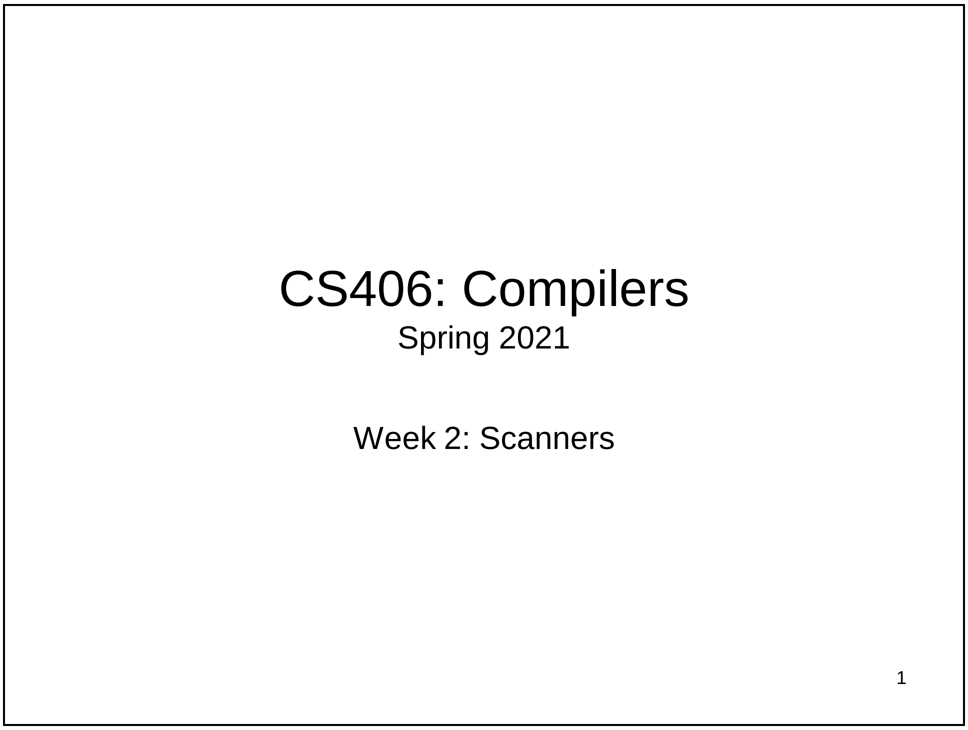
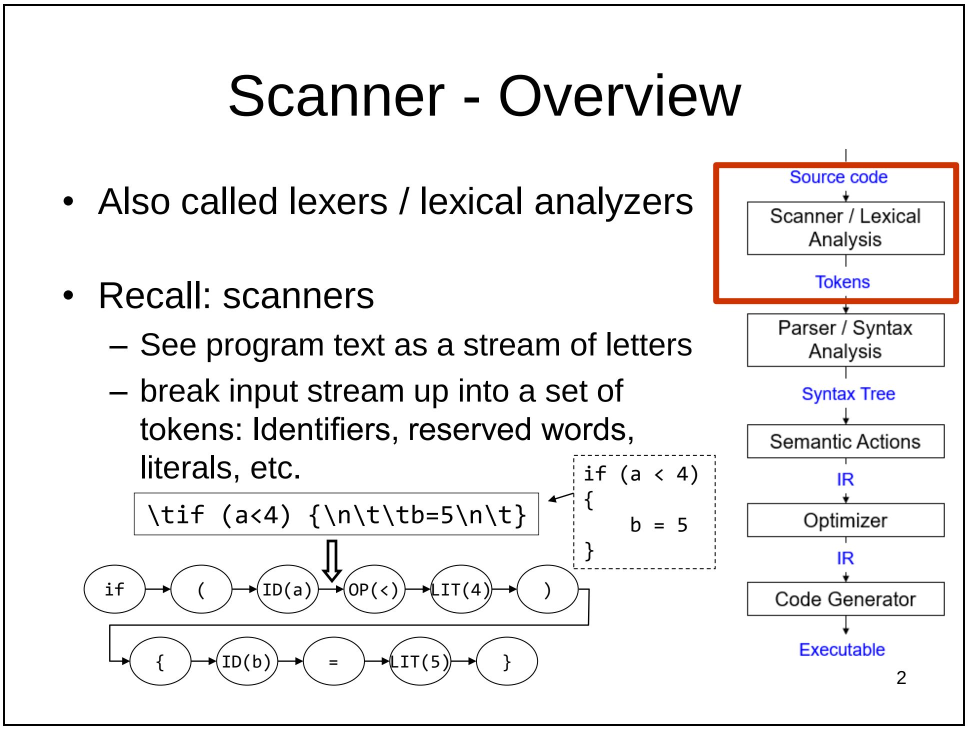


CS406: Compilers

Spring 2021

Week 2: Scanners

1



Scanner - Overview

- Also called lexers / lexical analyzers
- Recall: scanners
  - See program text as a stream of letters
  - break input stream up into a set of tokens: Identifiers, reserved words, literals, etc.

```
\tif (a<4) {\n\t\tb=5\n\t}
```

```
if (a < 4)
{
    b = 5
}
```

if → (→ ID(a) → OP(<) → LIT(4) →) → { → ID(b) → = → LIT(5) → }

Source code

Scanner / Lexical Analysis

Tokens

Parser / Syntax Analysis

Syntax Tree

Semantic Actions

IR

Optimizer

IR

Code Generator

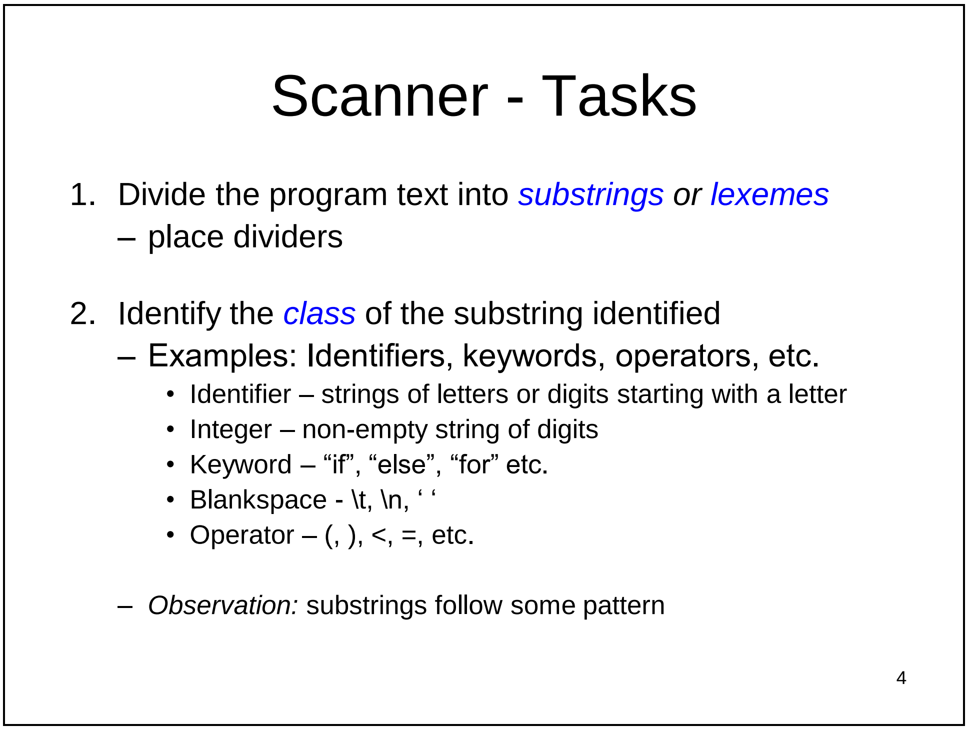
Executable

2

Recall that the first step in compiler construction is lexical analysis or scanning. We have lexers or scanners doing this job. Where scanners fit into the overall compiler design is shown in the figure on the right. The compiler sees the program text as a stream of letters, which are then grouped into words or tokens. We get a set of tokens as output from the lexical analyzer. The slide shows the input stream and corresponding output of scanner for the code snippet shown in dashed box.

Scanner - Motivation

- Why have a separate scanner when you can combine this with syntax analyzer (parser)?
  - Simplicity of design
    - E.g. rid parser of handling whitespaces
  - Improve compiler efficiency
    - E.g. sophisticated buffering algorithms for reading input
  - Improve compiler portability
    - E.g. handling ^M character in Linux (CR+LF in Windows)



Scanner - Tasks

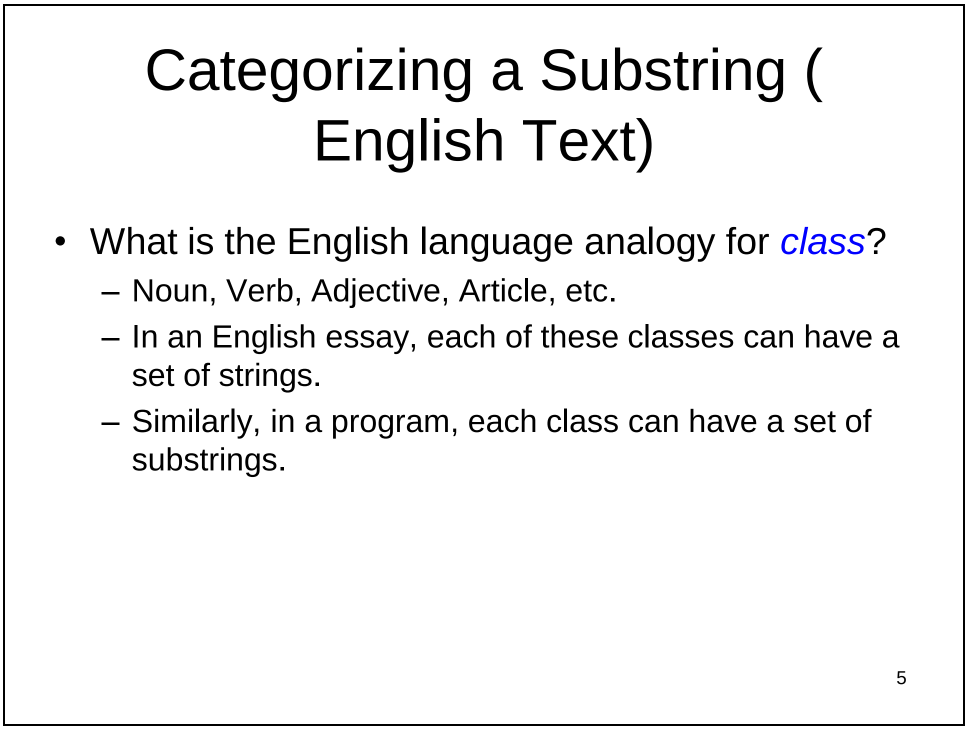
1. Divide the program text into *substrings or lexemes*
   - place dividers

2. Identify the *class* of the substring identified
   - Examples: Identifiers, keywords, operators, etc.
     - Identifier – strings of letters or digits starting with a letter
     - Integer – non-empty string of digits
     - Keyword – “if”, “else”, “for” etc.
     - Blankspace - \t, \n, ‘ ‘
     - Operator – (,), <, =, etc.

   - *Observation:* substrings follow some pattern

Here is an overview of how they work. As a first step, you need to place dividers at appropriate places in the input stream. You then get substrings or lexemes. We are segmenting the program text. Once substrings are identified, we need to categorize each substring. The categorization is done based on predefined set of categories such as identifiers, keywords, operators etc. The commonly accepted definition of each of these categories is shown in the slide.

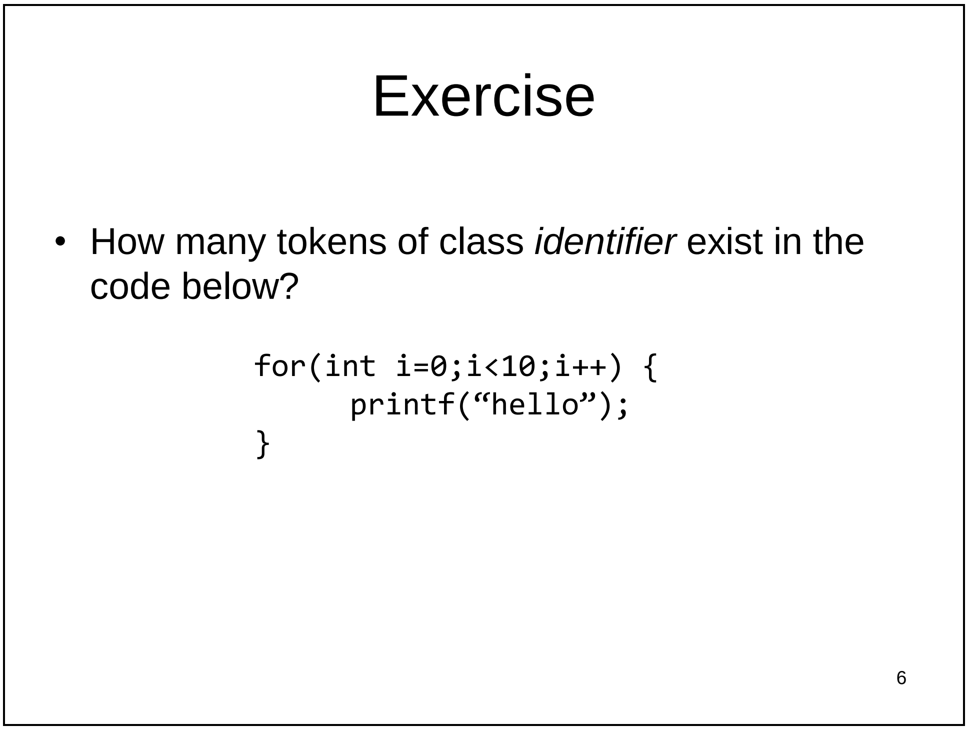
These definitions help us to identify patterns in substrings and classify the substrings as say an identifier, operator etc.



Categorizing a Substring (English Text)

- What is the English language analogy for *class*?
  - Noun, Verb, Adjective, Article, etc.
  - In an English essay, each of these classes can have a set of strings.
  - Similarly, in a program, each class can have a set of substrings.

5



Exercise

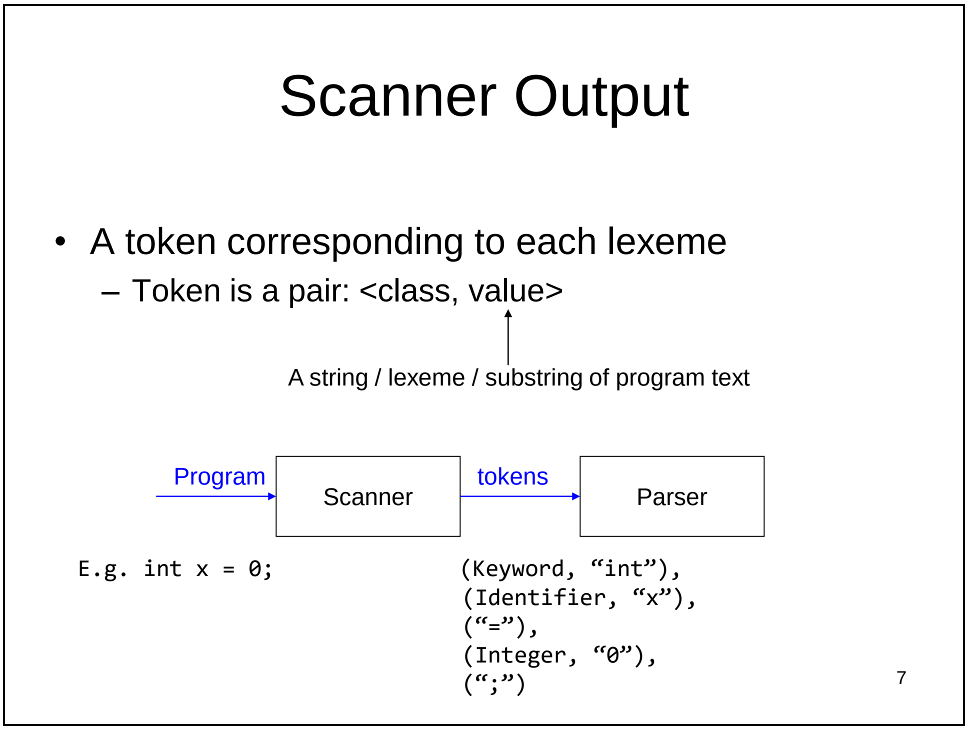
- How many tokens of class *identifier* exist in the code below?

```
for(int i=0;i<10;i++) {
     printf(“hello”);
}
```

3

If you said 1 (for ‘i’), then it is incorrect because as we look at the input stream, we encounter 3 ‘i’s. each of those ‘i’s is an identifier as per the definition of the identifier defined earlier.

4 if printf is included.



