Part I

Secret-key cryptosystems basics

Decrypt cryptotexts:

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GBLVMUB JOGPSNBUJLZ

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PROLOGUE - II.

Decrypt:

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VHFUHW GH GHXA
VHFUHW GH GLHX,
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CHAPTER 4: SECRET-KEY (SYMMETRIC) CRYPTOGRAPHY

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- These cryptosystems are too weak nowadays, too easy to break, especially with computers.
- However, these simple cryptosystems give a good illustration of several of the important ideas of the cryptography and cryptanalysis.
- Moreover, most of them can be very useful in combination with more modern cryptosystem - to add a new level of security.

BASICS

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- Foundations: cryptography gave rise to several new key concepts of the foundation of informatics: one-way functions, computationally perfect pseudorandom generators, zero-knowledge proofs, holographic proofs, program self-testing and self-correcting, . . .

APPROACHES and PARADOXES in CRYPTOGRAPHY

Sound approaches to cryptography

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Paradoxes of modern cryptography:

- **Positive results** of modern cryptography are based on **negative results** of computational complexity theory.
- Computers, that were designed originally for decryption, seem to be now more useful for **encryption**.

SECRET-KEY (SYMMETRIC) CRYPTOSYSTEMS - CIPHERS

The cryptography deals with problem of sending a message (plaintext, ciphertext, cleartext), through an insecure channel, that may be tapped by an adversary (eavesdropper, cryptanalyst), to a legal receiver.

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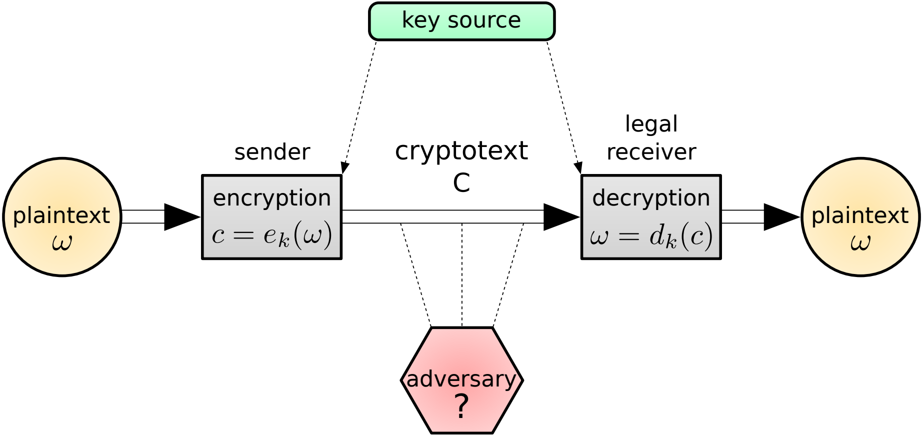
Secret-key (symmetric) cryptosystems scheme:



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Security of such a cryptosystem depends solely on the secrecy of shared key.

COMPONENTS of CRYPTOSYSTEMS:

Plaintext-space: P – a set of plaintexts (messages) over an alphabet $\sum$

Cryptotext-space: C – a set of cryptotexts (ciphertexts) over alphabet Δ

Key-space: K – a set of keys

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Note: As encryption algorithms we can use also **randomized algorithms.**

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Secret key cryptosystems provide secure transmission of messages along insecure channel provided **the secret keys are transmitted over an extra secure channel.**

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Practical security is in the case no one was able to break the cryptosystem so far after many years and many attempts.

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- **Current view** Codebreakers and cryptanalysts are artists that can superbly use modern mathematics, informatics and computing supertechnology for decrypting encrypted messages.

CRYPTO VIEW of MODERN HISTORY

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- **Second World War** was the war of physicists (atomic bombs).
- **Third World War** will be the war of informaticians (cryptographers and cryptanalysts).

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Transposition ciphers do not replace but only rearrange order of symbols in the plaintext - sometimes in a complicated way.

