CSE P 501 – Compilers

Languages, Automata, Regular Expressions & Scanners

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Agenda

- Quick review of basic concepts of formal grammars
- Regular expressions
- Lexical specification of programming languages
- Using finite automata to recognize regular expressions
- Scanners and Tokens

Programming Language Specs

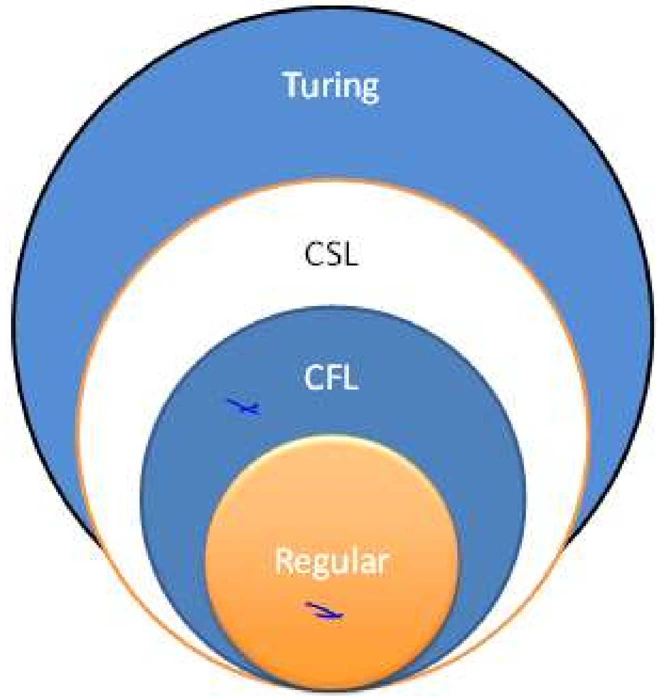
- Since the 1960s, the syntax of every significant programming language has been specified by a formal grammar
  - First done in 1959 with BNF (Backus-Naur Form), used to specify ALGOL 60 syntax
  - Borrowed from the linguistics community (Chomsky)

Formal Languages & Automata Theory (a review on one slide)

- Alphabet: a finite set of symbols and characters
- String: a finite, possibly empty sequence of symbols from an alphabet
- Language: a set of strings (possibly empty or infinite)
- Finite specifications of (possibly infinite) languages
  - Automaton – a recognizer; a machine that accepts all strings in a language (and rejects all other strings)
  - Grammar – a generator; a system for producing all strings in the language (and no other strings)
- A particular language may be specified by many different grammars and automata
- A grammar or automaton specifies only one language

Language (Chomsky) hierarchy:

- Regular (Type-3) languages are specified by regular expressions/grammars and finite automata (FSAs)
  - Specs and implementation of scanners
- Context-free (Type-2) languages are specified by context-free grammars and pushdown automata (PDAs)
  - Specs and implementation of parsers
- Context-sensitive (Type-1) languages … aren't too interesting (for us, at least)
- Recursively-enumerable (Type-0) languages are specified by general grammars and Turing machines



Example:
Grammar for a Tiny Toy Language

program ::= *statement* | *program statement*

statement ::= *assignStmt* | *ifStmt*

assignStmt ::= *id* = *expr* ;

