Part IV

Secret-key cryptosystems

CHAPTER 4: CLASSICAL (SECRET-KEY) CRYPTOSYSTEMS

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

CRYPTOLOGY, CRYPTOSYSTEMS - SECRET-KEY CRYPTOGRAPHY

Cryptology (= cryptography + cryptanalysis)
has more than two thousand years of history.

Basic historical observation

- People have always had fascination with keeping information away from others.
- Some people – rulers, diplomats, military people, businessmen – have always had needs to keep some information away from others.

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, . . .

Sound approaches to cryptography

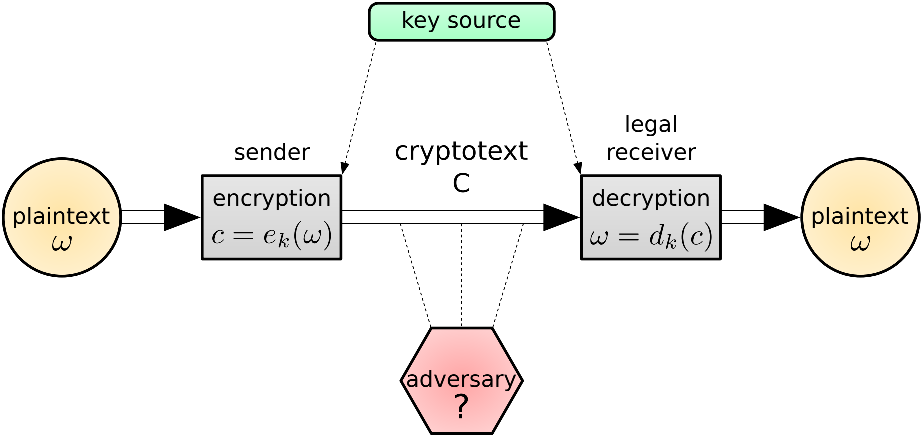
- Shannon's approach based on information theory (enemy could not have enough information to break a cryptosystem).
- Current approach based on complexity theory (enemy could not have enough computation power to break a cryptosystem).
- Very recent a new approach has been developed that is based on the laws and limitations of quantum physics (enemy would need to break laws of nature in order to break a cryptosystem).

Paradoxes of modern cryptography

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

CRYPTOSYSTEMS - CIPHERS

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



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

Each key $k \in K$ determines an **encryption algorithm e_k** and an **decryption algorithm d_k** such that, for any plaintext $w, e_k(w)$ is the corresponding cryptotext and

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

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

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

CAESAR can be used to encrypt words in any alphabet.

In order to encrypt words in English alphabet we use:

Key-space: $K = \{0, 1, \dots, 25\}$

For any key $k \in K$ an encryption algorithm e_k substitutes any letter by the letter occurring k positions ahead (cyclically) in the alphabet.

A decryption algorithm d_k substitutes any letter by the one occurring **k** positions backward (cyclically) in the alphabet.

CAESAR CRYPTOSYSTEM - SHIFT CIPHER II

Example $e_2(\text{EXAMPLE}) = \text{GZCORNG},$
$e_3(\text{EXAMPLE}) = \text{HADPSOH},$
$e_1(\text{HAL}) = \text{IBM},$
$e_3(\text{COLD}) = \text{FROG}$

ABCDEFGHIJKLMNOPQRSTUVWXYZ

Example Find the plaintext to the following cryptotext obtained by the encryption with CAESAR with $\mathbf{k} = ?$.

Cryptotext: **VHFUHW GH GHXA, VHFUHW GH GLHX, VHFUHW GH WURLV, VHFUHW GH WRXV.**

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

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

POLYBIOUS CRYPTOSYSTEM - I

It is cryptosystem developed by Polybious in 2nd century BC.

Polybious was a Greek soldier, historician and for 17 years a slave in Rome.

Romans were able to created powerful optical information communication networks that allowed them to deliver information and orders very fast along long distances and this way to control effciently huge teritory and made their armies flexible because they could deliver information and messages much faster than using horses.

It is expected that they already used Polybious crtosystem.

POLYBIOUS CRYPTOSYSTEM - II

can be used for encryption of words of the English alphabet without J.

