CSE 401/M501 – Compilers

Languages, Automata, Regular Expressions, & Scanners

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Autumn 2025

Administrivia

- Read: textbook ch. 1 and sec. 2.1-2.4
- First homework out later today, due next Thur. 11:59 pm
  - Written problems on regexps/DFAs
  - We'll cover most everything needed this week
  - You'll get email from gradescope when accounts are set up at the end of this week – submit hw1 there
- Office hours start today!
  - Let us know if we've got bad gaps in the schedule – we might be able to adjust
- Find a project partner if you haven't already
  - Be sure you agree on how you plan to share the work, etc.
  - We'll post a form shortly for ONE of you to send in partner info (worth 1 point for both of you *if* done right). Watch for ed announcement. Needed by early next week.

More Administrivia (added Fri.)

- HW1 is out now and gradescope accounts were created yesterday for all registered students. You should have gotten email at your @uw.edu address with a link.
  - hw1 due Thursday night, 11:59 pm.
- Project partner information form posted now and linked to the calendar. Please submit info by 11:59 pm Tuesday night (and read directions; +1 point if you get everything right ☺)
- Send email to cse401-staff if any logistics things need fixing (gradescope accounts, etc.)

Agenda for the next few classes

- 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

Programming Language Specs

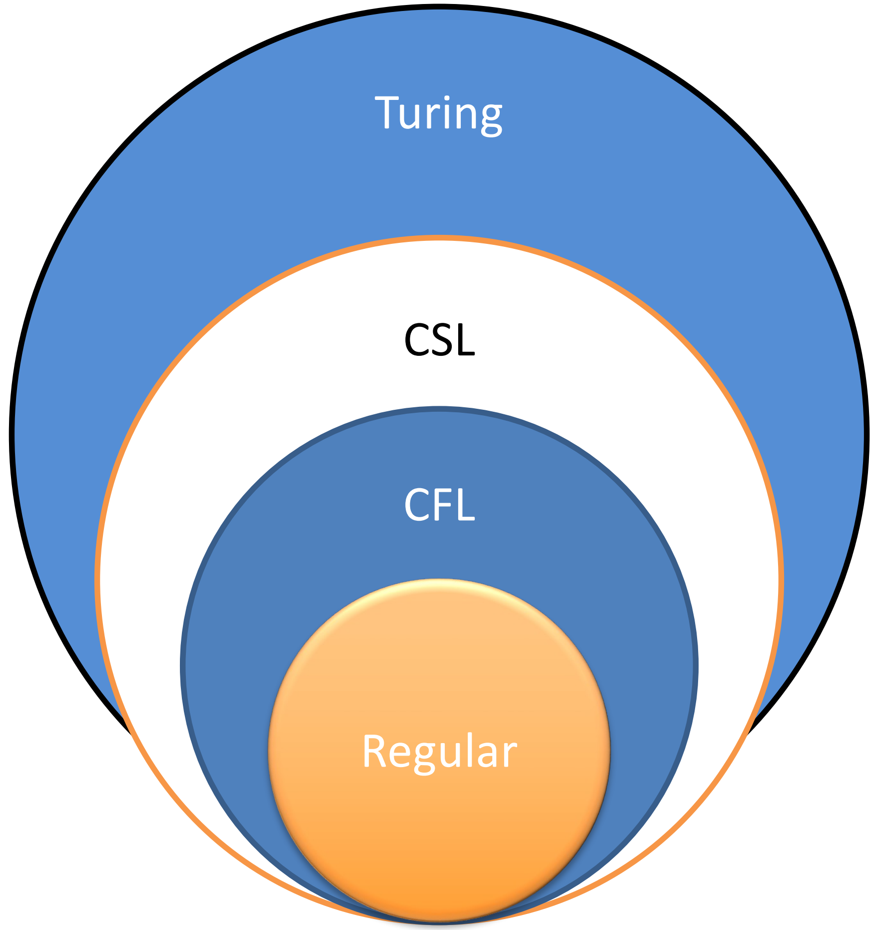
- Since the 1960s, the syntax of every significant programming language has been specified by a formal grammar
  - First done in 1959 with BNF (Backus-Naur Form), used to specify ALGOL 60 syntax
  - Borrowed from the linguistics community (Chomsky)

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: quick reminder

- 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 important (for us)
- Recursively-enumerable (Type-0) languages are specified by general grammars and Turing machines



