Lecture 6 – Regular Expressions and Languages

COSE215: Theory of Computation

Jihyeok Park

PLRG

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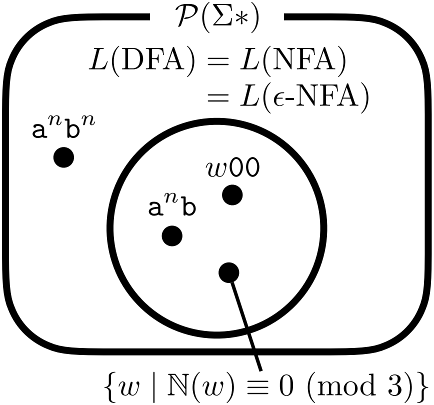
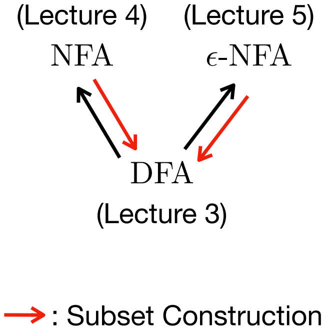
Recall


$\mathcal{P}(\Sigma*)$
$L(\text{DFA}) = L(\text{NFA})$
$= L(\epsilon\text{-NFA})$
$\mathtt{a}^n\mathtt{b}^n$
$w\mathtt{00}$
$\mathtt{a}^n\mathtt{b}$
$\{w \mid \mathbb{N}(w) \equiv 0 \pmod 3\}$


(Lecture 4)
NFA
(Lecture 5)
ϵ-NFA
DFA
(Lecture 3)
: Subset Construction

Languages – Operations

- The **union** of languages:

$$L_1 \cup L_2$$

- The **concatenation** of languages:

$$L_1 L_2 = \{w_1 w_2 \mid w_1 \in L_1 \land w_2 \in L_2\}$$

- The **Kleene star** of a language:

$$L^* = L^0 \cup L^1 \cup L^2 \cup \cdots = \bigcup_{n \geq 0} L^n$$

$$L_1 = \{\mathtt{a}^n \mid n \geq 0\} \qquad L_2 = \{\mathtt{b}^n \mid n \geq 0\}$$

$$\begin{aligned} L_1 \cup L_2 &= \{\mathtt{a}^n \text{ or } \mathtt{b}^n \mid n \geq 0\} \\ L_1 L_2 &= \{\mathtt{a}^n \mathtt{b}^m \mid n, m \geq 0\} \\ L_1^* = L_1 &= \{\mathtt{a}^n \mid n \geq 0\} \end{aligned}$$

Contents

Definition of Regular Expressions

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Definition (Regular Expressions)

A **regular expression** over a set of symbols Σ is inductively defined as follows:

- **(Basis Case)** $\varnothing$, ϵ, and $a \in \Sigma$ are regular expressions.
- **(Induction Case)** If R_1 and R_2 are regular expressions, then so are $R_1 \mid R_2$, $R_1 \cdot R_2$, R^*, and (R).

$$
\begin{array}{rcll}
R & ::= & \varnothing & \text{(Empty)} \\
& | & \epsilon & \text{(Epsilon)} \\
& | & a & \text{(Symbol)} \\
& | & R \mid R & \text{(Union)} \\
& | & R \cdot R & \text{(Concatenation)} \\
& | & R^* & \text{(Kleene Star)} \\
& | & (R) & \text{(Parentheses)}
\end{array}
$$

$$(\mathtt{a} \mid \epsilon)\ \mathtt{b}^*$$

Precedence of operators:

$$* > \cdot > |$$

Definition of Regular Expressions

```scala
// The type definitions of symbols
type Symbol = Char
// The definition of regular expressions
trait RE
case class REEmpty() extends RE
case class REEpsilon() extends RE
case class RESymbol(symbol: Symbol) extends RE
case class REUnion(left: RE, right: RE) extends RE
case class REConcat(left: RE, right: RE) extends RE
case class REStar(re: RE) extends RE
case class REParen(re: RE) extends RE
// An example of regular expression
val re: RE = REConcat(
  REParen(
    REUnion(
      RESymbol('a'),
      REEpsilon(),
    )
  ),
  REStar(
    RESymbol('b')
  ),
)
```

