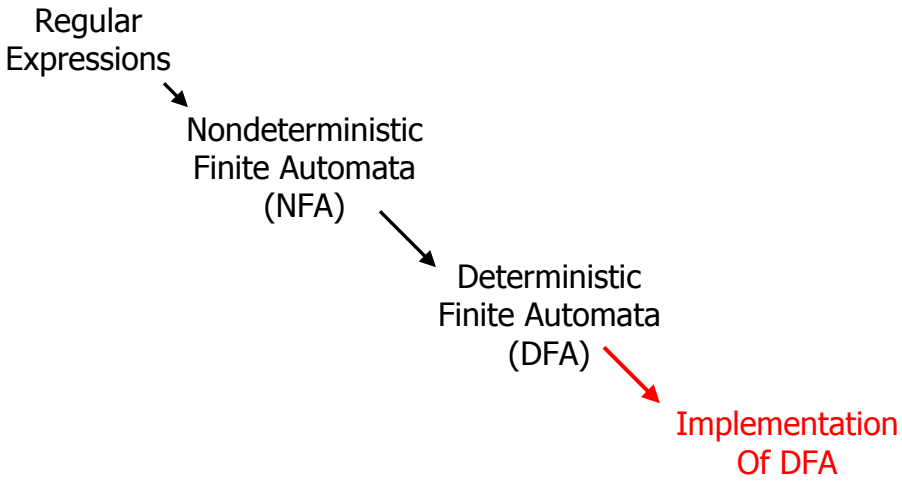
Lexical Analysis



Key Differences for a Scanner and RE Recognizer

- Given a single string, automata and regular expressions retuned a Boolean answer:
  - a given string is/is not in a language
- In contrast …
- Given an input (an EOF-terminated "long" string), a scanner returns a series of tokens
  - finds the longest lexeme, and
  - returns the corresponding token

A Sample Scanner

- The language of assignment statements:

  LHS = RHS
  LHS = RHS

  ...

  - left-hand side of assignment is a simple identifier:
    - a letter followed by one or more letters or digits
  - right-hand side is one of the following:
    - ID + ID
    - ID * ID
    - ID == ID

Step 1: Define tokens

- Our language has five tokens,
  - They can be defined by five regular expressions:

Token	Regular Expression

Step 2: Convert REs to NFAs

ASSIGN:

ID:

PLUS:

TIMES:

EQUALS:

Step 3: Convert NFAs to DFAs

ASSIGN:

ID:

PLUS:

TIMES:

EQUALS:

Step 4: Combining per-token DFAs

- Goal of a scanner:
  - find the *longest prefix* of the current input that corresponds to a token.
- This has two consequences:
  - lookahead:
    - Examine if the next input character can "extend" the current token. If yes, keep building a larger token.
  - a real scanner cannot get stuck:
    - What if we get stuck building the larger token? Solution: return characters back to input.

Furthermore …

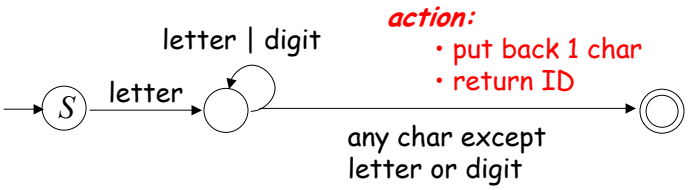
- In general the input can correspond to a series of tokens (lexemes), not just a single token
  - **Problem:** It is no longer correct to run the FSM until it gets stuck or whole string is consumed.
    So, how to partition the input into lexemes?
  - **Solution:** a token must be returned when a regular expression is matched
- Some lexemes (like whitespace and comments) do not correspond to tokens
  - **Problem:** how to "discard" these lexemes?
  - **Solution:** after finding such a lexeme, the scanner simply starts again and tries to match another regular expression

Extend the DFA

- *modify* the DFA so that an edge can have
  - an associated action to
    - "put back one character" or
    - "return token XXX",
  - such DFA is called a *transducer*
- we must *combine* the DFAs for all of the tokens in to a *single* DFA

Step 4: Example of extending the DFA

- The DFA that recognizes simple identifiers must be modified as follows:

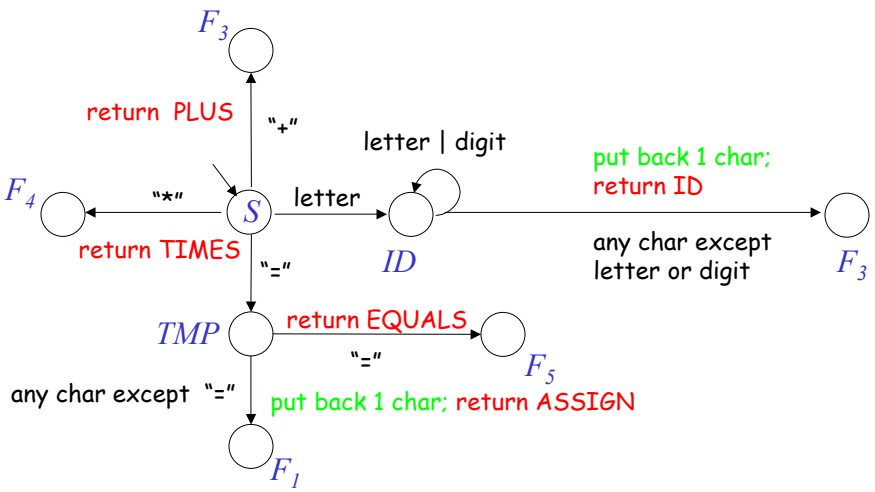


  - recall that scanner is called by parser (one token is return per each call)
  - hence action *return* puts the scanner into state S

Implementing the extended DFA

- The table-driven technique works, with a few small modifications:
  - Include a column for end-of-file
    - e.g., to find an identifier when it is the last input token
  - besides 'next state', a table entry includes
    - an (optional) action: put back *n* characters, return token
  - Instead of repeating
    - *"read a character; update the state variable"* until the machine gets stuck or the entire input is read,
    - *"read a character; update the state variable; perform the action"*
  - eventually, the action will be to return a value, so the scanner code will stop

Step 4: Example: Combined DFA for our language



Scanner Transition Table

Input/ State	+	*	=	Letter	Digit	EOF
S	NoA Final Plus	NoA Final Times	NoA TMP -	NoA ID -		
ID	PB1 Final Ident	PB1 Final Ident	PB1 Final Ident	NoA ID -	NoA ID -	PB1 Final Ident
TMP	PB1 Final Assn	PB1 Final Assn	NoA Final Equal	PB1 Final Assn	PB1 Final Assn	PB1 Final Assn

Actions: (Green)
NoA – no action
PB1 – put back 1 char

States (Blue)

Result Tokens (Red)

Possible Extensions

Augment "combined" finite-state machine to:

- Ignore white-spaces between tokens
  - white-spaces are spaces, tabs and newlines
- Give an error message if
  - a character other than +, *, =, letter, or digit occurs in the input, or
  - a digit is seen as the first character in the current input
  - (in both cases, ignore the bad character)
- Return an EOF token when there are no more tokens in the input

Updated Transition Table

Input/ State	+	*	=	Letter	Digit	EOF	WS	Other
S	NoA Final Plus	NoA Final Times	NoA TMP -	NoA ID -	Error S -	NoA Final EOF	NoA S -	Error S -
ID	PB1 Final Ident	PB1 Final Ident	PB1 Final Ident	NoA ID -	NoA ID -	PB1 Final Ident	PB1 Final Ident	PB1 Final Ident
TMP	PB1 Final Assn	PB1 Final Assn	NoA Final Equal	PB1 Final Assn	PB1 Final Assn	PB1 Final Assn	PB1 Final Assn	PB1 Final Assn

Implementation in Flex

assign_tokens.h:

```
#ifndef ASSIGN_TOKENS_H
#define ASSIGN_TOKENS_H

#define T_EOF           1
#define T_PLUS          11
#define T_TIMES         12
#define T_EQUALS        13
#define T_ASSIGN        21
#define T_IDENT         31

extern int char_num;
extern int line_num;
extern int s_char_num;
extern int s_line_num;

#endif
```

```
%{
#include "assign_tokens.h"
%}
DIGIT  [0-9]
LETTER [A-Za-z]
%%
\+      { char_num++; return T_PLUS; }
\*      { char_num++; return T_TIMES; }
=       { char_num++; return T_ASSIGN; }
==      { char_num += 2; return T_EQUALS; }
{LETTER}({LETTER}|{DIGIT})* {
 char_num += strlen(yytext); return T_IDENT; }
\n      { s_line_num++; s_char_num = 1;
          line_num++; char_num = 1; }
[ \t]   { s_char_num++; char_num++; }
.       { printf("Error!  Unexpected char (%s)
                  at line %d, char %d!\n",
                  yytext,line_num,char_num);
          s_char_num++; char_num++; }
<<EOF>> { return T_EOF; }
%%
```

Calling Flex from C++

```
#include <iostream.h>
#include <stdio.h>
#include "assign_tokens.h"

extern FILE *yyin;
extern char *yytext;
extern int yylex();

int char_num = 1;
int line_num = 1;
int s_char_num;
int s_line_num;
```

```
int main (int argc,
          char *argv[]) {
  if (argc != 2) {
    cout <<
     "Useage: assign_scan <file>" <<
     endl;
    return -1;
  }

  if ((yyin = fopen(argv[1],"r"))
       == NULL) {
    cout <<
     "Error!  Unable to open file "
     << argv[1] << endl;
    return -1;
  }
```