PARTICULAR CRYPTOSYSTEMS

CAESAR (100 - 42 B.C.) CRYPTOSYSTEM - SHIFT CIPHER I

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SHIFT CIPHER $SC(k)$ - $SC(3)$ is called CAESAR SHIFT

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Numerical version of $SC(k)$ is defined, for English, on the set $\{0, 1, 2, \ldots, 25\}$ by the encryption algorithm:

$$e_k(i) = (i + k)(mod\ 26)$$

Numerical version of the cipher Atbash used in the Bible.

$$e(i) = 25 - i$$

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Solution:

Secret de deux
secret de Dieu,
secret de trois
secret de tous.

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This system is now believed, by some, to be the oldest cipher used.

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C	L	M	N	O	P
D	Q	R	S	T	U
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Encryption algorithm: Each symbol is substituted by the pair of symbols denoting the row and the column of the checkerboard in which the symbol is placed.

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Encryption algorithm: Each symbol is substituted by the pair of symbols denoting the row and the column of the checkerboard in which the symbol is placed.

Example: **KONIEC** $\rightarrow$BJCICHBIAJAH
Decryption algorithm: ???

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KERCHHOFF's PRINCIPLE

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6. The cryptosystem should **not** be closed under composition, i.e. not for every two keys k_1, k_2 there is a key k such that

$$e_k(w) = e_{k_1}(e_{k_2}(w)).$$

7. **The set of keys should be very large.**

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- The encryption machine should be relatively easy to use.

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   where the cryptotexts c_i have been chosen by the cryptanalysts. The aim is to determine the key. (For example, if cryptanalysts get a temporary access to decryption machinery.)

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An eavesdropper can therefore be passive - Eve or active - Mallot.

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Anonymity: Alice does not want Bob to find out who sent the message

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Encoding: For a word w let c_w be the column vector of length n of the integer codes of symbols of w. $(A \to 0, B \to 1, C \to 2, \ldots)$

Encryption: $c_c = Mc_w \bmod 26$

Decryption: $c_w = M^{-1}c_c \bmod 26$

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Theorem

$$\text{If } M = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \text{ then } M^{-1} = \frac{1}{\det M} \begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix}$$

Proof: Exercise

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Since $2^{-1} \equiv 6 \pmod{11}$, the resulting matrix has the form

$$M^{-1} = \begin{pmatrix} 3 & 3 & 6 \\ 8 & 4 & 10 \\ 1 & 4 & 6 \end{pmatrix} \pmod{11}.$$

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in the journal **American Mathematical Monthly** in 1929.

Hill even tried to design a machine to use his cipher, but without a success.

SECRET-KEY (SYMMETRIC) CRYPTOSYSTEMS

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Two basic types of substitution cryptosystems

- **monoalphabetic cryptosystems** – they use a fixed substitution – CAESAR, POLYBIOUS
- **polyalphabetic cryptosystems** – substitution keeps changing during the encryption

SECRET-KEY (SYMMETRIC) CRYPTOSYSTEMS

A cryptosystem is called secret-key cryptosystem if some secret piece of information – the key – has to be agreed first between any two parties that have, or want, to communicate through the cryptosystem. Example: CAESAR, HILL. Another name is **symmetric cryptosystem (cryptography).**

Two basic types of secret-key cryptosystems

- **substitution** based cryptosystems
- **transposition** based cryptosystems

Two basic types of substitution cryptosystems

- **monoalphabetic cryptosystems** – they use a fixed substitution – CAESAR, POLYBIOUS
- **polyalphabetic cryptosystems** – substitution keeps changing during the encryption

A monoalphabetic cryptosystem with letter-by-letter substitution is uniquely specified by a permutation of letters, (number of permutations (keys) is 26!)

AFFINE CRYPTOSYSTEMS

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Example: Each **AFFINE cryptosystem** is given by two integers

$$0 \leq a, b \leq 25, gcd(a, 26) = 1.$$

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Example: Each **AFFINE cryptosystem** is given by two integers

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$a = 3, b = 5, \quad e_{3,5}(x) = (3x + 5) \bmod 26,$
$e_{3,5}(3) =$

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Example: Each **AFFINE cryptosystem** is given by two integers

$$0 \leq a, b \leq 25, gcd(a, 26) = 1.$$

Encryption: $e_{a,b}(x) = (ax + b) \bmod 26$

Example

$a = 3, b = 5, \quad e_{3,5}(x) = (3x + 5) \bmod 26,$
$e_{3,5}(3) = 14,$

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$e_{3,5}(3) = 14, \quad e_{3,5}(15) =$