Language of Regular Expressions

Definition (Language of Regular Expressions)

For a given regular expression R on a set of symbols Σ, the **language** $L(R)$ of R is inductively defined as follows:

$$\begin{array}{lcl@{\qquad}lcl}
L(\varnothing) & = & \varnothing & L(R_1 \mid R_2) & = & L(R_1) \cup L(R_2) \\
L(\epsilon) & = & \{\epsilon\} & L(R_1 R_2) & = & L(R_1) L(R_2) \\
L(a) & = & \{a\} & L(R^*) & = & L(R)^* \\
 & & & L((R)) & = & L(R)
\end{array}$$

$$\begin{aligned}
L((\epsilon|\mathtt{a})\mathtt{b}^*) &= L((\epsilon|\mathtt{a})) \cdot L(\mathtt{b}^*) \\
&= L(\epsilon|\mathtt{a}) \cdot L(\mathtt{b})^* \\
&= (L(\epsilon) \cup L(\mathtt{a})) \cdot L(\mathtt{b})^* \\
&= (\{\epsilon\} \cup \{\mathtt{a}\}) \cdot \{\mathtt{b}^n \mid n \geq 0\} \\
&= \{\mathtt{b}^n \text{ or } \mathtt{ab}^n \mid n \geq 0\}
\end{aligned}$$

Extended Regular Expressions

More operators:

$$
\begin{array}{rcll}
R & ::= & \cdots & \\
& | & R^{+} & \text{(Kleene plus)} \\
& | & R^{?} & \text{(Optional)}
\end{array}
$$

Actually, they are just **syntactic sugar** for the existing operators:

$$
\begin{array}{rcccl}
L(R^{+}) & = & L(RR^{*}) & = & L(R) \cdot L(R^{*}) \\
\\
L(R^{?}) & = & L(\epsilon \,|\, R) & = & L(\epsilon) \cup L(R)
\end{array}
$$

For examples,

$$
\begin{array}{rcl}
L(\mathtt{a}^{+}) & = & L(\mathtt{aa}^{*}) \\
& = & L(\mathtt{a}) \cdot L(\mathtt{a}^{*}) \\
& = & \{\mathtt{a}^{n} \mid n \geq 1\}
\end{array}
$$

$$
\begin{array}{rcl}
L(\mathtt{b}^{?}) & = & L(\epsilon) \cup L(\mathtt{b}) \\
& = & \{\epsilon, \mathtt{b}\}
\end{array}
$$

Examples

- $L = \{\epsilon, \mathtt{a}\}$

- $L = \{w \in \{0, 1^*\} \mid w \text{ contains at least two } 0's\}$

- $L = \{w \in \{0, 1^*\} \mid w \text{ contains exactly two } 0's\}$

- $L = \{w \in \{0, 1^*\} \mid w \text{ has three consecutive } 0's\}$

- $L = \{w \in \{\mathtt{a}, \mathtt{b}^*\} \mid \ \mathtt{a} \text{ and } \mathtt{b} \text{ alternate in } w\}$

Examples

- $L = \{a^n b^m \mid n \geq 3 \wedge m \equiv 0 (\text{mod } 2)\}$

- $L = \{a^n b^m \mid n + m \equiv 0 (\text{mod } 2)\}$

- $L = \{w \in \{0, 1^*\} \mid \text{ the number of 0's is divisible by 3}\}$

- $L = \{w \in \{0, 1^*\} \mid \mathbb{N}(w) \equiv 0 \pmod 3\}$
  where $\mathbb{N}(w)$ is a natural number represented by w.

$$\texttt{(0|1(01}^*\texttt{0)}^*\texttt{1)}^*$$

- $L = \{a^n b^n \mid n \geq 0\}$ – IMPOSSIBLE ($\nexists$ RE R. $L(R) = L$)

Exercise #1

- Please see https://github.com/ku-plrg-classroom/docs/tree/main/fa-examples.
- You don't have to submit it. This is just exercise for your practice.
- The goal is to implement the finite automata (FA) objects in the `Implementation.scala` file.

Summary

Next Lecture

- Equivalence of Regular Expressions and Finite Automata

Jihyeok Park
jihyeok_park@korea.ac.kr
https://plrg.korea.ac.kr