Chapter Seven: 
Regular Expressions
Regular Expressions

• We have seen that DFAs and NFAs have equal definitional power.

• It turns out that regular expressions also have exactly that same definitional power:
  – they can be used to define all the regular languages, and only the regular languages.
Outline

• 7.1 Regular Expressions, Formally Defined
• 7.2 Regular Expression Examples
• 7.3 For Every Regular Expression, a Regular Language
• 7.4 Regular Expressions and Structural Induction
• 7.5 For Every Regular Language, a Regular Expression
Regular Expression

- In order to define regular expressions we need to additional operators on languages:
  - Concatenation
  - Kleene closure
Concatenation of Languages

• The concatenation of two languages $L_1$ and $L_2$ is $L_1 L_2 = \{xy \mid x \in L_1 \text{ and } y \in L_2\}$
• The set of all strings that can be constructed by concatenating a string from the first language with a string from the second
• For example, if $L_1 = \{a, b\}$ and $L_2 = \{c, d\}$ then $L_1 L_2 = \{ac, ad, bc, bd\}$
Kleene Closure of a Language

- The Kleene closure of a language $L$ is $L^* = \{x_1x_2 \ldots x_n \mid n \geq 0, \text{ with all } x_i \in L\}$
- The set of strings that can be formed by concatenating any number of strings, each of which is an element of $L$
- In $L^*$, each $x_i$ may be a different element of $L$
- For example, $\{ab, cd\}^* = \{\varepsilon, ab, cd, abab, abcd, cdab, cdcd, ababab, \ldots\}$
- For all $L$, $\varepsilon \in L^*$
- For all $L$ containing at least one string other than $\varepsilon$, $L^*$ is infinite

Note: this is very similar to the set of all strings $\Sigma^*$ over alphabet $\Sigma$. In fact, sometimes we talk about the Kleene closure of the alphabet.
Regular Expressions

• A regular expression is a string $r$ that denotes a language $L(r)$ over some alphabet $\Sigma$

• Regular expressions make special use of the symbols $\varepsilon$, $\emptyset$, $+$, $*$, and parentheses

• We will assume that these special symbols are not included in $\Sigma$

• There are six kinds of regular expressions…
The Six Regular Expressions

• The six kinds of regular expressions, and the languages they denote, are:
  – Three kinds of *atomic* regular expressions:
    • Any symbol $a \in \Sigma$, with $L(a) = \{a\}$
    • The special symbol $\varepsilon$, with $L(\varepsilon) = \{\varepsilon\}$
    • The special symbol $\emptyset$, with $L(\emptyset) = \{\}$
  – Three kinds of *compound* regular expressions built from smaller regular expressions, here called $r$, $r_1$, and $r_2$:
    • $(r_1 + r_2)$, with $L(r_1 + r_2) = L(r_1) \cup L(r_2)$
    • $(r_1r_2)$, with $L(r_1r_2) = L(r_1)L(r_2)$
    • $(r)^*$, with $L((r)^*) = (L(r))^*$

• The parentheses may be omitted, in which case $*$ has highest precedence and $+$ has lowest
Outline

• 7.1 Regular Expressions, Formally Defined
• 7.2 Regular Expression Examples
• 7.3 For Every Regular Expression, a Regular Language
• 7.4 Regular Expressions and Structural Induction
• 7.5 For Every Regular Language, a Regular Expression
• Denotes the language \{ab\}
• Our formal definition permits this because
  – \(a\) is an atomic regular expression denoting \{a\}
  – \(b\) is an atomic regular expression denoting \{b\}
  – Their concatenation \((ab)\) is a compound
  – Unnecessary parentheses can be omitted
• Thus any string \(x\) in \(\Sigma^*\) can be used by itself as a regular expression, denoting \{x\}
\begin{align*}
ab+c
\end{align*}

- Denotes the language \{ab,c\}
- We omitted parentheses from the fully parenthesized form \(((ab)+c)\)
- The inner pair is unnecessary because + has lower precedence than concatenation
- Thus any finite language can be defined using a regular expression
- Just list the strings, separated by +

Hint: when you see a ‘+’ in a RE just think “or”
$ba^*$

- Denotes the language $\{ba^n|n \geq 0\}$: the set of strings consisting of $b$ followed by zero or more $a$s
- Not the same as $(ba)^*$, which denotes $\{(ba)^n|n \geq 0\}$
- * has higher precedence than concatenation
- The Kleene star is the only way to define an infinite language using regular expressions
\[(a+b)^*\]

