Compiler Construction

Lecture 4: Lexical Analysis III (Practical Aspects)

Thomas Noll

Lehrstuhl für Informatik 2
(Software Modeling and Verification)

RWTH Aachen University

noll@cs.rwth-aachen.de

http://www-i2.informatik.rwth-aachen.de/i2/cc08/

Summer semester 2008

Outline

Repetition: Extended Matching Problem

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.

To ensure uniqueness:

1. Principle of the longest match ("maximal munch tokenization")
   - for uniqueness of decomposition
   - make lexemes as long as possible
   - motivated by applications: usually every (nonempty) 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 order given)

Repetition: Implementation of FLM Analysis

Algorithm (FLM analysis)

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)*
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, and let it run on* w

Output: *FLM analysis of* w *(if it exists)*

Outline

A Backtracking NFA

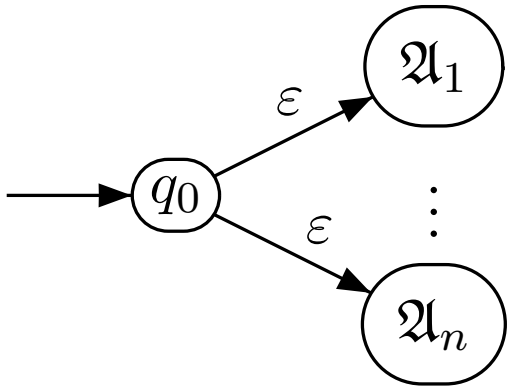
A similar construction is possible for the NFA method:

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

A Backtracking NFA

A similar construction is possible for the NFA method:

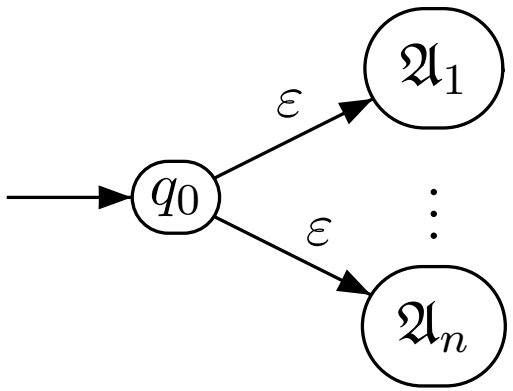
1. $\mathfrak{A}_i = \langle Q_i, \Omega, \delta_i, q_0^{(i)}, F_i \rangle \in NFA_\Omega$ $(i \in [n])$ by NFA method
2. "Product" automaton: $Q := \{q_0\} \uplus \biguplus_{i=1}^{n} Q_i$



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

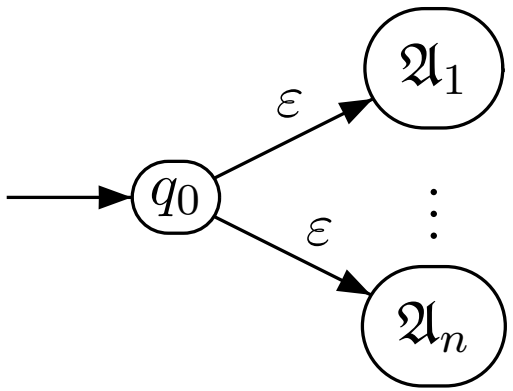


3. Partitioning of final states:
   - $M \subseteq Q$ is called a T_i-matching if
     $$M \cap F_i \neq \emptyset \text{ and for all } j \in [i-1] : M \cap F_j = \emptyset$$
   - yields set of T_i-matchings $F^{(i)} \subseteq 2^Q$
   - $M \subseteq Q$ is called productive if there exists a productive $q \in M$
   - yields productive state sets $P \subseteq 2^Q$

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



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 $P \subseteq 2^Q$
4. Backtracking automaton: similar to DFA case

Outline

Outline

Regular Definitions I

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

Regular Definitions I

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

Definition 4.1 (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 $i \in [n]$, $\alpha_i \in RE_{\Omega \uplus \{R_1, \ldots, R_{i-1}\}}$.

Regular Definitions I

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

Definition 4.1 (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 $i \in [n]$, $\alpha_i \in RE_{\Omega \uplus \{R_1, \ldots, R_{i-1}\}}$.