Scanner Output

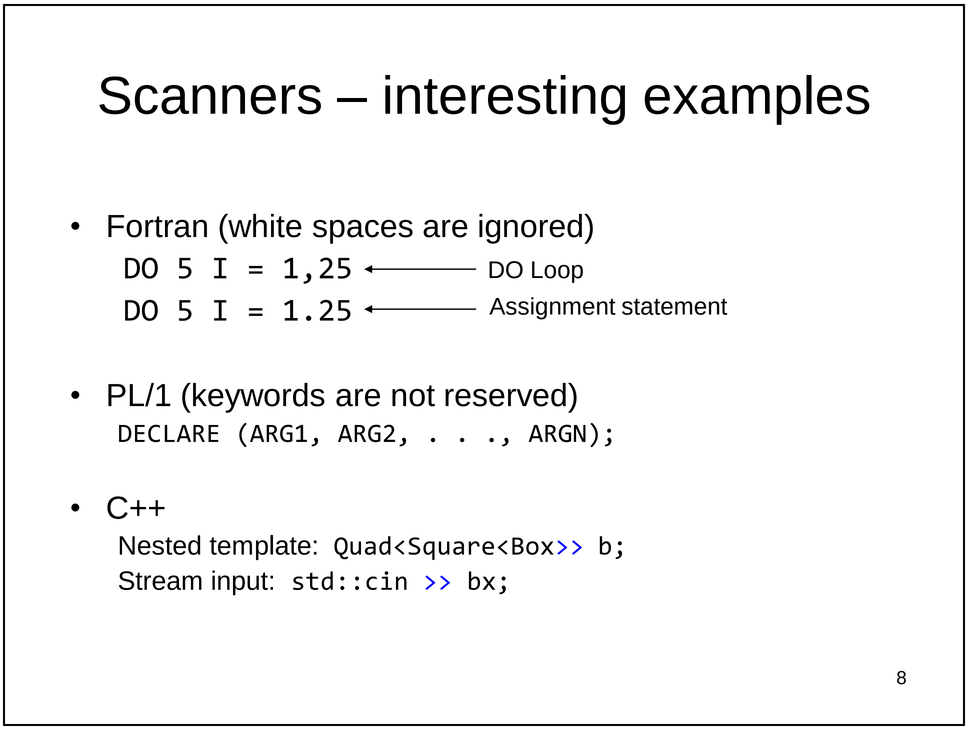
- A token corresponding to each lexeme
  - Token is a pair: <class, value>

A string / lexeme / substring of program text

```
E.g. int x = 0;
```

```
(Keyword, “int”),
(Identifier, “x”),
(“=”),
(Integer, “0”),
(“;”)
```

In practice, you need two pieces of info: 1) substring and 2) its category. These two pieces of info together form a ‘token’. In the slide, the value part of the pair is lexeme. The class part is the category of the token. The set of tokens that we get are passed on to parser. The example shows the set of tokens produced assuming that we have the following classes: Keyword, Identifier, =, Integer, ; Note that = and ; are separate classes having just a single string belonging to the set. This is how we have defined these classes. We could follow any other scheme of defining classes (e.g. = part of Operator).



Scanners – interesting examples

- Fortran (white spaces are ignored)

```
DO 5 I = 1,25 ←—— DO Loop
DO 5 I = 1.25 ←—— Assignment statement
```

- PL/1 (keywords are not reserved)

```
DECLARE (ARG1, ARG2, . . ., ARGN);
```

- C++

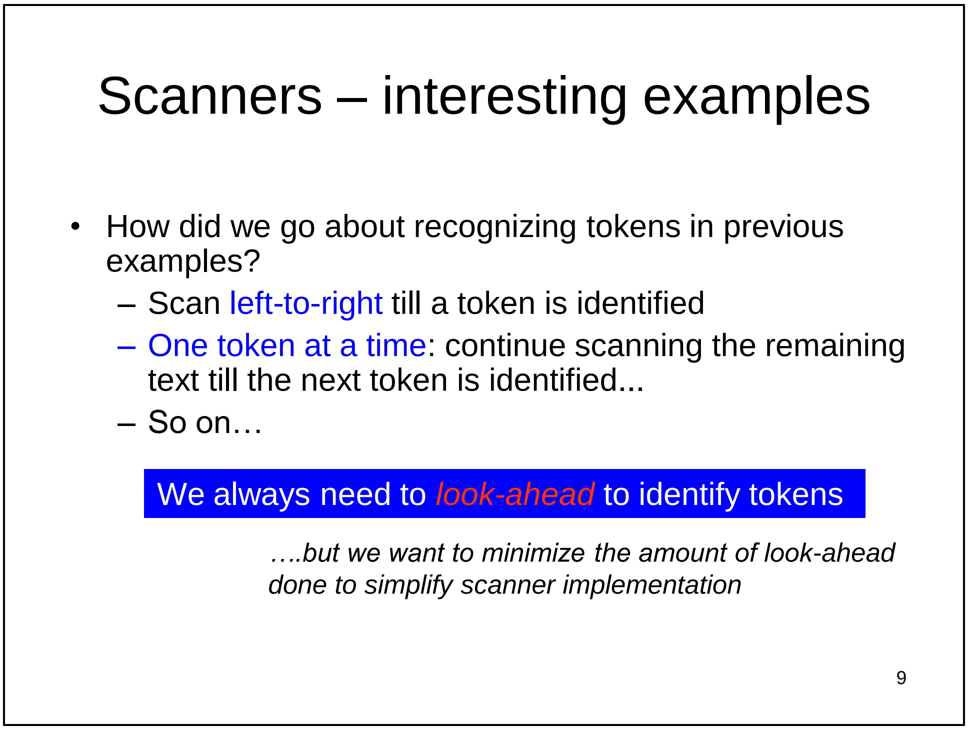
Nested template: `Quad<Square<Box>> b;`

Stream input: `std::cin >> bx;`

In Fortran, whitespaces are ignored. i.e. VAR1 is same as VA R1. The first statement is a DO loop in Fortran, while the second statement is an assignment statement. Do loops in fortran have the following syntax: “ do *label var = expr1, expr2, expr3 statements label* continue”, where *var* is the loop variable (often called the *loop index*) which must be integer. *expr1* specifies the initial value of *var*, *expr2* is the terminating bound, and *expr3* is the increment (step).

In PL/1, the language designed by IBM, keywords are not reserved. This means that we can have a code snippet such as “IF ELSE THEN THEN=ELSE; ELSE ELSE=THEN; here, only the first, third, and sixth words (excluding =) are keywords. Other example of PL/1 requires unbounded look-ahead.

These examples taught us what not to do. ANSI C has a limit of 31 chars for variable names. Still, some problems exist for e.g. C++.



Scanners – interesting examples

- How did we go about recognizing tokens in previous examples?
  - Scan left-to-right till a token is identified
  - One token at a time: continue scanning the remaining text till the next token is identified...
  - So on…

We always need to *look-ahead* to identify tokens

….but we want to minimize the amount of look-ahead done to simplify scanner implementation

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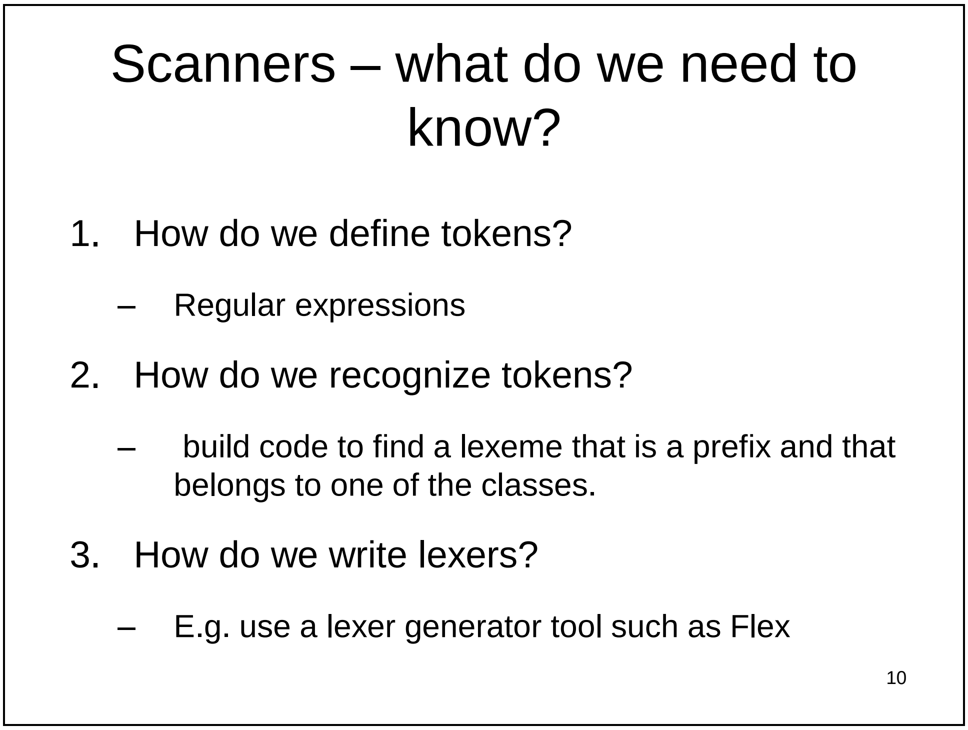
No matter what, while scanning left-to-right and recognizing one token at a time, we must do some amount of look-ahead to identify tokens.

In the case of PL/1, we have to do unbounded amount of lookahead. Because DECLARE(ARG1,…,ARGN) = <array initializer here> statement would interpret DECLARE as array and ARG1, …ARGN as array indices. DECLARE (ARG1, ARG2,…,ARGN) without the assignment would interpret DECLARE as a keyword declaring ARG1, ARG2, ..ARGN as variables.



Scanners – what do we need to know?

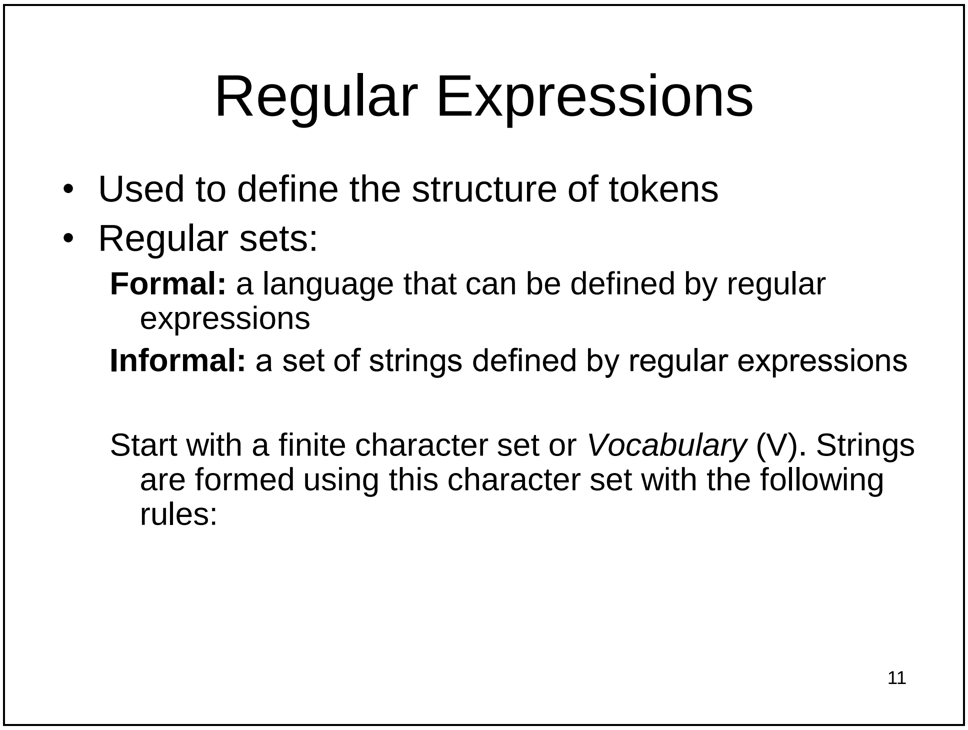
1. How do we define tokens?
   - Regular expressions
2. How do we recognize tokens?
   - build code to find a lexeme that is a prefix and that belongs to one of the classes.
3. How do we write lexers?
   - E.g. use a lexer generator tool such as Flex

We learnt that each token is a pair of <class, value>. The ‘value’ is a substring with some pattern that we define for the class of a substring/lexeme.

So, these patterns can be expressed with regular expressions.

We also need to translate these regular expressions to code so that the code is able to identify a prefix of the program text as a lexeme and the one belonging to one of the classes.

Fortunately, you don’t need to write code to translate regular expressions to code. Automatic lexer generator tools such as Flex, ANTLR, JFlex generate programs, which are pieces of code to identify tokens.



Regular Expressions

- Used to define the structure of tokens
- Regular sets:

Formal: a language that can be defined by regular expressions

Informal: a set of strings defined by regular expressions

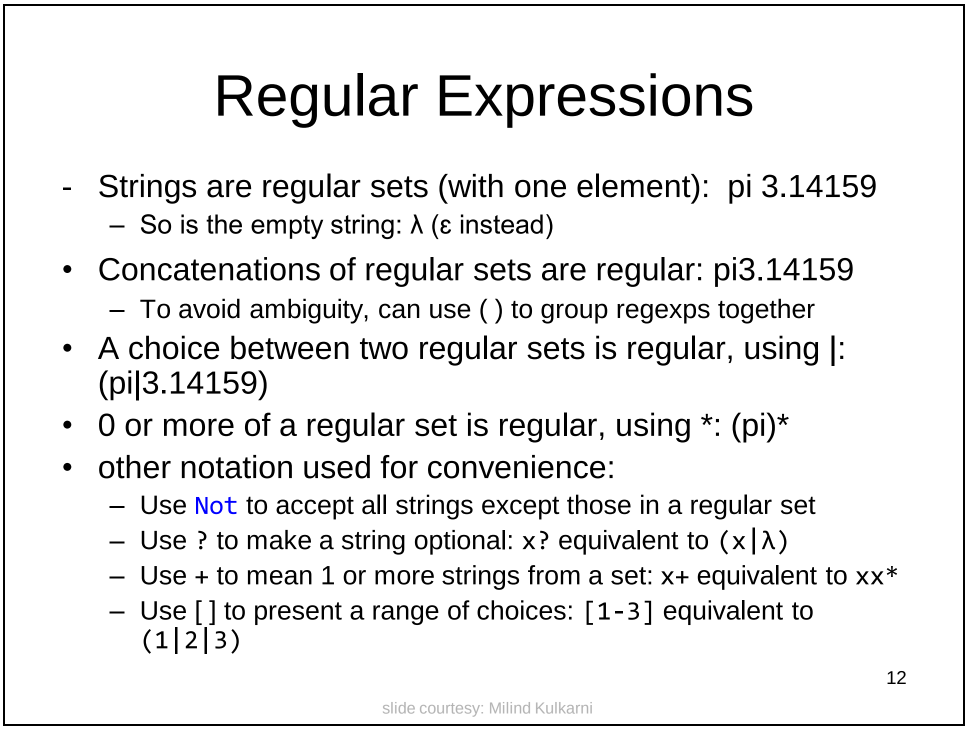
Start with a finite character set or *Vocabulary* (V). Strings are formed using this character set with the following rules:

As mentioned earlier, regular expressions are used to define the structure of tokens in a programming language.

A regular set is a language that can be defined by a regular expression. Informally, a regular set is a set of strings defined by regular expressions.

Regular Languages are those that can be defined by regular expressions. Alternate / equivalent definitions are: a regular language is one that is accepted by an NFA or by a DFA

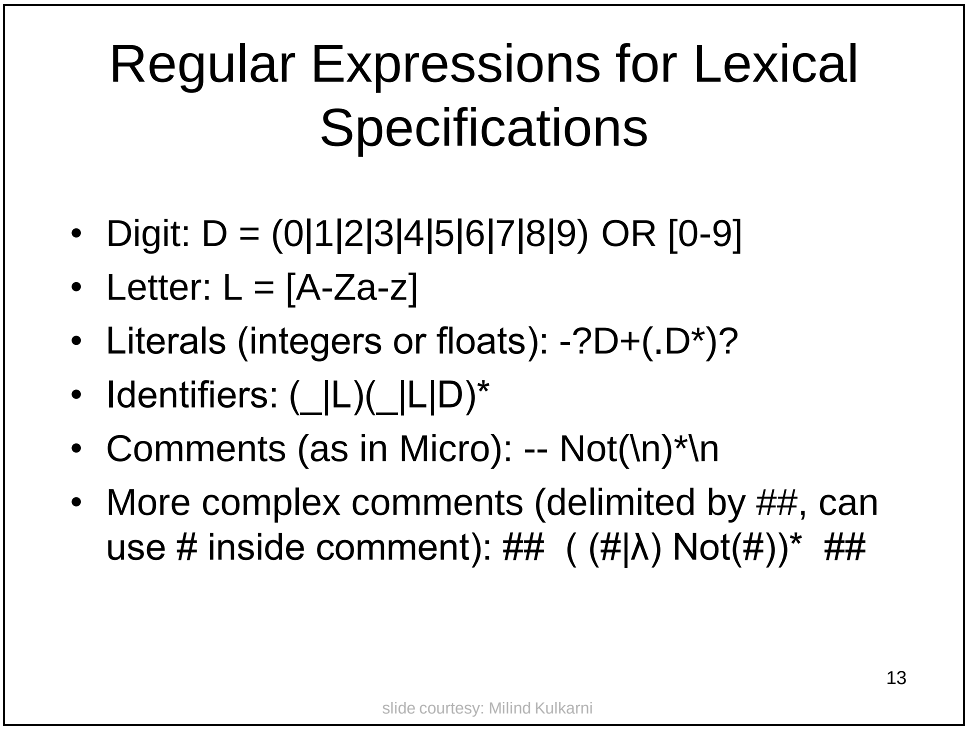
What is a language? A set of strings.



