Different Kind of Ciphers

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Classical Ciphers

- Plaintext is viewed as a sequence of elements (e.g., bits or characters)
- Substitution cipher: replacing each element of the plaintext with another element.
- Transposition (or permutation) cipher: rearranging the order of the elements of the plaintext.
- Product cipher: using multiple stages of substitutions and transpositions

Caesar Cipher

- Earliest known substitution cipher
- Invented by Julius Caesar
- Each letter is replaced by the letter three positions further down the alphabet.
- Plain: 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

  Cipher: 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
- Example: ohio state → RKLR VWDWH

Caesar Cipher

- Mathematically, map letters to numbers:

  a, b, c, ..., x, y, z

  0, 1, 2, ..., 23, 24, 25

- Then the general Caesar cipher is:

  $c = \mathrm{E}_K(p) = (p + k) \bmod 26$

  $p = \mathrm{D}_K(c) = (c - k) \bmod 26$

- Can be generalized with any alphabet.

Cryptanalysis of Caesar Cipher

- Key space: {0, 1, ..., 25}
- Vulnerable to brute-force attacks.
- E.g., break ciphertext "UNOU YZGZK“
- Need to recognize it when have the plaintext
- What if the plaintext is written in Swahili?

Monoalphabetic Substitution Cipher

- Shuffle the letters and map each plaintext letter to a different random ciphertext letter:

Plain letters: abcdefghijklmnopqrstuvwxyz

Cipher letters:
DKVQFIBJWPESCXHTMYAUOLRGZN

Plaintext: ifwewishtoreplaceletters

Ciphertext: WIRFRWAJUHYFTSDVFSFUUFYA

- What does a key look like?