Example: 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`

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 ;
```

Exercise: Derive a simple program

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

statement ::= *assignStmt* | *ifStmt*

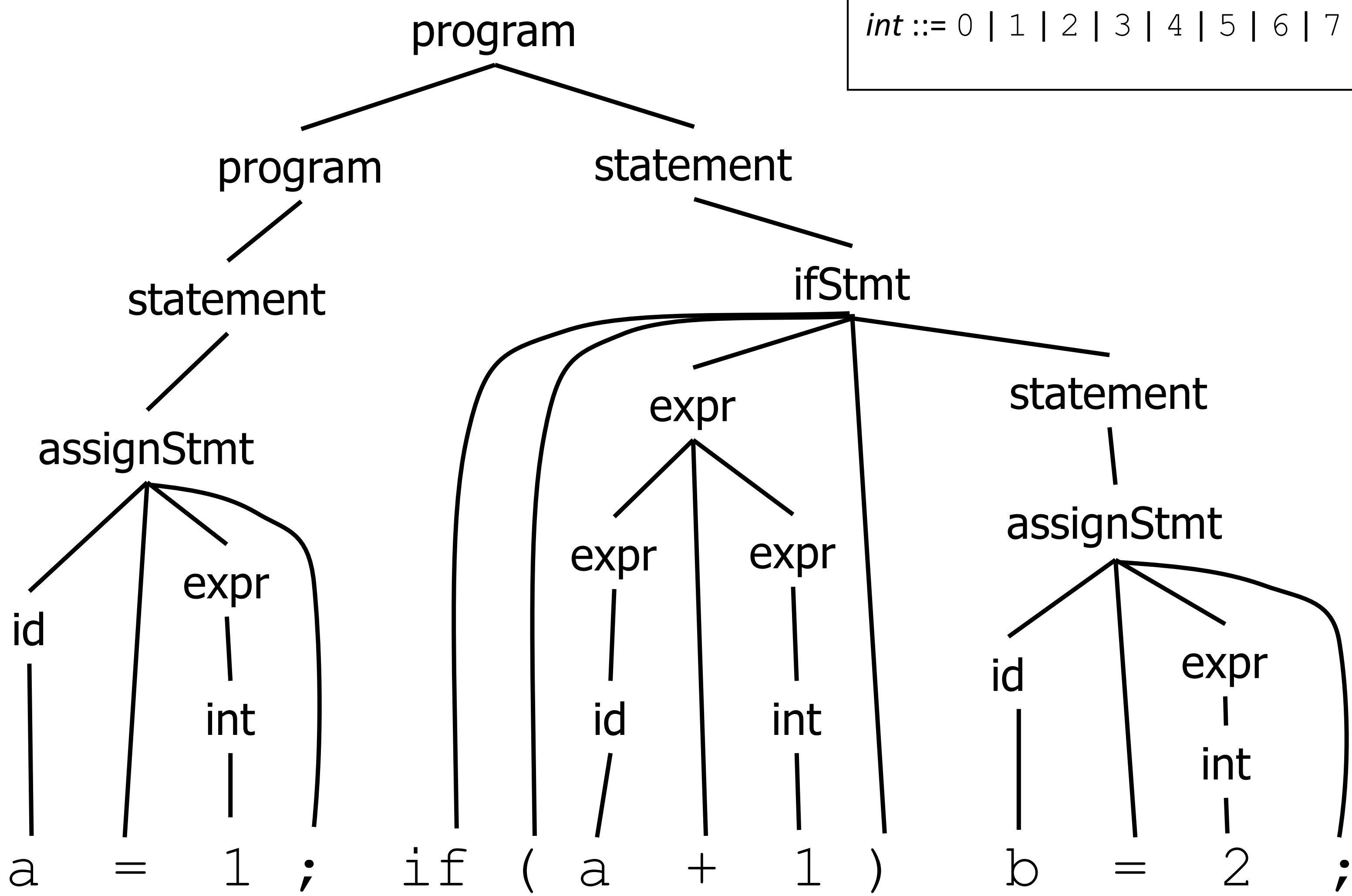
assignStmt ::= *id* = *expr* ;

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



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>

  is: in a derivation an instance of *nonterminal* can be replaced by the sequence of terminals and nonterminals on the right side of the production
- Often there are several productions for one nonterminal – can choose any of those rules to expand that nonterminal in different parts of a derivation, so grammar derivations are non-deterministic in general

Alternative Notations

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

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

