CSE 401 – Compilers

Languages, Automata, Regular Expressions & Scanners
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Winter 2009

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Agenda

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

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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
  - Borrowed from the linguistics community (Chomsky)

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Grammar for a Tiny Language

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

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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>
  - 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 in different parts of derivation

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Alternative Notations

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

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

  ifStmt → if (*expr*) *stmt*

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

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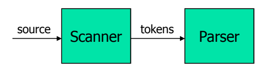
Parsing

- 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)
- Efficiency
  - Scanner recognizes regular expressions – proper subset of context free grammars
    - Much faster than general CFG parsing
    - (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

Definitions

- Pattern: a definition of a related set of lexical entities
  - Ex: all sequences of numeric characters, all sequences of alphanumeric characters starting with an alphabetic character
  - Regular expressions are used in practice to define patterns
- Lexeme: group of characters that matches a pattern
  - Ex: '1234', '43204222', 'snork', 'f0rk'
- Token: class of lexemes matching a pattern, distinguished by an attribute
  - Ex: 'snork' and 'f0rk' are both identifier lexemes with the actual names kept as an attribute

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

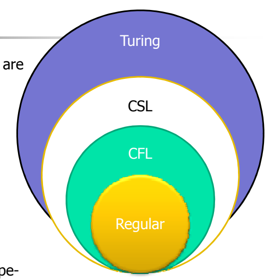
- Most modern languages are free-form
  - Layout doesn't matter
  - Whitespace separates tokens
- Alternatives
  - Fortran – line oriented
  - Haskell, Python – indentation and layout can imply grouping
- And other confusions
  - In C++ or Java, is >> a single operator or the end of two nested templates or generic classes?

Formal Languages & Automata Theory (a review in 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)
- Context-free (Type-2) languages are specified by context-free grammars and pushdown automata (PDAs)
- Context-sensitive (Type-1) languages … aren't too important
- Recursively-enumerable (Type-0) languages are specified by general grammars and Turing machines



One distinction among the levels is what is allowed on the right hand and on the left hand sides of grammar rules

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

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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

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Abbreviations

- 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

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Examples

re	Meaning
+	single + character
!	single ! character
=	single = character
!=	2 character sequence
<=	2 character sequence
xyzzy	5 character sequence

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More Examples

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

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Abbreviations

- Many systems allow 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)

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Example

- Possible syntax for numeric constants

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

Initial MiniJava Lexical Spec.

```
Program ::= (Token | Whitespace)*
Token ::= ID | Integer | ReservedWord | Operator |
           Delimiter
ID ::= Letter (Letter | Digit)*
Letter ::= a | ... | z | A | ... | Z
Digit ::= 0 | ... | 9
Integer ::= Digit+
ReservedWord::= class | public | static | extends |
       void | int | boolean | if | else |
       while | return | true | false | this | new |
       String | main | System.out.println
Operator ::= + | - | * | / | < | <= | >= | > | == |
       != | && | !
Delimiter ::= ; | . | , | = | ( | ) | { | } | [ | ]
```

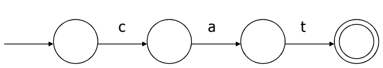
Recognizing REs

- 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 each time called, even if more input; i.e., run the FSA from the current location in the input each time the scanner is called
- Reject if no transition possible, or no more input and not in final state (DFA)

Example: FSA for "cat"



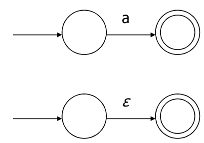
DFA vs NFA

- Deterministic Finite Automata (DFA)
  - No choice of which transition to take under any condition
  - 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 right path or backtrack

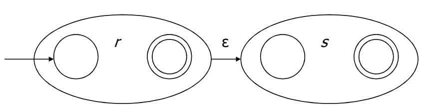
FAs in Scanners

- 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

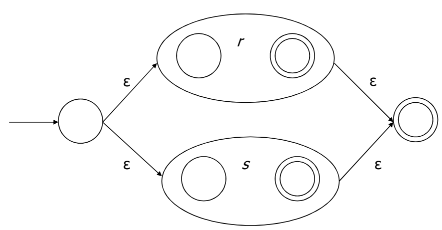
From RE to NFA: base cases



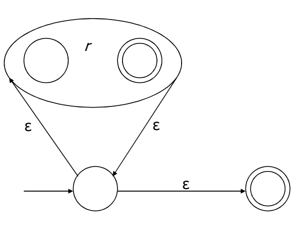
r s



r | *s*



*r**



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* 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 details

