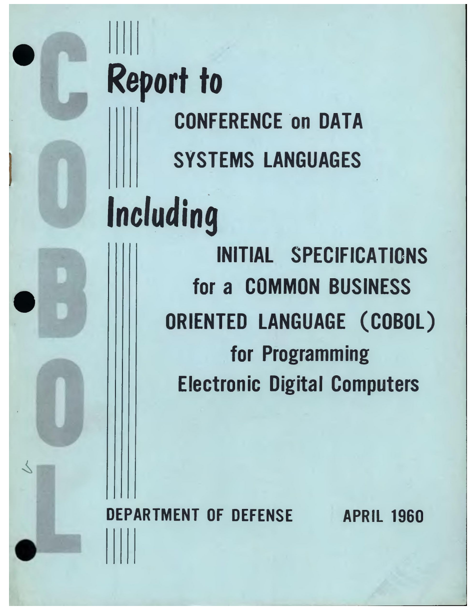
# Compilers

CSE 4305 / CSE 5317
M01 Lexical Analysis
2023 Fall


COBOL

Report to
CONFERENCE on DATA
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Including
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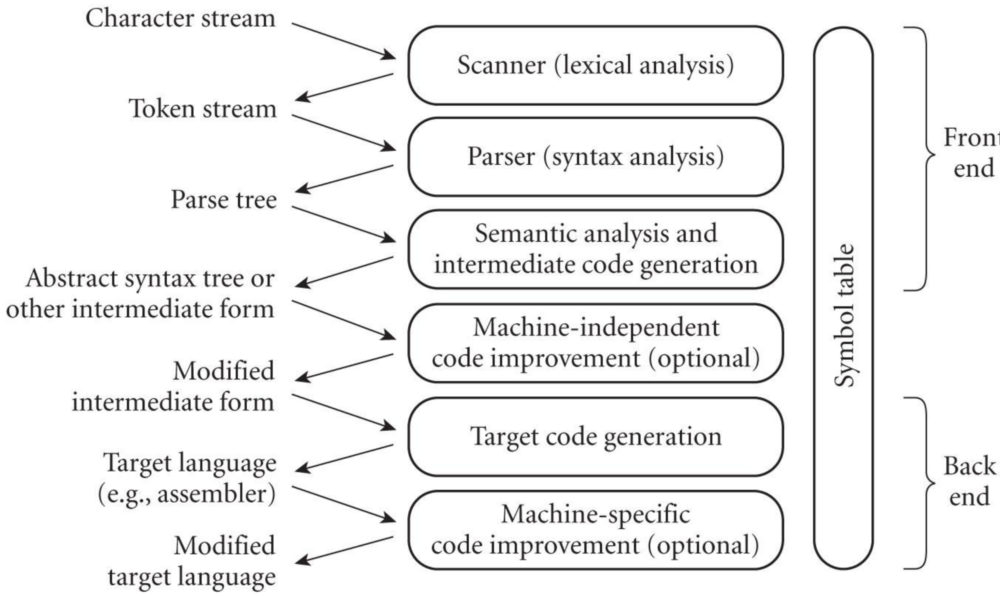
ORIENTED LANGUAGE (COBOL)
for Programming
Electronic Digital Computers

DEPARTMENT OF DEFENSE APRIL 1960

# M01
## *Lexical Analysis*

## Phases of Compilation




## Program Analysis

- A compiler's *Front End* is concerned with the *Analysis* of the source program.
  - Determining the *Meaning* of the source program.

- Generally thought of as breaking apart into three *phases*:
  - *Lexical Analysis*: Convert a text source program into *tokens*.
  - *Syntactic Analysis*: Convert a token stream into a *parse tree*.
  - *Semantic Analysis*: Enforce semantic rules and convert a parse tree into an *intermediate form*.
    - Two activities, but often happen in an interleaved fashion.

## Lexical Analysis

- Take a stream of individual characters and convert it into a stream of *tokens* (possibly with *attributes*).
- Detect *lexical* errors (badly formed literals, illegal characters, etc.)
  - But *not* misspelled keywords. (Why not?)
- Discard whitespace.
  - Useful only inside literals and to separate otherwise ambiguous constructs.
- Discard comments.
  - Some toolsets interpret comments as directives.

## Tokens

- A *token* is the basic building block of a program.
  - The shortest strings of characters in the source program that have individual meaning.
- Tokens come in various categories, according to the programming language's specification.
  - Common categories include *numbers*, *identifiers*, *keywords*, *operators*, *punctuation marks*, and so forth.

# Some Generic Token Categories …

| *Pattern* | *Category* | *Attribute* |
|---|---|---|
| letter or underscore possibly followed by letters, underscores, or decimal digits | `ID` | symbol table entry |
| decimal digits | `INTEGER_LITERAL` | int number |
| " characters " | `STRING_LITERAL` | string |
| `if` | `IF` | |
| `<` *or* `<=` *or* `==` *or* `>=` *or* `>` | `RELATIONAL_OPERATOR` | enum value |
| `[0-9]*(([0-9][.])\|([.][0-9]))[0-9]*` | `REAL_LITERAL` | FP number |
| `(` | `LEFT_PARENTHESIS` | |