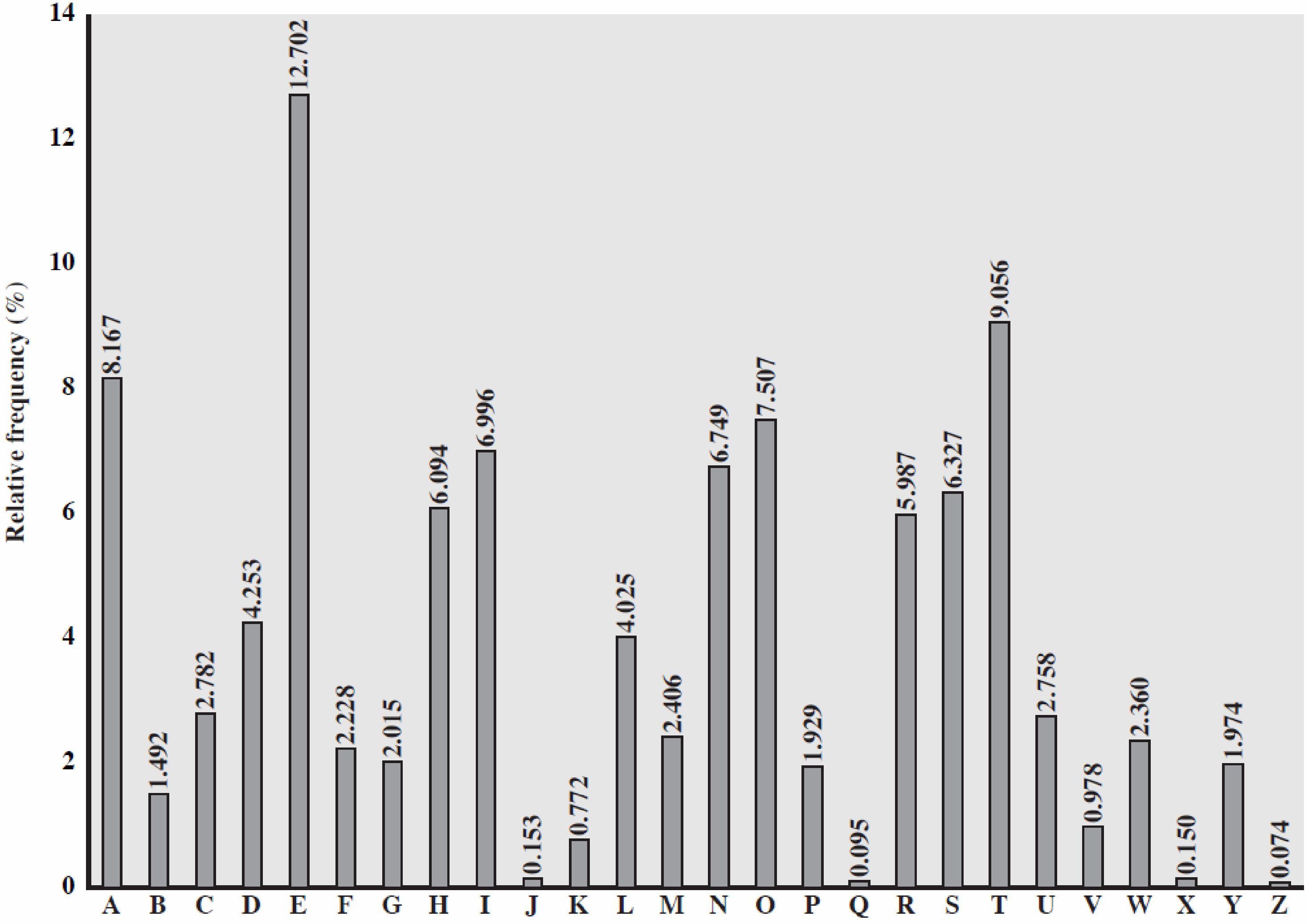
Monoalphabetic Cipher Security

- Now we have a total of 26! = 4 x 10^{26} keys.
- With so many keys, it is secure against brute-force attacks.
- But not secure against some cryptanalytic attacks.
- Problem is language characteristics.

Language Statistics and Cryptanalysis

- Human languages are not random.
- Letters are not equally frequently used.
- In English, E is by far the most common letter, followed by T, R, N, I, O, A, S.
- Other letters like Z, J, K, Q, X are fairly rare.
- There are tables of single, double & triple letter frequencies for various languages

English Letter Frequencies



Statistics for double & triple letters

- In decreasing order of frequency
- Double letters:

  th he an in er re es on, …
- Triple letters:

  the and ent ion tio for nde, …

Use in Cryptanalysis

- Key concept: monoalphabetic substitution does not change relative letter frequencies

- To attack, we
  - calculate letter frequencies for ciphertext
  - compare this distribution against the known one

Example Cryptanalysis

- Given ciphertext:

  UZQSOVUOHXMOPVGPOZPEVSGZWSZOPFPESXUDBMETSXAIZ

  VUEPHZHMDZSHZOWSFPAPPDTSVPQUZWYMXUZUHSX

  EPYEPOPDZSZUFPOMBZWPFUPZHMDJUDTMOHMQ

- Count relative letter frequencies (see next page)
- Guess {P, Z} = {e, t}
- Of double letters, ZW has highest frequency, so guess ZW = th and hence ZWP = the
- Proceeding with trial and error finally get:

  it was disclosed yesterday that several informal but
  direct contacts have been made with political
  representatives of the viet cong in moscow

Letter frequencies in ciphertext

P 13.33	H 5.83	F 3.33	B 1.67	C 0.00
Z 11.67	D 5.00	W 3.33	G 1.67	K 0.00
S 8.33	E 5.00	Q 2.50	Y 1.67	L 0.00
U 8.33	V 4.17	T 2.50	I 0.83	N 0.00
O 7.50	X 4.17	A 1.67	J 0.83	R 0.00
M 6.67				

Playfair Cipher

- Not even the large number of keys in a monoalphabetic cipher provides security.
- One approach to improving security is to encrypt multiple letters at a time.
- The **Playfair Cipher** is the best known such cipher.
- Invented by Charles Wheatstone in 1854, but named after his friend Baron Playfair.

