Phases of Syntax Analysis

1. Identify the words: **Lexical Analysis**.
   Converts a stream of characters (input program) into a stream of tokens.
   Also called *Scanning* or *Tokenizing*.
2. Identify the sentences: **Parsing**.
   Derive the structure of sentences: construct *parse trees* from a stream of tokens.

Lexical Analysis

Convert a stream of characters into a stream of *tokens*.

- Simplicity: Conventions about "words" are often different from conventions about "sentences".
- Efficiency: Word identification problem has a much more efficient solution than sentence identification problem.
- Portability: Character set, special characters, device features.

Terminology

- Token: Name given to a family of words.
  e.g., integer_constant
- Lexeme: Actual sequence of characters representing a word.
  e.g., 32894
- Pattern: Notation used to identify the set of lexemes represented by a token.
  e.g., $[0-9]+$

Terminology

A few more examples:

Token	Sample Lexemes	Pattern
while	`while`	`while`
integer_constant	32894, -1093, 0	[0-9]+
identifier	`buffer_size`	[a-zA-Z]+

Patterns

How do we *compactly* represent the set of all lexemes corresponding to a token?
For instance:

> The token integer_constant represents the set of all integers: that is, all sequences of digits (0–9), preceded by an optional sign (+ or −).

Obviously, we cannot simply enumerate all lexemes.

Use **Regular Expressions**.

Regular Expressions

Notation to represent (potentially) infinite sets of strings over alphabet Σ.

- a: stands for the set $\{\texttt{a}\}$ that contains a single string `a`.

- ▷ Analogous to *Union*.

- ab: stands for the set {ab} that contains a single string ab.
  - ▷ Analogous to *Product*.
  - ▷ $(a|b)(a|b)$: stands for the set {aa, ab, ba, bb}.
- a^*: stands for the set $\{\epsilon$, a, aa, aaa, $\ldots\}$ that contains all strings of zero or more a's.
  - ▷ Analogous to *closure* of the product operation.

Regular Expressions

Examples of Regular Expressions over {a, b}:

- $(a|b)^*$: Set of strings with zero or more a's and zero or more b's:
  $\{\epsilon, a, b, aa, ab, ba, bb, aaa, aab, \ldots\}$
- (a^*b^*): Set of strings with zero or more a's and zero or more b's such that all a's occur before any b:
  $\{\epsilon, a, b, aa, ab, bb, aaa, aab, abb, \ldots\}$
- $(a^*b^*)^*$: Set of strings with zero or more a's and zero or more b's:
  $\{\epsilon, a, b, aa, ab, ba, bb, aaa, aab, \ldots\}$

Language of Regular Expressions

Let R be the set of all regular expressions over Σ. Then,

- Empty String: $\epsilon \in R$
- Unit Strings: $\alpha \in \Sigma \Rightarrow \alpha \in R$
- Concatenation: $r_1, r_2 \in R \Rightarrow r_1 r_2 \in R$
- Alternative: $r_1, r_2 \in R \Rightarrow (r_1 \mid r_2) \in R$
- Kleene Closure: $r \in R \Rightarrow r^* \in R$

Regular Expressions

Example: $(a \mid b)^*$

$$\begin{array}{rcl}
L_0 & = & \{\epsilon\} \\
L_1 & = & L_0 \cdot \{\mathtt{a}, \mathtt{b}\} \\
 & = & \{\epsilon\} \cdot \{\mathtt{a}, \mathtt{b}\} \\
 & = & \{\mathtt{a}, \mathtt{b}\} \\
L_2 & = & L_1 \cdot \{\mathtt{a}, \mathtt{b}\} \\
 & = & \{\mathtt{a}, \mathtt{b}\} \cdot \{\mathtt{a}, \mathtt{b}\} \\
 & = & \{\mathtt{aa}, \mathtt{ab}, \mathtt{ba}, \mathtt{bb}\} \\
L_3 & = & L_2 \cdot \{\mathtt{a}, \mathtt{b}\} \\
 & \vdots & \\
L = \bigcup_{i=0}^{\infty} L_i & = & \{\epsilon, \mathtt{a}, \mathtt{b}, \mathtt{aa}, \mathtt{ab}, \mathtt{ba}, \mathtt{bb}, \ldots\}
\end{array}$$