Calling Flex from C++ (cont)

```
int token_num;
do {
  s_char_num = char_num;
  s_line_num = line_num;
  token_num = yylex();

  cout << "Token: ";
  switch (token_num) {
    case T_EOF:
      cout << "EOF"; break;
    case T_PLUS:
      cout << "+"; break;
    case T_TIMES:
      cout << "*"; break;
    case T_EQUALS:
      cout << "=="; break;
    case T_ASSIGN:
      cout << "="; break;
    case T_IDENT:
      cout << "Ident(" <<
        yytext << ")"; break;
  }
  cout <<
    " found starting at line "
    << s_line_num << " char "
    << s_char_num << "\n";
} while (token_num != T_EOF);

return 0;
}
```

Implementing Table Machine

- Need input stream with the ability to put back characters (standard in many C++ streams)
- Need table entries for every state/character combination
- Table entries should indicate (1) an action, (2) a resulting state, and (3) a return token (if any)

Adding PutBack to a Stream

```
#define MY_EOF      256
bool putback_char_p = 0;
int putback_char;
int prev_char_num;
int prev_line_num;
int char_num = 1;
int line_num = 1;
int next_char(ifstream &inf){
  int ch;
  if (putback_char_p) {
    putback_char_p = 0;
    ch = putback_char; }
  else ch = inf.get();
  if (ch == EOF) ch = MY_EOF;
  prev_char_num = char_num;
  prev_line_num = line_num;
  if (ch == '\n') { line_num++;
    char_num = 1; }
  else char_num++;
  return ch;
}
bool put_back_char (int ch) {
  if (putback_char_p) {
    cerr << "Error!!" << endl;
    return 0; }
  else {
    char_num = prev_char_num;
    line_num = prev_line_num;
    putback_char_p = 1;
    putback_char = ch;
    return 1; }
}
```

Implementing a State Machine

```
#define No_State          0
#define Start_State       1
#define ID_State          2
#define TMP_State         3
#define Final_State       4

#define T_EOF             1
#define T_PLUS            11
#define T_TIMES           12
#define T_EQUALS          13
#define T_ASSIGN          21
#define T_IDENT           31

#define No_Action         0
#define PutBack_1         1
#define Report_Error      2
```

```
int txtloc = 0;
char yytext[BUFFERSIZE];

class TableEntry {
  public:
    int raction;
    int rstate;
    int rtoken;
};

TableEntry
    stab[FINAL_STATE+1][MY_EOF+1];
```

Implementing a State Machine

```
ifstream yyin;

int yylex () {
  int restok, ch;
  int currs = Start_State;
  txtloc = 0;
  yytext[txtloc] = '\0';
  s_line_num = line_num;
  s_char_num = char_num;
  do {
    ch = next_char(yyin);
    int a =
      stat[currs][ch].raction;
    switch (a) {
      case No_Action:
        yytext[txtloc]=(char)ch; }
```

```
        txtloc++;
        yytext[txtloc]='\0';
        break;
      case PutBack_1_Action:
        put_back_char(ch);
        break;
      case Report_Error_Action:
        cout <<
        "Error!  Unexpected char ("
        << (char) ch <<
        ") at line " <<
        prev_line_num << ", char "
        << prev_char_num << "!"
        << endl;
        break;
```

Implementing a State Machine

```
    restok = stab[currs][ch].rtoken;
    currs = stab[currs][ch].rstate;
    if (currs == Start_State) {
      yytext_loc = 0;
      yytext[yytext_loc] = '\0';
      s_line_num = line_num;
      s_char_num = char_num;
    }
  } while (curr_state != Final_State);

  return result_token;
}
```

Changes to main?

- Call to initialize scanner table

Hand Crafting a Scanner – Identify and Finish

```
int yylex () {
  int ch;
  // Define yytext
  do {
    // Update start line numbers
    ch = next_char(yyin);
    if (letter_p(ch)) {
      // add ch to yytext
      do {
        ch = next_char(yyin);
        if (/* ch let,dig */)
          /* add ch to yytext */ }
        else {
          put_back_char(ch);
          return T_IDENT; }
      } while (1);
    }
else if (ch == MY_EOF)
  return T_EOF;
else {
  switch ((char) ch) {
    case '+': return T_PLUS;
    case '*': return T_TIMES;
    case ' ': case '\t':
        case '\n': break;
    case '=':
      ch = next_char(yyin);
      if (ch == '=')
        return T_EQUALS;
      else {
        put_back_char(ch);
        return T_ASSIGN;
      }
```

Hand Crafting a Scanner – Identify and Finish

```
            default: cout <<
              "Error!  Unexpected char (" <<
              (char) ch << ") at line " <<
              prev_line_num << ", char " <<
              prev_char_num << "!" << endl;
          }
        }
      } while (1);
    }
```