

Introduction

The relationship between programs and formal languages provides an example of the impact of theory on practice. Uses of formal theory include the following:

- lexical and parsing stages of compiler construction
- use of regular expressions in text editors
- state-charts in object-oriented modeling
- circuit-design
- DNA and protein sequence matching

On the other hand, theory acts also as an “early warning system” by providing a science of the impossible:

- what should not be attempted because it is impossible (or provably too costly)

A fundamental question in computing is whether there exist tasks/problems that cannot be solved algorithmically and, if yes, which tasks are algorithmically solvable and which are not. In fact, it can be established that the number of different computing problems is *larger* than the number of all possible programs (in some programming language such as Java or C), which means that there must exist problems that are not solvable by any program (or algorithm).

Note that the number of programs is infinite, and to show that the number of computing problems is larger, we need to compare the *sizes* of different infinite numbers.

In this course we use a different approach. Using a technique called *diagonalization* we establish that certain specific (and “useful”) computing problems cannot be solved by any

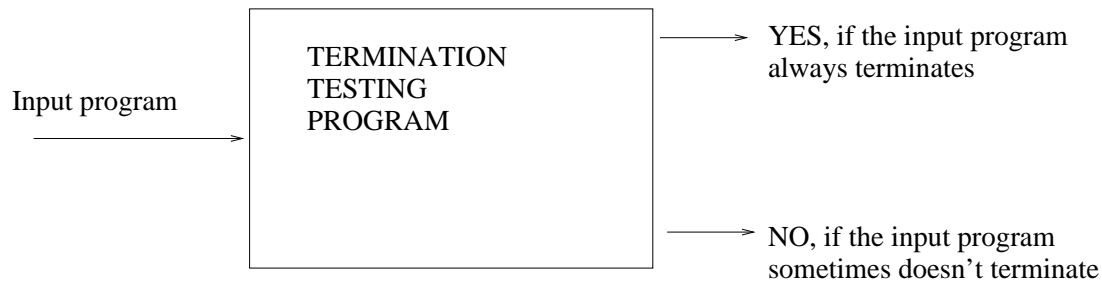


Figure 1: Example of an uncomputable problem.

program written in the language C . The most well-known one is the so called *halting problem* that asks whether an arbitrary program given as input terminates.

Example. A program with behavior as depicted in Figure 1 does not exist!

However, having an algorithm A for a computing problem P does not mean that P is solvable in practice. It may be the case that for inputs of moderate size A would need more time than the age of the universe.

A coarse classification of problems/functions:

1. Non-computable (that is, impossible to solve using an algorithm/a computer)
2. Possible-with-unlimited-resources BUT impossible-with-limited-resources
3. Possible-with-limited-resources

Typical questions we want to answer:

- Program existence: Does there exist a program for a given problem (or function)?
- Software specification: How should programs be specified?
- Software validation: Is a given program correct?

- Software construction: How is a correct program obtained?
- Semantics: What does a given program do? (this is related to correctness)
- Efficiency: Is there a more efficient (faster) program for the given problem?
- Hardware comparison: Is one machine more powerful than another one?

Given a programming problem it is easier to convince someone that there is a program which solves the problem (if one exists) than to convince someone that there is *no* program for the problem (if a program does not exist). In the former case it is sufficient to give the program and, in fact, usually it is sufficient to just outline the solution informally, or in pseudo code (if the purpose is just to convince the reader that a program exists).

Example. A program to compute the function $f(n) = n^2$.

On the other hand, if we want to show that a program for the given problem does *not* exist we need to show that none of the infinitely many possible programs solves the given problem (or computes a given function).

In order to be able to deal with negative results of this kind, we need to be precise about what constitutes a legal program! (or a legal algorithm)

Using a more practical perspective, a problem may be “uncomputable” also due to other types of reasons, for example, predicting the weather for a month in advance is impossible because the required input would be “infinite”.

Instead of considering general algorithms¹, we start here with a simpler problem:

- test whether arbitrary input strings (= sequences of symbols) can be matched by a given pattern.

¹The general limits of algorithmic computability will be discussed in the last part of the course.

Special notation and implementation techniques have been developed to specify and recognize such *patterns*:

- state-transition diagrams (automata): simple simulated machines
- regular expressions: rules for building patterns
- grammars: rules for generating patterns

Alphabets, strings and languages

This material is from Chapter 7 in the textbook.

- An alphabet is a finite, nonempty set of elements. The elements of the alphabet are called symbols (or tokens, characters).
- A string over an alphabet Σ is a finite sequence of symbols of Σ . (Strings are sometimes called also words.)
- A language over Σ is a set of strings over Σ .

Examples.

1. English alphabet $\{a, b, c, d, \dots, z\}$

Strings: cat, dog, mouse, xzrbstuph, ...

Language: the set of all correct English sentences

— not precisely defined ...

2. Alphabet: $\{a, b\}$

Strings: $\varepsilon, a, b, ab, ba, aa, bb, aaa, \dots$

Language: $\{a^i b^i \mid i \geq 0\}$
 $= \{\varepsilon, ab, aabb, aaabbb, \dots\}$

3. Alphabet: Java reserved words and identifiers

Example string: a Java program

Language: the set of all Java programs

We use the following definitions:

- The empty string is denoted ε .
 ε is a string over any alphabet.
- The length of a string is the number of occurrences of symbols in it. The length of a string s is denoted $|s|$.

Examples:

- The length of ε is 0, that is, $|\varepsilon| = 0$.
- The length of the string $bccb$ is 4, that is, $|bccb| = 4$.
- The concatenation of strings x and y is denoted xy . It is the string obtained by appending y to x .