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Example

$a = 3, b = 5, \quad e_{3,5}(x) = (3x + 5) \bmod 26,$
$e_{3,5}(3) = 14, \quad e_{3,5}(15) = 24, \quad e_{3,5}(D) =$

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A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

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A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Decryption: $d_{a,b}(y) = a^{-1}(y - b) \bmod 26$

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Frequency counts in English:

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E	12.31	L	4.03	B	1.62
T	9.59	D	3.65	G	1.61
A	8.05	C	3.20	V	0.93
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N	7.19	P	2.29	Q	0.20
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S	6.59	M	2.25	J	0.10
R	6.03	W	2.03	Z	0.09
H	5.14	Y	1.88		
	70.02		24.71		5.27

and for other languages:

English	%	German	%	Finnish	%	French	%	Italian	%	Spanish	%
E	12.31	E	18.46	A	12.06	E	15.87	E	11.79	E	13.15
T	9.59	N	11.42	I	10.59	A	9.42	A	11.74	A	12.69
A	8.05	I	8.02	T	9.76	I	8.41	I	11.28	O	9.49
O	7.94	R	7.14	N	8.64	S	7.90	O	9.83	S	7.60
N	7.19	S	7.04	E	8.11	T	7.29	N	6.88	N	6.95
I	7.18	A	5.38	S	7.83	N	7.15	L	6.51	R	6.25
S	6.59	T	5.22	L	5.86	R	6.46	R	6.37	I	6.25
R	6.03	U	5.01	O	5.54	U	6.24	T	5.62	L	5.94
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The 20 most common digrams are (in decreasing order) TH, HE, IN, ER, AN, RE, ED, ON, ES, ST, EN, AT, TO, NT, HA, ND, OU, EA, NG, AS.

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The 20 most common digrams are (in decreasing order) TH, HE, IN, ER, AN, RE, ED, ON, ES, ST, EN, AT, TO, NT, HA, ND, OU, EA, NG, AS. The six most common **trigrams** are: THE, ING, AND, HER, ERE, ENT.

FREQUENCY ANALYSIS for SEVERAL LANGUAGES

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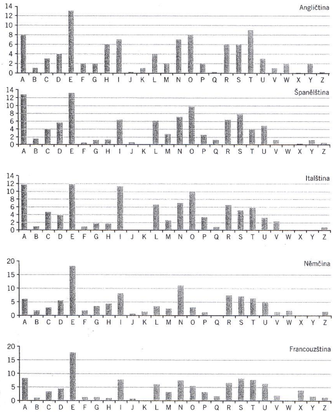
NEJČETNĚJŠÍ PÍSMENA V ZÁPADOEVROPSKÝCH JAZYCÍCH

Angličtina:	E T A O I N S H R D L U
Francouzština:	E N A S R I U T O L D C
Němčina:	E N R I S T U D A H G L
Italština:	E I A O R L N T S C D P
Španělština:	E A O S R I N L D C T U



OTHER CHARACTERISTICS of ENGLISH

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V ANGLIČTINĚ

Nejčastější písmena:	**e t a o i n s h r d l u**
Nejčastější první písmena:	**t a s o i c p b s h m**
Nejčastější poslední písmena:	**e t s d n r y o f l a g**
Nejčastější dvojice písmen:	**th er on an re he in ed nd ha at**
Nejčastější trojice písmen:	**the and tha ent ion tio for nde**
Nejčastější zdvojení písmen:	**ss ee tt ff ll mm oo**
Nejčastější písmena následující po E:	**r d s n a c t m e p w o**
Nejčastější dvojpísmenná slova:	**of to in it is be as at so we he**
Nejčastější trojpísmenná slova:	**the and for are but not you all**
Nejčastější čtyřpísmenná slova:	**that with have this will your from they**

