol:
  - Apply move to the newly-created state and the input symbol; this will return a set of states.
  - Apply the  $\varepsilon\text{-}closure$  to this set of states, possibly resulting in a new set. This set of NFA states will be a single state in the DFA.
- 3. Each time we generate a new DFA state, we must apply step 2 to it. The process is complete when applying step 2 does not yield any new states.
- 4. The finish states of the DFA are those which contain any of the finish states of the NFA.











#### **Result of subset construction for** $(a \mid b)^*abb$



Is this minimal?

## Minimized result for $(a \mid b)^*abb$


### **Transition Table Used In the Dragon Book**



### **Transition Table Used In the Dragon Book**



NFA State	DFA State	а	b
{0,1,2,4,7}	А	В	С
{1,2,3,4,6,7,8}	В	В	D
{1,2,4,5,6,7}	С	В	С
{1,2,4,5,6,7,9}	D	В	Е
{1,2,4,5,6,7,10}	E	В	С



An DFA can be exponentially larger than the corresponding NFA.

n states versus  $2^n$ 

Tools often try to strike a balance between the two representations.

# Lexical Analysis with Ocamllex

## **Constructing Scanners with Ocamllex**



## **Ocamllex Specifications**

```
(* Header: verbatim OCaml code; mandatory *)
(* Definitions: optional *)
let ident = regexp
let ...
(* Rules: mandatory *)
rule entrypoint1 [arg1 ... argn] =
  parse pattern1 { action (* OCaml code *) }
       patternn { action }
and entrypoint2 [arg1 ... argn]} =
and ...
  (* Trailer: verbatim OCaml code; optional *)
```

## Patterns (In Order of Decreasing Precedence)

Pattern	Meaning
'c'	A single character
_	Any character (underline)
eof	The end-of-file
"foo"	A literal string
['1' '5' 'a'-'z']	"1," "5," or any lowercase letter
[^ '0'-'9']	Any character except a digit
( pattern )	Grouping
identifier	A pattern defined in the ${\rm let}\xspace$ section
pattern *	Zero or more <i>patterns</i>
pattern $+$	One or more <i>pattern</i> s
pattern ?	Zero or one patterns
pattern <sub>1</sub> pattern <sub>2</sub>	$pattern_1$ followed by $pattern_2$
$pattern_1 \mid pattern_2$	Either pattern $_1$ or pattern $_2$
pattern as id	Bind the matched pattern to variable <i>id</i>

```
{ type token = PLUS | IF | ID of string | NUM of int }
let letter = ['a'-'z' 'A'-'Z']
let digit = ['0' - '9']
rule token =
 parse [' ' '\n' '\t'] { token lexbuf } (* Ignore whitespace *)
    | '+' { PLUS }
                                     (* A symbol *)
    | "if" { IF }
                                   (* A keyword *)
                                      (* Identifiers *)
    | letter (letter | digit | ' ')* as id { ID(id) }
                                    (* Numeric literals *)
    | digit+ as lit { NUM(int_of_string lit) }
    | "/*" { comment lexbuf } (* C-style comments *)
and comment =
  parse "*/" { token lexbuf } (* Return to normal scanning *)
     { comment lexbuf } (* Ignore other characters *)
```

#### **Nested Comments**

```
{ type token = PLUS | ID of string | NUM of int }
let letter = ['a'-'z' 'A'-'Z']
let diait = ['0'-'9']
rule token =
 parse [' ' '\n' '\t'] { token lexbuf } (* Ignore whitespace *)
    | '+' { PLUS }
                                     (* A symbol *)
    | letter (letter | digit | '_')* as id { ID(id) }
       digit+ as lit { NUM(int of string lit) }
    | "/*" { comment o lexbuf } (* C-style comments *)
and comment level =
  parse "*/" { if level == o then token lexbuf
        else comments (level - 1) lexbuf }
      | "/*" { comment (level + 1) lexbuf }
      { comment level lexbuf } (* ignore other characters *)
```

Typical style arising from scanner/parser division

Program text is a series of tokens possibly separated by whitespace and comments, which are both ignored.

- keywords (if while)
- punctuation (, ( +)
- identifiers (foo bar)
- numbers (10 -3.14159e+32)
- strings ("A String")

# Java C C++ C# Algol Pascal Some deviate a little (e.g., C and C++ have a separate preprocessor)

But not all languages are free-format.



#### The Python scripting language groups with indentation



This is succinct, but can be error-prone.

How do you wrap a conditional around instructions?

- Does syntax matter? Yes and no
- More important is a language's *semantics*—its meaning.
- The syntax is aesthetic, but can be a religious issue.
- But aesthetics matter to people, and can be critical.
- Verbosity does matter: smaller is usually better.
- Too small can be problematic: APL is a succinct language with its own character set.
- There are no APL programs, only puzzles.

#### Some syntax is error-prone. Classic FORTRAN example:

DO 5 *I* = 1,25 ! Loop header (for i = 1 to 25) DO 5 *I* = 1.25 ! Assignment to variable DO51

#### Trying too hard to reuse existing syntax in C++:

vector< vector<int> > foo; vector<vector<int>> foo; // Syntax error

C distinguishes > and >> as different operators.

Bjarne Stroustrup tells me they have finally fixed this.