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

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:

	F	G	H	I	J
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

KONIEC →BJCICHBIAJAH

Decryption algorithm: ???

KERCHHOFF's PRINCIPLE

The philosophy of modern cryptanalysis is embodied in the following principle formulated in 1883 by **Jean Guillaume Hubert Victor Francois Alexandre Auguste Kerckhoffs von Nieuwenhof** (1835 - 1903).

The security of a cryptosystem must not depend on keeping secret the encryption algorithm. The security should depend only on *keeping secret the key.*

BASIC REQUIREMENTS for GOOD CRYPTOSYSTEMS

(Sir Francis R. Bacon (1561 - 1626))

1. **Given e_k and a plaintext w, it should be easy to compute $c = e_k(w)$.**
2. Given d_k and a cryptotext c, it should be easy to compute $w = d_k(c)$.
3. A cryptotext $e_k(w)$ should not be much longer than the plaintext w.
4. It should be unfeasible to determine w from $e_k(w)$ without knowing d_k.
5. The so called **avalanche effect** should hold: A small change in the plaintext, or in the key, should lead to a big change in the cryptotext (i.e. a change of one bit of the plaintext should result in a change of all bits of the cryptotext, each with the probability close to 0.5).
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.**

CRYPTANALYSIS ATTACKS I

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

Main types of cryptanalytic attacks

1. **Cryptotexts-only attack.** The cryptanalysts get cryptotexts $c_1 = e_k(w_1), \ldots, c_n = e_k(w_n)$ and try to infer the key k or as many of the plaintexts $w_1, \ldots, w_n$ as possible.
2. **Known-plaintexts attack (given are some pairs [plaintext, cryptotext])** The cryptanalysts know some pairs $w_i, e_k(w_i), 1 \leq i \leq n$, and try to infer k, or at least w_{n+1} for a new cryptotext $e_k(w_{n+1})$.
3. **Chosen-plaintexts attack (given are cryptotext for some chosen plaintexts)** The cryptanalysts choose plaintexts $w_1, \ldots, w_n$ to get cryptotexts $e_k(w_1), \ldots, e_k(w_n)$, and try to infer k or at least w_{n+1} for a new cryptotext $c_{n+1} = e_k(w_{n+1})$. (For example, if they get temporary access to the encryption machinery.)

CRYPTANALYSIS ATTACKS II

4. **Known-encryption-algorithm attack**
   The encryption algorithm e_k is given and the cryptanalysts try to get the decryption algorithm d_k.

5. **Chosen-cryptotext attack (given are plaintexts for some chosen cryptotexts)**
   The cryptanalysts know some pairs

$$[c_i, d_k(c_i)], \quad 1 \leq i \leq n,$$

   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.)

WHAT CAN BAD EVE DO?

Let us assume that a clever Alice sends an encrypted message to Bob.
What can a bad enemy, called usually Eve (eavesdropper), do?

- Eve can read (and try to decrypt) the message.
- Eve can try to get the key that was used and then decrypt all messages encrypted with the same key.
- Eve can change the message sent by Alice into another message, in such a way that Bob will have the feeling, after he gets the changed message, that it was a message from Alice.
- Eve can pretend to be Alice and communicate with Bob, in such a way that Bob thinks he is communicating with Alice.

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

BASIC GOALS of BROADLY UNDERSTOOD CRYPTOGRAPHY

Confidentiality: Eve should not be able to decrypt the message Alice sends to Bob.

Data integrity: Bob wants to be sure that Alice's message has not been altered by Eve.

Authentication: Bob wants to be sure that only Alice could have sent the message he has received.

Non-repudiation: Alice should not be able to claim that she did not send messages that she has sent.

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

HILL CRYPTOSYSTEM I

The cryptosystem presented in this slide was probably never used.In spite of that this cryptosystem played an important role in the history of modern cryptography.

We describe Hill cryptosystem for a fixed n and the English alphabet.

Key-space: The set of all matrices M of degree n with elements from the set $\{0, 1, \ldots, 25\}$ such that $M^{-1} mod$ 26 exist.

Plaintext + cryptotext space: English words of length n.

