Compilers

CS414-2015S-01

Compiler Basics & Lexical Analysis

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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

- 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 one other person in the class would benefit from more explanation

01-2: Notes on the Class

- Projects are non-trivial
  - Using new tools (JavaCC)
  - Managing a large scale project
  - Lots of complex classes & advanced programming techniques.

01-3: Notes on the Class

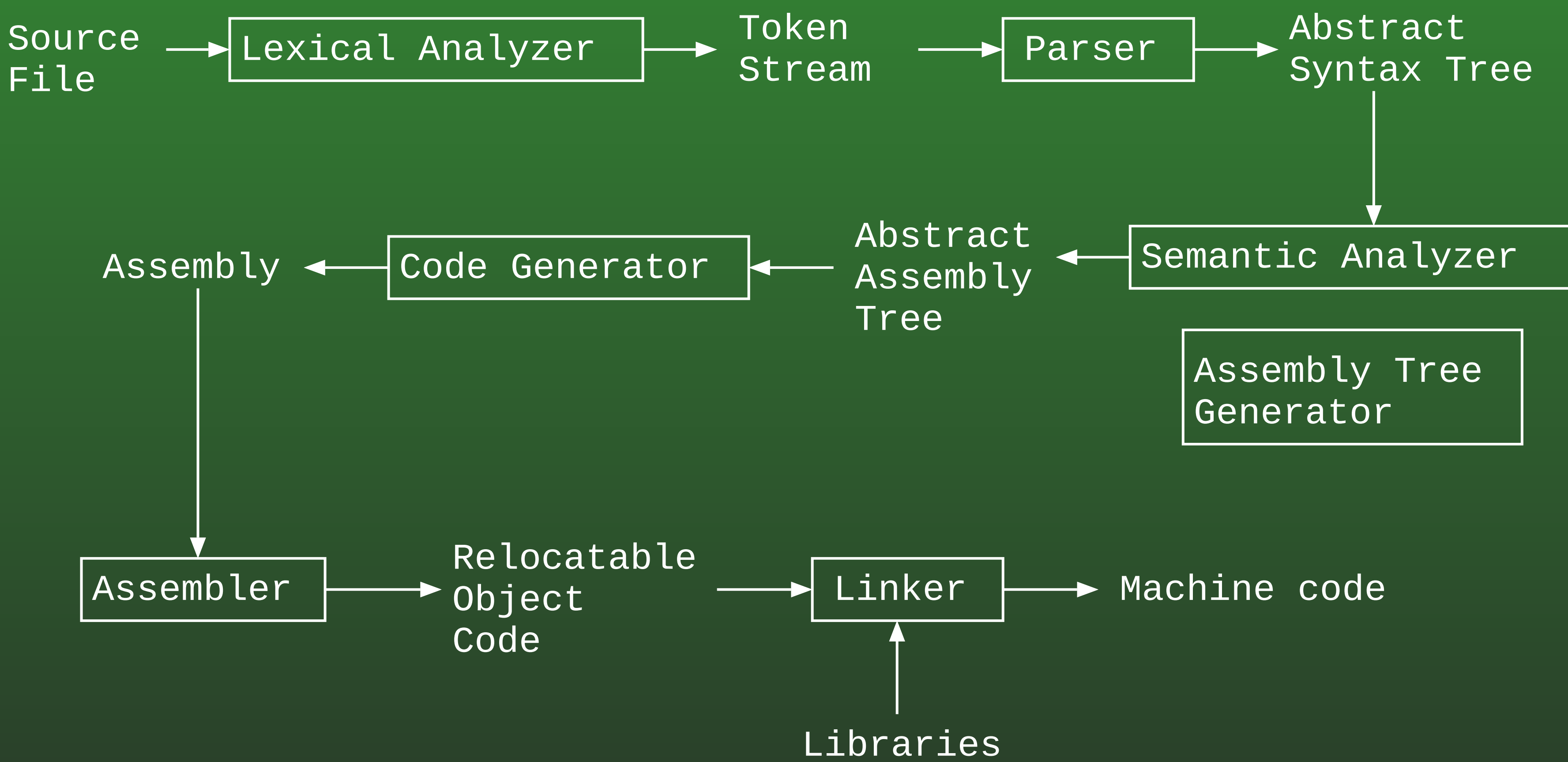
- Projects are non-trivial
  - Using new tools (JavaCC)
  - Managing a large scale project
  - Lots of complex classes & advanced programming techniques.
- *START EARLY!*
  - Projects will take longer than you think (especially starting with the semantic analyzer project)
- *ASK QUESTIONS!*

01-4: What is a compiler?

