EDAN65: Compilers, Lecture 02

Regular expressions and scanning

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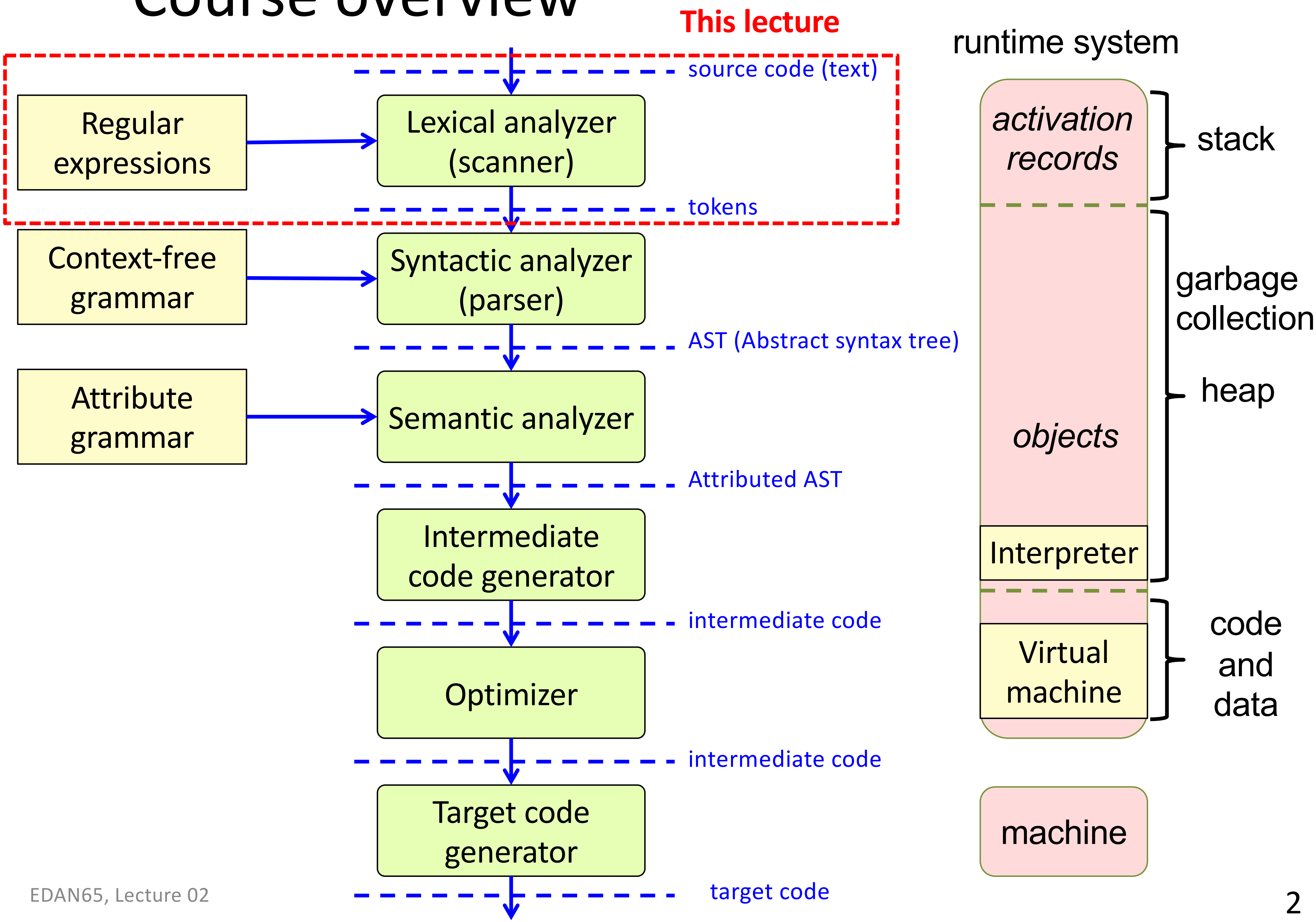
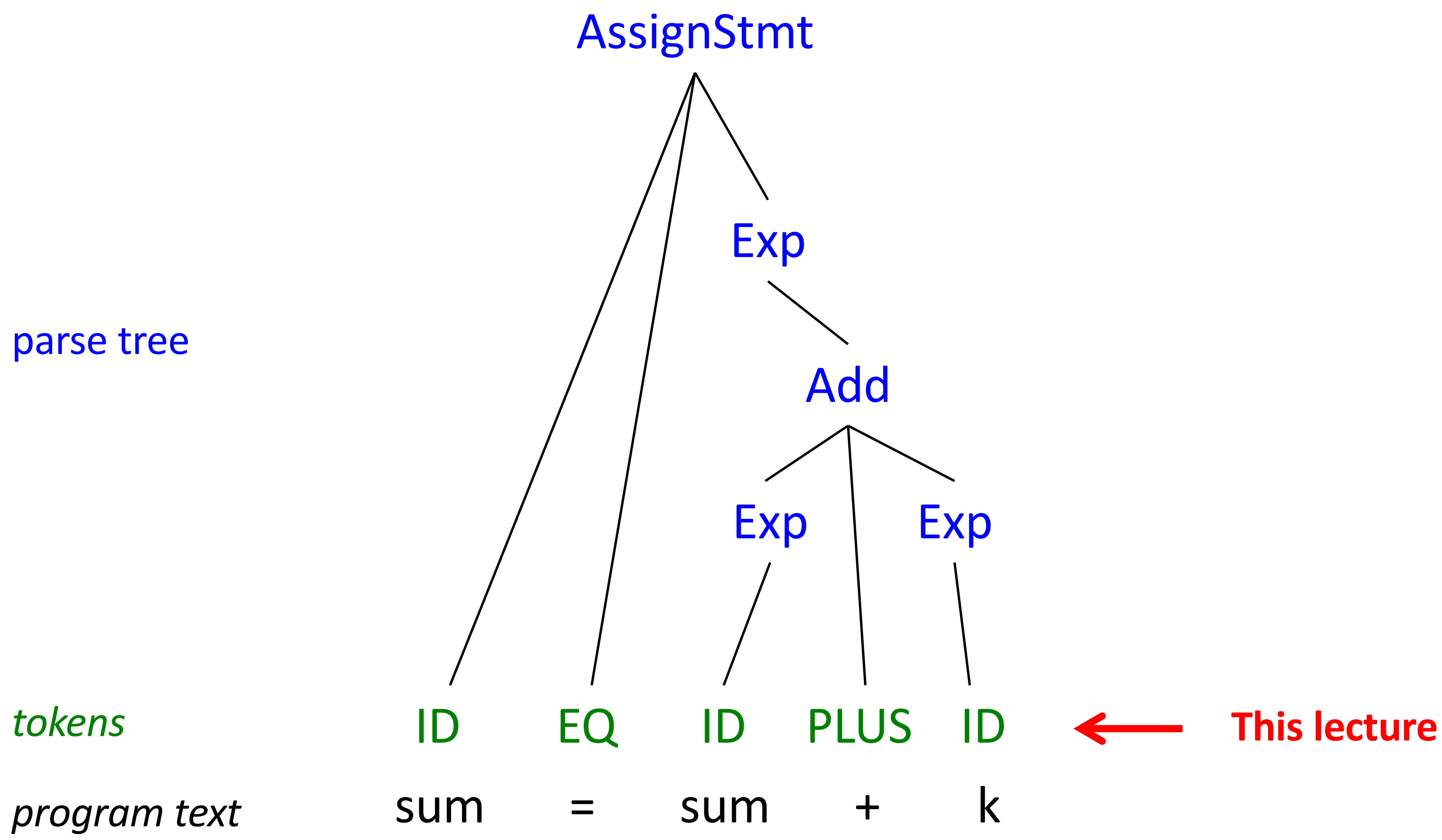
Course overview



