CSE P 501 – Compilers

Languages, Automata, Regular Expressions & Scanners

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Agenda

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

Read: textbook ch. 1 and ch. 2 sec. 2.1-2.4

Programming Language Specs

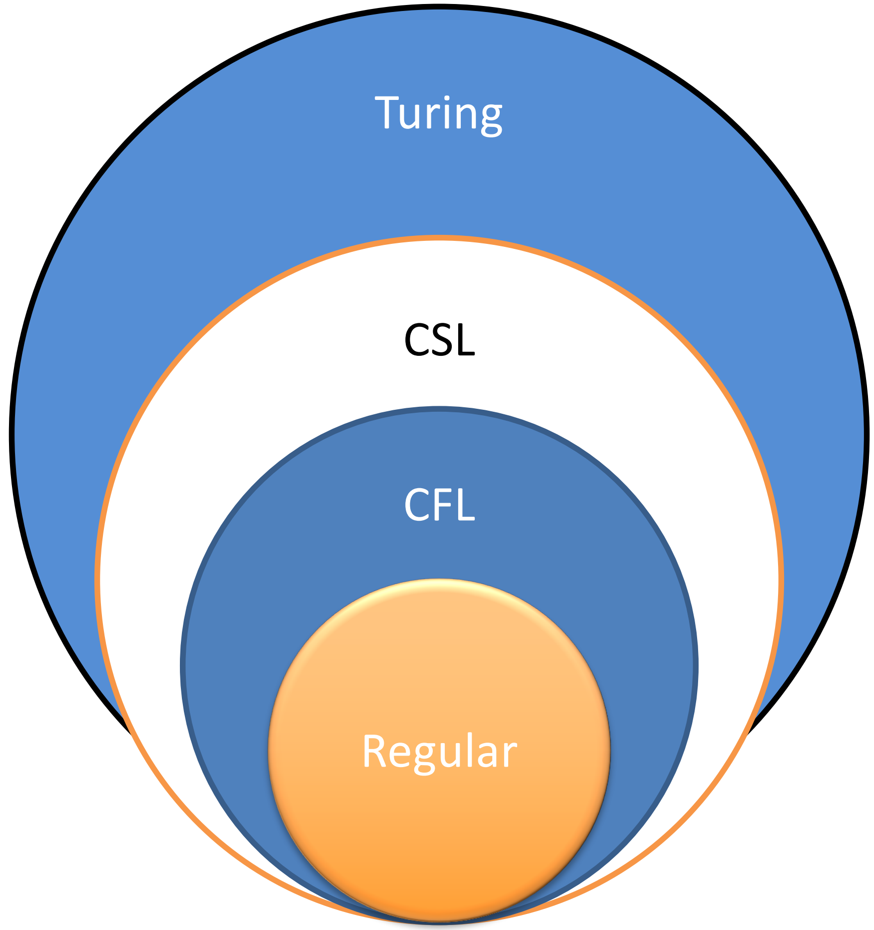
- Since the 1960s, the syntax of every significant programming language has been specified by a formal grammar
  - First done in 1959 with BNF (Backus-Naur Form), used to specify ALGOL 60 syntax
  - Borrowed from the linguistics community (Chomsky)

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* ;