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

Encryption: $c_c = Mc_w \bmod 26$

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

HILL CRYPTOSYSTEM - EXAMPLE

Example 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

$$M = \begin{bmatrix} 4 & 7 \\ 1 & 1 \end{bmatrix} \quad M^{-1} = \begin{bmatrix} 17 & 11 \\ 9 & 16 \end{bmatrix}$$

Plaintext: $w = \text{LONDON}$

$$w_{LO} = \begin{bmatrix} 11 \\ 14 \end{bmatrix}, \quad w_{ND} = \begin{bmatrix} 13 \\ 3 \end{bmatrix}, w_{ON} = \begin{bmatrix} 14 \\ 13 \end{bmatrix}$$

$$Mw_{LO} = \begin{bmatrix} 12 \\ 25 \end{bmatrix}, \quad Mw_{ND} = \begin{bmatrix} 21 \\ 16 \end{bmatrix}, Mw_{ON} = \begin{bmatrix} 17 \\ 1 \end{bmatrix}$$

Cryptotext: MZVQRB

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

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

Example: An **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

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

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

CRYPTANALYSIS

The basic cryptanalytic attack against monoalphabetic substitution cryptosystems begins with a frequency count: the number of each letter in the cryptotext is counted. **The distributions of letters in the cryptotext is then compared with some official distribution of letters in the plaintext language.**

The letter with the highest frequency in the cryptotext is likely to be substitute for the letter with highest frequency in the plaintext language . . . . The likelihood grows with the length of cryptotext.

Frequency counts in English:

	%		%		%
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

and for other languages:

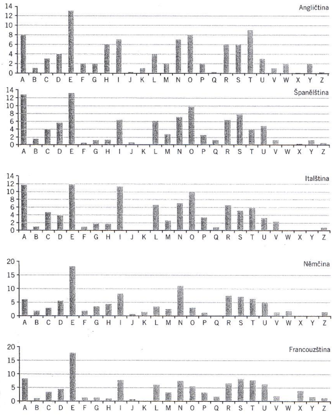
English	%	German	%	Finnish	%	French	%	Italian	%	Spanish	%
E	12.31	E	18.46	A	12.06	E	15.87	E	11.79	E	13.15
T	9.59	N	11.42	I	10.59	A	9.42	A	11.74	A	12.69
A	8.05	I	8.02	T	9.76	I	8.41	I	11.28	O	9.49
O	7.94	R	7.14	N	8.64	S	7.90	O	9.83	S	7.60
N	7.19	S	7.04	E	8.11	T	7.29	N	6.88	N	6.95
I	7.18	A	5.38	S	7.83	N	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

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 SEVRAL LANGUAGES

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

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**

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: $12 \times 26 = 312$.)

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:

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	

How to find the plaintext?

CRYPTANALYSIS - CONTINUATION I

Frequency analysis of plainext 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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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: $xa + b = y$

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

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

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

```
BHJUH NBULS VULRU SLYXH
ONUUN BWNUA XUSNL UYJSS
WXRLK GNBON UUNBW SWXKX
HKXDH UZDLK XBHJU HBNUO
NUMHU GSWHU XMBXR WXKXL
UXBHJ UHCXK XAXKZ SWKXX
LKOLJ KCXLC MXONU UBVUL
RRWHS HBHJU HNBXM BXRWX
KXNOZ LJBXX HBNFU BHJUH
LUSWX GLLKZ LJPHU ULSYX
BJKXS WHSSW XKXNB HBHJU
HYXWN UGSWX GLLK
```

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

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

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

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

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	

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:

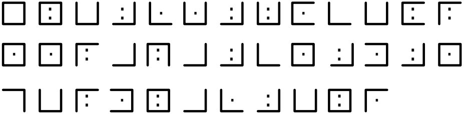
J·	K·	L·
M·	N·	O·
P·	Q·	R·

S	T	U
V	W	X
Y	Z	

For example the plaintext:

WE TALK ABOUT FINNISH SAUNA MANY TIMES LATER

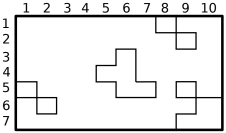
results in the cryptotext:



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



HOMOPHONIC CRYPTOSYSTEMS

Homophonic cryptosystems are natural generalization of monoalphabetic cryptosystems.

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.

