CSC 488S/CSC 2107S Lecture Notes

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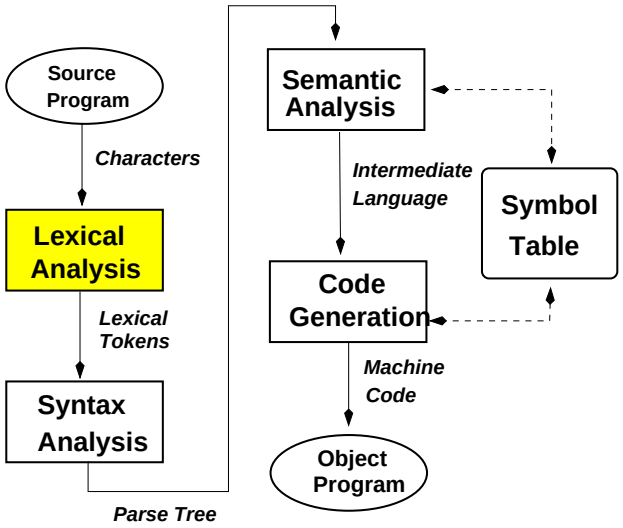
Winter 2012/2013 term at the University of Toronto



Reading Assignment

Fischer, Cytron, LeBlanc

Chapter 3

Omit Section 3.8

Lexical Analysis (scanning)

- Lexical analysis transforms its input (a stream of *characters*) from one or more source files into a stream of language-specific *lexical tokens*.
- A *lexical token* is a data structure that is used to pass information from lexical analysis to syntax analysis
- Lexical Analysis Tasks
  - Delete irrelevant information (whitespace, comments)
  - Determine lexical token boundaries in source stream
  - Transmit lexical tokens to next pass.
  - Deal with ill-formed lexical tokens, recover from lexical errors.
  - Process literal constants (optional).
  - Transmit source coordinates (file, line number) to next pass.
- **Lexical analysis must be really efficient for good compiler performance.**

Lexical Analysis

- Typical programming language objects a lexical analyzer must deal with.
  - Identifiers
  - Reserved words or Keywords.
  - Literal constants: integer, real, string ...
  - Special characters: + - * / ( ) & ...
  - Comments
- A programming language *should* be designed so that the lexical analyzer can determine lexical token boundaries easily.
- During language design a check should be made that the lexical structure of the language permits efficient token separation.
- In most languages, lexical tokens are designed to be easily separated based a left to right scan of the input stream.

Running Example Program

```
/* Turing program to find prime numbers <= 10,000 */
const n := 10000
var sieve, primes : array 2 .. n  of boolean
var next :  int := 2
for k1 := 2 .. n  /* initialize  */
   sieve[ k1 ] := true    primes[ k1 ] := false
end for
loop
    exit when next > n
    primes[ next ] := true
    for k2 : next .. n by next
        sieve[ k2 ] := false
    end for
    loop   /* find next prime */
        exit when next > n or sieve[ next ]
        next += 1
    end loop
end loop
/*  prime[i]  is true only for prime numbers */
```


Lexical Analysis – Running Example Program

Input - a stream of characters

/* Turing program to find prime numbers <= 10,000 */ const n := 10000 var sieve, primes : array 2 .. n of boolean var next : int := 2 for k1 := 2 .. n /* initialize */ sieve[k1] := true primes[k1] := false end for loop exit when next > n primes[next] := true for k2 : next .. n by next sieve[k2] := false end for loop /* find next prime */ exit when next > n or sieve[next] next += 1 end loop end loop /* prime[i] is true only for prime numbers */

Output - a stream of lexical tokens

const n := 10000 var sieve, primes : array 2 .. n of boolean var next : int := 2 for k1 := 2 .. n sieve [k1] := true primes [k1] := false end for loop exit when next > n primes [next] := true for k2 : next .. n by next sieve [k2] := false end for loop exit when next > n or sieve [next] next += 1 end loop end loop

Building Lexical Analyzers

- Describe the lexical structure of the language using *regular expressions*
- Generate a non-deterministic finite automata (NFA) that recognizes the strings (regular sets) specified by the regular expressions.
- Convert the NFA into a *deterministic finite automata* (DFA).[a]
- Implement the DFA using a table-driven algorithm or as hand coded algorithm.