  ifStmt → if (*expr*) *statement*

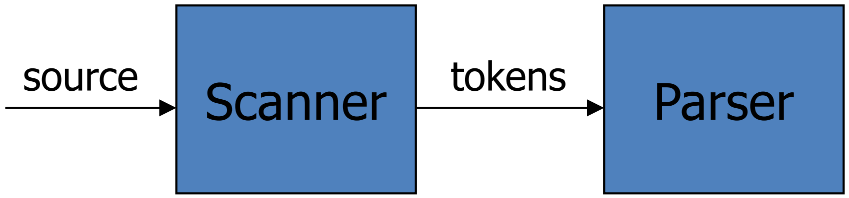
  <ifStmt> ::= if (<expr>) <statement>

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) and simpler interface for input
- 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 (reminder)

- 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 string
- 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 / variations
  - 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 computer tools, need some way to “escape” literal ‘*’ or ‘|’ characters vs. operators – but don’t worry, or use different fonts, for math regexps

Examples

re	Meaning
+	single + character
!	single ! character
=	single = character
!=	2 character sequence "!="
xyzzy	5 character sequence ”xyzzy”
(1|0)*	0 or more binary digits (or seq. of 0’s, 1’s)
(1|0)(1|0)*	1 or more binary digits (strings of 0’s, 1’s)
0|1(0|1)*	sequence of binary digits with no leading 0’s, except for 0 itself

