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Formal Languages

(Part 1)

Lecture 04

Day 04/31

CS 154

Formal Languages and Computability

Spring 2019

Agenda of Day 04

- Waiting List Enrollment ...
- Summary of Lecture 03
- Lecture 04: Teaching ...
  - Formal Languages (Part 1)

Summary of Lecture 03: We learned ...

Cartesian Products

- In many cases, we need ordered collections.
- We use Cartesian product to produce ordered collections.
- The Cartesian product of two sets A and B is ...
  - ... the set of all ordered pairs (a , b), where $a \in A$ and $b \in B$.

$$A \times B = \{(a , b) : a \in A , b \in B\}$$

- Does Cartesian product have commutative property?
  - In general, no, but in the following special cases, yes:
  - $(A = B) \lor (A = \phi) \lor (B = \phi)$

- We extend the Cartesian product to n sets to produce n-tuple.

$$S_1 \times S_2 \times \ldots \times S_n = \{(x_1, x_2, \ldots , x_n) : x_1 \in S_1 , \ldots , x_n \in S_n\}$$

Any question?

Summary of Lecture 03: We learned ...

Functions

- A function f from D to R is ...
  - ... a rule that assigns to some elements of D (domain) a unique element of R (range).
  - Denoted by: $f : D \rightarrow R$
- A total function is ...
  - ... a function that all of its domain elements are defined.
- A partial function is ...
  - ... a function that at least one member of its domain is "undefined".

Any question?

Summary of Lecture 03: We learned ...

Graphs

- A graph is a mathematical construct consisting of two sets:
  - A non-empty and finite set of vertices $V = \{v_1 , v_2 , \dots , v_n\}$
  - A finite set of edges $E = \{e_1 , e_2 , \dots , e_m\}$
- A walk is ...
  - ... a sequence of edges from v_i to v_n. $(v_i , v_j) , (v_j , v_k) , \dots , (v_m , v_n)$
- The length of a walk is ...
  - ... the number of edges traversed.
- A path is ...
  - ... a walk that no edge is repeated.
- A simple path is ...
  - ... a path that no vertex is repeated.
- A loop is ...
  - ... an edge from a vertex to itself.
- A cycle is ...
  - ... a path from a vertex (called base) to itself.
- A simple cycle is ...
  - ... a cycle that no vertex other than base is repeated.

Any question?

Objective of This and Next Lecture

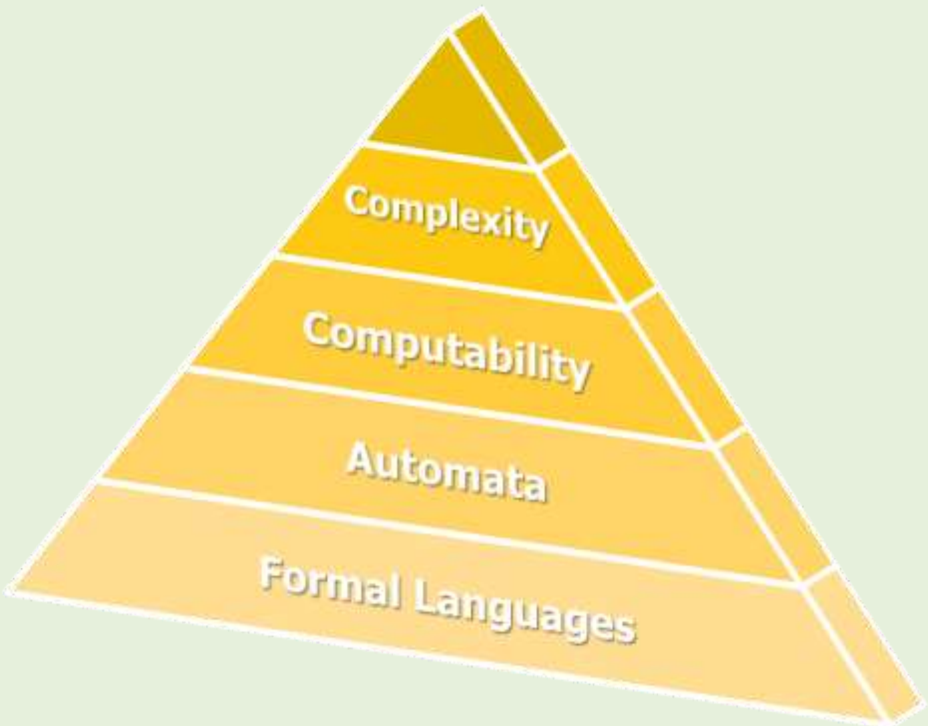
- Reviewing alphabets
- Reviewing strings
- Introducing formal languages
- Examining some surprising languages