[a] See *Fischer, Cytron, LeBlanc* Section 3.8 for the formal details

Regular Expressions

- Regular expression notation is a convenient way to precisely describe the lexical tokens in a language.
- The sets of strings defined by regular expressions are *regular sets*. Each regular expression defines a regular set.
- Let Σ (*Vocabulary*) be a finite set of characters.
  Typically *ASCII* or *Unicode*
  Σ defines the input to the lexical analyzer.
- λ is the empty or null string. $\emptyset$ is the empty set.
- Concatenation is used to build strings from the characters in Σ.
- Characters may be quoted in single quotes ′ to avoid ambiguity.
  Mandatory for the meta characters: '(' ')' '|' '+' '*'

Regular Expression Definition

1. $\emptyset$ is a regular expression denoting the empty set.
2. λ is a regular expression denoting the set that contains only the empty string. Note $\emptyset \neq \lambda$
3. A symbol S (a character in Σ) is a regular expression denoting a set containing only S.
4. If A and B are regular expressions then so are:

A | B	Alternation
A B	Concatenation
A^*	Kleene closure, zero or more copies of A
(A)	Parenthesized regular expression

5. Useful Sets:

A^+	Positive closure, *One* or more strings in A
Not(A)	Complement of A with respect to Σ (Σ - A)
A^k	k fold Concatenation, exactly k copies of strings from A

Regular Expression Examples

Digit	(0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9)
Letter	(A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z)
Hex Digit	(Digit | A | B | C | D | E | F)
Integer	$Digit^+$
OptionalSign	('+' | '-' | λ)
Signed integer	OptionalSign Integer
Identifier	Letter (Digit | Letter | '_')*
Real Number	$Digit^+$ '.' $Digit^*$ ((E | e) OptionalSign $Digit^+$ | λ)
Java comment	// (Not (Eol))* Eol

Finite Automata

- Finite automata (state machines) can be used to recognize tokens specified by a regular expression.
- A finite automaton (FA) is
  - A finite set of states
  - A set of transitions from one state to another.
    Transitions depend on input characters from the vocabulary Σ
  - A distinguished *start* state.
  - A set of final (*accepting*) states.
- Finite automata can be represented graphically using state transition diagrams.
- If the FA has a *unique* transition for every (state, input character) pair then it is a *deterministic* FA (DFA).
  Being deterministic is good.

A typical lexical analyzer built using a DFA works like this

- The input to the DFA is the next input character to the lexical analyzer.
- The main state of the DFA uses the character to classify the type of possible token.
  e.g. identifier, number, special character, comment, whitespace.
- For lexical tokens that can consist of more than one character, the main state transitions to a sub-state that deals with accumulating one type of lexical token.
  e.g identifier, number
- Once a complete token has been recognized by the DFA, it is packaged into a lexical token data structure and sent onward to semantic analysis.
- Each sub-state consumes the characters in its lexical token and ultimately returns to the main state to deal with the character immediately after its token

See Slides 46 and 47 for examples of DFA based table driven lexical analyzers.

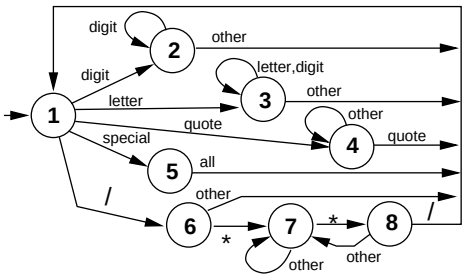
Example – Hand Coded Lexical Analyzer

```
while( ! eof ) {
    switch( currentChar ) {
    case letter:        accumulate identifier
                        distinguish identifiers
                           or reserved word
    case digit:         accumulate number
                        distinguish integer, float
    case quote:         accumulate string
    case comtStart:  discard comment
    case special:    accumulate special token
    case whiteSpace:    discard white space
    }
    if( tokenProduced )
         emit token
}
```


Example – Table Driven DFA Scanner

- Example of implementing a simple DFA scanner using a small table to define the DFA.
- Language with whitespace, integers, identifiers, strings , special characters, C style comments.
- Make lexical analysis decisions with 1 character look ahead.
- Advance in input, save start of long tokens.
- Save input pointer on entry to each state.
  If appropriate emit accumulated token on return to state 1
- Notation:
  N - change to state N
  +N - advance input pointer and change to state N

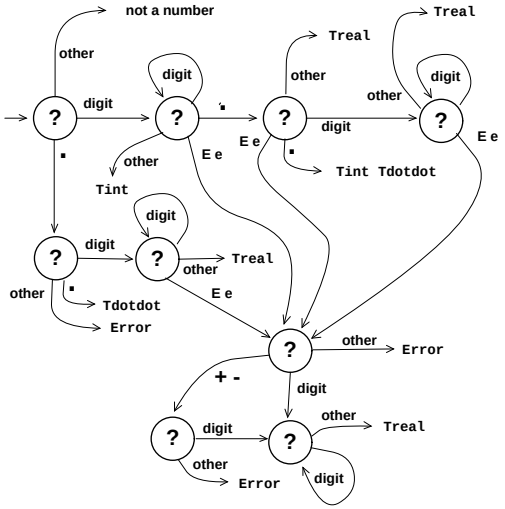
	Input Character							
State	blank	digit	letter	quote	Special	/	*	Purpose
1	+1	2	3	+4	5	+6	5	blanks & dispatch
2	1	+2	1	1	1	1	1	integers
3	1	+3	+3	1	1	1	1	identifiers
4	+4	+4	+4	+1	+4	+4	+4	'string'
5	1	1	1	1	+1	1	+1	special chars.
6	1	1	1	1	1	1	+7	emit token '/'
7	+7	+7	+7	+7	+7	+7	+8	comment body
8	+7	+7	+7	+7	+7	+1	7	end comment