Semantics of Regular Expressions

Semantic Function $\mathcal{L}$: Maps regular expressions to sets of strings.

$$
\begin{array}{rcll}
\mathcal{L}(\epsilon) & = & \{\epsilon\} & \\
\mathcal{L}(\alpha) & = & \{\alpha\} & (\alpha \in \Sigma) \\
\mathcal{L}(r_1 \mid r_2) & = & \mathcal{L}(r_1) \cup \mathcal{L}(r_2) & \\
\mathcal{L}(r_1\ r_2) & = & \mathcal{L}(r_1) \cdot \mathcal{L}(r_2) & \\
\mathcal{L}(r^*) & = & \{\epsilon\} \cup (\mathcal{L}(r) \cdot \mathcal{L}(r^*)) &
\end{array}
$$

Computing the Semantics

$$
\begin{array}{rcl}
\mathcal{L}(a) & = & \{\mathsf{a}\} \\
\mathcal{L}(a \mid b) & = & \mathcal{L}(a) \cup \mathcal{L}(b) \\
 & = & \{\mathsf{a}\} \cup \{\mathsf{b}\} \\
 & = & \{\mathsf{a}, \mathsf{b}\} \\
\mathcal{L}(ab) & = & \mathcal{L}(a) \cdot \mathcal{L}(b) \\
 & = & \{\mathsf{a}\} \cdot \{\mathsf{b}\} \\
 & = & \{\mathsf{ab}\} \\
\mathcal{L}((a \mid b)(a \mid b)) & = & \mathcal{L}(a \mid b) \cdot \mathcal{L}(a \mid b) \\
 & = & \{\mathsf{a}, \mathsf{b}\} \cdot \{\mathsf{a}, \mathsf{b}\} \\
 & = & \{\mathsf{aa}, \mathsf{ab}, \mathsf{ba}, \mathsf{bb}\}
\end{array}
$$

Computing the Semantics of Closure

Example: $\mathcal{L}((a \mid b)^*)$
$= \{\epsilon\} \cup (\mathcal{L}(a \mid b) \cdot \mathcal{L}((a \mid b)^*))$

$$
\begin{array}{rcll}
L_0 & = & \{\epsilon\} & \textit{Base case} \\
L_1 & = & \{\epsilon\} \cup (\{\mathsf{a}, \mathsf{b}\} \cdot L_0) & \\
 & = & \{\epsilon\} \cup (\{\mathsf{a}, \mathsf{b}\} \cdot \{\epsilon\}) & \\
 & = & \{\epsilon, \mathsf{a}, \mathsf{b}\} & \\
L_2 & = & \{\epsilon\} \cup (\{\mathsf{a}, \mathsf{b}\} \cdot L_1) & \\
 & = & \{\epsilon\} \cup (\{\mathsf{a}, \mathsf{b}\} \cdot \{\epsilon, \mathsf{a}, \mathsf{b}\}) & \\
 & = & \{\epsilon, \mathsf{a}, \mathsf{b}, \mathsf{aa}, \mathsf{ab}, \mathsf{ba}, \mathsf{bb}\} & \\
\vdots & & &
\end{array}
$$

$$
\mathcal{L}((a \mid b)^*) = L_\infty = \{\epsilon, \mathsf{a}, \mathsf{b}, \mathsf{aa}, \mathsf{ab}, \mathsf{ba}, \mathsf{bb}, \ldots\}
$$