ifStmt ::= if (*expr*) *statement*

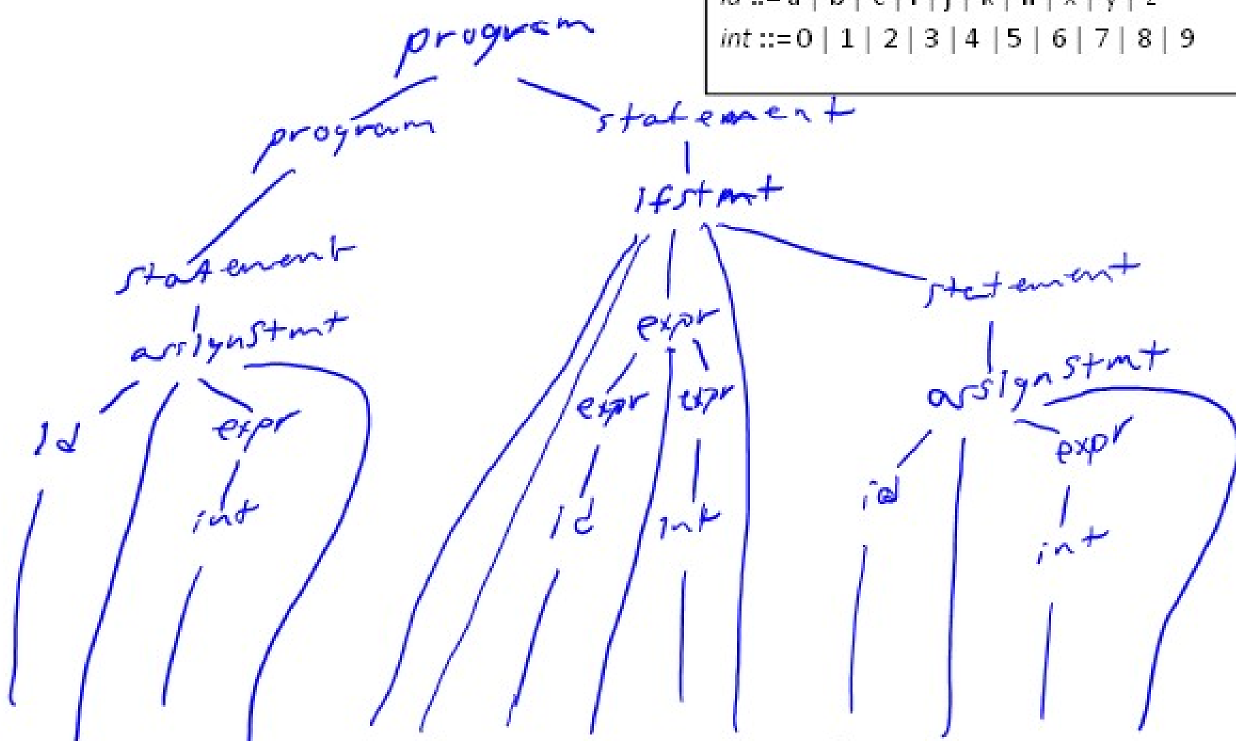
expr ::= *id* | *int* | *expr* + *expr*

id ::= a | b | c | i | j | k | n | x | y | z

int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

Exercise: Derive a simple program

program ::= *statement* | *program statement*
statement ::= *assignStmt* | *ifStmt*
assignStmt ::= *id* = *expr* ;
ifStmt ::= **if** (*expr*) *statement*
expr ::= *id* | *int* | *expr* + *expr*
id ::= a | b | c | i | j | k | n | x | y | z
int ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9



a = 1 ; if (a + 1) b = 2 ;

Productions

- The rules of a grammar are called productions
- Rules contain
  - Nonterminal symbols: grammar variables (*program*, *statement*, *id*, etc.)
  - Terminal symbols: concrete syntax that appears in programs (a, b, c, 0, 1, if, =, (,), ...
- Meaning of

  nonterminal ::= <sequence of terminals and nonterminals>

  In a derivation, an instance of nonterminal can be replaced by the sequence of terminals and nonterminals on the right of the production
- Often there are several productions for a nonterminal – can choose any at different points of a derivation

Alternative Notations

- There are several syntax notations for productions in common use; all mean the same thing

  ifStmt ::= if (*expr*) *statement*

  ifStmt → if (*expr*) *statement*

  <ifStmt> ::= if (<expr>) <statement>

Parsing

- Parsing: reconstruct the derivation (syntactic structure) of a program
- In principle, a single recognizer could work directly from a concrete, character-by-character grammar
- In practice this is never done

Parsing & Scanning

- In real compilers the recognizer is split into two phases
  - Scanner: translate input characters to tokens
    - Also, report lexical errors like illegal characters and illegal symbols
  - Parser: read token stream and reconstruct the derivation

Why Separate the Scanner and Parser?

- Simplicity & Separation of Concerns
  - Scanner hides details from parser (comments, whitespace, input files, etc.)
  - Parser is easier to build; has simpler input stream (tokens) / narrow interface
- Efficiency
  - Scanner recognizes regular expressions – proper subset of context free grammars

    (But still often consumes a surprising amount of the compiler's total execution time)

But …

foo x;
foo = 17;

- Not always possible to separate cleanly
- Example: C/C++/Java *type* vs *identifier*
  - Parser would like to know which names are types and which are identifiers, but…
  - Scanner doesn't know how things are declared
- So we hack around it somehow…
  - Either use simpler grammar and disambiguate later, or communicate between scanner & parser
  - Engineering issue: try to keep interfaces as simple & clean as possible

Typical Tokens in Programming Languages

- Operators & Punctuation
  - + - * / ( ) { } [ ] ; : :: < <= == = != ! …
  - Each of these is a distinct lexical class
- Keywords
  - if while for goto return switch void …
  - Each of these is also a distinct lexical class (*not* a string)
- Identifiers
  - A single ID lexical class, but parameterized by actual id
- Integer constants
  - A single INT lexical class, but parameterized by int value
- Other constants, etc.

Principle of Longest Match

- In most languages, the scanner should pick the longest possible string to make up the next token if there is a choice
- Example

if+(

if

return maybe != iffy;

should be recognized as 5 tokens

RETURN	ID(maybe)	NEQ	ID(iffy)	SCOLON

i.e., != is one token, not two; "iffy" is an ID, not IF followed by ID(fy)

Lexical Complications

- Most modern languages are free-form
  - Layout doesn't matter
  - Whitespace separates tokens
- Alternatives
  - Fortran – line oriented
  - Haskell, Python – indentation and layout can imply grouping

a>>

- And other confusions
  - In C++ or Java, is >> a shift operator or the end of two nested templates or generic classes?