Playfair cryptosystem

Invented around 1854 by Ch. Wheatstone.

Key – a Playfair square is defined by a word w of length at most 25. In w repeated letters are then removed, remaining letters of alphabets (except j) are then added and resulting word is divided to form an 5 x 5 array (a Playfair square).

Encryption: of a pair of letters x, y

1. If x and y are in the same row (column), then they are replaced by the pair of symbols to the right (bellow) them.
2. If x and y are in different rows and columns they are replaced by symbols in the opposite corners of rectangle created by x and y - the order is important and needs to be agreed on.

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

Several of the following polyalphabetic cryptosystems are modification of the CAESAR cryptosystem.

Design of cryptosystem: **First step**: A 26×26 table is first designed with the first row containing a permutation of all symbols of alphabet and all columns represent CAESAR shifts starting with the symbol of the first row.

Second step: For a plaintext w a key k is a word of the same length as w.

Encryption: the *i-th* letter of the plaintext - w_i - is encrypted by the letter from the w_i-row and k_i-column of the table.

VIGENERE cryptosystem is actually a cyclic, key driven, version of the CAESAR cryptosystem.

IMPORTANT EXAMPLES

VIGENERE-key cryptosystem: a short keyword p is chosen and periodically repeated to form the key to be used

$$k = Prefix_{|w|} p^{oo}$$

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

$$k = Prefix_{|w|} pw$$

VIGENERE and AUTOCLAVE cryptosystems

Example:

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

HISTORICAL COMMENT

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

CRYPTANALYSIS of cryptotexts produced by VIGENERE-key cryptosystems

1. Task 1 – to find the length of the keyword

Kasiski's (Prussian officier) method (published in 1862) - invented also by Charles Babbage (1853 - unpublished).

Basic observation: **If a subword of a plaintext is repeated at a distance that is a multiple of the length of the keyword, then the corresponding subwords of the cryptotext are the same.**

Example, cryptotext:

CHRGQPWOEIRULYANDOSHCHRIZKEBUSNOFKYWROPDCHRKGAXBNRHROAKERBKSCHRIWK

Substring "CHR" occurs in positions 1, 21, 41, 66: expected keyword length is therefore 5.

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

BREAKING VIGENER CRYPTOSYSTEM

Kasiski method and the index of coincidence can be used in the following way to break a VIGENERE cryptosystem - basic algorithm.

for all guesses of the length m of the key
(obtained using Kasiski method) **do**
    write cryptotext in an array with m columns - row by row;
    check if index of coincidence of each column is high;
    if yes you have the length of key;

to decode columns use decoding method for Caesar

FRIEDMAN METHOD to DETERMINE KEY LENGTH

Friedman method to determine the key length: Let n_i be the number of occurrences of the **i**-*th* letter in the cryptotext.

Let **L** be the length of the keyword.

Let **n** be the length of the cryptotext.

Then it holds, as shown on next slide:

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

Once the length of the keyword is found it is easy to determine the key using the statistical (frequency analysis) method of analyzing monoalphabetic cryptosystems.

DERIVATION of the FRIEDMAN METHOD I

1. Let n_i be the number of occurrences of i-th alphabet symbol in a text of length n. The probability that if one selects a pair of symbols from the text, then they are the same is

$$I = \frac{\sum_{i=1}^{26} n_i(n_i-1)}{n(n-1)} = \sum_{i=1}^{26} \frac{\binom{n_i}{2}}{\binom{n}{2}}$$

and it is called the index of coincidence.

2. Let p_i be the probability that a randomly chosen symbol is the i-th symbol of the alphabet. The probability that two randomly chosen symbols are the same is

$$\sum_{i=1}^{26} p_i^2$$

For English text one has

$$\sum_{i=1}^{26} p_i^2 = 0.065$$

For randomly chosen text:

$$\sum_{i=1}^{26} p_i^2 = \sum_{i=1}^{26} \frac{1}{26^2} = 0.038$$

Approximately

$$I = \sum_{i=1}^{26} p_i^2$$

DERIVATION of the FRIEDMAN METHOD Ii

Assume that a cryptotext is organized into l columns headed by the letters of the keyword

letters S_l	S_1	S_2	S_3	$\dots$	S_l
	x_1	x_2	x_3	$\dots$	x_l
	x_{l+1}	x_{l+2}	x_{l+3}		x_{2l}
	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: $\frac{l}{2} \cdot \frac{n}{l}(\frac{n}{l} - 1) = \frac{n(n-l)}{2l}$

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 **I** one of the previous slides.