Another Example

$\boldsymbol{\mathcal{L}((a^*b^*)^*)}$:

$$
\begin{array}{rcl}
\mathcal{L}(a^*) & = & \{\epsilon, \mathsf{a}, \mathsf{aa}, \ldots\} \\
\mathcal{L}(b^*) & = & \{\epsilon, \mathsf{b}, \mathsf{bb}, \ldots\} \\
\mathcal{L}(a^*b^*) & = & \{\epsilon, \mathsf{a}, \mathsf{b}, \mathsf{aa}, \mathsf{ab}, \mathsf{bb}, \\
 & & \quad \mathsf{aaa}, \mathsf{aab}, \mathsf{abb}, \mathsf{bbb}, \ldots\} \\
\mathcal{L}((a^*b^*)^*) & = & \{\epsilon\} \\
 & & \cup\{\epsilon, \mathsf{a}, \mathsf{b}, \mathsf{aa}, \mathsf{ab}, \mathsf{bb}, \\
 & & \quad \mathsf{aaa}, \mathsf{aab}, \mathsf{abb}, \mathsf{bbb}, \ldots\} \\
 & & \cup\{\epsilon, \mathsf{a}, \mathsf{b}, \mathsf{aa}, \mathsf{ab}, \mathsf{ba}, \mathsf{bb}, \\
 & & \quad \mathsf{aaa}, \mathsf{aab}, \mathsf{aba}, \mathsf{abb}, \mathsf{baa}, \mathsf{bab}, \mathsf{bba}, \mathsf{bbb}, \ldots\} \\
 & & \vdots \\
 & = & \{\epsilon, \mathsf{a}, \mathsf{b}, \mathsf{aa}, \mathsf{ab}, \mathsf{ba}, \mathsf{bb}, \ldots\}
\end{array}
$$

Regular Definitions

Assign "names" to regular expressions.
For example,

$$\begin{array}{rcl} \mathsf{digit} & \longrightarrow & \mathsf{0} \mid \mathsf{1} \mid \cdots \mid \mathsf{9} \\ \mathsf{natural} & \longrightarrow & \mathsf{digit}\ \mathsf{digit}^* \end{array}$$

SHORTHANDS:

- a^+: Set of strings with one or more occurrences of a.
- $a^?$: Set of strings with zero or one occurrences of a.

Example:

$$\mathsf{integer} \quad \longrightarrow \quad (+|-)^? \mathsf{digit}^+$$

Regular Definitions: Examples

$$\begin{array}{rcl} \mathsf{float} & \longrightarrow & \mathsf{integer}\ .\ \mathsf{fraction} \\ \mathsf{integer} & \longrightarrow & (+|-)^?\ \mathsf{no\_leading\_zero} \\ \mathsf{no\_leading\_zero} & \longrightarrow & (\mathsf{nonzero\_digit}\ \mathsf{digit}^*) \mid \mathsf{0} \\ \mathsf{fraction} & \longrightarrow & \mathsf{no\_trailing\_zero}\ \mathsf{exponent}^? \\ \mathsf{no\_trailing\_zero} & \longrightarrow & (\mathsf{digit}^*\ \mathsf{nonzero\_digit}) \mid \mathsf{0} \\ \mathsf{exponent} & \longrightarrow & (\mathtt{E} \mid \mathtt{e})\ \mathsf{integer} \\ \mathsf{digit} & \longrightarrow & \mathsf{0} \mid \mathsf{1} \mid \cdots \mid \mathsf{9} \\ \mathsf{nonzero\_digit} & \longrightarrow & \mathsf{1} \mid \mathsf{2} \mid \cdots \mid \mathsf{9} \end{array}$$

Regular Definitions and Lexical Analysis

Regular Expressions and Definitions *specify* sets of strings over an input alphabet.

- They can hence be used to specify the set of *lexemes* associated with a *token*.
  - ▷ Used as the *pattern* language

How do we decide whether an input string belongs to the set of strings specified by a regular expression?