Remark: since no recursion is 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 4.2 (Symbol classes in Pascal)

Identifiers:

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

Numerals: (unsigned)

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

Rel. operators:

$$\mathit{RelOp} = \texttt{<} + \texttt{<=} + \texttt{=} + \texttt{<>} + \texttt{>} + \texttt{>=}$$

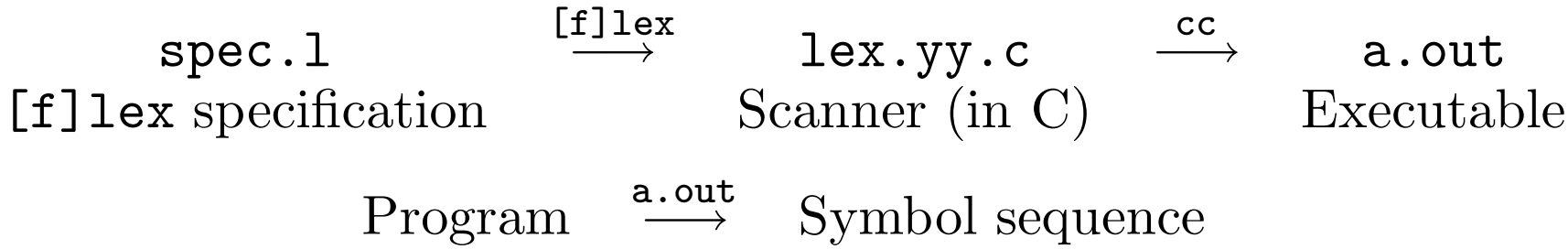
Keywords:

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

Outline

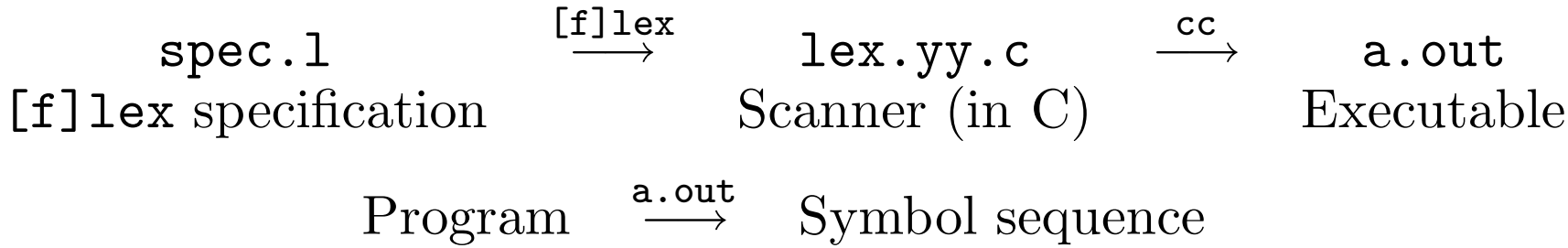
The [f]lex Tool

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



The [f]lex Tool

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



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!)

Rules: of the form *Pattern* { *Action* }
- *Pattern*: regular expression, possibly using *Names*
- *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 `.` or `.|\n` (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
α_1`|`α_2	alternative
α_1`/`α_2	α_1 but only if followed by α_2 (lookahead)

Outline

Longest Match in Practice

- In general: lookahead of arbitrary length (backtracking phase) required
  - see example on Slide 3.18: $\alpha_1 = a$, $\alpha_2 = a^*b$

Longest Match in Practice

- In general: lookahead of arbitrary length (backtracking phase) required
  - see example on Slide 3.18: $\alpha_1 = a$, $\alpha_2 = a^*b$
- "Modern" programming languages (Pascal, ...): 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)

Inadequacy of Longest Match

Example 4.3 (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!)

Inadequacy of Longest Match

Example 4.3 (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!)
   - intended analysis: $(\mathsf{int}, 12)(\mathsf{relop}, \mathsf{eq})(\mathsf{int}, 12)$

Inadequacy of Longest Match

Example 4.3 (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!)
   - intended analysis: $(\mathsf{int}, 12)(\mathsf{relop}, \mathsf{eq}), (\mathsf{int}, 12)$
   - LM yields: $(\mathsf{real}, 12.0)(\mathsf{id}, \texttt{EQ})(\mathsf{real}, 0.12)$

Inadequacy of Longest Match

Example 4.3 (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!)
   - intended analysis: $(\mathsf{int}, 12)(\mathsf{relop}, \mathsf{eq}), (\mathsf{int}, 12)$
   - LM yields: $(\mathsf{real}, 12.0)(\mathsf{id}, \texttt{EQ})(\mathsf{real}, 0.12)$
2. `DO` loops
   - (erroneous) input string: `DO␣5␣I␣=␣1.␣20` $\rightsquigarrow$ `DO5I=1.20`
     - LM analysis (correct): $(\mathsf{id}, \texttt{DO5I})(\mathsf{gets},)(\mathsf{real}, 1.2)$