ONE-TIME PAD CRYPTOSYSTEM – Vernam's cipher

Binary case: $\left.\begin{array}{ll}\text{plaintext} & w\\ \text{key} & k\\ \text{cryptotext} & c\end{array}\right\}$ are all binary words of the same length

Encryption: $c = w \oplus k$

Decryption: $w = c \oplus k$

Example:

$$w = 101101011$$
$$k = 011011010$$
$$c = 110110001$$

What happens if the same key is used twice or 3 times for encryption?

$$\text{If } \; c_1 = w_1 \oplus k, c_2 = w_2 \oplus k, c_3 = w_3 \oplus k$$

then

$$c_1 \oplus c_2 = w_1 \oplus w_2$$
$$c_1 \oplus c_3 = w_1 \oplus w_3$$
$$c_2 \oplus c_3 = w_2 \oplus w_3$$

Therefore if plaintexts w_1, w_2, w_3 are texts in a natural language, then the last three equalities allow often, from the knowledge of cryptotexts, to recover plaintexts - by exploiting a natural language redundancy.

PERFECT SECRET-KEY CRYPTOSYSTEMS

By Shannon, a cryptosystem is perfect if the knowledge of the cryptotext provides no information whatsoever about its plaintext (with the exception of its length).

It follows from Shannon's results that perfect secrecy is possible if the key-space is as large as the plaintext-space. In addition, a key has to be as long as plaintext and the same key should not be used twice.

An example of a perfect cryptosystem ONE-TIME PAD cryptosystem (Gilbert S. Vernam (1917) - AT&T + Major Joseph Mauborgne).

If used with the English alphabet, it is simply a polyalphabetic substitution cryptosystem of VIGENERE type with the key being a randomly chosen English word of the same length as the plaintext.

Proof of perfect secrecy: by the proper choice of the key any plaintext of the same length could provide the given cryptotext.

PERFECT SECRECY of ONE-TIME PAD

One-time pad cryptosystem is **perfectly secure** because

For any cryptotext

$$c = c_1 c_2 \dots c_n$$

and any plainetext

$$p = p_1 p_2 \dots p_n$$

there exists a key (and all keys were chosen with the same probability)

$$k = k_1 k_2 \dots k_n$$

such that

$$c = p \oplus k$$

Did we gain something? The problem of secure communication of the plaintext got transformed to the problem of secure communication of the key of the same length.

Yes:

1. ONE-TIME PAD cryptosystem is used in critical applications
2. It suggests an idea how to construct practically secure cryptosystems.

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

every element p of the set of plaintexts has the same probability

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

GENERAL FORM of POLYALPHABETIC CRYPTOSYSTEMS

A general form of polyalphabetic cryptosystems over an alphabet Σ is given by:

Set of keys K is formed by all sequences $(p_1, p_2, \ldots, p_t)$ where each p_i is is a permutation on Σ.

Encoding of a message $m = (m_1 m_2 \ldots m_t)$ by a key $(p_1, p_2, \ldots, p_t)$ is the message $(p_1(m_1)p_2(m_2) \ldots p_t(m_t))$.

Decoding is done with the key $(p_1^{-1} p_2^{-1} \ldots p_m^{-1})$.

TRANSPOSITION CRYPTOSYSTEMS

The basic idea is very simple: permute the plaintext to get the cryptotext. Less clear it is how to specify and perform efficiently permutations.

One idea: choose n, write plaintext into rows, with n symbols in each row and then read it by columns to get cryptotext.

Example

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	E	S	C	H	I	C
H	T	E	T	O	J	E	O	N	O

Cryptotexts obtained by transpositions, called anagrams, were popular among scientists of 17th century. They were used also to encrypt scientific findings.

Newton wrote to Leibniz

$$a^7c^2d^2e^{14}f^2i^7l^3m^1n^8o^4q^3r^2s^4t^8v^{12}x^1$$

what stands for: "data aequatione quodcumque fluentes quantitates involvente, fluxiones invenire et vice versa"

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

Solution: ??

