EDAN65: Compilers, Lecture 02

Regular expressions and scanning

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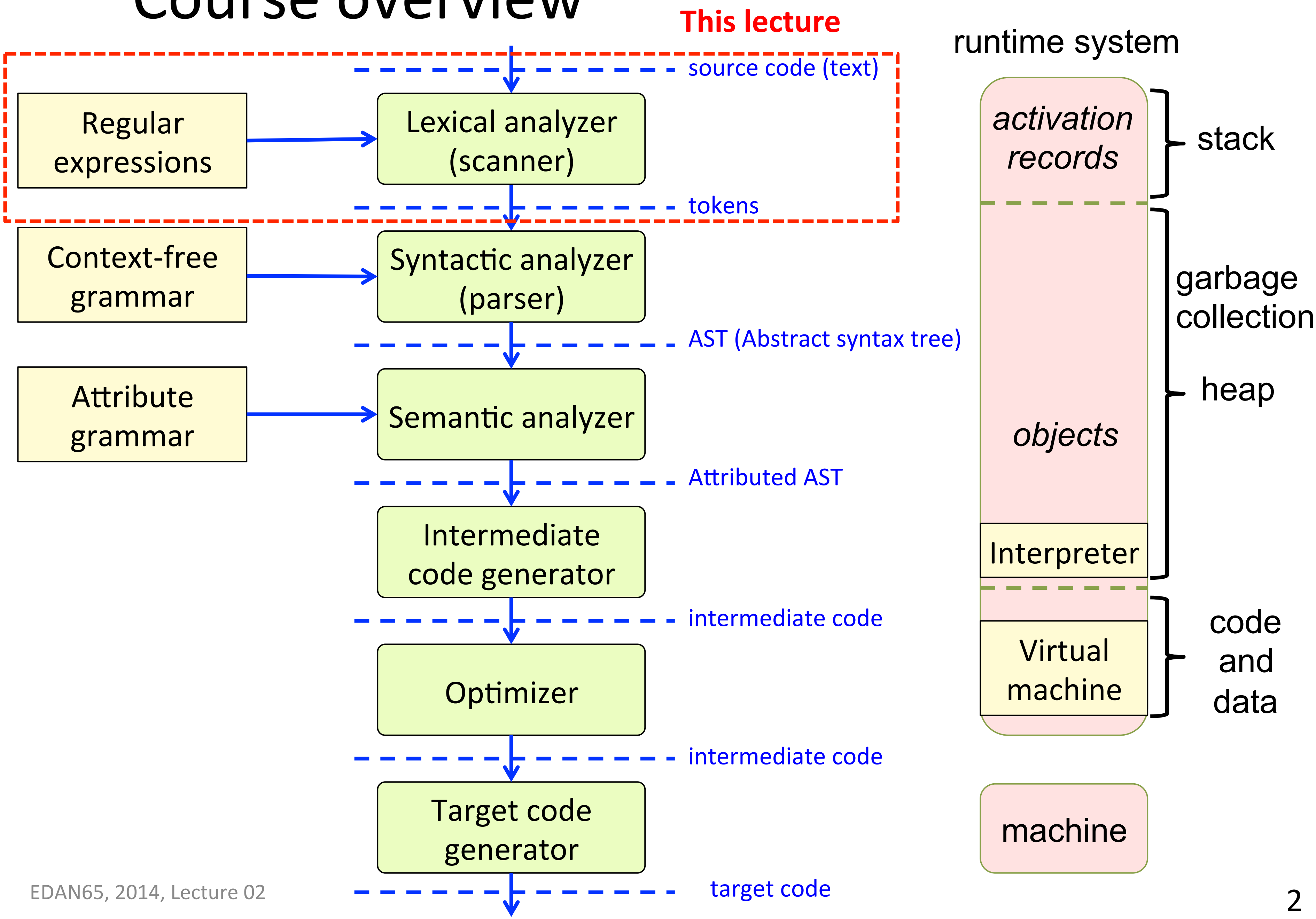
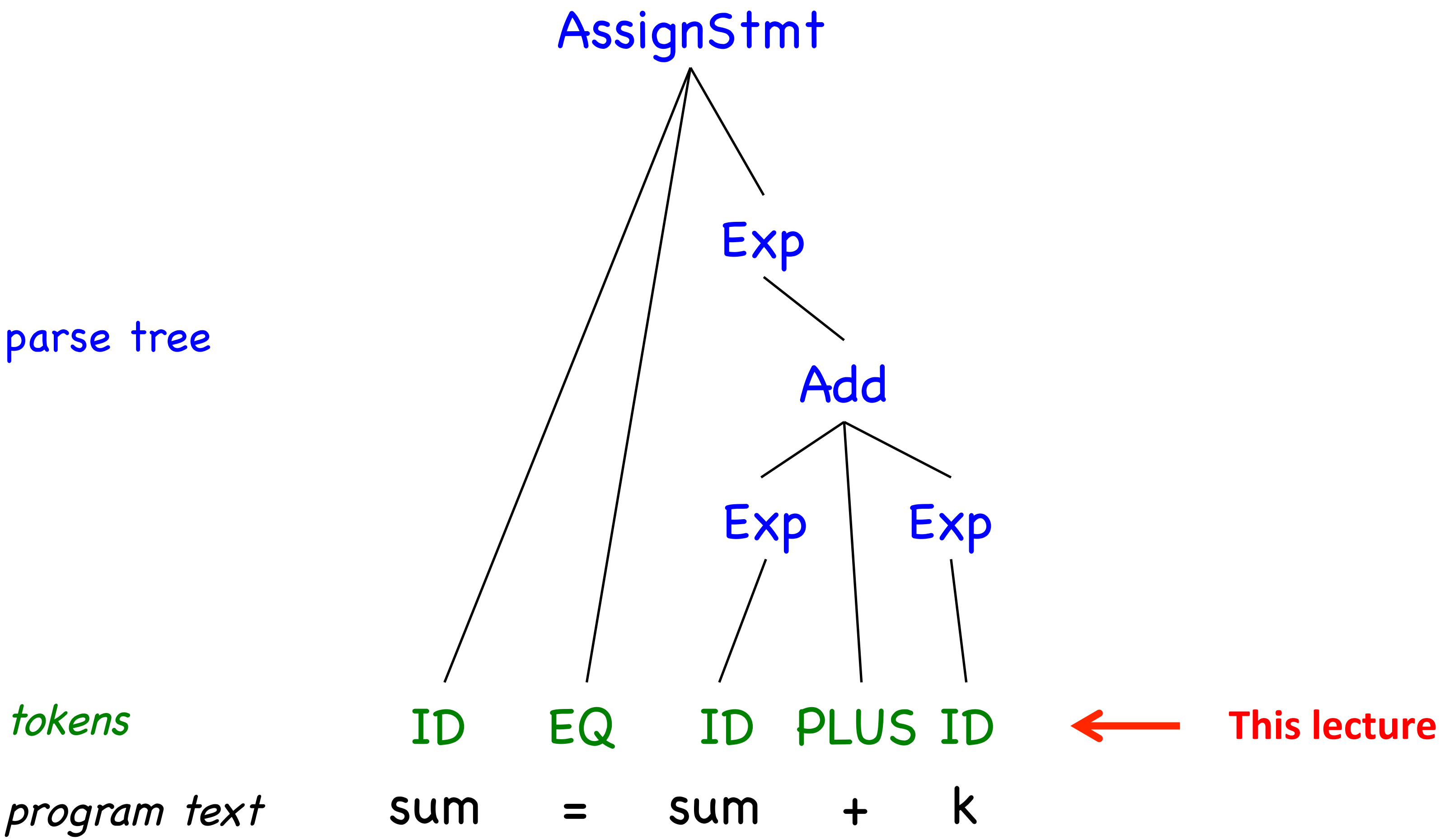
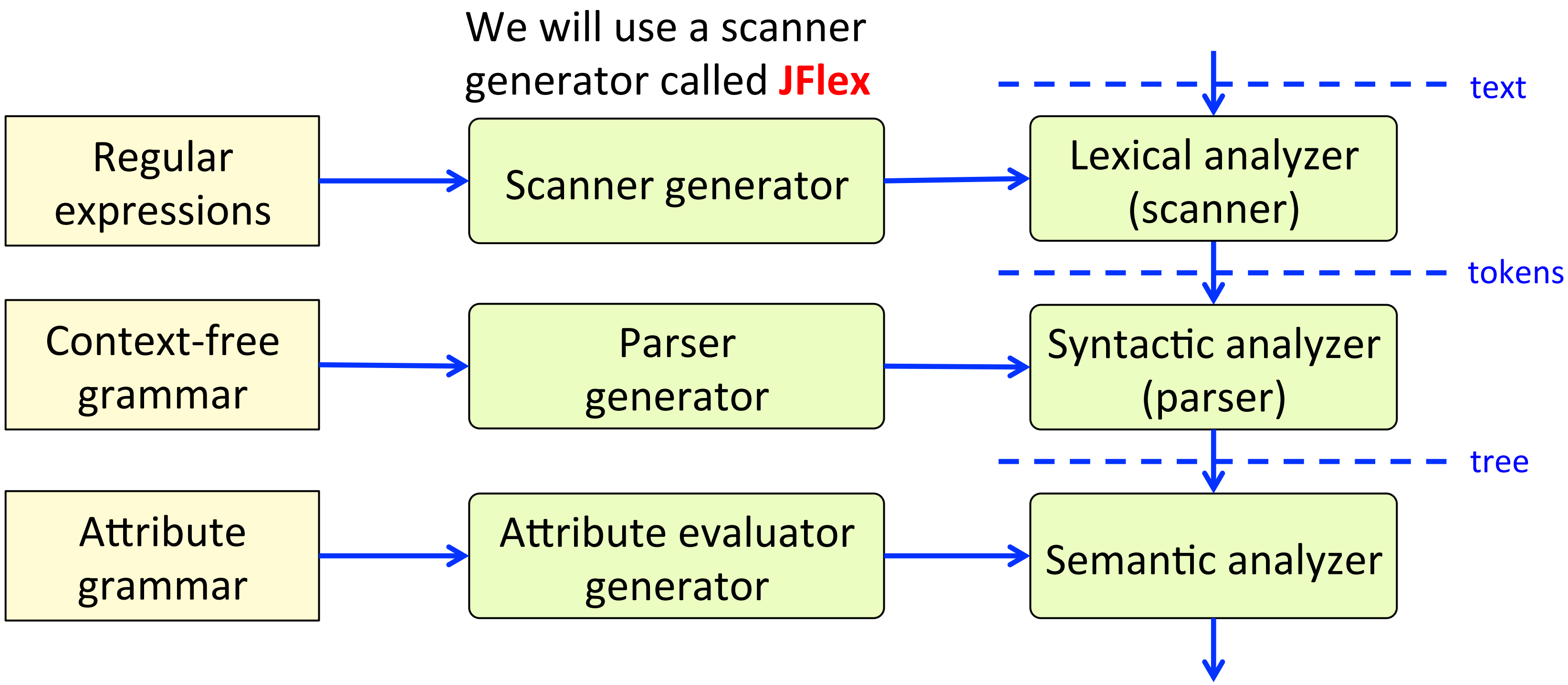
Course overview