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

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

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

Exercise: Derive a simple program

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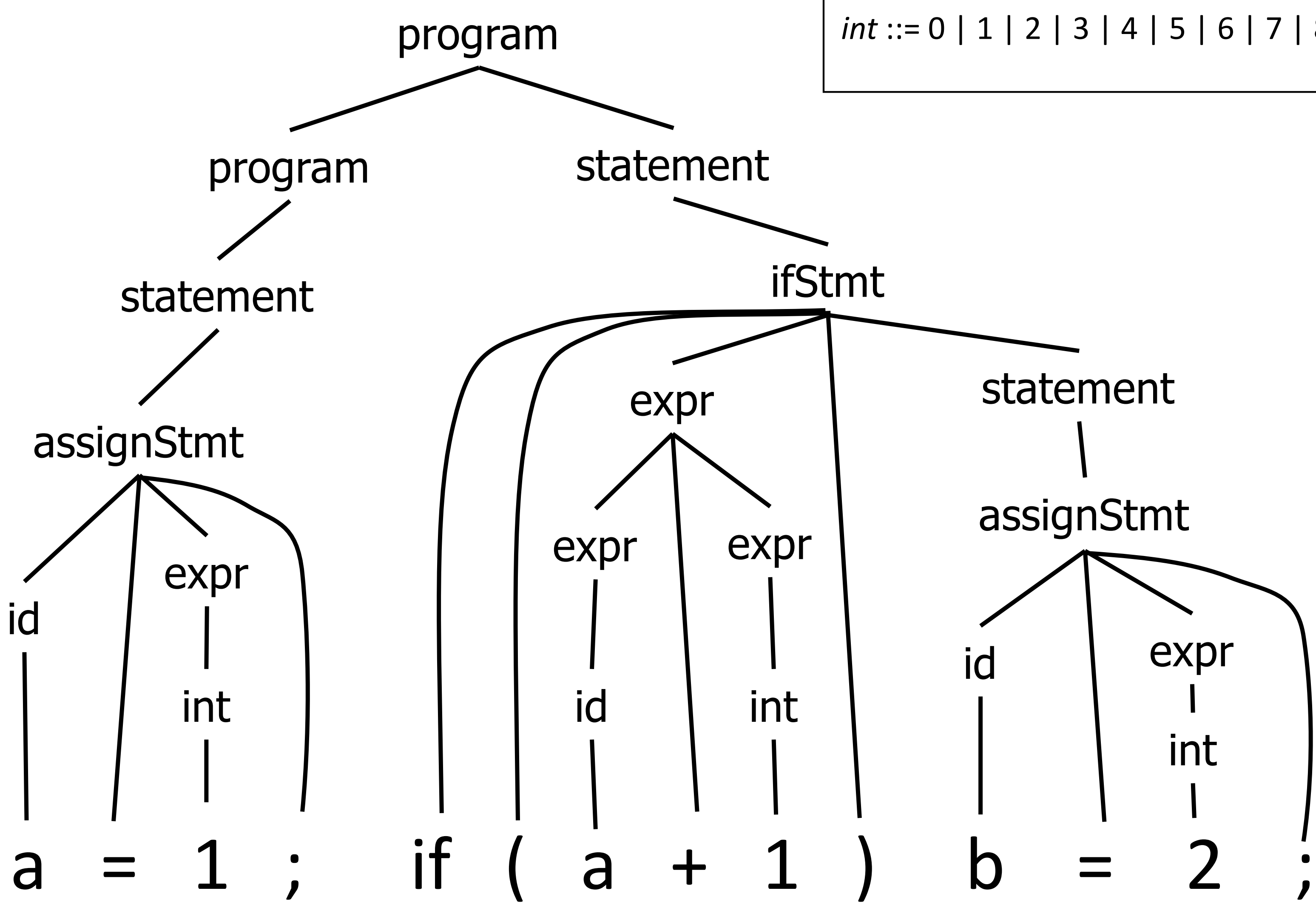


Productions

- 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>

  is: 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 one nonterminal – can choose any rule for nonterminal in different parts of derivation

Alternative Notations

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

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

  ifStmt → if (*expr*) *statement*

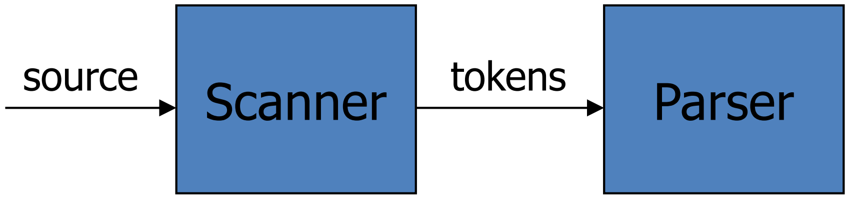
  <ifStmt> ::= if (<expr>) <statement>

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 (almost) 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 and skip past things with no semantic meaning in the language like comments, whitespace (in most languages)
  - 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) / simpler input interface (no files, etc.)
- 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 …

- 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

Scanner Example (review)

- 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	

  – Notes: tokens are atomic items, ***not*** character strings; comments & whitespace are not tokens (in most languages – counterexamples: Python indenting, Ruby and JavaScript newlines)
    - Token objects sometimes carry associated data (e.g., numeric value, variable name)