# Example …

```
if ( a <= 17.34 ) {
 b = b + 1;
} else {
 // Oops!
 print( "too big!" );
}
```

```
Characters    Token                Attribute
if            IF
(             LEFT_PARENTHESIS
a             ID                   "a"
<=            RELATIONAL_OPERATOR  LE
17.34         REAL_LITERAL         17.34
)             RIGHT_PARENTHESIS
{             LEFT_BRACE
b             ID                   "b"
=             ASSIGN_OPERATOR      ASSIGN
b             ID                   "b"
+             ADD_OPERATOR         PLUS
1             INTEGER_LITERAL      1
;             SEMICOLON
}             RIGHT_BRACE
else          ELSE
{             LEFT_BRACE
print         ID                   "print"
(             LEFT_PARENTHESIS
"too big!"    STRING_LITERAL       "too big!"
)             RIGHT_PARENTHESIS
;             SEMICOLON
}             RIGHT_BRACE
```

## Lexical Analysis

- So how to do this conversion?
- We could just hand-code a routine …
- Cool, huh?

```
Tokens for "fred _ 15 1234.345 "bob" Maddog87":
    ID 'fred'
    ID '_'
    INTEGER_LITERAL 15
    INTEGER_LITERAL 1234
Illegal character '.'
    INTEGER_LITERAL 345
Illegal character '"'
    ID 'bob'
Illegal character '"'
    ID 'Maddog87'
```

```c
void tokenize( char *inStr ) {
  int ptr = 0;

  while ( inStr[ ptr ] ) {
    if ( isspace( inStr[ ptr ] ) ) {
      ptr += 1;

    } else if ( isdigit( inStr[ ptr ] ) ) {
      int n = 0;

      while ( isdigit( inStr[ ptr ] ) ) {
        n = n*10 + inStr[ ptr ]-'0';
        ptr += 1;
      }

      printf( "    INTEGER_LITERAL %d\n", n );

    } else if ( isalpha( inStr[ ptr ] ) || inStr[ ptr ] == '_' ) {
      int ptrBegin = ptr;

      while ( isalpha( inStr[ ptr ] ) ||
              isdigit( inStr[ ptr ] ) ||
              inStr[ ptr ] == '_' ) {
        ptr += 1;
      }

      printf( "    ID '%.*s'\n", ptr-ptrBegin, &inStr[ptrBegin] );

    } else {
      printf( "Illegal character '%c'\n", inStr[ ptr ] );
      ptr += 1;
    }
  }
}
```

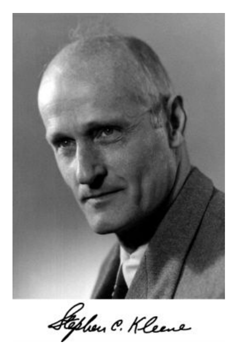
## Lexical Analysis

- Hand-coded lexical analyzers are fun for about 10 seconds and then one realizes that they're …
  - Tedious to write.
  - Difficult to extend.
    - Imagine adding `REAL_LITERAL` to this tokenizer.
  - Error-prone.
    - Imagine adding `REAL_LITERAL` to this tokenizer and not screwing up `INTEGER_LITERAL` along the way.
  - Hard to separate into *patterns* and *processing*.

## Lexical Analysis

- We want to express the *patterns* of token classes as *Regular Expressions*.
  - Easy to write, easy to update, reduced chance of errors, lots of theory to help with the processing.
- We want to express the *processing* of token classes independently of the *pattern*.
  - Reduced chance of error, easier to write, easier to update.

## Regular Expression (RE)



/ˈkleɪni/ KLAY-nee

1. A *character*
2. The *empty string*, denoted as ε
3. The *concatenation* of two REs

   Meaning one RE after the other RE
4. The *alternation* of two REs, denoted by |

   Meaning one RE *or* the other RE
5. An RE followed by the *Kleene star*, denoted as *

   Meaning *zero* or *more* repetitions of the RE

https://www.nap.edu/read/9649/chapter/10

## Regular Expressions

- Aside from the basic five items, there are some common notation extensions that make writing regular expressions more convenient.
- An RE followed by the *Kleene Plus*, denoted by `+`
  - Meaning *one* or *more* repetitions of the RE.
  - `a+` is equivalent to `aa*`, so no extra power.
- An RE followed by `?`
  - Meaning *zero* or *one* instances of the RE.
  - `a?` is equivalent to `(a|ε)`, so no extra power.
- A set or range of characters in brackets, `[]`
  - Meaning any *one* of the indicated characters.
  - E.g., `[0-9]` is equivalent to `0|1|2|3|4|5|6|7|8|9`, so no extra power.

## Regular Expressions

- Regular Expressions are just one category of *formal* languages.
- Formal language categories can be organized in a hierarchy according to the kinds of languages they can describe (and their parsing complexity, required resources, etc.)
- Different levels have different rules for their *productions*.