Examples: If $x = abc$ and $y = de$, then $xy = abcde$ and $yx = deabc$.

Note that ε acts as an identity for string concatenation: $x\varepsilon = \varepsilon x = x$ for all strings x , in particular, $\varepsilon\varepsilon = \varepsilon$.

Since concatenation is associative we do not need to use parentheses:

for all strings x, y, z we have $x(yz) = (xy)z$. How would you prove this?

- If x is a string, x^n denotes the concatenation of n copies of x (power of a string). Here $n \geq 0$.

Inductive definition:

1. $x^0 = \varepsilon$
2. $x^{i+1} = xx^i$, for $i \geq 0$.

Example.

$$(abc)^0 = \varepsilon$$

$$(abc)^3 = abcabcabc$$

- If $s = xy$, we say that x is a prefix of s and y is a suffix of s . If $s = xyz$, we say that y is a substring of s . Note that here x and/or z may be the empty string.

Examples:

1. ab is a prefix of aba
2. ba is a suffix of aba
3. ε is a prefix/suffix/substring of any string
4. a string is always a prefix/suffix/substring of itself
5. What are the substrings of cbc ?

Formal languages

A formal language has to be precisely defined, the word *formal* refers to the fact that we have a precise set of rules which tell us exactly which strings are in the language (respectively, are not in the language).

- A finite language can (at least in principle) be defined by listing all strings in it.

Example: $\{00, 01, 10, 11\}$

- Infinite languages can be defined by giving some condition that exactly characterizes the strings in the language.

Example.

$$\{0^n \mid n \geq 0\}$$

$$\{0^n 1^n \mid n \geq 1\}$$

Note that \emptyset (the empty set) is a language over any alphabet Σ . Also $\{\varepsilon\}$ (the language having only the string ε) is a language over any alphabet Σ . It is important to remember that $\emptyset \neq \{\varepsilon\}$. Why?

We can define new languages from “simpler” ones using operations on languages. Three important operations are

- union
- concatenation
- closure

Later we will see that all regular languages can be built from elements of Σ , the empty string ε and the empty set \emptyset using these operations.

Union

If R and S are languages over Σ , their union is denoted $R + S$. It consists of all strings that are in R or in S . (Thus $R + S$ is just a different notation for the union of sets, $R \cup S$.)

Concatenation

If R and S are languages, their concatenation is defined as

$$R \cdot S = \{rs \mid r \in R, s \in S\},$$

usually written simply as RS .

Examples.

If $R = \{a, ab\}$, $S = \{bc, c\}$, what is their concatenation RS ? Note: the concatenation consists of 3 different strings.

If $R_1 = \{a, \varepsilon\}$ and $S_1 = \{ab, b\}$, what is R_1S_1 ?

What are the following languages:

$$\emptyset \cdot R = \dots\dots\dots?$$

$$\{\varepsilon\} \cdot R = \dots\dots\dots?$$

$$\{\varepsilon\} \cdot \emptyset = \dots\dots\dots?$$

Closure of languages

The set of all strings over alphabet Σ is denoted Σ^* . This operation can be extended for any language S :

$$\begin{aligned} S^* &= \{s_1 \cdot \dots \cdot s_n \mid s_i \in S, i = 1, \dots, n, n \geq 0\} \\ &= \{\varepsilon\} + S + S^2 + S^3 + \dots \end{aligned}$$

Example. Let $S = \{01, 1\}$. Then

$$S^0 = \{\varepsilon\}$$

$$S^1 = S = \{01, 1\}$$

$$S^2 = \{0101, 011, 101, 11\}$$

$$S^* = \{\varepsilon, 1, 01, 11, 011, 101, 111, 0101, \dots\}$$

We denote also

$$\begin{aligned} S^+ &= \{s_1 \cdot \dots \cdot s_n \mid s_i \in S, i = 1, \dots, n, n \geq 1\} \\ &= S + S^2 + S^3 + \dots \end{aligned}$$

Note that $S^* = S^+ + \{\varepsilon\}$ for any language S .

Definition. A language S over alphabet Σ is said to be regular if S can be defined from elements of Σ , the empty string ε , and \emptyset using the operations union, concatenation and closure. The description of the language S in this form is called a regular expression for S .

In particular, all finite languages are regular. Why?

As we will see, the regular languages have “nice” properties and can be easily implemented. However, regular languages form only a “small” family of languages and we will develop techniques for showing that a language is not regular.

Application: Sequence matching problem

Each DNA molecule is composed of two strands that are made up of a sequence of nucleotides. Each nucleotide has one of four bases, represented by symbols A, T, C, G (and other parts). Proteins are large molecules that are composed of a sequence of amino acids. There are 20 amino acids that occur in proteins, denoted by standard one-letter symbols. In this way, DNA or protein molecules can be represented as strings. Analyzing DNA or protein sequences can help to determine which function they perform, or what parts of the sequence are important for a particular function. Comparing different DNA sequences tells us which organisms are related.

Related sequences are not necessarily identical. When comparing DNA or protein sequences we want to *align* them in a way that minimizes some type of distance between the sequences.

Regular expressions are used to specify *patterns* that describe a related set of strings (sequences). In this way we can compare the pattern to an individual sequence or to a database of sequences to find good matches. The applications often use *extended regular expressions* that allow operations other than union, concatenation and closure. (Examples in class.)

The tools used to solve sequence matching problems typically involve also *finite state machines* that are discussed in our next topic. The BLAST family of search engines use heuristic techniques to build a large *deterministic finite automaton* that, for a given query string, finds from a database of known sequences the most closely related ones.