Compiler Construction

Lecture 4: Lexical Analysis III (Practical Aspects)

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Outline

The Extended Matching Problem

Definition

Let $n \geq 1$ and $\alpha_1, \ldots, \alpha_n \in RE_\Omega$ with $\varepsilon \notin [\![\alpha_i]\!] \neq \emptyset$ for every $i \in [n]$ $(= \{1, \ldots, n\})$. Let $\Sigma := \{T_1, \ldots, T_n\}$ be an alphabet of corresponding tokens and $w \in \Omega^+$. If $w_1, \ldots, w_k \in \Omega^+$ such that

- $w = w_1 \ldots w_k$ and
- for every $j \in [k]$ there exists $i_j \in [n]$ such that $w_j \in [\![\alpha_{i_j}]\!]$,

then

- $(w_1, \ldots, w_k)$ is called a decomposition and
- $(T_{i_1}, \ldots, T_{i_k})$ is called an analysis

of w w.r.t. $\alpha_1, \ldots, \alpha_n$.

Problem (Extended matching problem)

Given $\alpha_1, \ldots, \alpha_n \in RE_\Omega$ and $w \in \Omega^+$, decide whether there exists a decomposition of w w.r.t. $\alpha_1, \ldots, \alpha_n$ and determine a corresponding analysis.

Ensuring Uniqueness

Two principles:

1. Principle of the longest match ("maximal munch tokenization")
   - for uniqueness of decomposition
   - make lexemes as long as possible
   - motivated by applications: e.g., every (non-empty) prefix of an identifier is also an identifier
2. Principle of the first match
   - for uniqueness of analysis
   - choose first matching regular expression (in the given order)
   - therefore: arrange keywords before identifiers (if keywords protected)

Implementation of FLM Analysis

Algorithm (FLM analysis – overview)

Input: *expressions* $\alpha_1, \ldots, \alpha_n \in RE_\Omega$, *tokens* $\{T_1, \ldots, T_n\}$, *input word* $w \in \Omega^+$

Procedure:

1. *for every* $i \in [n]$, *construct* $\mathfrak{A}_i \in DFA_\Omega$ *such that* $L(\mathfrak{A}_i) = [\![\alpha_i]\!]$ *(see DFA method; Algorithm 2.9)*
2. *construct the product automaton* $\mathfrak{A} \in DFA_\Omega$ *such that* $L(\mathfrak{A}) = \bigcup_{i=1}^{n} [\![\alpha_i]\!]$
3. *partition the set of final states of* $\mathfrak{A}$ *to follow the first-match principle*
4. *extend the resulting DFA to a backtracking DFA which implements the longest-match principle*
5. *let the backtracking DFA run on* w

Output: *FLM analysis of* w *(if existing)*

Definition (Backtracking DFA)

- The set of configurations of $\mathfrak{B}$ is given by
$$(\{N\} \uplus \Sigma) \times \Omega^* \cdot Q \cdot \Omega^* \times \Sigma^* \cdot \{\varepsilon, \mathrm{lexerr}\}$$
- The initial configuration for an input word $w \in \Omega^+$ is $(N, q_0 w, \varepsilon)$.
- The transitions of $\mathfrak{B}$ are defined as follows (where $q' := \delta(q, a)$):
  - normal mode: look for initial match
$$(N, qaw, W) \vdash \begin{cases} (T_i, q'w, W) & \text{if } q' \in F^{(i)} \\ (N, q'w, W) & \text{if } q' \in P \setminus F \\ \textbf{output: } W \cdot \mathrm{lexerr} & \text{if } q' \notin P \end{cases}$$
  - backtrack mode: look for longest match
$$(T, vqaw, W) \vdash \begin{cases} (T_i, q'w, W) & \text{if } q' \in F^{(i)} \\ (T, vaq'w, W) & \text{if } q' \in P \setminus F \\ (N, q_0 vaw, WT) & \text{if } q' \notin P \end{cases}$$
  - end of input
$$\begin{array}{rl} (T, q, W) \vdash \textbf{output: } WT & \text{if } q \in F \\ (N, q, W) \vdash \textbf{output: } W \cdot \mathrm{lexerr} & \text{if } q \in P \setminus F \\ (T, vaq, W) \vdash (N, q_0 va, WT) & \text{if } q \in P \setminus F \end{array}$$

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Time Complexity of FLM Analysis

Lemma 4.1

The worst-case time complexity of FLM analysis using the backtracking DFA on input $w \in \Omega^+$ *is* $\mathcal{O}(|w|^2)$.