FREQUENCY COUNTS in CZECH and SLOVAK

First resource

Czech		Slovak	
o	8.66	*a*	10.67
e	7.69	*o*	9.12
n	6.53	*e*	8.43
a	6.21	*i*	5.74
t	5.72	*n*	5.74
v	4.66	*s*	5.02
s	4.51	*t*	4.92
i	4.35	*v*	4.60
l	3.84	*k*	3.96

Second resource:

Czech		Slovak	
e	10.13	*a*	9.49
a	8.99	*o*	9.34
o	8.39	*e*	9.16
i	6.92	*i*	6.81
n	6.64	*n*	6.34
s	5.74	*s*	5.94
r	5.33	*r*	5.12
t	4.98	*t*	5.06
v	4.50	*v*	4.85

Discovery of FREQUENCY ANALYSIS - I.

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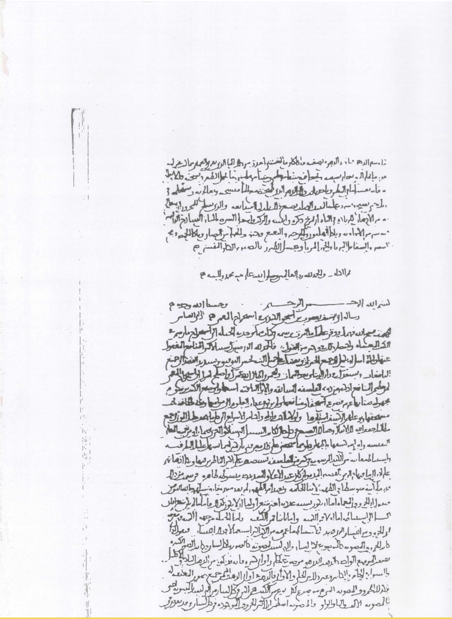
Frequency analysis was originally used to study Koran, to establish chronology of revelations by Muhammad in Koran.

Discovery of FREQUENCY ANALYSIS - II.



CRYPTANALYSIS of AFFINE CRYPTOSYSTEM - EXAMPLE

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Cryptanalysis of a cryptotext encrypted using the AFFINE cryptosystem with an encryption algorithm

$$e_{a,b}(x) = (ax + b) \bmod 26 = (xa + b) \bmod 26$$

where $0 \leq a, b \leq 25, gcd(a, 26) = 1$. (Number of keys: $12 \times 26 = 312$.)

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Example: Assume that an English plaintext is divided into blocks of 5 letters and encrypted by an AFFINE cryptosystem (ignoring space and interpunctions) as follows:

How to find the plaintext?

B H J U H	N B U L S	V U L R U	S L Y X H
O N U U N	B W N U A	X U S N L	U Y J S S
W X R L K	G N B O N	U U N B W	S W X K X
H K X D H	U Z D L K	X B H J U	H B N U O
N U M H U	G S W H U	X M B X R	W X K X L
U X B H J	U H C X K	X A X K Z	S W K X X
L K O L J	K C X L C	M X O N U	U B V U L
R R W H S	H B H J U	H N B X M	B X R W X
K X N O Z	L J B X X	H B N F U	B H J U H
L U S W X	G L L K Z	L J P H U	U L S Y X
B J K X S	W H S S W	X K X N B	H B H J U
H Y X W N	U G S W X	G L L K	

CRYPTANALYSIS - CONTINUATION I

Frequency analysis of plaintext and frequency table for English:

X - 32	J - 11	D - 2
U - 30	O - 6	V - 2
H - 23	R - 6	F - 1
B - 19	G - 5	P - 1
L - 19	M - 4	E - 0
N - 16	Y - 4	I - 0
K - 15	Z - 4	Q - 0
S - 15	C - 3	T - 0
W - 14	A - 2	

	%		%		%
E	12.31	L	4.03	B	1.62
T	9.59	D	3.65	G	1.61
A	8.05	C	3.20	V	0.93
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	70.02		24.71		5.27

