CS 321: Languages and Compiler Design I

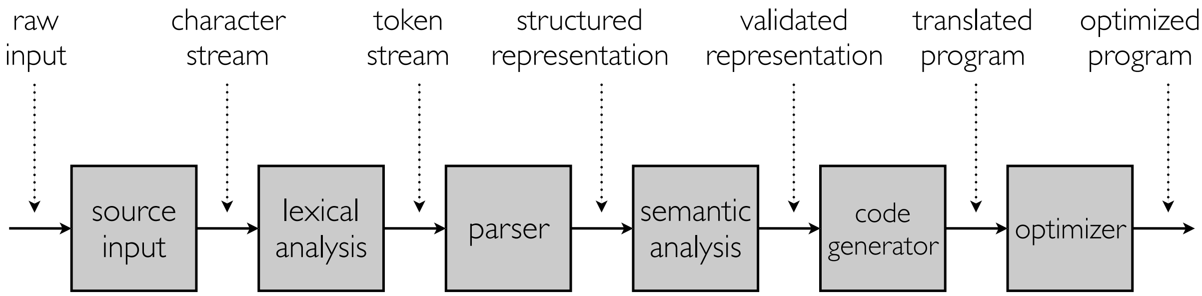
Mark P Jones, Portland State University

Winter 2014

Week 2: Lexical Analysis

Rough plan for the rest of the term ...

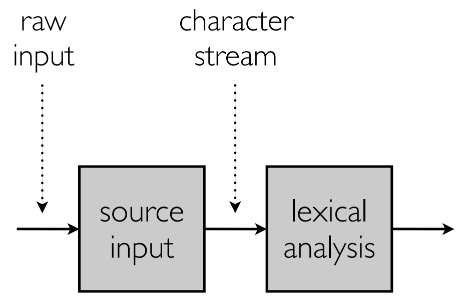
Through the phases ...



- Compilers are often structured as a pipeline of separate phases
- During the next few weeks, we'll follow the same structure, taking a more detailed look at each of the phases in turn
- Starting with ...

Source input

Implementing source input



Source input issues include:

- Getting characters into memory (your OS can help!)
- Dealing with character set encodings: ASCII, EBCDIC, ISO 8859_1, UTF, etc.
- In Java, ignore a trailing ^Z at the end of a file
- In Haskell, process "literate source files"
- Expand tabs if indentation is significant
- Process Unicode escapes. For example: \u2297 ⇒ ⊗

Introduction to syntax analysis

$$\text{language} = \begin{cases} \text{syntax} = \begin{cases} \text{concrete} \\ \text{abstract} \end{cases} \\ \\ \text{semantics} = \begin{cases} \text{static} \\ \text{dynamic} \end{cases} \end{cases}$$

concrete syntax: the representation of a program text in its source form as a sequence of bits/bytes/characters/lines

$$\text{language} = \begin{cases} \text{syntax} = \begin{cases} \text{concrete} \\ \text{abstract} \end{cases} \\ \\ \text{semantics} = \begin{cases} \text{static} \\ \text{dynamic} \end{cases} \end{cases}$$

abstract syntax: the representation of a program structure, independent of written form