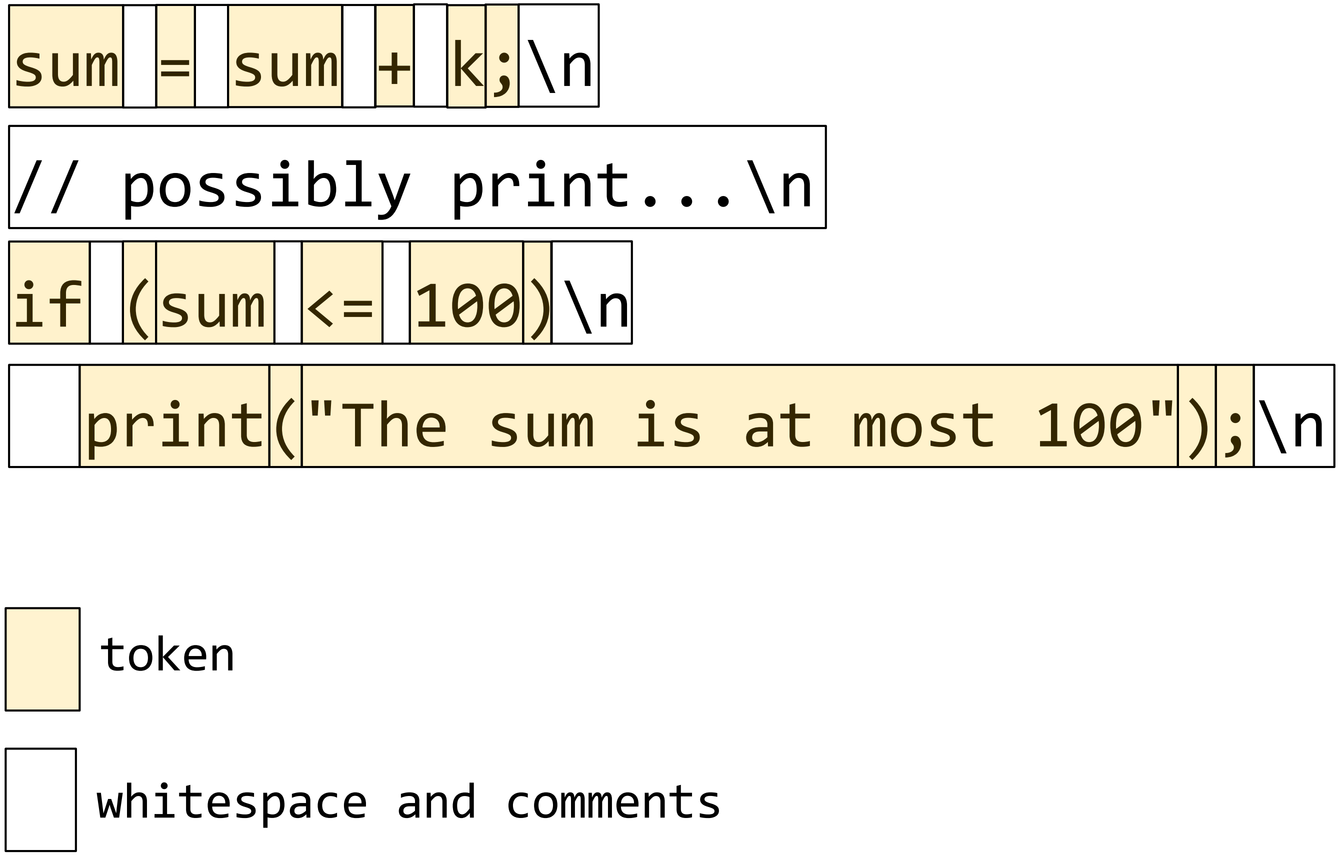
Analyzing program text



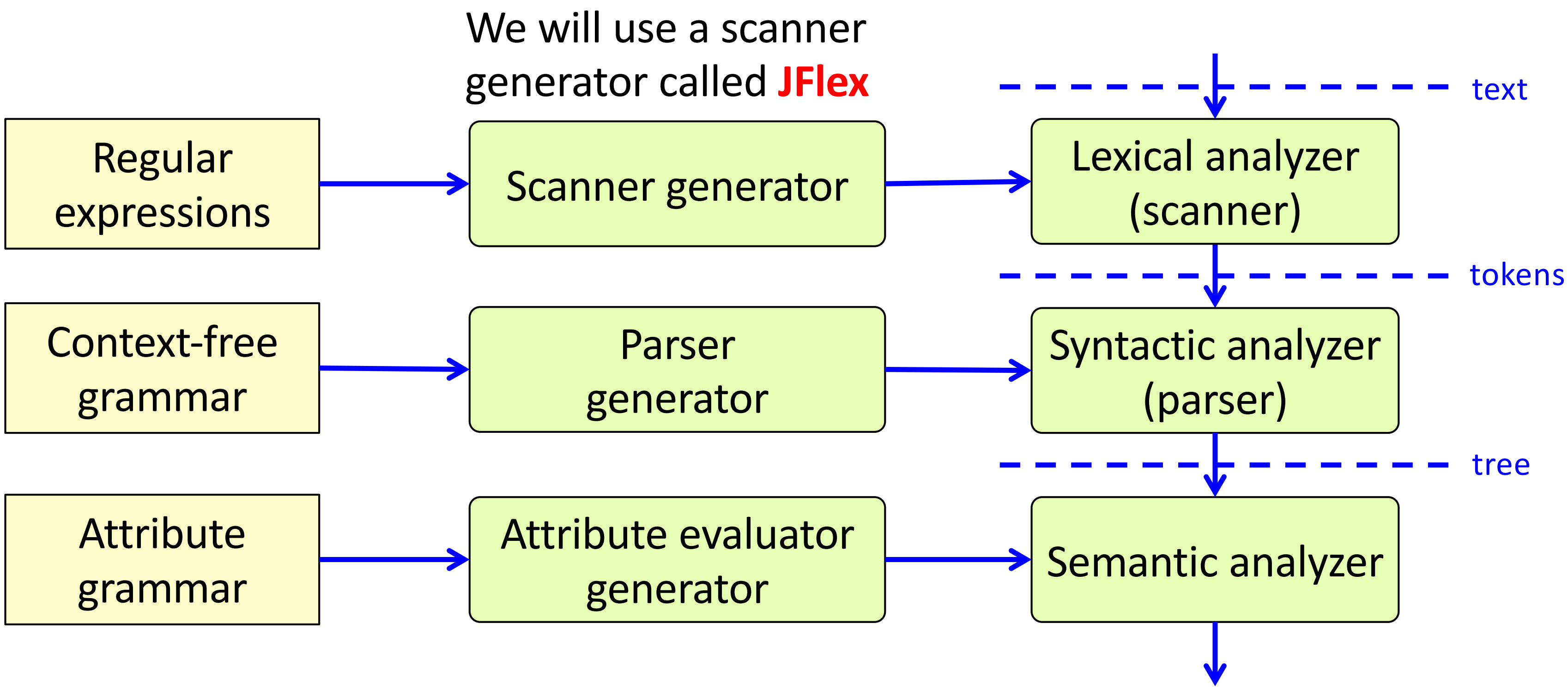
How split this Java code into tokens?

```
sum = sum + k;
// possibly print...
if (sum <= 100)
  print("The sum is at most 100");
```

How split this Java code into tokens?



Recall: Generating the compiler:



Some typical tokens

	Token	Example lexemes
Reserved words (keywords)	IF THEN FOR	if then for
Identifiers	ID	B alpha k10
Literals	INT FLOAT STRING CHAR	1230 99 2016 3.1416 0.2 "Hello" "" "100%" 'A' 'c' '%'
Operators	PLUS INCR NE	+ ++ !=
Separators	SEMI COMMA LPAREN	; , (

Some typical tokens

	Token	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 FLOAT STRING CHAR	1230 99 2016 3.1416 0.2 "Hello" "" "100%" 'A' 'c' '%'	[0-9]+ [0-9]+ "." [0-9]+ \" [^\"]* \" \' [^\'] \'
Operators	PLUS INCR NE	+ ++ !=	"+" "++" "!="
Separators	SEMI COMMA LPAREN	; , (	";" "," "("

JFlex syntax

Formal languages

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:
  $L_0 =$
- All binary numbers without unnecessary leading zeros:
  $L_1 =$
- All binary numbers with two digits:
  $L_2 =$
- ...

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
- ...

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 (But 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.)
- ...

