# Lexical Analysis

ICS312
**Machine-Level and Systems Programming**

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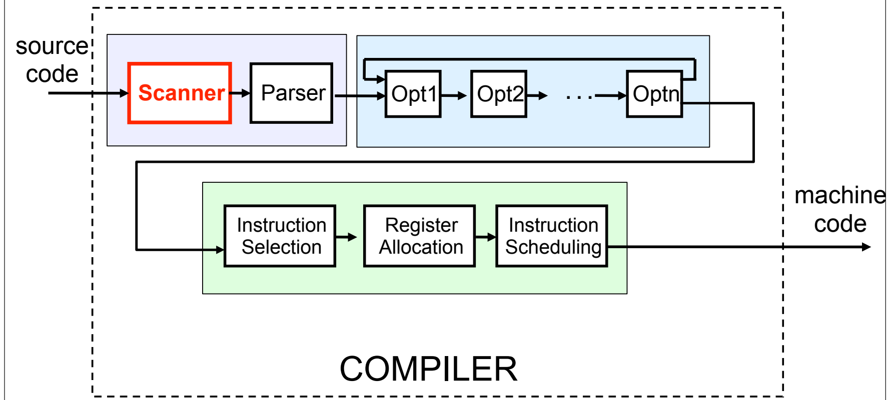
## The Big Picture Again




## Lexical Analysis

- Lexical Analysis, also called ‘scanning’ or ‘lexing’
- It does two things:
  - Transforms the input source string into a sequence of substrings
  - Classifies them according to their ‘role’
- The input is the source code
- The output is a list of tokens
- Example input:

```
if (x == y)
        z = 12;
else
        z = 7;
```

- This is really a single string:

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i | f | | ( | x | = | = | y | ) | \n | \t | z | | = | | 1 | 2 | ; | \n | e | l | s | e | \n | \t | z | | = | | 7 | ; | \n |

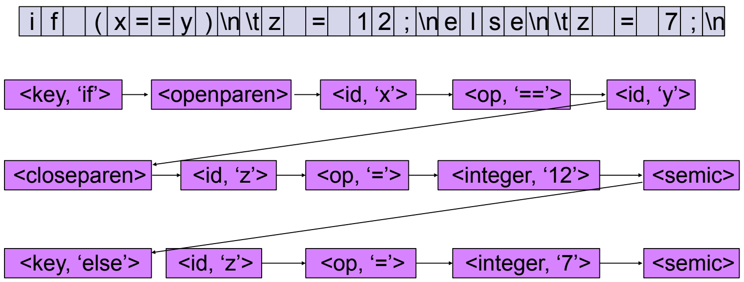
## Tokens

- A token is a syntactic category
- Example tokens:
  - Identifier
  - Integer
  - Floating-point number
  - Keyword
  - etc.
- In English we would talk about
  - Noun
  - Verb
  - Adjective
  - etc.

# Lexeme

- A lexeme is the string that represents an instance of a token
- The set of all possible lexemes that can represent a token instance is described by a pattern
- For instance, we can decide that the pattern for an identifier is
  - A string of letters, numbers, or underscores, that starts with a capital letter

# Lexing output




- Note that the lexer removes non-essential characters
  - Spaces, tabs, linefeeds
  - And comments!
  - Typically a good idea for the lexer to allow arbitrary numbers of white spaces, tabs, and linefeeds

# The Lookahead Problem

- Characters are read in from left to right, one at a time, from the input string
- The problem is that it is not always possible to determine whether a token is finished or not without looking at the next character
- Example:
  - Is character ‘f’ the full name of a variable, or the first letter of keyword ‘for’?
  - Is character ‘=‘ an assignment operator or the first character of the ‘==’ operator?
- In some languages, a lot of lookahead is needed
- Example: FORTRAN
  - Fortran removes ALL white spaces before processing the input string
  - DO 5 I = 1.25 is valid code that sets variable DO5I to 1.25
  - But ‘DO 5 I = 1.25’ could also be the beginning of a for loop!

# The Lookahead Problem

- It is typically a good idea to design languages that require ‘little’ lookahead
  - For each language, it should be possible to determine how many lookahead characters are needed
- Example with 1-character lookahead:
  - Say that I get an’if’ so far
  - I can *look* at the next character
  - If it’s a ‘ ‘, ‘(‘,’\t’, then I don’t read it; I stop here and emit a TOKEN_IF
  - Otherwise I read the next character and will most likely emit a TOKEN_ID
- In practice one implements lookhead/pushback
  - When in need to look at next characters, read them in and push them onto a data structure (stack/fifo)
  - When in need of a character get it from the data structure, and if empty from the file

# A Lexer by Hand? You're kidding!

- Example: Say we want to write the code to recognizes the keyword 'if'