Abbreviations

- The basic operations generate all possible regular expressions, but there are common abbreviations used for convenience. Common examples that we will use:

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 listed characters
[abx-z]	(a|b|x|y|z)	1 of the characters
[^abx-z]	(…|…|…|…)	1 char from all of Σ (a-z0-9$#*...) except for 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 abbreviations to make writing and reading definitions or specifications easier

  name ::= *re*

  - Restriction: abbreviations must 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)

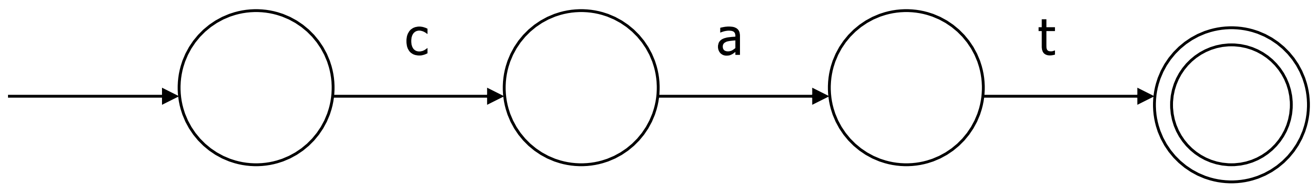
Recognizing regular languges

- 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 al do this automatically, given a set of REs
  - Same techniques used in grep, sed, text editors, 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
  - Common to allow multiple labels (symbols) on one edge to simplify diagrams