Source Program $\longrightarrow$ $\boxed{\texttt{Compiler}}$ $\longrightarrow$ Machine code

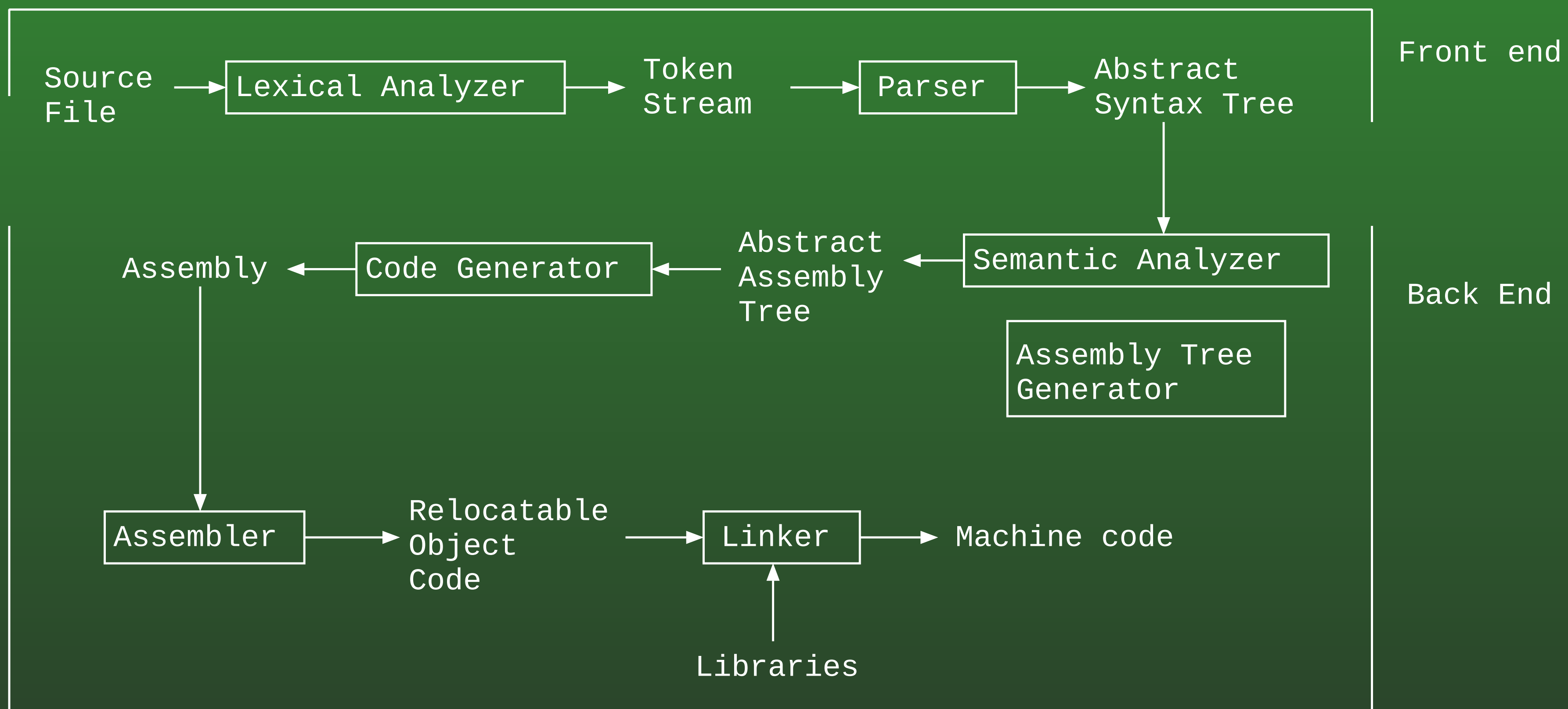
Simplified View

01-5: What is a compiler?