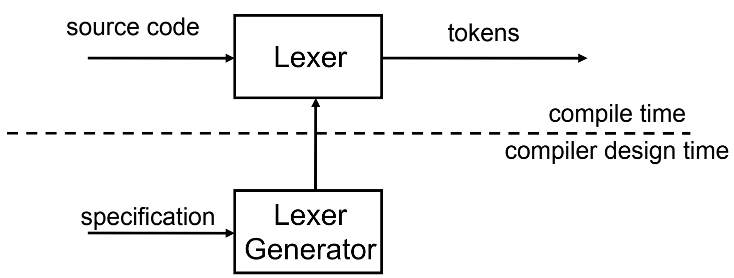
```
c = readchar();
if (c == 'i') {
        c = readchar();
        if (c == 'f') {
                c = readchar();
                if (c not alphanumeric) {
                        pushback(c);
                        emit(TOKEN_IF)
                } else {
                        // build a TOKEN_ID
                }
        } else {
                // something else
        }
} else {
        // something else
}
```

# A Lexer by Hand?

- There are many difficulties when writing a lexer by hand as in the previous slide
  - Many types of tokens
    - fixed string
    - special character sequences (operators)
    - numbers defined by specific/complex rules
  - Many possibilities of token overlaps
  - Hence, many nested if-then-else in the lexer's code
- Coding all this by hand is very painful
  - And it's difficult to get it right
- Nevertheless, some compilers have an implemented-by-hand lexer for higher speed

# Regular Expressions

- To avoid the endless nesting of if-then-else one needs a formalization of the lexing process
- If we have a good formalization, we could even generate the lexer's code automatically!




# Lexer Specification

- Question: How do we formalize the job a lexer has to do to recognize the tokens of a specific language?
- Answer: We need a language!
  - More specifically, we're going to talk about the language of tokens!
- What's a language?
  - An alphabet (typically called ∑)
    - e.g., the ASCII characters
  - A subset of all the possible strings over ∑
- We just need to provide a formal definition of a the language of the tokens over ∑
  - Which strings are tokens
  - Which strings are not tokens
- It turns out that for all (reasonable) programming languages, the tokens can be described by a regular language
  - i.e., a language that can be recognized by a finite automaton
  - A lot of theory here that I'm not going to get into

## Describing Tokens

- Most popular way to describe tokens: regular expressions
- Regular expressions are just notations, which happen to be able to represent regular languages
  - A regular expression is a string (in a meta-language) that describes a pattern (in the token language)
- L(A) is the language represented by regular expression A
  - Remember that a language is just a set of valid strings
- Basic: L('c') = {'c'}
- Concatenation: L(AB) = {ab | a in L(A) and b in L(B)}
  - L('i' 'f') = {'if'}
  - L(('i')('f')) = {'if'}
- Union: L(A|B) = {x | x in L(A) or x in L(B)}
  - L('if'|'then'|'else'} = {'if', 'then', 'else'}
  - L(('0'|'1') ('1'|'0')} = {'00', '01', '10', '11'}

## Regular Expression Overview

| Expression | Meaning |
|---|---|
| ε | empty pattern |
| a | Any pattern represented by 'a' |
| ab | Strings with pattern 'a' followed by pattern 'b' |
| a\|b | Strings with pattern 'a' or pattern 'b' |
| $a^*$ | Zero or more occurrences of pattern 'a' |
| $a^+$ | One or more occurrences of pattern 'a' |
| a? | (a \| ε) |
| . | Any single character (not very standard) |

- Let's look at how REs are used to describe tokens

## REs for Keywords

- It is easy to define a RE that describes all keywords

  Key = 'if' | 'else' | 'for' | 'while' | 'int' | ..

- These can be split in groups if needed

  Keyword = 'if' | 'else' | 'for' | …
  Type = 'int' | 'double' | 'long' | …

- The choice depends on what the next component (i.e., the parser) would like to see

## RE for Numbers

- Straightforward representation for integers
  - digits = '0' | '1' | '2' | '3' | '4' | '5' | '6' | '7' | '8' | '9'
  - integer = $\text{digits}^+$
- RE systems allow the use of '-' for ranges, sometimes with '[' and ']'
  - digits = [0-9]+
- Floating point numbers are much more complicated
  - 2.00, .12e-12, 312.00001E+12, 4, 3.141e-12
- Here is one attempt
  - ('+'|'-'|ε)($\text{digit}^+$ '.'? | $\text{digits}^*$ ('.' $\text{digit}^+$)) (('E'|'e')('+'|'-'|ε) digit+)))?
- Note the difference between meta-character and language-characters
  - '+' versus +, '-' versus -, '(' versus (, etc.
- Often books/documentations use different fonts for each level of language

