CSEP 501 – Compilers

Languages, Automata, Regular Expressions & Scanners
Hal Perkins
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Agenda

- Basic concepts of formal grammars (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 or Backus-Normal Form) used to specify the syntax of ALGOL 60
  - Borrowed from the linguistics community (Chomsky)

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

  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

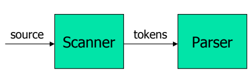
a = 1 ; if (a + 1) b = 2 ;

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

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 (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

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 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 signle ID lexical class, but parameterized by actual id
- Integer constants
  - A single INT lexical class, but parameterized by int value
- Other constants, etc.

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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 foobar != hohum;

  should be recognized as 5 tokens

  RETURN | ID(foobar) | NEQ | ID(hohum) | SCOLON

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

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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

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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

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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*

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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

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
hogwash	7 character sequence

More Examples

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

Abbreviations

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

  name ::= *re*

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

Example

- Possible syntax for numeric constants

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

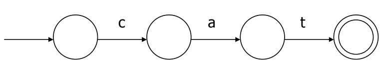
Recognizing REs

- 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, 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
  - 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 slightly different – accept longest match even if more input
- Reject if no transition possible or no more input and not in final state (DFA)

Example: FSA for "cat"



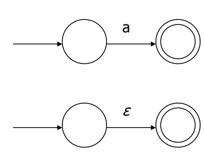
DFA vs NFA

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

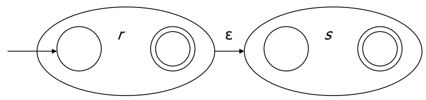
FAs in Scanners

- 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

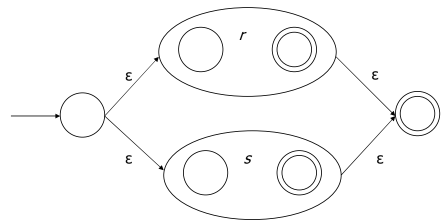
From RE to NFA: base cases



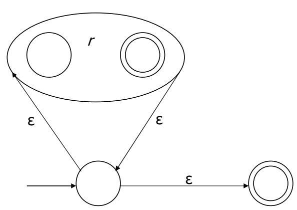
rs



r | *s*



r *



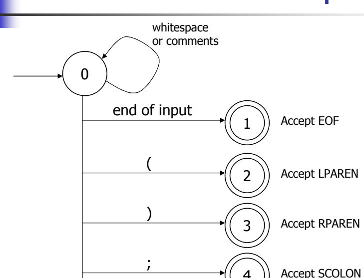
From NFA to DFA

- 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

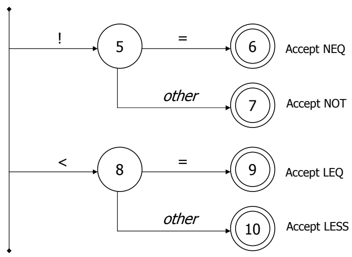
Example: DFA for hand-written scanner

- 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

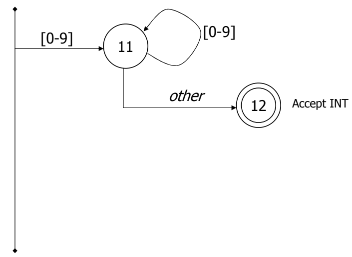
Scanner DFA Example (1)



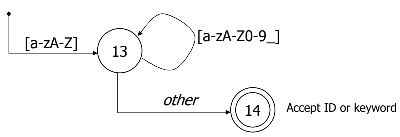
Scanner DFA Example (2)



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;
```


Project Notes

- For the course project, use a lexical analyzer generator
- Suggestion: SableCC (described in 2nd edition of Appel’s book)
  - Alternative: JLex (or JFlex) if you want to use a more traditional Lex/Yacc-like pair of compiler tools

Coming Attractions

- Homework this week: paper exercises on regular expressions, etc.
- Next week: first part of the compiler assignment – the scanner
  - Basically the project from Ch. 2 of Appel’s book if you want to get a bit ahead
- Next topic: parsing
  - Will do LR parsing first – suggest using this for the project (thus SableCC instead of JavaCC)
  - Good time to start reading ch. 3.