Lecture 02 – Lexical Analysis

THEORY OF COMPILATION

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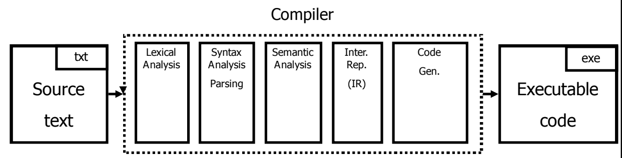

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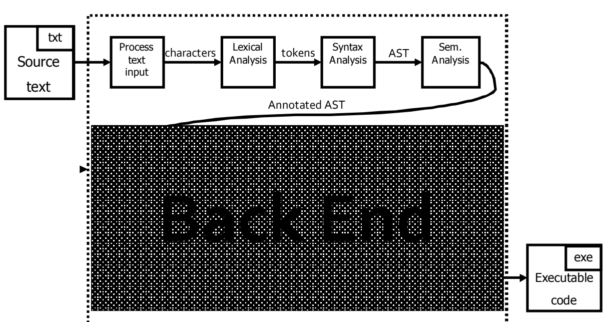
You are here…



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From characters to tokens

- What is a token?
  - Roughly – a “word” in the source language
  - Identifiers
  - Values
  - Language keywords
  - Really - anything that should appear in the input to syntax analysis
- Technically
  - Usually a pair of (kind,value)

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Example Tokens

Type	Examples
Identifier	x, y, z, foo, bar
NUM	42
FLOATNUM	3.141592654
STRING	"so long, and thanks for all the fish"
LPAREN	(
RPAREN	)
IF	if
…	

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Strings with special handling

Type	Examples
Comments	/* Ceci n'est pas un commentaire */
Preprocessor directives	#include<foo.h>
Macros	#define THE_ANSWER 42
White spaces	\t \n

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From characters to tokens

txt

x = b*b – 4*a*c

⇩

Token Stream

<ID,"x"> <EQ> <ID,"b"> <MULT> <ID,"b"> <MINUS> <INT,4> <MULT> <ID,"a"> <MULT> <ID,"c">

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Errors in lexical analysis

txt: pi = 3.141.562 ⇨ Illegal token

txt: pi = 3oranges ⇨ Illegal token

txt: pi = oranges3 ⇨ <ID,"pi">, <EQ>, <ID,"oranges3">

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How can we define tokens?

- Keywords – easy!
  - if, then, else, for, while, …
- Identifiers?
- Numerical Values?
- Strings?
- Characterize unbounded sets of values using a bounded description?

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Regular Expressions

Basic Patterns	Matching
x	The character x
.	Any character, usually except a new line
[xyz]	Any of the characters x,y,z
Repetition Operators	
R?	An R or nothing (=optionally an R)
R*	Zero or more occurrences of R
R+	One or more occurrences of R
Composition Operators	
R1R2	An R1 followed by R2
R1|R2	Either an R1 or R2
Grouping	
(R)	R itself

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Examples

- ab*|cd? =
- (a|b)* =
- (0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9)* =

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Escape characters

- What is the expression for one or more + symbols?
  - (+)+ won't work
  - (\+)+ will
- backslash \ before an operator turns it to standard character
- *, \?, \+, …

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Shorthands

- Use names for expressions
  - letter = a | b | … | z | A | B | … | Z
  - letter_ = letter | _
  - digit = 0 | 1 | 2 | … | 9
  - id = letter_ (letter_ | digit)*
- Use hyphen to denote a range
  - letter = a-z | A-Z
  - digit = 0-9

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Examples

- digit = 0-9
- digits = digit+
- number = digits (Є | .digits (Є | e (Є|+|-) digits))
- if = if
- then = then
- relop = < | > | <= | >= | = | <>

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Ambiguity

- if = if
- id = letter_ (letter_ | digit)*
- "if" is a valid word in the language of identifiers… so what should it be?
- How about the identifier "iffy"?
- Solution
  - Always find longest matching token
  - Break ties using order of definitions… first definition wins (=> list rules for keywords before identifiers)

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Creating a lexical analyzer

- Input
  - List of token definitions (pattern name, regex)
  - String to be analyzed
- Output
  - List of tokens
- How do we build an analyzer?

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Character classification

```
#define is_end_of_input(ch) ((ch) == '\0');
#define is_uc_letter(ch) ('A'<= (ch) && (ch) <= 'Z')
#define is_lc_letter(ch) ('a'<= (ch) && (ch) <= 'z')
#define is_letter(ch) (is_uc_letter(ch) || is_lc_letter(ch))
#define is_digit(ch) ('0'<= (ch) && (ch) <= '9')
…
```

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Main reading routine

```
void get_next_token() {
do {
 char c  = getchar();
 switch(c) {
   case is_letter(c) : return recognize_identifier(c);
   case is_digit(c) : return recognize_number(c);
    …
} while (c != EOF);
```

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But we have a much better way!

- Generate a lexical analyzer automatically from token definitions
- Main idea
  - Use finite-state automata to match regular expressions

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Reminder: Finite-State Automaton

- Deterministic automaton
- $M = (\Sigma, Q, \delta, q_0, F)$
  - Σ - alphabet
  - Q – finite set of state
  - $q_0 \in Q$ – initial state
  - $F \subseteq Q$ – final states
  - $\delta : Q \times \Sigma \rightarrow Q$ - transition function

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Reminder: Finite-State Automaton

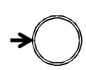
- Non-Deterministic automaton
- M = $(\Sigma, Q, \delta, q_o, F)$
  - Σ - alphabet
  - Q – finite set of state
  - $q_o \in Q$ – initial state
  - $F \subseteq Q$ – final states
  - $\delta : Q \times (\Sigma \cup \{\varepsilon\}) \longrightarrow 2^Q$ - transition function
- Possible ε-transitions
- For a word w, M can reach a number of states or get stuck. If some state reached is final, M accepts w.