Using Regular Definitions for Lexical Analysis

Q: Is ababbaabbb in $\mathcal{L}(((a^*b^*)^*)$?
A: Hm. Well. Let's see.

$$\begin{array}{rcl} \mathcal{L}((a^*b^*)^*) & = & \{\epsilon\} \\ & & \cup\{\epsilon, \mathtt{a}, \mathtt{b}, \mathtt{aa}, \mathtt{ab}, \mathtt{bb}, \\ & & \quad \mathtt{aaa}, \mathtt{aab}, \mathtt{abb}, \mathtt{bbb}, \ldots\} \\ & & \cup\{\epsilon, \mathtt{a}, \mathtt{b}, \mathtt{aa}, \mathtt{ab}, \mathtt{ba}, \mathtt{bb}, \\ & & \quad \mathtt{aaa}, \mathtt{aab}, \mathtt{aba}, \mathtt{abb}, \mathtt{baa}, \mathtt{bab}, \mathtt{bba}, \mathtt{bbb}, \ldots\} \\ & & \vdots \\ & = & ??? \end{array}$$

Recognizers

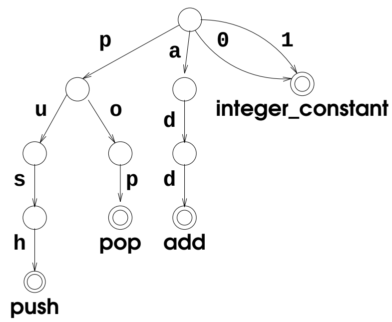
Construct *automata* that recognize strings belonging to a language.

- Finite State Automata ⇒ Regular Languages

- Push Down Automata ⇒ Context-free Languages
    - ▷ Stack is used to maintain counter, but only one counter can go arbitrarily high.

Recognizing Finite Sets of Strings

Identifying words from a small, finite, fixed vocabulary is straightforward.
For instance, consider a stack machine with `push`, `pop`, and `add` operations with two constants: `0` and `1`.
We can use the *automaton*:



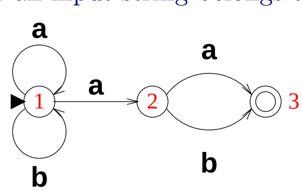
Finite State Automata

Represented by a labeled directed graph.

- A finite set of *states* (vertices).
- *Transitions* between states (edges).
- *Labels* on transitions are drawn from $\Sigma \cup \{\epsilon\}$.
- One distinguished *start* state.
- One or more distinguished *final* states.

Finite State Automata: An Example

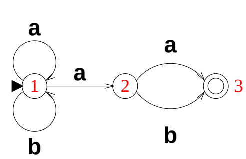
Consider the Regular Expression $(\boldsymbol{a} \mid \boldsymbol{b})^*\boldsymbol{a}(\boldsymbol{a} \mid \boldsymbol{b})$.
$\mathcal{L}((a \mid b)^*a(a \mid b)) = \{$`aa`, `ab`, `aaa`, `aab`, `baa`, `bab`,
`aaaa`, `aaab`, `abaa`, `abab`, `baaa`, $\ldots\}$.
The following automaton determines whether an input string belongs to $\mathcal{L}((a \mid b)^*a(a \mid b))$:



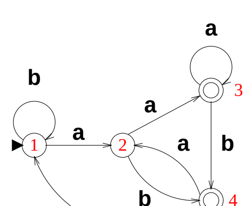
Determinism

$(\boldsymbol{a} \mid \boldsymbol{b})^*\boldsymbol{a}(\boldsymbol{a} \mid \boldsymbol{b})$:

Nondeterministic:
(NFA)



Deterministic:
(DFA)



Acceptance Criterion

A finite state automaton (NFA or DFA) *accepts* an input string x

... if beginning from the start state

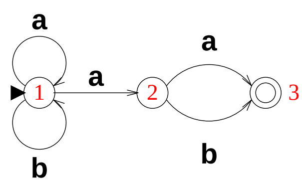
... we can trace some path through the automaton

... such that the sequence of edge labels spells x

... and end in a final state.