Different kinds of rules

Increasingly powerful:

- Regular expressions (for tokens)
- Context-free grammars (for syntax trees)
- Attribute grammars (context-free grammar + extra rules for further restricting the language)

Regular expressions (core notation)

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*)		scope

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* | *N P** means *M* | (*N* (*P**))

Example

a | b c*

Example

a | b c*

means

{"a", "b", "bc", "bcc", "bccc", ...}

Another example

$(a \mid b \mid \epsilon)\ c^*$

Another example

(a | b | ϵ) c*

means

{"a", "b", "", "ac", "bc", "c", "acc", "bcc", "cc", ...}

REs: core + 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

Regular expression	Language
(ab)+ c?	
[defq]	
[g-k]	
[a-z]*	
[^b-d]	
("hi")*	

assuming the alphabet is {a, b, ..., z}

Solution

Regular expression	Language
(ab)+ c?	{"ab", "abab", ..., "abc", "ababc", ...}
[defq]	{"d", "e", "f", "q"}
[g-k]	{"g", "h", "i", "j", "k"}
[a-z]*	{"", "a", "b", "c", ..., "z", "aa", "ab", ... "az", "ba", "bb", ... "bz", "ca", ...}
[^b-d]	{"a", "e", "f", ..., "z"}
("hi")*	{"", "hi", "hihi", "hihihi", ...}

assuming the alphabet is {a, b, ..., z}

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 unnecessary leading zeros (in the extended notation)

Core RE
a
M | *N*
M N
ϵ
*M**
(*M*)

Extended RE
M+
M?
[aou] [a-zA-Z]
[^0-9]
"a+b"

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 non-tokens

Non-Token	Example lexemes
WHITESPACE	blank tab newline return
ENDOFLINECOMMENT	// comment

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

Some typical non-tokens

Non-Token	Example lexemes
WHITESPACE	blank tab newline return
ENDOFLINECOMMENT	// comment

Regular expression (jflex)
`" " | \t | \n | \r`
`"//" [^\n\r]* [\n\r]?`

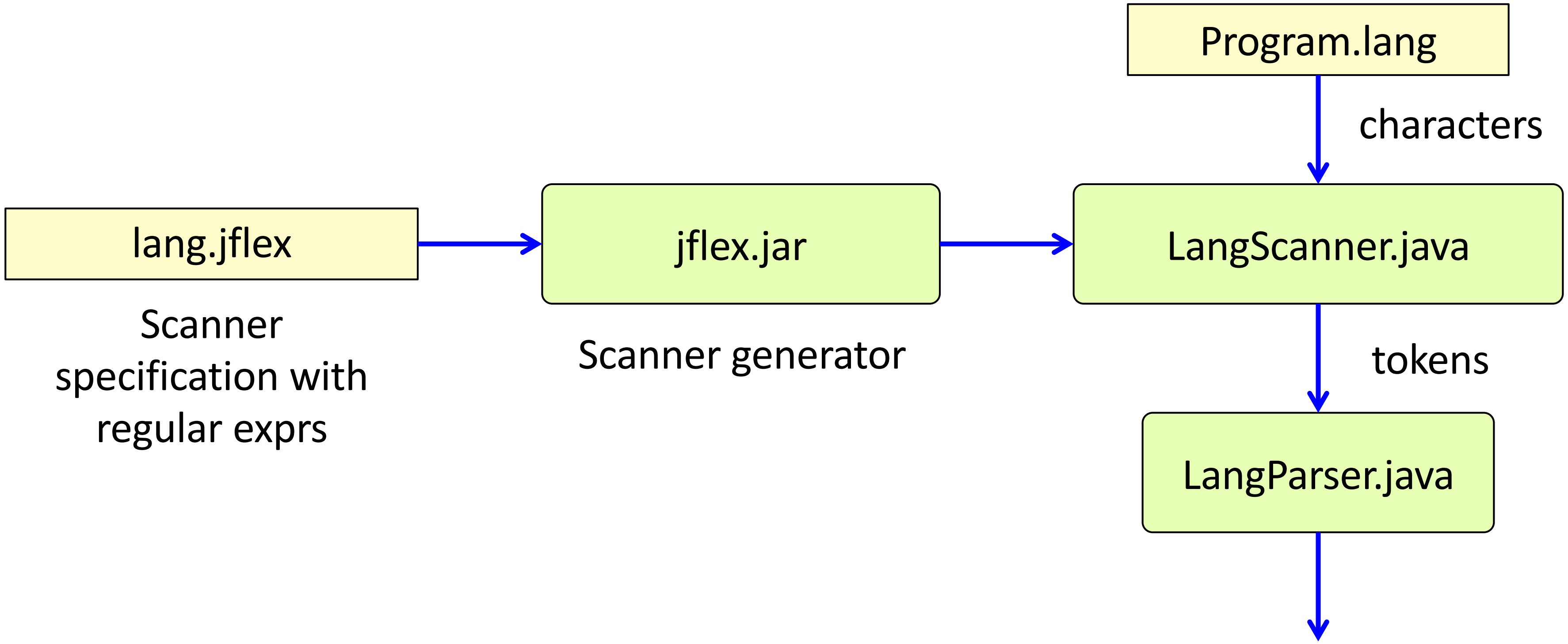
JFlex syntax

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 regular expression is matched.

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

A JFlex specification

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package lang;              // the generated scanner will belong to the package lang
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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 regular expression is matched.

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

What rules are used when scanning "a < b"?

Ambiguities?

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

// ignore whitespace
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Ambiguities?

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"<="                    { 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:

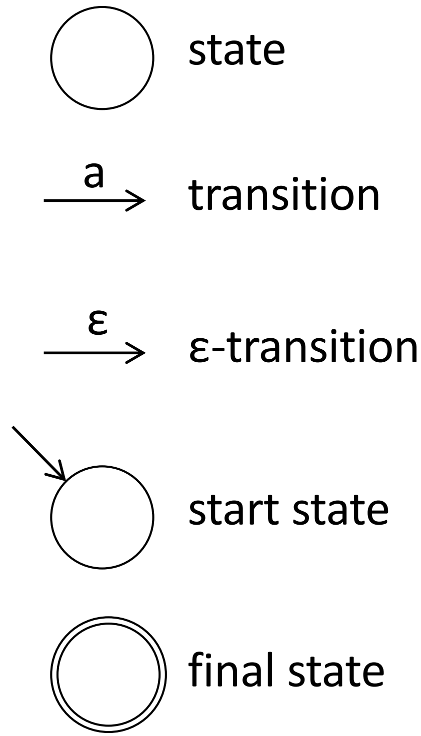
Regular expressions are equivalent to *finite automata* (finite-state machines).
(They can recognize the same class of formal languages: the *regular languages*.)

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.

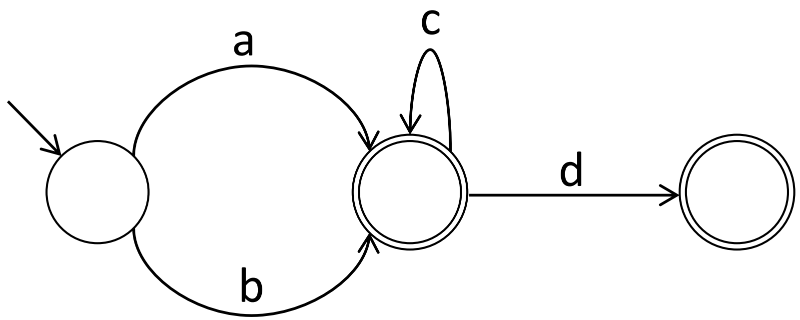
Finite automaton

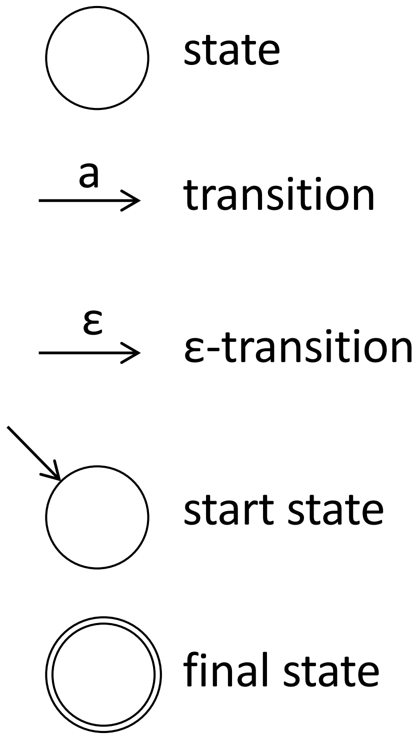


Regular expression:
[ab] c* d?

