CSE 413
Programming Languages & Implementation

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Grammars, Scanners & Regular Expressions

Agenda

- Overview of language recognizers
- Basic concepts of formal grammars
- Scanner Theory
  - Regular expressions
  - Finite automata (to recognize regular expressions)
- Scanner Implementation

And the point is…

- How do we execute this?

```
int nPos = 0;
int k = 0;
while (k < length) {
      if (a[k] > 0) {
          nPos++;
      }
}
```

- Or, more concretely, how do we program a computer to understand and carry out a computation described in a programming language?

Compilers vs. Interpreters (recall)

- Interpreter
  - A program that reads a source program and executes that program
- Compiler
  - A program that translates a program from one language (the source) to another (the target)

- For both of these we need to represent the program in some suitable data structure (usually a tree)
  - With MUPL we started with the tree and didn't worry about where it came from

Interpreter

- Interpreter
  - Execution engine
  - Program execution interleaved with analysis

```
running = true;
while (running) {
    analyze next statement;
    execute that statement;
}
```

  - May involve repeated analysis of some statements (loops, functions)
  - MUPL was a special case of this – a function to evaluate expressions under a given environment

Compiler

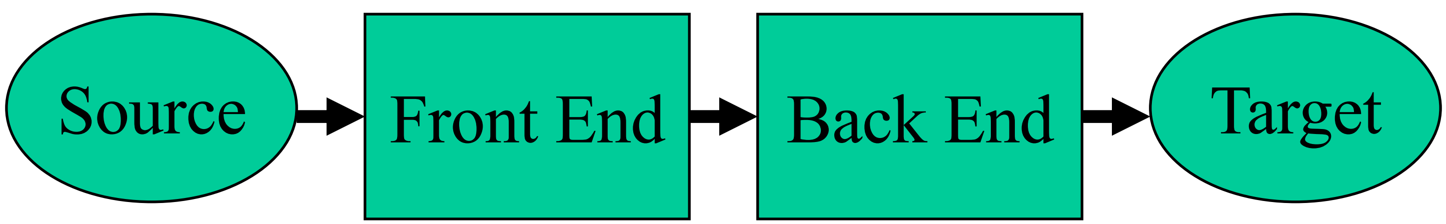
- Read and analyze entire program
- Translate to semantically equivalent program in another language
  - Presumably easier to execute or more efficient
  - Usually “improve” the program in some fashion
- Offline process
  - Tradeoff: compile time overhead (preprocessing step) vs execution performance

Hybrid approaches

- Well-known example: Java
  - Compile Java source to byte codes – Java Virtual Machine language (.class files)
  - Execution
    - Interpret byte codes directly (interpreter in JVM), or
    - Compile some or all byte codes to native code
      - Just-In-Time compiler (JIT) – detect hot spots & compile on the fly to native code when method is called

Compiler/Interpreter Structure

- First approximation
  - Front end: analysis
    - Read source program and understand its structure and meaning
  - Back end: synthesis
    - Execute or generate equivalent target program



Common Issues

- Compilers and interpreters both must read the input – a stream of characters – and "understand" it: analysis

```
w h i l e ( k < l e n g t h ) { <nl>
<tab> i f ( a [ k ] > 0 ) <nl> <tab>
<tab>{ n P o s + + ; } <nl> <tab> }
```

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 or Backus-Normal Form) used to specify the syntax of ALGOL 60
  - Adapted from the linguistics community (Chomsky)

Grammar for a Tiny 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

Context-Free Grammars

Formally, a grammar G is a tuple <N,Σ,P,S> where

- N a finite set of non-terminal symbols
- Σ a finite set of terminal symbols
- P a finite set of productions
  - A subset of $N \times (N \cup \Sigma)^*$
    - (can think of these as rules from $N \rightarrow (N \cup \Sigma)^*$)
- S the start symbol, a distinguished element of N
  - If not otherwise specified, this is usually assumed to be the non-terminal on the left of the first production

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 production

  nonterminal ::= <sequence of terminals and nonterminals>

  In a derivation, any instance of *nonterminal* can be replaced by the sequence of terminals and nonterminals on the right of the production
- Often, there are two or more productions for a single nonterminal – can use any at different points in a derivation