Analyzing program text



Recall: Generating the compiler:



Some typical tokens

	Token	Example lexemes	Regular expression
Reserved words (keywords)	IF	if	"if"
	THEN	then	"then"
	FOR	for	"for"
Identifiers	ID	B alpha k10	[A-Za-z][A-Za-z0-9]*
Literals	INT	1230 99 2014	[0-9]+
	FLOAT	3.1416 0.2	[0-9]+ "." [0-9]+
	CHAR	'A' 'c'	\' [^\'] \'
	STRING	"Hello" "" "j"	\" [^\"]* \"
Operators	PLUS	+	"+"
	INCR	++	"++"
	NE	!=	"!="
Separators	SEMI	;	";"
	COMMA	,	","
	LPAREN	(	"("

JFlex syntax

Formal languages

- An *alphabet*, Σ, is a set of symbols (nonempty and finite).
- A *string* is a sequence of symbols (each string is finite)
- A *formal language*, *L*, is a set of strings (can be infinite).

- We would like to have *rules* or *algorithms* for defining a language – deciding if a certain string over the alphabet belongs to the language or not.

Example: Languages over binary numbers

Suppose we have the alphabet $\Sigma = \{0, 1\}$

Example languages:

- The set of all possible combinations of zeros and ones:
  $L_0 = \{0, 1, 00, 01, 10, 11, 000, ...\}$
- All binary numbers without unnecessary leading zeros:
  $L_1 = \{0, 1, 10, 11, 100, 101, 110, 111, 1000, ...\}$
- All binary numbers with two digits:
  $L_2 = \{00, 01, 10, 11\}$
- ...

Example: Languages over UNICODE

Here, the alphabet Σ is the set of UNICODE characters

Example languages:

- All possible Java keywords: {”class”, ”import”, public”, ...}
- All possible lexemes corresponding to Java tokens.
- All possible lexemes corresponding to Java whitespace.
- All binary numbers
- ...

Example: Languages over Java tokens

Here, the alphabet Σ is the set of Java tokens

Example languages:

- All syntactically correct Java programs
- All that are syntactically incorrect
- All that are compile-time correct
- All that terminate
- ...

(This language cannot be computed: Termination is *undecidable*: it is not possible to construct an algorithm that decides for any string, if it is a terminating program or not.)

