Part I

Secret-key cryptosystems basics

PROLOGUE - I.

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PROLOGUE - I.

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RPNBMZ EBMFLP OFABKEFT

PROLOGUE - II.

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Decrypt:

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

- In this chapter we deal with some of the very old, or quite old, classical (secret-key or symmetric) cryptosystems and their cryptanalysis that were primarily used in the pre-computer era.

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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

CRYPTOLOGY - HISTORY + APPLICATIONS

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Importance of cryptography nowadays

- Applications: cryptography is the key tool to make modern information transmission secure, and to create secure information society.
- 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, . . .

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MAIN DEVELOPMENTS IN CRYPTOGRAOHY

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(2) started to develop cryptographic systems that also utilize elements and processes of the quantum world.

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As another consequence, cryptography has moved from an engineering art, built on heuristic techniques, to a scientific disciplin based on mathematically rigorous design requirements, solution techniques and correctness proofs.

Such broadly developed modern cryptography is the subject of this lecture.

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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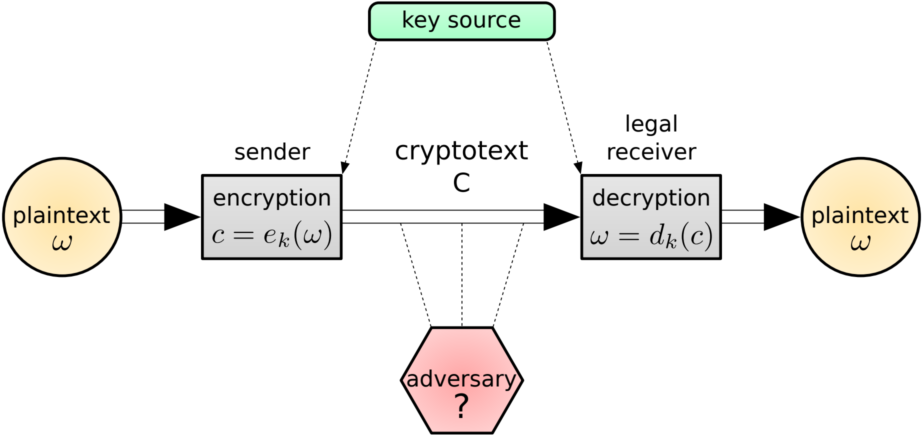
Secret-key (symmetric) cryptosystems scheme:



SECRET-KEY (PRIVATE-KEY - SYMMETRIC) CRYPTOSYSTEMS

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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

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$$w \in d_k(e_k(w)) \quad \text{or} \quad w = d_k(e_k(w)).$$

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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.

WHO ARE CODEBREAKERS - DEVELOPMENTS

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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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The decryption algorithm d_k for $SC(k)$ substitutes any letter by the one occurring k positions backward (cyclically) in the alphabet.

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

Example $e_2(\text{EXAMPLE}) =$

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Decrypt the cryptotext: **VHFUHW GH GHXA, VHFUHW GH GLHX, VHFUHW GH WURLV, VHFUHW GH WRXV.**

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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.

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

EXAMPLE

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Decrypt:

EXAMPLE

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Solution:

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Decrypt:

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

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** $\rightarrow$

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POLYBIOUS can be used to encrypt words of the English alphabet without J.

Key-space: Polybious checkerboards 5×5 with 25 English letters and with rows + columns labeled by symbols.

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It is expected that Romans already used Polybious cryptosystem.

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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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The aim of cryptanalysis is to get as much information about the plaintext or the key as possible.

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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: $c_c = Mc_w$ mod 26

Decryption: $c_w = M^{-1}c_c$ mod 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

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

SESTER S. HILL

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

SECRET-KEY (SYMMETRIC) CRYPTOSYSTEMS

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

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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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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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I	7.18	F	2.28	X	0.20
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
H	5.14	D	4.94	K	5.20	L	5.34	S	4.98	D	5.58

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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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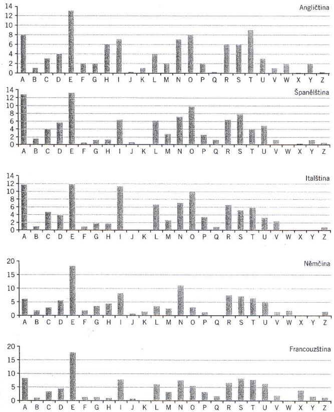
NEJČETNĚJŠÍ PÍSMENA V ZÁPADOEVROPSKÝCH JAZYCÍCH

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.