Alternative Notations

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

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

ifStmt $\longrightarrow$ if (*expr*) *stmt*

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

Example Derivation

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

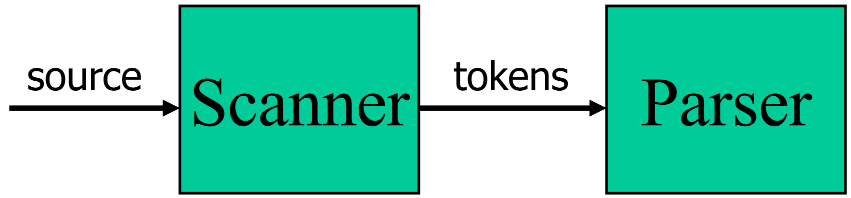
a = 1 ;   if (a + 1)   b = 2 ;

Parsing

- Parsing: reconstruct the derivation (syntactic structure) of a program
- In principle, a single recognizer could work directly from the 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
- Typically a procedural interface – parser asks the scanner for new tokens when needed



Scanner Example

- Input text

```
// this statement does very little
if (x >= y) y = 42;
```

- Token Stream

IF	LPAREN	ID(x)	GEQ	ID(y)
RPAREN	ID(y)	BECOMES	INT(42)	SCOLON

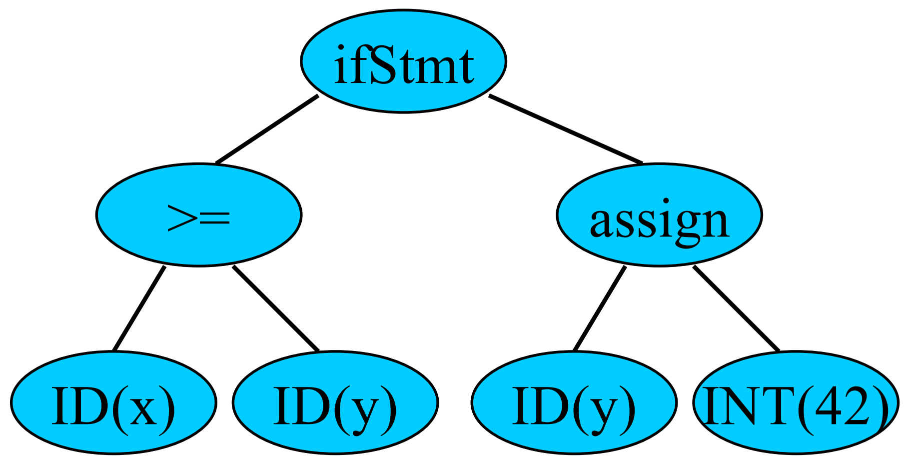
  - Tokens are atomic items, not character strings
  - Comments and whitespace are not tokens in most programming languages
    - But sometimes whitespace does matter
      Examples: Python indentation, Ruby newlines

Parser Example

- Token Stream Input

IF LPAREN ID(x)
GEQ ID(y) RPAREN
ID(y) BECOMES
INT(42) SCOLON

- Abstract Syntax Tree



Why Separate the Scanner and Parser?

- Simplicity & Separation of Concerns
  - Scanner hides details from parser (comments, whitespace, etc.)
  - Parser is easier to build; has simpler input stream (tokens)
- Efficiency
  - Scanner can use simpler, faster design
    - (But still often consumes a surprising amount of the compiler’s total execution time if you’re not careful)

Tokens

- Idea: we want a distinct token kind (lexical class) to represent each distinct terminal symbol in the programming language
  - Examine the grammar to find these
- Some tokens may have attributes. Examples:
  - All integer constants are a single kind of token, but the actual value (17, 42, …) will be an attribute
  - Identifier tokens carry the actual identifier string as an attribute of the token “identifier”

Typical Programming Language Tokens

- 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 (doubles, strings, …), 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

```
return iffy != dowhile;
```

should be recognized as 5 tokens

RETURN	ID(iffy)	NEQ	ID(dowhile)	SCOLON

not more (i.e., not parts of words or identifiers, not ! and = as separate tokens)

Formal Languages & Automata Theory (in one slide)

- Alphabet: a finite set of symbols
- String: a finite, possibly empty sequence of symbols from an alphabet
- Language: a set, often infinite, of strings
- 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