Regular Expressions

- Strings are regular sets (with one element): pi 3.14159
  - So is the empty string: λ (ε instead)
- Concatenations of regular sets are regular: pi3.14159
  - To avoid ambiguity, can use ( ) to group regexps together
- A choice between two regular sets is regular, using |: (pi|3.14159)
- 0 or more of a regular set is regular, using *: (pi)*
- other notation used for convenience:
  - Use `Not` to accept all strings except those in a regular set
  - Use `?` to make a string optional: `x?` equivalent to `(x|λ)`
  - Use + to mean 1 or more strings from a set: `x+` equivalent to `xx*`
  - Use [ ] to present a range of choices: `[1-3]` equivalent to `(1|2|3)`

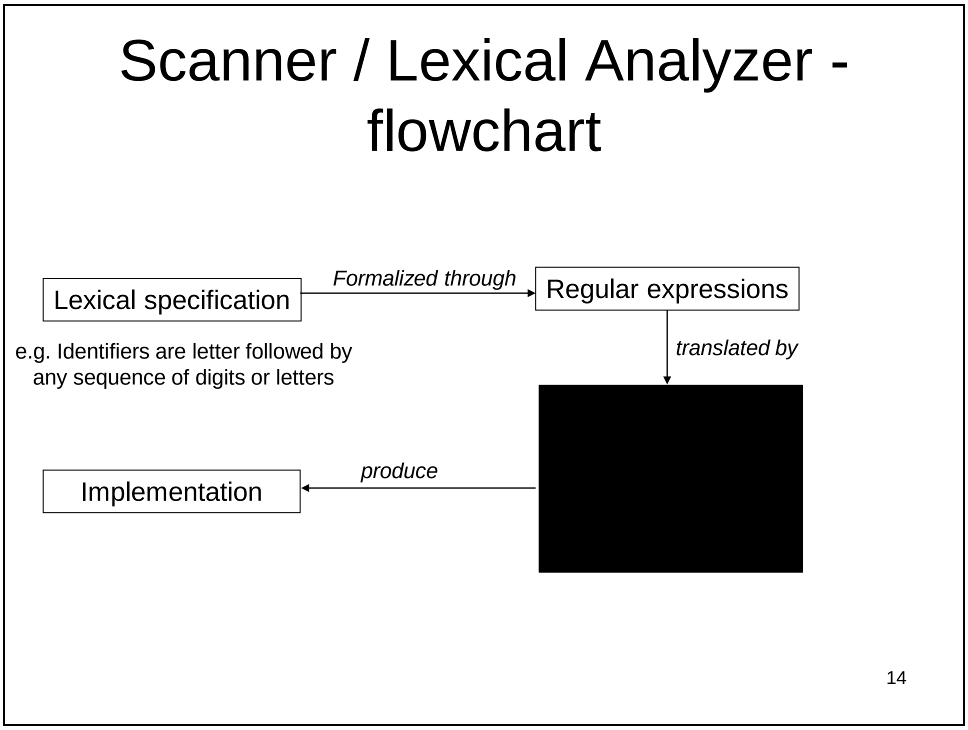
slide courtesy: Milind Kulkarni



Regular Expressions for Lexical Specifications

- Digit: D = (0|1|2|3|4|5|6|7|8|9) OR [0-9]
- Letter: L = [A-Za-z]
- Literals (integers or floats): -?D+(.D*)?
- Identifiers: (_|L)(_|L|D)*
- Comments (as in Micro): -- Not(\n)*\n
- More complex comments (delimited by ##, can use # inside comment): ## ((#|λ) Not(#))* ##

slide courtesy: Milind Kulkarni



Scanner / Lexical Analyzer - flowchart

Lexical specification

Formalized through

Regular expressions

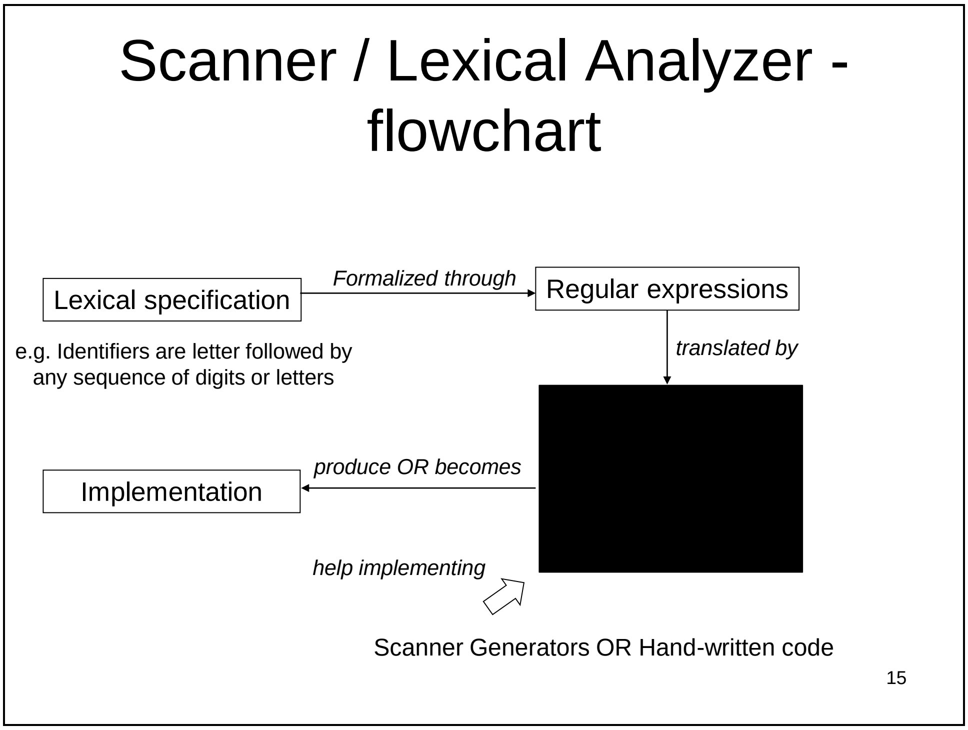
e.g. Identifiers are letter followed by any sequence of digits or letters

translated by

produce

Implementation

The black-box takes regular expressions and produces scanner software.



Scanner / Lexical Analyzer - flowchart

Lexical specification

Formalized through

Regular expressions

e.g. Identifiers are letter followed by any sequence of digits or letters

translated by

Implementation

produce OR becomes

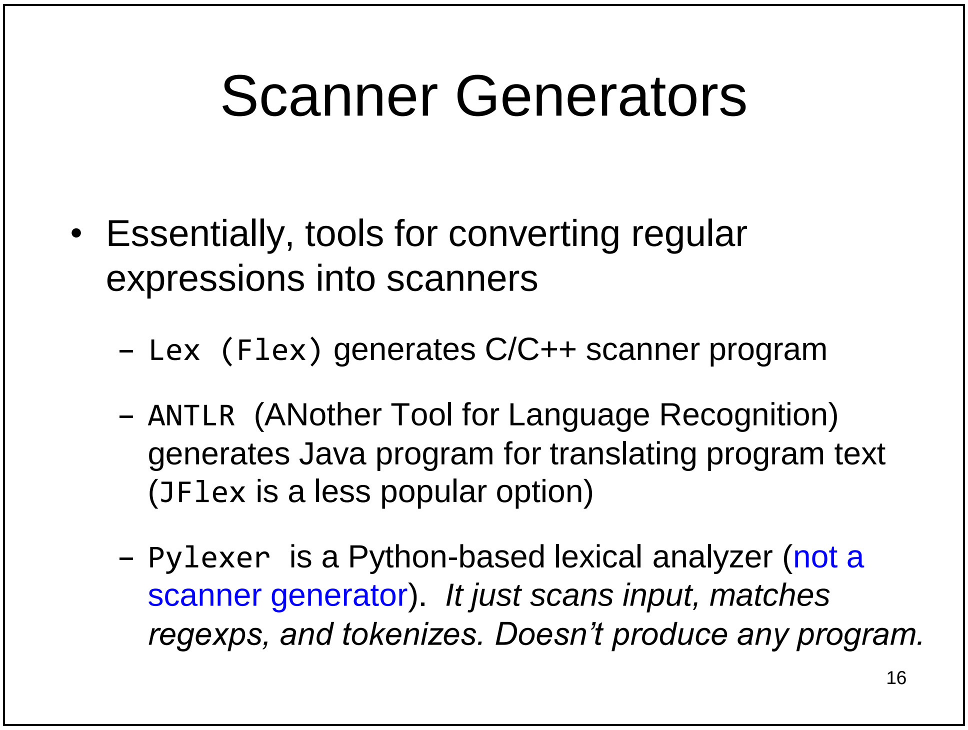
help implementing

Scanner Generators OR Hand-written code

You may take the help of a scanner-generator tool to implement the black-box or you may code the black-box yourself.

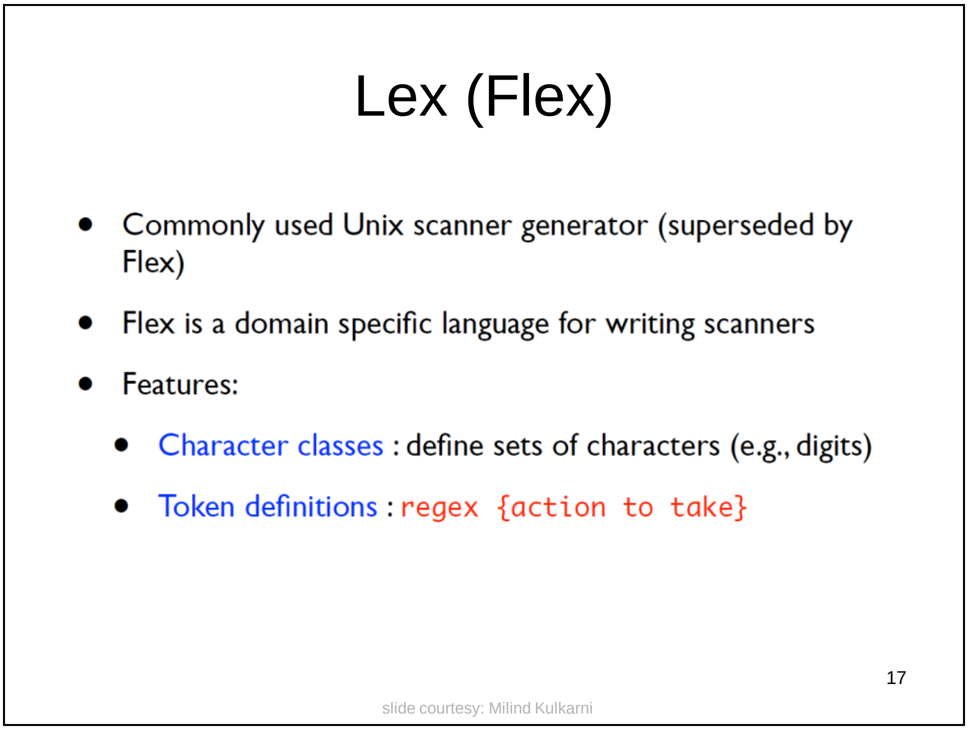
When you take the help of a scanner-generator tool such as Flex, you get a program as output (the ‘Implementation’ box) that is your scanner software.

When you code yourself the internals of the Black-Box, you need not duplicate the effort of the scanner generator i.e. you need not write code that when run, outputs the scanner program (the ‘implementation’ box). Rather, you can directly code the scanner program (and make the ‘Implementation’ box part of your code.)



Scanner Generators

- Essentially, tools for converting regular expressions into scanners
  - `Lex (Flex)` generates C/C++ scanner program
  - `ANTLR` (ANother Tool for Language Recognition) generates Java program for translating program text (`JFlex` is a less popular option)
  - `Pylexer` is a Python-based lexical analyzer (not a scanner generator). *It just scans input, matches regexps, and tokenizes. Doesn’t produce any program.*

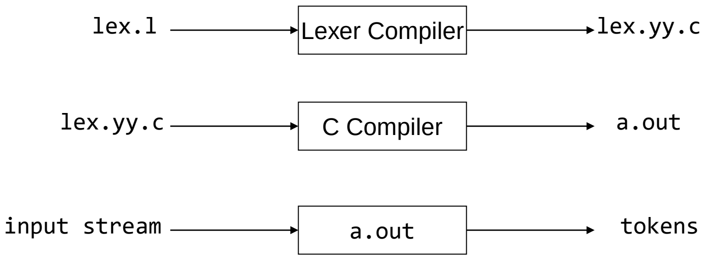


Lex (Flex)

- Commonly used Unix scanner generator (superseded by Flex)
- Flex is a domain specific language for writing scanners
- Features:
  - Character classes : define sets of characters (e.g., digits)
  - Token definitions : `regex {action to take}`

slide courtesy: Milind Kulkarni

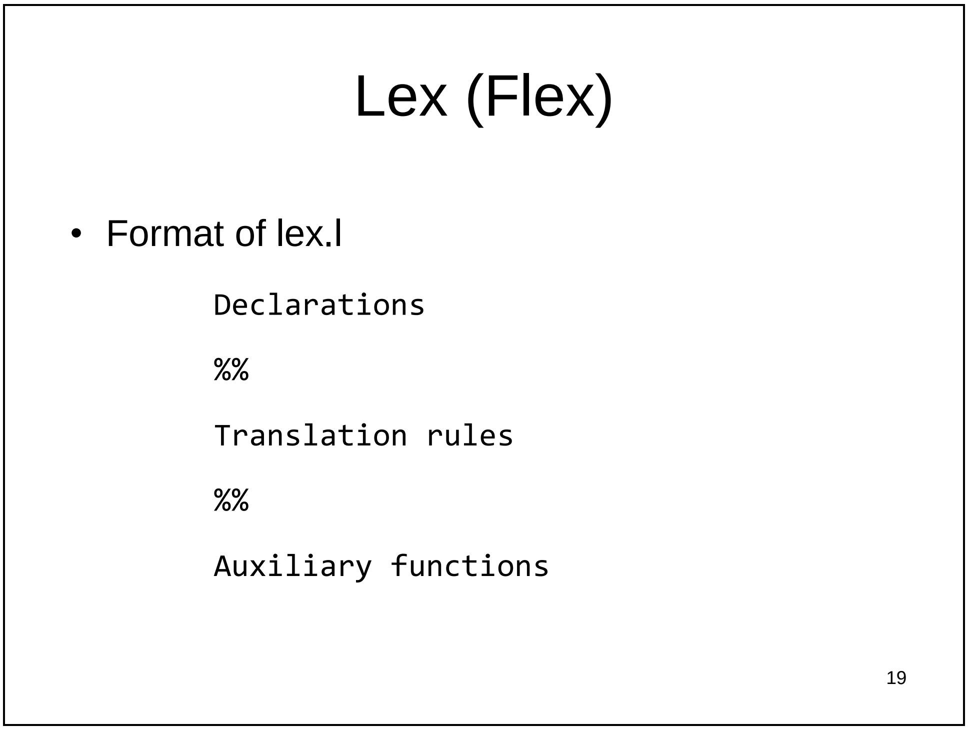
Lex (Flex)



lex.l → Lexer Compiler → lex.yy.c

lex.yy.c → C Compiler → a.out

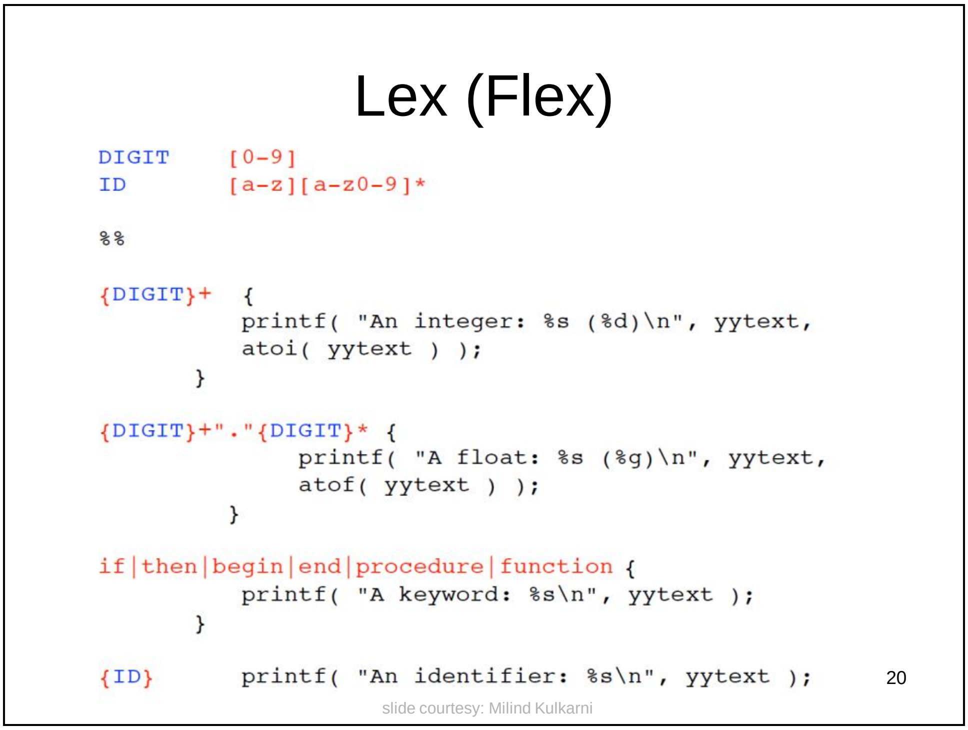
input stream → a.out → tokens



Lex (Flex)