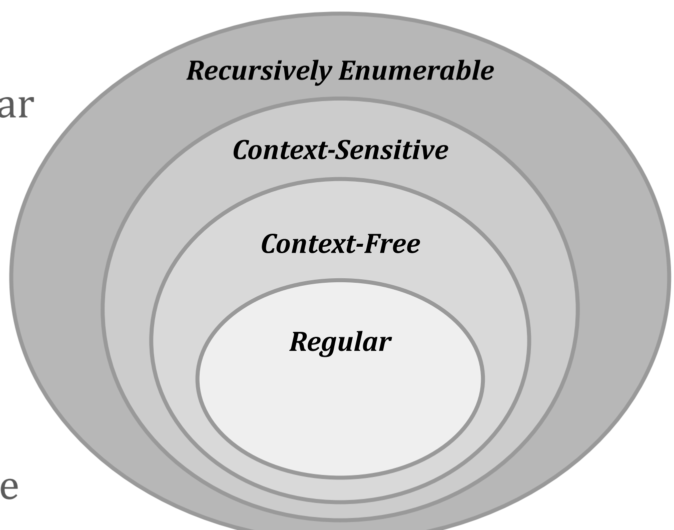
## Grammars and the Chomsky Language Hierarchy

- A *grammar* specification includes
  - A set of *terminal* symbols ( $T$ )
  - A set of *non-terminal* symbols ( $N$ )
    - $V = T \cup N$
  - A set of *production rules*
  - A *start symbol*
- Restrictions on the form of the production rules can be used to categorize grammars into classes, each of which is more *expressive* than the previous.
- The example expresses the language $\mathtt{a}^n\mathtt{b}^n$, for $n \geq 0$.

| | |
|---|---|
| Terminals | a, b |
| Non-terminals | $S$ |
| Production rules | $S \rightarrow \mathtt{a}S\mathtt{b}$<br>$S \rightarrow \varepsilon$ |
| Start symbol | $S$ |

## Grammars and the Chomsky Language Hierarchy

- The Chomsky Hierarchy shows four levels of grammar expressivity.
- Each properly includes the previous.
- The levels have increasing expressiveness, but also parsing complexity, resource requirements, etc.




after https://commons.wikimedia.org/wiki/File:Chomsky-hierarchy.svg

# [ *Grammars and the Chomsky Language Hierarchy* ]

| *Type* | *Name* | *Allowed Productions* | *Example Language* | *Example Grammar* | *Example Use* | *Recognizing Automaton* | *Storage Required* | *Parsing Complexity* |
|---|---|---|---|---|---|---|---|---|
| 0 | Recursively Enumerable | $\alpha \rightarrow \beta$<br>$\alpha \in V+$<br>$\beta \in V^*$ | | | (*Theoretical Interest*) | Turing Machine | Infinite Tape | Undecidable |
| 1 | Context Sensitive | $\alpha \rightarrow \beta$<br>$S \rightarrow \varepsilon$<br>$\lvert\alpha\rvert \le \lvert\beta\rvert$<br>$\alpha \in V^*NV^*$<br>$\beta \in V+$<br>*S not on any RHS* | $a^n b^n c^n$<br>$n > 0$ | $S \rightarrow aSBC$<br>$S \rightarrow aBC$<br>$CB \rightarrow BC$<br>$aB \rightarrow ab$<br>$bB \rightarrow bb$<br>$bC \rightarrow bc$<br>$cC \rightarrow cc$ | (*Theoretical Interest*) | Linear Bounded Automaton | Tape a linear multiple of input length | NP Complete |
| 2 | Context Free | $A \rightarrow \alpha$<br>$A \in N$<br>$\alpha \in V^*$ | $a^n b^n$<br>$n \ge 0$ | $S \rightarrow aSb$<br>$S \rightarrow \varepsilon$ | Arithmetic Expressions, Programming Languages | Pushdown Automaton | Pushdown stack | $O(n^3)$ |
| 3 | Regular | $A \rightarrow xB$<br>$A \rightarrow x$<br>$A, B \in N$<br>$x \in T^*$ | $a^n b$<br>$n > 0$ | $S \rightarrow aS$<br>$S \rightarrow ab$ | Token Formats, String Recognition | Finite Automaton | Finite | $O(n)$ |

# [ *"Recursive" Production Rules …* ]

- Later we'll learn that *recursion* is what separates *Context-Free Grammars* from *Regular Expressions*. No recursion in REs.
- On the previous chart, $S \longrightarrow \mathtt{a}S$ appears as a rule for an RE.
  - Hey, isn't that *recursive*? After all, *S* refers to itself, right?

- ***No!*** It just ***looks*** as if it's recursive. :)
- Because the *S* appears on the far right (there's nothing after *S* in the rule), this is just a way of expressing a Kleene-* operation (`a*`).
- A proof that this isn't true recursion requires going deeper in formal language theory than required for this class, so just accept it as true.

# Lexical Analysis

| ***Token Class*** | ***Regular Expression*** |
|---|---|
| ID | [_a-zA-Z][_a-zA-Z0-9]* |
| INTEGER_LITERAL | [0-9]+ |
| STRING_LITERAL | "[^"\n]*" |
| IF | if |
| RELATIONAL_OPERATOR | <\|<=\|==\|>=\|> |
| REAL_LITERAL | [0-9]*(([0-9][.])\|([.][0-9]))[0-9]* |
| LEFT_PARENTHESIS | ( |

# Processing Regular Expressions

- How to use Regular Expressions to do lexical scanning?
  - That is, how do we convert an RE into a *program*?

- Recognize that there's a correspondence between an RE and a *Finite Automaton*.
  - And a *Finite Automaton* is convertible into a *scanning* (or *recognizing*) program in a simple, mechanical way.

## Finite Automaton (FA)

- A *Finite Automaton* consists of …
  - A finite set of *symbols*, known as its *alphabet*.
  - A finite set of *states*.
  - A finite set of *edges* each of which …
    - … goes from one state to another (possibly the same) state.
    - … is labelled with a *symbol*.
  - One identified state known as the *start state*.
    - Usually state 1.
  - A subset of states identified as *final* (or *accepting*) states.