Regular Expressions and FAs

- The lexical grammar (structure) of most programming languages can be specified with regular expressions

    (Sometimes a little cheating is needed)

- Tokens can be recognized by a deterministic finite automaton
    - Can be either table-driven or built by hand based on lexical grammar

Regular Expressions

- Defined over some alphabet Σ
  - For programming languages, alphabet is usually ASCII or Unicode
- If *re* is a regular expression, *L*(*re*) is the language (set of strings) generated by *re*

Fundamental REs

re	*L*(*re*)	Notes
a	{ a }	Singleton set, for each a in Σ
ε	{ ε }	Empty string
∅	{ }	Empty language

Operations on REs

re	*L*(*re*)	Notes
rs	L(r)L(s)	Concatenation
r|s	L(r)∪ L(s)	Combination (union)
r*	L(r)*	0 or more occurrences (Kleene closure)

- Precedence: * (highest), concatenation, | (lowest)
- Parentheses can be used to group REs as needed
- In "real" regular expression tools, need some way to "escape" literal '*' or '|' characters vs. operators – but don't worry, or use different fonts, for math. regexps.

Examples

<table>
<tr><th>re</th><th>Meaning</th></tr>
<tr><td>+</td><td>single + character</td></tr>
<tr><td>!</td><td>single ! character</td></tr>
<tr><td>=</td><td>single = character</td></tr>
<tr><td>!=</td><td>2 character sequence "!="</td></tr>
<tr><td>xyzzy</td><td>5 character sequence ”xyzzy”</td></tr>
<tr><td>(1|0)*</td><td>0 or more binary digits</td></tr>
<tr><td>(1|0)(1|0)*</td><td>1 or more binary digits</td></tr>
<tr><td>0|1(0|1)*</td><td>sequence of binary digits with no leading 0’s, except for 0 itself</td></tr>
</table>

Derived Operators

- The basic operations generate all possible regular expressions, but there are common abbreviations used for convenience. Some examples:

Abbr.	Meaning	Notes
r+	(rr*)	1 or more occurrences
r?	(r | ε)	0 or 1 occurrence
[a-z]	(a|b|…|z)	1 character in given range
[abxyz]	(a|b|x|y|z)	1 of the given characters

More Examples

re	Meaning
[abc]+ (a|b|c)+ (a|b|c)(a|b|c)*	all strings w/ 1 or more a's, b's + c's
[abc]*	" 0 or more "
[0-9]+ (0|1|2|...|9)+	all non-empty strings of decimal digits
[1-9][0-9]*	— that don't start w/ 0
[a-zA-Z][a-zA-Z0-9_]*	id

Abbreviations / Naming

- Many systems allow naming abbreviations to make writing and reading definitions or specifications easier

  name ::= *re*

  – Restriction: abbreviations may not be circular (recursive) either directly or indirectly (else would be non-regular)

Example

- Possible syntax for numeric constants

  digit ::= [0-9]

  digits ::= *digit*+

  number ::= *digits* (. *digits*)?
  ([eE] (+ | -)? *digits*) ?

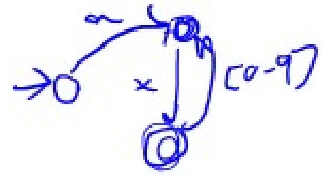
1.2e-3

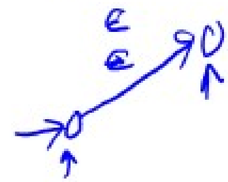
- How would you describe this set in English?
- What are some examples of legal constants (strings) generated by *number* ?
- What are the differences between these and numeric constants in YFPL? (Your Favorite Programming Language)

Recognizing REs

- Finite automata can be used to recognize strings generated by regular expressions
- Can build by hand or automatically
  - Reasonably straightforward, and can be done systematically
  - Tools like Lex, Flex, JFlex et seq do this automatically, given a set of Res
  - Same techniques used for grep, sed, other regular expression packages/tools

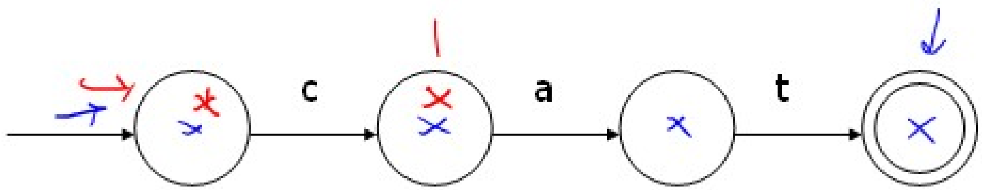
Finite State Automaton





- A finite set of states
  - One marked as initial state
  - One or more marked as final states
  - States sometimes labeled or numbered
- A set of transitions from state to state
  - Each labeled with symbol from Σ, or ε
- Operate by reading input symbols (usually characters)
  - Transition can be taken if labeled with current symbol
  - ε-transition can be taken at any time
- Accept when final state reached & no more input
  - Slightly different in a scanner where the FSA is a subroutine that accepts the longest input string matching a token regular expression, starting at the current location in the input
- Reject if no transition possible, or no more input and not in final state (DFA)
  - Some versions (including textbook) have an explicit "error" state and transitions to it on all "no legal transition possible" input. OK to omit that for CSE 401