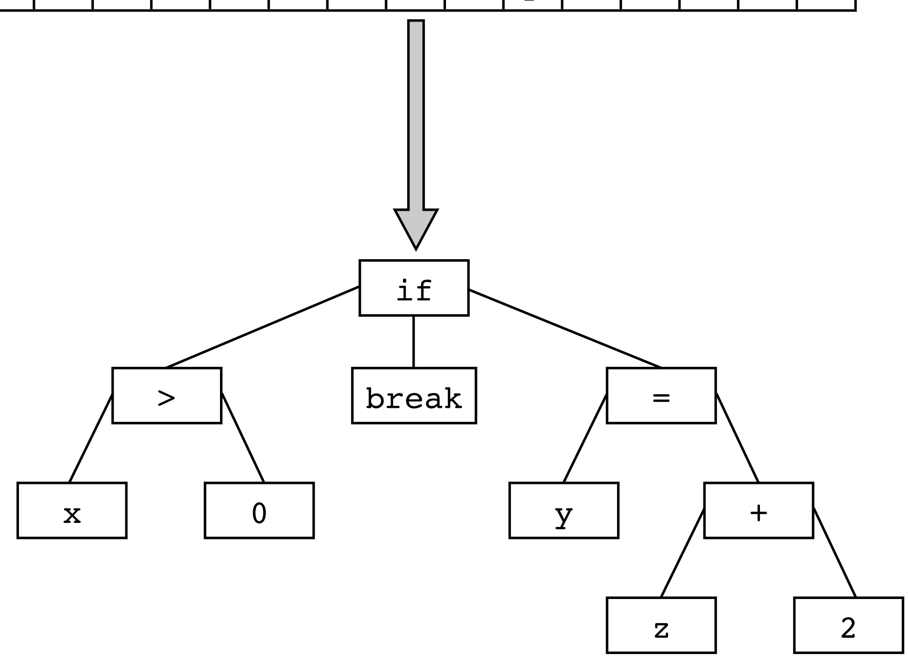
Syntax analysis

$$\text{language} = \begin{cases} \text{syntax} = \begin{cases} \text{concrete} \\ \text{abstract} \end{cases} \\ \text{semantics} = \begin{cases} \text{static} \\ \text{dynamic} \end{cases} \end{cases}$$

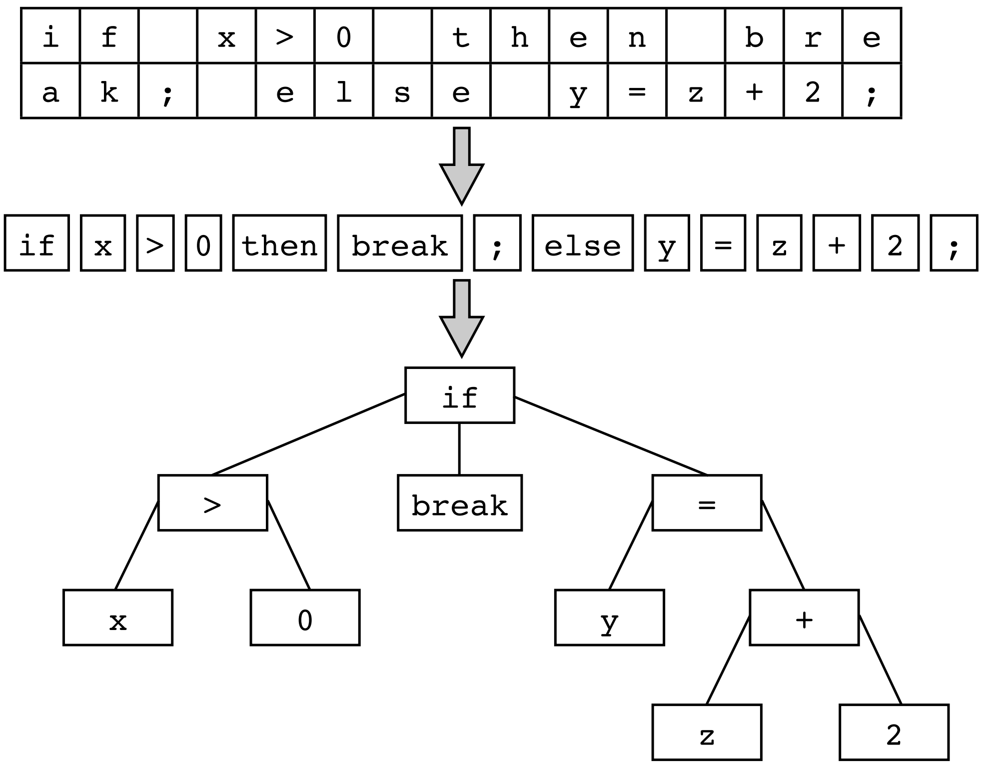
This is one of the areas where theoretical computer science has had major impact on the practice of software development

Syntax analysis

i	f		x	>	0		t	h	e	n		b	r	e
a	k	;		e	l	s	e		y	=	z	+	2	;



Syntax analysis



Combined lexical analysis and parsing?