- Denotes \(\{a,b\}^*\): the whole language of strings over the alphabet \(\{a,b\}\)
- The parentheses are necessary here, because \(\ast\) has higher precedence than +
- Kleene closure does not distribute, that is,
  - \((a+b)^* \neq a^*+b^*\)
  - \(a^*+b^*\) denotes \(\{a\}^* \cup \{b\}^*\)
• Denotes {}
• There is no other way to denote the empty set with regular expressions
• That's all you should ever use $\emptyset$ for
• It is not useful in compounds:
  - $L(r\emptyset) = L(\emptyset r) = {}$
  - $L(r+\emptyset) = L(\emptyset + r) = L(r)$
  - $L(\emptyset^*) = \{\varepsilon\}$
From Languages to RE

- Give the regular expressions for the following languages:
  - \{x \mid x \text{ is a string that starts with three 0s followed by arbitrary 0s and 1s and then ends with three 0s}\}
  - \{x \mid x \text{ is a string that starts with a 0 followed by an arbitrary number of 1s and ends with a 0 OR } x \text{ is a string that starts with a 1 followed by an arbitrary number of 0s and ends with a 1}\}
  - \{x^n \mid x \text{ is either the string ab or the string c and } n \geq 0\}
Outline

• 7.1 Regular Expressions, Formally Defined
• 7.2 Regular Expression Examples
• 7.3 For Every Regular Expression, a Regular Language
• 7.4 Regular Expressions and Structural Induction
• 7.5 For Every Regular Language, a Regular Expression
Regular Expression to NFA

• Approach: convert any regular expression to an NFA for the same language
Standard Form

• To make them easier to compose, our NFAs will all have the same standard form:
  – Exactly one accepting state, not the start state

• That is, for any regular expression $r$, we will show how to construct an NFA $N$ with $L(N) = L(r)$, pictured like this:
Atomic REs
Compound REs

where $r_1$ and $r_2$ are REs
Outline

• 7.1 Regular Expressions, Formally Defined
• 7.2 Regular Expression Examples
• 7.3 For Every Regular Expression, a Regular Language
• 7.4 Regular Expressions and Structural Induction
• 7.5 For Every Regular Language, a Regular Expression
NFA to Regular Expression

• There is a way to take any NFA and construct a regular expression for the same language.
• This gives us our next lemma:
  • Lemma: if $N$ is any NFA, there is some regular expression $r$ with $L(r) = L(N)$
  • A tricky construction, covered in Appendix A (very difficult to follow), the hand-out has a more intuitive proof.
Theorem (Kleene's Theorem)

A language is regular if and only if it is $L(r)$ for some regular expression $r$.

- Proof: follows from previous two lemmas.
Defining Regular Languages

• We can define the regular languages:
  – By DFA
  – By NFA
  – By regular expression
• These three have equal power for defining languages
Alphabets

• An *alphabet* is any finite set of symbols
  – \{0,1\}: binary alphabet
  – \{0,1,2,3,4,5,6,7,8,9\}: decimal alphabet
  – ASCII, Unicode: machine-text alphabets
  – Or just \{a,b\}: enough for many examples
  – {}: a legal but not usually interesting alphabet

• We will usually use \(\Sigma\) as the name of the alphabet we’re considering, as in \(\Sigma = \{a,b\}\)
Strings

- **A string** is a finite sequence of zero or more symbols.
- **Length of a string:** $|abbb| = 4$
- **A string over the alphabet** $\Sigma$ means a string all of whose symbols are in $\Sigma$
  - The set of all strings of length 2 over the alphabet $\{a,b\}$ is $\{aa, ab, ba, bb\}$
Languages

• A *language* is a set of strings over some fixed alphabet

• *Not* restricted to finite sets: in fact, finite sets are not usually interesting languages

• All our alphabets are finite, and all our strings are finite, but most of the languages we're interested in are infinite
The Quest

• Using set formers to describe complex languages is challenging
• They can often be vague, ambiguous, or self-contradictory
• A big part of our quest in the study of formal language is to develop better tools for defining and classifying languages
The Quest

• We went from this:
  – \{x \mid x \text{ is a string that starts with three 0s followed by arbitrary 0s and 1s and then ends with three 0s}\}

• to this:
  – 000(0+1)^*000
The Quest

• We just defined a major class of languages:  
  – the regular languages

• The hallmark of these languages is that their structure is such that simple computational models (DFA/NFA) can recognize them and that they can be defined using regular expressions.
The Quest

• The idea that the structure of languages is connected to computational models is important.

• Later on we see that the structure of languages is tightly coupled with idea of algorithms and classes of computational problems.
Assignment #4

- See website