## Finite Automaton (FA)

- A finite automaton *scans* a *finite* input string by …
  - Starting in the *start* state.
  - For each successive *symbol* in the input string, transiting along an edge from the current state that is labelled with the symbol.
  - *Or* at any time transiting along an accessible edge labelled with ε.

- After all symbols are used up (and all desired ε moves are made), if the current state is a *final* state, the FA *accepts* the input, otherwise it *rejects* the input.

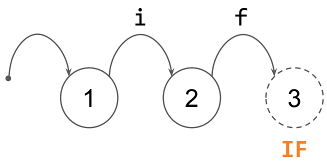
## Finite Automaton (FA)

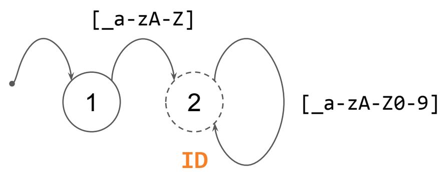
- The set of strings *accepted* by an FA is said to be its *language*.
- Though all FA are *finite*, the *language* accepted by an FA can be *infinite*.
  - Each *string* in the language, however, is itself *finite*.
  - E.g., the language $\texttt{a}^n$, $n > 0$ is the set of strings { `a`, `aa`, `aaa`, `aaaa`, … }, which is an infinite set. Each element however is of finite length.

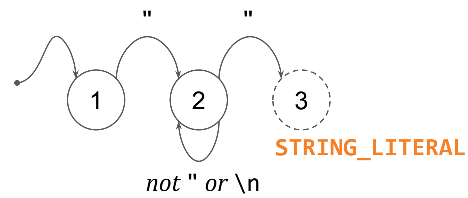
## Deterministic Finite Automaton (DFA)

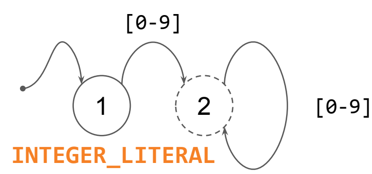
- If a Finite Automaton complies with the following two criteria, it is said to be *Deterministic* …
  - No two edges from a state can have the *same* symbol.
    - Each symbol valid for a state appears on only *one* edge.
  - No edge is labelled with ε.
    - ε is the *empty* transition, i.e., no symbol is consumed.
- When a FA is *deterministic*, the acceptance or rejection of an input string will take no more transitions than the length of the input.
  - Why?

# Deterministic Finite Automaton Examples



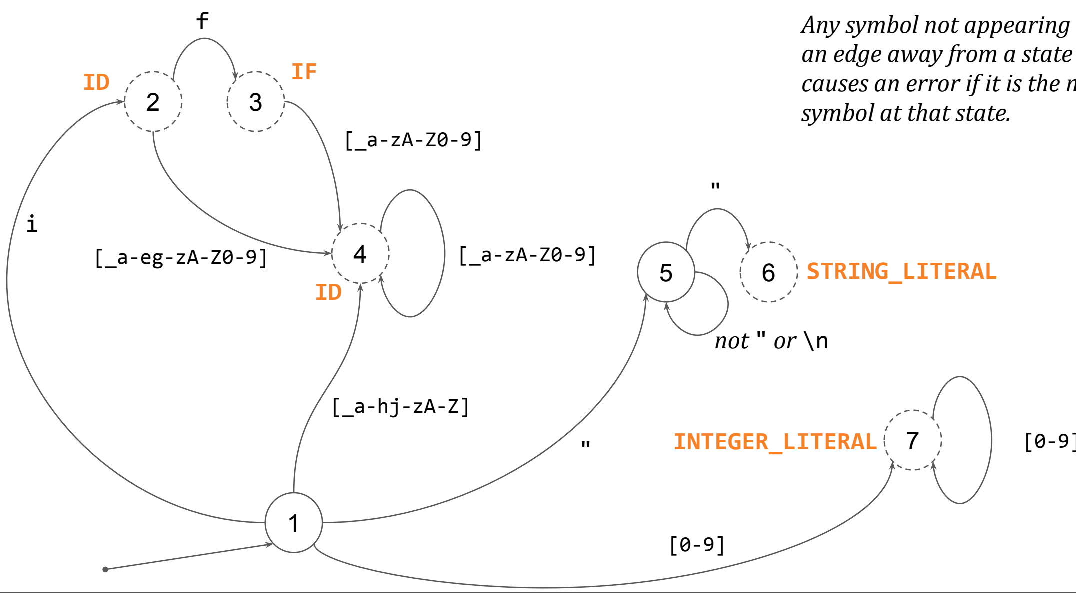

*Any symbol not appearing in an edge away from a state causes an error if it is the next symbol at that state.*

# Combining Deterministic Finite Automata

- OK, great, we have four DFAs each matching its own set of strings.
- We can *combine* these DFAs so we can match *any* of the four sets using just one DFA.

- `STRING_LITERAL` starts with a `"` and `INTEGER_LITERAL` starts with a decimal digit.
  - Neither overlaps with any of the other DFAs so simple to combine.
  - If we see `"`, we know it's a string; `[0-9]` indicates an integer.
- `ID` and `IF`, however, could clash: the characters `if` are not only an `IF`, they also form a valid `ID`.