KEYWORD CAESAR CRYPTOSYSTEM

This will be an example showing that cryptoanalysis often require qualified guessing. **Keyword Caesar cryptosystem** is given by choosing an integer $0 < k < 25$ and a string, called keyword, of length at most 25 with all letters different.

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.

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		Number		Number
U	32	X	8	W	3
C	31	K	7	Y	2
Q	23	N	7	G	1
F	22	E	6	H	1
V	20	M	6	J	0
P	15	R	6	L	0
T	15	B	5	O	0
I	14	Z	5	S	0
A	8	D	4		
	180=74.69%		54=22.41%		7=2.90%

Step 2. Cryptotext contains two one-letter words T and Q.They must be A and I. Since T occurs once and Q three times it is likely that T is I and Q is A.

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 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

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 $k = 4$ - find out hpw

UNICITY DISTANCE of CRYPTOSYSTEMS

Redundancy of natural languages is of the key importance for cryptanalysis.

Would all letters of a 26-symbol alphabet have the same probability, a character would carry $\lg 26 = 4.7$ bits of Information.

The estimated average amount of information carried per letter in a meaningful English text is 1.5 bits.

The unicity distance of a cryptosystem is the minimum length of the cryptotext required by a computationally unlimited adversary to recover the unique encryption key.

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

ANAGRAMS – EXAMPLES

German:

IRI BRÄTER, GENF	Briefträgerin
FRANK PEKL, REGEN	...
PEER ASSSTIL, MELK	...
INGO DILMR, PEINE	...
EMIL REST, GERA	...
KARL SORDORT, PEINE	...

English:

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

APPENDIX I

STREAMS CRYPTOSYSTEMS

Two basic types of cryptosystems are:

- Block cryptosystems (Hill cryptosystem,...) – they are used to encrypt simultaneously blocks of plaintext.
- Stream cryptosystems (CAESAR, ONE-TIME PAD,...) – they encrypt plaintext letter by letter, or block by block, using an encryption that may vary during the encryption process.

Stream cryptosystems are more appropriate in some applications (telecommunication), usually are simpler to implement (also in hardware), usually are faster and usually have no error propagation (what is of importance when transmission errors are highly probable).

Two basic types of stream cryptosystems: secret key cryptosystems (ONE-TIME PAD) and public-key cryptosystems (Blum-Goldwasser)

BLOCK versus STREAM CRYPTOSYSTEMS

In **block cryptosystems** the same key is used to encrypt arbitrarily long plaintext – block by block - (after dividing each long plaintext w into a sequence of subplaintexts (blocks) $w_1 w_2 w_3$).

In stream cryptosystems different blocks may be encrypted using different keys

- The fixed key k is used to encrypt all blocks. In such a case the resulting cryptotext has the form

$$c = c_1 c_2 c_3 \ldots = e_k(w_1) e_k(w_2) e_k(w_3) \ldots$$

- A stream of keys is used to encrypt subplaintexts. The basic idea is to generate a key-stream $K = k_1, k_2, k_3, \ldots$ and then to compute the cryptotext as follows

$$c = c_1 c_2 c_3 \ldots = e_{k1}(w_1) e_{k2}(w_2) e_{k3}(w_3).$$

CRYPTOSYSTEMS WITH STREAMS OF KEYS

Various techniques are used to compute a sequence of keys. For example, given a key k

$$k_i = f_i(k, k_1, k_2, \ldots, k_{i-1})$$

In such a case encryption and decryption processes generate the following sequences:

Encryption: To encrypt the plaintext $w_1 w_2 w_3 \ldots$ the sequence

$$k_1, c_1, k_2, c_2, k_3, c_3, \ldots$$

of keys and sub-cryptotexts is computed.

Decryption: To decrypt the cryptotext $c_1 c_2 c_3 \ldots$ the sequence

$$k_1, w_1, k_2, w_2, k_3, w_3, \ldots$$

of keys and subplaintexts is computed.

EXAMPLES

A keystream is called synchronous if it is independent of the plaintext.

KEYWORD VIGENERE cryptosystem can be seen as an example of a synchronous keystream cryptosystem.