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- upper bound:
  - each run from mode N to $T \in \Sigma$ consumes at least one input symbol (and possibly reads all input symbols), involving at most $\sum_{i=1}^{|w|} = \frac{n(n+1)}{2}$ transitions
  - if no Σ-mode is reached, lexerr is reported after $\leq |w|$ transitions □

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Remark: possible improvement by tabular method (similar to Knuth-Morris-Pratt Algorithm for pattern matching in strings)

Literature: Th. Reps: *"Maximal-Munch" Tokenization in Linear Time*, ACM TOPLAS 20(2), 1998, 259–273

Outline

A Backtracking NFA

A similar construction is possible for the NFA method:

1. $\mathfrak{A}_i = \langle Q_i, \Omega, \delta_i, q_0^{(i)}, F_i \rangle \in NFA_\Omega$ $(i \in [n])$ by NFA method

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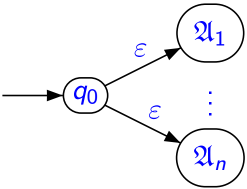
2. "Product" automaton: $Q := \{q_0\} \uplus \biguplus_{i=1}^n Q_i$



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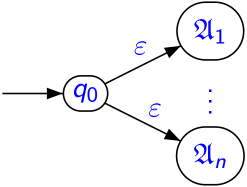

3. Partitioning of final states:
   - $M \subseteq Q$ is called a T_i-matching if

$$M \cap F_i \neq \emptyset \text{ and for all } j \in [i-1] : M \cap F_j = \emptyset$$

   - yields set of T_i-matchings $F^{(i)} \subseteq 2^Q$
   - $M \subseteq Q$ is called productive if there exists a productive $q \in M$
   - yields productive state sets $P \subseteq 2^Q$

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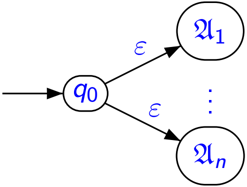

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   - yields productive state sets $P \subseteq 2^Q$
4. Backtracking automaton: similar to DFA case

Outline

Longest Match in Practice

- In general: lookahead of arbitrary length required
  - that is, $|v|$ unbounded in configurations (T, vqw, W)
  - see Lemma 4.1: $\alpha_1 = a$, $\alpha_2 = a^*b$, $w = a\ldots a$

Longest Match in Practice

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  - see Lemma 4.1: $\alpha_1 = a$, $\alpha_2 = a^*b$, $w = a \ldots a$
- "Modern" programming languages (Pascal, Java, ...): lookahead of one or two characters sufficient
  - separation of keywords, identifiers, etc. by spaces
  - Pascal: two-character lookahead required to distinguish `1.5` (real number) from `1..5` (integer range)

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However: principle of longest match not always applicable!

Inadequacy of Longest Match I

Example 4.2 (Longest match in FORTRAN)

1. Relational expressions
   - valid lexemes: `.EQ.` (relational operator), `EQ` (identifier), `12` (integer), `12.`, `.12` (reals)
   - input string: `12␣.EQ.␣12` $\rightsquigarrow$ `12.EQ.12` (ignoring blanks!)

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   - LM yields: $(\mathsf{real}, 12.0)(\mathsf{id}, \mathtt{EQ})(\mathsf{real}, 0.12)$

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   - (correct) input string: `DO␣5␣I␣=␣1,␣20` $\leadsto$ `DO5I=1,20`

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     - LM analysis (wrong): (id, `DO5I`)(gets,)(int, 1)(comma,)(int, 20)

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     - LM analysis (wrong): (id, `DO5I`)(gets,)(int, 1)(comma,)(int, 20)
   - (erroneous) input string: `DO␣5␣I␣=␣1.␣20` ⇝ `DO5I=1.20`
     - LM analysis (correct): (id, `DO5I`)(gets,)(real, 1.2)