Example: FSA for “~~cat~~”



~~c~~ow

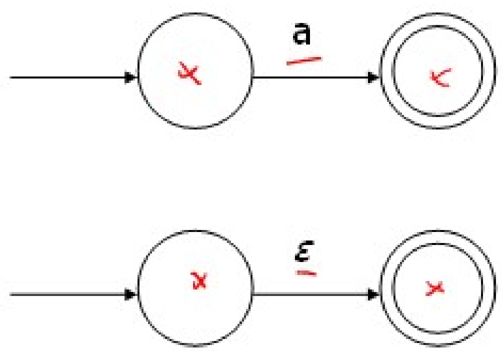
DFA vs NFA

- Deterministic Finite Automata (DFA)
  - No choice of which transition to take under any condition
  - No ε transitions (arcs)
- Non-deterministic Finite Automata (NFA)
  - Choice of transition in at least one case
  - Accept if some way to reach a final state on given input
  - Reject if no possible way to final state
  - i.e., may need to guess right path or backtrack

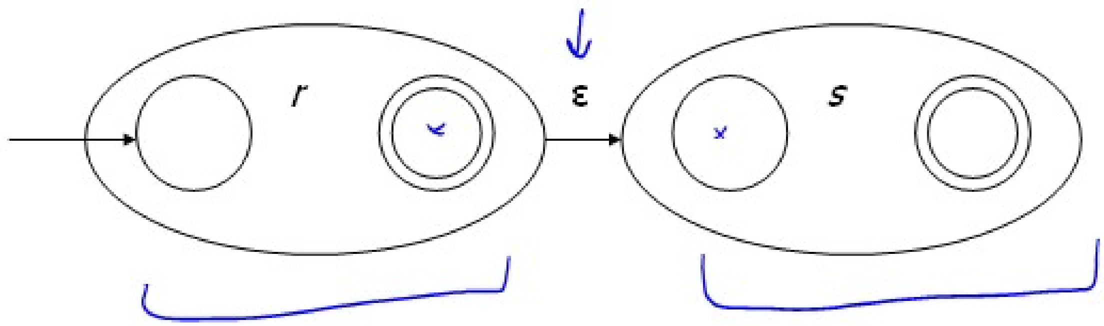
FAs in Scanners

- Want DFA for speed (no backtracking)
- But conversion from regular expressions to NFA is easy
- Fortunately, there is a well-defined procedure for converting a NFA to an equivalent DFA (subset construction – will not cover in detail)