From regular expressions to NFA

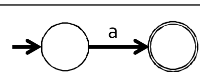
- Step 1: assign expression names and obtain pure regular expressions R1…Rm
- Step 2: construct an NFA Mi for each regular expression Ri
- Step 3: combine all Mi into a single NFA
- Ambiguity resolution: prefer longest accepting word

Basic constructs

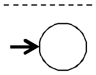
R = ε



R = a

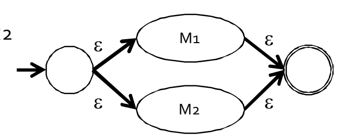


R = ϕ

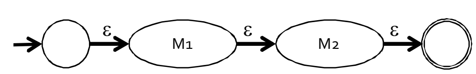


Composition

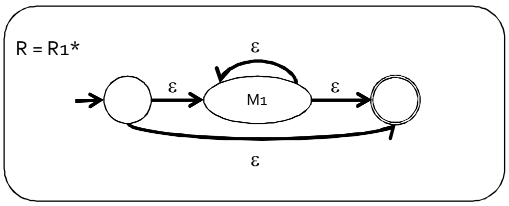
R = R1 | R2



R = R1R2



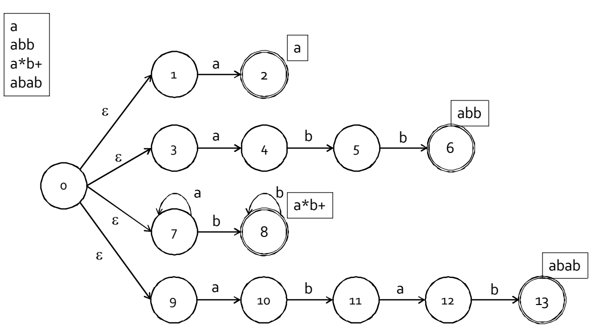
Repetition



What now?

- Naïve approach: try each automaton separately
- Given a word w:
  - Try M1(w)
  - Try M2(w)
  - …
  - Try Mn(w)
- Requires resetting after every attempt

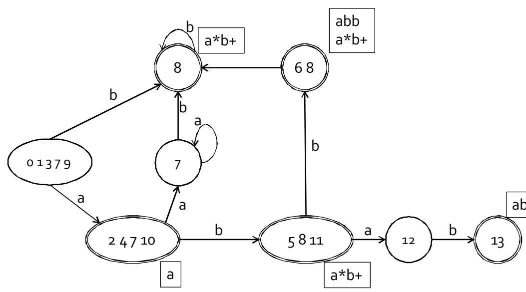
Combine automata



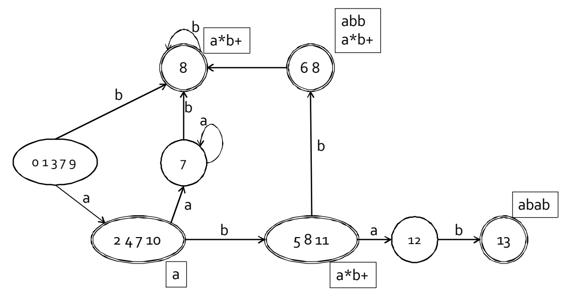
Ambiguity resolution

- Recall…
- Longest word
- Tie-breaker based on order of rules when words have same length
- Recipe
  - Turn NFA to DFA
  - Run until stuck, remember last accepting state, this is the token to be returned

Corresponding DFA



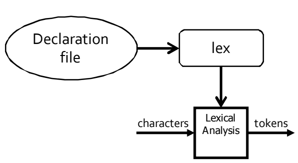
Examples



abaa: gets stuck after aba in state 12, backs up to state (5 8 11) pattern is a*b+, token is ab
abba: stops after second b in (6 8), token is abb because it comes first in spec

Good News

- All of this construction is done automatically for you by common tools
- lex is your friend
  - Automatically generates a lexical analyzer from declaration file



Lex declarations file

```
%{
#include "lex.h"
Token_Type Token;
int line_number=1
%}
whitespace [ \t]
letter [a-zA-Z]
digit [0-9]
…
%%
{digit}+ {return INTEGER;}
{identifier} {return IDENTIFIER;}
{whitespace} { /* ignore whitespace */ }
\n           { line_number++;}
.            { return ERROR; }
…
%%
void start_lex(void){}
void get_next_token(void) {…}
```

Summary

- Lexical analyzer
  - Turns character stream into token stream
  - Tokens defined using regular expressions
  - Regular expressions -> NFA -> DFA construction for identifying tokens
  - Automated constructions of lexical analyzer using lex

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Coming up next time

- Syntax analysis

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NFA vs. DFA

Automaton	SPACE	TIME
NFA	O(|r|)	O(|r|*|w|)
DFA	O(2^|r|)	O(|w|)

- $(a|b)^*a\underbrace{(a|b)(a|b)\ldots(a|b)}_{\text{n times}}$

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