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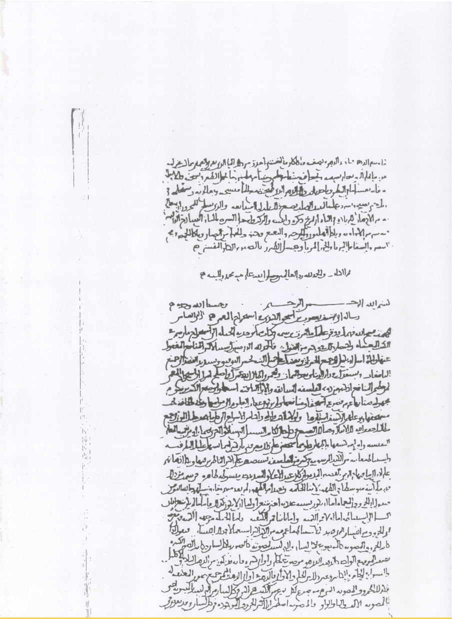

CRYPTANALYSIS of AFFINE CRYPTOSYSTEM - EXAMPLE

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

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

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
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H	5.14	Y	1.88		
	70.02		24.71		5.27

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

Encodings: $4a + b = 23 \pmod{26}$

$xa + b = y$ $\quad 19a + b = 20 \pmod{26}$

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

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

Solutions: $a = 5, b = 3 \rightarrow a^{-1} = 21$

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
O	7.94	U	3.10	K	0.52
N	7.19	P	2.29	Q	0.20
I	7.18	F	2.28	X	0.20
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

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

Encodings: $4a + b = 23 \pmod{26}$

$xa + b = y$ $\quad 19a + b = 20 \pmod{26}$

Solutions: $a = 5, b = 3 \rightarrow a^{-1} = 21$

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 $a = 17$

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

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

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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

SAUNA ISNOT KNOWN TOBEA
FINNI SHINV ENTIO NBUTT
HEWOR DISFI NNISH THERE
AREMA NYMOR ESAUN ASINF
INLAN DTHAN ELSEW HEREO
NESAU NAPER EVERY THREE
ORFOU RPEOP LEFIN NSKNO
WWHAT ASAUN AISEL SEWHE
REIFY OUSEE ASIGN SAUNA
ONTHE DOORY OUCAN NOTBE
SURET HATTH EREIS ASAUN
ABEHI NDTHE DOOR

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
V	W	X
Y	Z	

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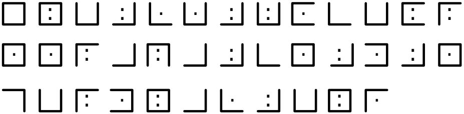
S	T	U
V	W	X
Y	Z	

For example the plaintext:

WE TALK ABOUT FINNISH SAUNA MANY TIMES LATER

results in the cryptotext:



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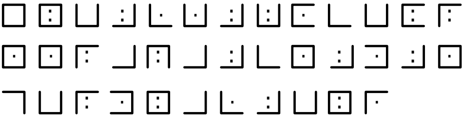
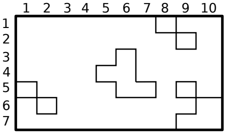


Garbage in between method: the message (plaintext or cryptotext) is supplemented by "garbage letters".

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

In 1969 Georges Perec published, in France,

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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.

HOMOPHONIC CRYPTOSYSTEMS

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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.

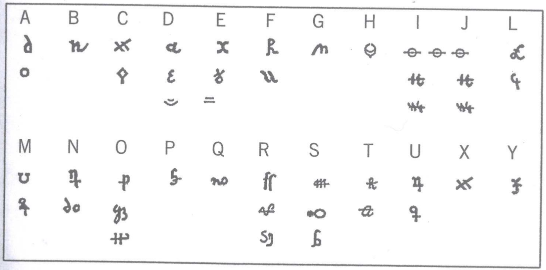
The first known homophonic substitution cipher is from 1401.

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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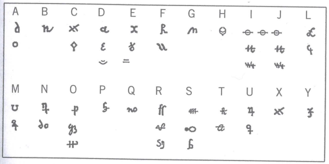

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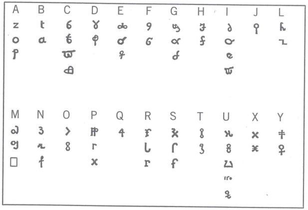
Vévoda z Montmorency



Playfair cryptosystem

Invented around 1854 by Ch. Wheatstone.