Regular Expressions and FAs

- The lexical grammar (structure) of most programming languages can be specified with regular expressions
  - Not always, e.g., FORTRAN and some others, but can usually cheat in the unusual corner cases
- Tokens can be recognized by a deterministic finite automaton (DFA)
  - Can be either table-driven or built by hand based on lexical grammar

- Facts (er, theorems): any language that can be generated by a regexp can be recognized by the corresponding DFA; for every DFA, there is a set of regular expressions that generate the language it recognizes

Regular Expressions

- Defined over some alphabet Σ
  - For programming languages, commonly 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	$L(r) \cup L(s)$	Combination (union)
r*	L(r)*	0 or more occurrences (Kleene closure)

- Precedence: * (highest), concatenation, | (lowest)
- Parentheses can be used to group REs as needed

Abbreviations

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

Examples

re	**Meaning**
+	single + character
!	single ! character
=	single = character
!=	2 character sequence
<=	2 character sequence
hogwash	7 character sequence

More Examples

re	Meaning
[abc]+	
[abc]*	
[0-9]+	
[1-9][0-9]*	
[a-zA-Z][a-zA-Z0-9_]*	

Abbreviations

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

  name ::= re

  – Restriction: abbreviations may not be circular (recursive) either directly or indirectly

    (otherwise it would no longer be a regular expression – would be a context-free grammar)

Example

- Possible syntax for numeric constants

```
digit ::= [0-9]
digits ::= digit+
number ::= digits  ( . digits )?
                          ( [eE] (+ | -)? digits ) ?
```

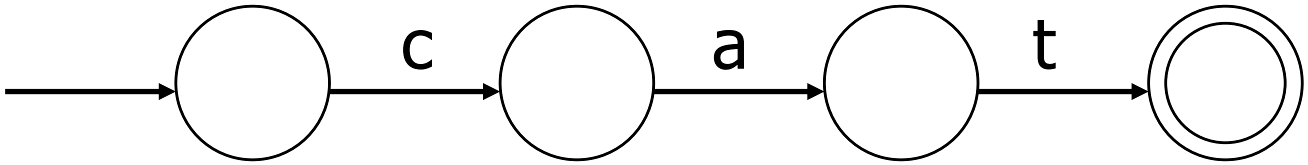
Recognizing REs

- Finite automata can be used to recognize strings generated by regular expressions
- Can build by hand or automatically
  - Not totally straightforward, but can be done systematically
  - Tools like Lex, Flex, and JLex do this automatically from a set of REs read as input
  - Even if you don't use a FA explicitly, it is a good way to think about the recognition problem

Finite State Automaton (FSA)

- 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
  - Difference in a scanner: start scan in initial state at previous point in input. When a final state is reached, recognize the token corresponding to that final state
- Reject if no transition possible, or no more input and not in final state (DFA)

Example: FSA for “cat”



DFA vs NFA

- Deterministic Finite Automata (DFA)
  - No choice of which transition to take under any condition
- Non-deterministic Finite Automata (NFA)
  - Choice of transition in at least one case
  - Accept - if some way to reach final state on given input
  - Reject - if no possible way to final state