Playfair Key Matrix

- Use a 5 x 5 matrix.
- Fill in letters of the key (w/o duplicates).
- Fill the rest of matrix with other letters.
- E.g., key = MONARCHY.

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

Encrypting and Decrypting

Plaintext is encrypted two letters at a time.

1. If a pair is a repeated letter, insert filler like 'X'.

   BALLOON→ BA LX LO ON

1. If both letters fall in the same row, replace each with the letter to its right (circularly). AR→RM
2. If both letters fall in the same column, replace each with the letter below it (circularly). MU→CM
3. Otherwise, each the letter is replaced by the letter in the same row but in the column of the other letter of the pair. HS→BP & EA→IM (or JM)

Security of Playfair Cipher

- Equivalent to a monoalphabetic cipher with an alphabet of 26 x 26 = 676 characters.
- Security is much improved over the simple monoalphabetic cipher.
- Was widely used for many decades
  - eg. by US & British military in WW1 and early WW2
- Once thought to be unbreakable.
- Actually, it **can** be broken, because it still leaves some structure of plaintext intact.

Hill Cipher

- Takes two or three or more letter combinations to the same size combinations, e.g. “the” → “rqv”
- Uses simple linear equations
- An example of a “block” cipher encrypting a block of text at a time
- Numbered alphabet: a = 0, b = 1, c = 3, etc.
  (in CAP, use ASCII code)

Example

```
C1 =  9*p1 + 18*p2 + 10*p3 (mod 26)
C2 = 16*p1 + 21*p2 +  1*p3 (mod 26)
C3 =  5*p1 + 12*p2 + 23*p3 (mod 26)
```

$$\begin{pmatrix} C1 \\ C2 \\ C3 \end{pmatrix} = \begin{pmatrix} 9 & 18 & 10 \\ 16 & 21 & 1 \\ 5 & 12 & 23 \end{pmatrix} \begin{pmatrix} p1 \\ p2 \\ p3 \end{pmatrix} \pmod{26}$$

I can’t do it → EOM TMY SVJ

8 2 0 13 19 3 14 8 19

$$\begin{pmatrix} 4 \\ 14 \\ 12 \end{pmatrix} = \begin{pmatrix} 9 & 18 & 10 \\ 16 & 21 & 1 \\ 5 & 12 & 23 \end{pmatrix} \begin{pmatrix} 8 \\ 2 \\ 0 \end{pmatrix} \pmod{26}$$

$$\begin{pmatrix} 19 \\ 12 \\ 14 \end{pmatrix} = \begin{pmatrix} 9 & 18 & 10 \\ 16 & 21 & 1 \\ 5 & 12 & 23 \end{pmatrix} \begin{pmatrix} 13 \\ 19 \\ 3 \end{pmatrix} \pmod{26}$$

$$\begin{pmatrix} 18 \\ 21 \\ 9 \end{pmatrix} = \begin{pmatrix} 9 & 18 & 10 \\ 16 & 21 & 1 \\ 5 & 12 & 23 \end{pmatrix} \begin{pmatrix} 14 \\ 8 \\ 19 \end{pmatrix} \pmod{26}$$

Hill – key is matrix

$$\begin{pmatrix} \mathbf{k11} & \mathbf{k12} & \mathbf{k13} \\ \mathbf{k21} & \mathbf{k22} & \mathbf{k23} \\ \mathbf{k31} & \mathbf{k32} & \mathbf{k33} \end{pmatrix}$$

Generalize to any size, larger blocks

Matrix must be invertible

Polyalphabetic Substitution Ciphers

- A sequence of monoalphabetic ciphers (M_1, M_2, M_3, ..., M_k) is used in turn to encrypt letters.
- A key determines which sequence of ciphers to use.
- Each plaintext letter has multiple corresponding ciphertext letters.
- This makes cryptanalysis harder since the letter frequency distribution will be flatter.