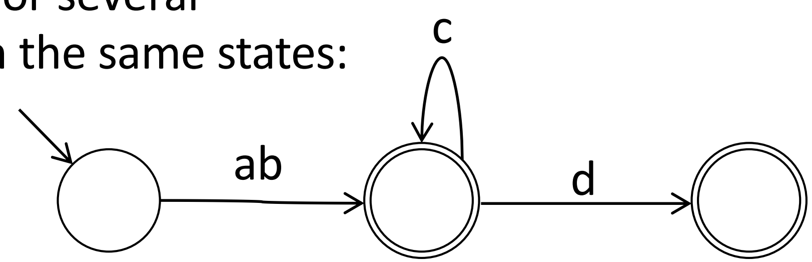
Finite automaton

Regular expression:
[ab] c* d?





or, with shorthand for several transitions between the same states:



Construct an automaton for each token regexp

"if"

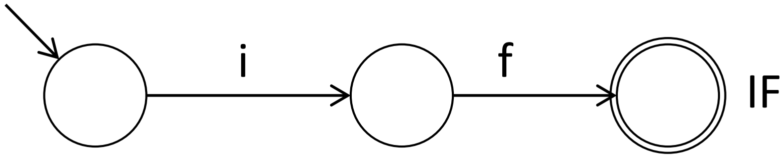
[0-9]+

" " | \n | \t

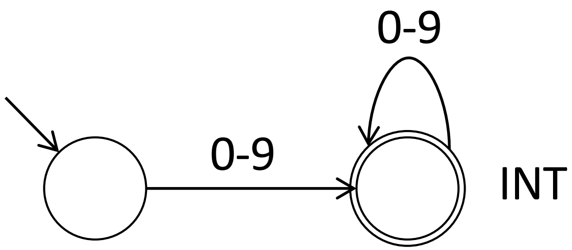
[a-zA-Z]+

Construct an automaton for each token regexp

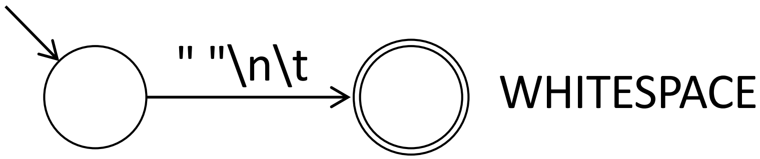
"if"



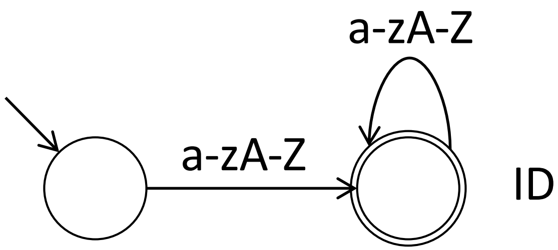
[0-9]+



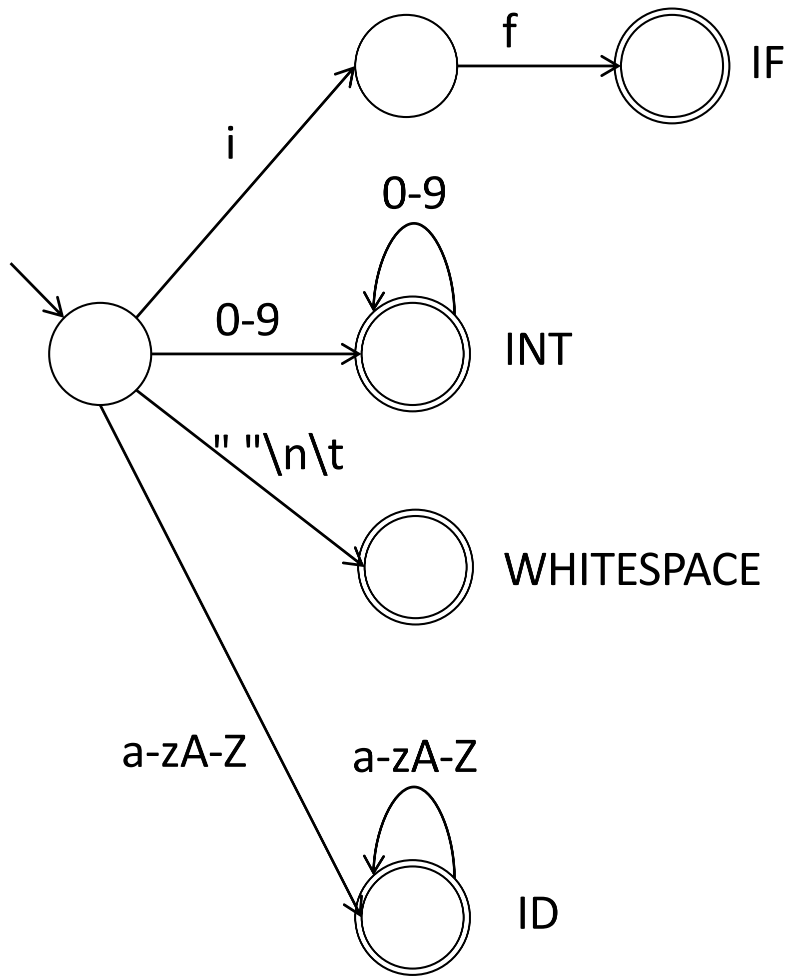
" " | \n | \t



[a-zA-Z]+



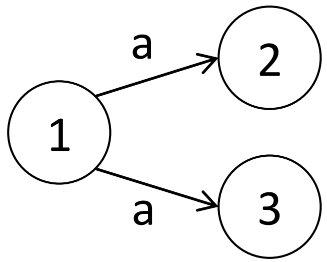
Merge the start states of the automata

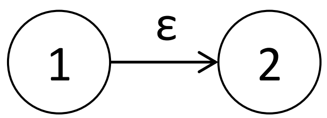


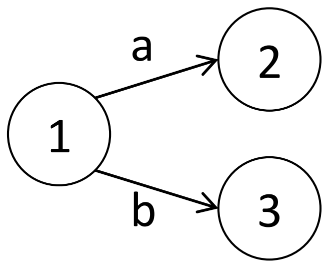
Is the new automaton deterministic?

Deterministic finite automata

Deterministic finite automaton: each transition is uniquely determined by the next symbol.







Deterministic finite automata

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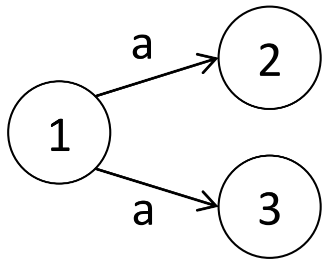
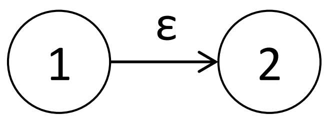
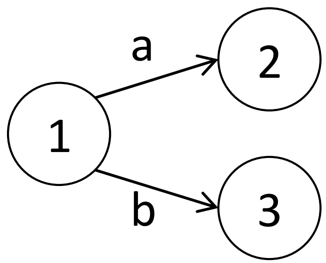


Nondeterministic: if we read "a" when in state 1, we don't know if we should go to state 2 or 3.



Nondeterministic: 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: when we are in state 1, the next symbol 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)

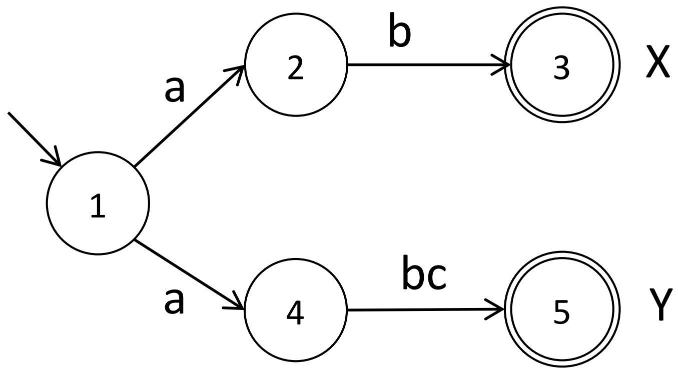
An NFA may have

- two outgoing edges with overlapping character sets
- epsilon edges

Every NFA can be translated to an equivalent DFA.

