Alphabets, strings and formal languages

Lecture 6

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- There are symbols that do not take values. Example: the letter A (as a letter not as a variable, of course)
- A rock (on its own) is not a symbol

Concatenation and strings

Definition: Let *A* be a set of symbols. A **concatenation of symbols** of *A* is the operation of **joining** together **an n-tuple of symbols of *A*, preserving the order of the symbols in the n-tuple**.

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Definition: The object **generated** by the concatenation of an *n*-tuple of symbols in A is called **string (of length *n*) over A**

Example of string generation

Thus, in order to generate a string *s* of length *n* over a given set A, select first an ***n*-tuple**

$$(a_1, a_2, ..., a_n) \in A \times A \times \cdots \times A$$

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– Example: Given $A = \{1, a, b\}$

$$\underbrace{(b, a, 1, b)}_{\text{Select an } n\text{-tuple}} \longrightarrow \underbrace{s = ba1b}_{\text{generate the string}}$$

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Properties of strings

Strings inherit all the properties of the tuples. In particular,

- The order of the symbols in the string is important
- The number of symbols in a string is important

Definition: Two **strings are different** if and only if **the tuples** used to write them **are different**

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3. $\lambda\lambda = \lambda$

All knowledge is represented in strings

Strings are fundamental to information **storage and representation**

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- A **picture** stores an image as an array of strings of pixels

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As an operation **reading** is (somewhat) the **inverse** of **writing** (or **concatenation**)

- Reading is analysis (identification of components) while concatenation is synthesis (object composition)

Illustration

Consider the string over {x, 1, Ω} s = 1x11x.

The reading of s is, step by step:

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4. 1x11x → (1, x, 1, 1)
5. 1x11x → (1, x, 1, 1, x)
6. Halt: string is read!

This is a good model for the operation of reading!

Are write and read functions?

Let's put our models in mathematical context:

$$Write : \bigcup_{j=1}^{\infty} (\overset{j}{\underset{i=1}{\mathrm{X}}} \mathrm{A}) \times \bigcup_{j=1}^{\infty} \mathrm{A}^{j}$$

$$Write(a_1, a_2, \cdots, a_j) = \{a_1 a_2 \cdots a_j\}$$

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Write is a function since a j-tuple over A never generate more than one string!

What about read?

Here is the model:

$$\text{Read} : \bigcup_{j=1}^{\infty} \text{A}^j \times \bigcup_{j=1}^{\infty} (\overset{j}{\underset{i=1}{\text{X}}} \text{A})$$

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This is not a general description!

$$\text{Read}(a_1 a_2 \cdots a_j) = \{(a_1, a_2, \cdots, a_j)\}$$

This relation **is not**, in general, **a function**

Read is not a function

Counterexample:

Let A = {1, a, b, b1}. Consider the string over A:

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Not a singleton: not a function!!

Alphabets

The **reading** of a string depends on **the set of all symbols available for writing**. Some sets render more than one reading

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The **reading** of a string depends on **the set of all symbols available for writing**. Some sets render more than one reading

Definition: A finite, nonempty set is an **alphabet** if each string over it renders a unique reading

Write is one – to – one

Theorem: Over an alphabet, Write is one – to – one

Proof:

Let $(a_1, a_2, \ldots, a_j) \neq (b_1, b_2, \ldots, b_j)$

Then, there is i, $1 \leq j \leq I$ so that $a_i \neq b_i$,

Therefore, by definition of equality of strings:

$Write(a_1, a_2, \ldots, a_j) \neq Write(b_1, b_2, \ldots, b_j)$

An important corollary

Corollary: Over an alphabet, Read is a function and it is in fact, the inverse of Write

Proof: Since Write is one to one, for each string s there is a unique tuple t such that Write(t) = s. Therefore, Read(s) = { t }, is a singleton. Also, Read(Write(t)) = t and Write(Read(s)) = s. Therefore, Read is the inverse of Write.

Examples

Alphabets:

$A=\{a, b, c\}$, $B=\{0, 1\}$

This is called binary alphabet

$C=\{ab, ac, bc\}$, $D=\{00, 01\}$

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Non-alphabet:

$E=\{a, b, ab\}$

$A \cup C = \{a, b, c, ab, ac, bc\}$

Remark: As the last example shows: the union of two alphabets is not always an alphabet!!! (**Despite what people may say!!!**)

Are these artificial examples?