Recognition with an NFA

Is <u>`abab`</u> $\in \boldsymbol{\mathcal{L}((a \mid b)^* a(a \mid b))}$?

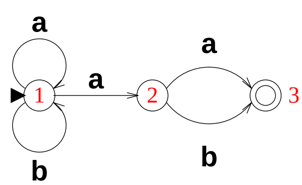


Input:		a	b	a	b	
Path 1:	1	1	1	1	1	
Path 2:	1	1	1	2	3	Accept
Path 3:	1	2	3	$\perp$	$\perp$	

Accept

Recognition with an NFA

Is <u>`abab`</u> $\in \boldsymbol{\mathcal{L}((a \mid b)^* a(a \mid b))}$?

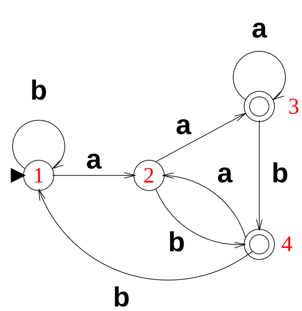


Input:		a	b	a	b	
Path 1:	1	1	1	1	1	
Path 2:	1	1	1	2	3	Accept
Path 3:	1	2	3	$\perp$	$\perp$	

Accept

Recognition with a DFA

Is <u>`abab`</u> $\in \boldsymbol{\mathcal{L}((a \mid b)^* a(a \mid b))}$?



NFA vs. DFA

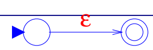
For every NFA, there is a DFA that accepts the same set of strings.

- NFA may have transitions labeled by ϵ.
  (Spontaneous transitions)
- All transition labels in a DFA belong to Σ.
- For some string x, there may be *many* accepting paths in an NFA.
- For all strings x, there is *one unique* accepting path in a DFA.
- Usually, an input string can be recognized *faster* with a DFA.
- NFAs are typically *smaller* than the corresponding DFAs.

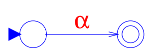
Regular Expressions to NFA

Thompson's Construction: For every regular expression r, derive an NFA $N(r)$ with unique start and final states.

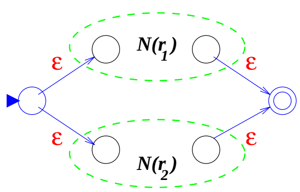
ϵ



$\alpha \in \Sigma$

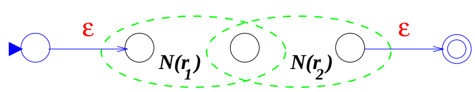


$(r_1 \mid r_2)$

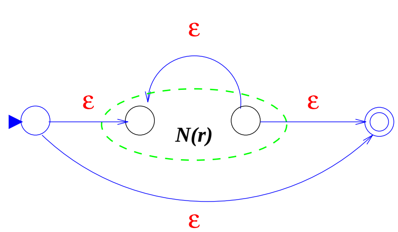


Regular Expressions to NFA (contd.)

$r_1 r_2$

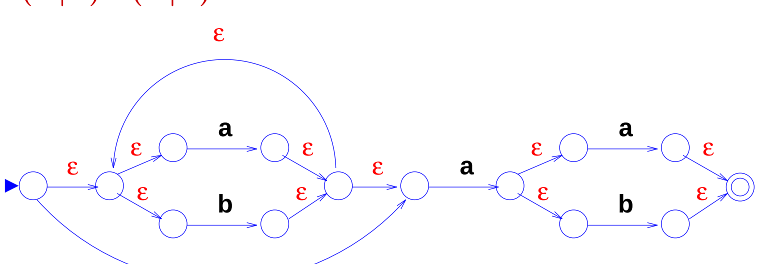


r^*



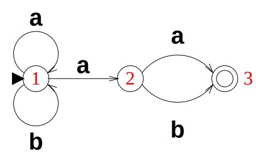
Example

$(a \mid b)^* a (a \mid b)$:



Recognition with an NFA

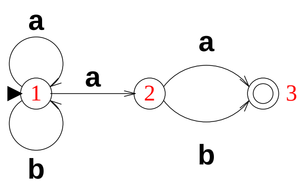
Is abab $\in \mathcal{L}((a \mid b)^*a(a \mid b))$?