Inadequacy of Longest Match II

Example 4.3 (Longest match in C)

- valid lexemes:
  - `x` (identifier)
  - `=` (assignment)
  - `=-` (subtractive assignment; K&R/ANSI-C: `-=`)
  - `1`, `-1` (integers)
- input string: `x=-1`

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- LM yields: $(\mathrm{id}, x)(\mathrm{dec},)(\mathrm{int}, 1)$

$\Rightarrow$ wrong interpretation

Possible solutions:

- Hand-written (non-FLM) scanners
- FLM with lookahead (later)

Outline

Regular Definitions I

Goal: modularizing the representation of regular sets by introducing additional identifiers

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Definition 4.4 (Regular definition)

Let $\{R_1, \ldots, R_n\}$ be a set of symbols disjoint from Ω. A regular definition (over Ω) is a sequence of equations

$$\begin{aligned} R_1 &= \alpha_1 \\ &\vdots \\ R_n &= \alpha_n \end{aligned}$$

such that, for every $i \in [n]$, $\alpha_i \in RE_{\Omega \uplus \{R_1, \ldots, R_{i-1}\}}$.

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such that, for every $i \in [n]$, $\alpha_i \in RE_{\Omega \uplus \{R_1,\ldots,R_{i-1}\}}$.

Remark: since recursion is not involved, every R_i can (iteratively) be substituted by a regular expression $\alpha \in RE_\Omega$
(otherwise $\Longrightarrow$ context-free languages)

Regular Definitions II

Example 4.5 (Symbol classes in Pascal)

Identifiers:

$$\begin{aligned} \mathit{Letter} &= \mathtt{A} \mid \ldots \mid \mathtt{Z} \mid \mathtt{a} \mid \ldots \mid \mathtt{z} \\ \mathit{Digit} &= \mathtt{0} \mid \ldots \mid \mathtt{9} \\ \mathit{Id} &= \mathit{Letter}\,(\mathit{Letter} \mid \mathit{Digit})^* \end{aligned}$$

Numerals:
(unsigned)

$$\begin{aligned} \mathit{Digits} &= \mathit{Digit}^+ \\ \mathit{Empty} &= \emptyset^* \\ \mathit{OptFrac} &= \mathtt{.}\,\mathit{Digits} \mid \mathit{Empty} \\ \mathit{OptExp} &= \mathtt{E}\,(\mathtt{+} \mid \mathtt{-} \mid \mathit{Empty})\,\mathit{Digits} \mid \mathit{Empty} \\ \mathit{Num} &= \mathit{Digits}\ \mathit{OptFrac}\ \mathit{OptExp} \end{aligned}$$

Rel. operators:

$$\mathit{RelOp} = \mathtt{<} \mid \mathtt{<=} \mid \mathtt{=} \mid \mathtt{<>} \mid \mathtt{>} \mid \mathtt{>=}$$

Keywords:

$$\begin{aligned} \mathit{If} &= \mathtt{if} \\ \mathit{Then} &= \mathtt{then} \\ \mathit{Else} &= \mathtt{else} \end{aligned}$$

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The `[f]lex` Tool

Usage of `[f]lex` ("[fast] lexical analyzer generator"):

`spec.l`	$\xrightarrow{\texttt{[f]lex}}$	`lex.yy.c`	$\xrightarrow{\texttt{cc}}$	`a.out`
`[f]lex` specification		Scanner (in C)		Executable

Program $\xrightarrow{\texttt{a.out}}$ Symbol sequence

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A `[f]lex` specification is of the form

Definitions *(optional)*
%%
Rules
%%
Auxiliary procedures *(optional)*

[f]lex Specifications

Definitions:

- C code for declarations etc.: %{ *Code* %}
- Regular definitions: *Name* *RegExp* ...
  (non-recursive!)