- It isn't technically necessary to separate lexical analysis and parsing
- But it does have several potential benefits

  Simpler design (separation of concerns)

  Potentially more efficient (parsing often uses more expensive techniques than lexical analysis)

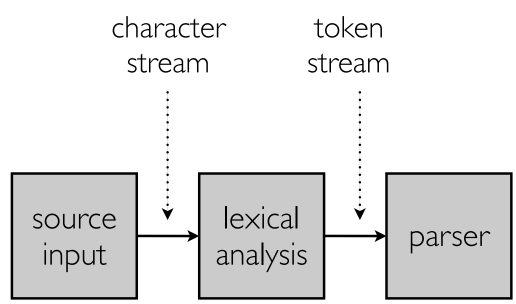
  Isolates machine/character set dependencies in the lexer

  Good tool support (e.g., lex, yacc)

- Modern language specifications often separate lexical and grammatical syntax

Basics of lexical analysis

Lexical analysis



- Lexical analysis is carried out by a

  lexical analyzer
  lexer
  scanner

  synonyms

- Goal: to recognize and identify the sequence of tokens represented by a the characters in a program text
- The definition of tokens (or "lexical structure") is an important part of many language specifications

Basic terminology

- Lexeme: a particular sequence of characters that might appear together in an input stream as the representation for a single entity
- Examples of lexemes in Java include:

  "`0.0`", "`3.14`", "`1e-97d`"
  "`true`", "`false`"
  "`if`", "`then`", "`int`"
  "`String`", "`main`"

Basic terminology

- Token: a name for a set of lexemes (a description of what each lexeme represents)
- Examples in Java include:

"`0.0`", "`3.14`", "`1e-97d`"	are double literals	tokens
"`true`", "`false`"	are boolean literals	
"`if`", "`then`", "`int`"	are keywords	
"`String`", "`main`"	are identifiers	

- Tokens/lexemes are normally chosen so that each lexeme has just one token type

Basic terminology

- Pattern: a description of the way that lexemes are written
- In the Java language specification:

  "an identifier is an unlimited-length sequence of Java letters and Java digits. An identifier cannot have the same spelling as a keyword ..."

- We'll see how to make this kind of thing more precise soon by using regular expressions as patterns

Common token types

- Keywords, symbols, punctuation

  `for`, `if`, `then`, `<=`, `+`, `(`, `;`, `.`, ...

- Literals and constants

  integers
  floating point numbers
  characters
  strings
  etc.

- Identifiers

  `String`, `main`, `awt`, `handler`, `Exception`, `i`, ...

Token attributes

- Some tokens may have associated attributes
- In some cases, the lexeme itself might be used as the attribute (e.g., the text of an identifier name)
- The value represented by a literal/constant might be treated as an attribute
- For error reporting, we might include positional information
  - name of source file
  - line/column number
  - etc...
- Attributes capture properties of the lexeme by itself
  - e.g., the initial value of a variable is *not* a token attribute

Other input elements

- Other elements that may appear in the input stream (but are not tokens) include:
  - Whitespace: the space, tab, newline character, etc., which typically have no significance in the language other than to separate tokens
  - Comments, in various forms
  - Illegal characters
- These are filtered out during lexical analysis and not passed as tokens to the parser

Common comment types

- Single line

```
// C++, Java
-- occam, Haskell
;  Scheme, Lisp
#  csh, bash, sh, make
C  fortran
```

- Non-nesting brackets

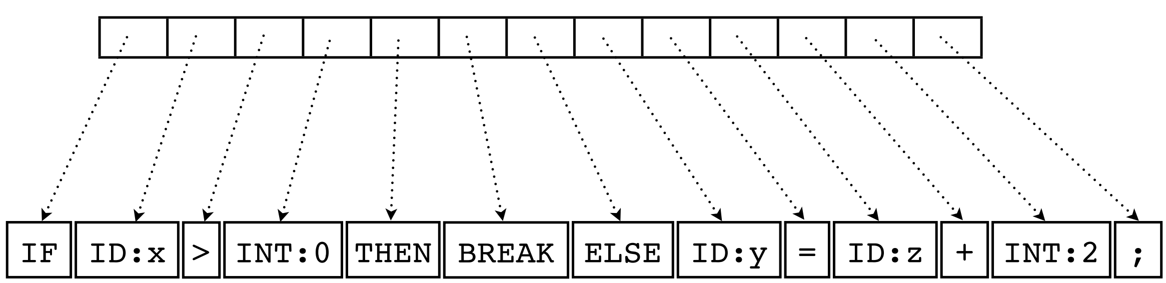
```
/* Prolog, C, C++, Java */
```

- Nesting brackets

```
(* Pascal, Modula-2, ML *)
{- Haskell -}
```


Representing token streams

- In principle, we could construct an array containing a separate data object for each lexeme in the input stream