First guess: $E = X, T = U$

Encodings: $xa + b = y$

$$4a + b = 23 \pmod{26}$$
$$19a + b = 20 \pmod{26}$$

Solutions: $a = 5, b = 3 \rightarrow a^{-1} =$

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X - 32	J - 11	D - 2
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Translation table

crypto	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
plain	P	K	F	A	V	Q	L	G	B	W	R	M	H	C	X	S	N	I	D	Y	T	O	J	E	Z	U

```
B H J U H   N B U L S   V U L R U   S L Y X H
O N U U N   B W N U A   X U S N L   U Y J S S
W X R L K   G N B O N   U U N B W   S W X K X
H K X D H   U Z D L K   X B H J U   H B N U O
N U M H U   G S W H U   X M B X R   W X K X L
U X B H J   U H C X K   X A X K Z   S W K X X
L K O L J   K C X L C   M X O N U   U B V U L
R R W H S   H B H J U   H N B X M   B X R W X
K X N O Z   L J B X X   H B N F U   B H J U H
L U S W X   G L L K Z   L J P H U   U L S Y X
B J K X S   W H S S W   X K X N B   H B H J U
H Y X W N   U G S W X   G L L K
```

provides from the above cryptotext the plaintext that starts with KGWTG CKTMO OTMIT DMZEG, which does not make sense.

CRYPTANALYSIS - CONTINUATION II

Second guess: $E = X, A = H$

Equations
$$4a + b = 23 \pmod{26}$$
$$b = 7 \pmod{26}$$

Solutions: $a = 4$ or $a = 17$ and therefore $a = 17$

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This gives the translation table

crypto	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
plain	V	S	P	M	J	G	D	A	X	U	R	O	L	I	F	C	Z	W	T	Q	N	K	H	E	B	Y

and the following plaintext from the above cryptotext

S A U N A I S N O T K N O W N T O B E A
F I N N I S H I N V E N T I O N B U T T
H E W O R D I S F I N N I S H T H E R E
A R E M A N Y M O R E S A U N A S I N F
I N L A N D T H A N E L S E W H E R E O
N E S A U N A P E R E V E R Y T H R E E
O R F O U R P E O P L E F I N N S K N O
W W H A T A S A U N A I S E L S E W H E
R E I F Y O U S E E A S I G N S A U N A
O N T H E D O O R Y O U C A N N O T B E
S U R E T H A T T H E R E I S A S A U N
A B E H I N D T H E D O O R

OTHER EXAMPLES of MONOALPHABETIC CRYPTOSYSTEMS

Symbols of the English alphabet will be replaced by squares with or without points and with or without surrounding lines using the following rule:

A:	B:	C:
D:	E:	F:
G:	H:	I:

J·	K·	L·
M·	N·	O·
P·	Q·	R·

S	T	U
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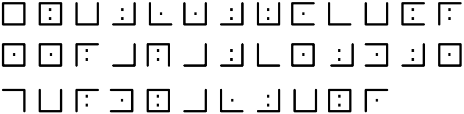
G:	H:	I:	P·	Q·	R·	Y	Z	

For example the plaintext:

WE TALK ABOUT FINNISH SAUNA MANY TIMES LATER

results in the cryptotext:



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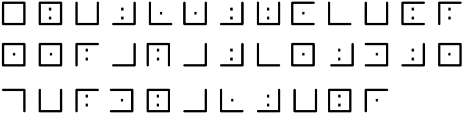
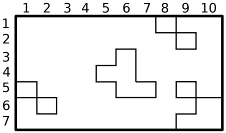


Garbage in between method: the message (plaintext or cryptotext) is supplemented by "garbage letters".

Richelieu cryptosystem used sheets of card board with holes.

I		L	O	V	E		**Y**	O	U
I		H	A	V	E		Y	**O**	U
D	E	E	P		**U**	N	D	E	R
M	Y		S	**K**	**I**	N		M	Y
L	O	V	E		**L**	**A**	S	**T**	S
F	**O**	R	E	V	E	R		I	**N**
H	Y	P	E	R	S	P	A	**C**	**E**



EXTREME CASES for FREQUENCY ANALYSIS

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British translation, due to Gilbert Adair, has appeared in 1994 under the title