Input:		a	b	a	b	
Path 1:	1	1	1	1	1	
Path 2:	1	1	1	2	3	Accept
Path 3:	1	2	3	$\perp$	$\perp$	
All Paths	$\{1\}$	$\{1,2\}$	$\{1,3\}$	$\{1,2\}$	$\{1,3\}$	Accept

Recognition with an NFA (contd.)

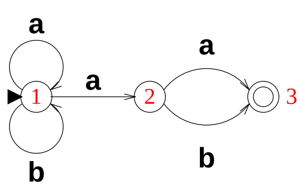
Is aaab $\in \mathcal{L}((a \mid b)^*a(a \mid b))$?



Input:		a	a	a	b	
Path 1:	1	1	1	1	1	
Path 2:	1	1	1	1	2	
Path 3:	1	1	1	2	3	Accept
Path 4:	1	1	2	3	$\perp$	
Path 5:	1	2	3	$\perp$	$\perp$	
All Paths	$\{1\}$	$\{1,2\}$	$\{1,2,3\}$	$\{1,2,3\}$	$\{1,2,3\}$	Accept

Recognition with an NFA (contd.)

Is aabb $\in \mathcal{L}((a \mid b)^*a(a \mid b))$?



Input:		a	a	a	b	
Path 1:	1	1	1	1	1	
Path 2:	1	1	2	3	$\perp$	
Path 3:	1	2	3	$\perp$	$\perp$	
All Paths	$\{1\}$	$\{1,2\}$	$\{1,2,3\}$	$\{1,3\}$	$\{1\}$	REJECT

Converting NFA to DFA

Subset construction
Given a set S of NFA states,

- compute $S_\epsilon = \epsilon\text{-closure}(S)$: S_ϵ is the set of all NFA states reachable by zero or more ϵ-transitions from S.
- compute $S_\alpha = \text{goto}(S, \alpha)$:
  - S' is the set of all NFA states reachable from S by taking a transition labeled α.
  - $S_\alpha = \epsilon\text{-closure}(S')$.

Converting NFA to DFA (contd).

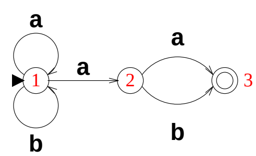
Each state in DFA corresponds to a *set of states* in NFA.
Start state of DFA = ϵ-closure(start state of NFA).
From a state s in DFA that corresponds to a set of states S in NFA:

add a transition labeled α to state s' that corresponds to a non-empty S' in NFA,

such that $S' = \text{goto}(S, \alpha)$.

$\Leftarrow s$ is a final state of DFA

NFA $\longrightarrow$ DFA: An Example



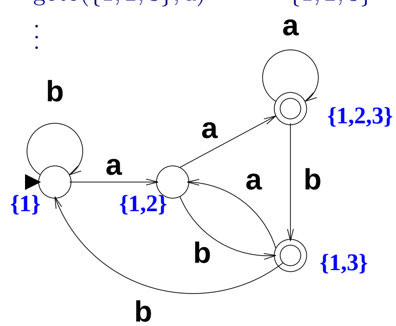
$$
\begin{array}{lcl}
\epsilon\text{-closure}(\{1\}) & = & \{1\} \\
\text{goto}(\{1\}, \mathtt{a}) & = & \{1,2\} \\
\text{goto}(\{1\}, \mathtt{b}) & = & \{1\} \\
\text{goto}(\{1,2\}, \mathtt{a}) & = & \{1,2,3\} \\
\text{goto}(\{1,2\}, \mathtt{b}) & = & \{1,3\} \\
\text{goto}(\{1,2,3\}, \mathtt{a}) & = & \{1,2,3\} \\
\vdots & &
\end{array}
$$