The Big Picture of the Course

- The foundation of the computer science is called:

  "Theory of Computation".

- This theory is divided into four branches:



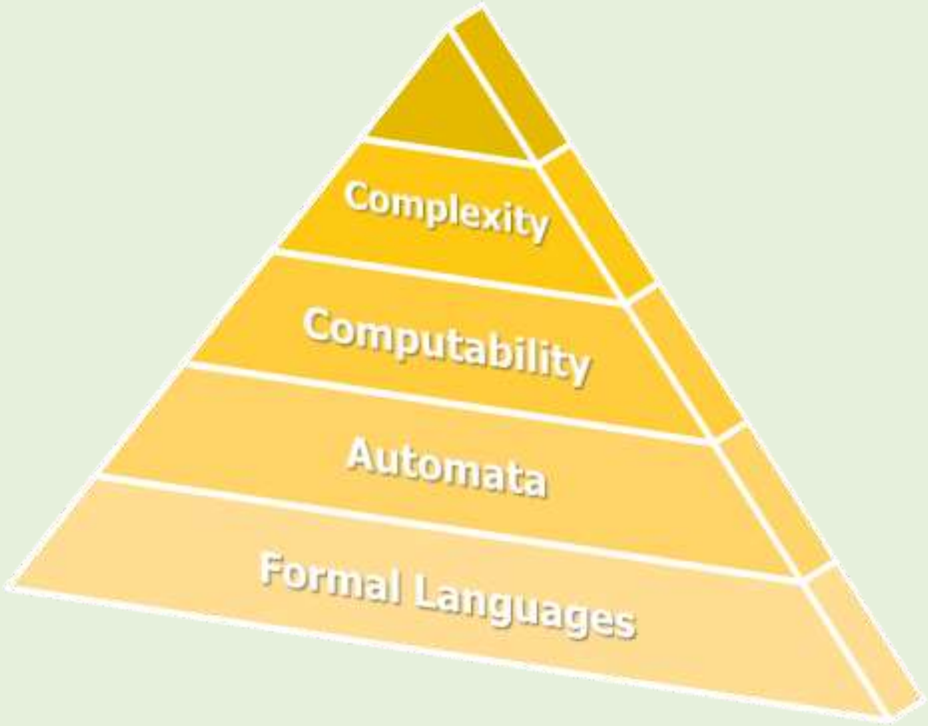
The Big Picture of the Course

- The first three from the bottom show:

  "What can be done with computers?"