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

```
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
  - Ruby, JavaScript – newlines can end statements, except when they don’t
- 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]+	
[abc]*	
[0-9]+	
[1-9][0-9]*	
[a-zA-Z][a-zA-Z0-9_]*	

More Examples

re	Meaning
[abc]+	Sequence of 1 or more a's, b's, c's
[abc]*	Sequence of 0 or more a's, b's, c's
[0-9]+	Sequence of 1 or more decimal digits
[1-9][0-9]*	Sequence of 1 or more decimal digits without a leading 0
[a-zA-Z][a-zA-Z0-9_]*	Identifiers in *Your Favorite Programming Language™*

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*) ?

- 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)

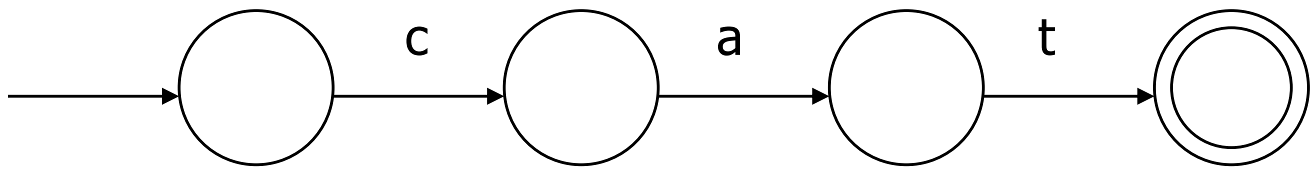
Recognizing REs

- 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 review on one slide)

- 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
    - For us: ok to have one arrow with several symbols from Σ to avoid clutter
- 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 with transitions to it for all "no legal transition possible" input. OK to omit for us

Example: FSA for “cat”



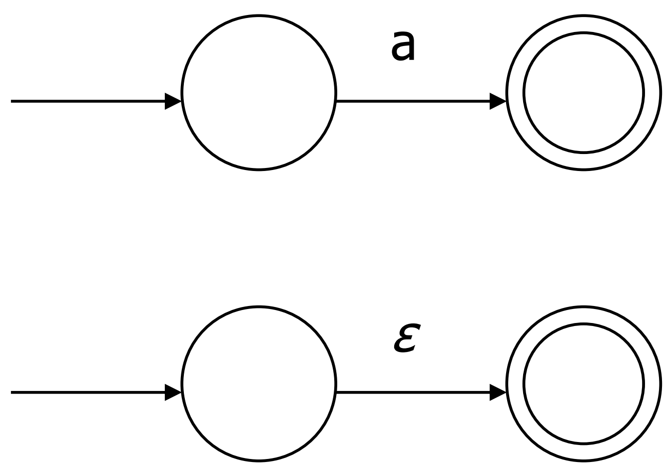
DFA vs NFA

- 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 match input and reach a final state
  - i.e., may need to guess right path or backtrack

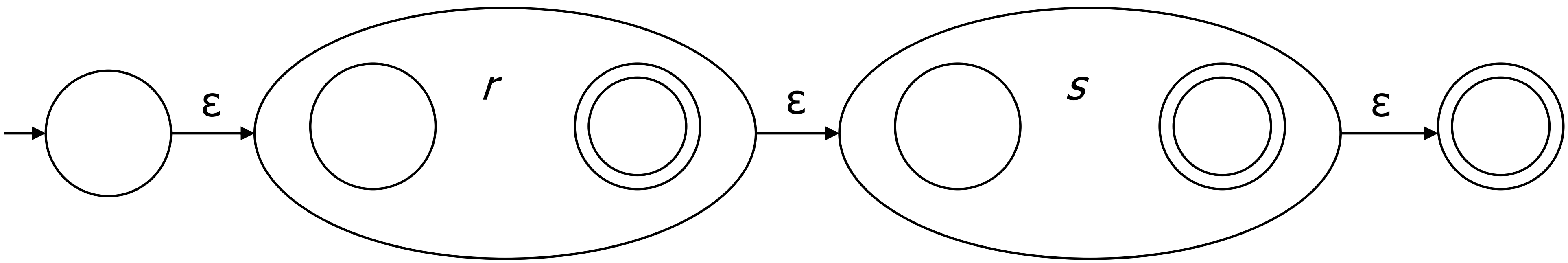
FAs in Scanners