NFA $\longrightarrow$ DFA: An Example (contd.)

$$
\begin{array}{lcl}
\epsilon\text{-closure}(\{1\}) & = & \{1\} \\
\text{goto}(\{1\}, \mathtt{a}) & = & \{1,2\} \\
\text{goto}(\{1\}, \mathtt{b}) & = & \{1\} \\
\text{goto}(\{1,2\}, \mathtt{a}) & = & \underline{\{1,2,3\}} \\
\text{goto}(\{1,2\}, \mathtt{b}) & = & \underline{\{1,3\}} \\
\text{goto}(\{1,2,3\}, \mathtt{a}) & = & \underline{\{1,2,3\}} \\
\text{goto}(\{1,2,3\}, \mathtt{b}) & = & \{1\} \\
\text{goto}(\{1,3\}, \mathtt{a}) & = & \{1,2\} \\
\text{goto}(\{1,3\}, \mathtt{b}) & = & \{1\}
\end{array}
$$

NFA $\longrightarrow$ DFA: An Example (contd.)

$$
\begin{array}{lcl}
\text{goto}(\{1\}, \mathtt{a}) & = & \{1,2\} \\
\text{goto}(\{1\}, \mathtt{b}) & = & \{1\} \\
\text{goto}(\{1,2\}, \mathtt{a}) & = & \{1,2,3\} \\
\text{goto}(\{1,2\}, \mathtt{b}) & = & \{1,3\} \\
\text{goto}(\{1,2,3\}, \mathtt{a}) & = & \{1,2,3\} \\
\vdots & &
\end{array}
$$



NFA vs. DFA

R = Size of Regular Expression
N = Length of Input String

	NFA	DFA
Size of Automaton	$O(R)$	$O(2^R)$
Recognition time		

Lexical Analysis

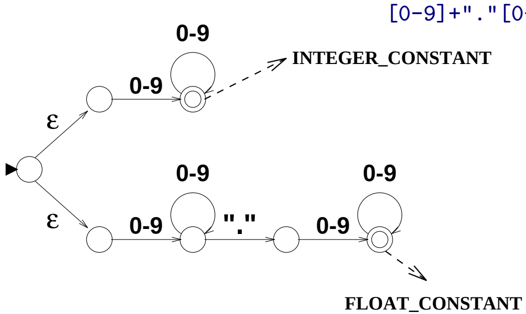
- Regular Expressions and Definitions are used to specify the set of strings (lexemes) corresponding to a *token*.
- An automaton (DFA/NFA) is built from the above specifications.
- Each final state is associated with an *action*: emit the corresponding token.

Specifying Lexical Analysis

Consider a recognizer for integers (sequence of digits) and floats (sequence of digits separated by a decimal point).

```
[0-9]+               { emit(INTEGER_CONSTANT); }

[0-9]+"."[0-9]+      { emit(FLOAT_CONSTANT); }
```



Lex

Tool for building lexical analyzers.
Input: lexical specifications (`.l` file)
Output: C function (`yylex`) that returns a token on each invocation.

```
%%
[0-9]+               { return(INTEGER_CONSTANT); }

[0-9]+"."[0-9]+      { return(FLOAT_CONSTANT); }
```

Tokens are simply integers (`#define`'s).

Lex Specifications

```
%{
    C header statements for inclusion
%}
  Regular Definitions    e.g.:
    digit    [0-9]
%%

  Token Specifications    e.g.:
    {digit}+               { return(INTEGER_CONSTANT); }

%%
  Support functions in C
```

Regular Expressions in Lex

- Range: `[0-7]`: Integers from 0 through 7 (inclusive)

  `[a-nx-zA-Q]`: Letters `a` thru `n`, `x` thru `z` and `A` thru `Q`.
- Exception: `[^/]`: Any character other than `/`.
- Definition: `{digit}`: Use the previously specified regular definition `digit`.
- Special characters: Connectives of regular expression, convenience features.