- Operate by reading input symbols (usually characters for scanners)
  - Transition can be taken if labeled with current input symbol (consumes input)
  - 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. Better to omit that for CSE 401.

Example: FSA for “cat”

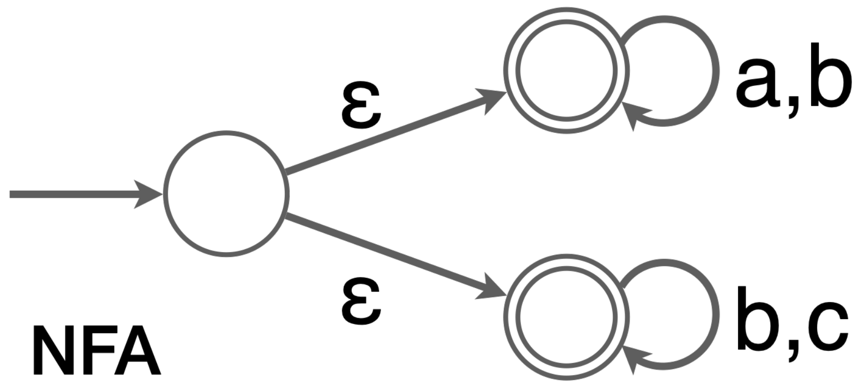


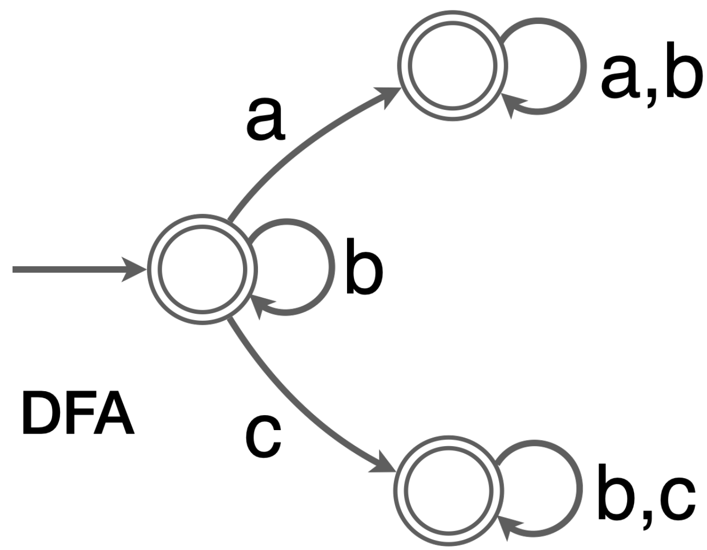
DFA vs NFA

- 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 final state
  - i.e., may need to guess right path or backtrack

DFA vs. NFA example

- (a|b)*|(b|c)*

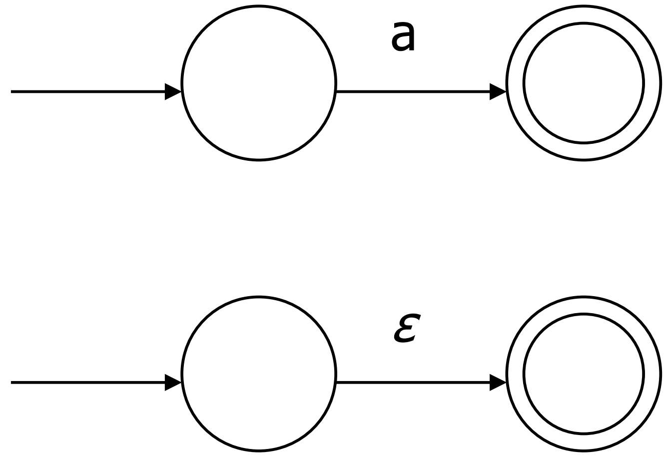




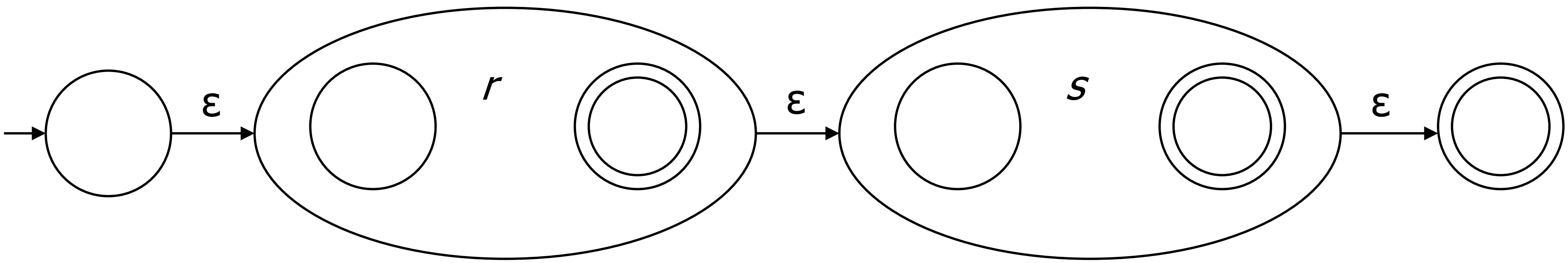
FAs in Scanners

- 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)

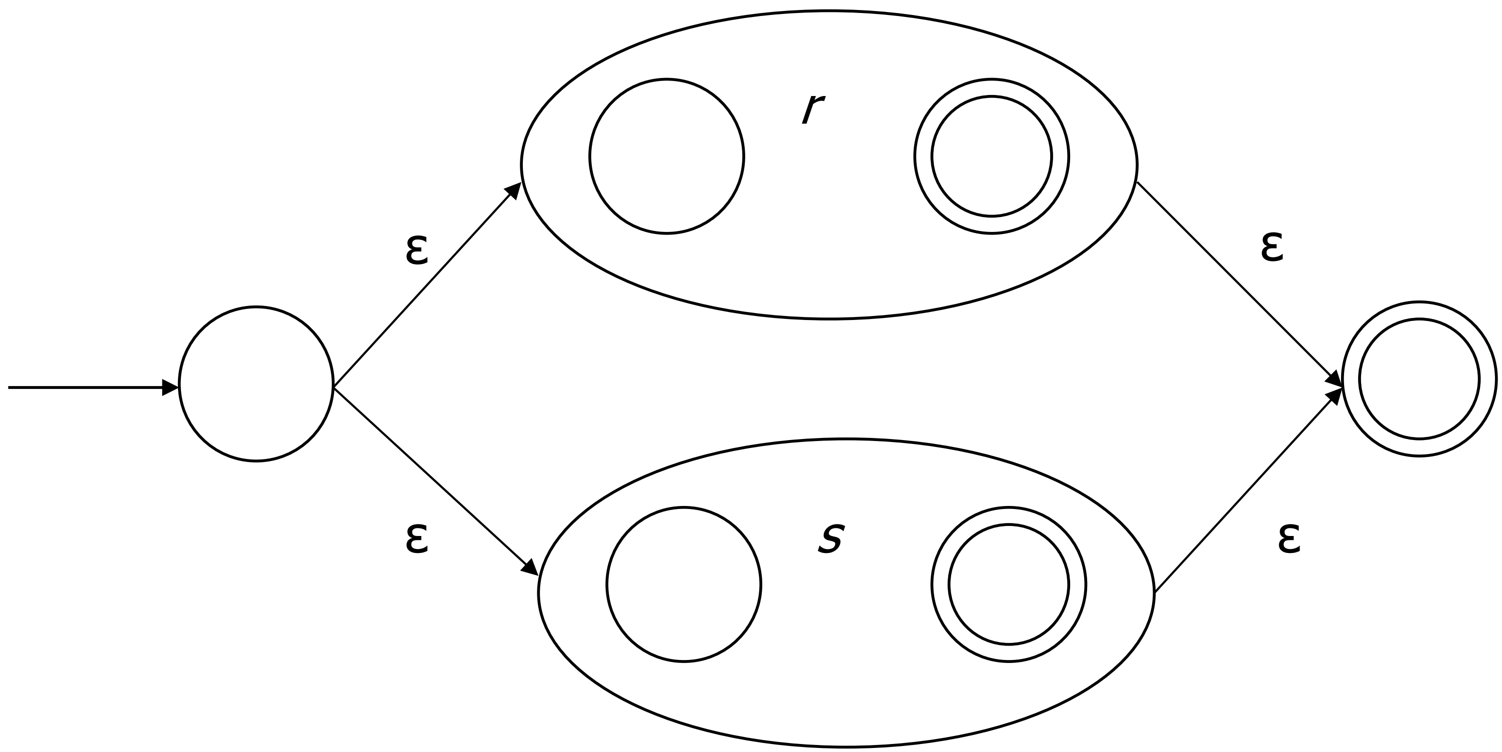
From RE to NFA: base cases



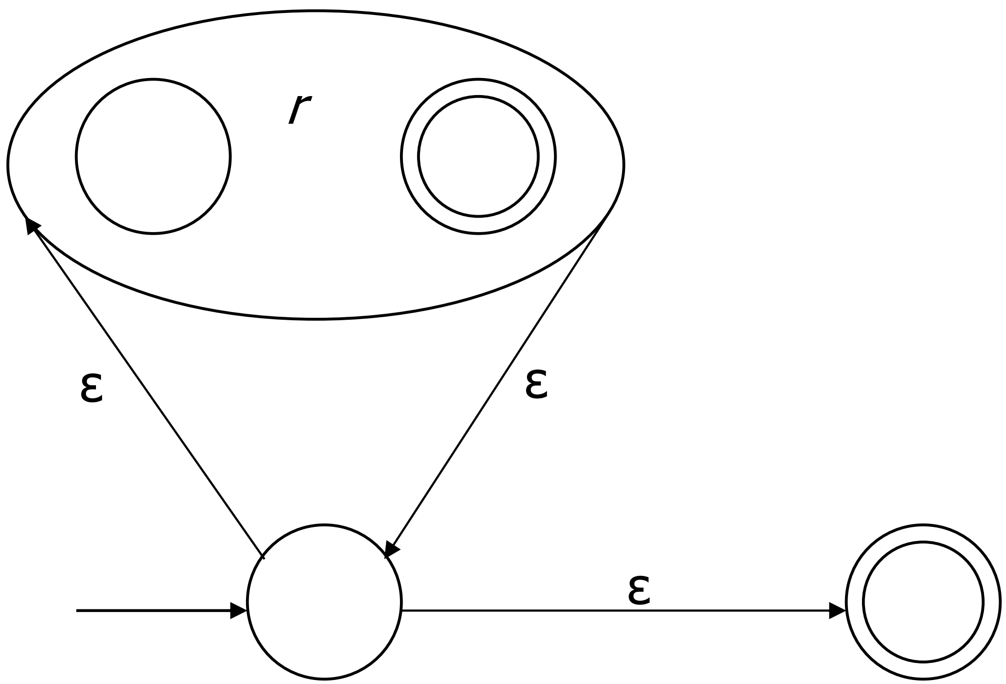
Operator: *r s*



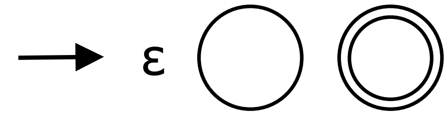
Operator: *r* | *s*



Operator: *r* *

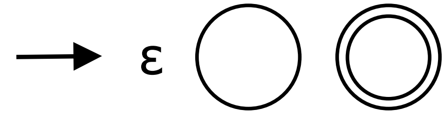