- Format of lex.l

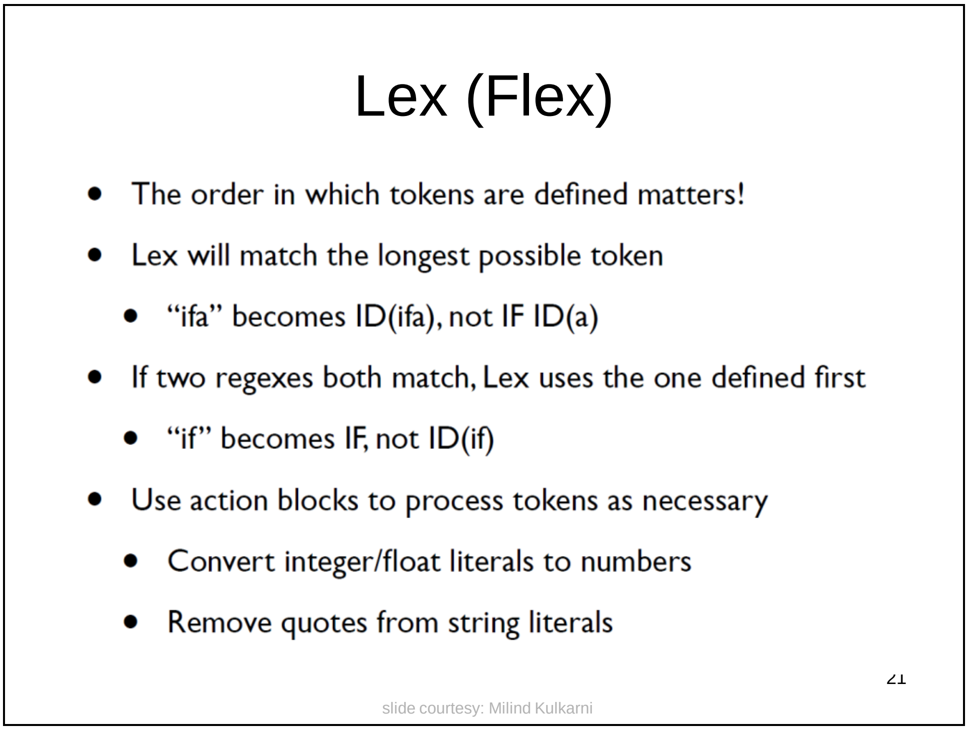
```
Declarations

%%

Translation rules

%%

Auxiliary functions
```



Lex (Flex)

```
DIGIT    [0-9]
ID       [a-z][a-z0-9]*

%%

{DIGIT}+  {
          printf( "An integer: %s (%d)\n", yytext,
          atoi( yytext ) );
       }

{DIGIT}+"."{DIGIT}* {
              printf( "A float: %s (%g)\n", yytext,
              atof( yytext ) );
         }

if|then|begin|end|procedure|function {
          printf( "A keyword: %s\n", yytext );
       }

{ID}      printf( "An identifier: %s\n", yytext );
```

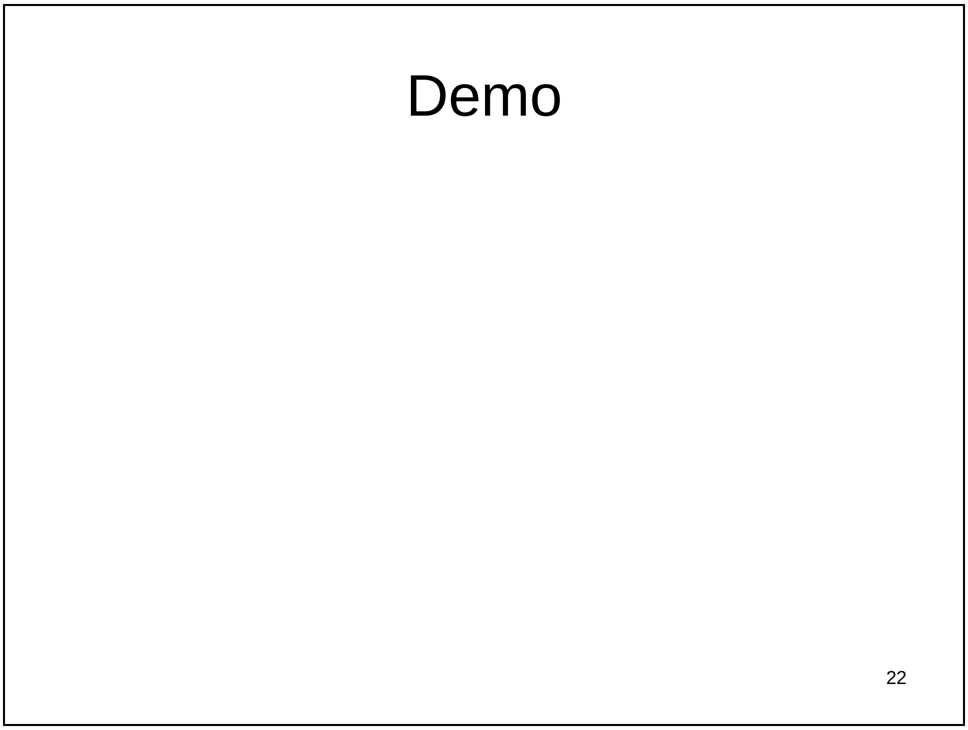
slide courtesy: Milind Kulkarni



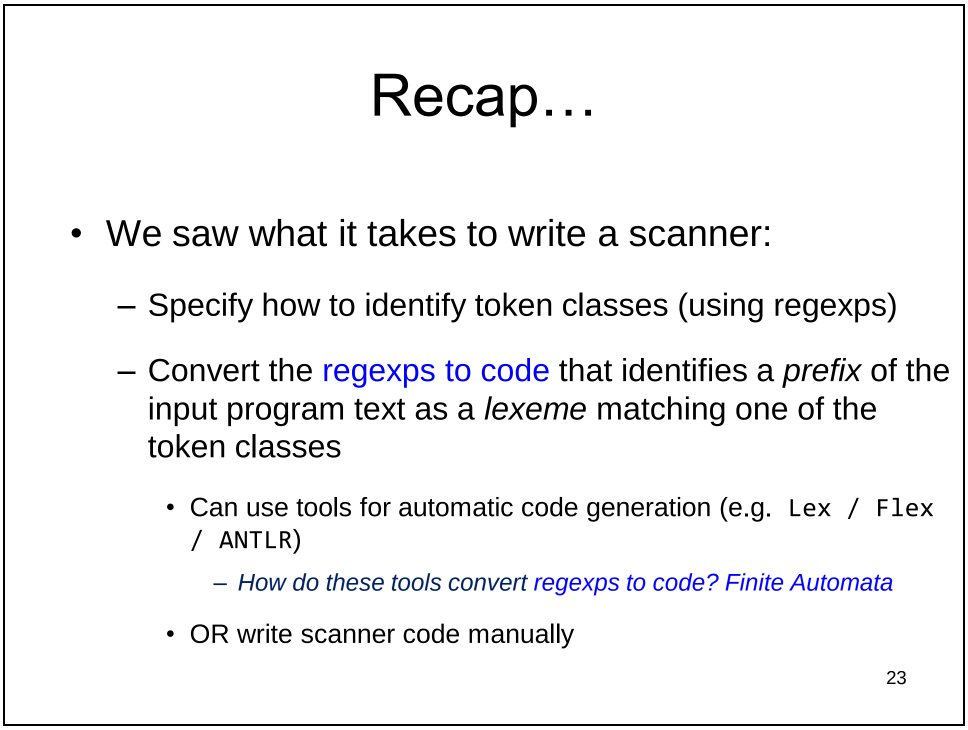
Lex (Flex)

- The order in which tokens are defined matters!
- Lex will match the longest possible token
  - "ifa" becomes ID(ifa), not IF ID(a)
- If two regexes both match, Lex uses the one defined first
  - "if" becomes IF, not ID(if)
- Use action blocks to process tokens as necessary
  - Convert integer/float literals to numbers
  - Remove quotes from string literals

slide courtesy: Milind Kulkarni



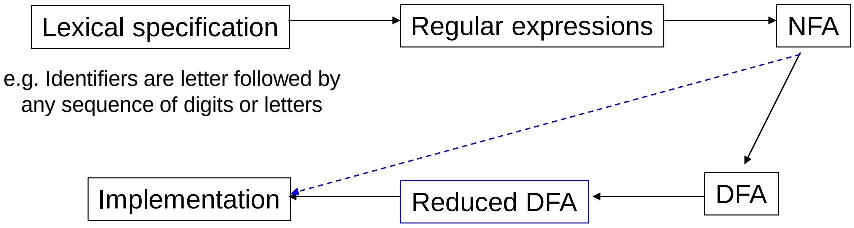
Demo



Recap…

- We saw what it takes to write a scanner:
  - Specify how to identify token classes (using regexps)
  - Convert the regexps to code that identifies a *prefix* of the input program text as a *lexeme* matching one of the token classes
    - Can use tools for automatic code generation (e.g. `Lex / Flex / ANTLR`)
      - *How do these tools convert regexps to code? Finite Automata*
    - OR write scanner code manually

Scanner - flowchart


Lexical specification

Regular expressions

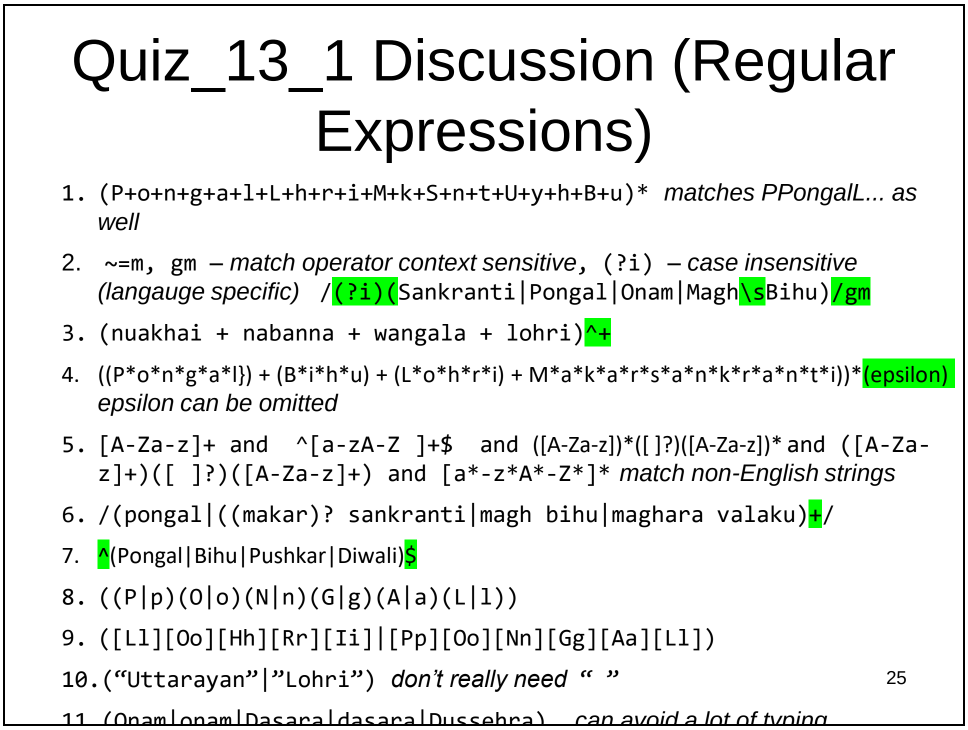
NFA

DFA

Reduced DFA

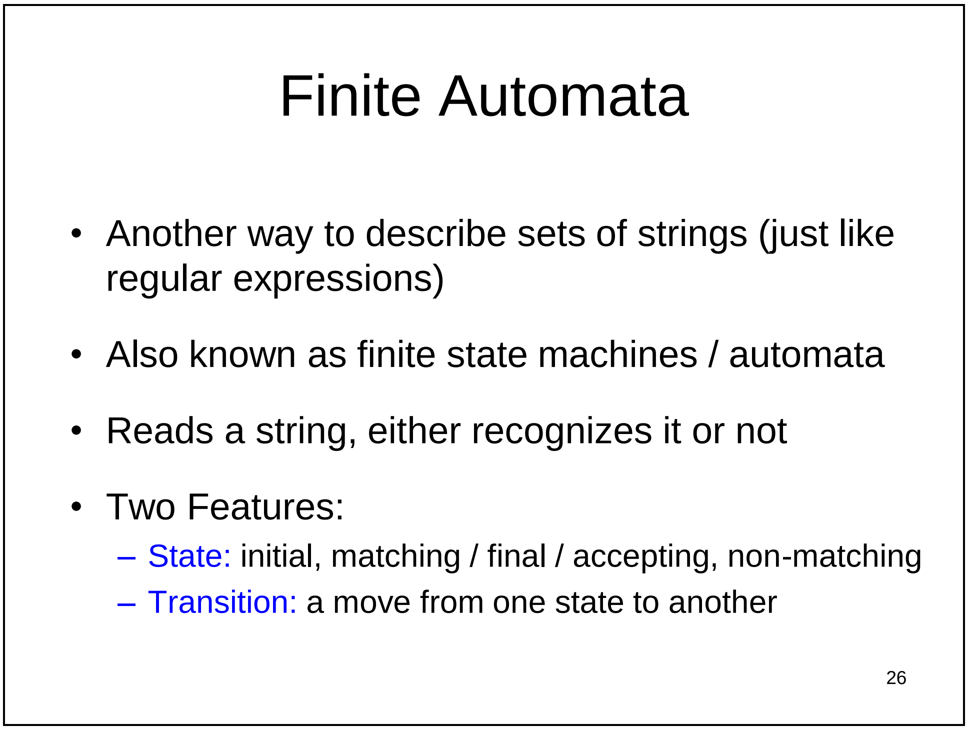
Implementation

e.g. Identifiers are letter followed by any sequence of digits or letters



Quiz_13_1 Discussion (Regular Expressions)

1. (P+o+n+g+a+l+L+h+r+i+M+k+S+n+t+U+y+h+B+u)* *matches PPongalL… as well*
2. ~=m, gm – *match operator context sensitive*, (?i) – *case insensitive (langauge specific)* /(?i)(Sankranti|Pongal|Onam|Magh\sBihu)/gm
3. (nuakhai + nabanna + wangala + lohri)^+
4. ((P*o*n*g*a*l}) + (B*i*h*u) + (L*o*h*r*i) + M*a*k*a*r*s*a*n*k*r*a*n*t*i))*(epsilon) *epsilon can be omitted*
5. [A-Za-z]+ and ^[a-zA-Z]+$ and ([A-Za-z])*([ ]?)([A-Za-z])* and ([A-Za-z]+)([ ]?)([A-Za-z]+) and [a*-z*A*-Z*]* *match non-English strings*
6. /(pongal|((makar)? sankranti|magh bihu|maghara valaku)+/
7. ^(Pongal|Bihu|Pushkar|Diwali)$
8. ((P|p)(O|o)(N|n)(G|g)(A|a)(L|l))
9. ([Ll][Oo][Hh][Rr][Ii]|[Pp][Oo][Nn][Gg][Aa][Ll])
10. (“Uttarayan”|”Lohri”) *don’t really need “ ”*
11. (Onam|onam|Dasara|dasara|Dussehra) *can avoid a lot of typing*

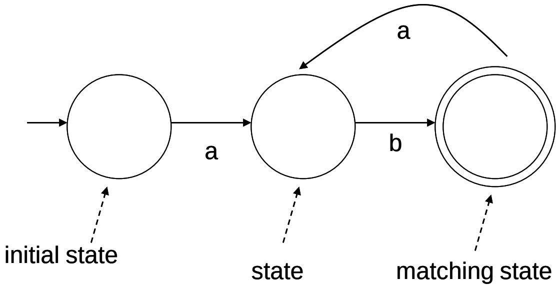


Finite Automata

- Another way to describe sets of strings (just like regular expressions)
- Also known as finite state machines / automata
- Reads a string, either recognizes it or not
- Two Features:
  - State: initial, matching / final / accepting, non-matching
  - Transition: a move from one state to another

Finite Automata

- Regular expressions and FA are equivalent*



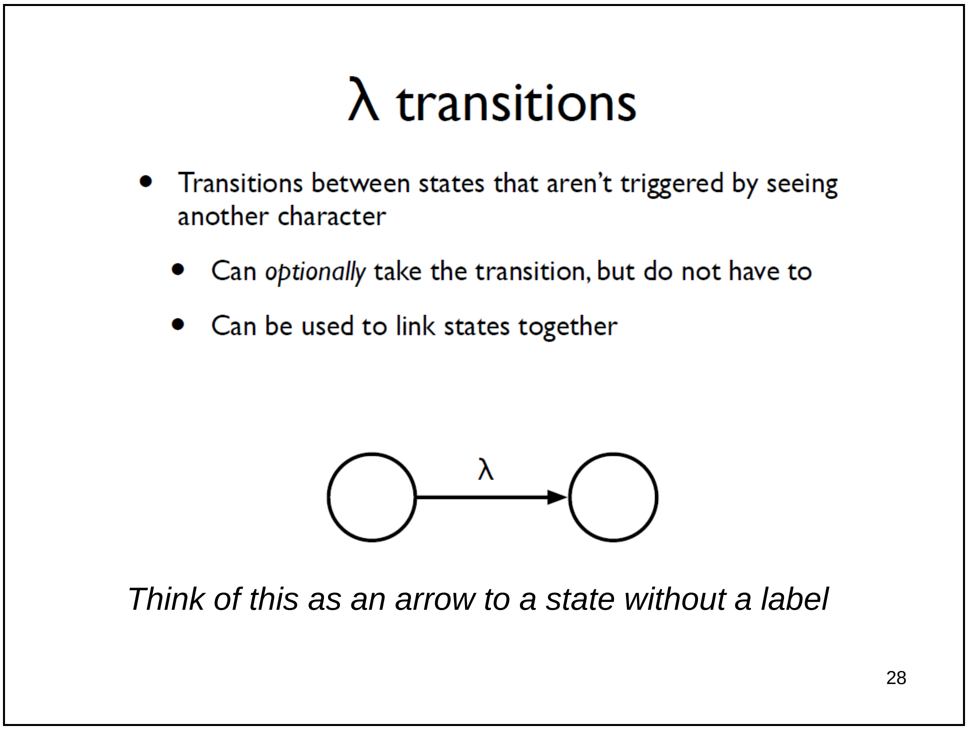
initial state

state

matching state

Exercise: what is the equivalent regular expression for this FA?

