Regular Expressions

CSE 413, Autumn 2005

Programming Languages

http://www.cs.washington.edu/education/courses/413/05au/

Agenda for Today

- Basic concepts of formal grammars
- Regular expressions
- Lexical specification of programming languages
- Using finite automata to recognize regular expressions

Programming Language Specifications

- 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

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

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 a single nonterminal – can use either at different times

Alternative Notations

- There are several syntax notations for productions in common use
  - » all mean the same thing
  - » “the non-terminal on the left can be replaced by the expression on the right”

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

ifStmt → **if (** *expr* **)** *stmt*

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

Example Derivation

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

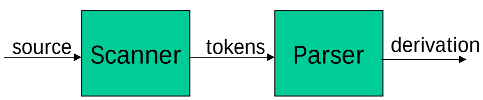
a = 1 ; if (a + 1) b = 2 ;

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 because there are more useful ways to organize the task that simplify each part

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



Recall: Characters vs Tokens

- Input text

```
// this line is a simple comment
if (x >= y) y = 42;
```

- Token Stream

IF | LPAREN | ID(x) | OP_GEQ | ID(y)

RPAREN | ID(y) | OP_ASSIGN | INT(42) | SCOLON

  - » Note: tokens are atomic items, not character strings
    - objects of class Token

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
- 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 type (*lexical class*) for each distinct terminal symbol in the programming language
  - » Examine the grammar to find these
- Some tokens may have attributes
  - » Examples:
    - integer literal token will have the actual integer value (17, 42,...) as an attribute
    - identifiers will have a string with the actual id as an attribute and perhaps some type information

Typical Programming Language Tokens

- Operators & Punctuation
  - » `+ - * / ( ) { } [ ] ; : < <= == = != ! …`
  - » Each of these is a distinct lexical class
- Keywords (reserved)
  - » 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 literals
  - » 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 forbar != beginning;`

  should be recognized as 5 tokens

  | RETURN | ID(forbar) | NEQ | ID(beginning) | SCOLON |

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

Languages & Automata Theory

- 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 language may be specified by many different grammars and automata
- A grammar or automaton specifies only one language

Regular Expressions and Finite Automata

- The lexical grammar (structure) of most programming languages can be specified with regular expressions
  - » Sometimes a little ad-hoc "cheating" is useful
- 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, commonly ASCII or Unicode
- If *re* is a regular expression, *L*(*re*) is the language (set of strings) generated by *re*
- Note that this is opposite of the way we often think about regular expressions
  - » *generating* strings vs *matching* strings
  - » either way, the relevant set of strings is *L*(*re*)

Fundamental Regular Expressions

re	*L*(*re*)	Notes
a	{ a }	Singleton set, for each a in Σ
ε	{ ε }	Empty string
∅	{ }	Empty language

Operations on Regular Expressions

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	L(*re*)
a	single character a
!	single character !
!=	specific 2-character sequence !=
[!<>]=	a 2-character sequence: !=, <=, or >=
\[	single character [
hogwash	7 character sequence

More Examples

re	L(*re*)
[abc]+	
[abc]*	
[0-9]+	
[1-9][0-9]*	
[a-zA-Z][a-zA-Z0-9_]*	

Abbreviations

- Many systems allow naming the regular expressions to make writing and reading definitions easier

  name ::= *re*

  for example

  digit ::= [0-9]

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

Example

- Possible syntax for numeric constants

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

  digits ::= *digit*+

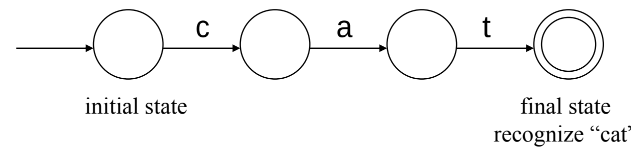
  digit ::= [0-9]