- Different types of token object are needed for different types of token when the number and type of attributes vary
- In practice, many compilers do not build token objects, but instead expect tokens to be read <u>in pieces</u>, and <u>on demand</u>

Lexical analysis for mini

```
/** Read the next token and return the
 *  corresponding integer code.
 */
int nextToken();

/** Returns the code for the current token.
 */
int getToken() {
    return token;
}

/** Returns the text (if any) for the current lexeme.
 */
String getLexeme() {
    return lexemeText;
}

/** Return a position describing where the current token
 *  was found.
 */
Position getPos();
```

advance to the next lexeme and return a code for the token type

read current token code

read current lexeme text

read current position

Recognizing identifiers

Suppose that c contains the character at the front of the input stream:

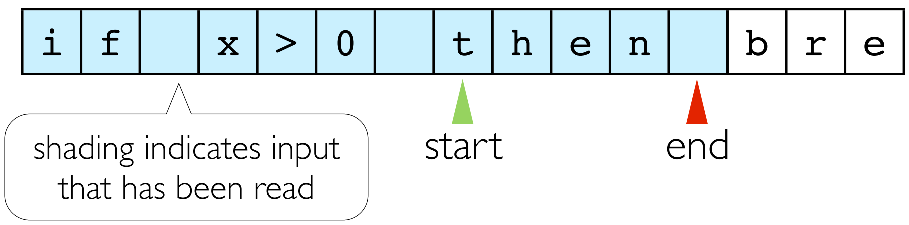
```
if (isIdentifierStart(c)) {

    do {
        c = readNextInputChar();
    } while (c!=EOF &&
             isIdentifierPart(c));

    return token=IDENT;
}
```

a symbolic constant, defined elsewhere, to represent identifier tokens

Buffering

input characters must be stored in a buffer ...

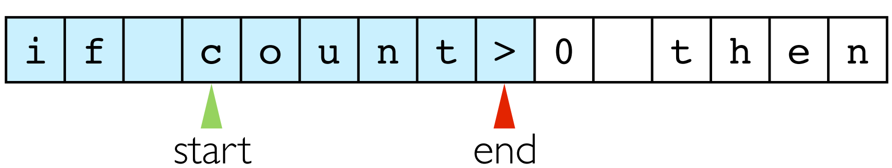
- because we often need to store the characters that constitute a lexeme until we find the end:



Buffering

input characters must be stored in a buffer ...

- because we might not know that we’ve reached the end of a token until we read the following character:

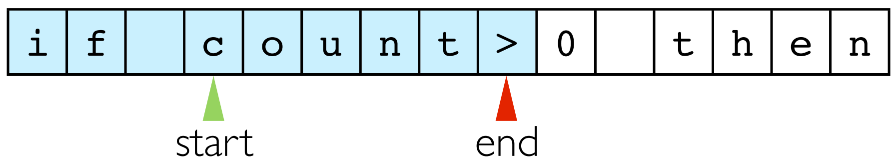


Buffering

input characters must be stored in a buffer ...

- because we might need to look ahead to see what tokens are coming:

Fortran 77



`do 10 c = 1,10` $\Longrightarrow$ `do` | `10` | `c` | `=` | `1` | `,` | `10`

`do 10 c = 1.10` $\Longrightarrow$ `do10c` | `=` | `1.10`

Impact on language design

- In some languages, only the first 32 characters of an identifier are significant; string literals cannot have more than 256 characters; etc.