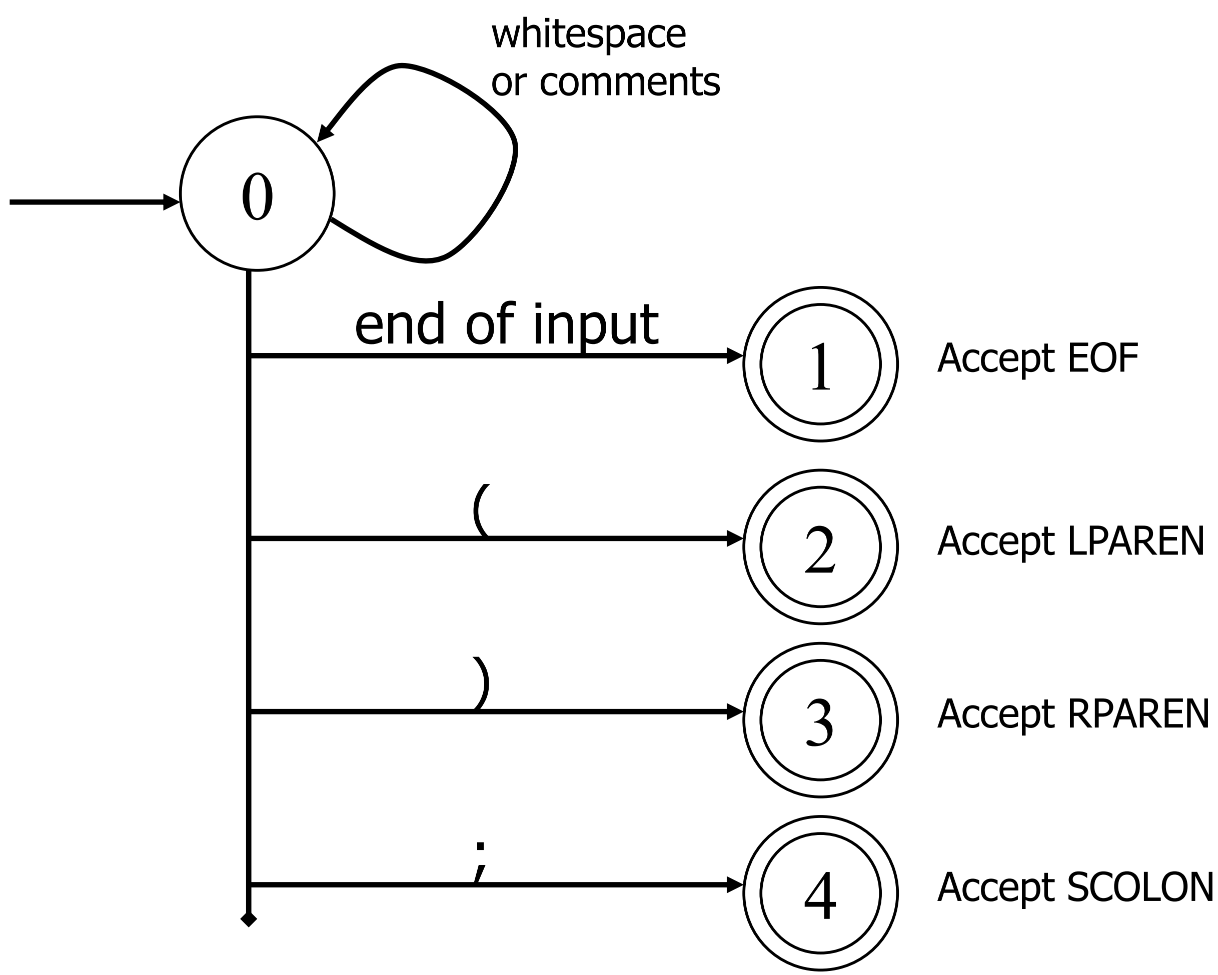
FAs in Scanners

- Want DFA for speed (no backtracking)
- Conversion from regular expressions to NFA is easy
- There is a well-defined procedure for converting a NFA to an equivalent DFA (subset construction)
  - See any formal language or compiler textbook for details (RE to NFA to DFA to minimized DFA)