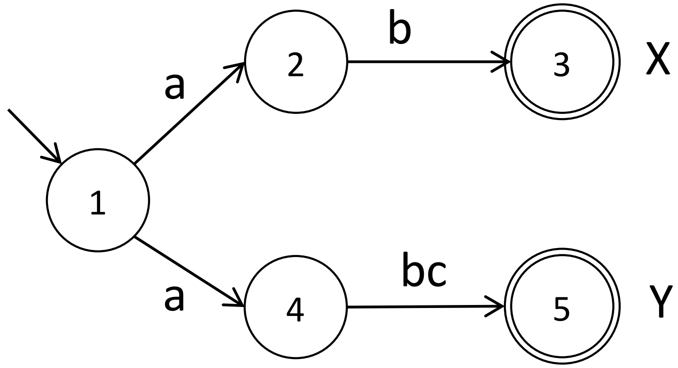
Example 1

NFA

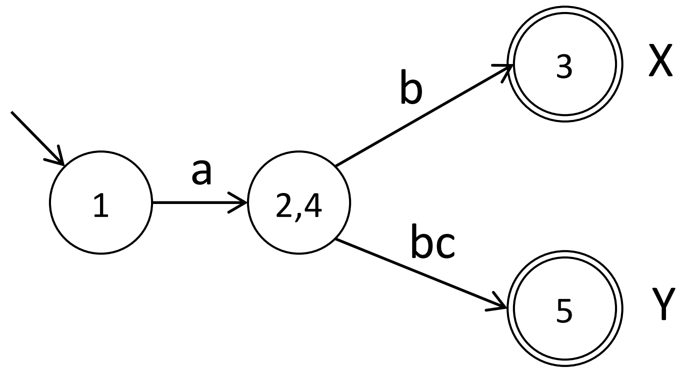


Example 1

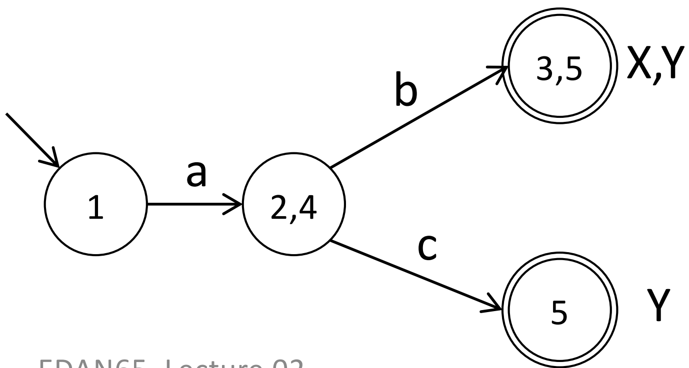
NFA



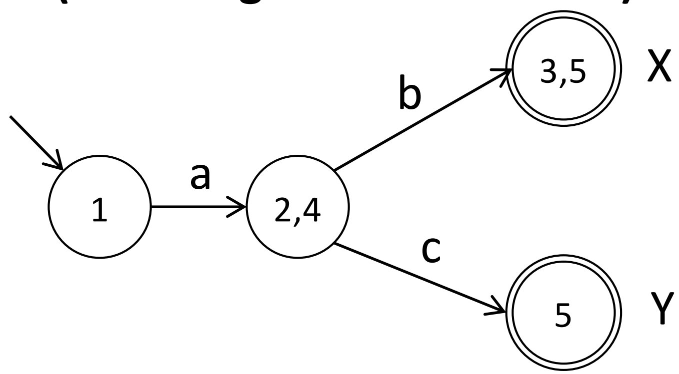
Still NFA



DFA, but ambiguous final token

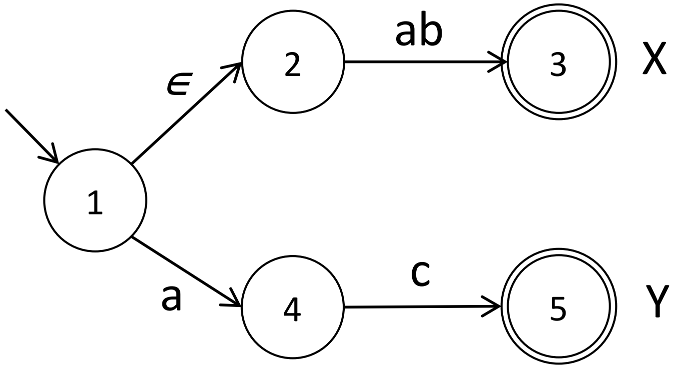


Use rule priority to pick X (assuming rule X is before Y)



Example 2

NFA



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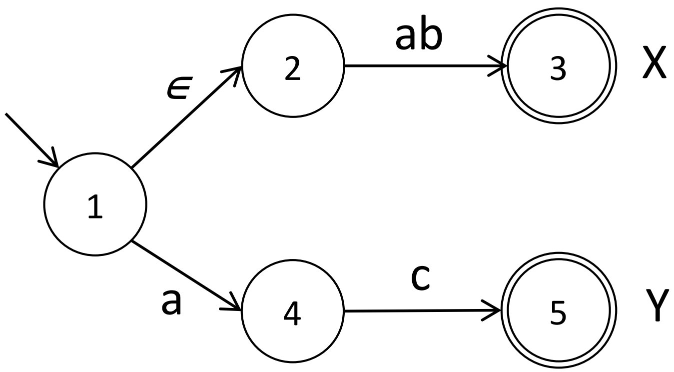
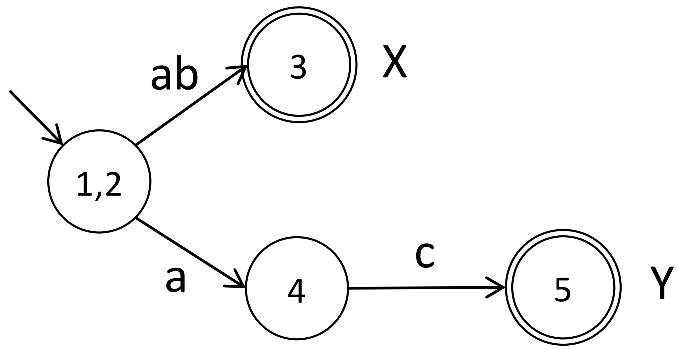
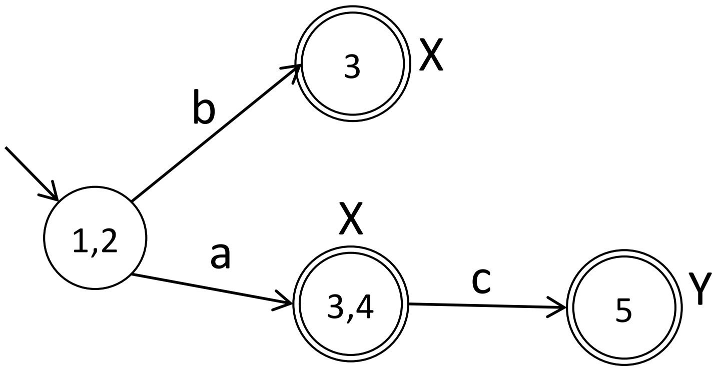
NFA



still NFA



Equivalent DFA



Should we stay at (3,4), or continue to 5?
Use longest match to continue if possible.

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*)

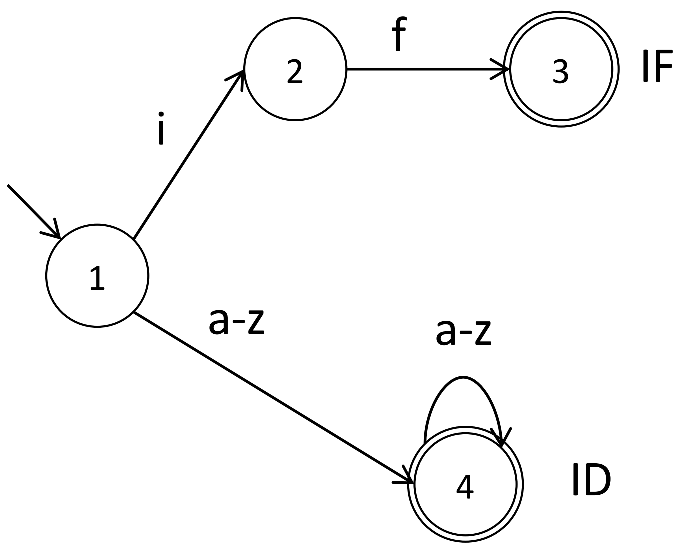
Construct the corresponding DFA

- 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)