- 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)

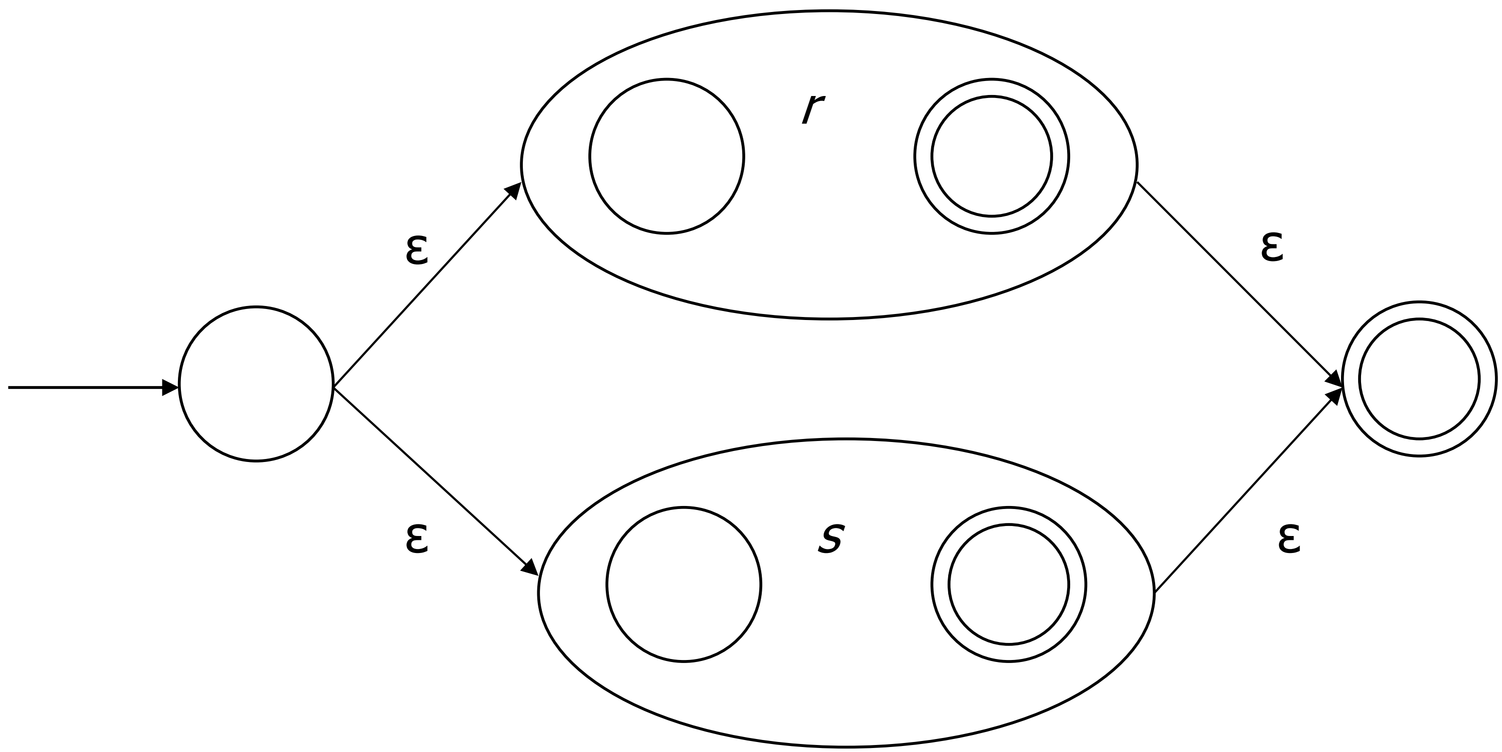
From RE to NFA: base cases



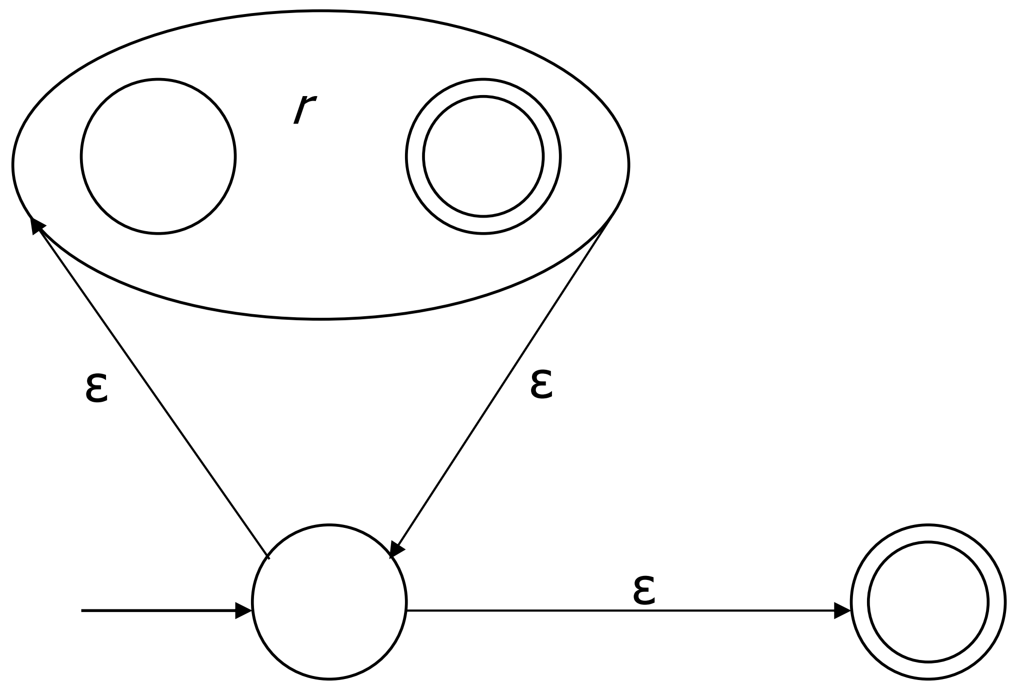
r s



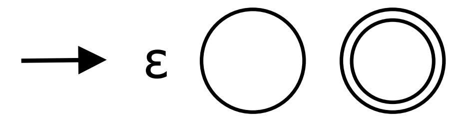
r | *s*



r *

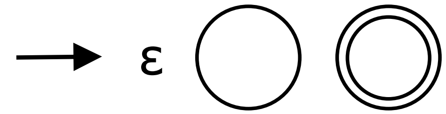


Exercise



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

Exercise



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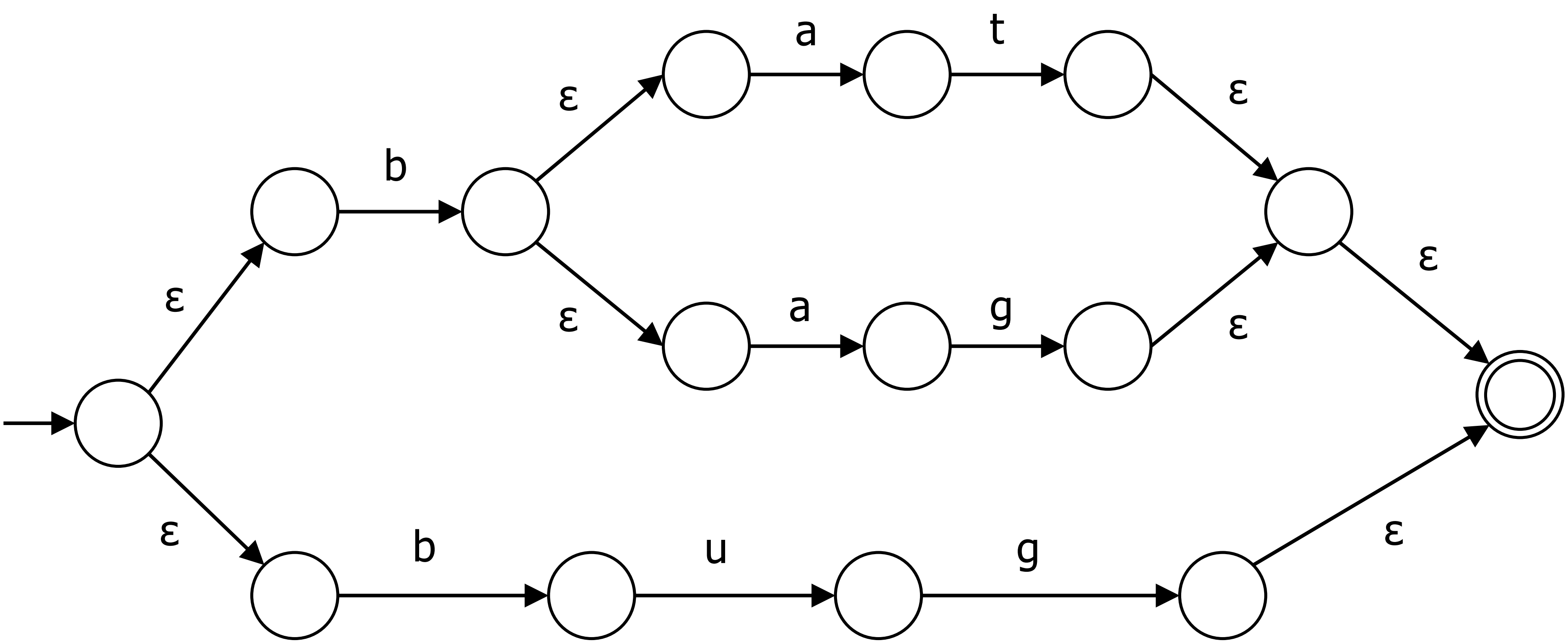


From NFA to DFA

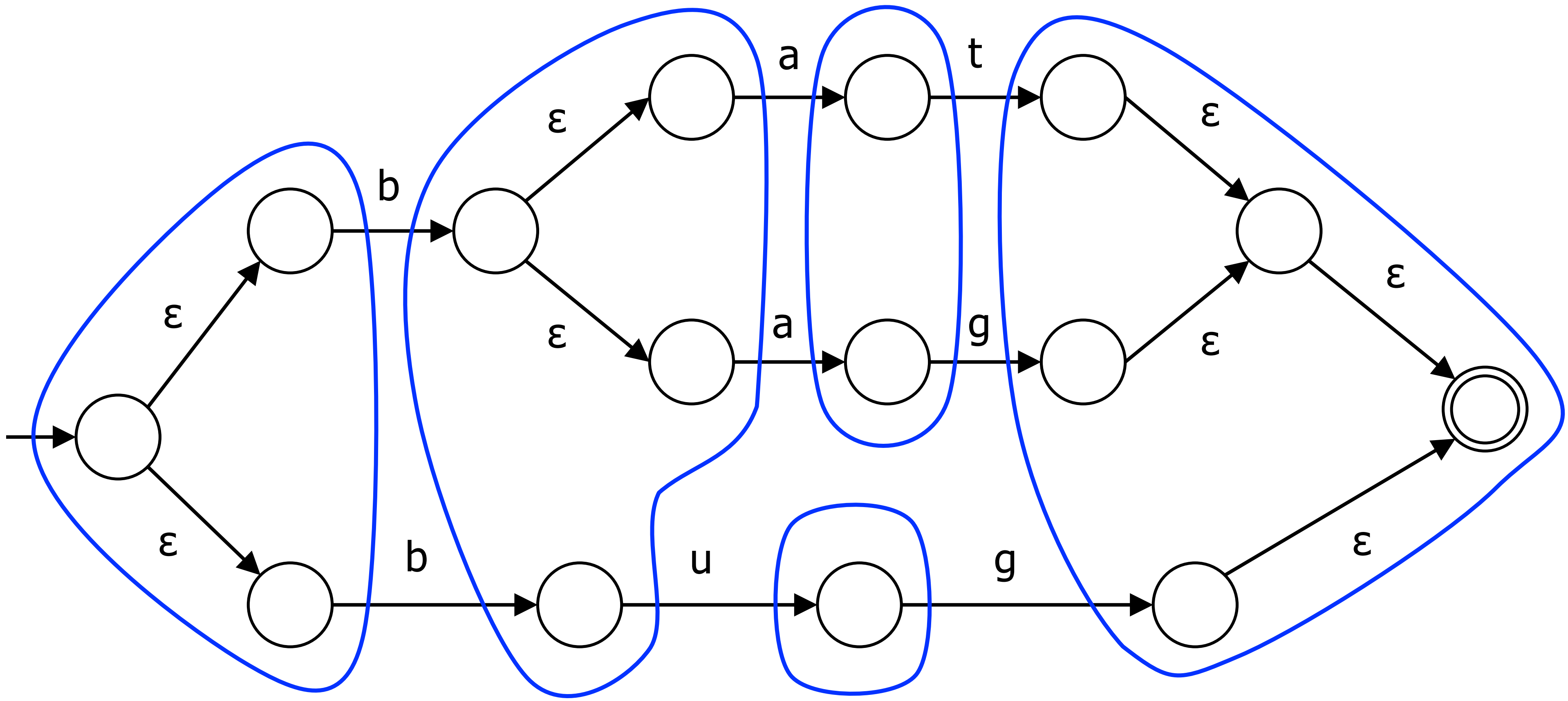
- Subset construction
  - Construct a DFA from the NFA, where each DFA state represents a set of NFA states
- Key idea
  - State of the DFA after reading some input is the set of all NFA states that could have reached after reading the same input
