Lexical Analysis

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Today

- Role of lexical analysis
- Regular languages, regular expressions
- Finite-state machines
- From regular expressions to finite-state machines
- A language for specifying lexical analysis
- The generation of a scanner
- Flex

Lexical Analysis (Scanning)

- Functionality

  Input: program as sequence of characters

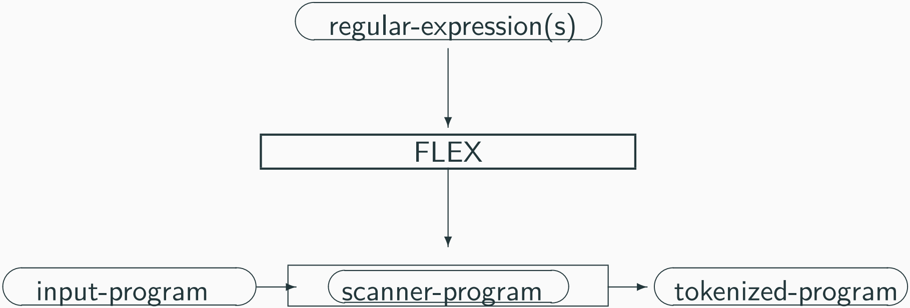
  Output: program as sequence of symbols (tokens)

- Report errors, symbols illegal in the programming language
- Additional bookkeeping:
  - Identify language keywords and standard identifiers
  - Eliminate “whitespace”, e.g., consecutive blanks and newlines
  - Track text coordinates for error report generation
  - Construct table of all symbols occurring (symbol table)

Automatic Generation of Lexical Analyzers

- The symbols of programming languages can be specified by regular expressions.
- Examples:
  - `program` as a sequence of characters.
  - `(alpha (alpha | digit)*)` for identifiers
  - `"/*" until "*/"` for comments
- The recognition of input strings can be performed by a finite-state machine.
- A table representation or a program for the automaton is automatically generated from a regular expression.

Automatic Generation of Lexical Analyzers cont'd



Notations

A language L is a set of words x over an alphabet Σ.

$a_1 a_2 \dots a_n$,	a word over Σ, $a_i \in \Sigma$
ε	The empty word
Σ^n	The words of length n over Σ
Σ^*	The set of finite words over Σ
Σ^+	The set of non-empty finite words over Σ
$x.y$	The concatenation of x and y

Language Operations

$L_1 \cup L_2$		Union
$L_1 L_2$	$= \{x.y \mid x \in L_1, y \in L_2\}$	Concatenation
$\overline{L}$	$= \Sigma^* - L$	Complement
L^n	$= \{x_1 \dots x_n \mid x_i \in L, 1 \leq i \leq n\}$	
L^*	$= \bigcup_{n \geq 0} L^n$	Closure
L^+	$= \bigcup_{n \geq 1} L^n$	

Regular Languages

Defined inductively

- $\emptyset$ is a regular language over Σ
- $\{\varepsilon\}$ is a regular language over Σ
- For all $a \in \Sigma$, $\{a\}$ is a regular language over Σ
- If R_1 and R_2 are regular languages over Σ, then so are:
  - $R_1 \cup R_2$,
  - $R_1 R_2$, and
  - R_1^*

Regular Expressions and the Denoted Regular Languages

Defined inductively

- $\underline{\emptyset}$ is a regular expression over Σ denoting $\emptyset$,
- $\underline{\varepsilon}$ is a regular expression over Σ denoting $\{\varepsilon\}$,
- For all $a \in \Sigma$, a is a regular expression over Σ denoting $\{a\}$,
- If r_1 and r_2 are regular expressions over Σ denoting R_1 and R_2, resp., then so are:
  - $\underline{(}r_1\underline{|}r_2\underline{)}$, which denotes $R_1 \cup R_2$,
  - $\underline{(}r_1 r_2\underline{)}$, which denotes $R_1 R_2$, and
  - $\underline{(}r_1\underline{)}\underline{^*}$, which denotes R_1^*.
- Metacharacters, $\underline{\emptyset}, \underline{\varepsilon}, \underline{(}, \underline{)}, \underline{|}, \underline{*}$ don't really exist, are replaced by their non-underlined versions.
  Clash between characters in Σ and metacharacters $\{\underline{(}, \underline{)}, \underline{|}, \underline{^*}\}$

Example

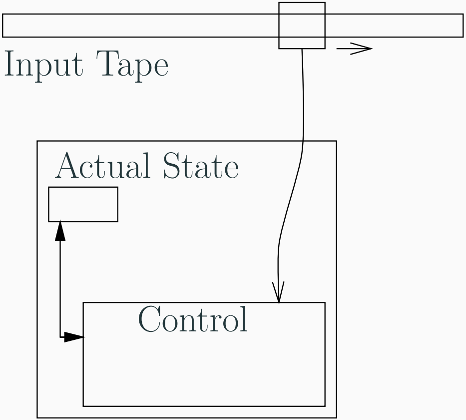
Expression	Language	Example words
$a \| b$	$\{a, b\}$	a, b
ab^*a	$\{a\}\{b\}^*\{a\}$	$aa, aba, abba, abbba, \ldots$
$(ab)^*$	$\{ab\}^*$	$\varepsilon, ab, abab, \ldots$
$abba$	$\{abba\}$	$abba$

Automata

- process input
- make transitions from configurations to configurations;
- configurations consist of (the rest of) the input and some memory;
- the memory may be small, just one variable with finitely many values,
- but the memory may also be able to grow without bound, adding and removing values at one of its ends;
- the type of memory determines its ability to recognize a class of languages,

Finite State Machine

The simplest type of automaton, its memory consists of only one variable, which can store one out of finitely many values, its states,



A Non-Deterministic Finite-State Machine (NFSM)

$M = \langle \Sigma, Q, \Delta, q_0, F \rangle$ where:

- Σ — finite alphabet
- Q — finite set of states
- $q_0 \in Q$ — initial state
- $F \subseteq Q$ — final states
- $\Delta \subseteq Q \times (\Sigma \cup \{\varepsilon\}) \times Q$ — transition relation

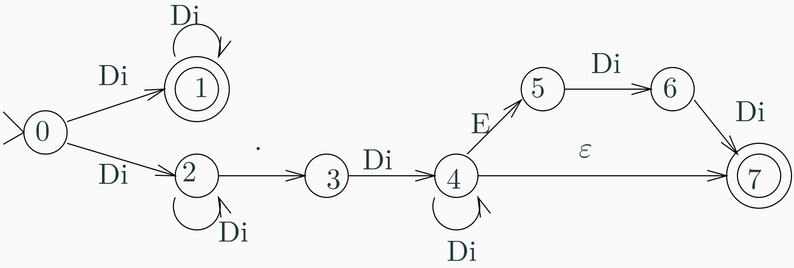
May be represented as a transition diagram

- Nodes — States
- q_0 has a special "entry" mark
- final states doubly encircled
- An edge from p into q labeled by a if $(p, a, q) \in \Delta$

Example: Integer and Real Constants

	Di $\in \{0, 1, \ldots, 9\}$	.	E	ε
0	{1,2}	$\emptyset$	$\emptyset$	$\emptyset$
1	{1}	$\emptyset$	$\emptyset$	$\emptyset$
2	{2}	{3}	$\emptyset$	$\emptyset$
3	{4}	$\emptyset$	$\emptyset$	$\emptyset$
4	{4}	$\emptyset$	{5}	{7}
5	{6}	$\emptyset$	$\emptyset$	$\emptyset$
6	{7}	$\emptyset$	$\emptyset$	$\emptyset$
7	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$

$$q_0 = 0$$
$$F = \{1, 7\}$$



Finite-state machines — Scanners

Finite-state machines

- get an input word,
- start in their initial state,
- make a series of transitions under the characters constituting the input word,
- accept (or reject).

Scanners

- get an input string (a sequence of words),
- start in their initial state,
- attempt to find the end of the next word,
- when found, restart in their initial state with the rest of the input,
- terminate when the end of the input is reached or an error is encountered.

Maximal Munch strategy

Find longest prefix of remaining input that is a legal symbol.

- first input character of the scanner:
  first “non-consumed” character,
- in final state, and exists transition under the next character:
  make transition and remember position
- in final state, and no transition under the next character:
  symbol found
- actual state not final and no transition under the next character: backtrack to last passed final state
  - There is none: Illegal string
  - Otherwise: Actual symbol ended there.

Warning: Certain overlapping symbol definitions will result in quadratic runtime: $\rightarrow$ exercise

Other Example Automata

- integer constant
- real constant
- identifier
- string
- comments

The Language Accepted by a Finite-State Machine

- $M = \langle \Sigma, Q, \Delta, q_0, F \rangle$
- For $q \in Q$, $w \in \Sigma^*$, (q, w) is a configuration
- The binary relation step on configurations is defined by:

$$(q, aw) \vdash_M (p, w)$$

  if $(q, a, p) \in \Delta$
- The reflexive transitive closure of $\vdash_M$ is denoted by $\vdash_M^*$
- The language accepted by M

$$L(M) = \{w \in \Sigma^* \mid \exists q_f \in F : (q_0, w) \vdash_M^* (q_f, \varepsilon)\}$$

From Regular Expressions to Finite Automata

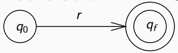
Theorem

(i) For every regular language R, there exists an NFSM M, such that $L(M) = R$.

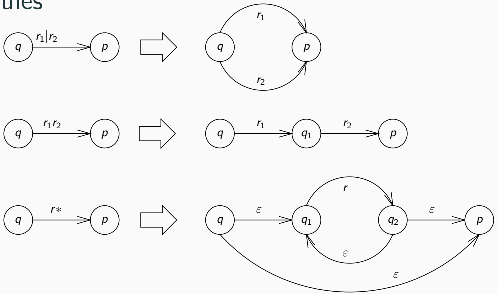
(ii) For every regular expression r, there exists an NFSM that accepts the regular language defined by r.

A Constructive Proof for (ii) (Algorithm)

- A regular language is defined by a regular expression r
- Construct an "NFSM" with one final state, q_f, and the transition



- Decompose r and develop the NFSM according to the following rules



until only transitions under single characters and ε remain.

Examples

- $a(a|0)^*$ over $\Sigma = \{a, 0\}$
- Identifier
- String

Nondeterminism

- Several transitions may be possible under the same character in a given state
- ε-moves (next character is not read) may “compete” with non-ε-moves.
- Deterministic simulation requires “backtracking”

Deterministic Finite-State Machine (DFSM)

- No ε-transitions
- At most one transition from every state under a given character, i.e. for every $q \in Q$, $a \in \Sigma$,

$$|\{q' \,|\, (q, a, q') \in \Delta\}| \leq 1$$

From Non-Deterministic to Deterministic Automata

Theorem

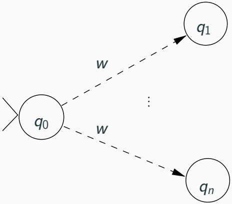
For every NFSM, $M = \langle \Sigma, Q, \Delta, q_0, F \rangle$ there exists a DFSM, $M' = \langle \Sigma, Q', \delta, q_0', F' \rangle$ such that $L(M) = L(M')$.

A Scheme of a Constructive Proof (Subset Construction)

Construct a DFSM whose states are sets of states of the NFSM.

The DFSM simulates all possible transition paths under an input word in parallel.

Set of new states $\{\{q_1, \ldots, q_n\} \mid n \geq 1 \wedge \exists w : (q_0, w) \vdash_M^* (q_i, \varepsilon)\}$



The Construction Algorithm

Used in the construction: the set of ε-Successors,
$\varepsilon\text{-}SS(q) = \{p \mid (q, \varepsilon) \vdash_M^* (p, \varepsilon)\}$

- Starts with $q_0' = \varepsilon\text{-}SS(q_0)$ as the initial DFSM state.
- Iteratively creates more states and more transitions.
- For each DFSM state $S \subseteq Q$ already constructed and character $a \in \Sigma$,

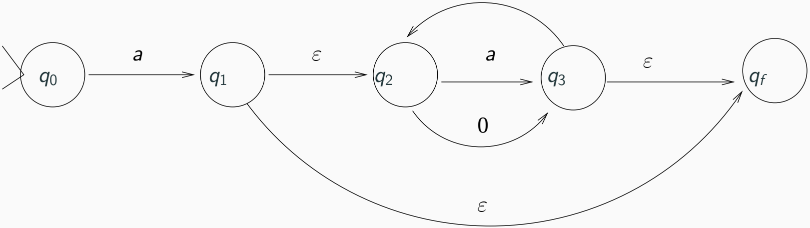
  $$\delta(S, a) = \bigcup_{q \in S} \bigcup_{(q,a,p) \in \Delta} \varepsilon\text{-}SS(p)$$

  if non-empty

  add new state $\delta(S, a)$ if not previously constructed;

  add transition from S to $\delta(S, a)$.
- A DFSM state S is accepting (in F') if there exists $q \in S$ such that $q \in F$

Example: $a(a|0)^*$

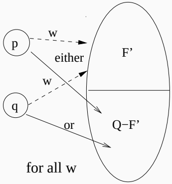


DFSM minimization

DFSM need not have minimal size, i.e. minimal number of states and transitions.

q and p are undistinguishable (have the same acceptance behavior) iff

for all words w $(q, w) \vdash_M^*$ and $(p, w) \vdash_M^*$ lead into either F' or $Q' - F'$.



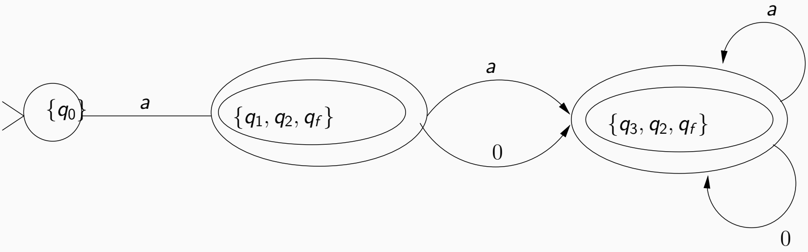
Undistinguishability is an equivalence relation.

Goal: merge undistinguishable states $\equiv$ consider equivalence classes as new states.

DFSM minimization algorithm

- Input a DFSM $M = \langle \Sigma, Q, \delta, q_0, F \rangle$
- Iteratively refine a partition of the set of states, where each set in the partition consists of states so far undistinguishable.
- Start with the partition $\Pi = \{F, Q - F\}$
- Refine the current Π by splitting sets $S \in \Pi$ if there exist $q_1, q_2 \in S$ and $a \in \Sigma$ such that
  - $\delta(q_1, a) \in S_1$ and $\delta(q_2, a) \in S_2$ and $S_1 \neq S_2$
- Note that this assumes that δ is total (can easily be totalized by introducing an error state)
- Merge sets of undistinguishable states into a single state.

Example: $a(a|0)^*$



A Language for specifying lexical analyzers

$(0|1|2|3|4|5|6|7|8|9)(0|1|2|3|4|5|6|7|8|9)^*$
$(\varepsilon|.(0|1|2|3|4|5|6|7|8|9)(0|1|2|3|4|5|6|7|8|9)^*$
$(\varepsilon|E(0|1|2|3|4|5|6|7|8|9)(0|1|2|3|4|5|6|7|8|9)))$

Descriptional Comfort

Character Classes:

Identical meaning for the DFSM (exceptions!), e.g.,

le = a - z A - Z

di = 0 - 9

Efficient implementation: Addressing the transitions indirectly through an array indexed by the character codes.

Symbol Classes:

Identical meaning for the parser, e.g.,

Identifiers

Comparison operators

Strings

Descriptional Comfort cont'd

Sequences of regular definitions:

$$\begin{array}{rcl} A_1 & = & R_1 \\ A_2 & = & R_2 \\ & \cdots & \\ A_n & = & R_n \end{array}$$

Sequences of Regular Definitions

Goal: Separate final states for each definition

1. Substitute right sides for left sides
2. Create an NFSM for every regular expression separately;
3. Merge all the NFSMs using ε transitions from the start state;
4. Construct a DFSM;
5. Minimize starting with partition

$$\{F_1, F_2, \ldots, F_n, Q - \bigcup_{i=1}^{n} F_i\}$$

Flex Specification

Definitions
%%
Rules
%%
C-Routines

Flex Example

```
%{
extern int line_number;
extern float atof(char *);
%}
DIG     [0-9]
LET    [a-zA-Z]
%%
[=#<>+-*]          { return(*yytext); }
({DIG}+)  { yylval.intc  = atoi(yytext); return(301); }
({DIG}*\.{DIG}+(E(\+|\-)?{DIG}+)?)
          {yylval.realc = atof(yytext); return(302); }
\"(\\.|[^\"\\])*\" { strcpy(yylval.strc, yytext);
                     return(303); }
"<="               { return(304); }
:=                 { return(305); }
\.\.               { return(306); }
```

Flex Example cont'd

```
ARRAY                { return(307); }
BOOLEAN              { return(308); }
DECLARE              { return(309); }
{LET}({LET}|{DIG})* { yylval.symb = look_up(yytext);
                      return(310); }
[ \t]+               { /* White space */ }
\n                   { line_number++; }
.                    { fprintf(stderr,
   "WARNING: Symbol '%c' is illegal, ignored!\n", *yytext);}
%%
```