## Combining Deterministic Finite Automata

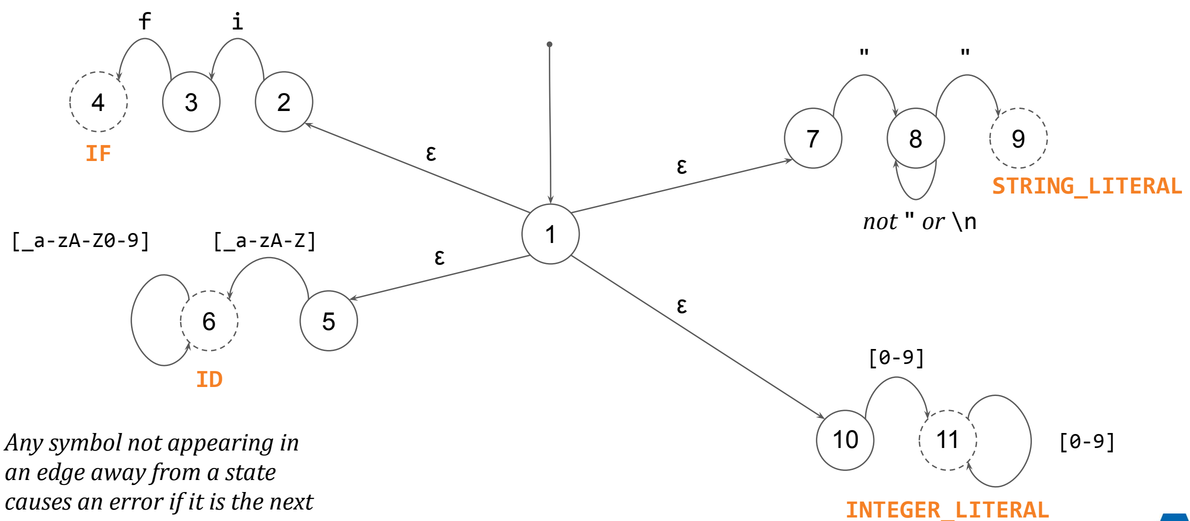



*Any symbol not appearing in an edge away from a state causes an error if it is the next symbol at that state.*

## Lexical Analysis

- What a pain in the butt!
- Imagine having to do that kind of construction for a programming language with dozens of overlapping token class definitions.
- However, we can express this complex Finite Automaton in a more convenient form …

## Simpler Combination of DFAs …




*Any symbol not appearing in an edge away from a state causes an error if it is the next symbol at that state.*

## Simpler Combination of DFAs …

- Wow. That was *easy*!
- All we did was make a new start state and transition from it to the start states of each of the four DFAs we already had.

- Um, how do we know which transition to take?
  - The edges are labelled with “ε”, which consumes no input.
- We have to *guess* which is the correct transition.
- We’re no longer a *Deterministic* Finite Automaton.
- We’ve become *Nondeterministic*.

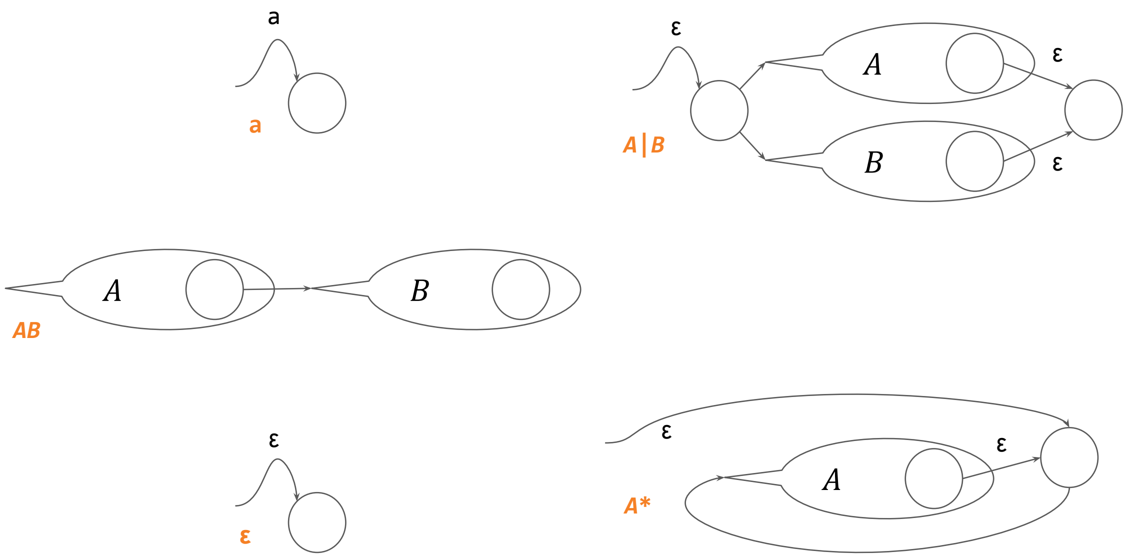
## Nondeterministic Finite Automata (NFA)

- If an FA satisfies either of the two following criteria, it is *Non-Deterministic* …
  - At least one state has at least two edges going to different other states and bearing the the same symbol.
  - At least one edge is labelled with ε.
- Does being *non-deterministic* increase the descriptive power of a Finite Automaton?
  - ***No!*** Why not?