Defining languages using rules

Increasingly powerful:

- Regular expressions (for tokens)
- Context-free grammars (for syntax trees)
- Attribute grammars (for arbitrary decidable languages)

Regular expressions (core notation)

RE	read	is called
a	a	symbol
$M \mid N$	M or N	alternative
$M\ N$	M followed by N	concatenation
ϵ	the empty string	epsilon
M^*	zero or more M	repetition (Kleene star)
(M)		

where a is a symbol in the alphabet (e.g., {0,1} or UNICODE)
and M and N are regular expressions

Each regular expression defines a language over the alphabet
(a set of strings that belong to the langauge).

Priorities: $M \mid N\ P^*$ means $M \mid (N\ (P^*))$

Example

$a \mid b\ c^*$

means

$\{a, b, bc, bcc, bccc, ...\}$

Regular expressions (extended notation)

Core RE	read	is called
a	*a*	symbol
M | *N*	*M* or *N*	alternative
M N	*M* followed by *N*	concatenation
ϵ	the empty string	epsilon
*M**	zero or more *M*	repetition (Kleene star)
(*M*)		

Extended RE	read	means
M+	at least one ...	*M M**
M?	*optional ...*	ϵ | *M*
[aou] [a-zA-Z]	*one of ... (a character class)*	a | o | u a | b | ... | z | A | B | ... | Z
[^0-9] (Appel notation: ~[0-9])	not ...	one character, but not anyone of those listed
"a+b"	the string ...	a \+ b

Exercise

Write a regular expression that defines the language of all decimal numbers, like

3.14   0.75   4711   0   ...

But not numbers lacking an integer part. And not numbers with a decimal point but lacking a fractional part. So not numbers like

17.   .236   .

Leading and trailing zeros are allowed. So the following are ok:

007   008.00   0.0   1.700

a) Use the extended notation.
b) Then translate the expression to the core notation
c) Then write an expression that disallows leading zeros

Solution

a)

```
[0-9]+ ("."[0-9]+)?
```

b)

```
(0 |...| 9)(0 |...| 9)* (∈ | ("."((0 |...| 9)(0 |...| 9)*)))
```

c)

```
(0 | [1-9] [0-9]*) ("."[0-9]+)?
```

Escaped characters

Use backslash to escape metacharacters and non-printing control characters.

Metacharacters
\+
*
\(
\)
|
\\
…

Non-printing control characters	
\n	newline
\r	return
\t	tab
\f	formfeed
…	

Some typical tokens

Kind	Name	Example lexemes	Regular expression
Reserved words (keywords)	IF THEN FOR	if then for	"if" "then" "for"
Identifiers	ID	B alpha k10	[A-Za-z]([A-Za-z0-9])*
Literals	INT	123 0 99	[0-9]+
	FLOAT	3.1416 0.2	[0-9]+ "." [0-9]+
	CHAR	'A' 'c'	\' [^\'] \'
	STRING	"Hello" "" "j"	\" [^\"]* \"
Operators	PLUS INCR NE	+ ++ !=	"+" "++" "!="
Separators	SEMI COMMA LPAREN	; , (	";" "," "("

Some typical non-tokens

<table>
<tr><th>Non-Token</th><th>Example lexemes</th><th>Regular expression (jflex)</th></tr>
<tr><td>WHITESPACE</td><td>blank tab newline return</td><td><code>" " | "\t" | "\n" | "\r"</code></td></tr>
<tr><td>ENDOFLINECOMMENT</td><td>// comment</td><td><code>"//" [^\n\r]* ([\n\r])?</code></td></tr>
</table>

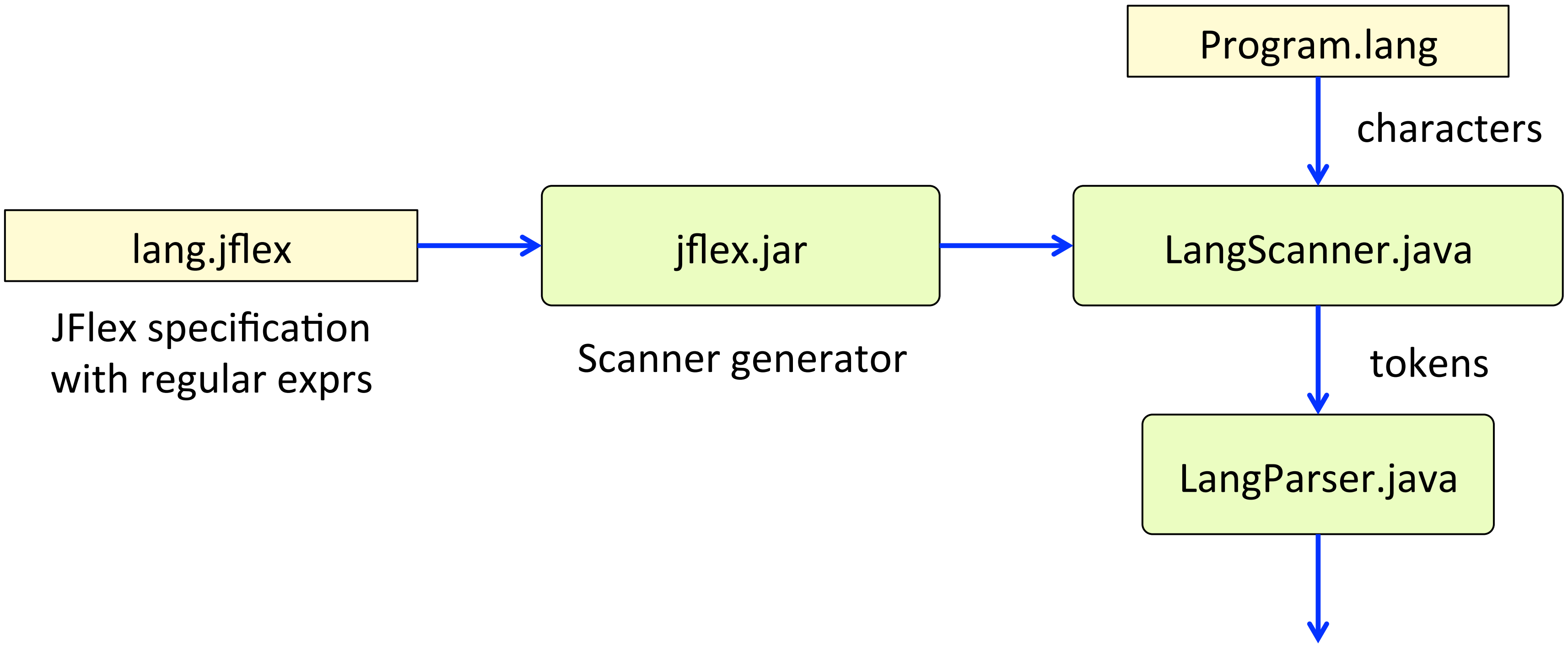
JFlex syntax

Non-tokens are also recognized by the scanner, just like tokens.
But they are not sent on to the parser.