Example - Real Constants in Turing

- Reference Manual definition - literal real constant:
  - An *explicitRealConstant* consists of an optional plus or minus sign a significant digits part and an exponent part.
  - The significant digits part `...` consists of a sequence of one or more digits optionally containing a decimal point. The decimal point is allowed to follow the last digit as in 16. or precede the first digit as in .25
  - The exponent part consists of the letter `e` or `E` followed optionally by a plus or minus sign followed by one or more digits. If the significant figures [sic] part contains a decimal point then the exponent part is not required.
- Issues
  - Must have at least one digit in the significant digits part. Must have at least one digit in the exponent part.
  - Context sensitive to distinguish integer constants from real constants.
  - Context sensitive: exponent can be omitted *iff* there was a decimal point in the significant digits part.
  - Leading/trailing decimal point interacts with use of `..` for integer subrange. e.g. `3.4` vs. `3..4`
  - Handle leading sign as unary `+` or `-` during syntax analysis. Lexical analyzer can't easily distinguish `X - 3.5` from `X - -3.5` or `X - - -3.5` .
  - Must detect malformed constants like `3.4.5E+`
  - Arbitrary number of digits in exponent part is unrealistic. Exponent range is -38 .. + 38 on 32-bit machines. But must allow `1.0E+000000000000000003`

DFA Recognizer for Turing Numeric Constants



Building Tables During Lexical Analysis

- To save space in the lexical token stream, the lexical analyzer can build tables of certain kinds of tokens, e.g. identifiers, string constants, other constants. These tables are then used by later passes
- The lexical token that gets passed on to the syntax analysis pass contains a field that identifies the type of token and the tokens index into an appropriate table.
- **Indices that uniquely identify tokens are sufficient for most purposes in syntax and semantic analysis.**
- Examples:

Original Token	Encoded as	
`veryLongIdentifier`	Ident	23
`shorterIdentifier`	Ident	29
`"Hello World"`	StrCon	19

- If the compilers symbol table is based on a hash table, could also compute (once) the hash key for each identifier during lexical analysis.

Handling Reserved Words and Keywords

- In many programming languages, reserved words or keywords are lexically indistinguishable from identifiers.
- There are several possible approaches for recognizing *special* words:
  - Write a regular expression to recognize each special word.
    Order the regular expressions to recognize these words before identifiers.
    This requires buffering and backup in the lexical analyzer.
  - Write a regular expression to recognize all identifiers.
    Use a fast table lookup to check whether the identifier is really a special word.
    Production compilers typically use this approach.
  - If the lexical analyzer is building an identifier table, preload the special words into the table so that low table indices indicate special words
- For keyword languages, flag the identifier as a *maybe keyword* and let syntax analysis decide.

What Makes Lexical Analysis Difficult

- Dealing with long tokens, e.g. strings in PL/I can contain 32,768 characters.
- Tokens that can be split across input boundaries.
- Special handling in character strings. e.g. \nnn in C.
- Context sensitive input, e.g.string constant concatenation in C. .e.g ”AB” ”CD”
- Processing numeric constant values close to the hardware limits for minimum and maximum values e.g. -2147483648 or 1.7976931348623157e+308 This requires some **very careful computation** in the part of the lexical analyzer that converts constants.
- Separation requiring lookahead.
  More than one character lookahead is usually painful.
  e.g. 123456 vs 123456E+12
- Dealing with large initializations, e.g. initialization in array declarations in C and Java

Lexically Challenged Languages – FORTRAN

- Designed before lexical analysis and parsing were well understood
  - Keywords not reserved words
  - Blank insensitive
- Example: `DO 10 I = 1`

Lexically Challenged Languages – PL/I

- Designed to be all things to all programmers
  - Keywords not reserved words
  - Awkward lexical structure
- `IF IF = THEN THEN THEN = ELSE ELSE ELSE = IF = THEN`
- `’10101101110100111010110110001’`
- `DECLARE( I1, N3, K )`

Lexically Challenged Languages – C

- **backslash continuation** If the backslash character \ occurs at the *end* of an input line, then the next input line is taken as an immediate continuation of the first line. The backslash can occur almost anywhere including in the middle of an identifier, reserved word or constant.
- **trigraphs** ANSI C contains a mechanism for supporting keyboards that do not contain all of the characters required to express C programs. A trigraph is a 3-character sequence beginning with ?? that stands for some other single character.
  The 9 ANSI trigraphs are

Trigraph	Is	Trigraph	Is	Trigraph	Is
??(	[	??)	]	??<	{
??>	}	??/	\	??=	#
??-	~	??’	^	??!	|

  These trigraphs may be used anywhere that the corresponding character could be used.