The definition of alphabets containing strings of symbols may look like as an unnatural way of getting a non – alphabet

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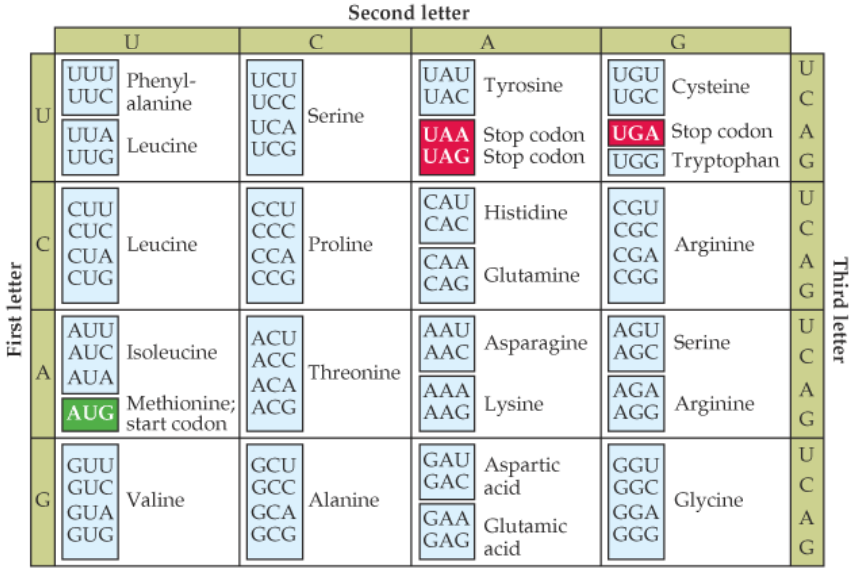
It is worth pointing out that, in general, proving that a set is indeed an alphabet may be difficult: not only sets that contain strings produce more than one reading!

Some biochemical alphabets

- **DNA alphabet**:
  - D = {A, T, G, C}
- **RNA alphabet**:
  - R = {A, U, G, C}
- **Protein transcription alphabet**: symbols are “codons”. Each codon is formed with three RNA symbols



First letter	Second letter: U	Second letter: C	Second letter: A	Second letter: G	Third letter
U	UUU, UUC: Phenylalanine	UCU, UCC, UCA, UCG: Serine	UAU, UAC: Tyrosine	UGU, UGC: Cysteine	U C A G
	UUA, UUG: Leucine		UAA, UAG: Stop codon Stop codon	UGA: Stop codon; UGG: Tryptophan	
C	CUU, CUC, CUA, CUG: Leucine	CCU, CCC, CCA, CCG: Proline	CAU, CAC: Histidine	CGU, CGC, CGA, CGG: Arginine	U C A G
			CAA, CAG: Glutamine		
A	AUU, AUC, AUA: Isoleucine	ACU, ACC, ACA, ACG: Threonine	AAU, AAC: Asparagine	AGU, AGC: Serine	U C A G
	AUG: Methionine; start codon		AAA, AAG: Lysine	AGA, AGG: Arginine	
G	GUU, GUC, GUA, GUG: Valine	GCU, GCC, GCA, GCG: Alanine	GAU, GAC: Aspartic acid	GGU, GGC, GGA, GGG: Glycine	U C A G
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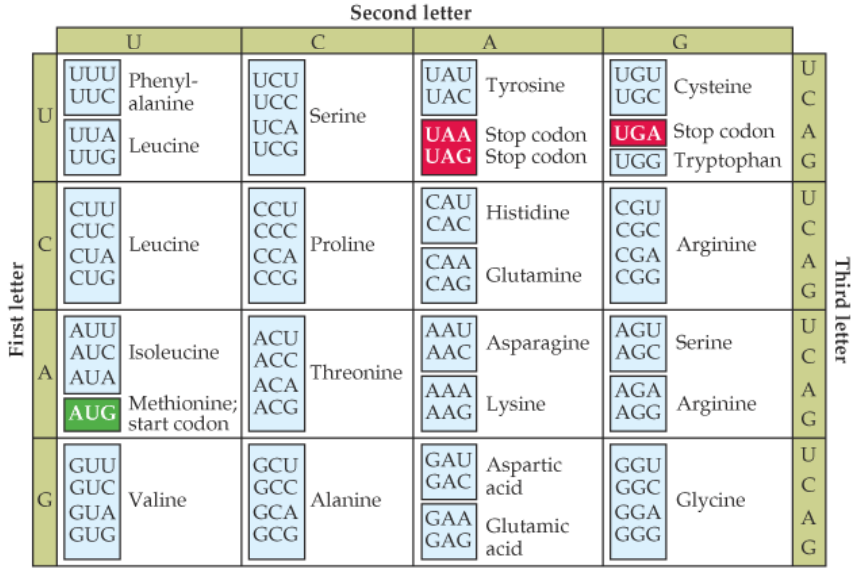
Here is an example of a natural alphabet that contains strings!



