CSE P 501 – Compilers

Languages, Automata, Regular Expressions & Scanners

Hal Perkins

Autumn 2011

Agenda

- Basic concepts of formal languages and grammars (mostly review)
- 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)

nonterminal ::=

Grammar for a Tiny Language

- *program* ::= *statement* | *program statement*
- *statement* ::= *assignStmt* | *ifStmt*
- *assignStmt* ::= *id* = *expr* ;
- *ifStmt* ::= if (*expr*) *stmtatement*
- *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

  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 two or more productions for one nonterminal – use any in different parts of derivation

Alternative Notations

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

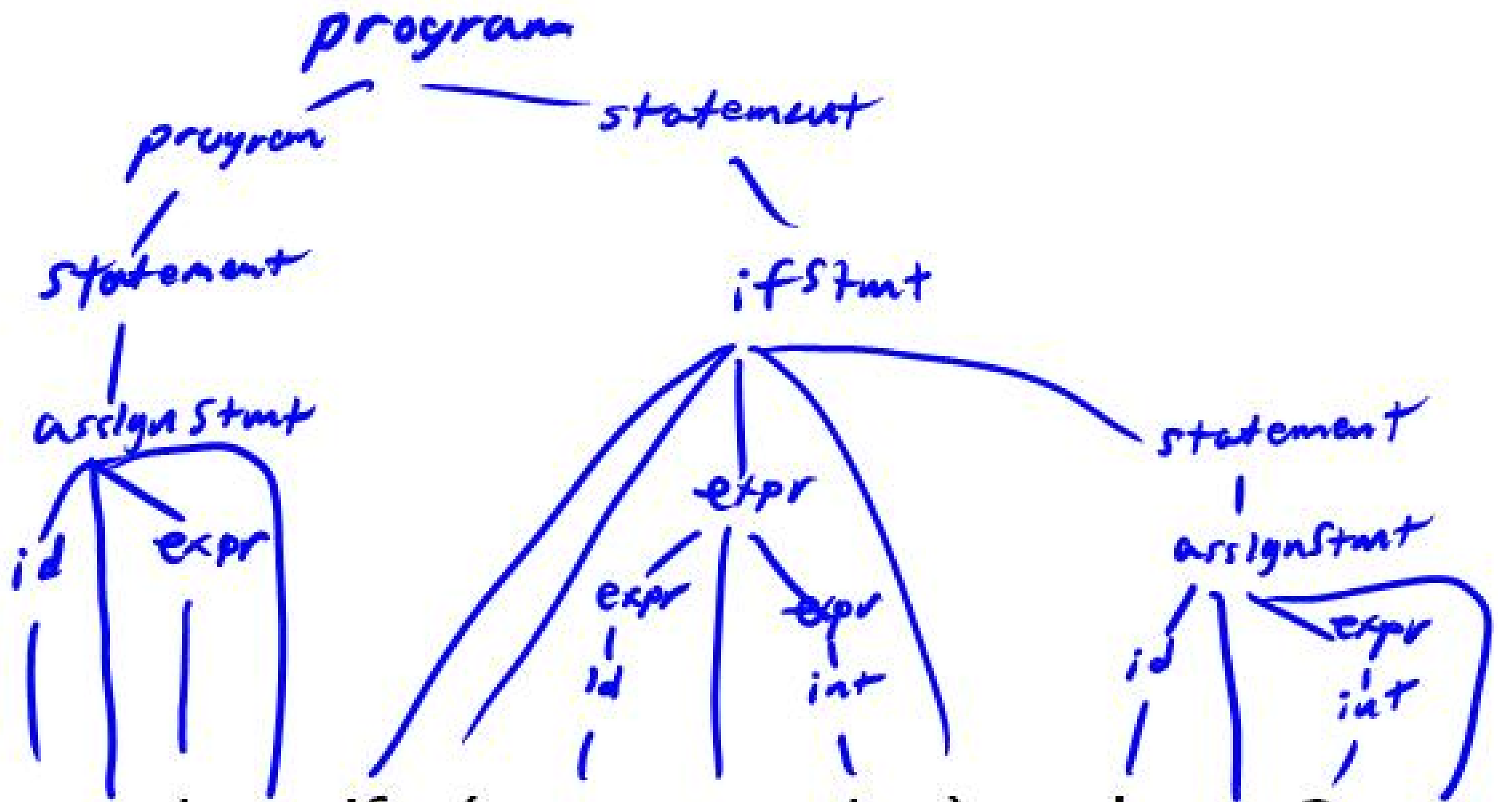
  ifStmt ::= if (*expr*) *statement*

  ifStmt → if (*expr*) *statement*

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

Example Derivation

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

Characters vs Tokens

- 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

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)
- Efficiency
  - Scanner can use simpler, faster design
    - (But still often consumes a surprising amount of the compiler's total execution time)

