Caesar cipher

An example of a simple symmetric encryption scheme is the Caesar cipher

"If he had anything confidential to say, he wrote it in cipher, that is, by so changing the order of the letters of the alphabet, that not a word could be made out. If anyone wishes to decipher these, and get at their meaning, he must substitute the fourth letter of the alphabet, namely D, for A, and so with the others."

– Suetonius, Life of Julius Caesar

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Each character of the plaintext is replaced with the character 3 positions down the alphabet, in a modular fashion

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
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
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

Caesar cipher: example

$m = \texttt{A T T A C K A T D A W N}$

$$\Big\downarrow \ \mathsf{Enc}(m)$$

Caesar cipher: example

$$\begin{tikzcd} m = \texttt{ATTACKATDAWN} \arrow[d, "\mathsf{Enc}(m)"] \\ c = \texttt{DWWDFNDWGDZQ} \end{tikzcd}$$

Caesar cipher: example

$$m = \texttt{A T T A C K A T D A W N}$$

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$$c = \texttt{D W W D F N D W G D Z Q}$$

$$c = \texttt{U H W U H D W Q R Z}$$

$$\Big\downarrow \; \text{Dec}(c)$$

$$m =$$

Caesar cipher: example

$$\begin{tikzcd} m = \texttt{A T T A C K A T D A W N} \arrow[d, "\mathsf{Enc}(m)"] \\ c = \texttt{D W W D F N D W G D Z Q} \end{tikzcd}$$

$$\begin{tikzcd} c = \texttt{U H W U H D W Q R Z} \arrow[d, "\mathsf{Dec}(c)"] \\ m = \texttt{R E T R E A T N O W} \end{tikzcd}$$

Shift ciphers

The Caesar cipher is a special type of *shift cipher*

In a shift cipher, each character is replaced with the character k positions down the alphabet (in a modular fashion)

The *key* of the cipher is the integer k

(the key is also called the *shift* of the cipher)

$k = 5$

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
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
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

Shift ciphers

$$m = \texttt{F L A N K T H E E N E M Y}$$

$$\Big\downarrow \ \mathsf{Enc}_5(m)$$

$$c = \texttt{K Q F S P Y M J J S J R D}$$

$$c = \texttt{X J S I M J Q U}$$

$$\Big\downarrow \ \mathsf{Dec}_5(c)$$

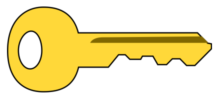
$k = 5$

$$\begin{array}{cccccccccccccccccccccccccc}
\texttt{A} & \texttt{B} & \texttt{C} & \texttt{D} & \texttt{E} & \texttt{F} & \texttt{G} & \texttt{H} & \texttt{I} & \texttt{J} & \texttt{K} & \texttt{L} & \texttt{M} & \texttt{N} & \texttt{O} & \texttt{P} & \texttt{Q} & \texttt{R} & \texttt{S} & \texttt{T} & \texttt{U} & \texttt{V} & \texttt{W} & \texttt{X} & \texttt{Y} & \texttt{Z} \\
\downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
\texttt{F} & \texttt{G} & \texttt{H} & \texttt{I} & \texttt{J} & \texttt{K} & \texttt{L} & \texttt{M} & \texttt{N} & \texttt{O} & \texttt{P} & \texttt{Q} & \texttt{R} & \texttt{S} & \texttt{T} & \texttt{U} & \texttt{V} & \texttt{W} & \texttt{X} & \texttt{Y} & \texttt{Z} & \texttt{A} & \texttt{B} & \texttt{C} & \texttt{D} & \texttt{E}
\end{array}$$

Shift ciphers

$$\begin{tikzcd}
m = \mathtt{F\ L\ A\ N\ K\ T\ H\ E\ E\ N\ E\ M\ Y} \arrow[d, "\mathsf{Enc}_5(m)"] \\
c = \mathtt{K\ Q\ F\ S\ P\ Y\ M\ J\ J\ S\ J\ R\ D}
\end{tikzcd}$$

$$\begin{tikzcd}
c = \mathtt{X\ J\ S\ I\ M\ J\ Q\ U} \arrow[d, "\mathsf{Dec}_5(c)"] \\
m = \mathtt{S\ E\ N\ D\ H\ E\ L\ P}
\end{tikzcd}$$