* Ignoring the *`empty`* regular language



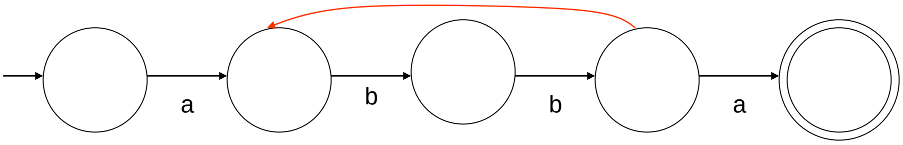
λ transitions

- Transitions between states that aren’t triggered by seeing another character
    - Can *optionally* take the transition, but do not have to
    - Can be used to link states together

Think of this as an arrow to a state without a label

Non-deterministic Finite Automata

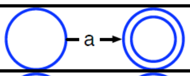
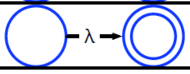
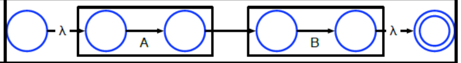
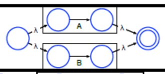
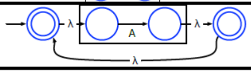
- A FA is non-deterministic if, from one state reading a single character could result in transition to multiple states (or has λ transitions)
- Sometimes regular expressions and NFAs have a close correspondence



≡

a(bb)+a

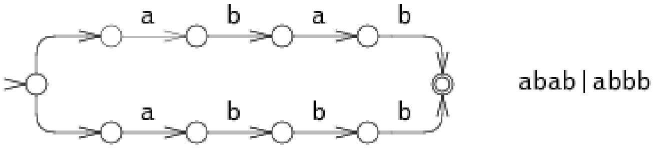
Building a FA from a regexp

Expression	FA
a	
λ	
AB	
A|B	
A*	

Mini-exercise: how do we build an FA that accepts Not(A)?

What about A? (? as in optional)

Non-deterministic Finite Automata



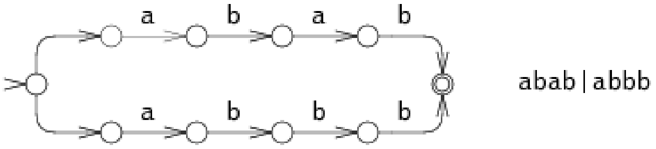
- NFAs are concise but slow
- Example:
  - Running the NFA for input string `abbb` requires exploring all execution paths

* picture example taken from https://swtch.com/~rsc/regexp/regexp1.html

“Running” an NFA

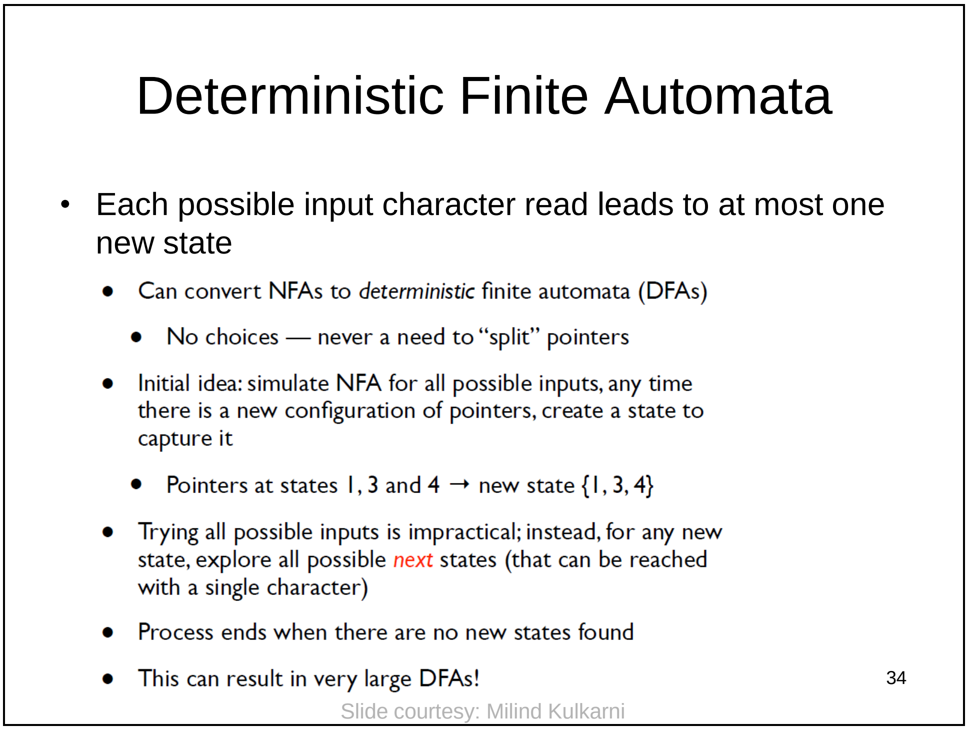
- Intuition: take every possible path through an NFA
  - Think: parallel execution of NFA
  - Maintain a “pointer” that tracks the current state
  - Every time there is a choice, “split” the pointer, and have one pointer follow each choice
  - Track each pointer simultaneously
    - If a pointer gets stuck, stop tracking it
    - If any pointer reaches an accept state at the end of input, accept

Non-deterministic Finite Automata



- NFAs are concise but slow
- Example:
  - Running the NFA for input string `abbb` requires exploring all execution paths
  - **Optimization: run through the execution paths in parallel**
    - ***Complicated. Can we do better?***

* picture example taken from https://swtch.com/~rsc/regexp/regexp1.html



Deterministic Finite Automata

- Each possible input character read leads to at most one new state
  - Can convert NFAs to *deterministic* finite automata (DFAs)
    - No choices — never a need to "split" pointers
  - Initial idea: simulate NFA for all possible inputs, any time there is a new configuration of pointers, create a state to capture it
    - Pointers at states 1, 3 and 4 → new state {1, 3, 4}
  - Trying all possible inputs is impractical; instead, for any new state, explore all possible *next* states (that can be reached with a single character)
  - Process ends when there are no new states found
  - This can result in very large DFAs!

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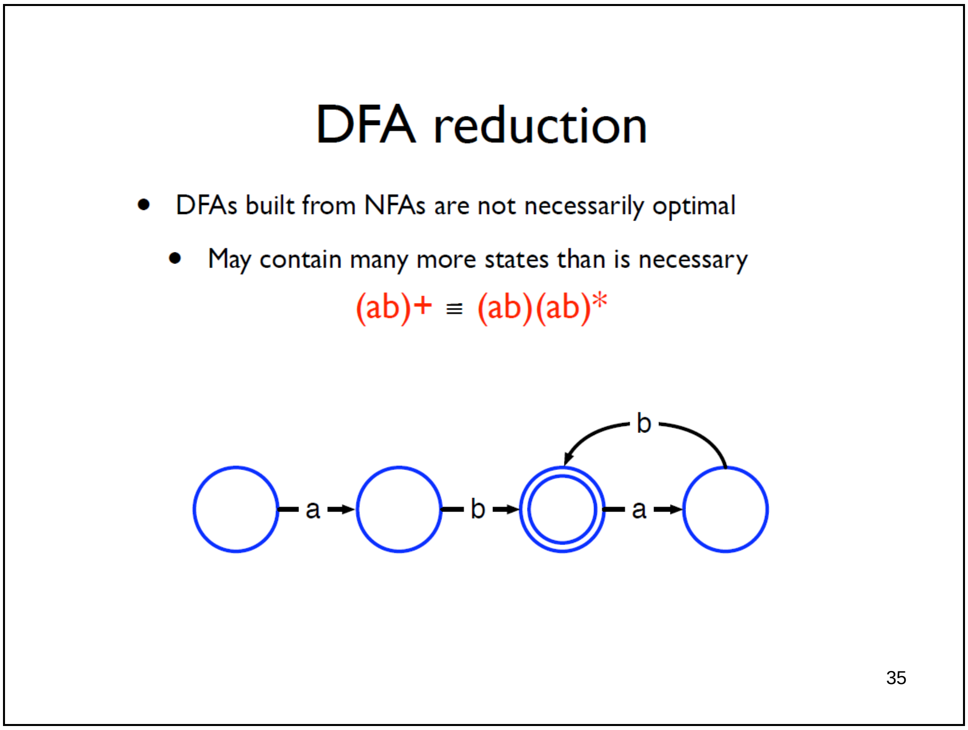
Slide courtesy: Milind Kulkarni



DFA reduction

- DFAs built from NFAs are not necessarily optimal
  - May contain many more states than is necessary

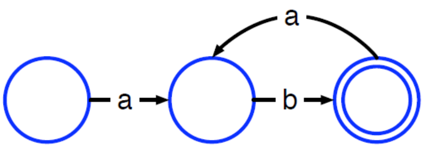
$(ab)+ \equiv (ab)(ab)^*$

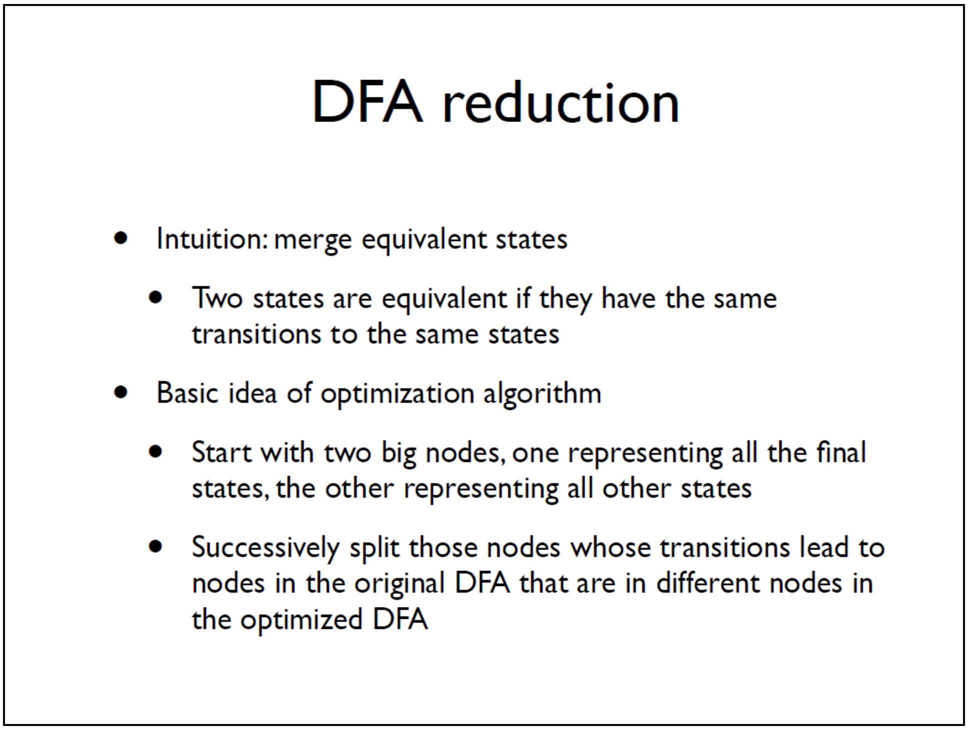
35

DFA reduction

- DFAs built from NFAs are not necessarily optimal
  - May contain many more states than is necessary

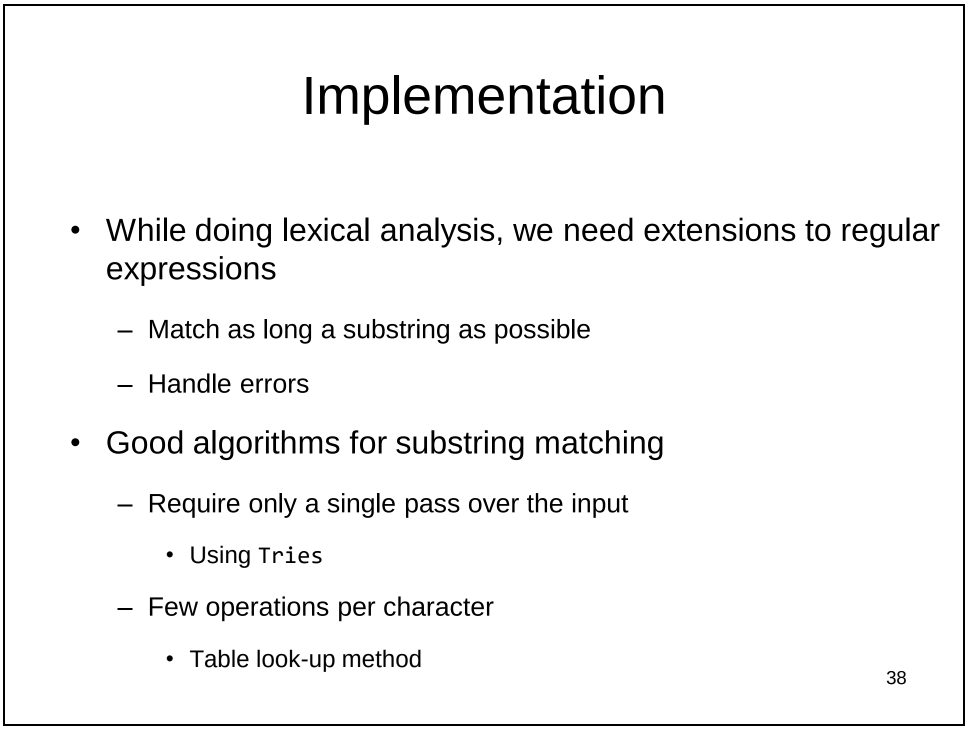
(ab)+ ≡ (ab)(ab)*





DFA reduction

- Intuition: merge equivalent states
  - Two states are equivalent if they have the same transitions to the same states
- Basic idea of optimization algorithm
  - Start with two big nodes, one representing all the final states, the other representing all other states
  - Successively split those nodes whose transitions lead to nodes in the original DFA that are in different nodes in the optimized DFA



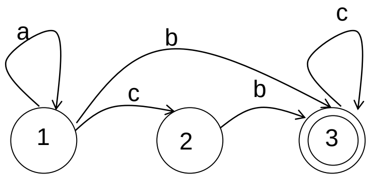
Implementation

- While doing lexical analysis, we need extensions to regular expressions
  - Match as long a substring as possible
  - Handle errors
- Good algorithms for substring matching
  - Require only a single pass over the input
    - Using `Tries`
  - Few operations per character
    - Table look-up method

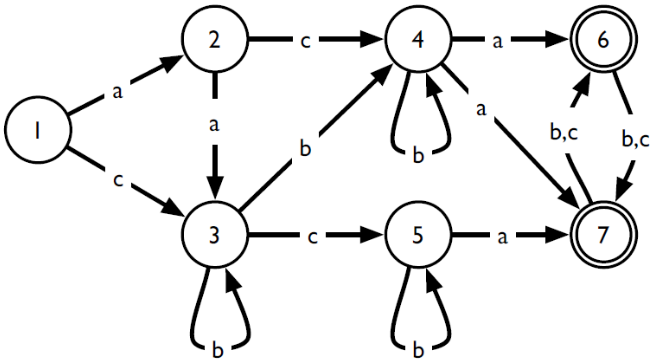
Implementation: Transition Tables

- A table encodes states and transitions of FA
  - 1 row per state
  - 1 column per character in the alphabet
  - Table entry: state (label)

State / Character	**a**	**b**	**c**
1	1	3	2
2	-	3	-
3	-	-	3

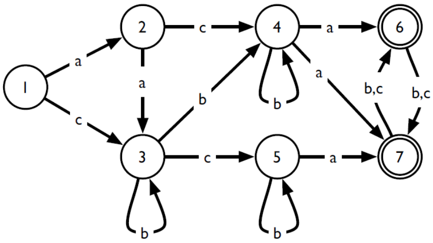


Example



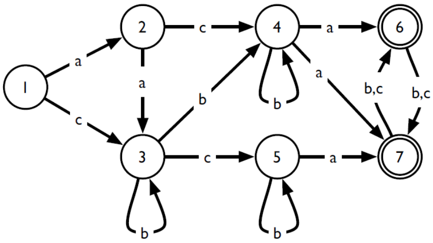
NFA OR DFA?