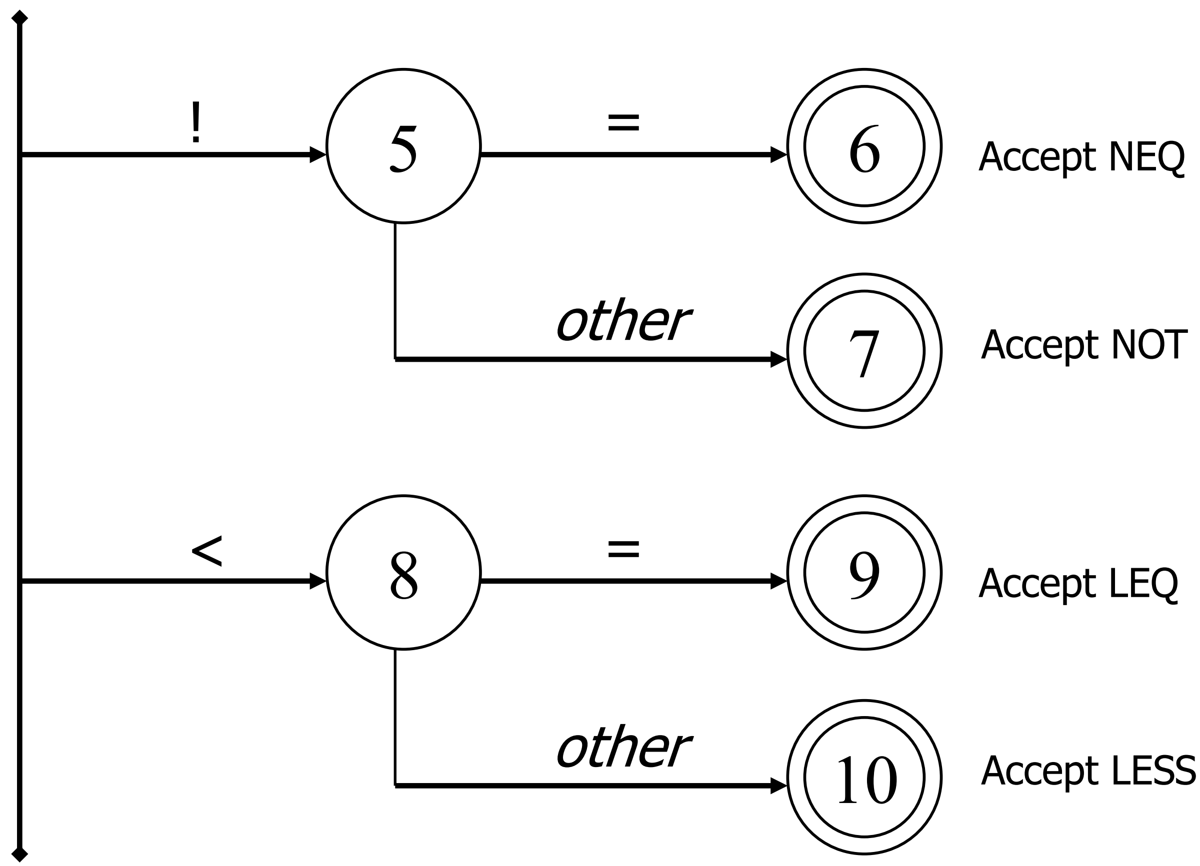
Example: DFA for hand-written scanner

- Idea: show a hand-written DFA for some typical programming language constructs
  - Then use the DFA to construct a hand-written scanner
- Setting: Scanner is called whenever the parser needs a new token
  - Scanner remembers current position in input file
  - Starting there, use a DFA to recognize the longest possible input sequence that makes up a token, update the “current position”, and return that token