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Languages

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Examples:

1. Every alphabet is a formal language over itself
2. The set of natural numbers is a language over the alphabet *A={0, 1, 2, …,9}*

More examples of languages

- Let *A={0, 1}* then *A* is a language over *A*
- Languages over the binary alphabet *{0, 1}* are pervasive in computation
- $A=\{\lambda\}$ is a language (and an alphabet)
- Natural languages are formal languages that in addition to **denotation** have **connotation** (intended meaning)

Basic facts about languages

Theorem 5.3*:*

(a) The union of two languages over the same alphabet is a language

(b) The intersection of two languages over the same alphabet is a language

(c) The difference of two languages over the same alphabet is a language

Proof of (a)

Let L and M be languages over the same alphabet A.

Then, $(\forall s)(s \in L \cup M) \Rightarrow s \in L \vee s \in M$

$\Rightarrow s$ is a string over A

Thus, $L \cup M$ is a language over A.

Proof of (b)

Let L and M be languages over the same alphabet A.

Then, $(\forall s)(s \in L \cap M) \Rightarrow s \in L \wedge s \in M$

$\Rightarrow s$ is a string over A

Thus, $L \cap M$ is a language over A.

Proof of (c)

Let L and M be languages, $L \subseteq M$.

Then, $(\forall s)(s \in M)$ s is a string over A

Since $M - L \subseteq M$

$(\forall s)(s \in M - L \Rightarrow s \in M)$

Therefore, $(\forall s)(s \in M - L$ is a string over $A)$

String concatenation

Definition: Let *L* and *S* be nonempty languages. The **string concatenation over *L*** is defined to be the operation

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Example*:* Let *L* be the language of all strings over the alphabet *A={a, b, 1}.* Let's take *s=abaab* and *t=1a1ab1* (two strings in *L).* Their concatenation is

$$Cat(s,t)=st=abaab1a1ab1$$

Properties of concatenation

Associativity $(\forall s,t,r)(s,t,r \text{ strings over } A)$

$$Cat(s,Cat(t,r)) = Cat(Cat(s,t),r)$$

Non-commutativity

$$(\exists s,t)(s,t \text{ strings over } A) \wedge Cat(s,t) \neq Cat(t,s)$$

Existence of an identity (null string)

$$(\exists \lambda)(\lambda \text{ string}) \wedge ((\forall s)(s \text{ string over } A)$$

$$Cat(\lambda,s) = Cat(s,\lambda) = s)$$

Observation: the null string **is not** the empty set

Closure under string concatenation

Definition: A language *L* is said to be **closed under string concatenation** if *L=Cat(L)*

Examples:

- The language $L = \{\lambda\}$ is closed under string concatenation
- The language $L = \phi$ is also closed under string concatenation (Why?)
- The language *L* of all strings over an alphabet is closed under string concatenation

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More examples

The language L = {0, 00, 000, … } = $\{0^n : n \geq 1\}$

is closed under concatenation. In order to see this, take any two strings in L, this is $s = 0^n$ and $t = 0^m, s, t \geq 1.$

Then, $st = 0^n 0^m = 0^{n+m} \in L$

The language $L = \{01^n : n \geq 1\}$ **is not closed under string concatenation** since, for instance: $Cat\,(01,011) = 01011 \notin L$

Why does closure matters?

