01204211 Discrete Mathematics
Lecture 7a: Languages and regular expressions

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What is computation?

Models of computations

Languages = specifications

Formal definition: strings

Intuitively, a string is a *finite* sequence of symbols. However, to be able to formally prove properties of strings we need a precise definition.

Let a finite set Σ be the **alphabet**. (E.g., for bit strings, $\Sigma = \{0, 1\}$; for digits, $\Sigma = \{0, 1, \ldots, 9\}$; for English string $\Sigma = \{a, b, \ldots, z\}$.)
The following is a recursive definition of strings.

Recursive definition of strings

A **string** w over alphabet Σ is either

- the empty string ε, or
- $a \cdot x$ where $a \in \Sigma$ and x is a string.

The set of all strings over alphabet Σ is denoted by Σ^*.

Review: more recursive definitions

Lengths

For a string w, let $|w|$ be the length of w defined as

$$|w| = \begin{cases} 0 & \text{when } w = \varepsilon \\ 1 + |x| & \text{when } w = a \cdot x \end{cases}$$

Concatenation

For strings w and z, the concatenation $w \bullet z$ is defiend recursively as

$$w \bullet z = \begin{cases} z & \text{when } w = \varepsilon \\ a \cdot (x \bullet z) & \text{when } w = a \cdot x \end{cases}$$

Review: proving facts about strings

Lemma 1

For strings w *and* z*,* $|w \bullet x| = |w| + |x|$*.*

Proof.

$\square$

Formal languages

A **formal language** is a set of strings over some finite alphabet Σ.
Examples:

Careful...

These are different languages: $\emptyset, \{\varepsilon\}$
And ε is not a language.

How to describe languages?

Composition

Combining languages

If A and B are languages over alphabet Σ.

- Basic set operations: $A \cup B$, $A \cap B$, $\bar{A} = \Sigma^* \setminus A$.
- Concatenation: $A \bullet B$.
- Kleene closure or Kleene star: A^*.

Also $A^+ = A \bullet A^*$

Examples

Regular languages

Definition: regular languages

A language L is **regular** if and only if it satisfies one of the following conditions:

- L is empty;
- L contains one string (can be the empty string ε);
- L is a union of two regular languages;
- L is the concatenation of two regular languages; or
- L is the Kleene closure of a regular language.

Examples

Regular expressions

Regular expressions: examples

Subexpressions

Regex is everywhere

Proofs about regular expressions - structural induction

Lemma 2

Every regular expression that does not use the symbol $\emptyset$ represents a non-empty language.

Proof.
Let R be a regular expression that does not use the symbol $\emptyset$. We prove by (structural) induction that R represents a non-empty language.
Induction hypothesis: Every subexpression of R that does not use the symbol $\emptyset$ represents a non-empty language.
Case 1: $R = \emptyset$.

Case 2: R is a single string.

Proof. (cont.2/4)

Case 3: $R = S + T$ for some regular expressions S and T.

Proof. (cont.3/4)

Case 4: $R = S \bullet T$ for some regular expressions S and T.

Proof. (cont.4/4)

Case 5: $R = S^*$ for some regular expression S.

In every case, the language $L(R)$ is non-empty.

Lemma 3

Every non-empty regular language is represented by a regular expression that does not use the symbol $\emptyset$.

Let R be a regular expression. We prove that if $L(R) \neq \emptyset$, then there exists a regular expression R' such that $L(R) = L(R')$ and R' does not contain $\emptyset$.
We prove by induction. What should the induction hypothesis be?

I.H.: For every subexpression S of R, if $L(S) \neq \emptyset$, there exists an $\emptyset$-free regular expression S' such that $L(S) = L(S')$.

What are the cases that we have to consider?

- $R = \emptyset$
- R is a single string.
- $R = S + T$ for some regular expressions S and T.
- $R = S \bullet T$ for some regular expressions S and T.
- $R = S^*$ for some regular expression S.