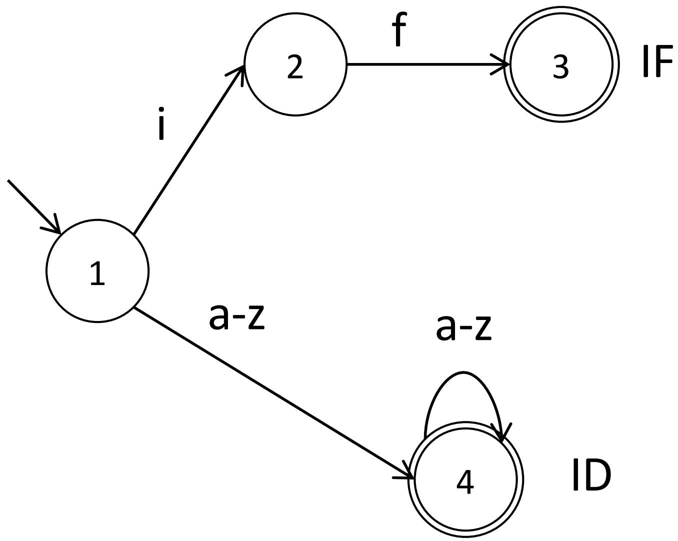
Example

NFA

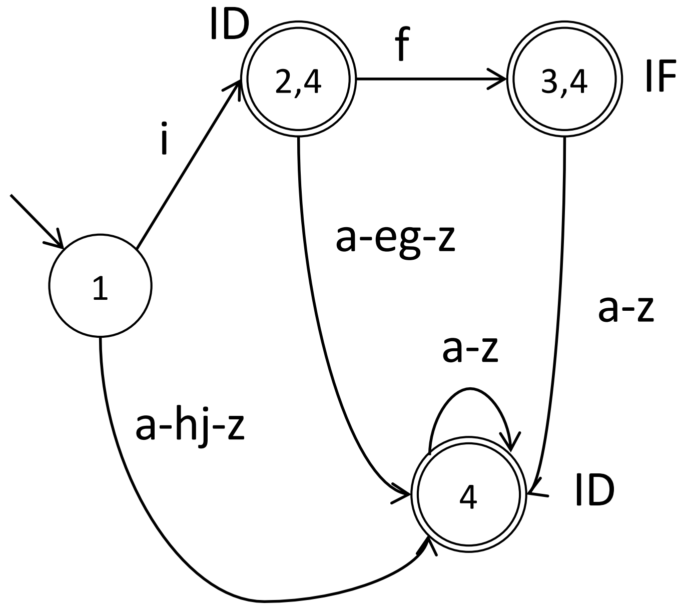


Example

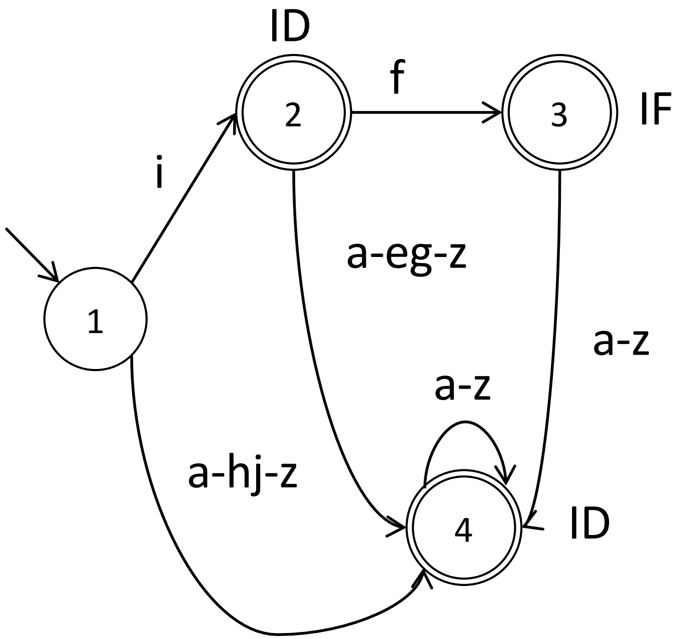
NFA



DFA



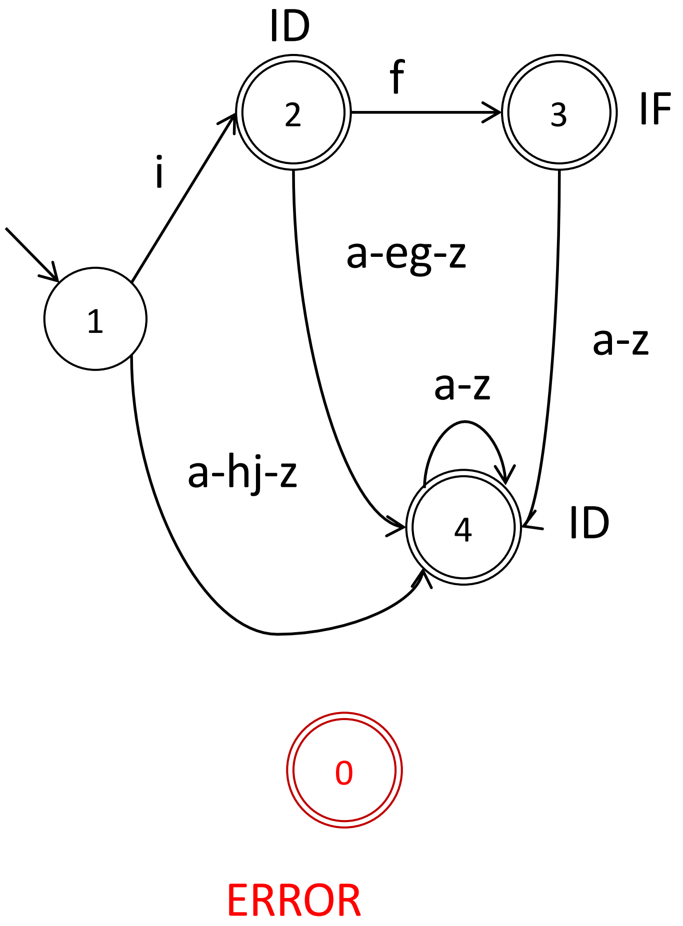
Error handling



Conceptually (we typically don't draw this explicitly – too much clutter):

- 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.

Error handling



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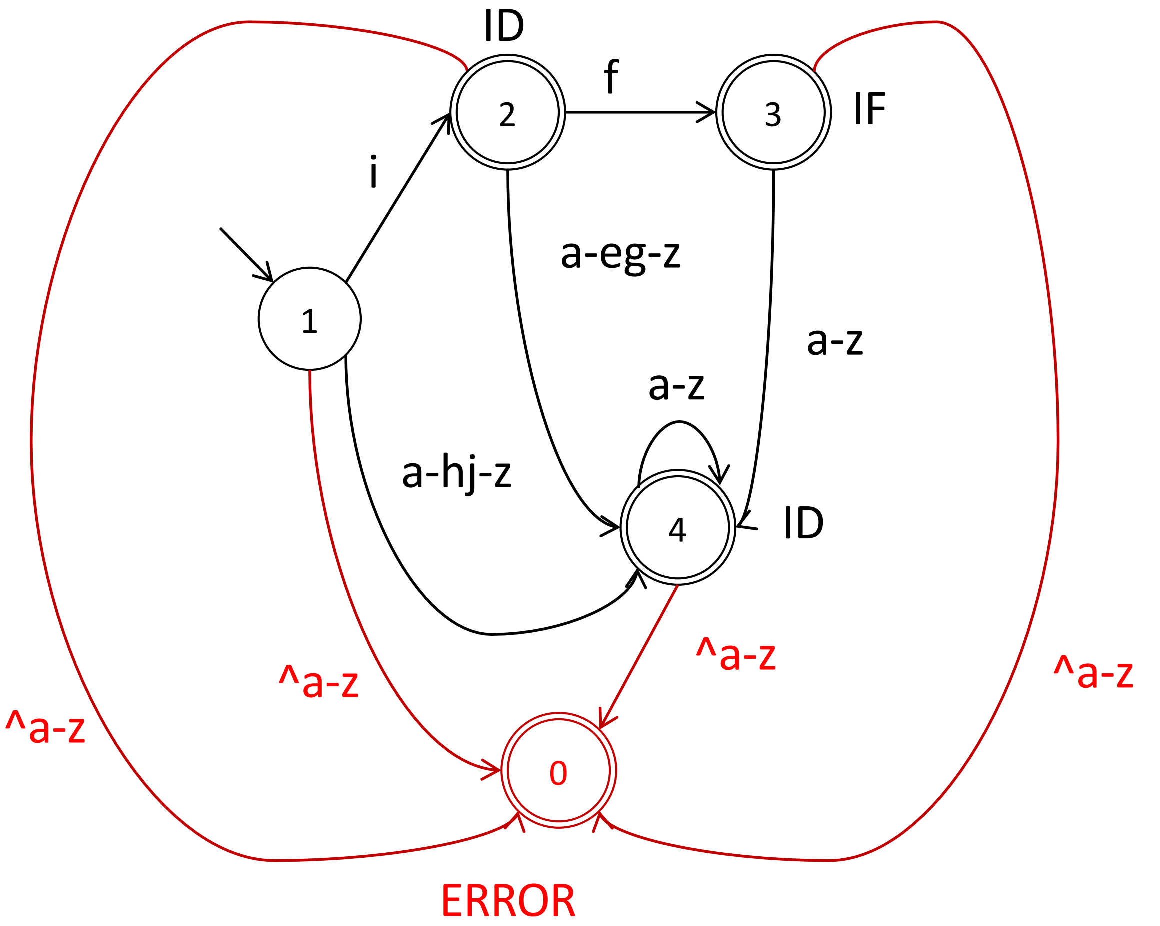