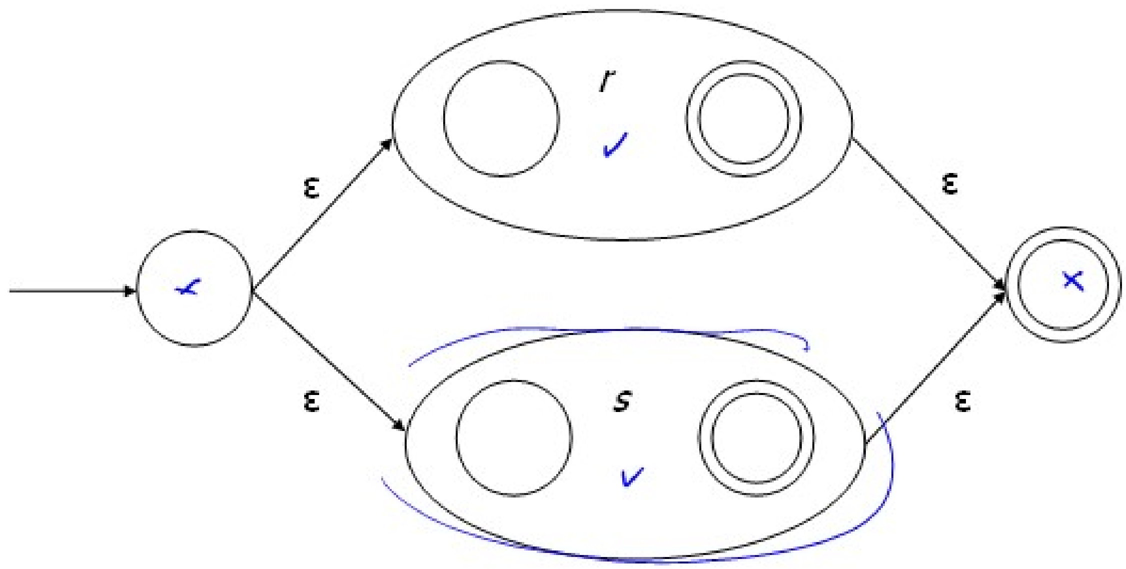
From RE to NFA: base cases



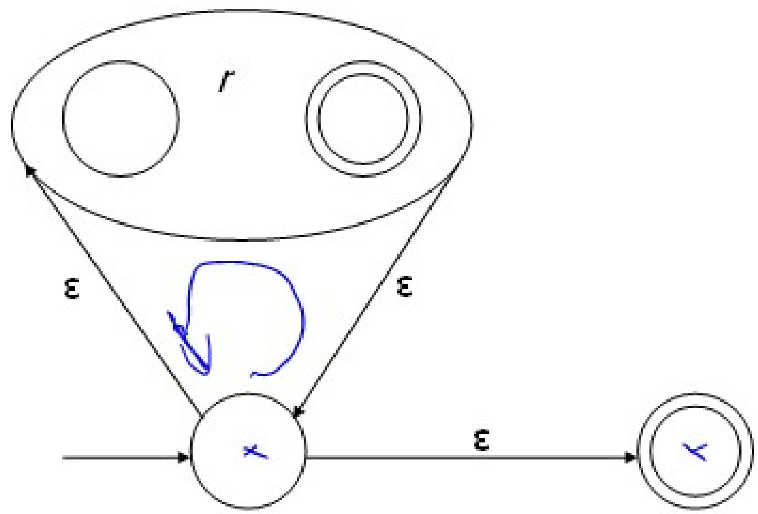
r s



$r \mid s$

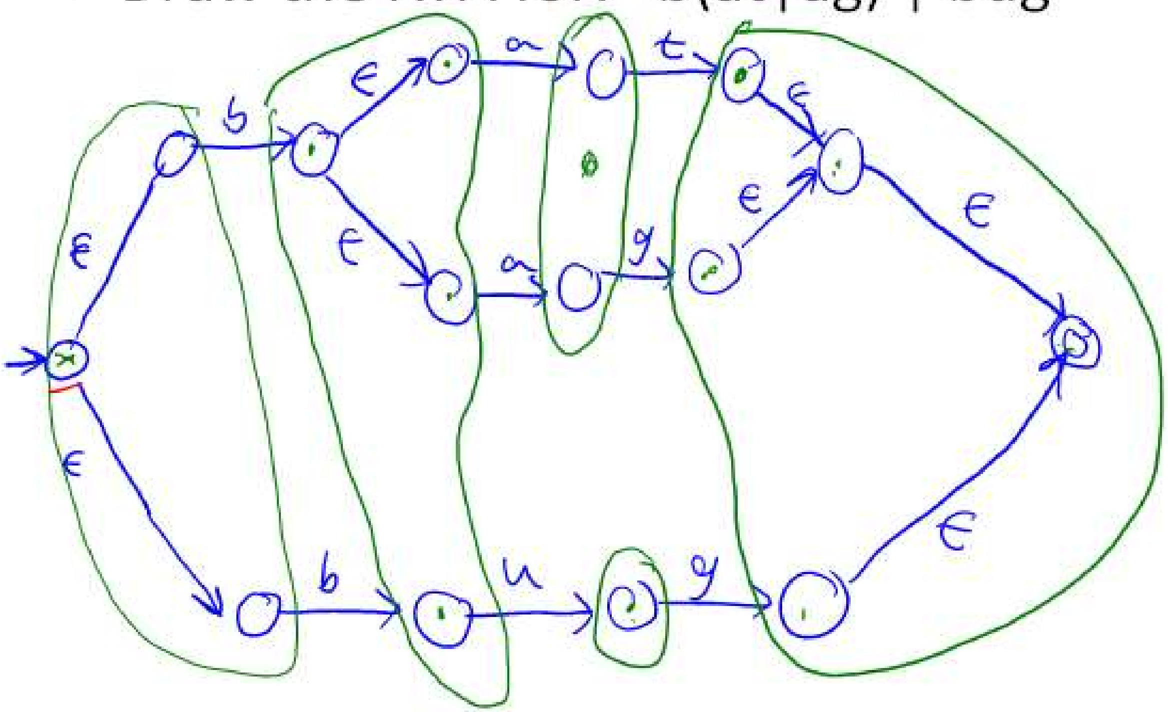


r *

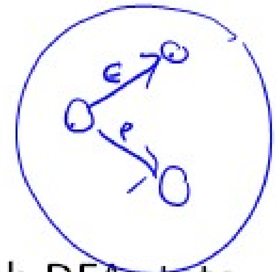


Exercise

- Draw the NFA for: b(at|ag) | bug



From NFA to DFA



- Subset construction
  - Construct a DFA from the NFA, where each DFA state represents a set of NFA states
- Key idea
  - State of the DFA after reading some input is the set of all NFA states that could have reached after reading the same input
- Algorithm: example of a fixed-point computation
- If NFA has n states, DFA has at most 2^n states
  - => DFA is finite, can construct in finite # steps
- Resulting DFA may have more states than needed
  - See books for construction and minimization algorithms