(The newline/return ending an end-of-line comment is optional in order to allow a file to end with an end-of-line comment, without an extra newline/return.)

JFlex: A scanner generator

Generating a scanner for a language *lang*



A JFlex specification

```
package lang;              // the generated scanner will belong to the package lang
import lang.Token;         // Our own class for tokens
...

// ignore whitespace
" " | \t | \n | \r | \f    { /* ignore */ }

// tokens
"if"                  { return new Token("IF"); }
"="                   { return new Token("ASSIGN"); }
"<"                   { return new Token("LT"); }
"<="                  { return new Token("LE"); }
[a-zA-Z]+             { return new Token("ID", yytext()); }
...
```

Rules and lexical actions

Each rule has the form:

regular-expression { *lexical action* }

The lexical action consists of arbitrary Java code.

It is run when a token is matched.

The method yytext() returns the lexeme (the token value).

Ambiguities?

```
package lang;             // the generated scanner will belong to the package lang
import lang.Token;        // Class for tokens
...

// ignore whitespace
" " | \t | \n | \r | \f    { /* ignore */ }

// tokens
"if"                 { return new Token("IF"); }
"="                  { return new Token("ASSIGN"); }
"<"                  { return new Token("LT"); }
"<="                 { return new Token("LE"); }
[a-zA-Z]+            { return new Token("ID", yytext()); }
...
```

Are the token definitions ambiguous?

Which rules match "<="?

Which rules match "if"?

Which rules match "ifff"?

Which rules match "xyz"?

Extra rules for resolving ambiguities

Longest match

If one rule can be used to match a token, but there is another rule that will match a longer token, the latter rule will be chosen. This way, the scanner will match the longest token possible.

Rule priority

If two rules can be used to match the same sequence of characters, the first one takes priority.

Implementation of scanners

Observation:

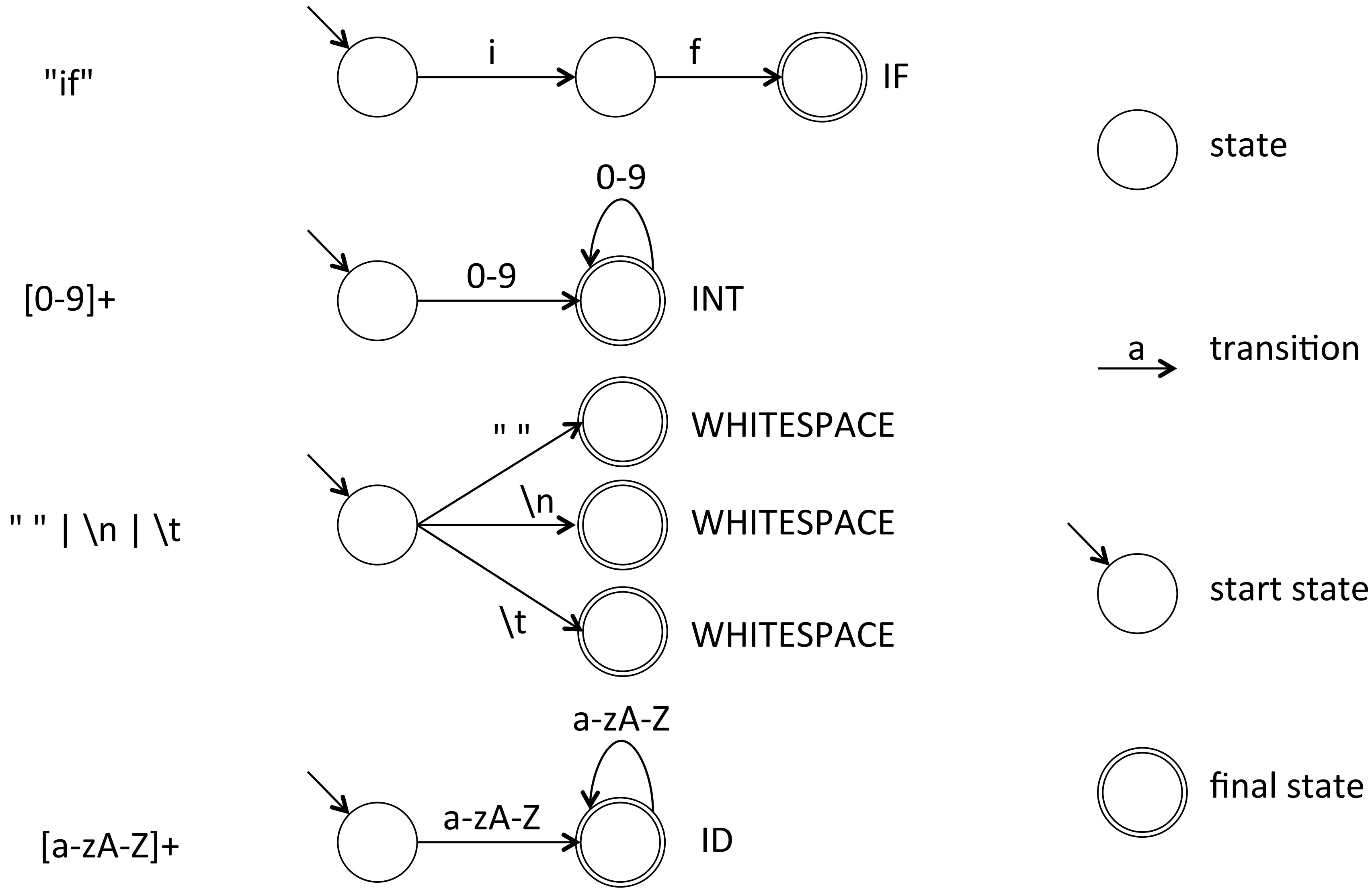
Regular expressions are equivalent to *finite automata* (finite-state machines).
(They can recognize the same class of formal languages: the *regular languages*.)