- Algorithm: example of a fixed-point computation
- If 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

Exercise (informal – but ok for us)

- 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"

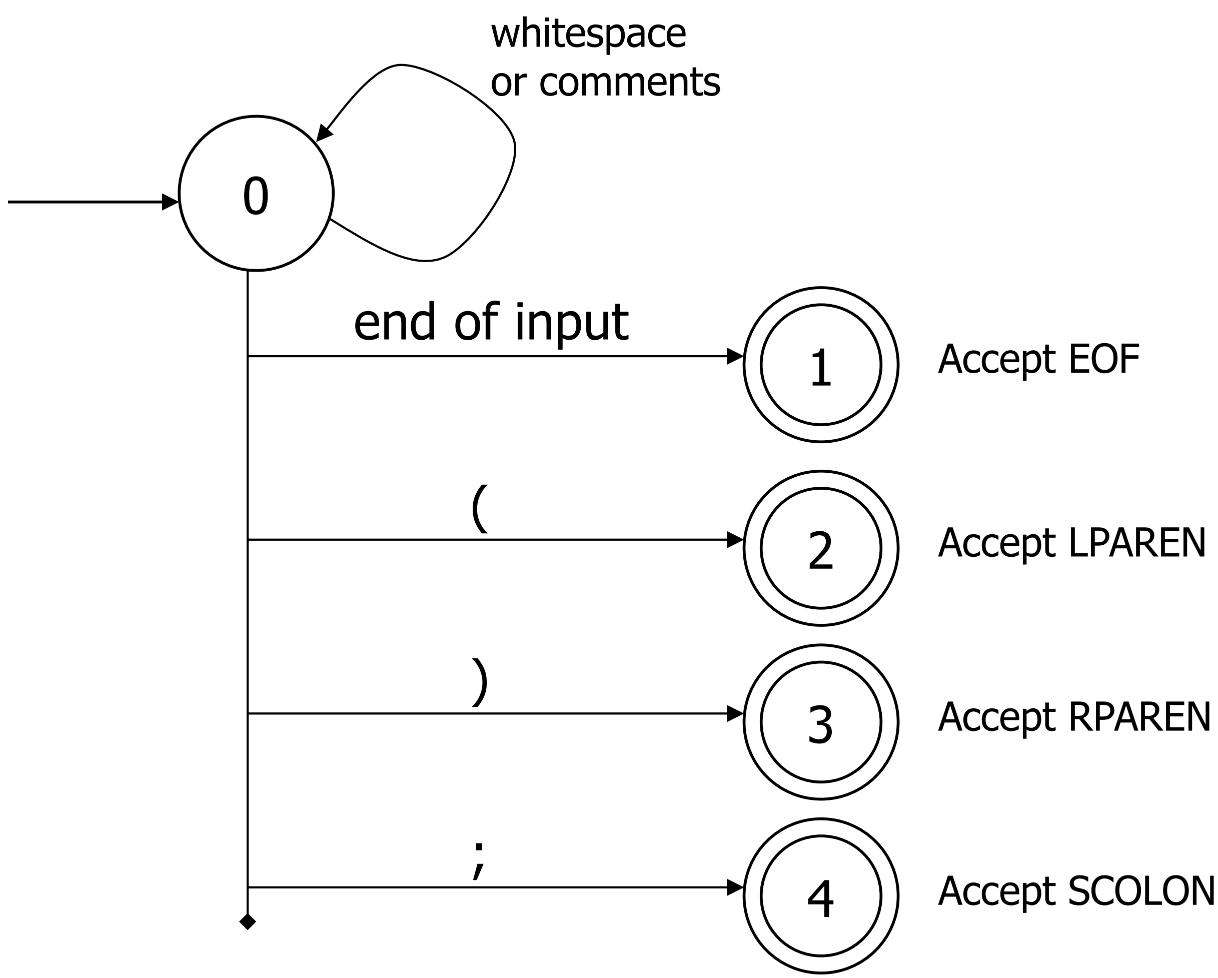
DFA => code [continued]

- 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

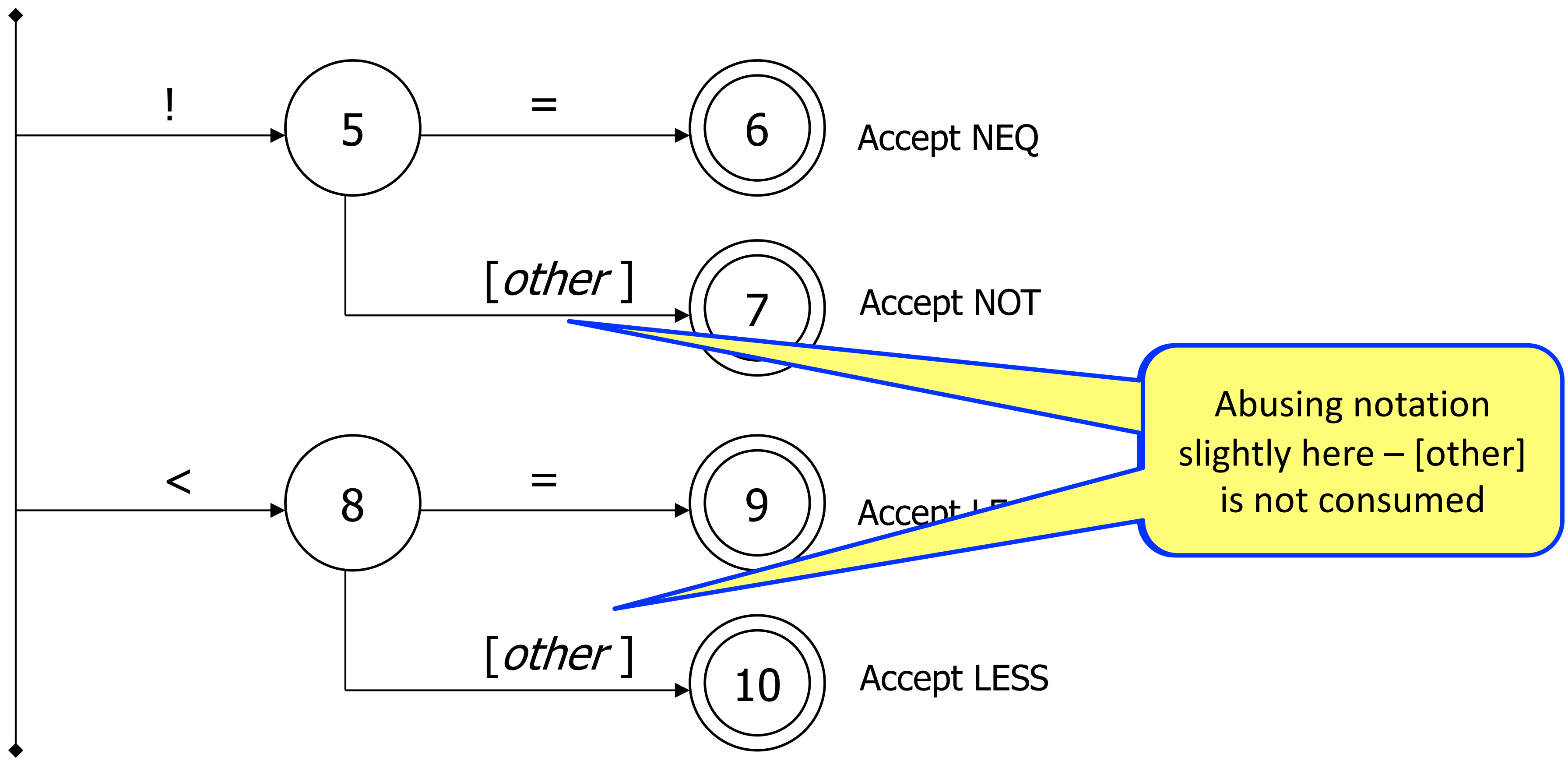
Example: DFA for hand-written scanner

- Idea: show a hand-written DFA for some typical programming language constructs
  - Then use to outline hand-written scanner
- Setting: Scanner is called when 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

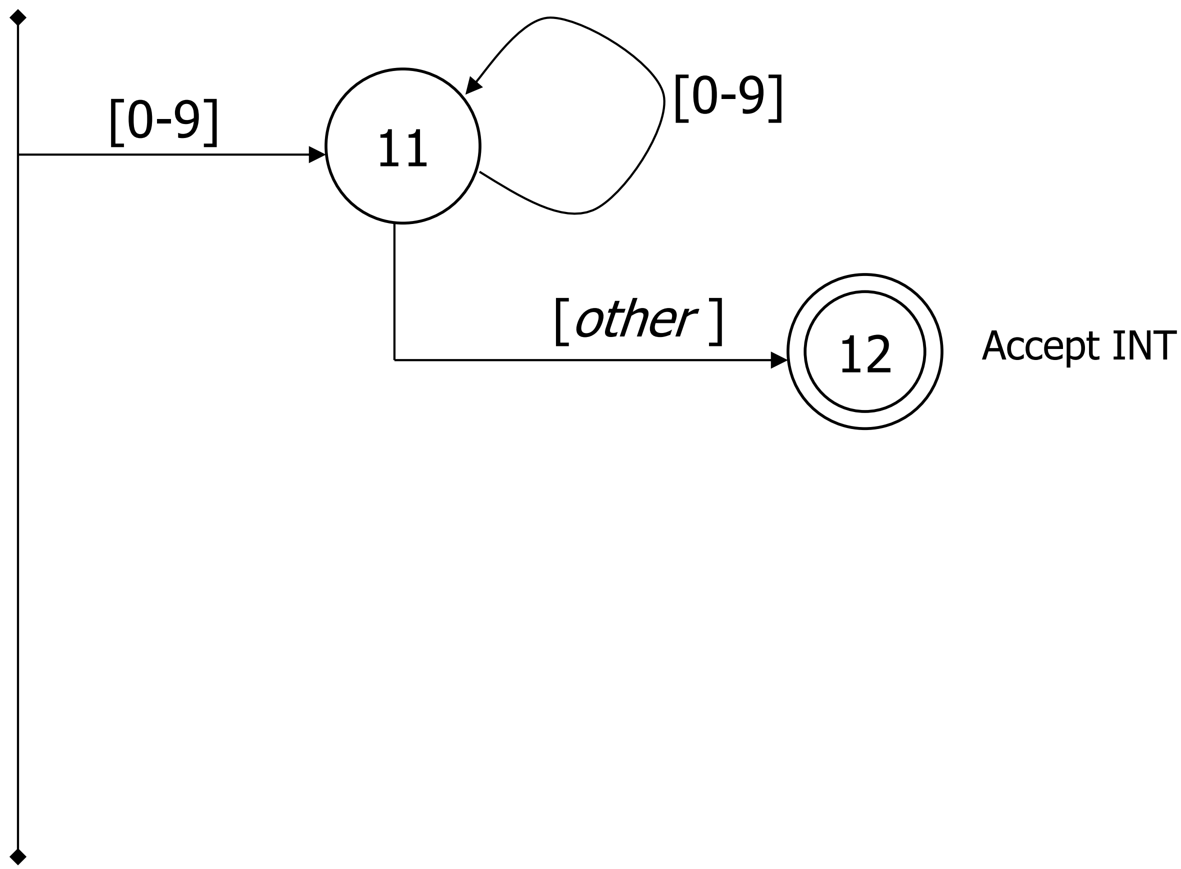