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Rules: of the form *Pattern* { *Action* }

- *Pattern*: regular expression, possibly using *Name*s
- *Action*: C code for computing
  symbol = (token, attribute)
  - token: integer `return` value, 0 = `EOF`
  - attribute: passed in global variable `yylval`
  - lexeme: accessible by `yytext`
- matching rule found by FLM strategy
- lexical errors catched by `.` (any character)

Example [f]lex Specification

```
%{
  #include <stdio.h>
  typedef enum {EOF, IF, ID, RELOP, LT, ...} token_t;
  unsigned int yylval;   /* attribute values */
%}
LETTER      [A-Za-z]
DIGIT       [0-9]
ALPHANUM    {LETTER}|{DIGIT}
SPACE       [ \t\n]
%%
"if"                    { return IF; }
"<"                     { yylval = LT; return RELOP; }
{LETTER}{ALPHANUM}*     { yylval = install_id(); return ID; }
{SPACE}+                /* eat up whitespace */
.                       { fprintf (stderr, "Invalid character '%c'\n", yytext[0]); }
%%
int main(void) {
  token_t token;
  while ((token = yylex()) != EOF)
    printf ("(Token %d, Attribute %d)\n", token, yylval);
  exit (0);
}
unsigned int install_id () {...}   /* identifier name in yytext */
```

Regular Expressions in `[f]lex`

Syntax	Meaning
printable character	this character
`\n`, `\t`, `\123`, etc.	newline, tab, octal representation, etc.
`.`	any character except `\n`
`[`*Chars*`]`	one of *Chars*; ranges possible ("`0-9`")
`[^`*Chars*`]`	none of *Chars*
`\\`, `\.`, `\[`, etc.	`\`, `.`, `[`, etc.
`"`*Text*`"`	*Text* without interpretation of `.`, `[`, `\`, etc.
`^`α	α at beginning of line
α`$`	α at end of line
`{`*Name*`}`	*RegExp* for *Name*
α`?`	zero or one α
α`*`	zero or more α
α`+`	one or more α
α`{`n, m`}`	between n and m times α ("$, m$" optional)
`(`α`)`	α
$\alpha_1\alpha_2$	concatenation
$\alpha_1 \vert \alpha_2$	alternative
α_1`/`α_2	α_1 but only if followed by α_2 (lookahead)

Using the Lookahead Operator

Example 4.6 (Lookahead in FORTRAN)

1. `DO` loops (cf. Example 4.2)
   - input string: `DO 5 I = 1, 20`
   - LM yields: (id,)(gets,)(int, 1)(comma,)(int, 20)
   - observation: decision for do token only possible after reading ","
   - specification of `DO` keyword in `[f]lex`, using lookahead:
     `DO / ({LETTER}|{DIGIT})* = ({LETTER}|{DIGIT})* ,`

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   - LM yields: (id,)(gets,)(int, 1)(comma,)(int, 20)
   - observation: decision for do token only possible after reading “,”
   - specification of `DO` keyword in `[f]lex`, using lookahead:
     `DO / ({LETTER}|{DIGIT})* = ({LETTER}|{DIGIT})* ,`
2. `IF` statement
   - problem: FORTRAN keywords not reserved
   - example: `IF(I,J) = 3` (assignment to an element of matrix `IF`)
   - conditional: `IF (`*condition*`) THEN ...` (with `IF` keyword)
   - specification of `IF` keyword in `[f]lex`, using lookahead:
     `IF / \( .* \) THEN`

Longest Match and Lookahead in [f]lex

```
%{
  #include <stdio.h>
  typedef enum {EoF, AB, A} token_t;
%}
%%
ab      { return AB; }
a/bc    { return A; }
.       { fprintf (stderr, "Invalid character '%c'\n", yytext[0]); }
%%
int main(void) {
  token_t token;
  while ((token = yylex()) != EoF) printf ("Token %d\n", token);
  exit (0);
}
```

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  exit (0);
}
```

returns on input

- a: `Invalid character 'a'`
- ab: `Token 1`
- abc: `Token 2  Invalid character 'b'  Invalid character 'c'`

$\Longrightarrow$ lookahead counts for length of match

Outline

Preprocessing

Preprocessing = preparation of source code before (lexical) analysis

Preprocessing steps

- macro substitution

```
#define is_capital(ch) ((ch) >= 'A' && (ch) <= 'Z')
```

- file inclusion

```
#include "header.h"
```

- conditional compilation

```
#ifdef UNIX
char* separator = '/'
#endif
#ifdef WINDOWS
char* separator = '\\'
#endif
```

- elimination of comments