$k = 5$

$$\begin{array}{cccccccccccccccccccccccccc}
\mathtt{A} & \mathtt{B} & \mathtt{C} & \mathtt{D} & \mathtt{E} & \mathtt{F} & \mathtt{G} & \mathtt{H} & \mathtt{I} & \mathtt{J} & \mathtt{K} & \mathtt{L} & \mathtt{M} & \mathtt{N} & \mathtt{O} & \mathtt{P} & \mathtt{Q} & \mathtt{R} & \mathtt{S} & \mathtt{T} & \mathtt{U} & \mathtt{V} & \mathtt{W} & \mathtt{X} & \mathtt{Y} & \mathtt{Z} \\
\downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
\mathtt{F} & \mathtt{G} & \mathtt{H} & \mathtt{I} & \mathtt{J} & \mathtt{K} & \mathtt{L} & \mathtt{M} & \mathtt{N} & \mathtt{O} & \mathtt{P} & \mathtt{Q} & \mathtt{R} & \mathtt{S} & \mathtt{T} & \mathtt{U} & \mathtt{V} & \mathtt{W} & \mathtt{X} & \mathtt{Y} & \mathtt{Z} & \mathtt{A} & \mathtt{B} & \mathtt{C} & \mathtt{D} & \mathtt{E}
\end{array}$$

Shift ciphers

Message space: $\mathcal{M} = \{A, \ldots, Z\}^*$

Shift ciphers

Message space: $\mathcal{M} = \{0, 1, \ldots, 25\}^*$

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Key space:

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Ciphertext space: $\mathcal{C} = \{0, \ldots, 25\}^*$

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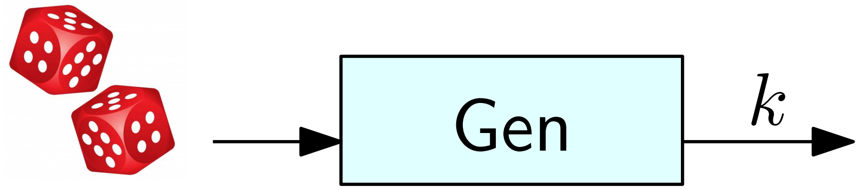
Key generation:



Shift ciphers

Message space: $\mathcal{M} = \{0, 1, \ldots, 25\}^*$

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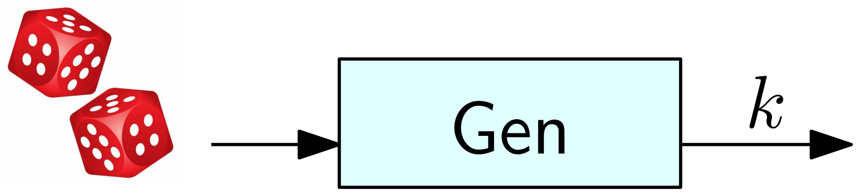
Key generation: return k chosen u.a.r. from $\mathcal{K}$



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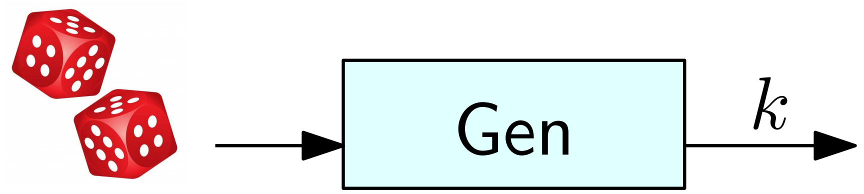
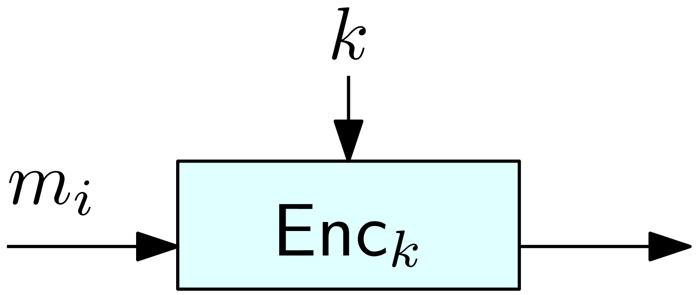
Encryption function:

$$\mathsf{Enc}_k(m) = \mathsf{Enc}_k(m_1) \| \mathsf{Enc}_k(m_2) \| \ldots \| \mathsf{Enc}_k(m_\ell)$$

$$m = m_1 m_2 \ldots m_\ell$$





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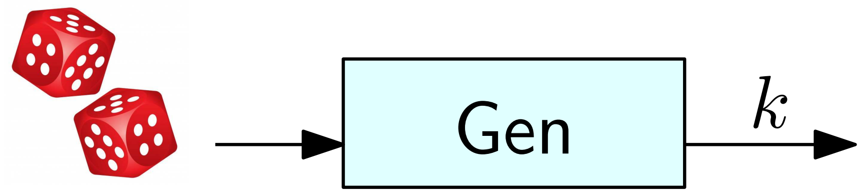