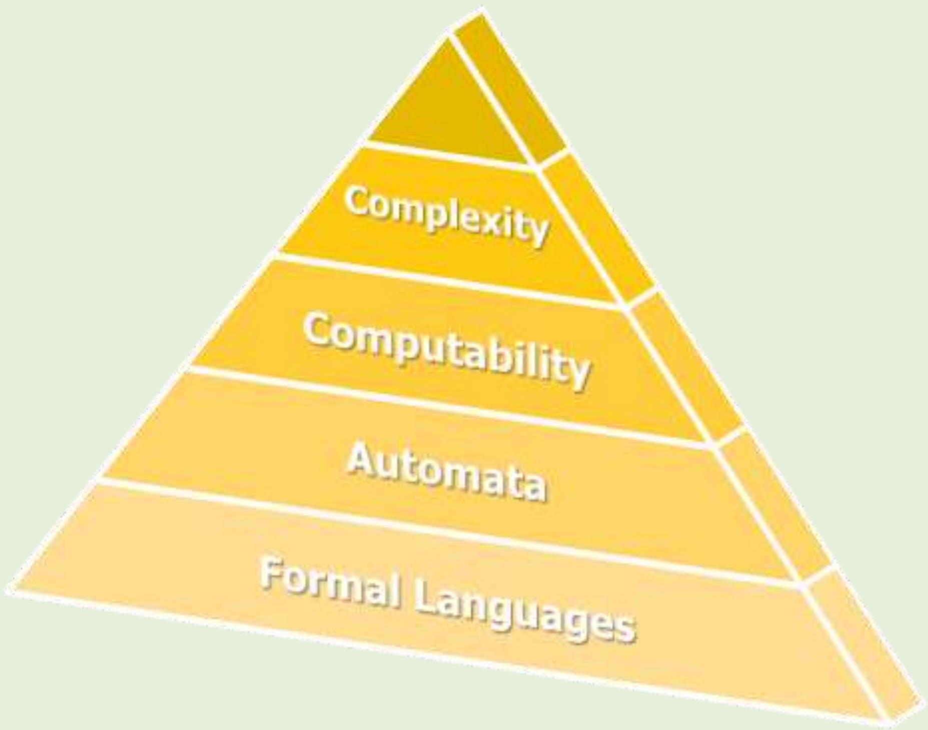
- The forth one, complexity, shows:

  "What can be done in practice?"



The Big Picture of the Course

- Let's start with "Formal Languages"!
- But first, we need to introduce "alphabets" and "strings".



Alphabets & Strings

Alphabets

Definition

- An alphabet is a nonempty and finite set of "symbols".
- It is denoted by Σ.
- Symbols are assumed to be indivisible.

- In this course, we use lowercase letters a, b, c, ... for alphabets' symbols.

- In some cases, we might use digits like 0, and 1 or other symbols as well.

Alphabets Example

Example 1

- Σ = {a, b} This is our celebrity alphabet!
- Σ = {0, 1}
- Σ = {ε, α, β}

- Can the following set be an alphabet?
  Σ = {Ԙ , Ѭ , پ , Γ }

Strings

Definition

- A string is a finite sequence of symbols from the alphabet.
- So, we do NOT have a string of infinite sequence of symbols.

Example 2

Let $\Sigma = \{a, c, d, e, g, h, l, o, p, r, s, t, u\}$.

Are the following strings valid strings over Σ?

cat , dog , horse , house , apple

Strings Examples

Example 3

- Let $\Sigma = \{a, b\}$.
- Are the following strings valid strings over Σ?
- baba , aabb , bbbbbbbbbbbba , ...
- Not all of them!
  - "..." is not a valid string because "." is not in the alphabet!
  - Note that in formal languages arena,
    we don't care whether the strings are meaningful or not!

- We use lowercase letters w, u, v, ... for "string variables".
- w = baba
- u = bbbbbbbbbbbba

Strings Size (aka Length)

Definition

- The size of a string is the number of its symbols.
- The size of string w is denoted by $|w|$.

Example 4

$|aaa| = 3$

$|babba| = 5$

$|aaba| = 4$

- In general:

$$|a_1 \, a_2 \, \ldots \, a_n| = n$$

Empty String

Definition

- An empty string is a string with no symbol.
  - In other words: A sequence of zero symbols
- Empty string is denoted by λ (pronounced "lambda").

- What is the length of λ? $|\lambda| = ?$

  $|\lambda| = 0$

Notes

1. In some books, empty string might be shown as: ε (epsilon)
2. λ cannot be used as a symbol in alphabet.

Operations on Strings

Concatenation of Strings

Definition

- Concatenation of two strings u and v is the string uv.

Example 5

Let u = aaba and v = bb ; uv = ?

uv = aababb

- The length of concatenation:

$$|uv| = |u| + |v|$$

- λ is the neutral element for concatenation:

$$\lambda w = w\lambda = w$$

Example 6

$\lambda aabb = aab\lambda b = a\lambda abb = a\lambda abb\lambda = aabb$

Reverse of Strings

Definition

- Reverse of a string w is obtained by writing the symbols in reverse order.
- Reverse of w is denoted by w^R. (pronounced "w reverse")
- If $w = a_1 a_2 \dots a_{n-1} a_n$, then $w^R = a_n a_{n-1} \dots a_2 a_1$

Example 7

Let w = aaba ; $w^R = ?$

w^R = abaa

A Side Note: Palindrome

- The string w is called palindrome if w reads the same from left to right as from right to left.