Lexical Errors

- Lexical analyzer must deal with ill-formed and incomplete lexical tokens.
- Examples:
  - Incorrectly formed: 3.4.5 3.4E- 0x7FFG8
  - Oversize tokens: 11111111111111111111111111111111111111111111111111111111
    Supercalifragalisticexpialadocious
  - Numeric value out of range: 1.23456E+99 99999999999999999
  - Unterminated string or comment: ”Hi There /* Obfuscate here
  - Illegal characters: ? #
- Error handling strategies:
  - Emit error message for lexical error
  - Repair strategies:
    Correct token if possible.
    Discard bad token or replace with ”safe” value
    Stop run away strings, comments on line boundaries.

Handling Inclusion

- lexical analyzer must often implement source inclusion,
  e.g. **#include**< file > in C .
- Processing of an include directive
  - Locate the file to be included.
  - Switch lexical analyzer input source to the file.
  - Perform lexical analysis on the file, emitting tokens as needed.
  - At end of file switch lexical analyzer input source back to previous source (after the include directive).
  - This process must be recursive to deal with nested includes
- Source inclusion is typically implemented as a *stack* of input sources,
  - the lexical analyzer reads from the source on top of the stack.
  - A new source is pushed onto the stack when an include command is processed.
  - The stack is popped when end of file is reached on the included file.

Managing Source Program Coordinates

- The subsequent phases of the compiler need to know where each lexical token originated to be able to emit source code specific error messages. e.g.,
  `Syntax Error on line 23 of file foo.c`
- Conceptually tag each lexical token with an identification of the source file and line number where it originated. Really ambitious systems include offset in the line.
- In practice, this makes lexical tokens large and unwieldy.
  Most practical systems are based on transmitting only *changes* in source coordinates (as invisible internal lexical tokens) to the subsequent phases. Each phase must then include logic to keep track of the current source program coordinate.

Source Coordinate Management Example

- Send a *new source file token* at
  - The start of compilation.
  - The start of processing an included file (e.g. #include)
    The lexical analyzer may get this information from a pre processor.
  - At the end of processing an included file (e.g. revert to previous file)
- Send a *new source line token* at
  - The start of compilation.
  - Each time the lexical analyzer moves to a new line containing a lexical token (optimizes whitespace deletion).
  - At the start of processing an included file.
  - At the end of processing an included file to revert to the previous files coordinate system.

Lexical Analyzer Optimization

- First design a *correct* lexical analyzer.
  Then optimize it for speed.
- Most important optimizations[a] :
  - Input in bulk, not character by character.
  - Touch each input character as few times as possible.
  - Don't copy input if you can avoid it.
  - Discard white space and comments efficiently.
    Often 50% .. 60% of the source.
  - Make reserved word testing as fast as possible.
  - Evaluate literal constants efficiently.
- Optimizations should not make lexical analyzer difficult to maintain or modify.

[a] See: W. M. Waite, The Cost of Lexical Analysis, Software–Practice and Experience, v.16, n.5, May 1986

Example - Accumulating Identifiers

- Naive

```
char ch, idBuffer[200]  ;
int i ;
. . .
i = 0 ;
while( ('a' <= ch && ch <= 'z') || ( 'A' <= ch && ch <= 'Z' )
       || ( '0' <= ch && ch <= '9' ) || ch == '_' ) {
   idBuffer[i++] = ch ;
   ch = getchar() ;
}
/* identifier is in idBuffer[ 0 .. i - 1 ]  */
```

- Optimized

```
BOOL identifierChar[ 256 ] ;  /* true for a..z, A..Z, 0..9 _ */
                              /* false otherwise */
char * iStart, * iEnd, *inPtr ;
. . .
iStart = inPtr ;
while( identifierChar[ *inPtr++ ] ) ;
iEnd = inPtr ;
/* Identifier is in input buffer iStart .. iEnd - 1  */
```


Scanner Generators - Lex, Flex & JFlex

- Lex, Flex (Flexible Lex) and JFlex (Flex for Java) are automated *scanner generators* that transform a regular expression description of a language's lexical tokens into source code for a scanner.
- A regular expression defines a class of lexical token.
  The compiler writer can specify an arbitrary piece of code that gets executed when the token is recognized.
- The generated scanners are good for student projects and prototype compilers but may not be efficient enough for production compilers.