Another type of the binary keystream cryptosystem is specified by an initial sequence of keys $k_1, k_2, k_3 \dots k_m$

and an initial sequence of binary constants $b_1, b_2, b_3 \dots b_{m-1}$

and the remaining keys are computed using the rule

$$k_{i+m} = \sum_{j=0}^{m-1} b_j k_{i+j} \bmod 2$$

A keystream is called periodic with period p if $k_{i+p} = k_i$ for all i.

Example Let the keystream be generated by the rule

$$k_{i+4} = k_i \oplus k_{i+1}$$

If the initial sequence of keys is (1,0,0,0), then we get the following keystream:

$$1,0,0,0,1,0,0,1,1,0,1,0\ 1,1,1,\ \dots$$

of period 15.

PERFECT SECRECY - BASIC CONCEPTS

Let **P, K** and **C** be sets of plaintexts, keys and cryptotexts.
Let $p_K(k)$ be the probability that the key k is chosen from **K** and let a priory probability that plaintext w is chosen be $p_p(w)$.
If for a key $k \in K, C(k) = \{e_k(w) | w \in P\}$, then for the probability $P_C(y)$ that c is the cryptotext that is transmitted it holds

$$p_c(c) = \sum_{\{k|c \in C(k)\}} p_K(k) p_P(d_k(c)).$$

For the conditional probability $p_c(c|w)$ that c is the cryptotext if w is the plaintext it holds

$$p_c(c|w) = \sum_{\{k|w=d_k(c)\}} p_K(k).$$

Using Bayes' conditional probability formula $p(y)p(x|y) = p(x)p(y|x)$ we get for probability $p_P(w|c)$ that w is the plaintext if c is the cryptotext the expression

$$p_P = \frac{P_P(w) \sum_{\{k|w=d_k(c)\}} p_K(k)}{\sum_{\{k|c \in C(K)\}} p_K(k) p_P(d_K(c))}.$$

PERFECT SECRECY - BASIC RESULTS

Definition A cryptosystem has perfect secrecy if

$$p_P(w|c) = p_P(w) \text{ for all } w \in P \text{ and } c \in C.$$

(That is, the a posterior probability that the plaintext is w,given that the cryptotext is c is obtained, is the same as a priory probability that the plaintext is w.)

Example CAESAR cryptosystem has perfect secrecy if any of the 26 keys is used with the same probability to encode any symbol of the plaintext.

Proof Exercise.

An analysis of perfect secrecy: The condition $p_P(w|c) = p_P(w)$ is for all $w \in P$ and $c \in C$ equivalent to the condition $p_C(c|w) = p_C(c)$.

Let us now assume that $p_C(c) > 0$ for all $c \in C$.

Fix $w \in P$. For each $c \in C$ we have $p_C(c|w) = p_C(c) > 0$. Hence, for each $c \in C$ there must exist at least one key k such that $e_k(w) = c$. Consequently, $|K| \geq |C| \geq |P|$.

In a special case $|K| = |C| = |P|$, the following nice characterization of the perfect secrecy can be obtained:

Theorem A cryptosystem in which $|P| = |K| = |C|$ provides perfect secrecy if and only if every key is used with the same probability and for every $w \in P$ and every $c \in C$ there is a unique key k such that $e_k(w) = c$.

Proof Exercise.

APPENDIX II

CAESAR UPDATED

- It is common to assume that English alphabet has 26 letters when CAESAR cryptosystems is described.
- This is misleading because at CAESAR time the alphabet had only 21 symbols.
  - Letters "X" and "Z" were foreign characters, used in order to transcript Greek words;
  - Letters "I" and "J" were the same one – "I".
  - Letters "U" and "V" were also the same – "V"
  - Letter "W" did not exist.
- CAESAR cryptosystem is a special case of the AFFINE cryptosystem.

CRYPTOGRAPHY as a WAR WEAPON

- After great success of cryptography in second World war, cryptography products were considered as war weapons and regulated as such.
- Import-export organisations, salesmen, developers, researchers and publishers were controlled by government agencies in many countries.
- Switzerland was one of the only cryptographic paradise when one could freely set up mirror companies for cryptographic products