Example: NFA -> DFA



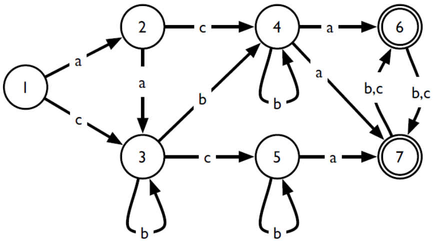
State / Char	a	b	c
1	2	-	3

Example: NFA -> DFA



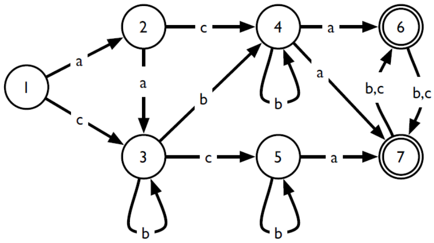
State / Char	a	b	c
1	2	-	3
2	3	-	4

Example: NFA -> DFA



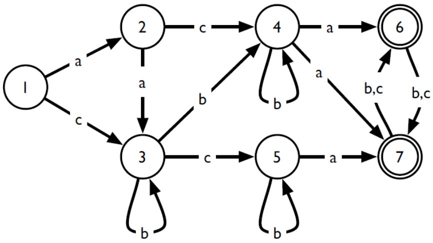
State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5

Example: NFA -> DFA



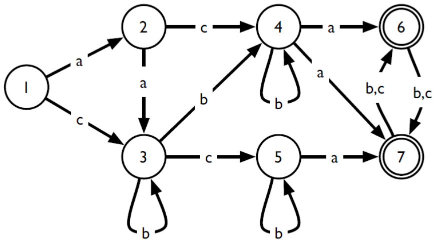
State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	6,7	4	-

Example: NFA -> DFA



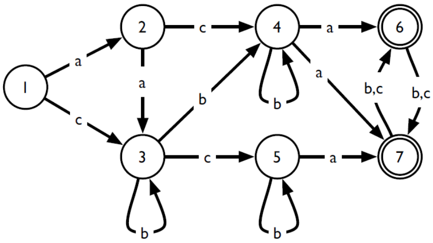
State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	6,7	4	-
3,4	6,7	3,4	5

Example: NFA -> DFA



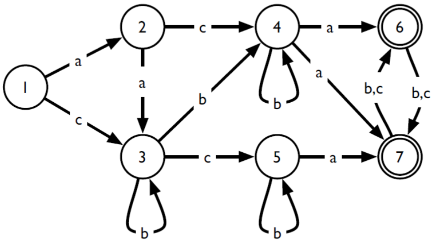
State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	6,7	4	-
3,4	6,7	3,4	5
5	7	5	-

Example: NFA -> DFA



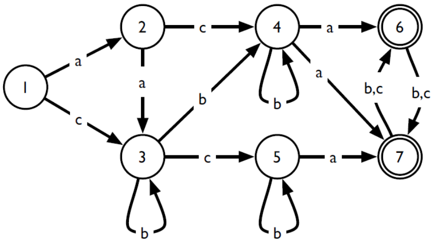
State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	6,7	4	-
3,4	6,7	3,4	5
5	7	5	-
6,7	-	6,7	6,7

Example: NFA -> DFA



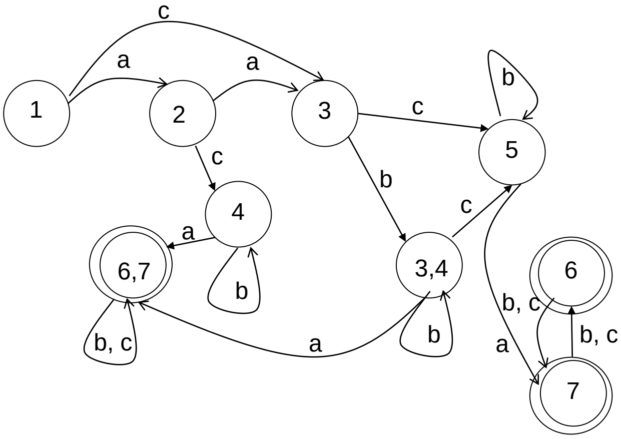
State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	6,7	4	-
3,4	6,7	3,4	5
5	7	5	-
6,7	-	6,7	6,7
7	-	6	6

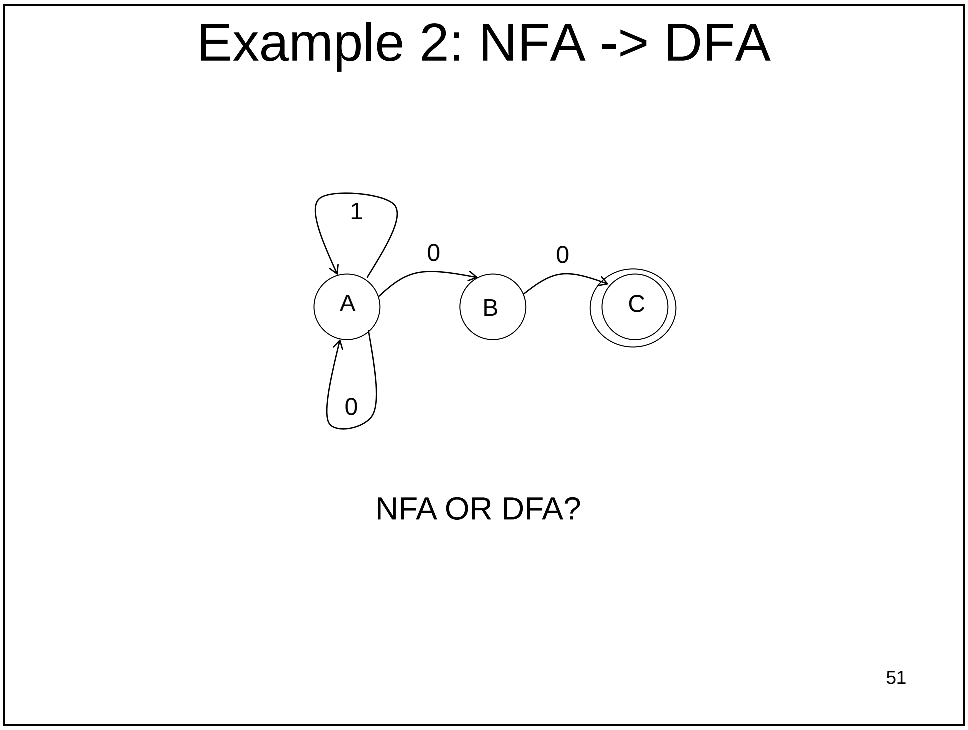
Example: NFA -> DFA



State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	6,7	4	-
3,4	6,7	3,4	5
5	7	5	-
6,7	-	6,7	6,7
7	-	6	6
6	-	7	7

Example: DFA





Example 2: NFA -> DFA

NFA OR DFA?

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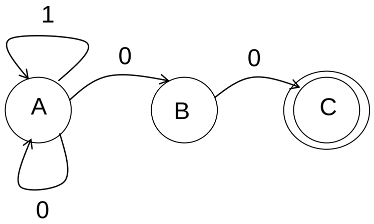
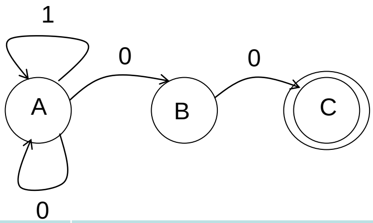
Example 2: NFA -> DFA



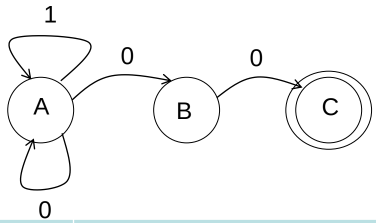
State/ char	0	1	Final ?	Comments
A	{A, B}	A	No	In state A, on seeing input 0, we have a choice to go to either state A or B

Example 2: NFA -> DFA



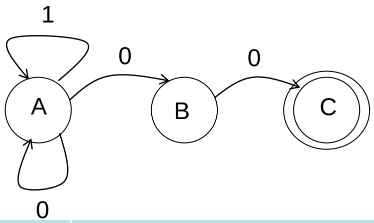
State/ char	0	1	Final ?	Comments
A	{A, B}	A	No	In state A, on seeing input 0, FA gives us a choice to go to either state A or state B
A,B	{A,B,C}	A	No	In state A,B we have two component states A and B. From A on input 0, FA takes us to states A and B. From B on 0 FA takes us to C. So, the set of states reachable from A,B on input 0 is A,B,C. Similarly, for input 1, from A FA takes us to A. From B on input 1, FA gets stuck in an error state.

Example 2: NFA -> DFA



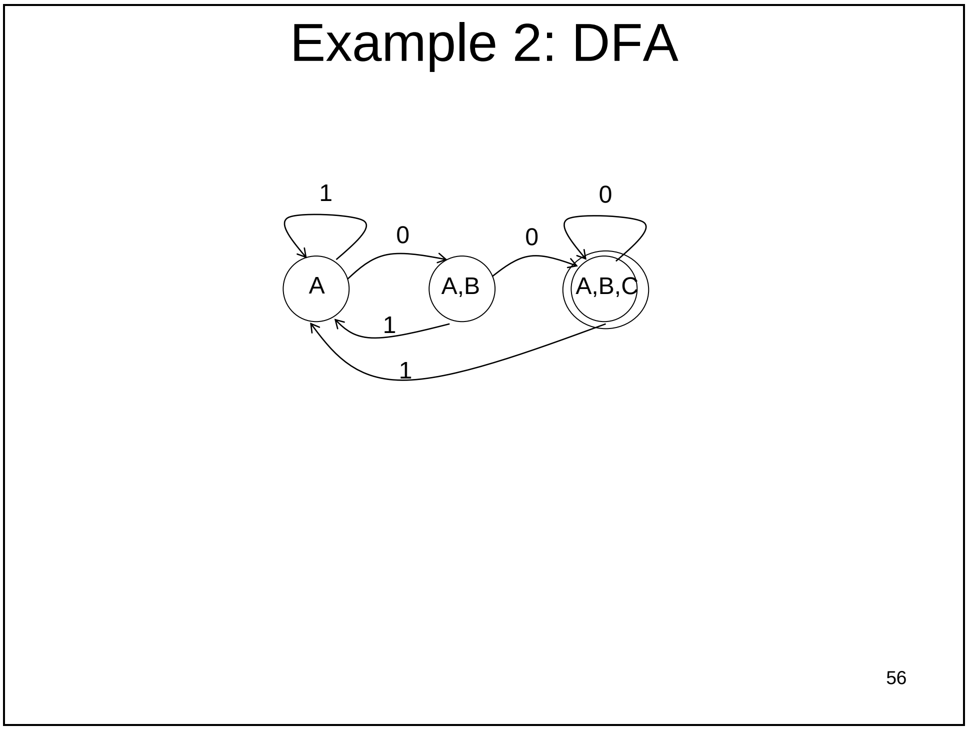
State/ char	0	1	Final ?	Comments
A	{A, B}	A	No	In state A, on seeing input 0, FA gives us a choice to go to either state A or state B
A,B	{A,B,C}	A	No	In state A,B we have two component states A and B. From A on input 0, FA takes us to states A and B. From B on 0 FA takes us to C. So, the set of states reachable from A,B on input 0 is A,B,C. Similarly, for input 1, from A FA takes us to A. From B on input 1, FA gets stuck in an error state.
A,B,C	{A,B,C}	A	Yes	One of the component states C is final in the FA. Hence, A,B,C is a final state.

Example 2: NFA -> DFA



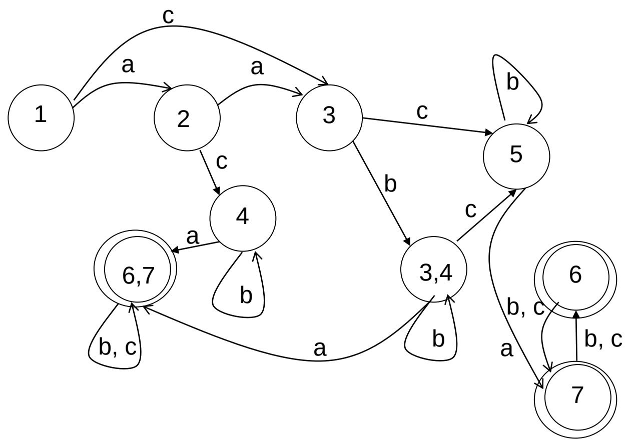
State/ char	0	1	Final ?	Comments
A	{A, B}	A	No	In state A, on seeing input 0, FA gives us a choice to go to either state A or state B
A,B	{A,B,C}	A	No	In state A,B we have two component states A and tes A and B. From B on 0 FA takes us to C. So, the set of states reachable from A,B on input 0 is A,B,C. Similarly, for input 1, from A FA takes us to A. From B on input 1, FA gets stuck in an error state.
A,B,C	{A,B,C}	A	Yes	One of the component states C is final in the FA. Hence, A,B,C is a final state.

Should we consider states B and C in the table?



Example 2: DFA

Example: DFA



What states can be merged?

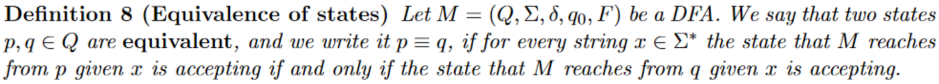
Example: Reduced DFA

What states can be merged?

State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	6,7	4	-
3,4	6,7	3,4	5
5	7	5	-
6,7	-	6,7	6,7
7	-	6	6
6	-	7	7

Example: Reduced DFA

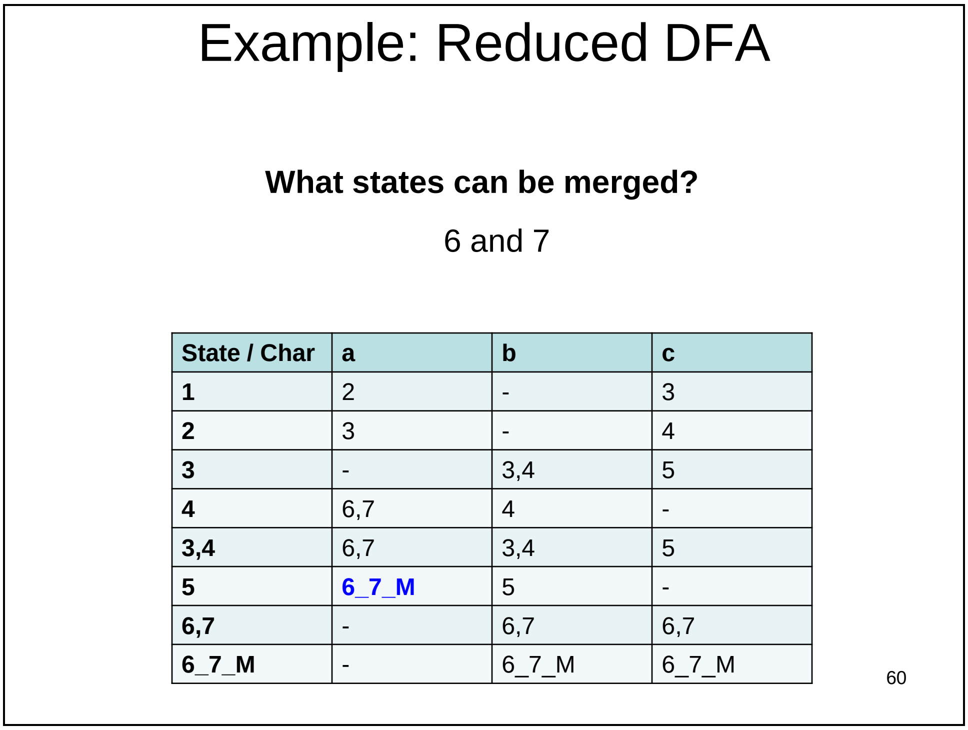
What states can be merged?