Overall approach:

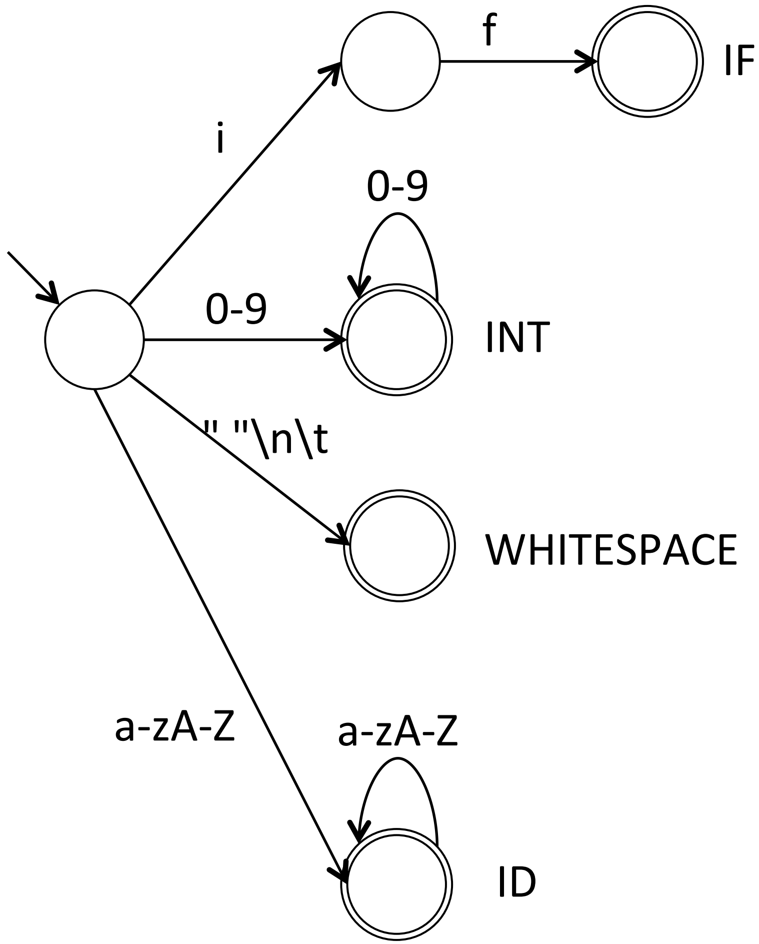
- Translate each token regular expression to a finite automaton.
  Label the final state with the token.
- Merge all the automata.
- The resulting automaton will in general be *nondeterministic*
- Translate the nondeterministic automaton to a *deterministic* automaton.
- Implement the deterministic automaton,
  either using switch statements or a table.

A scanner generator automates this process.

Construct an automaton for each token



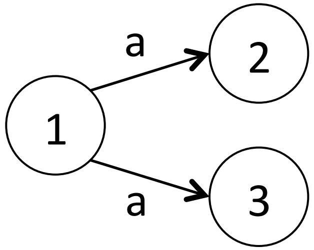
Merge the start states of the automata



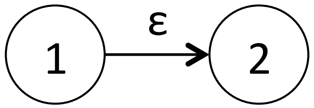
Is the new automaton deterministic?

Deterministic finite automata

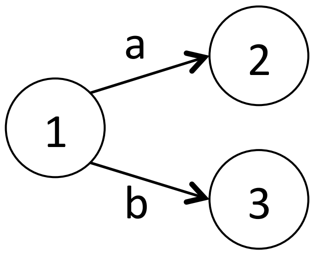
In a deterministic finite automaton each transition is uniquely determined by the input.



Nondeterministic, since if we read a when in state 1, we don't know if we should go to state 2 or 3.



Nondeterministic, since when we are in state 1, we don't know if we should stay there, or go to state 2 without reading any input. (Epsilon denotes the empty string.)



Deterministic, since from state 1, the next input determines if we go to state 2 or 3.

DFA versus NFA

Deterministic Finite Automaton (DFA)

A finite automaton is deterministic if

- all outgoing edges from any given state have disjoint character sets
- there are no epsilon edges

Can be implemented efficiently

Non-deterministic Finite Automaton (NFA)

An NFA may have

- two outgoing edges with overlapping character sets
- epsilon edges

Every DFA is also an NFA.

Every NFA can be translated to an equivalent DFA.

Translating an NFA to a DFA

Simulate the NFA

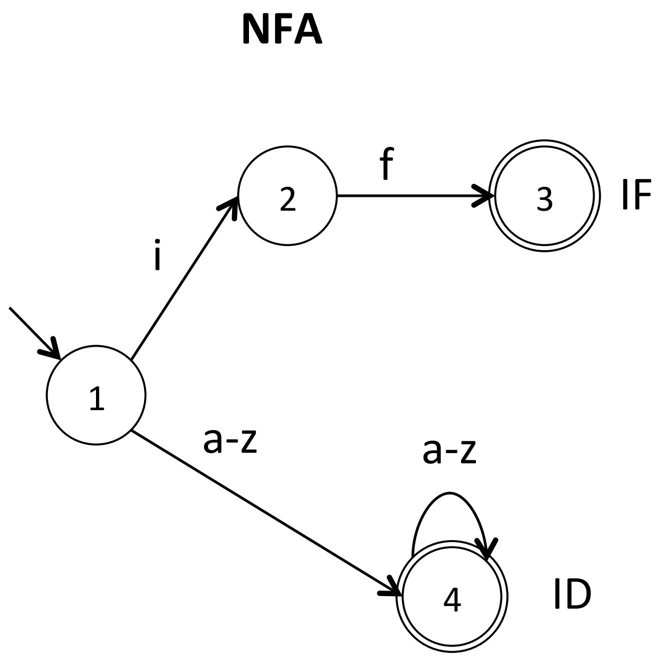
- keep track of a *set* of current NFA-states
- follow ε edges to extend the current set (take the *closure*)

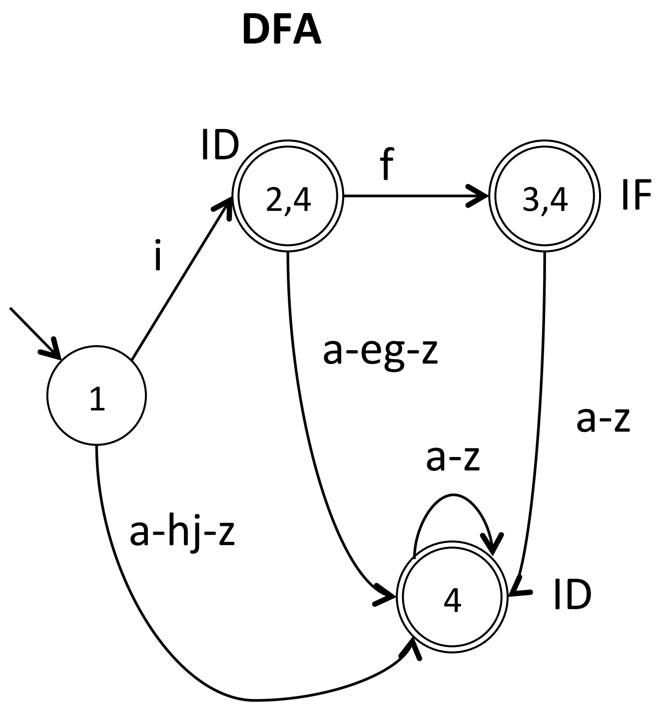
Construct the corresponding DFA

- Each such *set* of NFA states corresponds to *one* DFA state
- If any of the NFA states is final, the DFA state is also final, and is marked with the corresponding token.
- If there is more than one token to choose from, select the token that is defined first (rule priority).