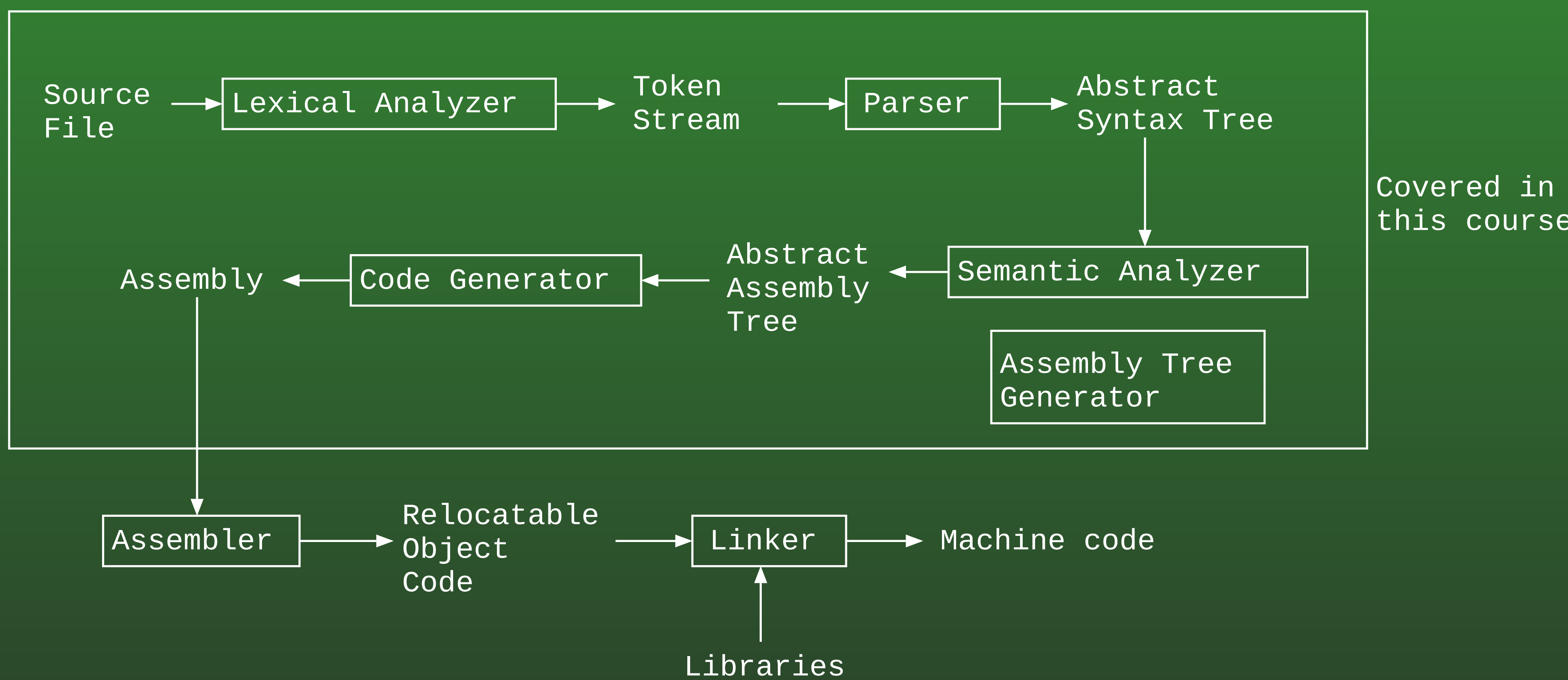


More Accurate View

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

```
IDENTIFIER(void)
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() == 'O') {
         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

- $\mathbf{Alphabet}$ Σ: Set of all possible symbols (characters) in the input file
  - Think of Σ as the set of symbols on the keyboard
- $\mathbf{String}$ w: Sequence of symbols from an alphabet
- $\mathbf{String\ length}$ $|w|$ Number of characters in a string: |car| = 3, |abba| = 4
  - $\mathbf{Empty\ String}$ ϵ: String of length 0: $|\epsilon| = 0$
- $\mathbf{Formal\ Language}$: 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, $L_1L_2 = \{xy | x \in L_1, y \in L_2\}$

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

01-20: Kleene Closure

Given a formal language L:

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

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

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

all strings over {a,b}

binary integers (with leading zeroes)

all strings over {a,b} that

begin and end with a

all strings over {a,b} that

contain aa

all strings over {a,b} that

do not contain aa

01-24: Regular Expression Examples

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

Reg. Exp. Shorthand

[a,b,c,d]	=	(a|b|c|d)
[d-g]	=	[d,e,f,g] = (b|e|f|g)
[d-f,M-O]	=	[d,e,f,M,N,O]
	=	(d|e|f|M|N|O)
(α)?	=	Optionally α (i.e., $(\alpha \mid \epsilon)$)
(α)+	=	$\alpha(\alpha)$*

01-26: Regular Expressions & Unix

- Many unix tools use regular expressions
- Example: grep '<reg exp>' filename
  - Prints all lines that contain a match to the regular expression
  - Special characters:
    - ^ beginning of line
    - $ end of line
  - (grep examples on other screen)

01-27: JavaCC Regular Expressions

- All characters & strings must be in quotation marks
  - `"else"`
  - `"+"`
  - `("a"|"b")`
- All regular expressions involving * must be parenthesized
  - `("a")*`, not `"a"*`

01-28: JavaCC Shorthand

["a","b","c","d"]	=	("a"|"b"|"c"|"d")
["d"-"g"]	=	["d","e","f","g"] = ("b"|"e"|"f"|"g")
["d"-"f","M"-"O"]	=	["d","e","f","M","N","O"]
	=	("d"|"e"|"f"|"M"|"N"|"O")
(α)?	=	Optionally α (i.e., $(\alpha \mid \epsilon)$)
(α)+	=	α(α)*
(~["a","b"])	=	Any character *except* “a” or “b”.
		Can only be used with [] notation
		~(a(a|b)*b) is not legal

01-29: r.e. Shorthand Examples

Regular Expression	Langauge
	{if}
	Set of legal identifiers
	Set of integer literals
	(leading zeroes allowed)
	Set of real literals

01-30: r.e. Shorthand Examples

Regular Expression	Langauge
"if"	{if}
["a"-"z"](["0"-"9","a"-"z"])*	Set of legal identifiers
["0"-"9"]	Set of integer literals (leading zeroes allowed)
(["0"-"9"]+"."(["0"-"9"]*))| ((["0"-"9"])*"."["0"-"9"]+)	Set of real literals

01-31: Lexical Analyzer Generator

JavaCC is a Lexical Analyzer Generator and a Parser 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

01-32: Structure of a JavaCC file