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Implementation alternatives for DFAs

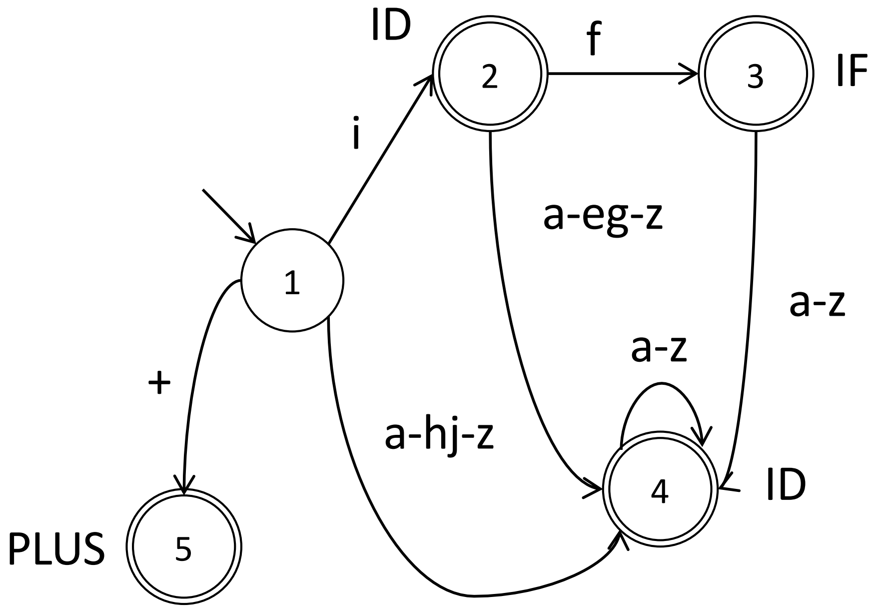
Table-driven

- 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 (goto) to another switch statement
- The current state is represented by the program counter.

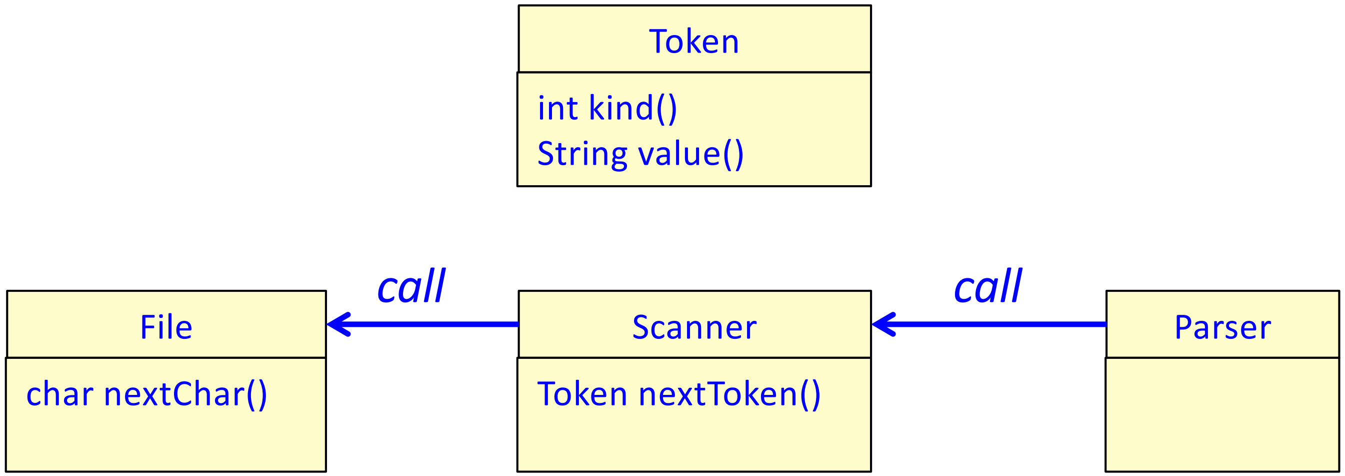
Table-driven implementation



alphabet

states	…	+	…	a	…	e	f	g	…	h	i	j	…	z	…	final	token 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]);
}
```

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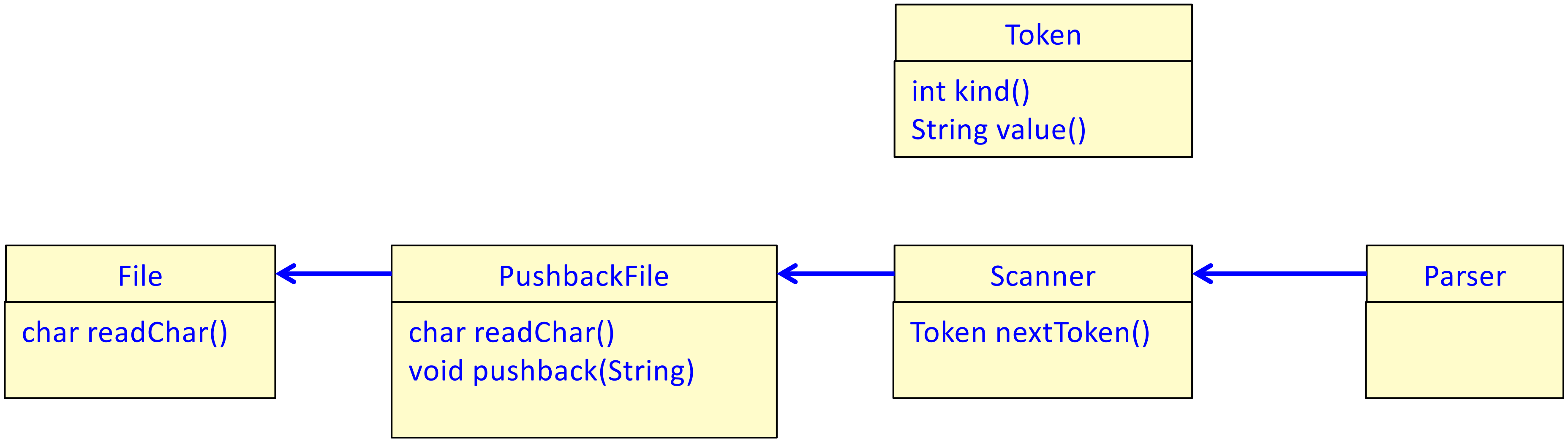
```

Needs to be extended with handling of:

- longest match
- end of file
- non tokens (like whitespace)
- token values (like the identifier name)
- errors (no token could be matched)

Extend to longest match, design



Idea:

- When a token is matched, keep track of it, but don't stop scanning.
- When the error state is reached, return the last (=longest) 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 end of the file is reached