Definition 8 (Equivalence of states) *Let $M = (Q, \Sigma, \delta, q_0, F)$ be a DFA. We say that two states $p, q \in Q$ are* **equivalent**, *and we write it $p \equiv q$, if for every string $x \in \Sigma^*$ the state that M reaches from p given x is accepting if and only if the state that M reaches from q given x is accepting.*

State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	6,7	4	-
3,4	6,7	3,4	5
5	7	5	-
6,7	-	6,7	6,7
7	-	6	6
6	-	7	7

Definition 8 pic source: https://people.eecs.berkeley.edu/~luca/cs172/notemindfa.pdf

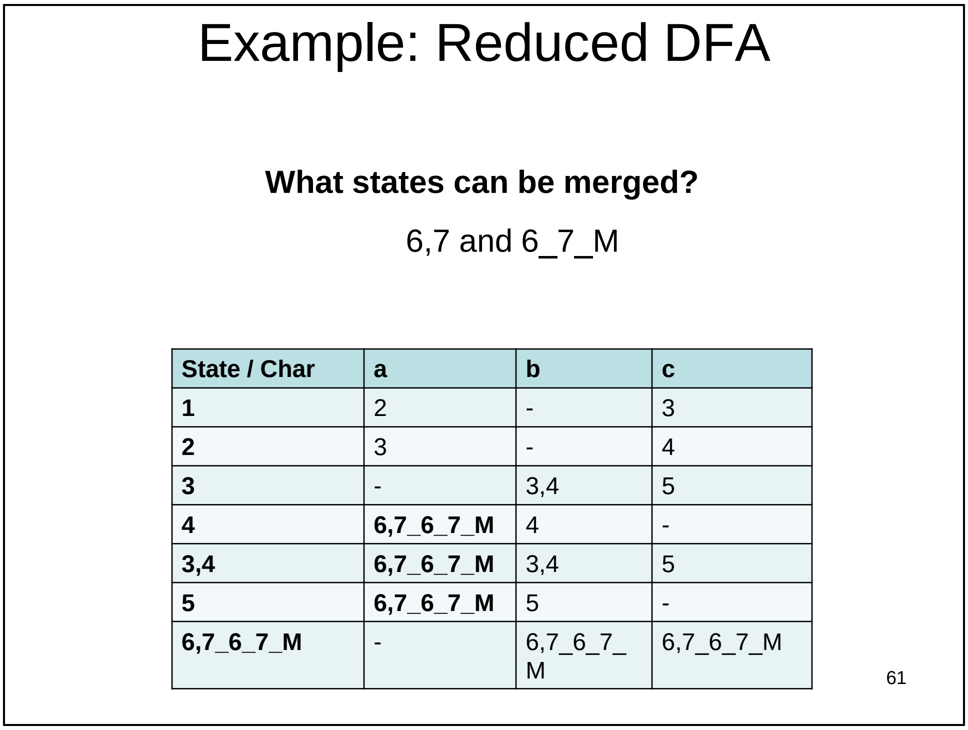


Example: Reduced DFA

What states can be merged?

6 and 7

State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	6,7	4	-
3,4	6,7	3,4	5
5	**6_7_M**	5	-
6,7	-	6,7	6,7
6_7_M	-	6_7_M	6_7_M

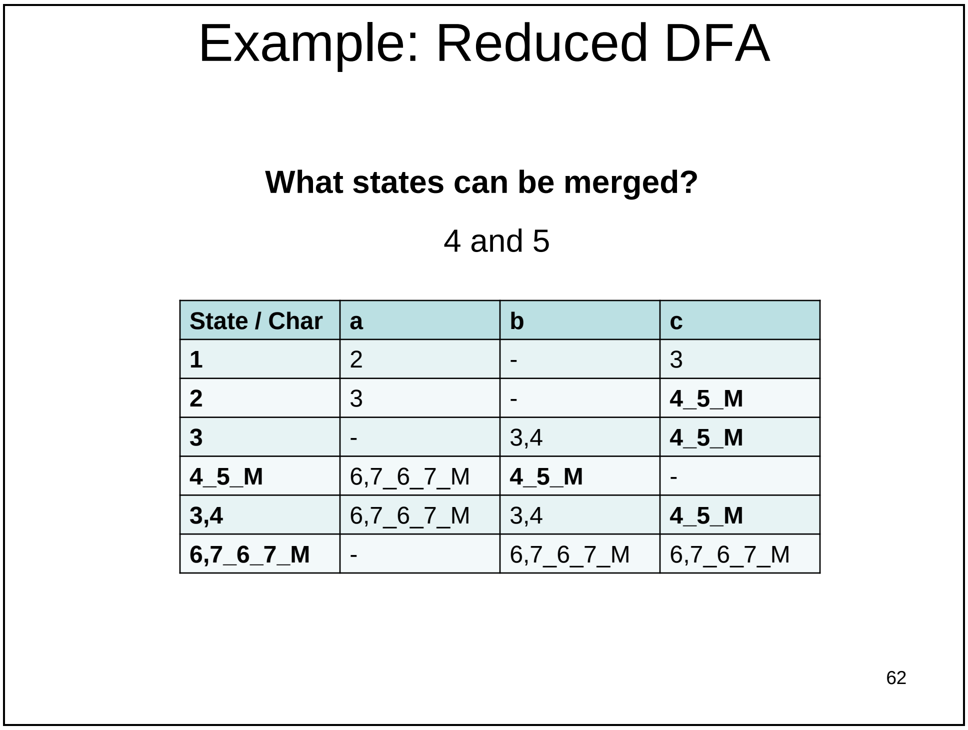


Example: Reduced DFA

What states can be merged?

6,7 and 6_7_M

State / Char	a	b	c
1	2	-	3
2	3	-	4
3	-	3,4	5
4	**6,7_6_7_M**	4	-
3,4	**6,7_6_7_M**	3,4	5
5	**6,7_6_7_M**	5	-
6,7_6_7_M	-	6,7_6_7_M	6,7_6_7_M

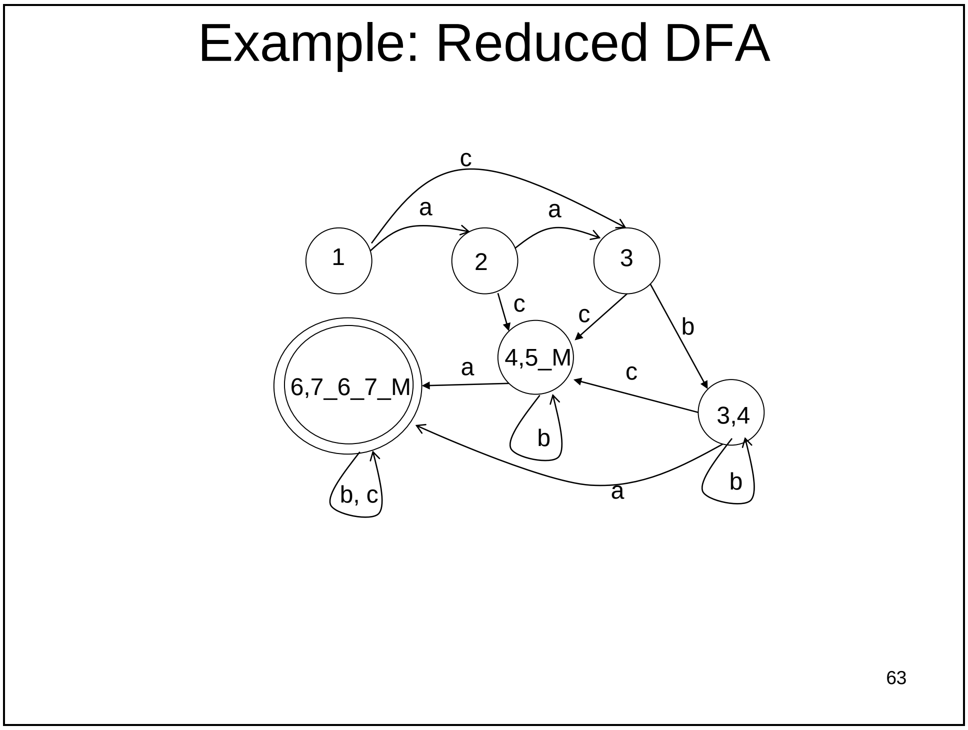


Example: Reduced DFA

What states can be merged?

4 and 5

State / Char	**a**	**b**	**c**
1	2	-	3
2	3	-	**4_5_M**
3	-	3,4	**4_5_M**
4_5_M	6,7_6_7_M	**4_5_M**	-
3,4	6,7_6_7_M	3,4	**4_5_M**
6,7_6_7_M	-	6,7_6_7_M	6,7_6_7_M



Example: Reduced DFA

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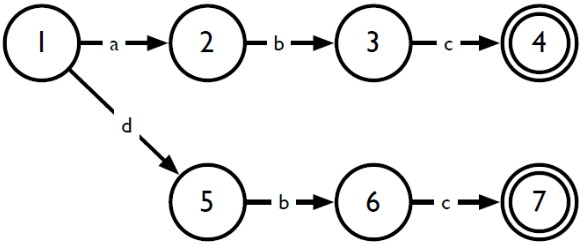
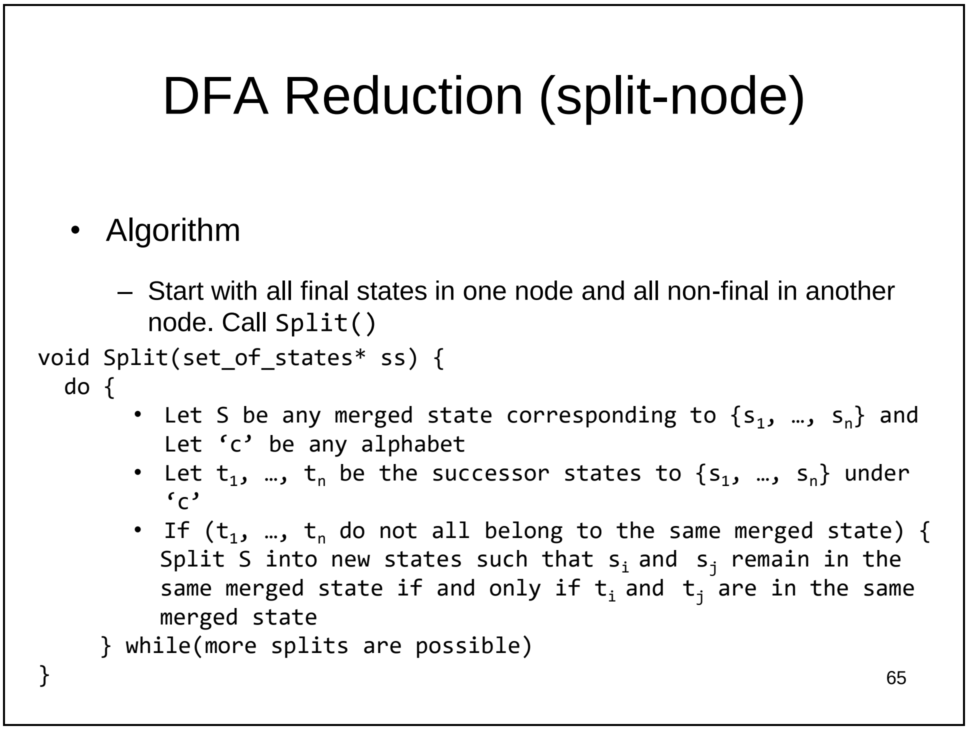
Exercise

- *Reduce the DFA*





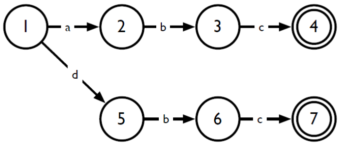
DFA Reduction (split-node)

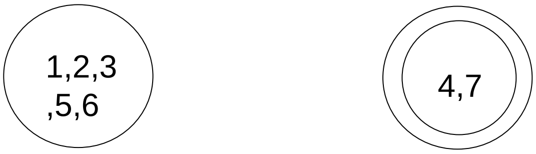
- Algorithm
  - Start with all final states in one node and all non-final in another node. Call `Split()`

```
void Split(set_of_states* ss) {
  do {
       • Let S be any merged state corresponding to {$s_1$, …, $s_n$} and
         Let ‘c’ be any alphabet
       • Let $t_1$, …, $t_n$ be the successor states to {$s_1$, …, $s_n$} under
         ‘c’
       • If ($t_1$, …, $t_n$ do not all belong to the same merged state) {
         Split S into new states such that $s_i$ and $s_j$ remain in the
         same merged state if and only if $t_i$ and $t_j$ are in the same
         merged state
     } while(more splits are possible)
}
```

DFA Reduction (split-node)

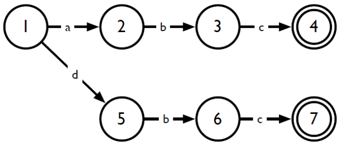
- Start with two big nodes
  - All final states in one and all non-final in another

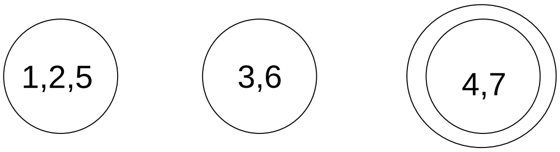




DFA Reduction (split-node)

- Split 3,6 from 1,2, 3, 5, 6
  - 3,6 have common successor under ‘c’. 1,2,5 have no successor under ‘c’



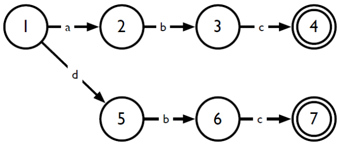

1,2,5

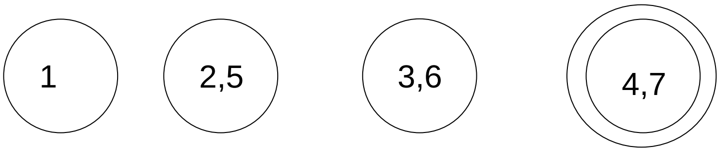
3,6

4,7

DFA Reduction (split-node)

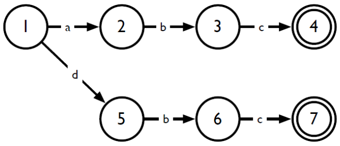
- Split 1 from 1,2, 5
  - 2 and 5 go to merged state 3,6 under ‘b’. 1 does not.

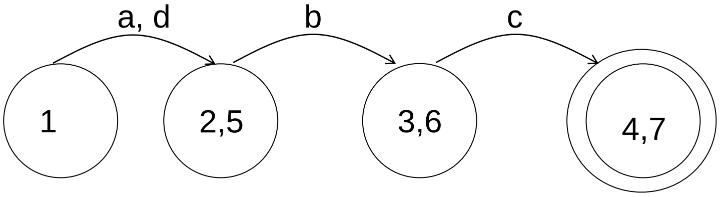


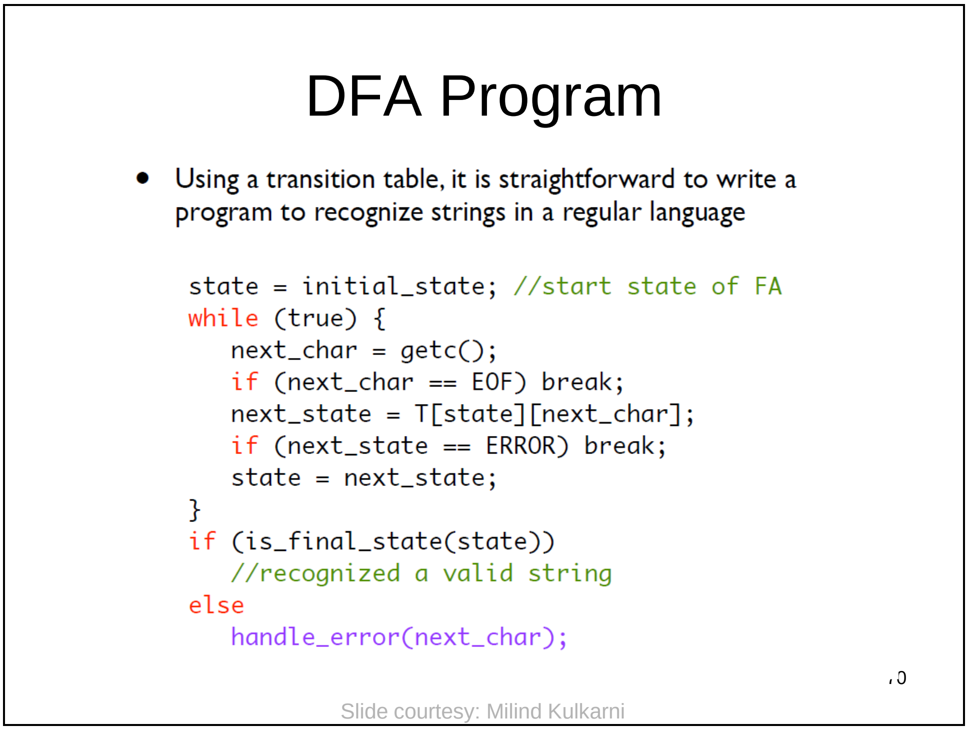


DFA Reduction (split-node)