To Tokens

- Every "final" state of a DFA emits a token
- Tokens are the internal compiler names for the lexemes
  - `==` becomes equal
  - `(` becomes leftParen
  - **private** becomes private
- You choose the names
- Also, there may be additional data … `\r\n` might include line count

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 fair amount of tedious work
  - may have subtle differences from the language specification

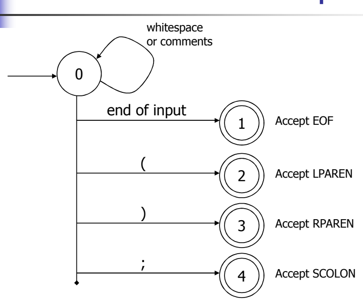
DFA => code [continued]

- Option 2: use tool to generate table driven parser
  - 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"
  - Table lookups may be slower than direct code, but switch implementation is a possible revision

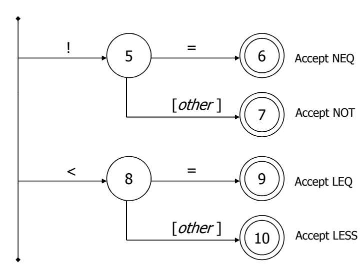
Example: DFA for hand-written scanner

- 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: Example for illustration only – you'll use tools for the project (see further below)

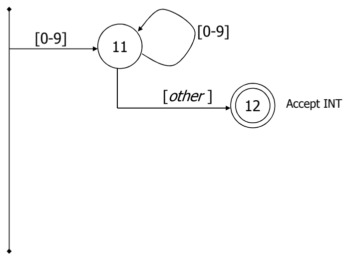
Scanner DFA Example (1)



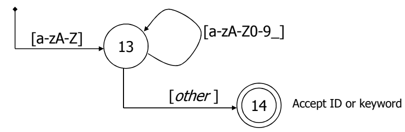
Scanner DFA Example (2)



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
  // lexical classes
  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;
```


Automatic Scanner Generation ForMiniJava

- We use the jflex tool to automatically create a scanner from a specification file, `Scanner/minijava.jflex`
- We use the CUP tool to automatically create a parser from a specification file, `Parser/minijava.cup`
- Token classes are shared by jflex and CUP. CUP generates code for the token classes specified by the `Symbol` class
- The MiniJava Makefile automatically rebuilds the scanner (or parser) whenever its specification file changes

Symbol Class

Tokens are represented as instances of class Symbol

```
class Symbol {
Int sym;      // which token class?
Object value; // any extra data for this lexeme
...
}
```

A different integer constant is defined for each token class in the `sym` helper class

```
class sym {
    static int CLASS = 1;
    static int IDENTIFIER = 2;
    static int COMMA = 3;
  ...
}
```

Can use this in printing code for `Symbols`; see `symbolToString` in `minijava.jflex`

Token Declarations in CUP

- Declare new token classes in `Parser/minijava.cup`, using `terminal` declarations
  - include Java type if `Symbol` stores extra data
- Examples

```
/* reserved words: */
terminal CLASS, PUBLIC, STATIC, EXTENDS;
 ...
/* operators: */
terminal PLUS, MINUS, STAR, SLASH, EXCLAIM;
...
/* delimiters: */
terminal OPEN_PAREN, CLOSE_PAREN;
terminal EQUALS, SEMICOLON, COMMA, PERIOD;
...
/* tokens with values: */
terminal String IDENTIFIER;
terminal Integer INT_LITERAL;
```

`jflex` Token Specifications

- Helper definitions for character classes and re's
  ```
  letter = [a-z A-Z]
  eol = [\r\n]
  ```
- Simple token definitions are of the form:
  `regexp { Java stmt }`

  `regexp` can be (at least):
  - a string literal in double-quotes, e.g. `"class"`, `"<="`
  - a reference to a named helper, in braces, e.g. `{letter}`
  - a character list or range,in square brackets ,e.g. `[a-z A-Z]`
  - a negated character list or range, e.g. `[^\r\n]`
  - `.` (which matches any single character)
  - *`regexp regexp`*, *`regexp|regexp`*, *`regexp*`*, *`regexp+`*, *`regexp?`*, *`(regexp)`*

`jflex` Specifications (cont.)

- *Java stmt* (the accept action) in a token specification is typically:
  - `return symbol(sym.CLASS);` for a simple token
  - `return symbol(sym.CLASS,yytext());` for a token with extra data based on the lexeme string`yytext()`
  - empty for whitespace

Coming Attractions

- Homework this week: paper exercises on regular expressions, etc.
- Next week: first part of the compiler assignment – the scanner
- Next topic: parsing
  - Will do LR parsing first – we need this for the project, then LL (recursive-descent) parsing