01-0: **Syllabus**

- Office Hours
- Course Text
- Prerequisites
- Test Dates & Testing Policies
- Projects
  - Teams of up to 2
- Grading Policies
- Questions?

01-1: **Notes on the Class**

- I tend to talk quickly. Don't be afraid to ask me to slow down!
- We will cover some pretty complex stuff here, which can be difficult to get the first (or even the second) time. *ASK QUESTIONS*
- While specific questions are always preferred, "I don't get it" is always an acceptable question. I am always happy to stop, re-explain a topic in a different way.
  - If you are confused, I can *guarantee* that at least 1 other person in the class would benefit from more explanation

01-2: **Notes on the Class**

- Projects are non-trivial
  - Using new tools (lex, yacc)
  - Managing a large scale project
  - Lots of pointer chasing, with large, complex data structures

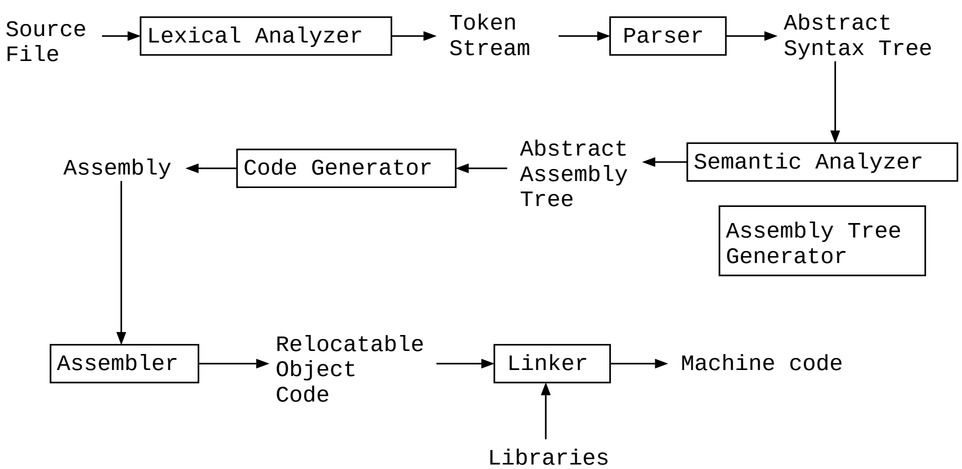
01-3: **Notes on the Class**

- Projects are non-trivial
  - Using new tools (lex, yacc)
  - Managing a large scale project
  - Lots of pointer chasing, with large, complex data structures
- *START EARLY!*
  - Projects will take longer than you think (especially starting with the semantic analyzer project)
- *ASK QUESTIONS!*

01-4: **What is a compiler?**

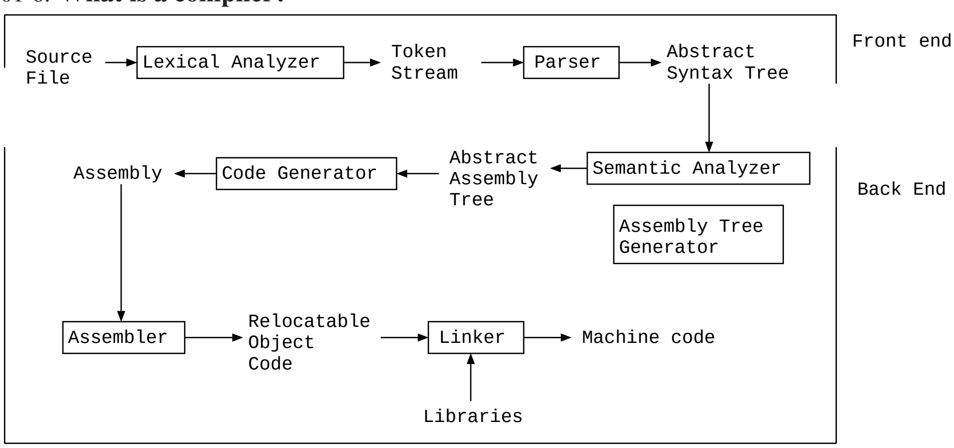
Simplified View

01-5: **What is a compiler?**

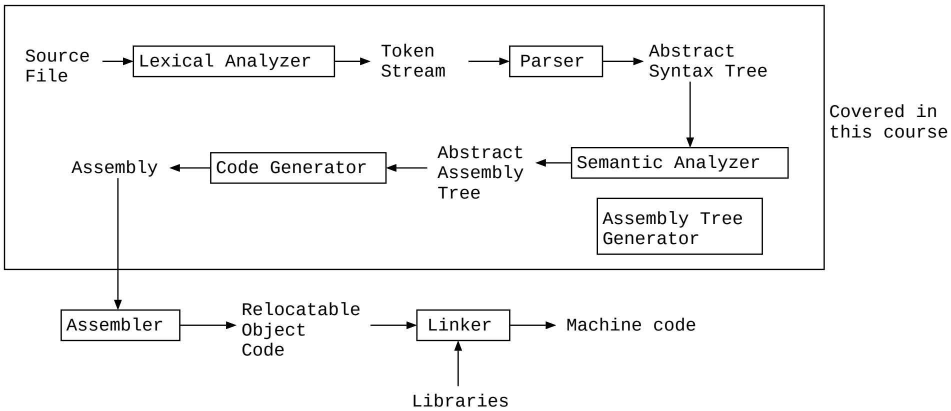


More Accurate View

01-6: **What is a compiler?**



01-7: **What is a compiler?**



01-8: **Why Use Decomposition?**

01-9: **Why Use Decomposition?**

Software Engineering!