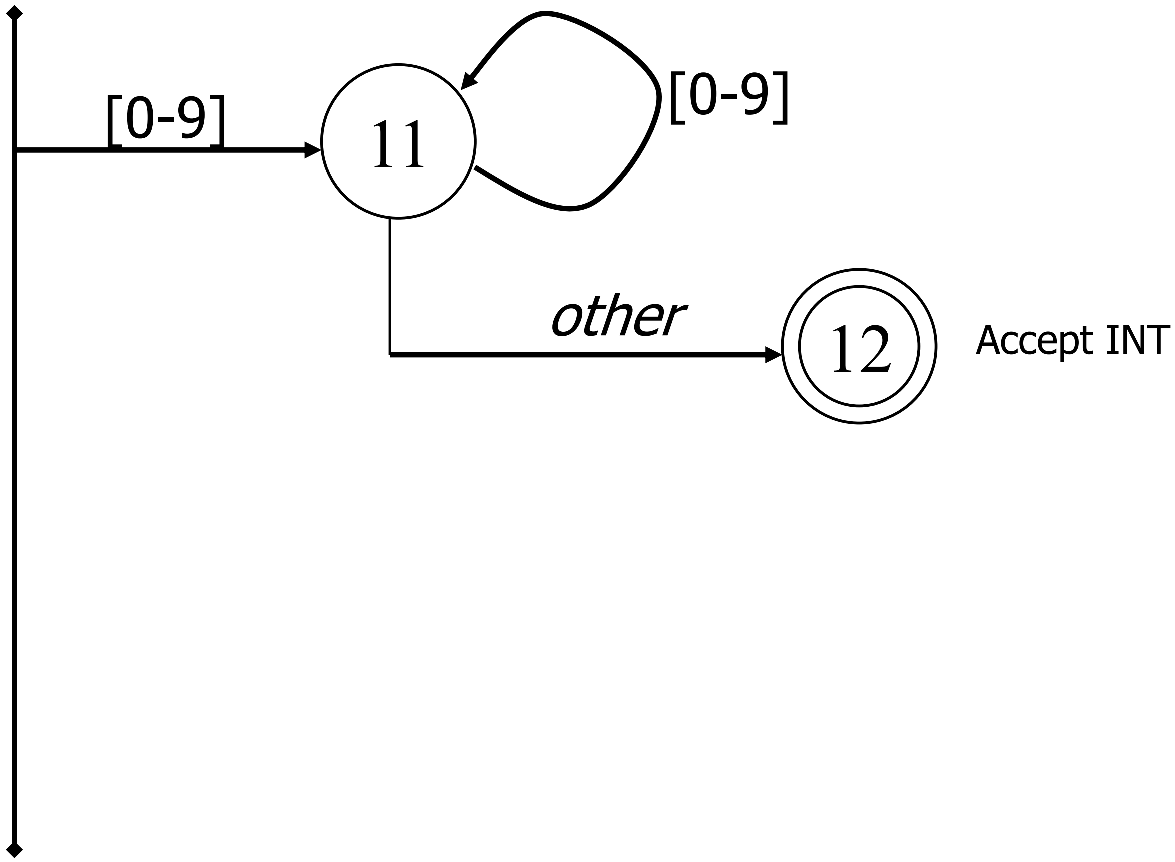
Scanner DFA Example (1)



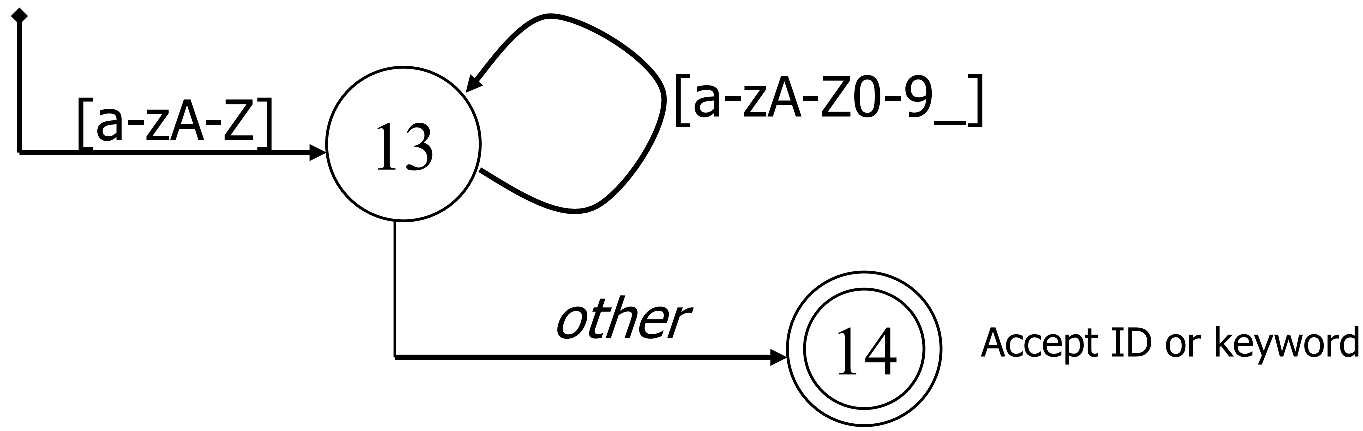
Scanner DFA Example (2)



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 with 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. Something like:

```
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
    // lexical classes (should really be an enum type)
    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. …           // but use enums if you've got 'em
```

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() pseudocode

```
// 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;
```

Alternatives

- Use a tool to build the scanner from the (regexp) grammar
  - Often can be more efficient than hand-coded!

- Build an ad-hoc scanner using regular expression package in implementation language
  - Ruby, Perl, Java, many others
  - Suggest you use this for our project (good excuse to learn the Ruby regexp package)