Vigenère Cipher

- Simplest polyalphabetic substitution cipher
- Consider the set of all Caesar ciphers:

$$\{ C_a, C_b, C_c, \ldots, C_z \}$$

- Key: e.g. security
- Encrypt each letter using C_s, C_e, C_c, C_u, C_r, C_i, C_t, C_y in turn.
- Repeat from start after C_y.
- Decryption simply works in reverse.

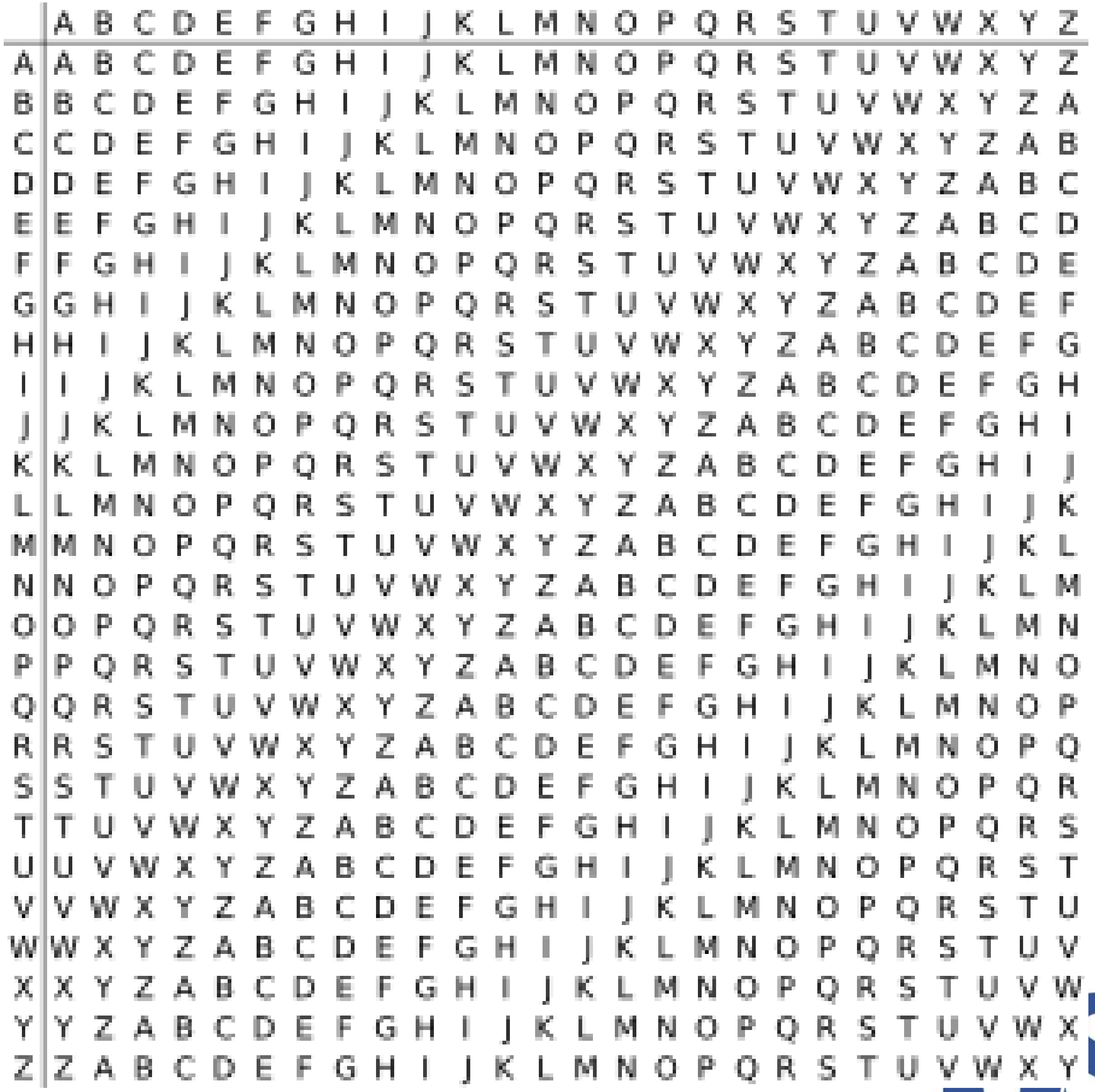
Example of Vigenère Cipher

- Keyword: *deceptive*

key: deceptivedeceptivedeceptive

plaintext: wearediscoveredsaveyourself

ciphertext: ZICVTWQNGRZGVTWAVZHCQYGLMGJ



	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
A	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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