  Why? Because these put a bound on the size of the buffer that is needed

- In modern language designs, typically only one or two characters of lookahead are required for lexical analysis

- In modern language designs, whitespace is not typically allowed in the middle of a lexeme

Buffering in the mini compiler's lexer

```
Source source;
String line;
int col = (-1);
int c;

void nextLine() {
    line = source.readLine();
    col  = (-1);
    nextChar();
}

int nextChar() {
    if (line==null) {
        c   = EOF;
        col = 0;  // EOF is always at column 0
    } else if (++col>=line.length()) {
        c   = EOL;
    } else {
        c   = line.charAt(col);
    }
    return c;
}
```

a buffer containing a single line of text

current position in the buffer

read the next buffer from the source

read the next character from the current line buffer

Buffering in the mini compiler's lexer

```
/** Read the next token and return the corresponding integer code.
 */
public int nextToken() {
    for (;;) {
        skipWhitespace();
        lexemeText = null;
        switch (c) {
            case EOF   : return token=ENDINPUT;

            // Separators:
            case '('   : nextChar();
                         return token='(';
            case ')'   : nextChar();
                         return token=')';
            case '{'   : nextChar();
                         return token='{';
            case '}'   : nextChar();
                         return token='}';
            case ';'   : nextChar();
                         return token=';';
            case ','   : nextChar();
                         return token=',';
            ...
```

variable to hold text for current lexeme

simple, single character tokens

Continued ...

```
...
case '='  : nextChar();
            if (c=='=') {
                nextChar();
                return token=EQEQ;
            } else {
                return token='=';
            }
...
case '&'  : nextChar();
            if (c=='&') {
                nextChar();
                return token=CAND;
            } else {
                return token='&';
            }
...
```

could be either "=" or "==" ... which is it?

could be either "&" or "&&" ... which is it?

Continued ...

```
...
case '/'  : nextChar();
            if (c=='/') {
                skipOneLineComment();
            } else if (c=='*') {
               skipBracketComment();
            } else {
               return token = '/';
            }
            break;

...

default   : if (Character.isJavaIdentifierStart((char)c)) {
                return identifier();
            } else if (Character.digit((char)c, 10)>=0) {
                return number();
            } else {
                illegalCharacter();
                nextChar();
            }
        }
    }
}
```

could be either :
"//..." (single line comment)
"/*...*/" (bracketed comment)
"/" (division)
which is it?

variable length tokens: identifiers and integer literals

Recognizing identifiers (reprise)

If we only want to detect that an identifier was detected ...

```
if (isIdentifierStart(c)) {

    do {
        c = getChar();
    } while (c!= EOF &&
             isIdentifierPart(c));

    return token=IDENT;
}
```

How do we modify this to capture *which* identifier it was?

Identifying identifiers

The current input line also serves as a buffer for the lexeme text:

```
c = line.charAt(col);
if (isIdentifierStart(c)) {
    int start = col;
    do {
        c = line.charAt(++col);
    } while (col<=line.length &&
             isIdentifierPart(c));
    lexemeText = line.substring(start, col);
    return token=IDENT;
}
```

(If there are lexemes that can span multiple lines, then additional buffering would be required.)

Reflections

- We've seen several simple programming patterns here

  recognizing single characters
  recognizing distinct operators with a common prefix
  recognizing variable length lexemes
  ...

- None of these is particularly difficult (or interesting)
- One conclusion: this is a straightforward way to construct a lexer; a good approach for a quick project
- Another take: somewhat ad-hoc and error prone; maybe not the best approach from a software engineering perspective

Summary

- Lexical analysis converts character streams into token streams
- Buffering plays an important role
- But the techniques we've seen so far seem a little ad hoc ...

Lexical analysis using finite automata

Recognizing identifiers

- In the Java language specification:

  "an identifier is an unlimited-length sequence of Java letters and Java digits, the first of which must be a Java letter. An identifier cannot have the same spelling as a keyword ..."

- How can we make this description more precise?