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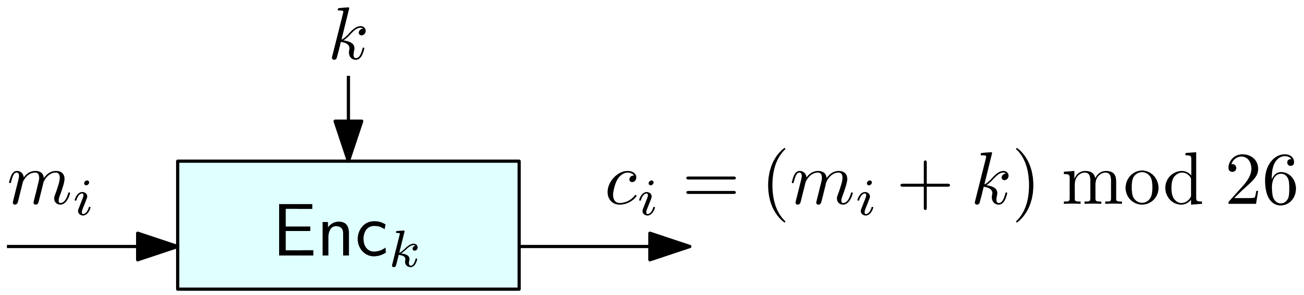
$$\mathsf{Enc}_k(m) = \mathsf{Enc}_k(m_1) \| \mathsf{Enc}_k(m_2) \| \ldots \| \mathsf{Enc}_k(m_\ell)$$

$$\mathsf{Enc}_k(m_i) = (m_i + k) \bmod 26$$



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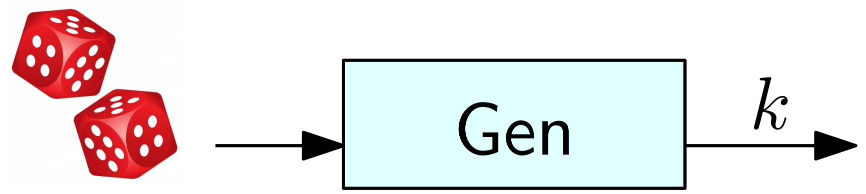
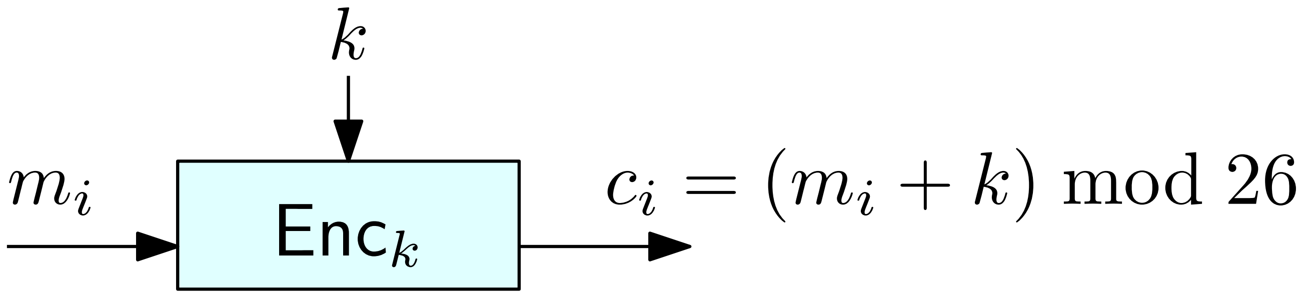
Decryption function:

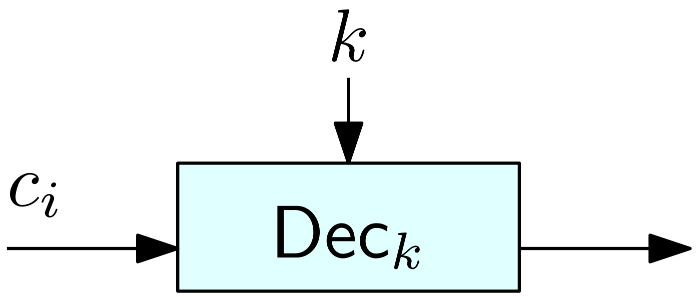
$$\mathsf{Dec}_k(c) = \mathsf{Dec}_k(c_1) \| \mathsf{Dec}_k(c_2) \| \ldots \| \mathsf{Dec}_k(c_\ell)$$