Security of Vigenère Ciphers

- There are multiple (how many?) ciphertext letters corresponding to each plaintext letter.
- So, letter frequencies are obscured but not totally lost.
- To break Vigenere cipher:
  1. Try to guess the key length. How?
  2. If key length is N, the cipher consists of N Caesar ciphers. Plaintext letters at positions k, N+k, 2N+k, 3N+k, etc., are encoded by the same cipher.
  3. Attack each individual cipher as before.

Guessing the Key Length

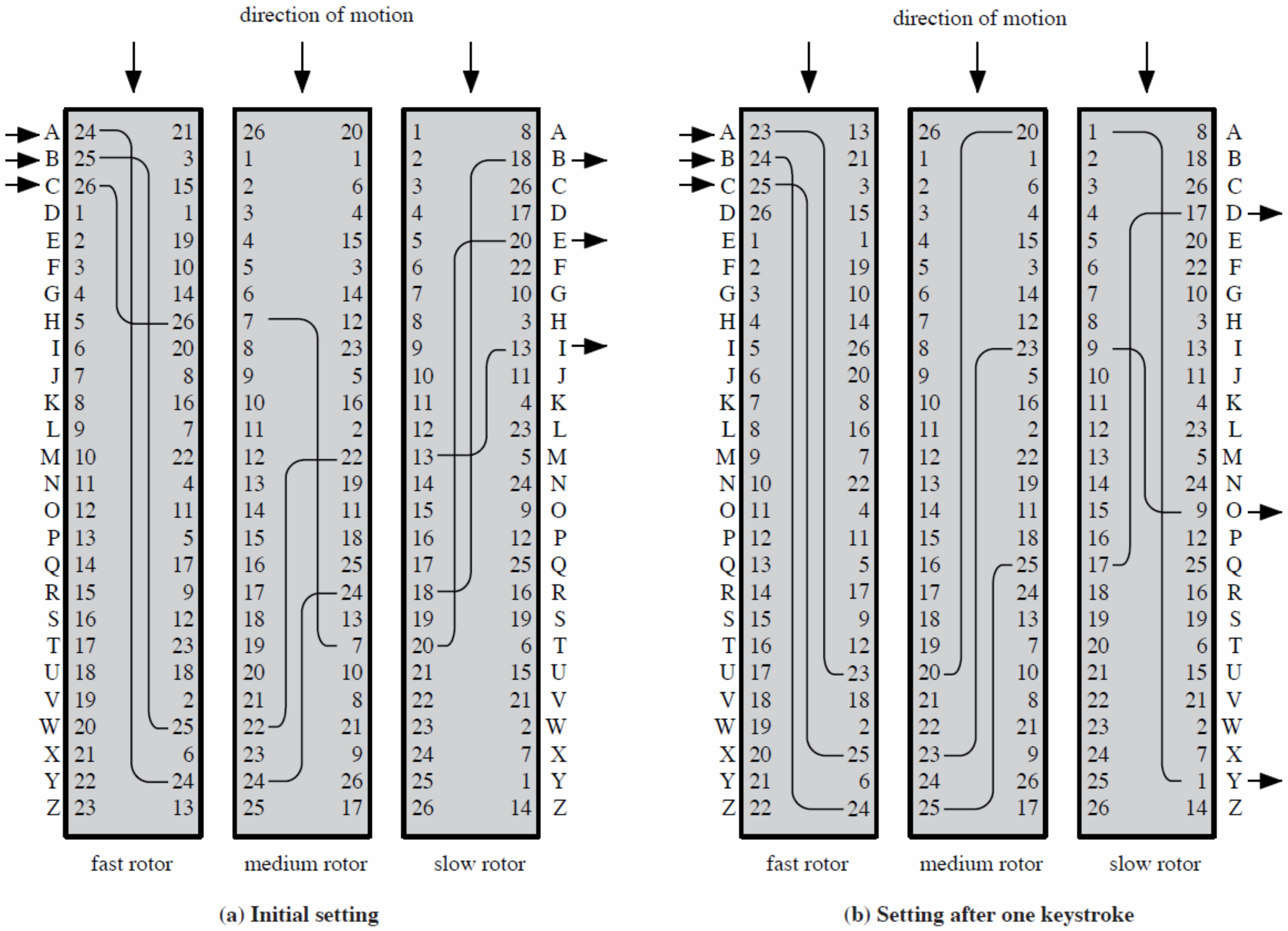
- Main idea: Plaintext words separated by multiples of the key length are encoded in the same way.
- In our example, if plaintext = "…thexxxxxxthe…" then "the" will be encrypted to the same ciphertext words.
- So look at the ciphertext for repeated patterns.
- E.g. repeated "VTW" in the previous example suggests a key length of 3 or 9:

  ciphertext: ZICVTWQNGRZGVTWAVZHCQYGLMGJ

- Of course, the repetition could be a random fluke.

Rotor Cipher Machines

- Before modern ciphers, rotor machines were most common complex ciphers in use.
- Widely used in WW2.
- Used a series of rotating cylinders.
- Implemented a polyalphabetic substitution cipher of period K.
- With 3 cylinders, $K = 26^3 = 17,576$.
- With 5 cylinders, $K = 26^5 = 12 \times 10^6$.
- What is a key?
  - If the adversary has a machine
  - If the adversary doesn't have a machine

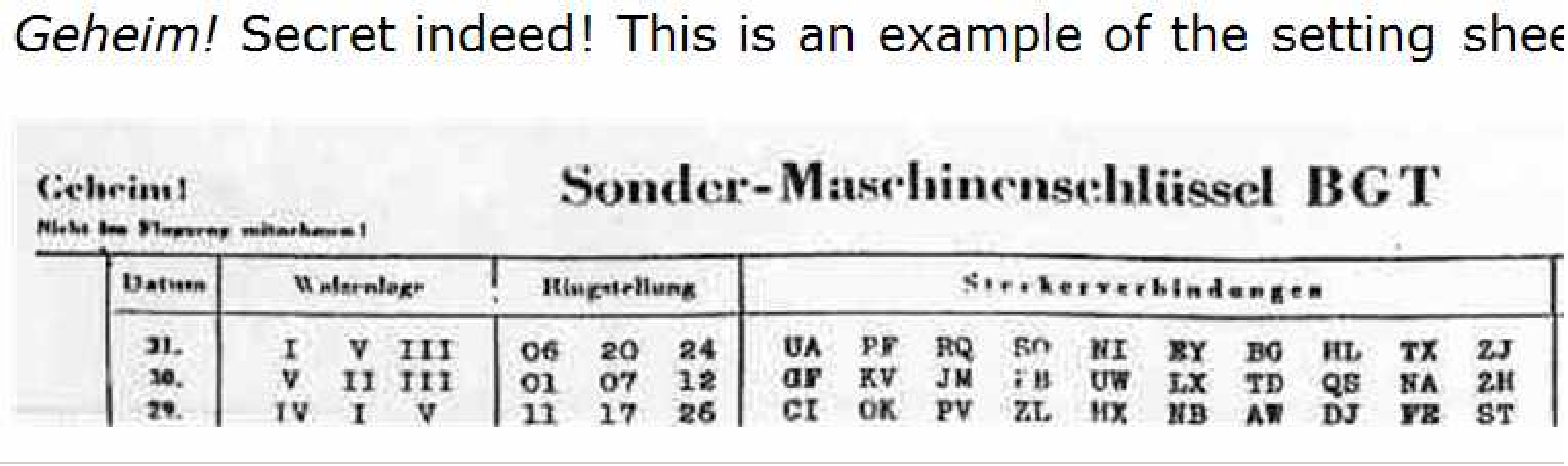


(a) Initial setting

(b) Setting after one keystroke

Figure 2.7 Three-Rotor Machine With Wiring Represented by Numbered Contacts

German secret setting sheets



Geheim! Secret indeed! This is an example of the setting shee

Geheim!