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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

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Second step: For a plaintext w a key k has to be chosen that should be a word of the same length as w.

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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

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

Keyword: H A M B U R G

Plaintext: I N J E D E M M E N S C H E N G E S I C H T E S T E H T S E I N E G

Vigenere-key:

Autoclave-key:

Vigenere-encrypt..:

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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
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POLYALPHABETIC SUBSTITUTION CRYPTOSYSTEMS III

VIGENERE and AUTOCLAVE cryptosystems

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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

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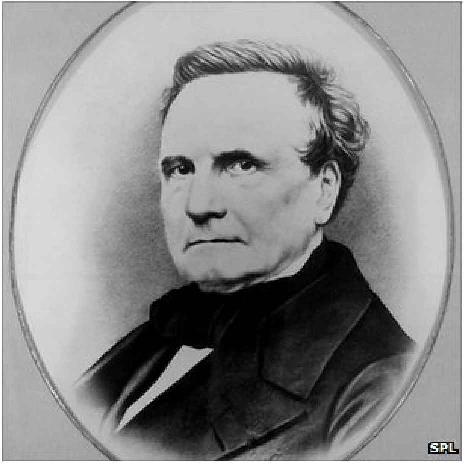
Method. Determine the greatest common divisor of the distances between identical subwords (of length 3 or more) of the cryptotext.

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 the same column: $L \cdot \frac{1}{2} \cdot \frac{n}{L}(\frac{n}{L} - 1) = \frac{n(n-L)}{2L}$

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	x_1	x_2	x_3	$\dots$	x_L
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	x_{2L+1}	x_{2L+2}	x_{2L+3}	$\dots$	x_{3L}
	.	.	.		.

First observation Each column is obtained using the CAESAR cryptosystem.
Probability that two randomly chosen letters are the same in

- the same column is 0.065.
- different columns is 0.038.

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

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

DERIVATION of the FRIEDMAN METHOD - II.

Assume that a cryptotext is writen into L columns headed by the letters of the keyword

key letters	S_1	S_2	S_3	...	S_L
	x_1	x_2	x_3	...	x_L
	x_{L+1}	x_{L+2}	x_{L+3}		x_{2L}
	x_{2L+1}	x_{2L+2}	x_{2L+3}	...	x_{3L}
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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

ONE-TIME PAD CRYPTOSYSTEM – Vernam's cipher

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plaintext	w	are all binary words of the same length
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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.

PERFECT SECRET-KEY CRYPTOSYSTEMS- I.

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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

$$c = k \oplus p.$$

PERFECT SECRECY of ONE-TIME PAD

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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

For

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

I	N	J	E	D	E	M	M	E	N
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H	T	E	S	T	E	H	T	S	E
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Example $a^2cdef^3g^2i^2jkmn^3o^5prs^2t^2u^3z$

Solution: ??

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The keyword is then written bellow the English alphabet letters, beginning with the k-symbol, and the remaining letters are written in the alphabetic order and cyclically after the keyword.

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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
```

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
Z	5
D	4
	54=22.41%

	Number
W	3
Y	2
G	1
H	1
J	0
L	0
O	0
S	0
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KEYWORD CAESAR - Example II

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The three letter word UPC occurs 7 times and all other 3-letter words occur only once. Hence

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

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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 $|M| = (4.7/1.8)|K|$

ANAGRAMS – EXAMPLES

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IRI BRÄTER, GENF

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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

SOME SOLUTIONS

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APPENDIX I

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- Till recently it was assumed that secret codebooks are necessary for secret communication.

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- Famous was the nomenclator designed by very famous French cryptologist Rosignol, for Ludvig XIV, that was not broken for several hundred of years.

NOMENCLATORS

- For several centuries so called "Nomenclators" were used for encryption an decryption.
- Nomenclators were in use from the end of 14th century for 450 years.
- Nomenclators combined a substitution cryptosystem (in which symbols were replaced by numbers) with codebook ciphers in which words were replaced by numbers.
- At the beginning codebooks had codes only for names of people (therefore such a name - nomenclators), later codes were used also for names of places and so on.
- Some nomenclators had huge codebooks, up to 50 000 entries.
- Famous was the nomenclator designed by very famous French cryptologist Rosignol, for Ludvig XIV, that was not broken for several hundred of years.
- 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.