## RE for Identifiers

- Here is a typical description
  - letter = a-z | A-Z
  - ident = letter ( letter | digit | '_')*
    - Starts with a letter
    - Has any number of letter or digit or '_' afterwards
- In C: ident = (letter | '_') (letter | digit | '_')*

## RE for Phone Numbers

- Simple RE
  - digit = 0-9
  - area = digit digit digit
  - exchange = digit digit digit
  - local = digit digit digit digit
  - phonenumber = '(' area ')' ' '? exchange ('-'|' ') local
- The above describes the $10^{3+3+4}$ strings of the L(phonenumber) language

## REs in Practice

- The Linux grep utility allows the use of REs
  - Example with phone numbers
    - grep '([0-9]\{3\}) \{0,1\}[0-9]\{3\}[-| ][0-9]\{4\}' file
  - The syntax is different from that we've seen, but equivalent
  - Sadly, there is no single standard for RE syntax
- Perl implements regular expressions
- (Good) text editors implement regular expressions
  - .e.g., for string replacements
- At the end of the day, we often have built for ourselves tons of regular expressions
  - Many programs you use everyday use REs internally, including compilers

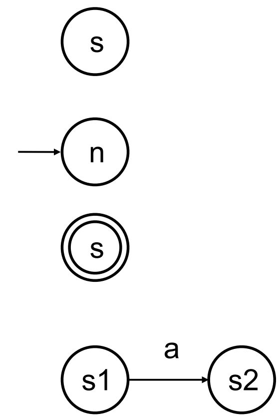
## Now What?

- Now we have a nice way to formalize each token (which is a set of possible strings)
- Each token is described by a RE
  - And hopefully we have made sure that our REs are correct
  - Easier than writing the lexer from scratch
  - But still requires that one be careful
- Question: How do we use these REs to parse the input source code and generate the token stream?
- A little bit of 'theory'
  - REs characterize Regular Languages
  - Regular Languages are recognized by Finite Automata
  - Therefore we can implement REs as automata

## Finite Automata

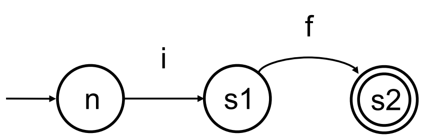
- A finite automaton is defined by
  - An input alphabet: ∑
  - A set of states: S
  - A start state: n
  - A set of accepting states: F (a subset of S)
  - A set of transitions between states: subset of SxS
- Transition Example
  - s1: a → s2
  - If the automaton is in state s1, reading a character ‘a’ in the input takes the automaton in state s2
  - Whenever reaching the ‘end of the input,’ if the state the automaton is in in a accept state, then we accept the input
  - Otherwise we reject the input

## Finite Automata as Graphs



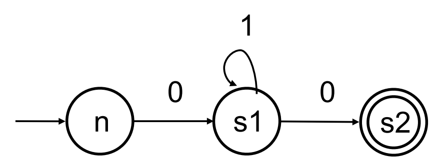

- A state
- The start state
- An accepting state
- A transition

## Automaton Examples




- This automaton accepts input ‘if’

## Automaton Examples



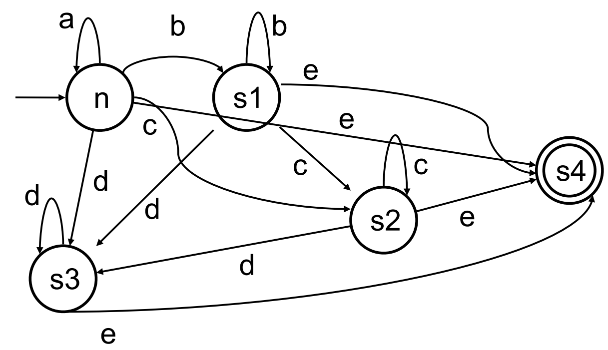

- This automaton accepts strings that start with a 0, then have any number of 1’s, and end with a 0
- Note the natural correspondence between automata and REs: $01^*0$
- Question: can we represent all REs with simple automata?
- Answer: yes
- Therefore, if we write a piece of code that implements arbitrary automata, we have a piece of code that implements arbitrary REs, and we have a lexer!
  - Not _this_ simple, but close

# Non-deterministic Automata

- The automata we have seen so far are called Deterministic Finite Automata (DFA)
  - At each state, there is at most one edge for a given symbol
  - At each state, transition can happen only if an input symbol is read
    - Or the string is rejected
- It turns out that it's easier to translate REs to Non-deterministic Finite Automata (NFA)
  - There can be ‘ε-transitions’!
    - Taken arbitrarily without consuming an input character
  - There can be multiple possible transitions for a given input symbol at a state
    - The automaton can take them all simultaneously (see later)