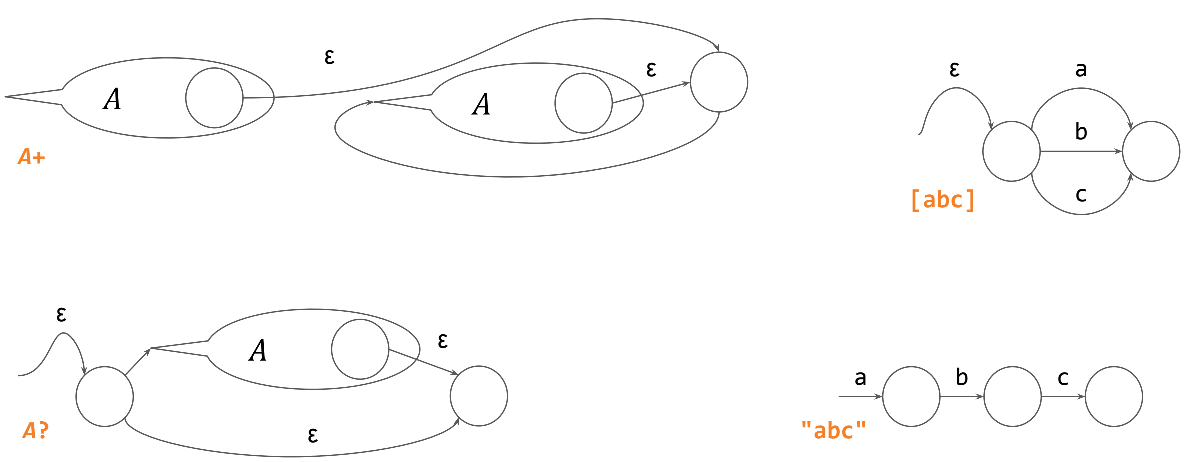
## Making a Regular Expression into an NFA

- Turns out that it's trivial to convert a Regular Expression into an NFA.
- We'll show this *Constructively* by giving ways to convert each of the five kinds of Regular Expressions into an NFA.
- In the following, a is any symbol, ε is the empty string, and *A* and *B* are any NFAs representing regular expressions.

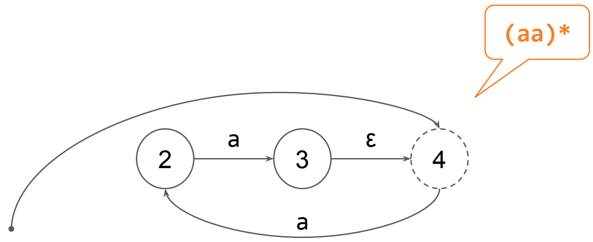
# Making an RE into an NFA



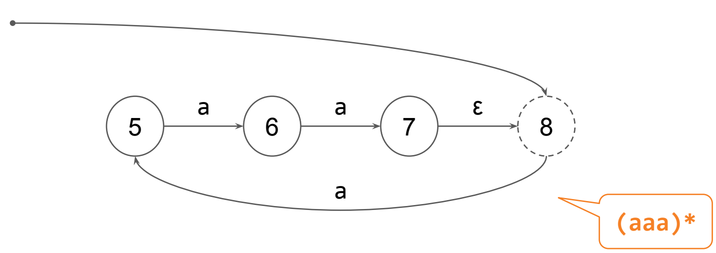

# Making an RE into an NFA



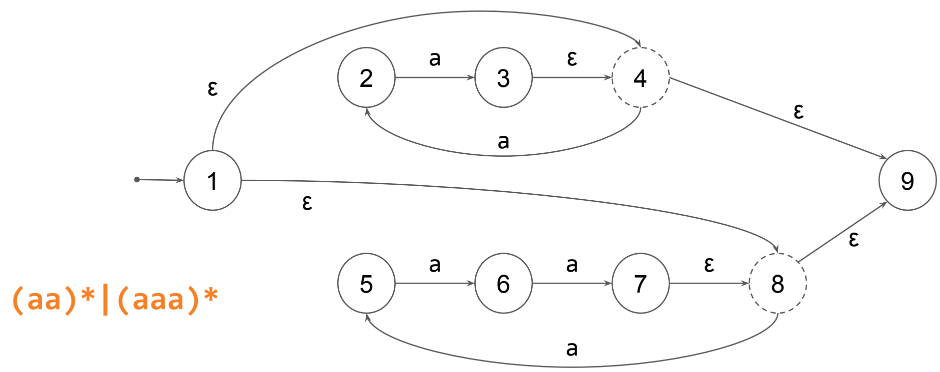
## Making an RE into an NFA Example …




## Making an RE into an NFA Example …



## Making an RE into an NFA Example …




## Using an NFA for Lexical Scanning

- It was trivial to convert that RE into an NFA.
- What about using the NFA for lexical scanning?
- This is not so trivial.
- As symbols are consumed, we might have to *guess* which edge to traverse.
  - If a state has multiple outgoing edges with the same symbol.
- We also might have to *guess* whether to use an edge or not.
  - If a state has outgoing edge(s) with ε.
- `FYI:` Few (like *no*) computers have good guessing hardware. :)