Inadequacy of Longest Match

Example 4.3 (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!)
   - intended analysis: $(\mathsf{int}, 12)(\mathsf{relop}, \mathsf{eq}), (\mathsf{int}, 12)$
   - LM yields: $(\mathsf{real}, 12.0)(\mathsf{id}, \texttt{EQ})(\mathsf{real}, 0.12)$
2. `DO` loops
   - (erroneous) input string: `DO␣5␣I␣=␣1.␣20` $\rightsquigarrow$ `DO5I=1.20`
     - LM analysis (correct): $(\mathsf{id}, \texttt{DO5I})(\mathsf{gets},)(\mathsf{real}, 1.2)$
   - (correct) input string: `DO␣5␣I␣=␣1,␣20` $\rightsquigarrow$ `DO5I=1,20`

Inadequacy of Longest Match

Example 4.3 (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!)
   - intended analysis: $(\mathsf{int}, 12)(\mathsf{relop}, \mathsf{eq}), (\mathsf{int}, 12)$
   - LM yields: $(\mathsf{real}, 12.0)(\mathsf{id}, \texttt{EQ})(\mathsf{real}, 0.12)$
2. `DO` loops
   - (erroneous) input string: `DO␣5␣I␣=␣1.␣20` $\rightsquigarrow$ `DO5I=1.20`
     - LM analysis (correct): $(\mathsf{id}, \texttt{DO5I})(\mathsf{gets},)(\mathsf{real}, 1.2)$
   - (correct) input string: `DO␣5␣I␣=␣1,␣20` $\rightsquigarrow$ `DO5I=1,20`
     - intended analysis: $(\mathsf{do},)(\mathsf{label}, 5)(\mathsf{id}, \texttt{I})(\mathsf{gets},)(\mathsf{int}, 1)(\mathsf{comma},)(\mathsf{int}, 20)$

Inadequacy of Longest Match

Example 4.3 (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!)
   - intended analysis: $(\mathsf{int}, 12)(\mathsf{relop}, \mathsf{eq}), (\mathsf{int}, 12)$
   - LM yields: $(\mathsf{real}, 12.0)(\mathsf{id}, \texttt{EQ})(\mathsf{real}, 0.12)$
2. `DO` loops
   - (erroneous) input string: `DO␣5␣I␣=␣1.␣20` $\rightsquigarrow$ `DO5I=1.20`
     - LM analysis (correct): $(\mathsf{id}, \texttt{DO5I})(\mathsf{gets},)(\mathsf{real}, 1.2)$
   - (correct) input string: `DO␣5␣I␣=␣1,␣20` $\rightsquigarrow$ `DO5I=1,20`
     - intended analysis:
       $(\mathsf{do},)(\mathsf{label}, 5)(\mathsf{id}, \texttt{I})(\mathsf{gets},)(\mathsf{int}, 1)(\mathsf{comma},)(\mathsf{int}, 20)$
     - LM yields: $(\mathsf{id},)(\mathsf{gets},)(\mathsf{int}, 1)(\mathsf{comma},)(\mathsf{int}, 20)$

Inadequacy of Longest Match

Example 4.3 (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!)
   - intended analysis: $(\mathsf{int}, 12)(\mathsf{relop}, \mathsf{eq}), (\mathsf{int}, 12)$
   - LM yields: $(\mathsf{real}, 12.0)(\mathsf{id}, \texttt{EQ})(\mathsf{real}, 0.12)$
2. `DO` loops
   - (erroneous) input string: `DO␣5␣I␣=␣1.␣20` $\rightsquigarrow$ `DO5I=1.20`
     - LM analysis (correct): $(\mathsf{id}, \texttt{DO5I})(\mathsf{gets},)(\mathsf{real}, 1.2)$
   - (correct) input string: `DO␣5␣I␣=␣1,␣20` $\rightsquigarrow$ `DO5I=1,20`
     - intended analysis: $(\mathsf{do},)(\mathsf{label}, 5)(\mathsf{id}, \texttt{I})(\mathsf{gets},)(\mathsf{int}, 1)(\mathsf{comma},)(\mathsf{int}, 20)$
     - LM yields: $(\mathsf{id},)(\mathsf{gets},)(\mathsf{int}, 1)(\mathsf{comma},)(\mathsf{int}, 20)$
     - observation: decision for do only possible after reading ","
     - specification of `DO` keyword in `[f]lex`, using lookahead: `DO/({LETTER}|{DIGIT})*=({LETTER}|{DIGIT})*,`

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);
}
```

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);
}
```

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