Exercise

- Build DFA for b(at|ag)|bug, given the NFA

To Tokens

- A scanner is a DFA that finds the next token each time it is called
- Every "final" state of a DFA emits (returns) a token
- Tokens are the internal compiler names for the lexemes
  - ==   becomes EQUAL
  - (becomes LPAREN
  - while becomes WHILE
  - xyzzy becomes ID(xyzzy)
- You choose the names
- Also, there may be additional data … \r\n might count lines; tokens might include line numbers

DFA => Code

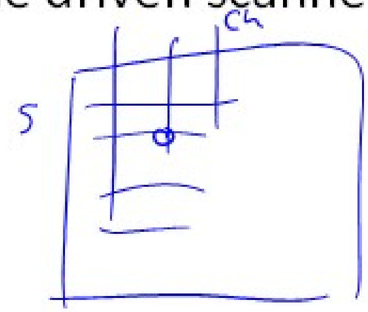
- Option 1: Implement by hand using procedures
  - one procedure for each token
  - each procedure reads one character
  - choices implemented using if and switch statements
- Pros
  - straightforward to write
  - fast
- Cons
  - a lot of tedious work
  - may have subtle differences from the language specification

DFA => Code [continued]

- Option 1a: Like option 1, but structured as a single procedure with multiple return points
  - choices implemented using if and switch statements
- Pros
  - also straightforward to write
  - faster
- Cons
  - a lot of tedious work
  - may have subtle differences from the language specification

DFA => code [continued]

- Option 2: use tool to generate table driven scanner
  - Rows: states of DFA
  - Columns: input characters
  - Entries: action
    - Go to next state
    - Accept token, go to start state
    - Error



- Pros
  - Convenient
  - Exactly matches specification, if tool generated
- Cons
  - "Magic"

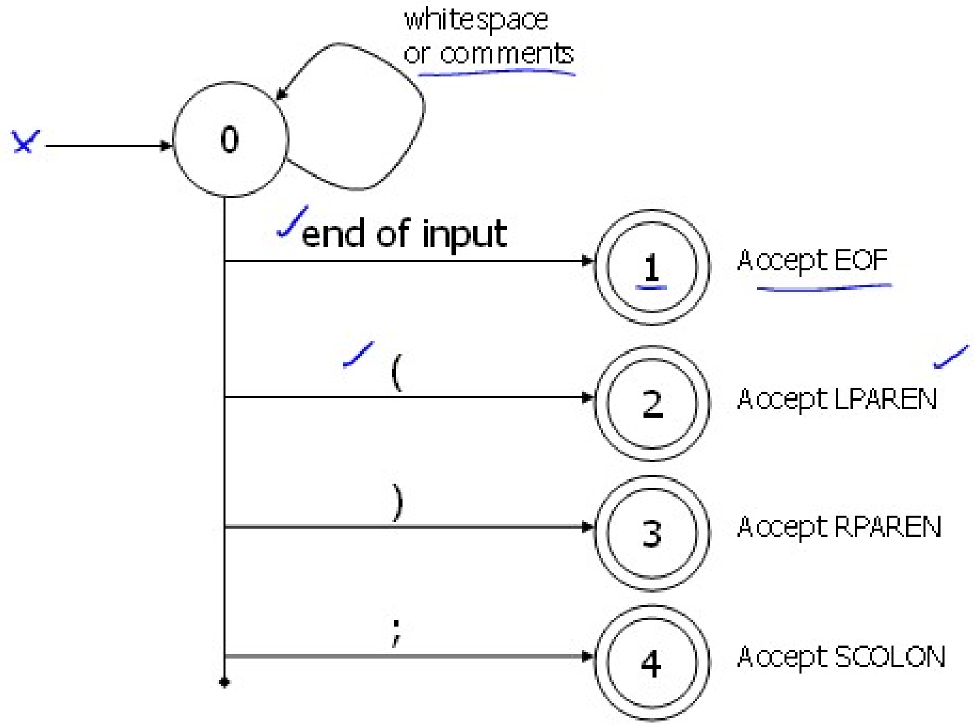
DFA => code [continued]

- Option 2a: use tool to generate scanner
  - Transitions embedded in the code
  - Choices use conditional statements, loops
- Pros
  - Convenient
  - Exactly matches specification, if tool generated
- Cons
  - “Magic”
  - Lots of code – big but potentially quite fast
    - Would never write something like this by hand, but can generate it easily enough