Recognizing Regular Expressions

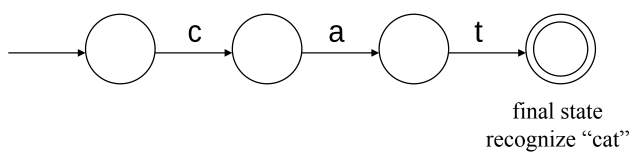
- Finite automata can be used to recognize strings generated by regular expressions
- Can build by hand or automatically
  - » Not totally straightforward, but can be done systematically
  - » Tools like Lex, Flex, and JLex do this automatically, given a set of REs

Finite State Automaton

- A finite set of states
  - » One marked as initial state
  - » One or more marked as final states
- 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



Example: FSA for "cat"



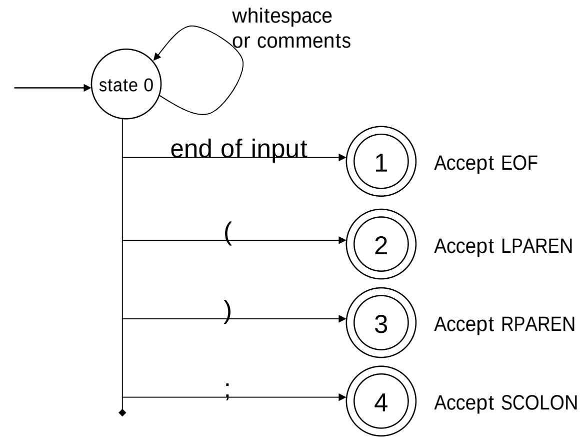
Accept or Reject

- Accept
  - » if final state reached and no more input
  - » if in an accepting state when no valid transition for the next symbol or no more input
- Reject
  - » if no more input and not in final state
  - » if no transition possible and not in accepting state

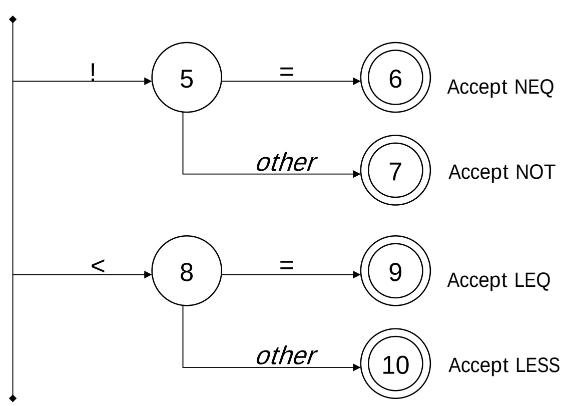
DFA example

- Idea: show a hand-written DFA for some typical programming language constructs
  - » Can 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

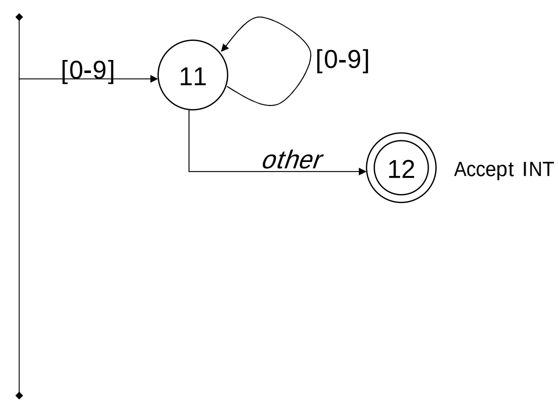
Scanner DFA Example (1)



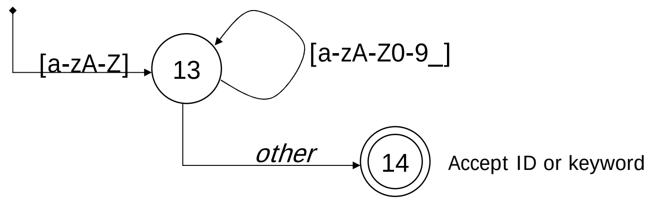
Scanner DFA Example (2)



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)