Scanner DFA Example (1)



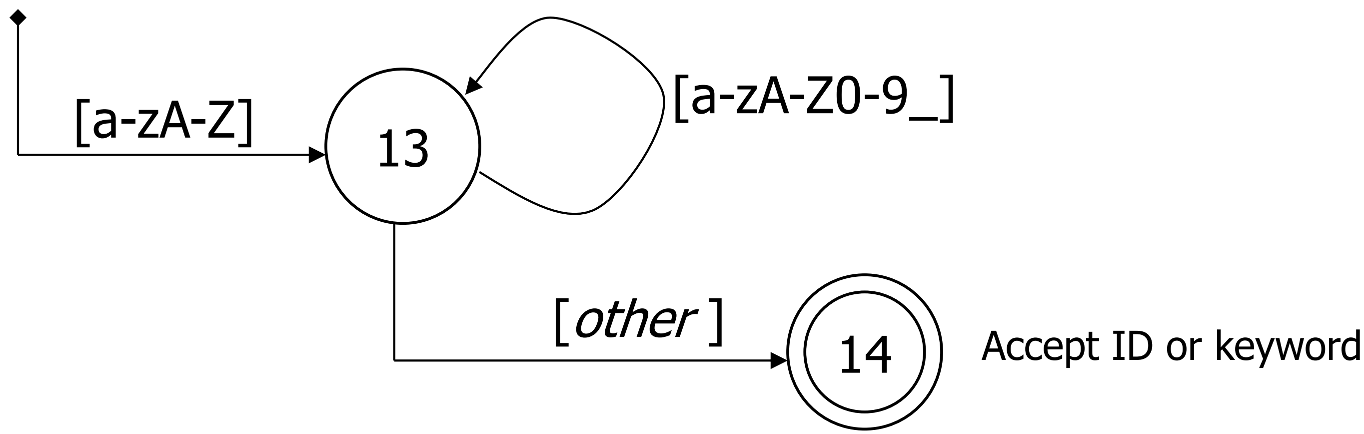
Scanner DFA Example (2)



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;
    public enum Kind {        // lexical class
        EOF,                  //   "end of file" token
        ID,                   //   identifier, not keyword
        INT,                  //   integer
        LPAREN,               //   punctuation/operators…
        SCOLN,
        WHILE,                //   keywords (reserved words) …
    // 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.Kind.EOF); return result;
 }

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

     // etc. …
```

getToken() (2)

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

case '<': // < or <=
    getch();
    if (nextch == '=') {
      result = new Token(Token.Kind.LEQ); getch(); return result;
    } else {
      result = new Token(Token.Kind.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.Kind.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.Kind.ID, s);
  }
  return result;
```

MiniJava Scanner Generation

- 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

- HW1 out now: 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

Coming Attractions

- 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
- First part of the project – scanner – out next week and short demo in class then
- See you next Tuesday!