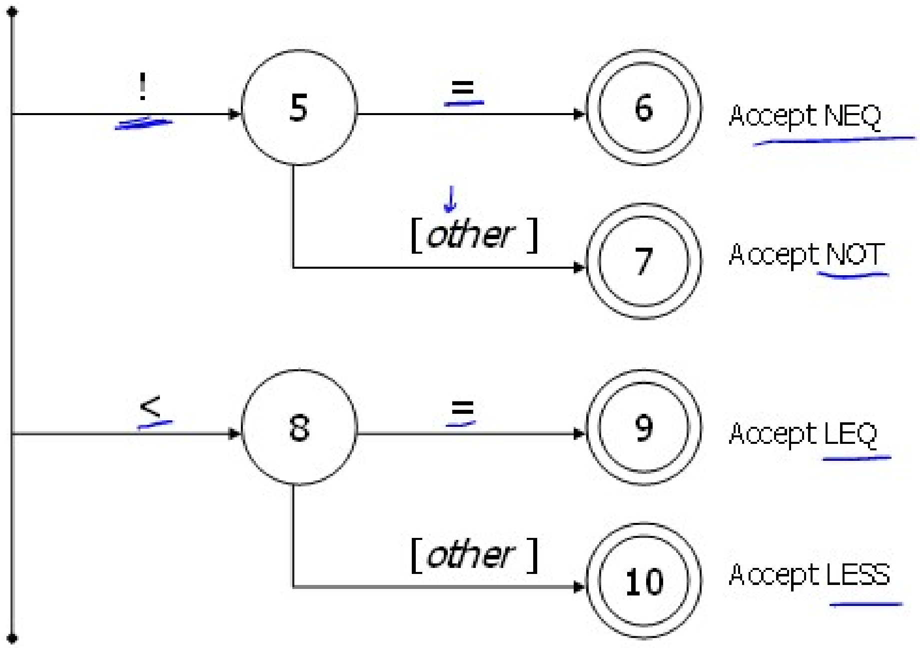
Example: DFA for hand-written scanner

- Idea: show a hand-written DFA for some typical programming language constructs
  - Then use to outline hand-written scanner
- Setting: Scanner is called whenever the parser needs a new token
  - Scanner knows (saves) current position in input
  - From there, use a DFA to recognize the longest possible input sequence that makes up a token and return that token; save updated position for next time
- Disclaimer: Example for illustration only – you'll use tools for the course project
  - & we're abusing the DFA notation a little – not all arrows in the diagram correspond to consuming an input character, but meaning should be pretty obvious

Scanner DFA Example (1)



Scanner DFA Example (2)



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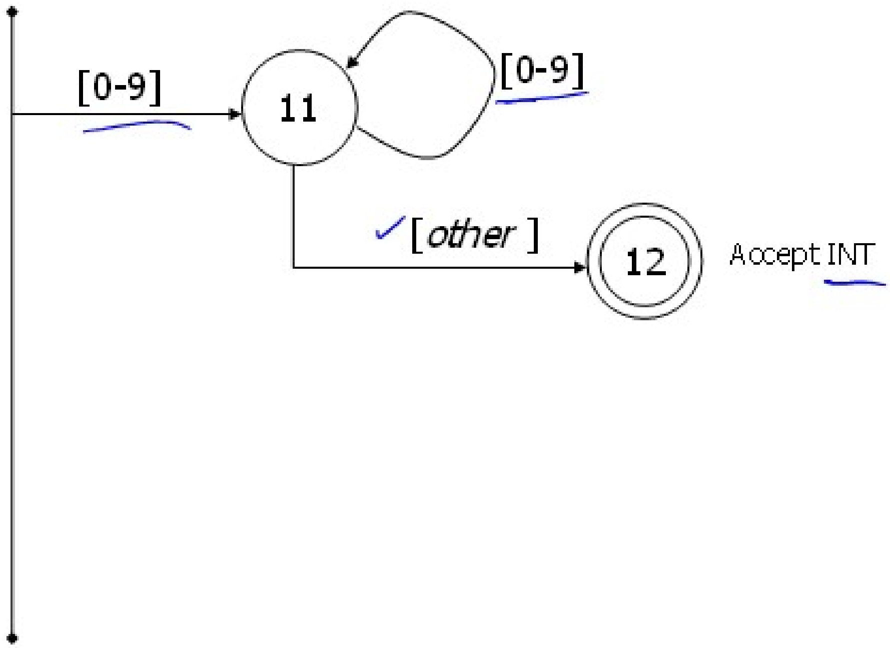
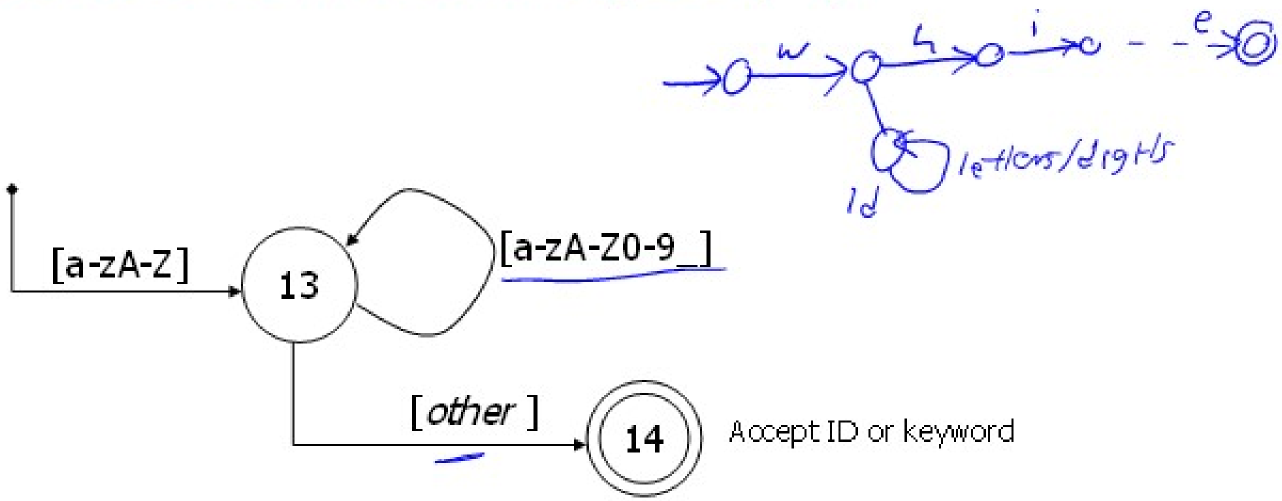
Scanner DFA Example (3)