## [ *"Guessing"* ]

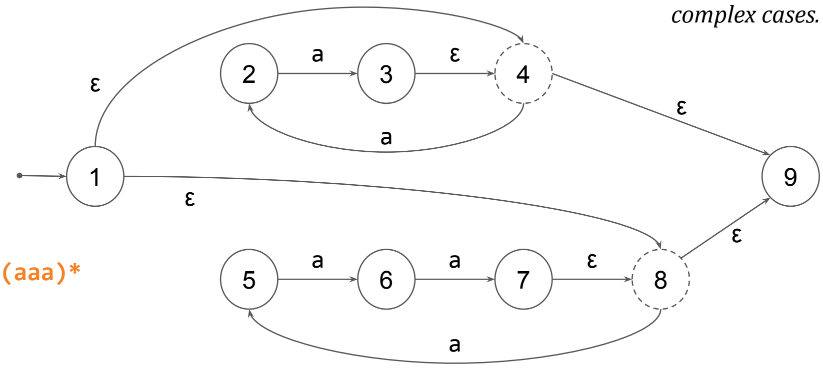
- Non-Deterministic algorithms are difficult to convert to an actual program as running them requires *Successful Guessing*.
- Instead of guessing, the program could keep track of each "guess" point, backtrack on failure, and try a different guess.
  - While eventually successful, this can take a l-o-o-o-n-g time and is painful to program correctly and efficiently.
- Or, the Non-Deterministic algorithm could be transformed into a Deterministic version, which wouldn't require guessing.
  - This might not even be *possible*. Having a firm theoretical basis for analysis is definitely required.

## Converting an NFA into a DFA

- We have to keep track of whichever state the NFA *might* be in at any point.
- We do this by taking the current state and computing its ε-*closure*.
  - That is, all states that can be reached from it solely by ε transitions (perhaps several in a row …).
- This results in a (possibly) *combined state*.
- For that combined state, we compute the ε-closure of the destination combined states for each symbol on outgoing edges.
- And then repeat until we formed the total set of possible ε-closed combined states …

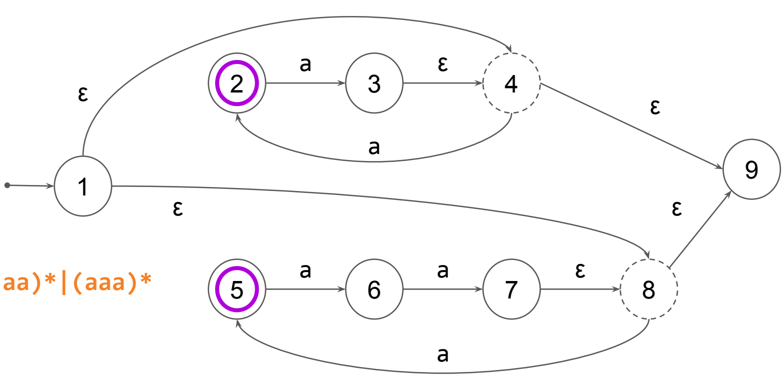
# NFA to DFA Example …

*This is a simple example with only one symbol,* a*. The process is the same for more complex cases.*




(aa)*|(aaa)*

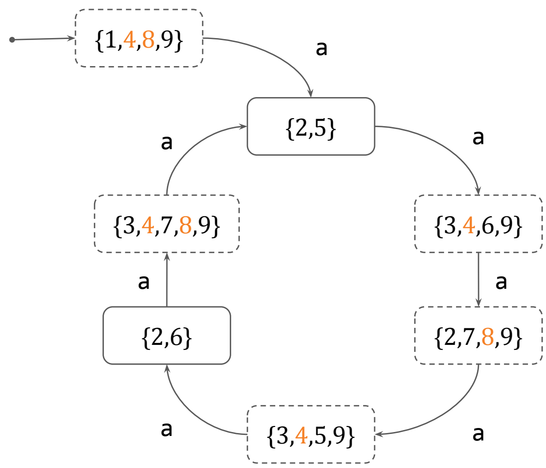
# NFA to DFA Example …




(aa)*|(aaa)*

| State | a⟶ | ε⟶ |
|---|---|---|
| *Start* {1} | {1} | {1,4,8,9} |
| {1,4,8,9} | {2,5} | {2,5} |
| {2,5} | {3,6} | {3,4,6,9} |
| {3,4,6,9} | {2,7} | {2,7,8,9} |
| {2,7,8,9} | {3,5} | {3,4,5,9} |
| {3,4,5,9} | {2,6} | {2,6} |
| {2,6} | {3,7} | {3,4,7,8,9} |
| {3,4,7,8,9} | {2,5} | {2,5} |

# NFA to DFA Example …




| State | a⟶ | ε⟶ |
|---|---|---|
| *Start* {1} | {1} | {1,4,8,9} |
| {1,4,8,9} | {2,5} | {2,5} |
| {2,5} | {3,6} | {3,4,6,9} |
| {3,4,6,9} | {2,7} | {2,7,8,9} |
| {2,7,8,9} | {3,5} | {3,4,5,9} |
| {3,4,5,9} | {2,6} | {2,6} |
| {2,6} | {3,7} | {3,4,7,8,9} |
| {3,4,7,8,9} | {2,5} | {2,5} |

**(aa)*|(aaa)***

# Converting an NFA into a DFA

- Once the complete set of combined states is generated, the set of *final states* can be identified.
- A combined state that includes *any* final state from the original NFA is a final state in the DFA.
  - These are marked with a special **color** in the previous slides.
  - The final combined states are *dashed* boxes.

## Converting a DFA to a Program

- As we stated previously, deciding if a DFA *accepts* a string is O($n$), where $n$ is the length of the string.
  - Every transition of the DFA is deterministic and therefore consumes a symbol from the input string.