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"); }
```

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...
<<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
...		

Limitations of regular expressions for scanning

- Nested comments?
- Layout-sensitive syntax?
- Context-sensitive token definitions?
  For example, multi-language documents.

Limitations of regular expressions for scanning

- Nested comments?
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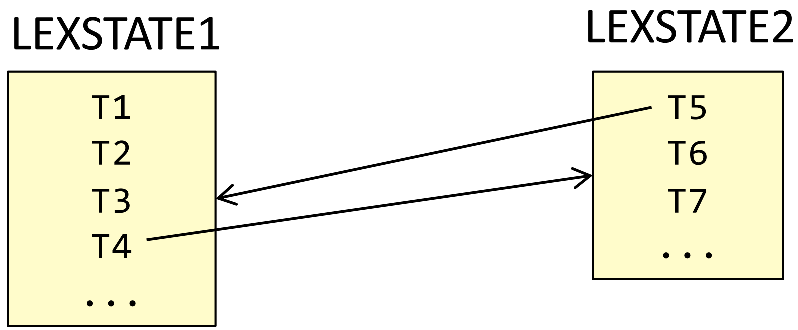
  For example, multi-language documents.

- Two mechanisms in scanner generators for workarounds:
  - **Lexical actions**:
    do more than create a token, e.g., count nesting levels of comments.
  - **Lexical states**:
    switch between different sets of token definitions.

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;
}
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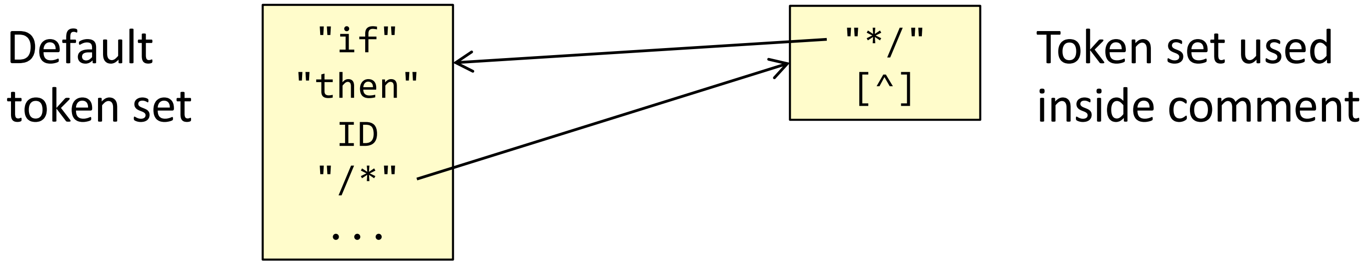

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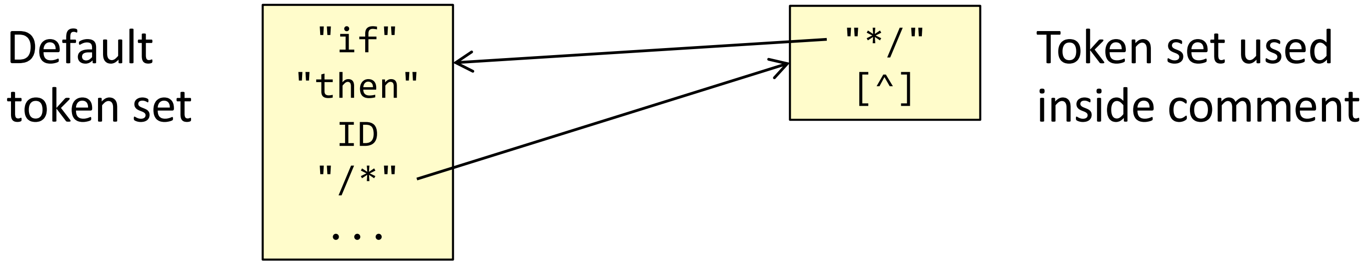

Writing an ordinary regular expression for this is difficult:

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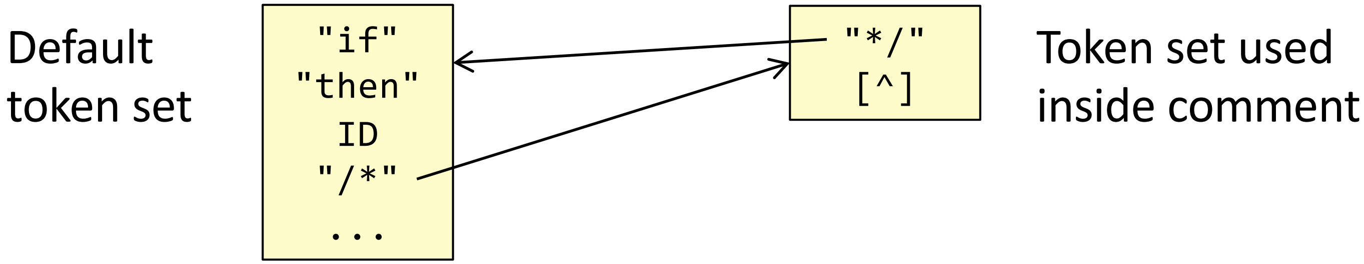


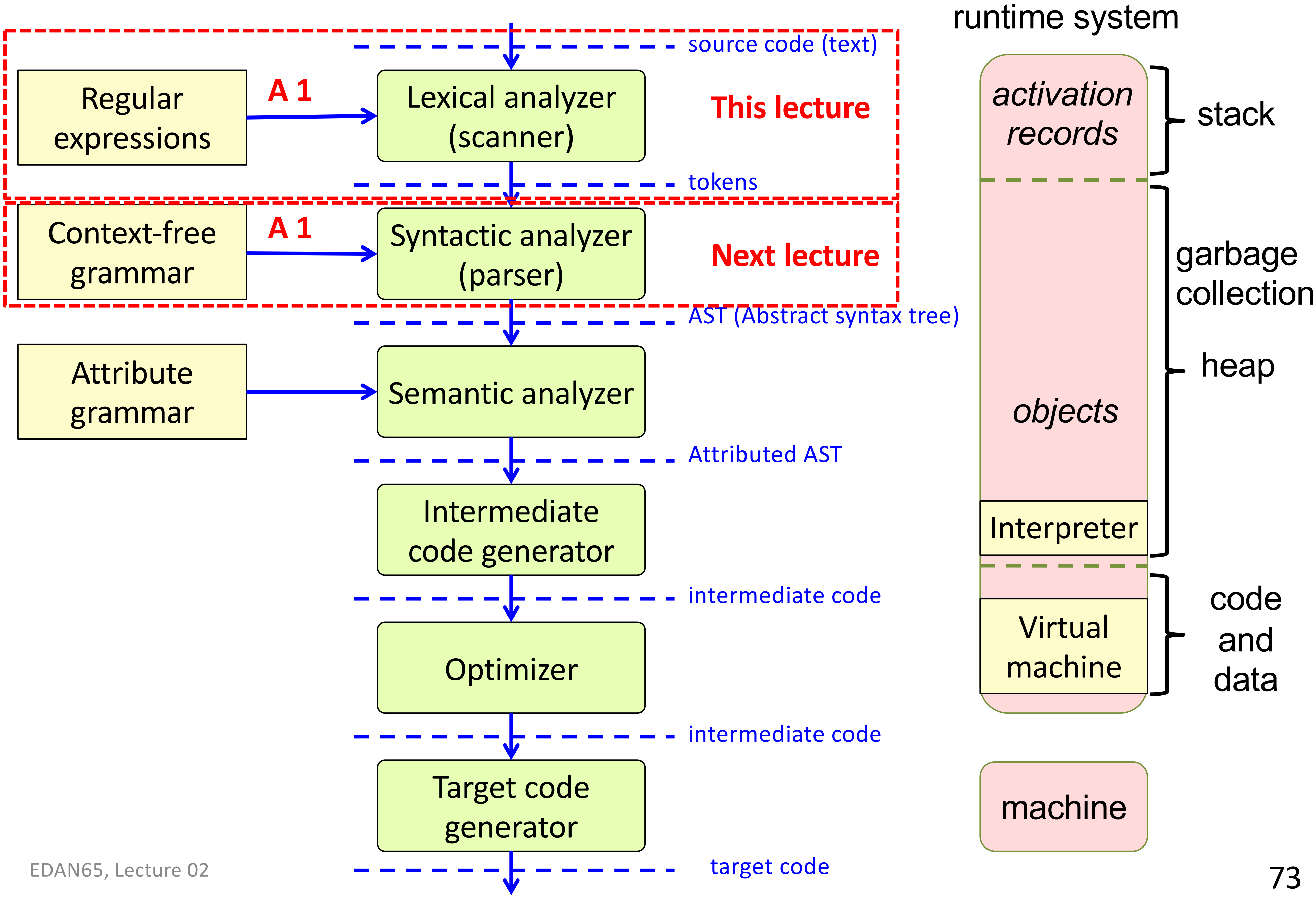
Writing an ordinary regular expression for this is difficult:

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

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.