A void

Appendix A

The Opening Paragraph of *A Void* by Georges Perec, translated by Gilbert Adair

Today, by radio, and also on giant hoardings, a rabbi, an admiral notorious for his links to masonry, a trio of cardinals, a trio, too, of insignificant politicians (bought and paid for by a rich and corrupt Anglo-Canadian banking corporation), inform us all of how our country now risks dying of starvation. A rumor, that's my initial thought as I switch off my radio, a rumor or possibly a hoax. Propaganda, I murmur anxiously–as though, just by saying so, I might allay my doubts–typical politicians' propaganda. But public opinion gradually absorbs it as a fact. Individuals start strutting around with stout clubs. "Food, glorious food!" is a common cry (occasionally sung to Bart's music), with ordinary hardworking folk harassing officials, both local and national, and cursing capitalists and captains of industry. Cops shrink from going out on night shift. In Mâcon a mob storms a municipal building. In Rocadamour ruffians rob a hangar full of foodstuffs, pillaging tons of tuna fish, milk and cocoa, as also a vast quantity of corn–all of it, alas, totally unfit for human consumption. Without fuss or ado, and naturally without any sort of trial, an indignant crowd hangs 26 solicitors on a hastily built scaffold in front of Nancy's law courts (this Nancy is a town, not a woman) and ransacks a local journal, a disgusting right-wing rag that is siding against it. Up and down this land of ours looting has brought docks, shops and farms to a virtual standstill.

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They are substitution cryptosystems in which each letter is replaced by arbitrarily chosen substitutes from fixed and disjoint sets of substitutes.

The number of substitutes of a letter is usually proportional to the frequency of the letter.

Though homophonic cryptosystems are not unbreakable, they are much more secure than ordinary monoalphabetic substitution cryptosystems.

The first known homophonic substitution cipher is from 1401.

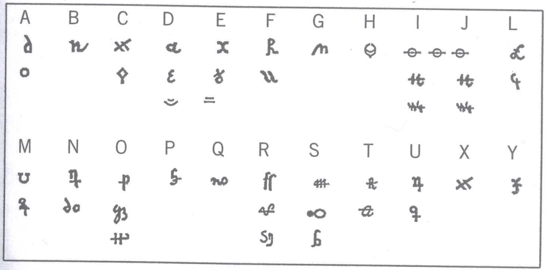
EXAMPLES of HOMOPHONIC CRYPTOSYTEMS - I.

Jindřich IV. Francouzský

Homofonní tabulku Jindřicha IV. (viz níže) určitě navrhoval François Viète, oficiální králův kryptograf, luštitel a matematik. Jde o praktickou a účinnou šifru, jakou lze čekat od autora, který zná všechny triky i jejich meze. Většina souhlásek má více variant podle jejich skutečné četnosti. Slovník obsahuje pouhá tři slova.

Tabulka zahrnuje i značkovací symbol:

To stačí k označení všech začátků i konců bezvýznamných úseků, na rozdíl od označování textových částí z Montmorencyho tabulky.



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odstavec = že = vy =

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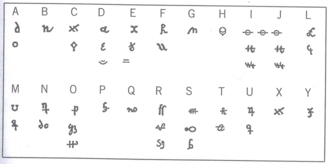

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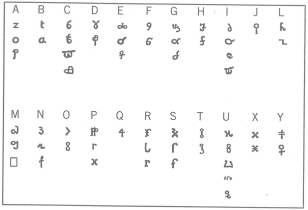
Vévoda z Montmorency



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Example: PLAYFAIR is encrypted as LCNMNFSC

Playfair was used in World War I by British army.

Playfair square:

S	D	Z	I	U
H	A	F	N	G
B	M	V	Y	W
R	P	L	C	X
T	O	E	K	Q

VIGENERE and AUTOCLAVE cryptosystems

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AUTOCLAVE-key cryptosystem: a short keyword is chosen and appended by plaintext

POLYALPHABETIC SUBSTITUTION CRYPTOSYSTEMS III

VIGENERE and AUTOCLAVE cryptosystems

Vigenére table:

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D
F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E
G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F
H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G
I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H
J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I
K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J
L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K
M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L
N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M
O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N
P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y

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B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D
F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E
G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F
H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G
I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H
J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I
K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J
L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K
M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L
N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M
O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N
P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
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Autoclave-key:
Vigenere-encrypt..:
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POLYALPHABETIC SUBSTITUTION CRYPTOSYSTEMS III

VIGENERE and AUTOCLAVE cryptosystems

Vigenére table:

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D
F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E
G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F
H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G
I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H
J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I
K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J
L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K
M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L
N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M
O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N
P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
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C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D
F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E
G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F
H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G
I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H
J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I
K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J
L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K
M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L
N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M
O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N
P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
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COMMENT

- Autoclave-key cipher is also called autokey cipher.