Nicht im Flugzeug mitnehmen!

Sonder-Maschinenschlüssel BGT

Datum	Walzenlage			Ringstellung			Steckerverbindungen									
31.	I	V	III	06	20	24	UA	PF	RQ	SO	NI	EY	BG	HL	TX	ZJ
30.	V	II	III	01	07	12	GF	KV	JM	[illegible]	UW	LX	TD	QS	NA	ZH
29.	IV	I	V	11	17	26	CI	OK	PV	ZL	MX	NB	AW	DJ	FE	ST

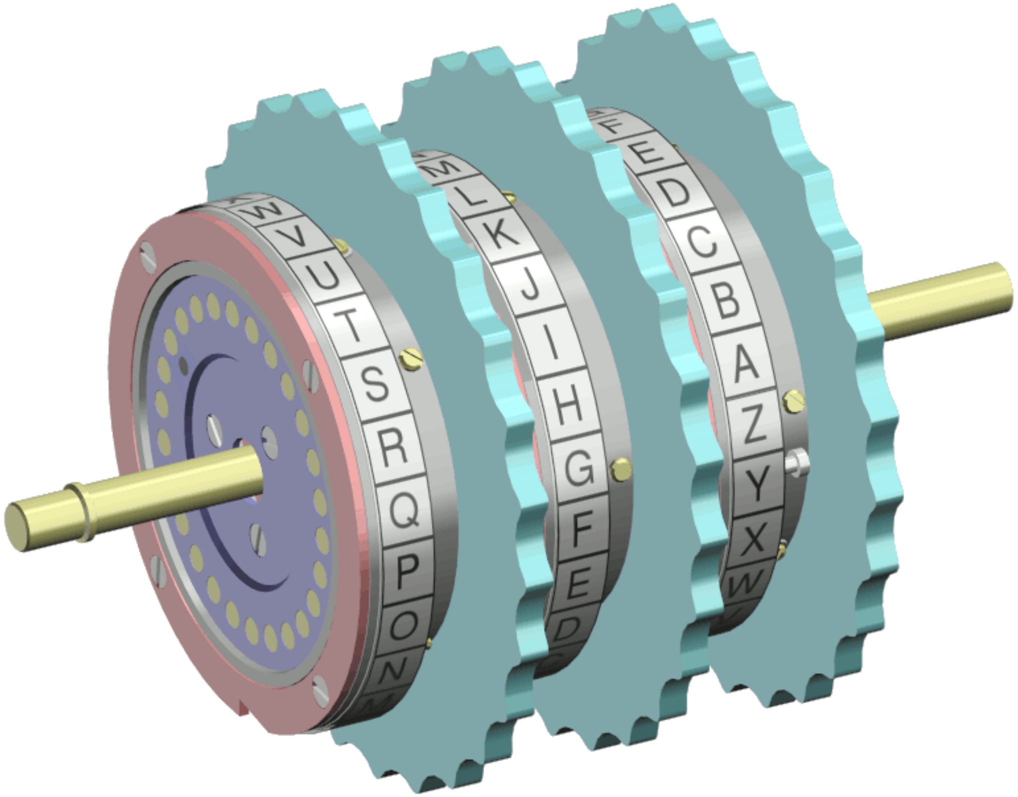
Date

Which rotors to use (there were 10 rotors)