Examples

- radar, reviver, rotator

Some Funny Palindromes (Ignore spaces, apostrophes, commas)

- MADAM I'M ADAM
- STEP NOT ON PETS
- NO LEMONS, NO MELON
- DENNIS AND EDNA SINNED
- A MAN, A PLAN, A CANAL, PANAMA

Homework

- Prove that $(uv)^R = v^R u^R$

Substring

Definition

- Substring of a string w is any string of consecutive symbols of w.

Example 8

String	Substring
aababb	aa
aababb	ab
aababb	bab
aababb	b
aababb	λ
aababb	aababb

Prefix and Suffix

Definition

- Let w be a string. If w = uv, then ...

  u is called "prefix".

  v is called "suffix".

Example 9

Let w = aababb

If we consider u = aa as a prefix of w,
then the rest would be the suffix.

v = babb.

- Are these the only prefix and suffix?

Prefix and Suffix

Example 9 (cont'd)

- The complete list of all possible prefixes and suffixes of w are:

Prefix = u	Suffix = v
λ	aababb
a	ababb
aa	babb
aab	abb
aaba	bb
aabab	b
aababb	λ

- So, λ is prefix and suffix of every string (NOT at the same time). because: w = λ w = w λ

Exponential Operator

Definition

- Let w be a string and n be a natural number.
- w^n is defined as the concatenation of n copies of w.

$$w^n = \underbrace{w\ w\ w\ \ldots\ w}_{n \text{ times}}$$

Example 10

Let $w = a$; $w^2 = ?$; $w^3 = ?$

$w^2 = w\ w = aa = a^2$

$w^3 = w\ w\ w = aaa = a^3$

- Concatenation in formal languages looks like multiplication in elementary algebra.

Exponential Operator

Example 11

Let $w = aaba$; $w^2 = ?$; $w^3 = ?$

$w^2 = w\ w = aabaaaba = a^2ba^3ba$

$w^3 = w\ w\ w = aabaaabaaaba = a^2ba^3ba^3ba$

- In general: $w\ w^n = w^n\ w = w^{n+1}$
  where $n \in \mathbb{N}$ (natural numbers)

Example 12

Let $w = a^m b^m$ where m is a constant.

$|w| = ?$

$|w| = |a^m b^m| = 2m$

Exponential Operator

Special case

- $w^0 = ?$
- $w^0 = \lambda$
- How can you prove this?
- Hint: use $w\,w^n = w^n\,w = w^{n+1}$

Example 13

$(aaba)^0 = \lambda$

- Note that $aaba^0 = aab$

Formal Languages

Introduction of Two New Operations on Sets

- Before introducing formal languages,
  we need to introduce two new operations on sets.

- We did not mention them because
  we needed the concept of concatenation.

Star Operator on Alphabets

Definition

- Let Σ be an alphabet.
- Σ^* is the set of "all possible strings" obtained by concatenating "ZERO or more" symbols from Σ.

Example 14

Let $\Sigma = \{a\}$; $\Sigma^* = ?$

$\Sigma^* = \{a\}^* = \{\lambda, a, aa, aaa, aaaa, \ldots\}$

Star Operator on Alphabets

Example 15

Let $\Sigma = \{a, b\}$; $\Sigma^* = ?$

$\Sigma^* = \{a, b\}^* = \{\lambda, a, b, aa, ab, ba, bb, aaa, aab, ...\}$

- Note what strategy we used to enumerate all combinations.

- Let $\Sigma = \{a, b, c\}$; $\Sigma^* = ?$

Plus Operator on Alphabets

Definition

- Let Σ be an alphabet.
- Σ^+ is the set of "all possible strings" obtained by concatenating "ONE or more" symbols from Σ.

Example 16

Let $\Sigma = \{a\}$; $\Sigma^+ = ?$

$\Sigma^+ = \{a\}^+ = \{a, aa, aaa, aaaa, ...\}$

- Note that the only difference between Σ^+ and Σ^* is that Σ^+ does NOT contain λ.