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- So called **running-key cipher** uses very long key that is a passage from a book (for example from Bible).

BLAISE de VIGENERE (1523-1596)

HISTORICAL COMMENT

The encryption method that is commonly called as Vigenere method was actually discovered in 1553 by Giovan Batista Belaso.

VIGÉNERE CRYPTOSYSTEM

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- VIGENERE cryptosystem was practically not used for the next 200 years, in spite of its perfection.
- It seems that the reason for ignorance of the VIGENERE cryptosystem was its apparent complexity.

CRYPTANALYSIS of cryptotexts produced by VIGENERE-key cryptosystems

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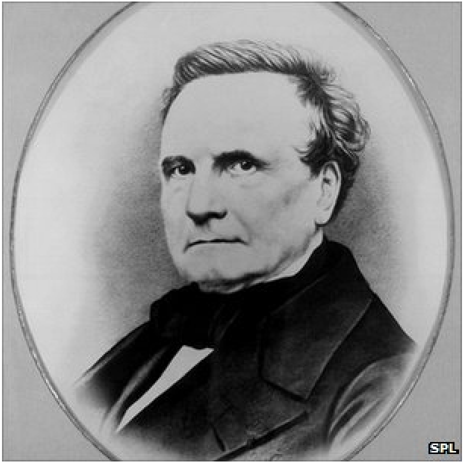
Method. Determine the greatest common divisor of the distances between identical subwords (of length 3 or more) of the cryptotext.

Charles Babbage (1791-1871)



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Then it holds, as shown on next slide:

$$L = \frac{0.027n}{(n-1)I - 0.038n + 0.065}, \;\; I = \sum_{i=1}^{26} \frac{n_i(n_i-1)}{n(n-1)}$$

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Once the length of the keyword is found it is easy to determine the key using the frequency analysis method for monoalphabetic cryptosystems.

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The number of pairs of letters in different columns: $\frac{L(L-1)}{2} \cdot \frac{n^2}{L^2} = \frac{n^2(L-1)}{2L}$

The expected number A of pairs of equals letters is $A = \frac{n(n-L)}{2L} \cdot 0.065 + \frac{n^2(L-1)}{2L} \cdot 0.038$

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The number of pairs of letters in the same column: $L \cdot \frac{1}{2} \cdot \frac{n}{L}(\frac{n}{L} - 1) = \frac{n(n-L)}{2L}$

The number of pairs of letters in different columns: $\frac{L(L-1)}{2} \cdot \frac{n^2}{L^2} = \frac{n^2(L-1)}{2L}$

The expected number A of pairs of equals letters is $A = \frac{n(n-L)}{2L} \cdot 0.065 + \frac{n^2(L-1)}{2L} \cdot 0.038$

Since $I = \frac{A}{\frac{n(n-1)}{2}} = \frac{1}{L(n-1)}[0.027n + L(0.038n - 0.065)]$

one gets the formula for L from one of the previous slides.

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to decode columns use decoding method for Caesar

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$$w = 101101011$$
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NEVER USE ONE-TIME PAD TWICE WITH THE SAME KEY

The reuse of keys by Soviet Union spies (due to the maanufacturer's accidental duplication of one-time-pad pages) enabled US cryptanalysts to unmask the atomic spy Klaus Fuchs in 1949.

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Example ONE-TIME PAD cryptosystem is perfectly secure because for any pair c, p there exists a key k such that

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IDEA: Find a simple way to generate almost perfectly random key shared by both communicating parties and make them to use this key for one-time pad encoding and decoding!!!!

PERFECT SECRECY of ONE-TIME PAD ONCE MORE

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every cryptotext c

PERFECT SECRECY of ONE-TIME PAD ONCE MORE

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that p was the plaintext the encryption of which provided c as the cryptotext.