Tokens

- Idea: we want a distinct token kind (lexical class) for each distinct terminal symbol in the programming language
  - Examine the grammar to find these
- Some tokens may have attributes
  - Examples: integer constant token will have the actual integer (17, 42, …) as an attribute; identifiers will have a string with the actual id

Typical Tokens in Programming Languages

- Operators & Punctuation
  - + - * / ( ) { } [ ] ; : :: < <= == = != ! …
  - Each of these is normally 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)

Formal Languages & Automata Theory (a review 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
  - (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

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
xyzzy	5 character sequence

0123|Hello

-17

~17

0-17

More Examples

re	Meaning
[abc]+	(a|b|c)(a|b|c)* → all strings 1 or more a's b's c's
[abc]*	" " 0 " " " " "
[0-9]+	all str. 1 or more decimal digits
[1-9][0-9]*	all strings 1 or more decimal digits no leading 0
[a-zA-Z][a-zA-Z0-9_]*	identifiers

Abbreviations

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

abc = a*
{abc}

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) ?

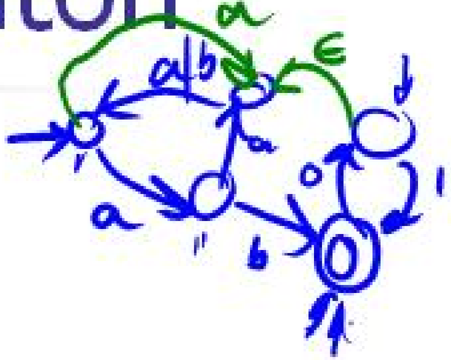
Italic

- How would you describe this set in English?
- What are some examples of legal constants (strings) generated by *number*?

Recognizing REs

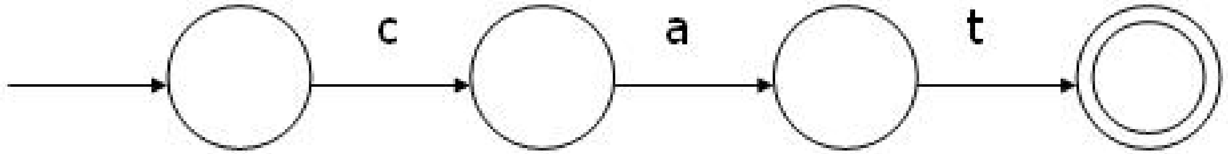
- Finite automata can be used to recognize strings generated by regular expressions
- Can build by hand or automatically
  - Not totally straightforward, but can be done systematically
  - Tools like Lex, Flex, Jlex et seq do this automatically, given a set of REs

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
  - Scanner uses a FSA as a subroutine – accept longest match from current location each time called, even if more input
  - Reject if no transition possible, or no more input and not in final state (DFA)

Example: FSA for "cat"



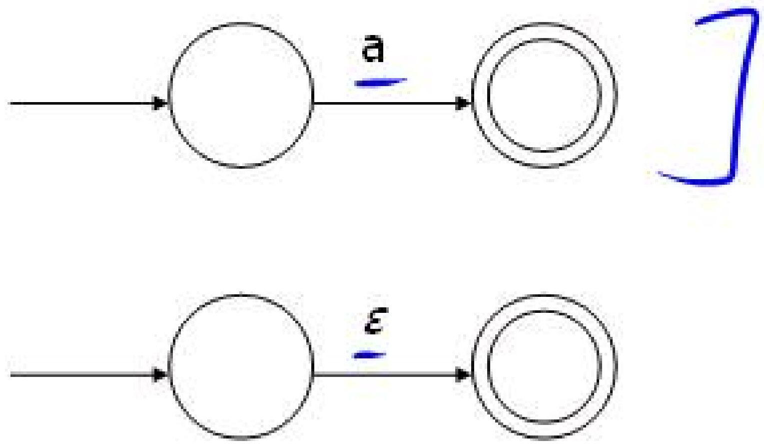
DFA vs NFA

- Deterministic Finite Automata (DFA)
  - No choice of which transition to take under any condition
  - In particular, no ε transitions (arcs)
- 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
  - i.e., may need to guess or backtrack