```
options{
    /* Code to set various options flags  */
}

PARSER_BEGIN(foo)

public class foo {
    /* This segment is often empty     */
}

PARSER_END(foo)

TOKEN_MGR_DECLS :
{
   /*  Declarations used by lexical analyzer   */
}

/* Token Rules & Actions */
```

01-33: Token Rules in JavaCC

- Tokens are described by rules with the following syntax:

```
TOKEN :
{
      <TOKEN_NAME: RegularExpression>
}
```

  - TOKEN_NAME is the name of the token being described
  - RegularExpression is a regular expression that describes the token

01-34: Token Rules in JavaCC

- Token rule examples:

```
TOKEN :
{
       <ELSE: "else">
}

TOKEN :
{
      <INTEGER_LITERAL: (["0"-"9"])+>
}
```

01-35: Token Rules in JavaCC

- Several different tokens can be described in the same TOKEN block, with token descriptions separated by |.

```
TOKEN :
{
        <ELSE: "else">
|       <INTEGER_LITERAL: (["0"-"9"])+>
|       <SEMICOLON: ";">
}
```

01-36: getNextToken

- When we run javacc on the input file `foo.jj`, it creates the class `fooTokenManager`
- The class `fooTokenManager` contains the static method `getNextToken()`
- Every call to `getNextToken()` returns the next token in the input stream.

getNextToken

- When `getNextToken` is called, a regular expression is found that matches the next characters in the input stream.
- What if more than one regular expression matches?

```
TOKEN :
{
        <ELSE: "else">
|       <IDENTIFIER: (["a"-"z"])+>
}
```

01-38: getNextToken

- When more than one regular expression matches the input stream:
  - Use the longest match
    - “elsed” should match to IDENTIFIER, not to ELSE followed by the identifier “d”
  - If two matches have the same length, use the rule that appears first in the `.jj` file
    - “else” should match to ELSE, not IDENTIFIER

01-39: JavaCC Example

```
PARSER_BEGIN(simple)
public class simple {

}
PARSER_END(simple)

TOKEN :
{
        <ELSE: "else">
|       <SEMICOLON: ";">
|       <FOR: "for">
|       <INTEGER_LITERAL: (["0"-"9"])+>
|       <IDENTIFIER: ["a"-"z"](["a"-"z","0"-"9"])*>
}
```

else;ford for

01-40: SKIP Rules

- Tell JavaCC what to ignore (typically whitespace) using SKIP rules
- SKIP rule is just like a TOKEN rule, except that no TOKEN is returned.

```
SKIP:
{
      < regularexpression1 >
|     < regularexpression2 >
|       ...
|     < regularexpressionn >
}
```

01-41: Example SKIP Rules

```
PARSER_BEGIN(simple2)
public class simple2 {
}
PARSER_END(simple2)

SKIP :
{
        < " " >
|       < "\n" >
|       < "\t" >
}

TOKEN :
{
        <ELSE: "else">
|       <SEMICOLON: ";">
|       <FOR: "for">
|       <INTEGER_LITERAL: (["0"-"9"])+>
|       <IDENTIFIER: ["A"-"Z"](["A"-"Z","0"-"9"])*>
}
```

01-42: JavaCC States

- Comments can be dealt with using SKIP rules
- How could we skip over 1-line C++ Style comments?