- Smaller units are easier to write, test and debug
- Code Reuse
    - Writing a suite of compilers (C, Fortran, C++, etc) for a new architecture
    - Create a new language – want compilers available for several platforms

01-10: **Lexical Analysis**

- Converting input file to stream of tokens

```
void main() {
  print(4);
}
```

01-11: **Lexical Analysis**

- Converting input file to stream of tokens

```
void main() {     IDENTIFIER(void)
  print(4);       IDENTIFIER(main)
}                 LEFT-PARENTHESIS
                  RIGHT-PARENTHESIS
                  LEFT-BRACE
                  IDENTIFIER(print)
                  LEFT-PARENTHESIS
                  INTEGER-LITERAL(4)
                  RIGHT-PARENTHESIS
                  SEMICOLON
                  RIGHT-BRACE
```

01-12: **Lexical Analysis**

Brute-Force Approach

- Lots of nested if statements

```
if (c = nextchar() == 'P') {
   if (c = nextchar() == 'R') {
      if (c = nextchar() == '0') {
         if (c = nextchar() == 'G') {
           /*  Code to handle the rest of either
               PROGRAM or any identifier that starts
               with PROG
           */
         } else if (c == 'C') {
           /*  Code to handle the rest of either
               PROCEDURE or any identifier that starts
               with PROC
           */
       ...
```

01-13: **Lexical Analysis**

Brute-Force Approach

- Break the input file into words, separated by spaces or tabs
  - This can be tricky – not all tokens are separated by whitespace
  - Use string comparison to determine tokens

01-14: **Deterministic Finite Automata**

- Set of states
- Initial State
- Final State(s)
- Transitions

DFA for else, end, identifiers

Combine DFA 01-15: **DFAs and Lexical Analyzers**

- Given a DFA, it is easy to create C code to implement it
- DFAs are easier to understand than C code
  - Visual – almost like structure charts
- ... However, creating a DFA for a complete lexical analyzer is still complex

01-16: **Automatic Creation of DFAs**

We'd like a tool:

- Describe the tokens in the language
- Automatically create DFA for tokens
- Then, automatically create C code that implements the DFA

We need a method for describing tokens

01-17: **Formal Languages**

- **Alphabet** Σ: Set of all possible symbols (characters) in the input file
  - Think of Σ as the set of symbols on the keyboard
- **String** w: Sequence of symbols from an alphabet

- **String length** $|w|$ Number of characters in a string: |car| = 3, |abba| = 4
  - **Empty String** ϵ: String of length 0: $|\epsilon| = 0$
- **Formal Language**: Set of strings over an alphabet

Formal Language $\neq$ Programming language – Formal Language is only a set of strings.

01-18: **Formal Languages**

Example formal languages:

- Integers $\{0, 23, 44, \ldots\}$
- Floating Point Numbers $\{3.4, 5.97, \ldots\}$
- Identifiers {foo, bar, ...}

01-19: **Language Concatenation**

- **Language Concatenation** Given two formal languages L_1 and L_2, the concatenation of L_1 and L_2, $L_1 L_2 = \{xy | x \in L_1, y \in L_2\}$

For example:
{fire, truck, car} {car, dog} =
{firecar, firedog, truckcar, truckdog, carcar, cardog}

01-20: **Kleene Closure** Given a formal language L:

$$\begin{array}{lcl} L^0 & = & \{\epsilon\} \\ L^1 & = & L \\ L^2 & = & LL \\ L^3 & = & LLL \\ L^4 & = & LLLL \end{array}$$

$$L^* = L^0 \bigcup L^1 \bigcup L^2 \bigcup \ldots \bigcup L^n \bigcup \ldots$$

01-21: **Regular Expressions**

Regular expressions are use to describe formal languages over an alphabet Σ:

Regular Expression	Language
ϵ	$L[\epsilon] = \{\epsilon\}$
$\mathtt{a} \in \Sigma$	$L[\mathtt{a}] = \{\mathtt{a}\}$
(MR)	$L[MR] = L[M]L[R]$
$(M\|R)$	$L[(M\|R)] = L[M] \bigcup L[R]$
$(M*)$	$L[(M*)] = L[M]*$

01-22: **r.e. Precedence**

From highest to Lowest:

Kleene Closure *
Concatenation
Alternation |

ab*c|e = (a(b*)c) | e

01-23: **Regular Expression Examples**

(a|b)*	all strings over {a,b}
(0|1)*	binary integers (with leading zeroes)
a(a|b)*a	all strings over {a,b} that begin and end with a
(a|b)*aa(a|b)*	all strings over {a,b} that contain aa
b*(abb*)*(a|ϵ)	all strings over {a,b} that do not contain aa

01-24: **r.e. Shorthand**

[abcd]	=	(a|b|c|d)
[b-g]	=	[befg] = (b|e|f|g)
[b-gM-O]	=	[befgMNO] = (b|e|f|g|M|N|O)
M?	=	(M | ϵ)
M+	=	MM*
.	=	Any character except newline
”vc”	=	The string vc exactly
4”.”5	=	String 4.5 (not 4¡any¿5)

01-25: **r.e. Shorthand Examples**

Regular Expression	Langauge
if	{if}
[a-z][0-9a-z]*	Set of legal identifiers
[0-9]	Set of integers (with leading zeroes)
([0-9]+”.”[0-9]*)| ([0-9]*”.”[0-9]+)	Set of real numbers

01-26: **Lexical Analyzer Generator**

Lex is a lexical analyzer generator

- Input: Set of regular expressions (each of which describes a type of token in the language)
- Output: A lexical analyzer, which reads an input file and separates it into tokens

01-27: **Structure of lex file**

```
%{

/* C declarations */

%}

/* Lex definitions */

%%

/* Regular expressions and actions */
```

01-28: **How Lex Works**

- Lex creates a function int yylex(), which does the following:

```
while(true) {
     <find a rule that matches the next
        section of the input>
```

```
        <execute action associated with
           that rule>
    }
```

- Thus, a call to yylex() will keep matching rules and performing actions, until an action contains a return statement

01-29: **Lex Example**

```
%{
#include "tokens.h"
%}

%%

for       { return FOR; }
if        { return IF; }
```

01-30: **Lex Example**

```
%{
#include "tokens.h"
%}

%%

for       { return FOR; }
if        { return IF; }
","       { return COMMA; }
```

01-31: **Lex Example**

```
%{
#include "tokens.h"
%}

%%

for       { return FOR; }
if        { return IF; }
","       { return COMMA; }
" "       {  }
\n        {  }
```

01-32: **Lex Example**

```
%{
#include "tokens.h"
%}

%%

for       { return FOR; }
if        { return IF; }
```

```
","       { return COMMA; }
" "       {  }
\n        {  }
[0-9]+    { return INTEGER_LITERAL; }
```

01-33: **Lex Example**

```
%{
#include <string.h>
#include "tokens.h"
%}
%%

for       { return FOR; }
if        { return IF; }
","       { return COMMA; }
" "       {  }
\n        {  }
[0-9]+    { yylval.integer_value.value =
              atoi(yytex);
            return INTEGER_LITERAL;    }
```

01-34: **Lex Loop** Lex creates a function yylex, which does the following:

- Find regular expression that matches the input
- Execute the action associated with that regular expression
- Repeat, until a return statement is reached – return the appropriate value

01-35: **Lex Matching** What if more than one regular expression matches?

- Find the longest possible match
  - if382 returns an IDENTIFIER, not an IF followed by an INTEGER_LITERAL
- If two matches are the same length, match the string that appears earliest in the file.
  - if returns an IF, not an IDENTIFIER (as long as the rule for IDENTIFIER appears after the rule for IF)

01-36: **Lex States**

- We can label each regular expression/action pair with a "state"
- Unlabeled regular expression/action pairs are assumed to be in the default INITIAL state
- Lex will only match regular expressions for the current state
- Can switch between states with a BEGIN action

01-37: **Using Lex States**

```
%{
#include "tokens.h"
%}

%x COMMENT

%%
else                    { return ELSE; }
for                     { return FOR; }
" "                     { }
\n                      { }
"/*"                    { BEGIN(COMMENT); }
<COMMENT>"*/"           { BEGIN(INITIAL); }
<COMMENT>\n             { }
<COMMENT>.              { }
%%
```

01-38: **Token Positions**

```
%{
#include "tokens.h"
#include <string.h>
int current_line_number = 1;
void newline() {
  current_line_number++;
}
%}
%%
else                  { yylval.line_number = current_line_number;
                        return ELSE; }
" "                   {     }
\n                    { newline(); }
";"                   { yylval.line_number = current_line_number;
                        return SEMICOLON; }
[a-zA-Z][a-zA-Z0-9]*  { yylval.string_value.line_number = current_line_number;
                        yylval.string_value.value = malloc(sizeof(char) *
                                                 (strlen(yytext)+1));
                        strcpy(yylval.string_value.value,yytext);
                        return IDENTIFIER; }
```

01-39: **Random Details**

- tokens.h
- Skeleton .lex file
  - Note Current_Line is defined in errors.h
- errors.h file
- main (driver) program
- makefile