Exercise

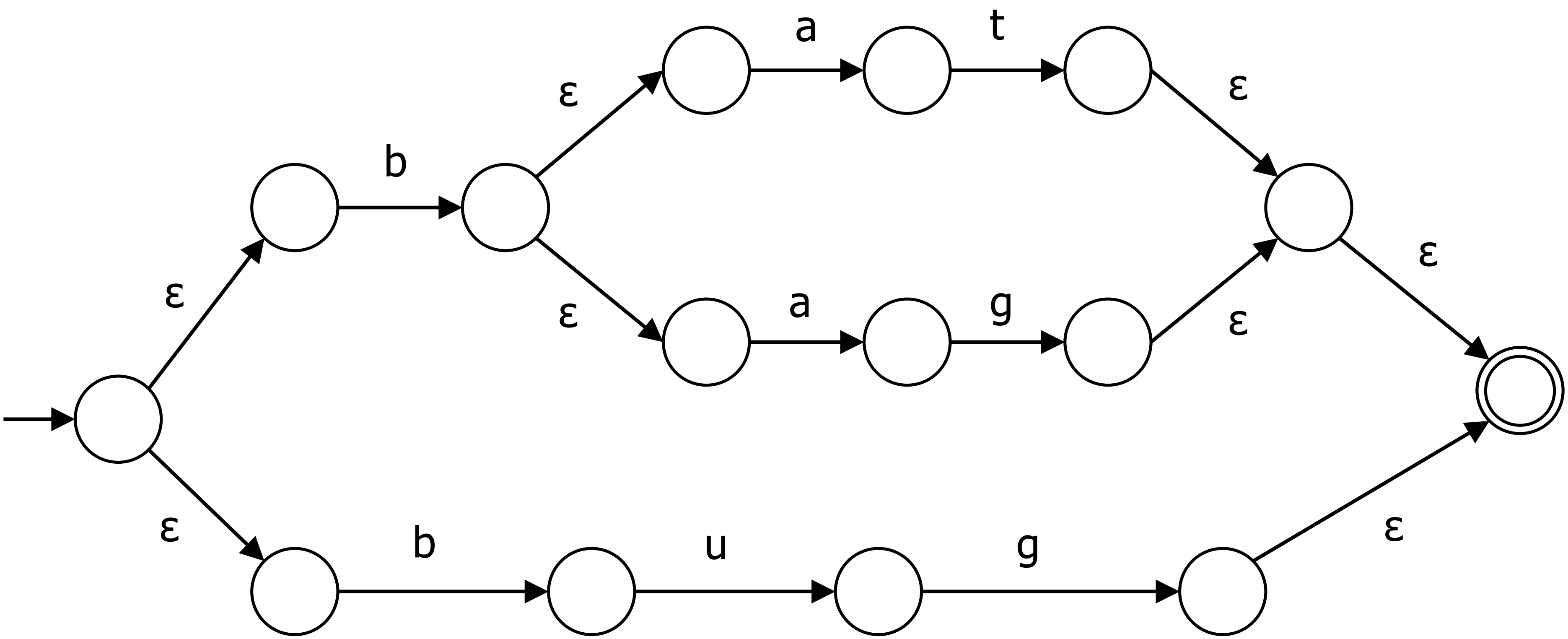


- Draw the NFA for: b(at|ag) | bug

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 (slightly informal)
  - State of the DFA after reading some input is the set of all NFA states that could be 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

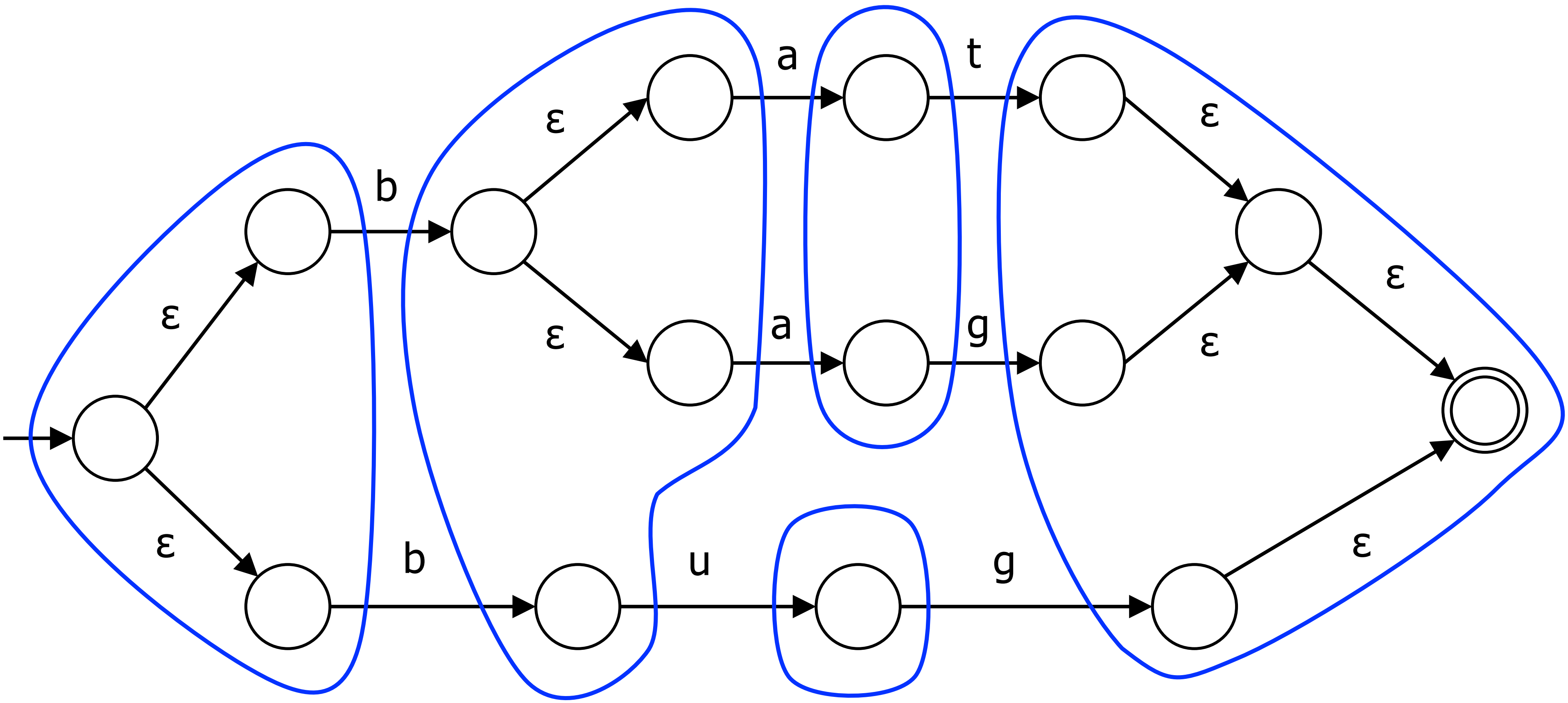
  => Algorithm adds states to DFA only when it discovers that they are reachable, so normally not too expensive
- Resulting DFA may have more states than needed
  - See books for construction and minimization details

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, starting from the next location in the input past the previous token it discovered
- Every "final" state of scanner 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; token data structure might include source 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"

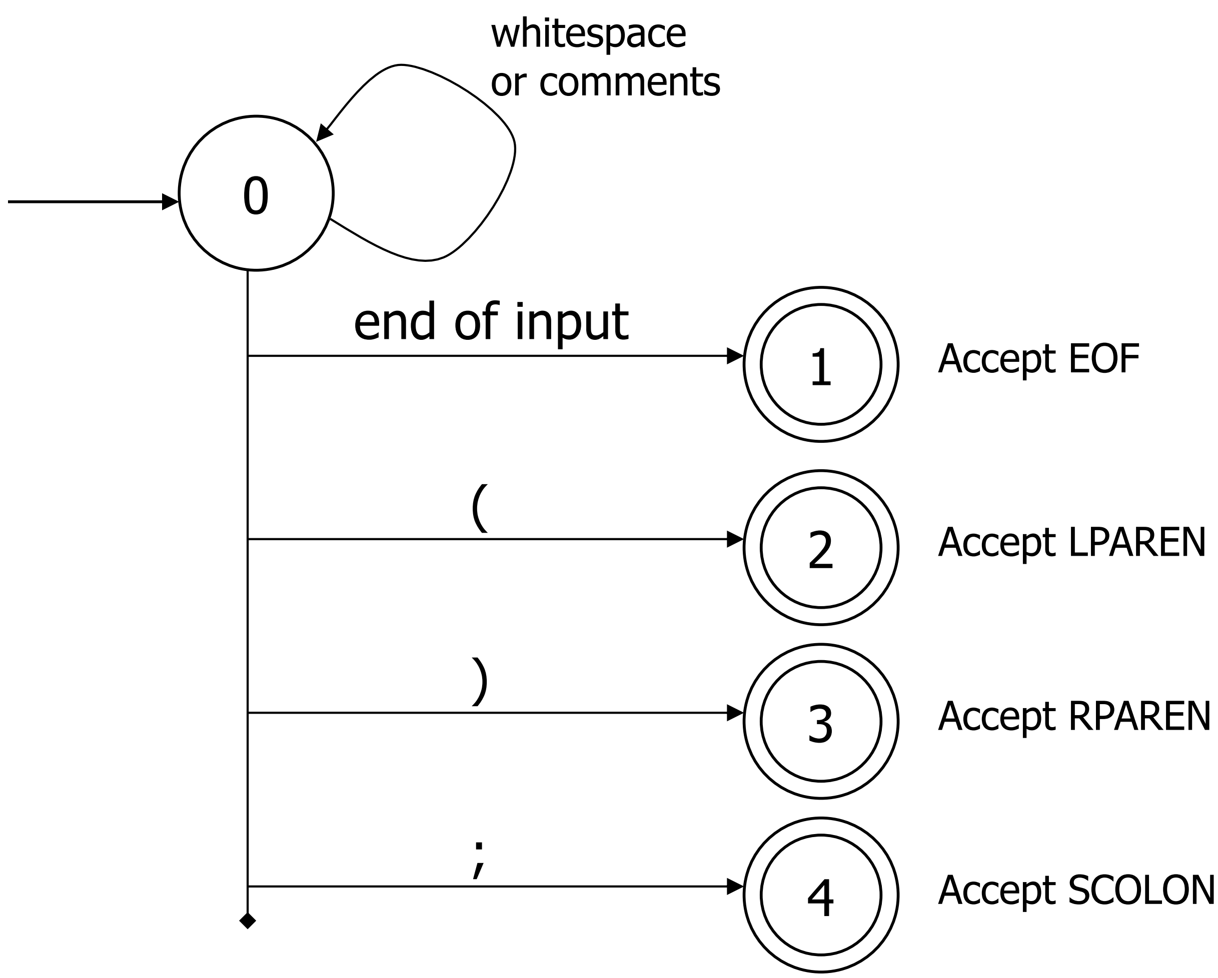