Recognizing identifiers

- A concrete implementation:

```
c = line.charAt(col);
if (isIdentifierStart(c)) {
    int start = col;
    do {
        c = line.charAt(++col);
    } while (col<=line.length &&
             isIdentifierPart(c));
    lexemeText = line.substring(start, col);
    return token=IDENT;
}
```

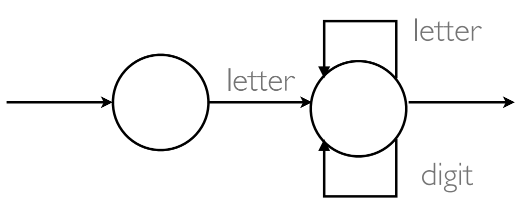
- How can we avoid unnecessary details?

Recognizing identifiers

- In more abstract terms:

  The pattern can be described by a regular expression:
  letter (letter|digit)*

  The recognition of an identifier can be described by a finite automaton:



- But this doesn't specify:

  How letter and digit are defined
  When does an identifier stop?
  What if we get stuck?

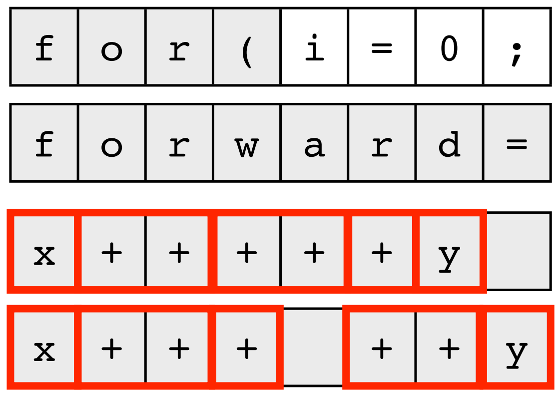
Maximal munch / longest lexeme

- A widely used convention:

  if there are two (or more) different lexemes that can be read at a given point in the input stream, always choose the longest alternative

- For example:

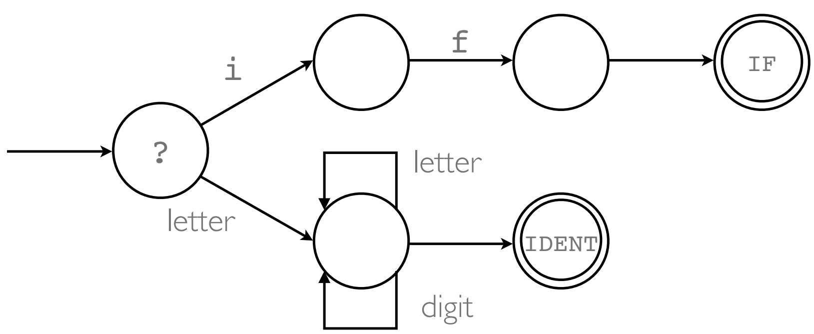
- Another classic:



[shading indicates how much of the input was read before the end of the token was found]

Non-determinism

- The lexeme "`if`" looks a lot like an identifier



- What do we do if the first input character is "`i`"?
- What if the first character is "`i`", we follow the top branch ... and then the next character is "`b`"?

Solution 1: backtracking

- When faced with multiple alternatives:

  Explore each alternative in turn

  Pick the alternative that leads to the longest lexeme

- Again, buffers play a key role, recording past input in case we need to go back

- But, in general, this approach is complex to program and potentially expensive to execute

Solution 2: postprocessing

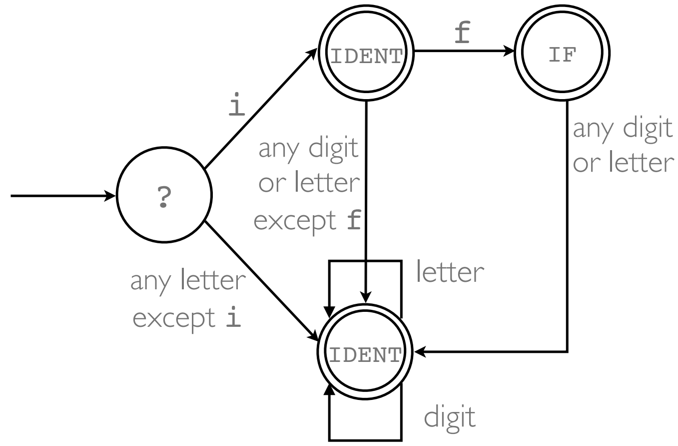
- To begin with, just treat and recognize "if" as a normal identifier

- But before we return identifiers as tokens, check them against a built-in table of keywords, and return a different type of token as necessary

- Simple and efficient (so long as we can look up entries in the keyword table without too much difficulty), but not always applicable

Solution 3: delay the decision!