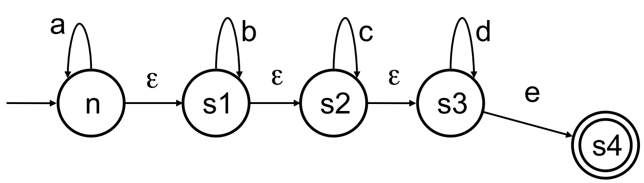
# Example REs and DFA

- Say we want to represent RE ‘$a^*b^*c^*d^*e$’ with aDFA




# Example REs and NFA

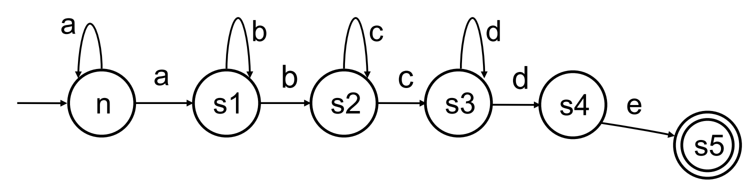
- ‘$a^*b^*c^*d^*e$’: much simpler with a NFA




- With ε-transitions, the automaton can ‘choose’ to skip ahead, non-deterministically

# Example REs and NFA

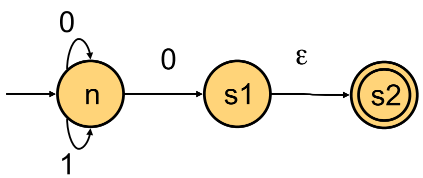
- ‘$a^+b^+c^+d^+e$’: easy modification




- But now we have multiple choices for a given character at each state!
  - e.g., two ‘a’ arrows leaving n

## NFA Acceptance

- When using an NFA, one must constantly keep track of all possible states
- If at the end of the input (at least) one of these states is an accepting state, then accept, otherwise reject




input string: 010

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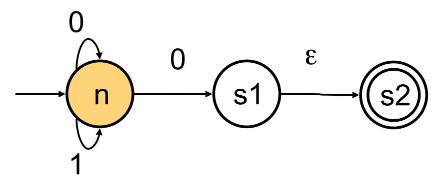


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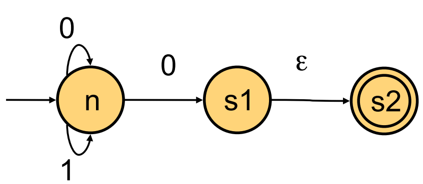


input string: 010

ACCEPT because of s2

## REs and NFA

- So now we're left with two possibilities
- Possibility #1: design DFAs
  - Easy to follow transitions once implemented
  - But really cumbersome
- Possibility #2: design NFAs
  - Really trivial to implement REs as NFAs
  - But what happens on input characters?
    - Non-deterministic transitions
    - Should keep track of all possible states at a given point in the input!
- It turns out that:
  - NFAs are not more powerful than DFAs
  - There are systematic algorithms to convert NFAs into DFAs and to limit their sizes
  - There are simple techniques to implement DFAs in software quickly

## Implementing a Lexer

- Implementing a Lexer is now straightforward
  - Come up with a RE for each token category
  - Come up with an NFA for each RE
  - Convert the NFA (automatically) to a DFA
  - Write a piece of code that implements a DFA
    - Pretty easy with a decent data-structure, which is a basically a transition table
  - Implement your lexer as a 'bunch of DFAs'
  - No nested if-then-else ad infinitum :)
- The above has been understood for decades and we now have automatic lexer generators!
- Well-known examples are lex and flex
- Let's look at ANTLR

## ANTLR

- ANTLR: A tool to generate lexer/parsers
- Let's look on the course Web site for how to download/ install/run ANTLR...
- Say we want to define a language with the following:
  - Reserved keywords: int, if, endif, while, endwhile, print
  - An addition operator: '+'
  - An assignment operator: '='
  - An equal operator: '=='
  - A not-equal operator: '!='
  - Integers
  - Variable names as strings of lower-case letters
  - Semicolons for terminating statements
  - Left and right parentheses
  - The ability to ignore white spaces, tabs, carriage returns, etc.

## ANTLR

- Basics of Regular Expressions in ANTLR:
  - Regular expression name (chosen by you)
  - Colon
  - Regular expression
  - Semicolon
- Example:
  - DIGIT : [0-9] ;
  - VARIABLE: [a-z]+ ;
  - EQUAL: '==' ;
- Let's look at the full example on the Web site, and run it...
  - Not that this example has some "parser stuff" at the beginning, but we're ignoring that for now

## Conclusion

- 20,000 ft view
  - Lexing relies on Regular Expressions, which rely on NFAs, which rely on DFAs, which are easy to implement
  - Therefore lexing is 'easy'
- Lexing has been well-understood for decades and lexer generators are known
  - We've seen and will use ANTLR
- The only motivation to write a lexer by hand: speed