Scanner DFA Example (4)



- Strategies for handling identifiers vs keywords
  - Hand-written scanner: look up identifier-like things in table of keywords to classify (good application of perfect hashing)
  - Machine-generated scanner: generate DFA will appropriate transitions to recognize keywords
    - Lots 'o states, but efficient (no extra lookup step)

Implementing a Scanner by Hand – Token Representation

- A token is a simple, tagged structure

```
public class Token {
   public int kind;          // token's lexical class
   public int intVal;        // integer value if class = INT
   public String id;         // actual identifier if class = ID
   // useful extra information for debugging / diagnostics:
   public int line;
   public int column;
   // lexical classes (ancient java – better to use enums)
   public static final int EOF = 0;     // "end of file" token
   public static final int ID   = 1;    // identifier, not keyword
   public static final int INT = 2;     // integer
   public static final int LPAREN = 4;
   public static final int SCOLN   = 5;
   public static final int WHILE   = 6;
   // etc. etc. etc. ...
```

Simple Scanner Example

```
// global state and methods

static char nextch;     // next unprocessed input character

// advance to next input char
void getch() { … }

// skip whitespace and comments
void skipWhitespace() { … }
```

Scanner getToken() method

```
// return next input token
public Token getToken() {
 Token result;

 skipWhiteSpace();

 if (no more input) {
    result = new Token(Token.EOF); return result;
 }

 switch(nextch) {
    case '(': result = new Token(Token.LPAREN); getch(); return result;
    case ')': result = new Token(Token.RPAREN); getch(); return result;
    case ';': result = new Token(Token.SCOLON); getch(); return result;

    // etc. ...
```

getToken() (2)

```
case '!': // ! or !=
  getch();
  if (nextch == '=') {
    result = new Token(Token.NEQ); getch(); return result;
  } else {
    result = new Token(Token.NOT); return result;
  }

case '<': // < or <=
  getch();
  if (nextch == '=') {
    result = new Token(Token.LEQ); getch(); return result;
  } else {
    result = new Token(Token.LESS); return result;
  }
// etc. ...
```

getToken() (3)

```
case '0': case '1': case '2': case '3': case '4':
case '5': case '6': case '7': case '8': case '9':
   // integer constant
   String num = nextch;
   getch();
   while (nextch is a digit) {
     num = num + nextch; getch();
   }
   result = new Token(Token.INT, Integer(num).intValue());
   return result;
...
```

getToken() (4)

```
case 'a': ... case 'z':
case 'A': ... case 'Z':  // id or keyword
  string s = nextch; getch();
  while (nextch is a letter, digit, or underscore) {
    s = s + nextch; getch();
  }
  if (s is a keyword) {
    result = new Token(keywordTable.getKind(s));
  } else {
    result = new Token(Token.ID, s);
  }
  return result;
```

MiniJava Scanner Generation

x=17y;

x=17#y;

- We'll use the jflex tool to automatically create a scanner from a specification file
- We'll use the CUP tool to automatically create a parser from a specification file
- Token class defs. shared by jflex and CUP. Lexical classes are listed in CUP's input file and it generates the token class definition.

TODO & Coming Attractions

- Homework this week: paper exercises on regular expressions & automata. Due Monday night – submit via gradescope (details on assignment)
- Find a partner for the project and fill out partner info form on web site by next week
- Next topic: parsing
  - Will do LR parsing first – we need this for the project, then LL (recursive-descent) parsing, which you should also know
  - Good time to start reading ahead