String concatenation is pervasive as a language operation If a language is closed under string concatenation, the operation of concatenation is a **language invariant** (*i.e.* does not alter the language). In particular, if the language is closed under string concatenation, any concatenation satisfies the predicate that defines membership in the language

Example:

$Q(w):"\text{w string over}\{0,1\}\wedge w \text{ ends with } 0"$

$L=\{w:Q(w)=1\}$

$\text{Now, since the concatenation of any finite collection of strings over } \{0,1\} \text{ ending with } 0 \text{ is a string that ends with } 0, L \text{ is closed under string concatenation. Therefore,}$

$(\forall s,w\in L)Q(sw)=1$

Theorem on string concatenation

Theorem 5.4: If *L* is a nonempty language that is closed under string concatenation, then *L* is finite if and only if $L = \{\lambda\}$.

Proof: If $L = \{\lambda\}$, since $Cat(\lambda, \lambda) = \lambda\lambda = \lambda$ we have that $Cat(L) = \{\lambda\} = L$. Therefore, *L* is closed under string concatenation, and finite.

If $L \neq \{\lambda\}$, then there exists $s \in L \wedge s \neq \lambda$.

Proof (cont.)

Since *L* is closed under string concatenation the following inductive construction produces a infinite subset of *L*

Base case:

$Cat(s,s) = ss = s^2 \in L$ (true because *L* is closed)

Induction:

$(\forall n) Cat(s, s^{n-1}) = s^n \in L \Rightarrow Cat(s, s^n) = s^{n+1} \in L$

(true because *L* is closed)

Thus, the set $\{s, s^2, ..., s^n, ...\} = \{s^n : n \geq 1\} \subseteq L$ is an infinite subset of *L.* And therefore, *L* is infinite.

Closure of a language

Definition: Let A be an alphabet and L be a language over A. Then, the **star – closure** (or Klein – closure) of L is the smallest language over A that contains L and is closed under string concatenation. The star – closure of L is denoted L*.

Remark: In general, L is a subset of L*. In fact, L = L* if and only if L is star – closed

Star – closure of an alphabet

Theorem: Let A be an alphabet. Then, any language L over A is a subset of A*

Proof: Let s be a string in L. Since L is a language over A, s is the result of a concatenation of symbols in A. But then, s is an element of A*

Encodings

Let A, B be two alphabets. An **encoding of** *A* **in** *B* is a **one-to-one** mapping

$$e : \mathrm{A} \rightarrow \mathrm{B}^*$$

satisfying the **additional condition** that the set

$$e(\mathrm{A}) = \{w : w \in \mathrm{B}^* \wedge (\exists x \in \mathrm{A}) \wedge e(x) = w\}$$

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Example: Let $\mathrm{A} = \{0,1\}; \mathrm{B} = \{a, b\}$. Then,

$e(0) = a; e(1) = b$ is an encoding, but

$e(0) = ab; e(1) = abab$, is NOT

Popular examples of encodings

ASCII: The ASCII encoding specifies a one-to-one correspondence between an alphabet of letters and punctuation symbols of a written language and a set of binary strings (i.e. strings over {0, 1})

Some values are:

e(A)=1000001

e(B)=1000010

e(C)=1000011,…etc,

e(,)=01011100

e(.)= 01011110,…etc.

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e(.)= 01011110,…etc.

Hexadecimal numbers: the encoding specifies a one-to-one correspondence between the alphabet

A={0,1,2,…,9,A,B,C,D,E,F}

And strings over the alphabet

B={0,1,2,…,9}. The encoding is:

e(0)=0

e(1)=1,…,e(9)=9,

e(A)=10, e(B)=11, e(C)=12,

e(D)=13, e(E)=14, e(F)=15

Knowledge representation is independent of alphabets

Encodings are **alphabet translators**. Their existence ensures that **the ability to represent objects does not depend on the choice of an alphabet**

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Indeed, if A, B are two different alphabets, and $w = a_1 a_2 ... a_n$ is a string over A .Then, its "translation" as a string over B is

$$e(a_1)e(a_2)...e(a_n)$$

A simple illustration

The word in Spanish language:

CABA

is encoded by ASCII over {0, 1}* as

e(C)e(A)e(B)e(A)

= **1000011100000110000101000001**