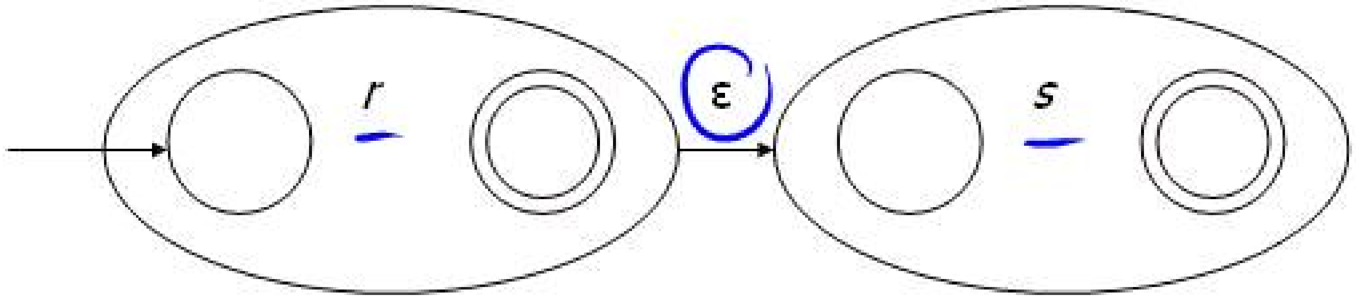
FAs in Scanners

- 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

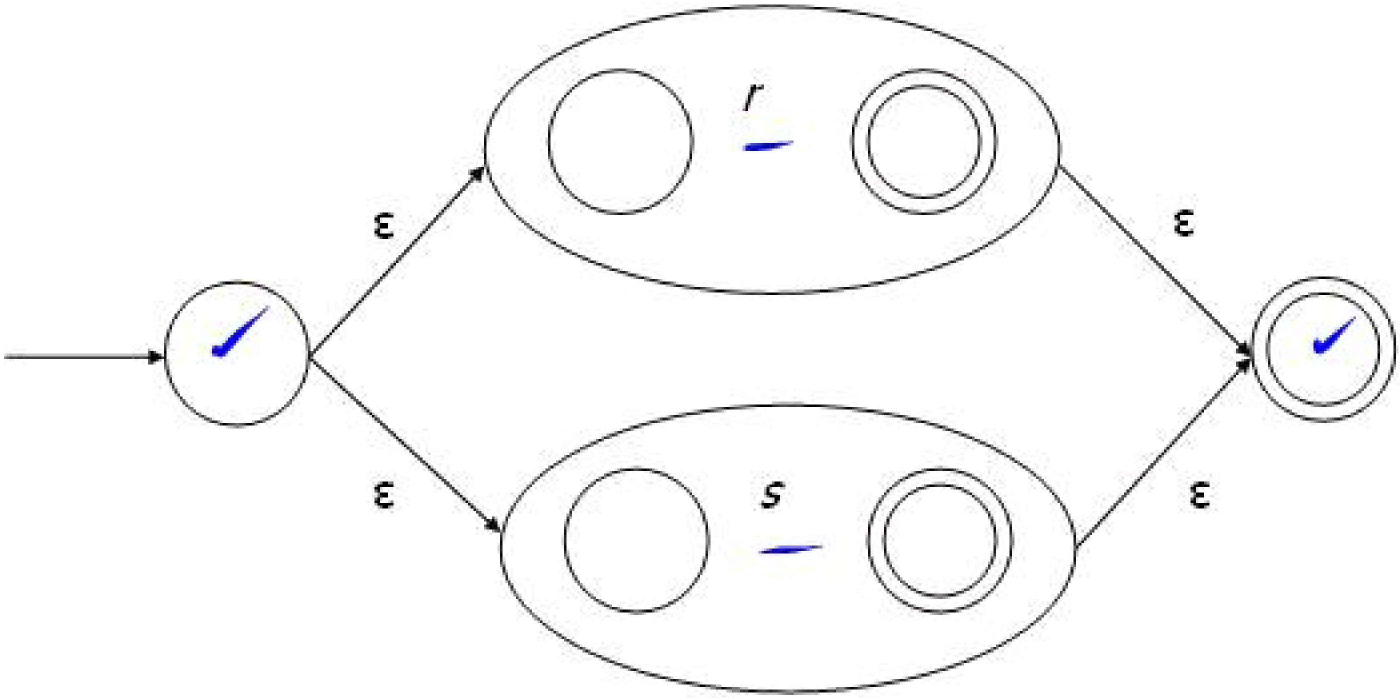
From RE to NFA: base cases



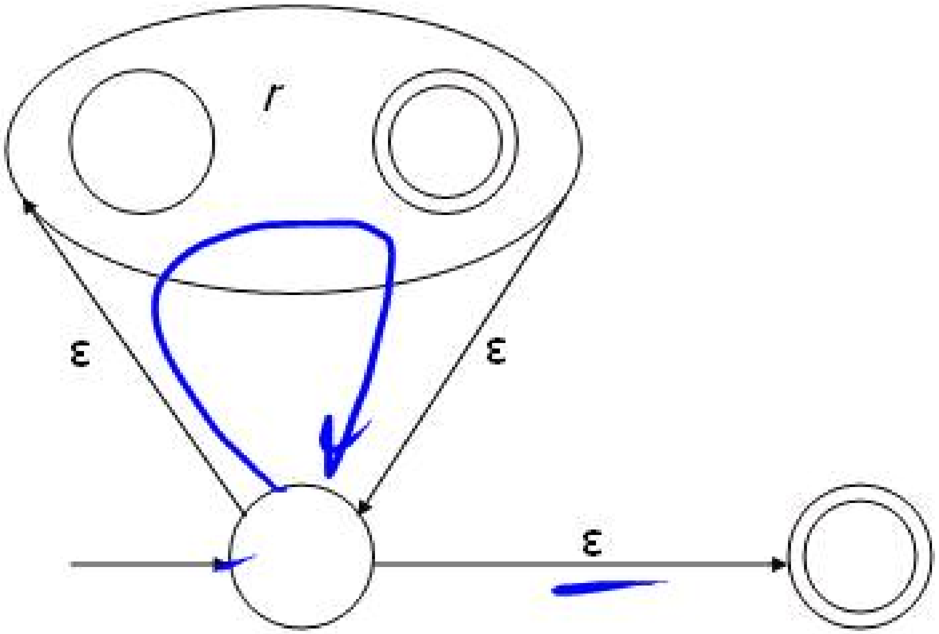
rs



r | s

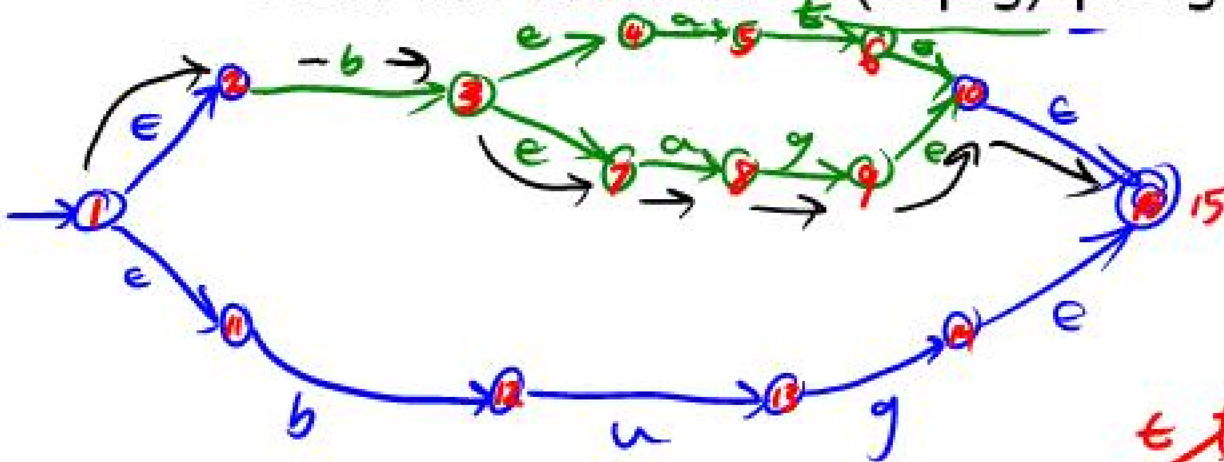


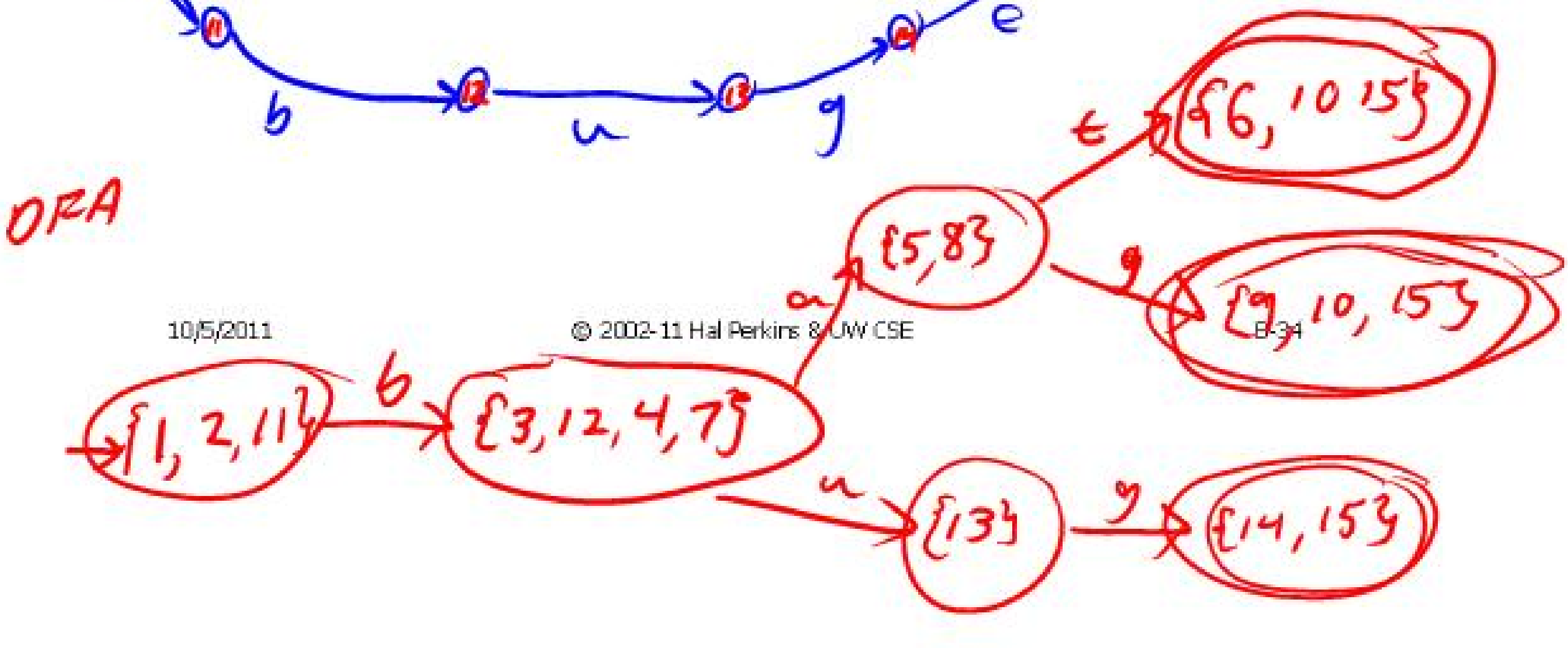
r *



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
  - The state of the DFA after reading some input is the set of *all* states the NFA 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 details

Example: DFA for hand-written scanner

- Idea: show a hand-written DFA for some typical programming language constructs
  - Then use to construct hand-written scanner
- Setting: Scanner is called whenever the parser needs a new token
  - Scanner stores current position in input
  - Starting there, use a DFA to recognize the longest possible input sequence that makes up a token and return that token
- Disclaimer: For illustration only. Course project will use scanner generator