DFA => code [continued]

- Option 2a: use tool to generate scanner program
  - Transitions embedded in the code, no table lookup
  - 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

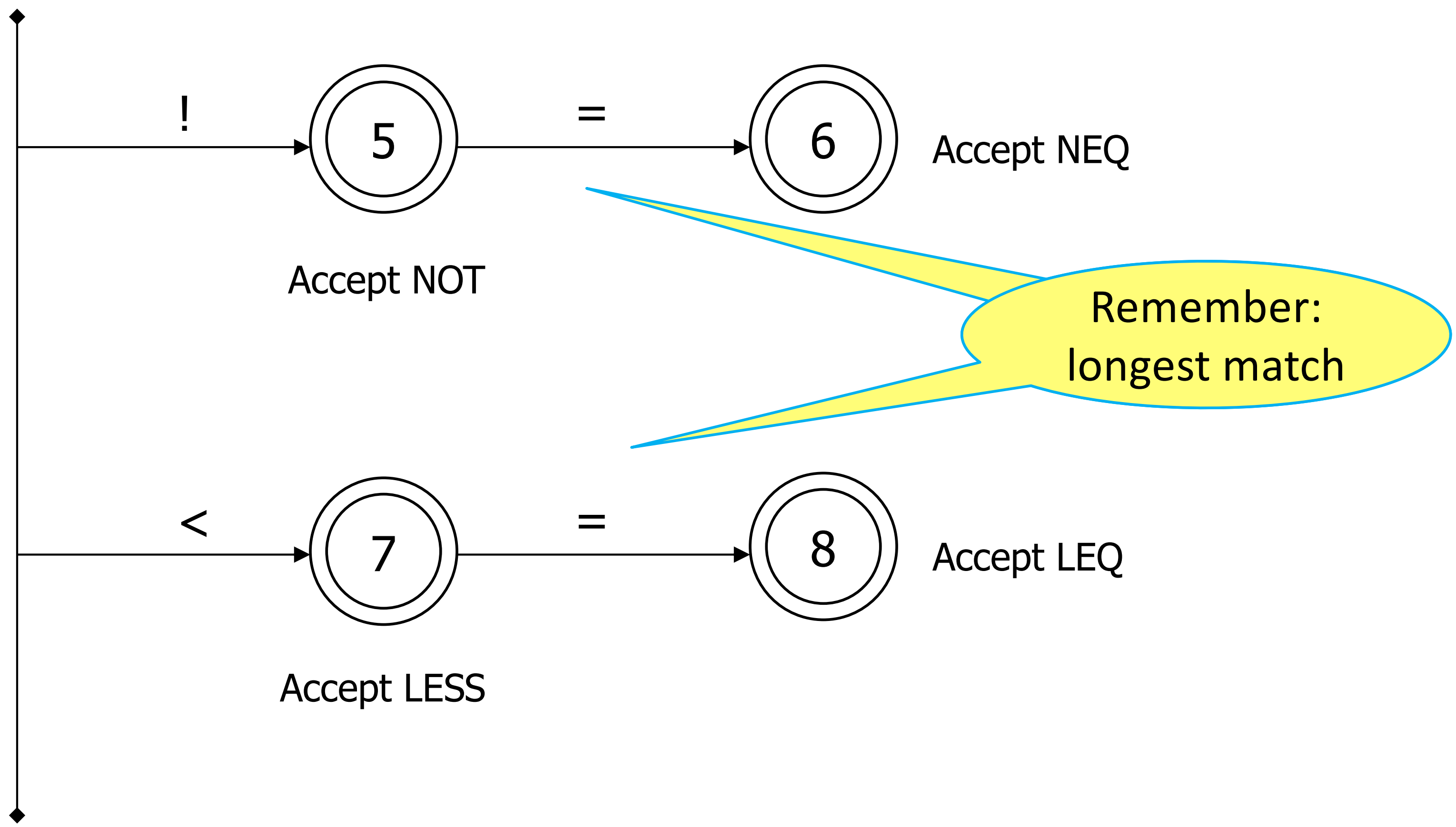
Example: DFA for hand-written scanner

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

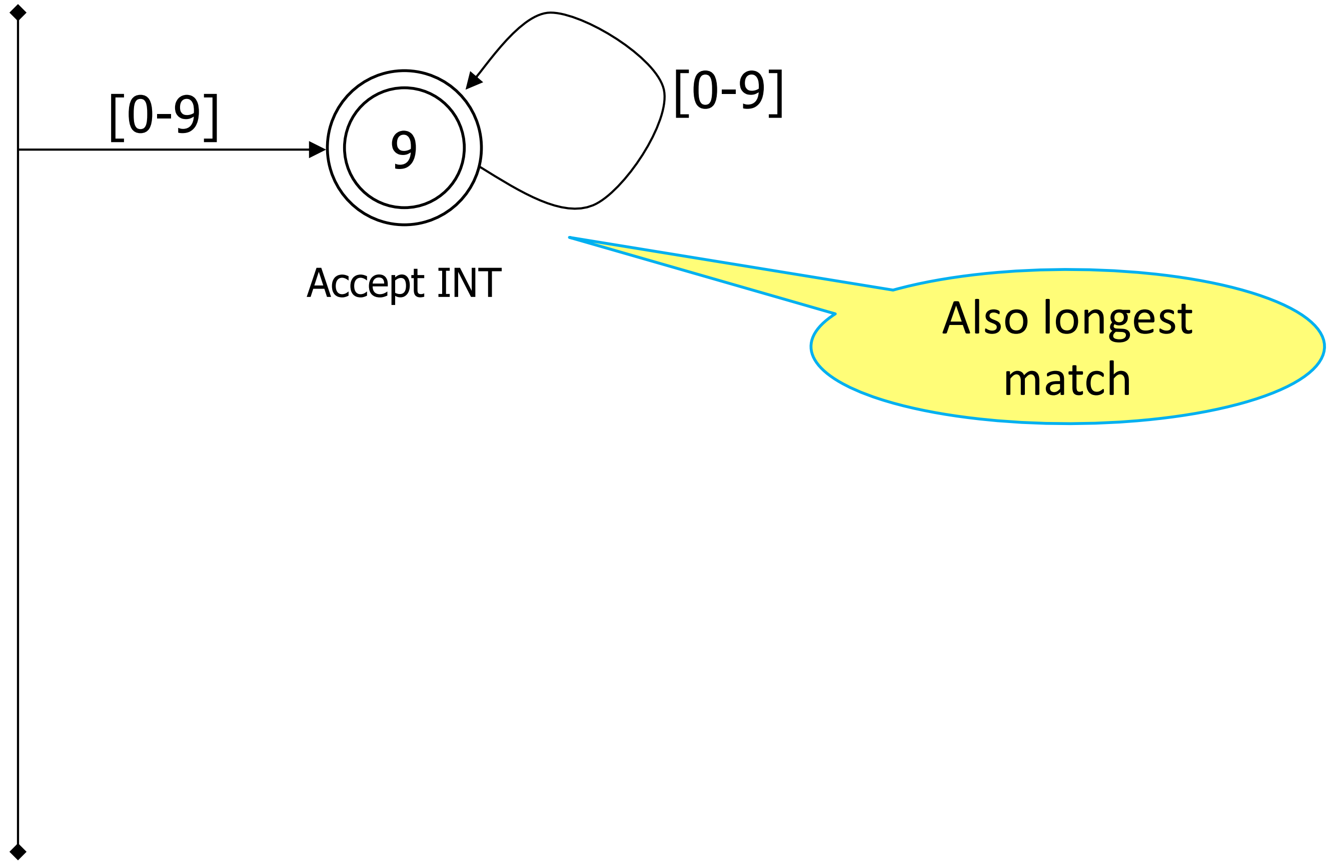
Scanner DFA Example (1)



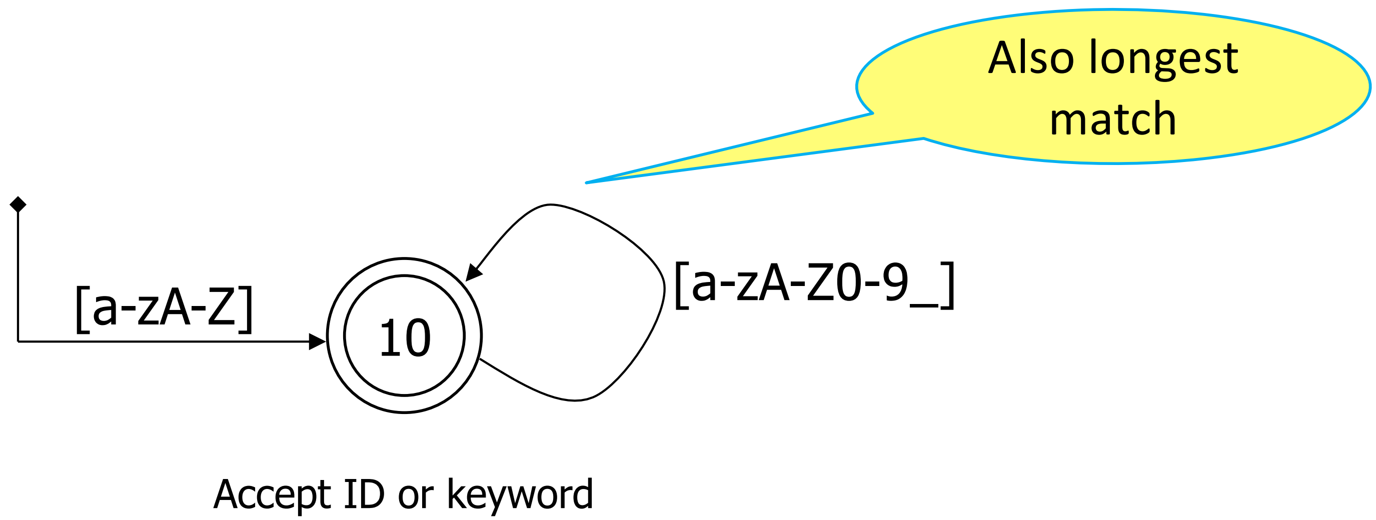
Scanner DFA Example (2)



Scanner DFA Example (3)



Scanner DFA Example (4)



- Strategies for disambiguating identifiers vs keywords
  - Hand-written scanner: look up identifier-like things in table of keywords to classify (classic 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

```
public class Token {
  public Kind kind;        // token's lexical class – which "kind" of token
  public int intVal;       // integer value if kind = INT
  public String id;        // actual identifier if kind = ID
  // useful extra information for debugging / diagnostics:
  public int line;
  public int column;
  // lexical classes:
  public enum Kind {
    EOF,                   //  "end of file" token
    ID,                    //  identifier, not keyword
    INT,                   //  integer
    LPAREN,                //  punctuation …
    SCOLN,
    WHILE,                 //  keywords …
    // 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.parseInt(num));
    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. are shared by jflex and CUP. Lexical classes are listed in CUP's input file and it generates the token class definition.
- Details in this week's sections

Coming Attractions

- First homework 1: paper exercises on regular expressions, automata, etc., due Thur.
- Then: first part of the compiler assignment – the scanner – sections this week
- Next topic: grammars and 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 (ch. 3)