- No more splits possible





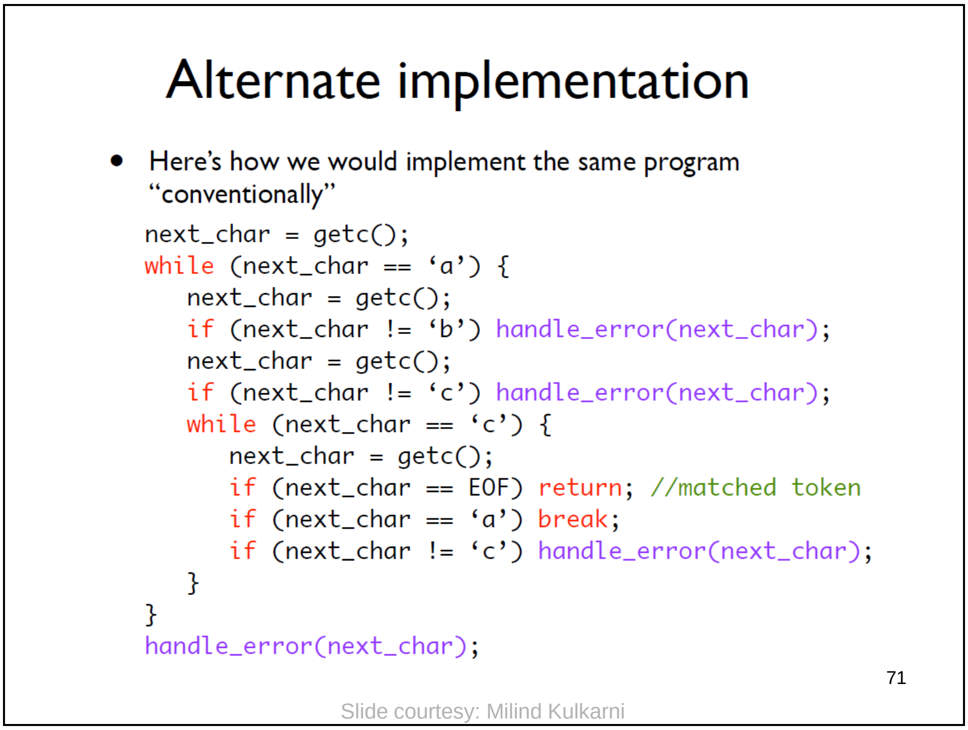


DFA Program

- Using a transition table, it is straightforward to write a program to recognize strings in a regular language

```
state = initial_state; //start state of FA
while (true) {
   next_char = getc();
   if (next_char == EOF) break;
   next_state = T[state][next_char];
   if (next_state == ERROR) break;
   state = next_state;
}
if (is_final_state(state))
   //recognized a valid string
else
   handle_error(next_char);
```

Slide courtesy: Milind Kulkarni



Alternate implementation

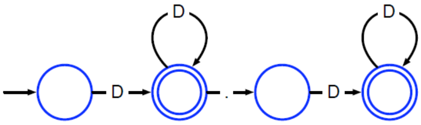
- Here’s how we would implement the same program “conventionally”

```
next_char = getc();
while (next_char == ‘a’) {
    next_char = getc();
    if (next_char != ‘b’) handle_error(next_char);
    next_char = getc();
    if (next_char != ‘c’) handle_error(next_char);
    while (next_char == ‘c’) {
        next_char = getc();
        if (next_char == EOF) return; //matched token
        if (next_char == ‘a’) break;
        if (next_char != ‘c’) handle_error(next_char);
    }
}
handle_error(next_char);
```

Slide courtesy: Milind Kulkarni

Handling Lookahead

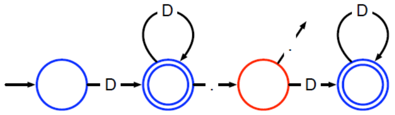
- E.g. distinguish between `int a` and `inta`
  - If the next char belongs to current token, continue
  - Else next char becomes part of next token
- Multi-character lookahead?
  - E.g. `DO I = 1, 100` (loop) vs. `DO I = 1.100` (variable assignment)
  - Solutions: Backup or insert special “action” state



Handling Lookahead

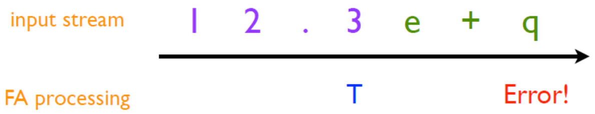
- E.g. distinguish between `int a` and `inta`
  - If the next char belongs to current token, continue
  - Else next char becomes part of next token
- Multi-character lookahead?
  - E.g. `DO I = 1, 100` (loop) vs. `DO I = 1.100` (variable assignment)
  - Solutions: Backup or insert special “action” state

123..44

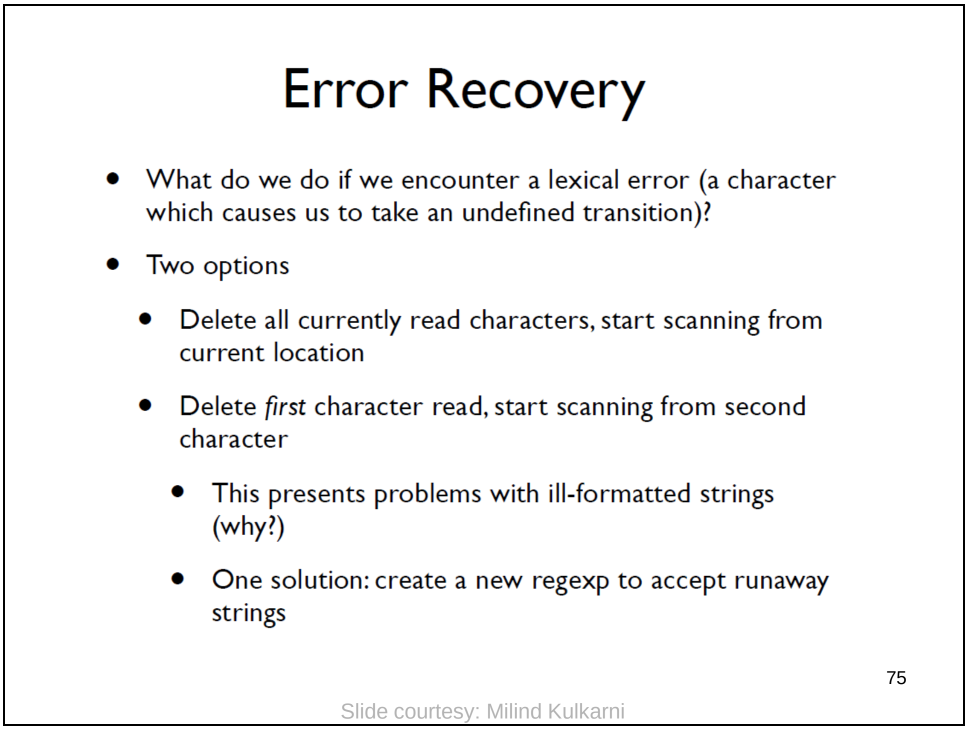


General approach

- Remember states (T) that can be final states
- Buffer the characters from then on
- If stuck in a non-final state, back up to T, restore buffered characters to stream
- Example: 12.3e+q



Slide courtesy: Milind Kulkarni



Error Recovery

- What do we do if we encounter a lexical error (a character which causes us to take an undefined transition)?
- Two options
  - Delete all currently read characters, start scanning from current location
  - Delete *first* character read, start scanning from second character
    - This presents problems with ill-formatted strings (why?)
    - One solution: create a new regexp to accept runaway strings

75

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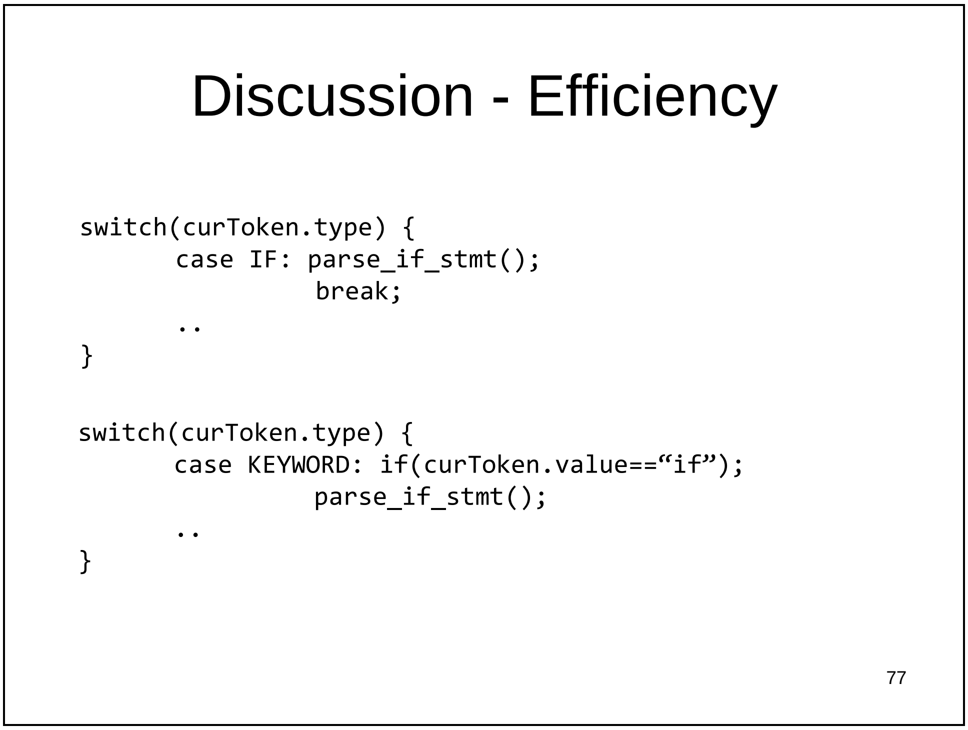
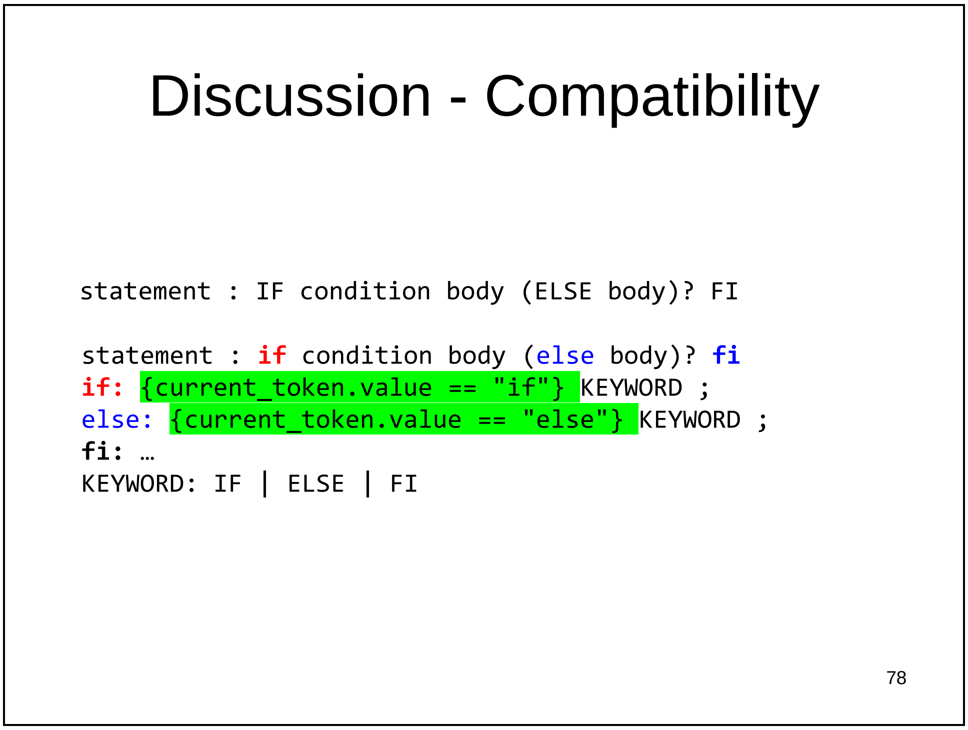
Discussion

- Why separate class (token type) for each keyword?
  - Efficiency
    - Parsers take decisions based on token types. When decision making not possible, switch to token values, which are strings. String comparison is more expensive
  - Compatibility with parser generators
    - Some parser generators don’t support semantic predicates
  - Autocomplete / Intellisense



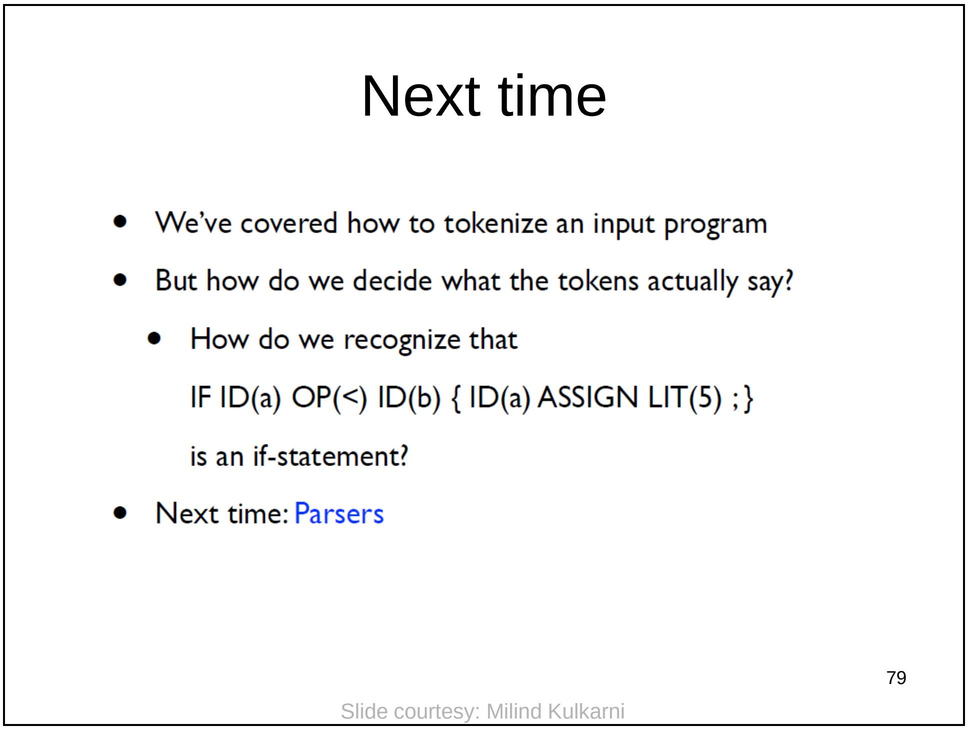
Discussion - Efficiency

```
switch(curToken.type) {
       case IF: parse_if_stmt();
                break;
       ..
}

switch(curToken.type) {
       case KEYWORD: if(curToken.value==“if”);
                parse_if_stmt();
       ..
}
```



Discussion - Compatibility

```
statement : IF condition body (ELSE body)? FI

statement : if condition body (else body)? fi
if: {current_token.value == "if"} KEYWORD ;
else: {current_token.value == "else"} KEYWORD ;
fi: …
KEYWORD: IF | ELSE | FI
```



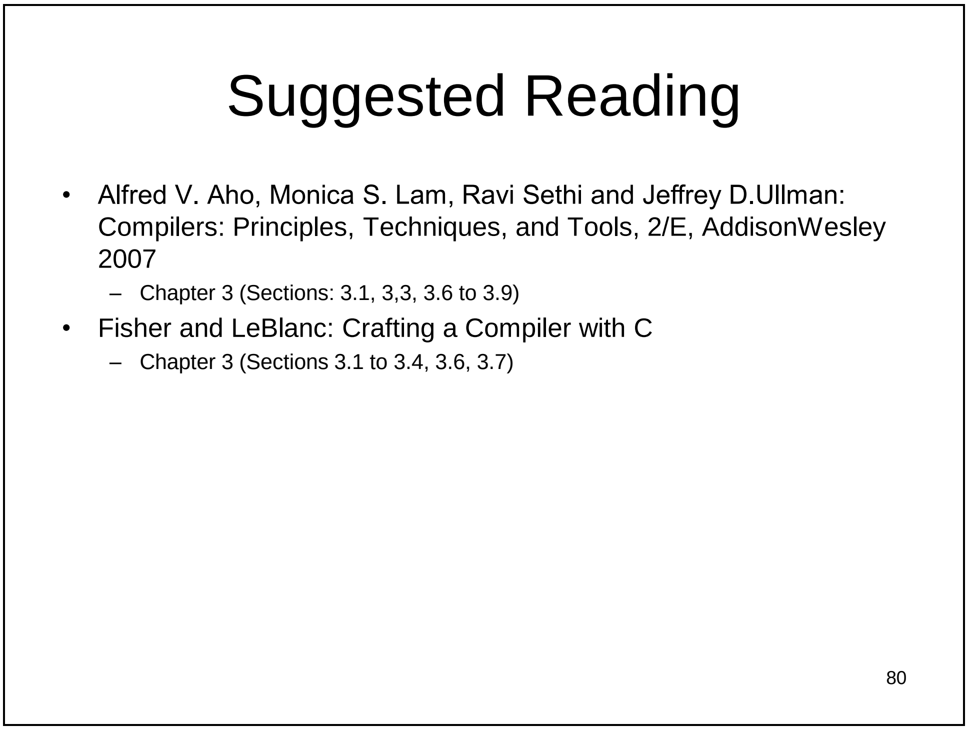
Next time

- We've covered how to tokenize an input program
- But how do we decide what the tokens actually say?
  - How do we recognize that

    IF ID(a) OP(<) ID(b) { ID(a) ASSIGN LIT(5) ; }

    is an if-statement?
- Next time: Parsers

Slide courtesy: Milind Kulkarni



Suggested Reading

- Alfred V. Aho, Monica S. Lam, Ravi Sethi and Jeffrey D.Ullman: Compilers: Principles, Techniques, and Tools, 2/E, AddisonWesley 2007
  - Chapter 3 (Sections: 3.1, 3,3, 3.6 to 3.9)
- Fisher and LeBlanc: Crafting a Compiler with C
  - Chapter 3 (Sections 3.1 to 3.4, 3.6, 3.7)