- Find an equivalent machine without the conflict



- Recognizes the same set of lexemes, but without the ambiguity in how they are categorized as tokens
- Fiddly, hard to get right by hand

Another example

How do we recognize a comment?

it begins with `/*`

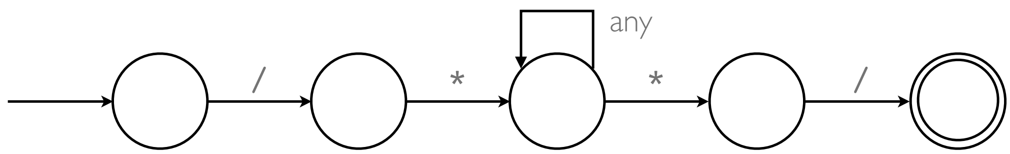
it ends with `*/`

any characters can appear in between

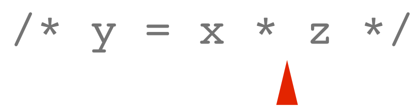
... (well, almost any characters)

Naive description

- A simple first attempt to recognize comments might lead to the following state machine:

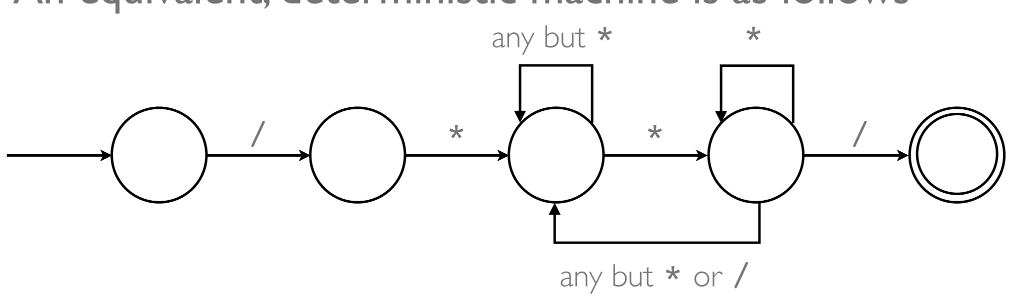


- But this machine can get stuck if we follow the second * branch too soon



A more careful approach

- The previous state machine is non-deterministic: there is a choice of distinct successor states for the character *, and we can't tell which branch to take without looking ahead
- An equivalent, deterministic machine is as follows



Code to read a comment

```
  if (c=='/') {          // Skip bracketed comment
    nextChar();
    if (c=='*') {
        nextChar();
        for (;;) {
            if (c=='*') {
                do { nextChar(); } while (c=='*');
                if (c=='/') {
                    nextChar();
                    return;
                }
            }
            if (c==EOF) { … Unterminated comment … }
            if (c==EOL) nextLine(); else nextChar();
        }
    }
}
```

complication: interaction with error handling

complication: interaction with source input

Handwritten lexical analyzers

- Doesn’t require sophisticated programming
- Often requires care to avoid non-determinism or potentially expensive backtracking
- Can be fine-tuned for performance and for the language concerned
- But it might also be something we would want to automate ...

Can a machine do better?

- It can be hard to write a (correct) lexer by hand ...
- But that's not surprising: finite state machines are low level, much like "an assembly language for lexical analysis"
- Can we build a lexical analyzer generator that will take care of all the dirty details (correctly) and let compiler developers work at a higher-level?
- If so, what would the input look like?

The lex family of lexer generators

The lex family

- `lex` is a tool for generating C programs to implement lexical analyzers

  input is a set of (regular expression + associated action) rules

  output is C source code for a lexer

- It can also be used a a quick way to generate simple text processing utilities
- `lex` dates from the mid-seventies and has spawned a family of clones: flex, JLex, JFlex, Alex, ML lex, etc...
- `lex` is based on ideas from the theory of formal languages and automata; remember CS311? Coming up in Lab 2!