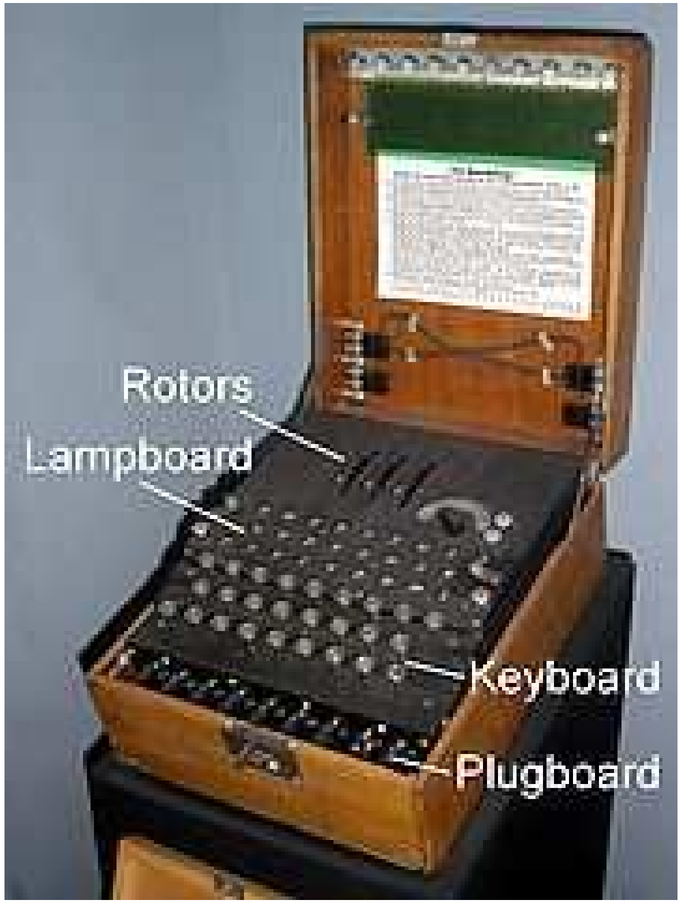
Ring setting

Plugboard setting

The Rotors



Enigma Rotor Machine



Enigma Rotor Machine

Transposition Ciphers

- Also called **permutation** ciphers.
- Shuffle the plaintext, without altering the actual letters used.
- Example: Row Transposition Ciphers

Row Transposition Ciphers

- Plaintext is written row by row in a rectangle.

- Ciphertext: write out the columns in an order specified by a key.

Key: 3 4 2 1 5 6 7

a	t	t	a	c	k	p
o	s	t	p	o	n	e
d	u	n	t	i	l	t
w	o	a	m	x	y	z

Product Ciphers

- Uses a sequence of substitutions and transpositions
  - Harder to break than just substitutions or transpositions
- This is a bridge from classical to modern ciphers.

Unconditional & Computational Security

- A cipher is unconditionally secure if it is secure no matter how much resources (time, space) the attacker has.
- A cipher is computationally secure if the best algorithm for breaking it will require so much resources (e.g., 1000 years) that practically the cryptosystem is secure.
- All the ciphers we have examined are not unconditionally secure.

An unconditionally Secure Cipher

Vernam's one-time pad cipher

- Key = $k_1k_2k_3k_4\mathrm{K}$ (random, used one-time only)
- Plaintext = $m_1m_2m_3m_4\mathrm{K}$
- Ciphertext = $c_1c_2c_3c_4\mathrm{K}$

  where $c_i = m_i \oplus k_i$
- Can be proved to be unconditionally secure.

One-time Pad

- Use a random key as long as the message. Must not reuse the key sequence ever again.

- Both parties must have key sequence

- Hotline between USA and USSR was rumoured to use a one-time pad.

- Destroy key sequence after use

- **EXAMPLE**

  Key is number of places to shift letter

  ```
  K    321424
  P    launch
       ------
  C    OCVREL
  ```

- Suggest a good 1-time pad function for binary data?

Steganography

- Hide a message in another message.

- E.g., hide your plaintext in a graphic image
  - Each pixel has 3 bytes specifying the RGB color
  - The least significant bits of pixels can be changed w/o greatly affecting the image quality
  - So can hide messages in these LSBs

- Advantage: hiding existence of messages

- Drawback: high overhead