Plus Operator on Alphabets

Example 17

Let $\Sigma = \{a, b\}$; $\Sigma^+ = ?$

$\Sigma^+ = \{a, b\}^+ = \{a, b, aa, ab, ba, bb, aaa, aab, ...\}$

- Since the only difference between Σ^+ and Σ^* is that Σ^+ does NOT contain λ, hence:

$$\Sigma^+ = \Sigma^* - \{\lambda\}$$

$$\Sigma^* = \Sigma^+ \cup \{\lambda\}$$

- Also note that Σ is finite but both Σ^+ and Σ^* are infinite.

Formal Languages Definition

Definition

- Let Σ be an alphabet.
- Any subset of Σ^* is called a "formal language" over Σ.

- Σ^* contains all possible strings that can be made by the symbols of Σ.
- That's why it's called the "universal formal language" over Σ.
  - Recall the definition of "universal set".

Formal Languages Example

Example 18

Let $\Sigma = \{a, b\}$ be an alphabet.

Then:

$\Sigma^* = \{a, b\}^* = \{\lambda, a, b, aa, ab, ba, bb, aaa, aab, ...\}$

- The following subsets of Σ^* are examples of formal languages over Σ:

- $L_1 = \{a, b, aa, aab\}$ because $L_1 \subseteq \Sigma^*$
- $L_2 = \{\lambda, ba, bb, bbb, aaa, aab\}$ because $L_2 \subseteq \Sigma^*$

Formal Languages

Example 18 (cont'd)

How about the following sets? Are they formal languages? Why?

$L_3 = \phi = \{\ \}$

$L_4 = \{\lambda\}$

Yes they are because both are subsets of Σ^*.

Two Special Formal Languages

- Empty language : $\{\ \}$ or ϕ
- Language containing only empty string : $\{\lambda\}$

Formal Languages Notes

1. For simplicity, we use "language" to refer to the formal language.
   - To refer natural languages, we specifically will mention "natural" word.

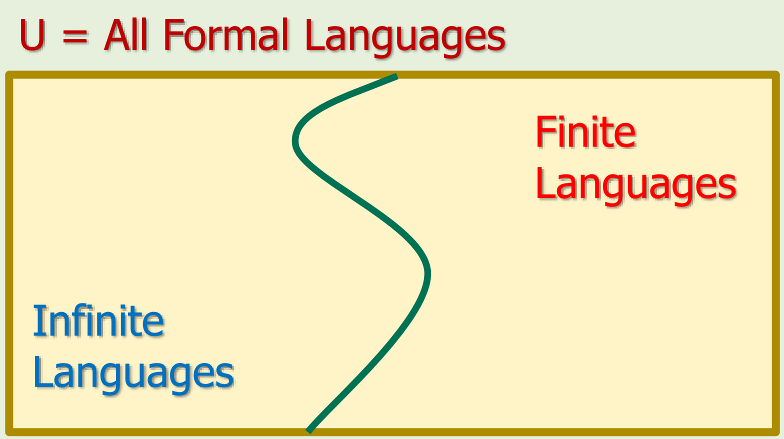
2. A language is a "set".
   So, it has all properties of sets.

3. $\{\lambda\}$ is a language while λ is a string.
   - $|\lambda| = 0$; This is the size of the string λ.
   - $|\{\lambda\}| = 1$

Formal Languages Notes

4. In some books, strings are called "sentences" to analogize the formal languages with the natural languages.
   - In this course, we mostly use strings!

5. Like sets, we have both "finite" and "infinite" languages.
   - This is our first categorization of formal languages.



Formal Languages Exercises

Example 19

Given the following languages by set-builder over $\Sigma = \{a, b\}$.

Represent them by using roster method (enumerate the strings):

1. $L_1 = \{a^n b^n : n \geq 0\}$ This is our celebrity language!
2. $L_2 = \{a^n b^{2n} : n \geq 0\}$
3. $L_3 = \{a^{n+2} b^n : n \geq 0\}$
4. $L_4 = \{a^n b^m : n \geq 0, m \geq 0\}$

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