Fragments from mini.jflex

```
"("              { return '('; }
")"              { return ')'; }
"{"              { return '{'; }
"}"              { return '}'; }
";"              { return ';'; }
...
"="              { return '='; }
"=="             { return EQL; }
">"              { return '>'; }
">="             { return GTE; }
...
"while"          { return WHILE; }
"if"             { return IF; }
"else"           { return ELSE; }
"print"          { return PRINT; }
"return"         { return RETURN; }
"new"            { return NEW; }
...
{Letter}({Letter}|{Digit})*
                 { semantic = new Id(yytext());     return IDENT; }

[0-9]+           { semantic = new IntLit(yytext()); return INTLIT; }

{ \t\n}          { /* ignore whitespace */ }
```

execute the associated action when we see input matching the left hand pattern

simple things should be easy

let the lexer generator figure out how to deal with ambiguity!

Inside a lexer generator

The internals of a typical lexer generator typically involve multiple steps

regular expressions

↓

non-deterministic finite automata (NFA)

↓

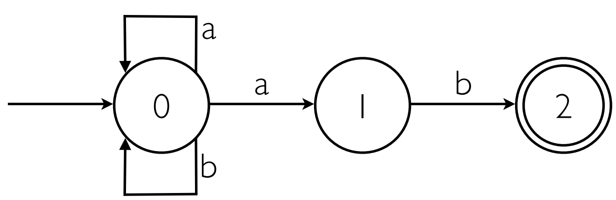
deterministic finite automata (DFA)

↓

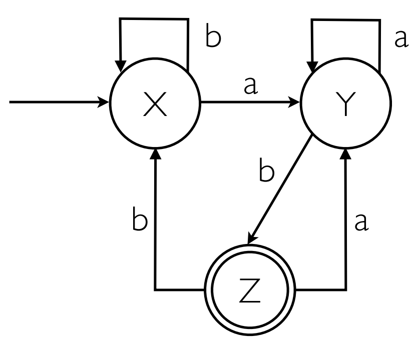
executable code / tables

Example

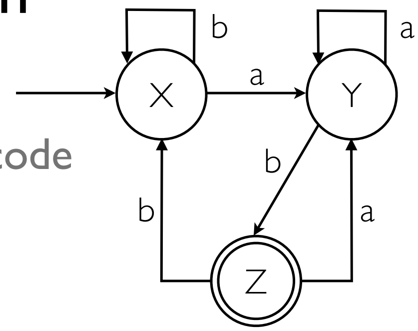
- Given a regular expression (a|b)*ab, we can build a corresponding NFA:



- And then we can derive a suitable DFA:



From DFA to implementation



So you've built a DFA ... what next?

- Option 1: generate custom executable code

```
stateX:  switch (getchar()) {
           case 'a' : goto stateY;
           case 'b' : goto stateX;
           default  : goto error;
         }
stateY:  ...
```

- Option 2: encode the machine in a table and interpret the transitions in the table during matching

State	'a'	'b'	'c'	accept?
X	Y	X	err	no
Y	Y	Z	err	no
Z	Y	X	err	yes

Variations on the theme

- There are lots of lex-like tools, each catering to particular

  programming languages
  operating systems/environments

- Most of them have more features that I have described on the previous slides; read the manual!
- They vary in minor details of syntax, etc., but the lex heritage is usually very clear
- For work in C/C++, I recommend flex
- For standalone lexer work in Java, I recommend JFlex. We'll also be using JavaCC for integrated lexing/parsing.

Handwritten or machine generated?

- A mildly controversial topic!
- Issues include:

  How efficient is the generated code?

  How easily does it interface to other code?

  How natural is the input? (If the language you are compiling has some awkward features, the lexers produced by a tool might need some massaging to "do the right thing")

  How good are the error messages?

Summary

- Regular expressions provide a high-level language for describing lexemes
- lex and family are useful tools for writing text processing utilities ... as well as lexers
- lex works by mapping regular expressions to NFAs, which are converted into DFAs, which are used to produce executable code

  key benefit: automates the task of eliminating non-determinism

- A handwritten or a machine generated lexer? The choice is yours!