```
// This is a comment
```

01-43: JavaCC States

- Comments can be dealt with using SKIP rules
- How we could skip over 1-line C++ Style comments:

```
// This is a comment
```

- Using a SKIP rule

```
SKIP :
{
          < "//" (~["\n"])* "\n" >
}
```

01-44: JavaCC States

- Writing a regular expression to match multi-line comments (using /* and */) is much more difficult
- Writing a regular expression to match nested comments is impossible (take Automata Theory for a proof :))
- What can we do?
  - Use JavaCC States

01-45: JavaCC States

- We can label each TOKEN and SKIP rule with a “state”
- Unlabeled TOKEN and SKIP rules are assumed to be in the default state (named DEFAULT, unsurprisingly enough)
- Can switch to a new state after matching a TOKEN or SKIP rule using the : NEWSTATE notation

01-46: JavaCC States

```
SKIP :
{
        < " " >
|       < "\n" >
|       < "\t" >
}
SKIP :
{
        < "/*" >    : IN_COMMENT
}
<IN_COMMENT>
SKIP :
{
        < "*/" > : DEFAULT
|       < ~[] >
}
TOKEN :
{
        <ELSE: "else">
|       ... (etc)
}
```

01-47: Actions in TOKEN & SKIP

- We can add Java code to any SKIP or TOKEN rule
- That code will be executed when the SKIP or TOKEN rule is matched.
- Any methods / variables defined in the TOKEN_MGR_DECLS section can be used by these actions

01-48: Actions in TOKEN & SKIP

```
PARSER_BEGIN(remComments)
public class remComments { }
PARSER_END(remComments)

TOKEN_MGR_DECLS :
{
   public  static int numcomments = 0;
}

SKIP :
{
   < "/*" >    : IN_COMMENT
}

SKIP :
{
  < "//" (~["\n"])* "\n" >  { numcomments++; }
}
```

01-49: Actions in TOKEN & SKIP

```
<IN_COMMENT>
SKIP :
{
   < "*/" > { numcomments++; SwitchTo(DEFAULT);}
}

<IN_COMMENT>
SKIP :
{
  < ~[] >
}

TOKEN :
{
  <ANY: ~[]>
}
```

01-50: Tokens

- Each call to getNextToken returns a “Token” object
- Token class is automatically created by javaCC.
- Variables of type Token contain the following public variables:
  - `public int kind;` The type of token. When javacc is run on the file foo.jj, a file fooConstants.java is created, which contains the symbolic names for each constant

```
public interface simplejavaConstants {
  int EOF = 0;
  int CLASSS = 8;
  int DO = 9;
  int ELSE = 10;
  ...
```

01-51: Tokens

- Each call to getNextToken returns a “Token” object
- Token class is automatically created by javaCC.
- Variables of type Token contain the following public variables:
  - `public int beginLine, beginColumn, endLine, endColumn;` The location of the token in the input file

01-52: Tokens

- Each call to getNextToken returns a “Token” object
- Token class is automatically created by javaCC.
- Variables of type Token contain the following public variables:
  - `public String image;` The text that was matched to create the token.

01-53: Generated TokenManager

```
class TokenTest {
    public static void main(String args[]) {
        Token t;
        Java.io.InputStream infile;
        pascalTokenManager tm;
        boolean loop = true;

        if (args.length < 1) {
          System.out.print("Enter filename as command line argument");
          return;
        }
        try {
           infile = new Java.io.FileInputStream(args[0]);
        } catch (Java.io.FileNotFoundException e) {
            System.out.println("File " + args[0] + " not found.");
            return;
        }
        tm = new sjavaTokenManager(new SimpleCharStream(infile));
```

01-54: Generated TokenManager

```
        t = tm.getNextToken();
        while(t.kind != sjavaConstants.EOF) {
            System.out.println("Token : "+ t + " : ");
            System.out.println(pascalConstants.tokenImage[t.kind]);
        }
    }
}
```

01-55: Lexer Project

- Write a .jj file for simpleJava tokens
- Need to handle all whitespace (tabs, spaces, end-of-line)
- Need to handle nested comments (to an arbitrary nesting level)

01-56: Project Details

- JavaCC is available at https://javacc.dev.java.net/
- To compile your project

```
% javacc simplejava.jj
% javac *.java
```

- To test your project

```
% java TokenTest <test filename>
```

- To submit your program: Create a branch:

https://www.cs.usfca.edu/svn/<username>/cs414/lexer/