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- Moreover, modern block ciphers often include smaller substitution tables, called S-boxes.

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Example $a^2 cdef^3 g^2 i^2 jkmn^3 o^5 prs^2 t^2 u^3 z$

Solution: ??

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Example: keyword: HOW MANY ELKS, $k = 8$

0								8																	
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
P	Q	R	T	U	V	X	Z	H	O	W	M	A	N	Y	E	L	K	S	B	C	D	F	G	I	J

KEYWORD CAESAR - Example I

Example Decrypt the following cryptotext encrypted using the KEYWORD CAESAR and determine the keyword and *k*

T IVD ZCRTIC FQNIQ TU TF
Q XAVFCZ FEQXC PCQUCZ WK
Q FUVBC FNRRTXTCIUAK WTY
DTUP MCFECXU UV UPC BVANHC
VR UPC FEQXC UPC FUVBC
XVIUQTIF FUVICF NFNQAAK
VI UPC UVE UV UQGC Q FQNIQ
WQUP TU TF QAFV ICXCFFQMK
UPQU UPC FUVBC TF EMVECMAK
PCQUCZ QIZ UPQU KVN PQBC
UPC RQXTATUK VR UPMVDTIY
DQUCM VI UPC FUVICF

KEYWORD CAESAR - Example II

Step 1. Make the frequency counts:

	Number
U	32
C	31
Q	23
F	22
V	20
P	15
T	15
I	14
A	8
	180=74.69%

	Number
X	8
K	7
N	7
E	6
M	6
R	6
B	5
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UPC is likely to be THE.

Let us now decrypt the remaining letters in the high frequency group: F,V,I

From the words TU, TF $\Rightarrow$ F=S
From UV $\Rightarrow$ V=O
From VI $\Rightarrow$ I=N

CONTINUATION

So we have: T=I, Q=A, U=T, P=H, C=E, F=S, V=O, I=N and now in

```
T   I V D   Z C R T I C   F Q N I Q   T U   T F
Q   X A V F C Z   F E Q X C   P C Q U C Z   W K
Q   F U V B C   F N R R T X T C I U A K   W T Y
D T U P   M C F E C X U   U V   U P C   B V A N H C
V R   U P C   F E Q X C   U P C   F U V B C
X V I U Q T I F   F U V I C F   N F N Q A A K
V I   U P C   U V E   U V   U Q G C   Q   F Q N I Q
W Q U P   T U   T F   Q A F V   I C X C F F Q M K
U P Q U   U P C   F U V B C   T F   E M V E C M A K
P C Q U C Z   Q I Z   U P Q U   K V N   P Q B C
U P C   R Q X T A T U K   V R   U P M V D T I Y
D Q U C M   V I   U P C   F U V I C F
```

we have several words with only one unknown letter what leads to another guesses and the table:

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
L	V	E	W	P	S	K	M	N	?	Y	?	R	U	?	H	A	F	?	I	T	O	B	C	G	D

This leads to the keyword **CRYPTOGRAPHY GIVES ME FUN** and $k = 4$ -

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- Shannon demonstrated several important features of the statical nature of natural languages that makes solution to many problems of ciphers very straightforward.

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- Possible plaintexts are **thatis, ofyour, season, oxford, thatof,....** but there is no way to determine the plaintext uniquely.

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$$U_{C,K,L} = \frac{H_K}{D_L}$$

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So the plaintext redundancy is $4.7 - 1.5 = 3.2$.

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Empirical evidence indicates that if a simple substitution cryptosystem is applied to a a meaningful English message, then about 25 cryptotext characters are enough for an experienced cryptanalyst to recover the plaintext.

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- Therefore the unicity distance for English is 1 when $|M| = (4.7/1.8)|K|$

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English:

algorithms	logarithms
antagonist	stagnation
compressed	decompress
coordinate	decoration
creativity	reactivity
deductions	discounted
descriptor	predictors
impression	permission
introduces	reductions
procedures	reproduces

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APPENDIX I

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- It was the design of the telegraph and the need for *field ciphers* to be used in combat that ended the massive use of nomenclators and started a new history of cryptography dominated by polyalphabetic substitution cryptosystems.