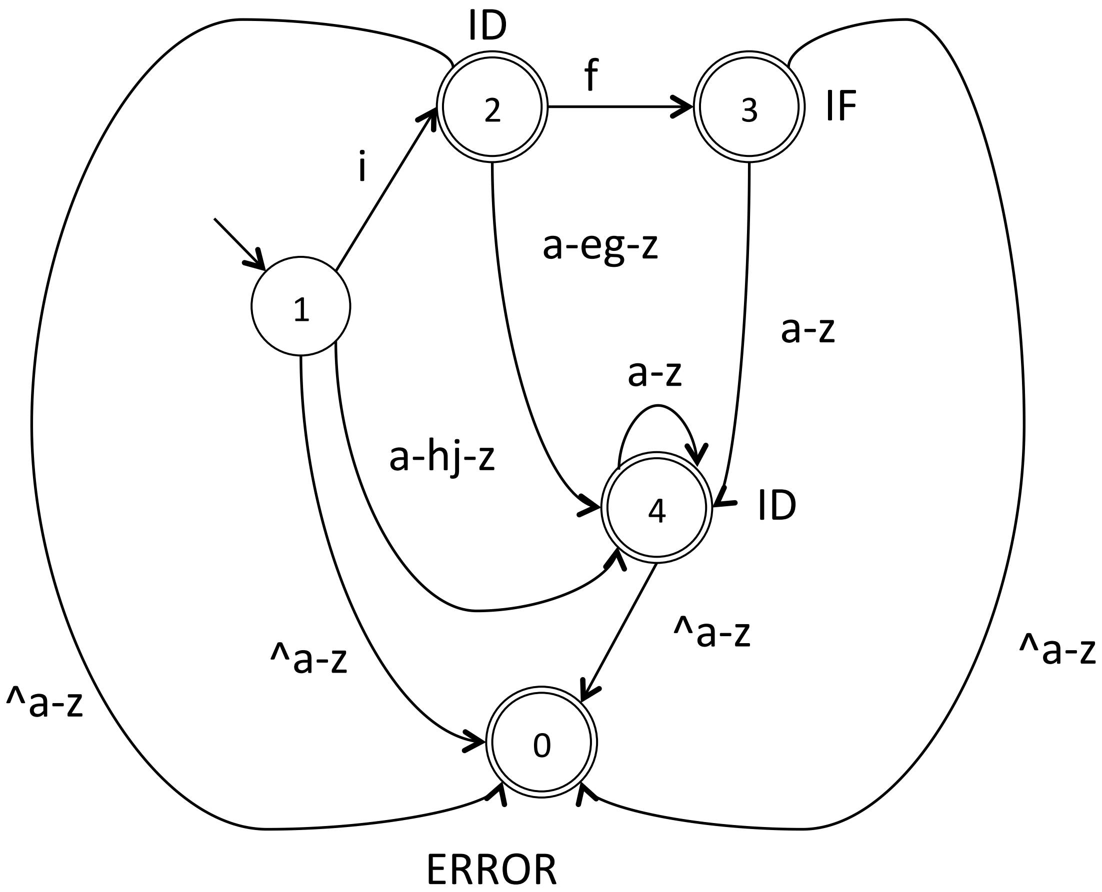
(Minimize the DFA for efficiency)

Example





Error handling



- Add a "dead state" (state 0), corresponding to erroneous input.
- Add transitions to the "dead state" for all erroneous input.
- Generate an "ERROR token" when the dead state is reached.

Implementation alternatives for DFAs

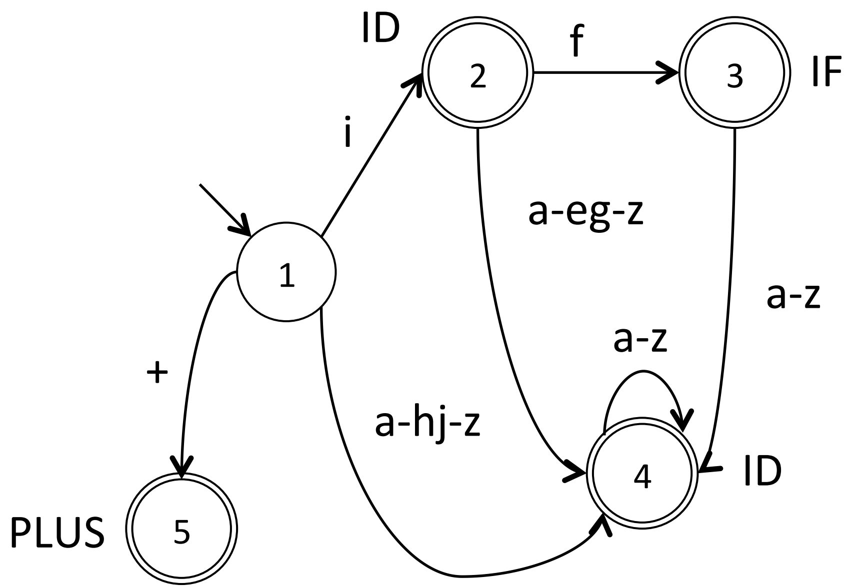
Table-driven

- Represent the automaton by a table
- Additional table to keep track of final states and token kinds
- A global variable keeps track of the current state

Switch statements

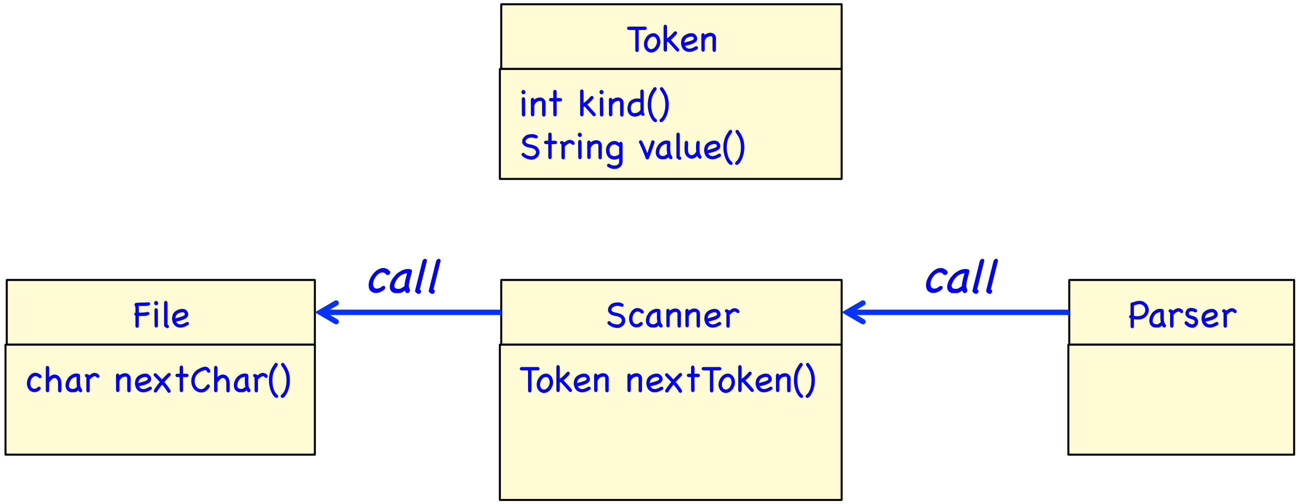
- Each state is implemented as a switch statement
- Each case implements a state transition as a jump (to another switch statement)
- The current state is represented by the program counter.