- It's not hard to write a program that mechanically converts a set of *Regular Expressions* (and their corresponding action routines) into a *program*.
  - Such a program is a *Lexical Analyzer Generator*.

## Lexical-Analyzer Generators

- Remember that we said an advantage of REs as a formalism is that there's lots of theory already developed to help us.
- `lex` was developed in ***1975*** to take sets of regular expressions and actions associated with each and automatically generate a lexical scanner.
  - Worked with C under UNIX.
- Zillions of subsequent tools were created to do the same kind of thing but with different notations, different target languages, different environments, etc.

## flex

- We will be using `flex` (***f**ast* ***lex**ical analyzer generator*) …
  - A derivative of the original `lex` tool.

```
(base) dalioba@Hoong:~$ apt-cache policy flex
flex:
  Installed: 2.6.4-6.2
  Candidate: 2.6.4-6.2
  Version table:
 *** 2.6.4-6.2 500
        500 http://archive.ubuntu.com/ubuntu focal/main amd64 Packages
        100 /var/lib/dpkg/status
(base) dalioba@Hoong:~$ flex --version
flex 2.6.4
(base) dalioba@Hoong:~$
```

## Lexical Analysis

- Remember the hand-coded tokenizer routine?
- We thought it was pretty cool, huh?

```
Tokens for "fred _ 15 1234.345 "bob" Maddog87":
    ID 'fred'
    ID '_'
    INTEGER_LITERAL 15
    INTEGER_LITERAL 1234
Illegal character '.'
    INTEGER_LITERAL 345
Illegal character '"'
    ID 'bob'
Illegal character '"'
    ID 'Maddog87'
```

```
void tokenize( char *inStr ) {
  int ptr = 0;

  while ( inStr[ ptr ] ) {
    if ( isspace( inStr[ ptr ] ) ) {
      ptr += 1;

    } else if ( isdigit( inStr[ ptr ] ) ) {
      int n = 0;

      while ( isdigit( inStr[ ptr ] ) ) {
        n = n*10 + inStr[ ptr ]-'0';
        ptr += 1;
      }

      printf( "    INTEGER_LITERAL %d\n", n );

    } else if ( isalpha( inStr[ ptr ] ) || inStr[ ptr ] == '_' ) {
      int ptrBegin = ptr;

      while ( isalpha( inStr[ ptr ] ) ||
              isdigit( inStr[ ptr ] ) ||
              inStr[ ptr ] == '_' ) {
        ptr += 1;
      }

      printf( "    ID '%.*s'\n", ptr-ptrBegin, &inStr[ptrBegin] );

    } else {
      printf( "Illegal character '%c'\n", inStr[ ptr ] );
      ptr += 1;
    }
  }
```

## `flex` Version

- Each token category has its own processing routine.
- Token formats expressed as regular expressions.
- Cool, huh?

```
Tokens for "fred _ 15 1234.345 "bob" Maddog87":
    ID 'fred'
    ID '_'
    INTEGER_LITERAL 15
    INTEGER_LITERAL 1234
Illegal character '.'
    INTEGER_LITERAL 345
Illegal character '"'
    ID 'bob'
Illegal character '"'
    ID 'Maddog87'
```

```
[0-9]+  {
  printf( "    INTEGER_LITERAL %s\n", yytext );
}

[_a-zA-Z][_a-zA-Z0-9]*  {
  printf( "    ID '%s'\n", yytext );
}

[ \t\r\n] { /* Ignore whitespace */ }

.        { printf( "Illegal character '%s'\n", yytext ); }
```

## `flex` Version (2)

- Now with `REAL_LITERAL`.
- Not hard to add.
- *Really* cool, huh?

```
[0-9]+  {
  printf( "    INTEGER_LITERAL %s\n", yytext );
}

[0-9]+\.[0-9]+ {
  printf( "    REAL_LITERAL %s\n", yytext );
}

[_a-zA-Z][_a-zA-Z0-9]*  {
  printf( "    ID '%s'\n", yytext );
}

[ \t\r\n] { /* Ignore whitespace */ }

.        { printf( "Illegal character '%s'\n", yytext ); }
```

```
Tokens for "fred _ 15 1234.345 "bob" Maddog87":
    ID 'fred'
    ID '_'
    INTEGER_LITERAL 15
    REAL_LITERAL 1234.345
Illegal character '"'
    ID 'bob'
Illegal character '"'
    ID 'Maddog87'
```

## `flex` Version (3)

- Now with `STRING_LITERAL`.
- Again, not hard to add.
- *Really, really* cool, huh?

```
[0-9]+  {
  printf( "    INTEGER_LITERAL %s\n", yytext );
}

[0-9]+\.[0-9]+ {
  printf( "    REAL_LITERAL %s\n", yytext );
}

["][^"\n]*["]  {
  printf( "    STRING_LITERAL %s\n", yytext );
}

[_a-zA-Z][_a-zA-Z0-9]*  {
  printf( "    ID '%s'\n", yytext );
}

[ \t\r\n] { /* Ignore whitespace */ }

.       { printf( "Illegal character '%s'\n", yytext ); }
```

```
Tokens for "fred _ 15 1234.345 "bob" Maddog87":
    ID 'fred'
    ID '_'
    INTEGER_LITERAL 15
    REAL_LITERAL 1234.345
    STRING_LITERAL "bob"
    ID 'Maddog87'
```

UNIVERSITY OF TEXAS ARLINGTON

DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING