CSc 453
Lexical Analysis (Scanning)

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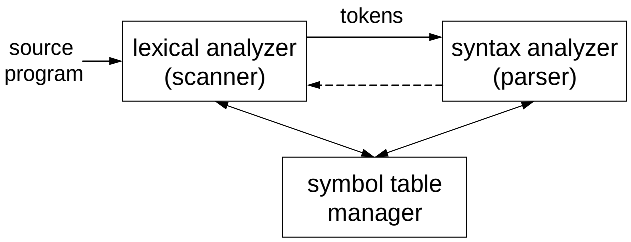
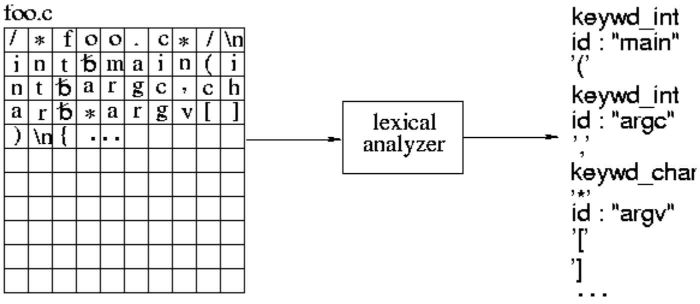
Overview



- *Main task*: to read input characters and group them into "*tokens*."
- *Secondary tasks*:
  - Skip comments and whitespace;
  - Correlate error messages with source program (e.g., line number of error).

Overview (cont'd)



Implementing Lexical Analyzers

Different approaches:

- Using a scanner generator, e.g., **lex** or **flex**. This automatically generates a lexical analyzer from a high-level description of the tokens.

  (easiest to implement; least efficient)
- Programming it in a language such as C, using the I/O facilities of the language.

  (intermediate in ease, efficiency)
- Writing it in assembly language and explicitly managing the input.

  (hardest to implement, but most efficient)

Lexical Analysis: Terminology

- ***token***: a name for a set of input strings with related structure.

  Example: “identifier,” “integer constant”
- ***pattern***: a rule describing the set of strings associated with a token.

  Example: “a letter followed by zero or more letters, digits, or underscores.”
- ***lexeme***: the actual input string that matches a pattern.

  Example: `count`

Examples

Input: `count = 123`

Tokens:

identifier : *Rule*: “letter followed by …”
Lexeme: count

assg_op : *Rule*: =
Lexeme: =

integer_const : *Rule*: “digit followed by …”
Lexeme: 123

Attributes for Tokens

- If more than one lexeme can match the pattern for a token, the scanner must indicate the actual lexeme that matched.
- This information is given using an *attribute* associated with the token.

Example: The program statement

```
count = 123
```

yields the following token-attribute pairs:

⟨*identifier*, pointer to the string **`"count"`**⟩

⟨*assg_op*, ⟩

⟨*integer_const*, the integer value **123**⟩

Specifying Tokens: regular expressions

- ***Terminology:***

alphabet : a finite set of symbols

string : a finite sequence of alphabet symbols

language : a (finite or infinite) set of strings.

- ***Regular Operations on languages***:

Union: $R \cup S = \{ x \mid x \in R \text{ or } x \in S\}$

Concatenation: $RS = \{ xy \mid x \in R \text{ and } y \in S\}$

Kleene closure: R^* = R concatenated with itself 0 or more times

$= \{\varepsilon\} \cup R \cup RR \cup RRR \cup$

= strings obtained by concatenating a finite number of strings from the set R.

Regular Expressions

A pattern notation for describing certain kinds of sets over strings:

Given an alphabet Σ:

- ε is a regular exp. (denotes the language $\{\varepsilon\}$)
- for each $a \in \Sigma$, a is a regular exp. (denotes the language $\{a\}$)
- if ***r*** and ***s*** are regular exps. denoting L(***r***) and L(***s***) respectively, then so are:
    - (***r***) | (***s***) (denotes the language L(***r***) $\cup$ L(***s***))
    - (***r***)(***s***) (denotes the language L(***r***)L(***s***))
    - (***r***)* (denotes the language L(***r***)*)

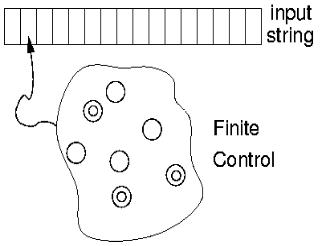
Common Extensions to r.e. Notation

- One or more repetitions of r : $r+$
- A range of characters : [a-zA-Z], [0-9]
- An optional expression: $r?$
- Any single character: **.**
- Giving names to regular expressions, e.g.:
    - letter = [a-zA-Z_]
    - digit = 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
    - ident = letter (letter | digit)*
    - Integer_const = digit+

Recognizing Tokens: Finite Automata

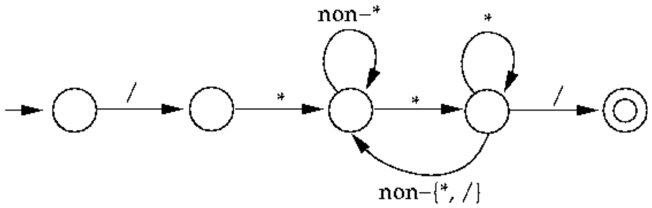
A *finite automaton* is a 5-tuple (Q, Σ, T, q0, F), where:

- Σ is a finite alphabet;
- Q is a finite set of states;
- T: $Q \times \Sigma \rightarrow Q$ is the transition function;
- q0 $\in$ Q the initial state; and
- $F \subseteq Q$ is a set of final states.



Finite Automata: An Example

A (deterministic) finite automaton (DFA) to match C-style comments:



Formalizing Automata Behavior

To formalize automata behavior, we extend the transition function to deal with strings:

$Ŧ : Q \times \Sigma^* \to Q$

$Ŧ(q, \varepsilon) = q$

$Ŧ(q, aw) = Ŧ(r, w)$ where $r = T(q, a)$

The *language* accepted by an automaton *M* is

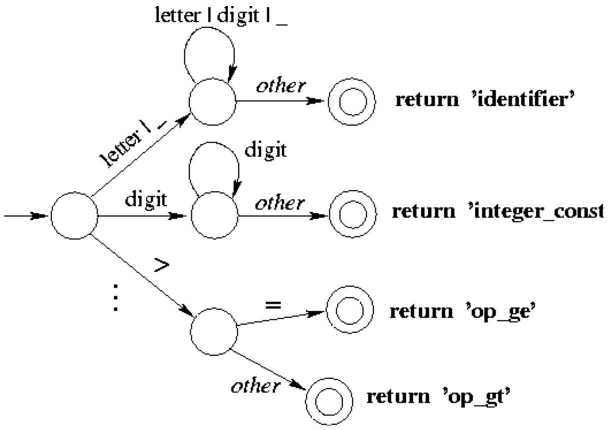
$L(M) = \{ w \mid Ŧ(q0, w) \in F \}$.

A language L is *regular* if it is accepted by some finite automaton.

Finite Automata and Lexical Analysis

- The tokens of a language are specified using regular expressions.
- A scanner is a big DFA, essentially the “aggregate” of the automata for the individual tokens.
- Issues:
  - What does the scanner automaton look like?
  - How much should we match? (When do we stop?)
  - What do we do when a match is found?
  - Buffer management (for efficiency reasons).

Structure of a Scanner Automaton



How much should we match?

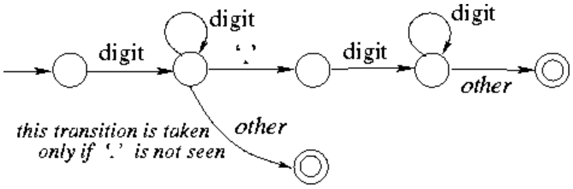
In general, find the longest match possible.

E.g., on input 123.45, match this as

num_const(123.45)

rather than

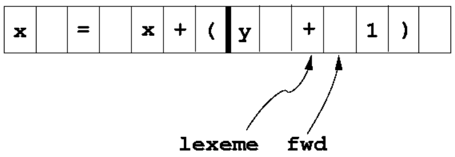
num_const(123), ".", num_const(45).



Input Buffering

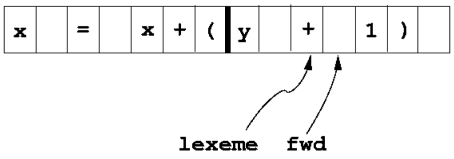
- Scanner performance is crucial:
  - This is the only part of the compiler that examines the entire input program one character at a time.
  - Disk input can be slow.
  - The scanner accounts for ~25-30% of total compile time.
- We need lookahead to determine when a match has been found.
- Scanners use _*double-buffering*_ to minimize the overheads associated with this.

Buffer Pairs



- Use two *N*-byte buffers (*N* = size of a disk block; typically, *N* = 1024 or 4096).
- Read *N* bytes into one half of the buffer each time. If input has less than *N* bytes, put a special EOF marker in the buffer.
- When one buffer has been processed, read *N* bytes into the other buffer ("_*circular buffers*_").

Buffer pairs (cont'd)

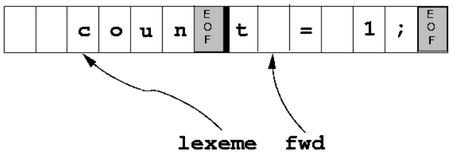


Code:

```
if (fwd at end of first half)
    reload second half;
    set fwd to point to beginning of second half;
else if (fwd at end of second half)
    reload first half;
    set fwd to point to beginning of first half;
else
    fwd++;
```

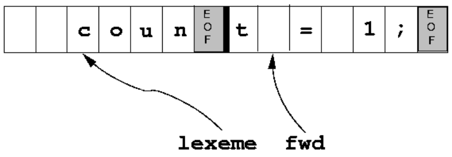
it takes two tests for each advance of the fwd pointer.

Buffer pairs: Sentinels



- *Objective*: Optimize the common case by reducing the number of tests to one per advance of fwd.
- *Idea*: Extend each buffer half to hold a *sentinel* at the end.
  - This is a special character that cannot occur in a program (e.g., EOF).
  - It signals the need for some special action (fill other buffer-half, or terminate processing).

Buffer pairs with sentinels (cont'd)



Code:

```
fwd++;
if ( *fwd == EOF )  {            /* special processing needed */
    if (fwd at end of first half)
        . . .
    else if (fwd at end of second half)
        . . .
    else      /* end of input */
        terminate processing.
}
```

common case now needs just a single test per character.

Handling Reserved Words

1. Hard-wire them directly into the scanner automaton:
    - harder to modify;
    - increases the size and complexity of the automaton;
    - performance benefits unclear (fewer tests, but cache effects due to larger code size).
2. Fold them into "identifier" case, then look up a keyword table:
    - simpler, smaller code;
    - table lookup cost can be mitigated using perfect hashing.

Implementing Finite Automata 1

Encoded as program code:

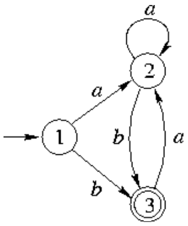
- each state corresponds to a (labeled code fragment)
- state transitions represented as control transfers.

E.g.:

```
while ( TRUE ) {
    …
    state_k: ch = NextChar();   /* buffer mgt happens here */
               switch (ch) {
                 case … : goto  ...;     /* state transition */
                   …
               }
    state_m:           /* final state */
               copy lexeme to where parser can get at it;
               return token_type;
    …
}
```

Direct-Coded Automaton: Example

```
int scanner()
{  char ch;
   while (TRUE) {
      ch = NextChar( );
      state_1: switch (ch) {          /* initial state */
           case ‘a’ : goto state_2;
           case ‘b’ : goto state_3;
           default : Error();
         }
      state_2: …
      state_3: switch (ch) {
           case ‘a’ : goto state_2;
           default : return SUCCESS;
         }
    } /* while */
}
```



Implementing Finite Automata 2

Table-driven automata (e.g., ***lex***, ***flex***):

- Use a table to encode transitions:

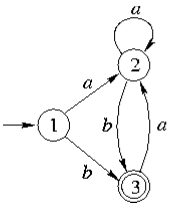
  next_state = *T*(curr_state, next_char);
- Use one bit in state no. to indicate whether it's a final (or error) state. If so, consult a separate table for what action to take.

T	*next input character*		
Current state			

Table-Driven Automaton: Example

```
#define isFinal(s)      ((s) < 0)
int scanner()
{  char ch;
   int currState = 1;

   while (TRUE) {
      ch = NextChar( );
      if (ch == EOF) return 0;  /* fail */
      currState = T [currState, ch];
      if (IsFinal(currState)) {
         return 1;  /* success */
      }
   } /* while */
}
```



T	*input*	
state	*a*	*b*
1	2	3
2	2	3
3	2	-1

What do we do on finding a match?

- A match is found when:
  - The current automaton state is a final state; and
  - No transition is enabled on the next input character.
- Actions on finding a match:
  - if appropriate, copy lexeme (or other token attribute) to where the parser can access it;
  - save any necessary scanner state so that scanning can subsequently resume at the right place;
  - return a value indicating the token found.