  e.g.: `| * ^`

Special Characters in Lex

`| * + ? ( )`	Same as in regular expressions
`[ ]`	Enclose ranges and exceptions
`{ }`	Enclose "names" of regular definitions
`^`	Used to negate a specified range (in Exception)
`.`	Match any single character except newline
`\`	Escape the next character
`\n`, `\t`	Newline and Tab

For literal matching, enclose special characters in double quotes (`"`) *e.g.:* `"*"`
Or use `\` to escape. *e.g.:* `\"`

Examples

`for`	Sequence of `f`, `o`, `r`
`"||"`	C-style OR operator (two vert. bars)
`.*`	Sequence of non-newline characters
`[^*/]+`	Sequence of characters except `*` and `/`
`\"[^"]*\"`	Sequence of non-quote characters beginning and ending with a quote
`({letter}|"_")({letter}|{digit}|"_")*`	C-style identifiers

A Complete Example

```
%{
#include <stdio.h>
#include "tokens.h"
%}
digit  [0-9]
hexdigit  [0-9a-f]
%%

"+"                    { return(PLUS); }
"-"                    { return(MINUS); }
{digit}+               { return(INTEGER_CONSTANT); }
{digit}+"."{digit}+    { return(FLOAT_CONSTANT); }
.                      { return(SYNTAX_ERROR); }
%%
```

Actions

Actions are attached to final states.

- Distinguish the different final states.

- Can be used to set *attribute values*.
- Fragment of C code (blocks enclosed by '{' and '}').

Attributes

Additional information about a token's lexeme.

- Stored in variable `yylval`
- Type of attributes (usually a union) specified by `YYSTYPE`
- Additional variables:
  - `yytext`: Lexeme (*Actual text string*)
  - `yyleng`: length of string in `yytext`
  - ▷ `yylineno`: Current line number (number of '`\n`' seen thus far)
    - ∗ enabled by `%option yylineno`

Priority of matching

What if an input string matches more than one pattern?

```
"if"                { return(TOKEN_IF); }
{letter}+           { return(TOKEN_ID); }
"while"             { return(TOKEN_WHILE); }
```

- A pattern that matches the longest string is chosen.
  Example: `if1` is matched with an identifier, not the keyword `if`.
- Of patterns that match strings of same length, the first (from the top of file) is chosen.
  Example: `while` is matched as an identifier, not the keyword `while`.

Constructing Scanners using (f)lex

- Scanner specifications: *specifications*`.l`

  specifications`.l` $\xrightarrow{\texttt{(f)lex}}$ `lex.yy.c`

- Generated scanner in `lex.yy.c`

  `lex.yy.c` $\xrightarrow{\texttt{(g)cc}}$ *executable*

  - `yywrap()`: hook for signalling end of file.
  - Use `-lfl` (flex) or `-ll` (lex) flags at link time to include default function `yywrap()` that always returns 1.

Implementing a Scanner

$transition : state \times \Sigma \rightarrow state$

```
algorithm scanner() {
    current_state = start state;
    while (1) {
        c = getc(); /* on end of file, ... */
        if defined(transition(current_state, c))
            current_state = transition(current_state, c);
        else
            return s;
    }
}
```

Implementing a Scanner (contd.)

Implementing the *transition* function:

- Simplest: 2-D array.
  Space inefficient.
- Traditionally compressed using row/colum equivalence. (default on `(f)lex`)
  Good space-time tradeoff.
- Further table compression using various techniques:
  - Example: RDM (Row Displacement Method):
    Store rows in overlapping manner using 2 1-D arrays.

  Smaller tables, but longer access times.

Lexical Analysis: A Summary

Convert a stream of characters into a stream of tokens.

- Make rest of compiler independent of character set
- Strip off comments
- Recognize line numbers
- Ignore white space characters
- Process macros (definitions and uses)
- Interface with **symbol** (name) **table**.