Table-driven implementation



	...	+	...	a	...	e	f	g	...	h	i	j	...	z	...	final	kind
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	true	ERROR
1	0	5	0	4	4	4	4	4	4	4	2	4	4	4	0	false	
2	0	0	0	4	4	4	3	4	4	4	4	4	4	4	0	true	ID
3	0	0	0	4	4	4	4	4	4	4	4	4	4	4	0	true	IF
4	0	0	0	4	4	4	4	4	4	4	4	4	4	4	0	true	ID
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	true	PLUS

Scanner implementation, design



Scanner implementation, sketch

Idea: Scan the next token by

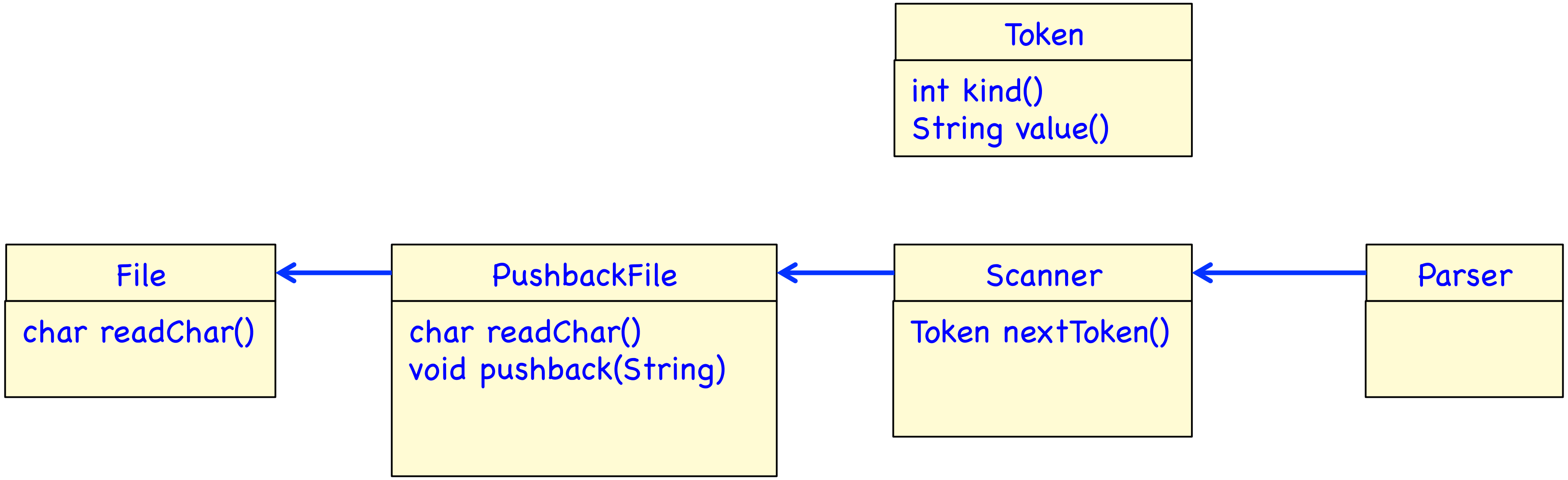
- starting in the start state
- scan characters until we reach a final state
- return a new token

```
Token nextToken() {
   state = 1; // start state
   while (! isFinal[state]) {
      ch = file.readChar();
      state = edges[state, ch];
   }
   return new Token(kind[state]);
}
```

Needs to be extended with handling of:

- longest match
- end of file
- non tokens (like whitespace)
- token values (like the identifier name)

Extend to longest match, design



Idea:

- When a token is matched, don't stop scanning.
- When the error state is reached, return the last token matched.
- Push read characters that are unused back into the file, so they can be scanned again.
- Use a PushbackFile to accomplish this.

Extend to handle longest match, sketch

- When a token is matched (a final state reached), don't stop scanning.
- Keep track of the currently scanned string, `str`.
- Keep track of the latest matched token (`lastFinalState`, `lastTokenValue`).
- Continue scanning until we reach the error state.
- Restore the input stream using PushBackFile.
- Return the latest matched token.
- (or return the ERROR token if there was no latest matched token)

```
Token nextToken() {
   state = 1;
   str = "";
   lastFinalState = 0; lastTokenValue = "";
   while (state != 0) {
      ch = pushbackfile.readChar();
      str = str + ch;          // In Java, StringBuilder would be more efficient
      state = edges[state, ch];
      if (isFinal[state]) {
         lastFinalState = state;
         lastTokenValue = str;
      }
   }
   pushbackfile.pushback(str.substring(lastTokenValue.length));
   return new Token(kind[lastFinalState], lastTokenValue);
}
```

Handling End-of-file (EOF) and non-tokens

EOF

- construct an explicit EOF token when the EOF character is read

Non-tokens (Whitespace & Comments)

- view as tokens of a special kind
- scan them as normal tokens, but don't create token objects for them
- loop in next() until a real token has been found

Errors

- construct an explicit ERROR token to be returned when no valid token can be found.

Specifying EOF and ERROR in JFlex

```
package lang;             // the generated scanner will belong to the package lang
import lang.Token;        // Class for tokens
...

// ignore whitespace
" " | \t | \n | \r | \f    { /* ignore */ }

// tokens
"if"                    { return new Token("IF"); }
"="                     { return new Token("ASSIGN"); }
"<"                     { return new Token("LT"); }
"<="                    { return new Token("LE"); }
[a-zA-Z]+               { return new Token("ID", yytext()); }
...
<<EOF>>                 { return new Token("EOF"); }
[^]                     { return new Token("ERROR"); }
```

<<EOF>> is a special regular expression in JFlex, matching end of file.

[^] means any character. Due to rule priority, this will match any character not matched by previous rules.

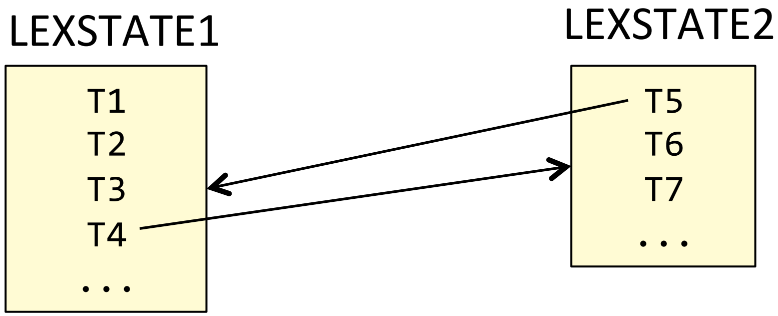
Example scanner generators

tool	author	generates
lex	Schmidt, Lesk. 1975	C-code
flex ("fast lex")	Paxon. 1987	C-code
jlex		Java code
jflex		Java code
...		

Lexical states

- Some tokens are difficult or impossible to define with regular expressions.

- *Lexical states* (sets of token rules) give the possibility to switch token sets (DFAs) during scanning.



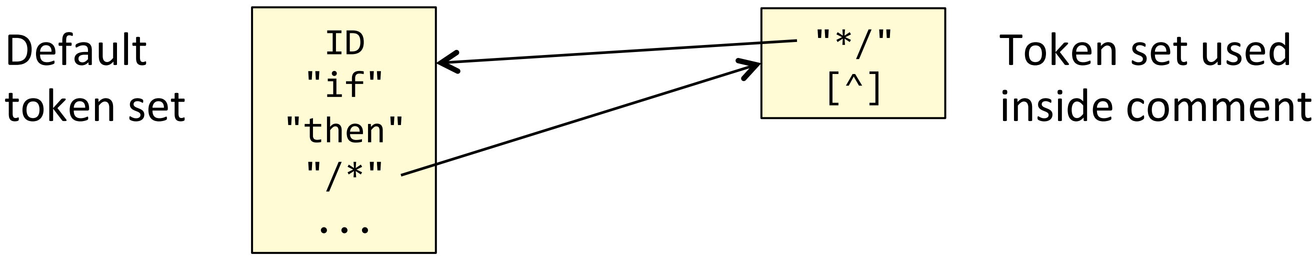
- Useful for multi-line comments, HTML, scanning multi-language documents, etc.
- Supported by many scanner generators (including JFlex)

Example: multi-line comments

Would like to scan the complete comment as one token:

```
/*
int m() {
   return 15 / 3 * 4 * 2;
}
*/
```

Can be solved easily with lexical states:



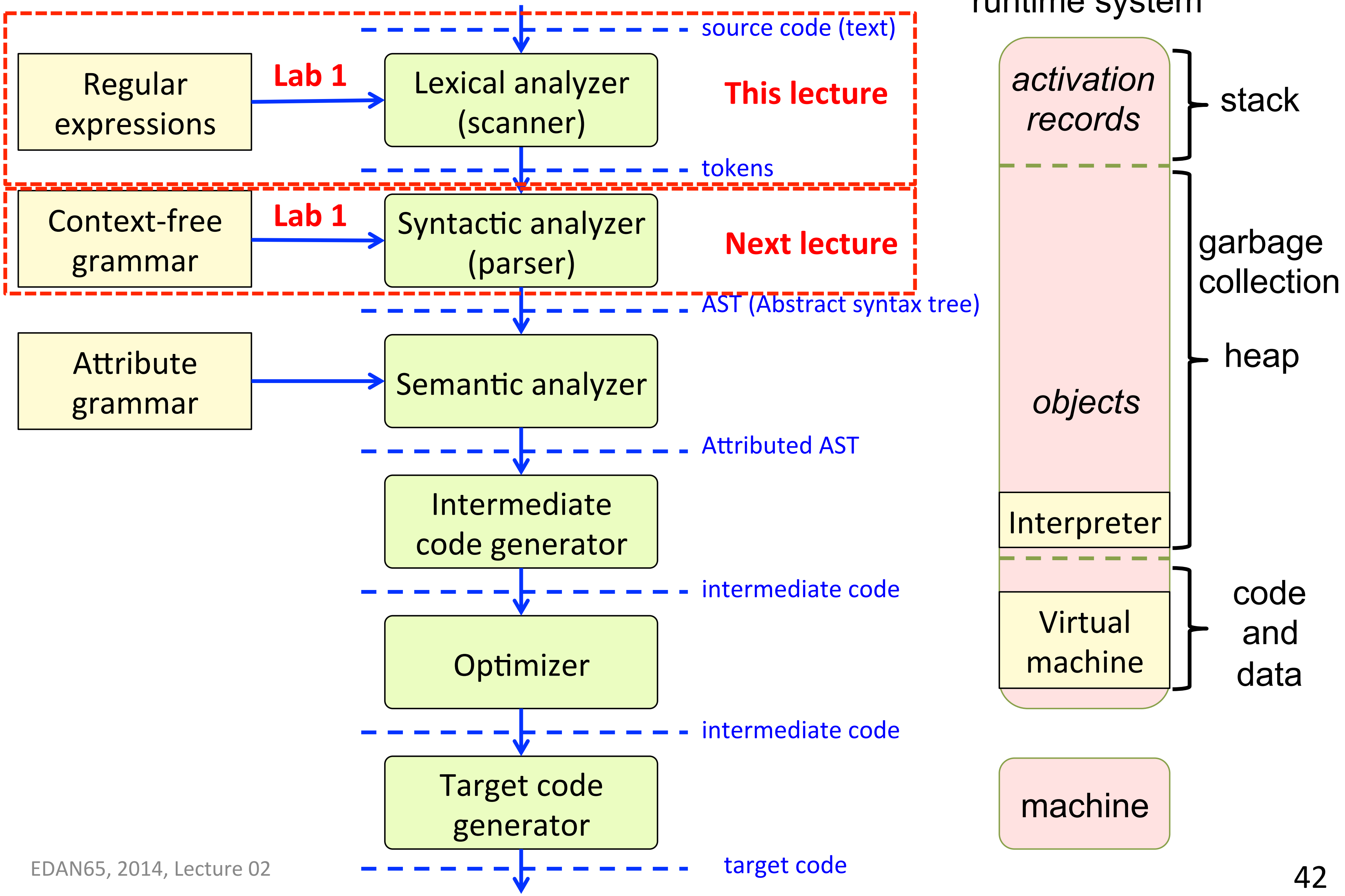
Writing an ordinary regular expression for this is difficult:

```
"/*"((\*+[^/*])|([^*]))*\**"*/"
```

However, some scanner generators, like JFlex, has the special operator *upto* (~) that can be used instead:

```
"/*" ~"*/"   { /* Comment */ }
```

Course overview



Summary questions

- What is a formal language?
- What is a regular expression?
- What is meant by an ambiguous lexical definition?
- Give some typical examples of ambiguities and how they may be resolved.
- What is a lexical action?
- Give an example of how to construct an NFA for a given lexical definition
- Give an example of how to construct a DFA for a given NFA
- What is the difference between a DFA and and NFA?
- Give an example of how to implement a DFA in Java.
- How is rule priority handled in the implementation? Longest match? EOF? Whitespace? Errors?
- What are lexical states? When are they useful?

You can start on Assignment 1 now. But you will have to wait until the next lecture for the parts about parsing.