$m = m_1 m_2 \ldots m_\ell$

$c = c_1 c_2 \ldots c_\ell$







Shift ciphers

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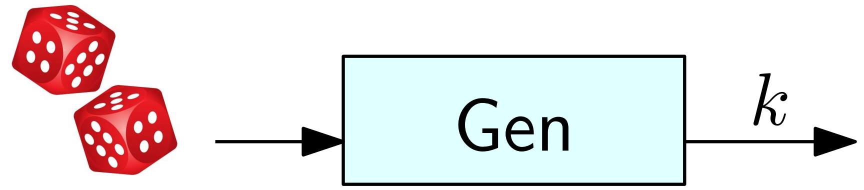

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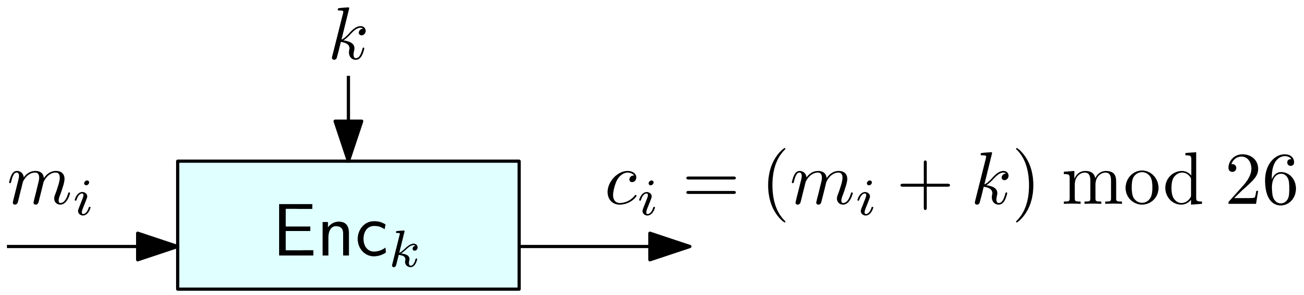

$c_i = (m_i + k) \bmod 26$

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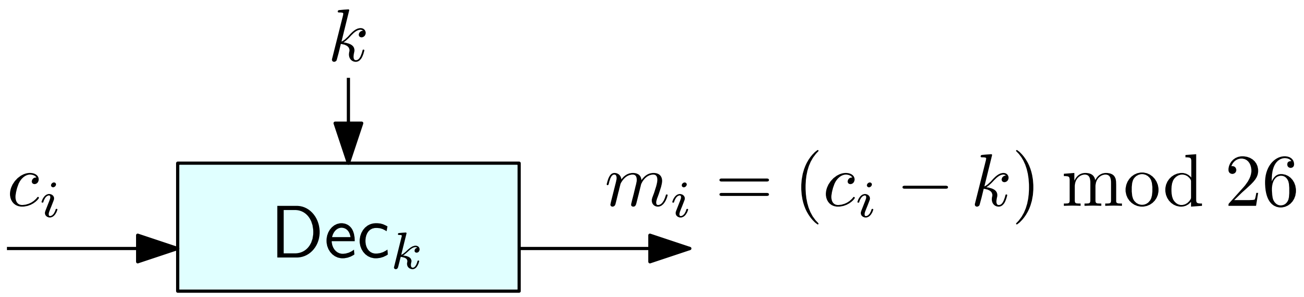

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Shift ciphers

Correctness:

We need to prove that $\mathsf{Dec}_k(\mathsf{Enc}_k(m)) = m$

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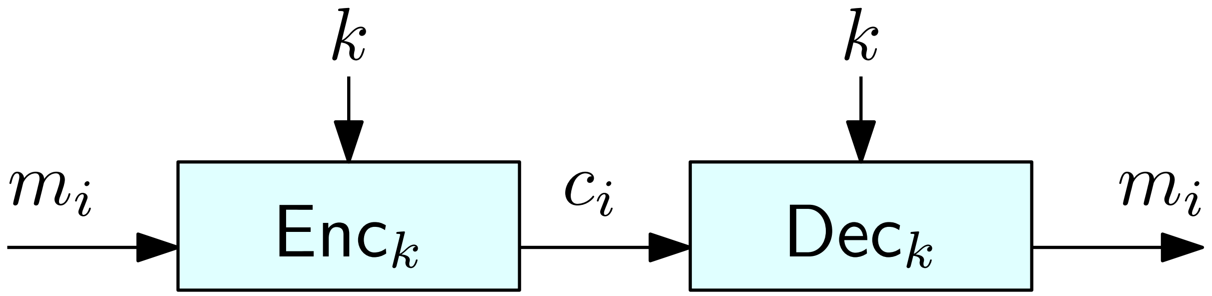

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$$\mathsf{Dec}_k(\mathsf{Enc}_k(m_i))$$

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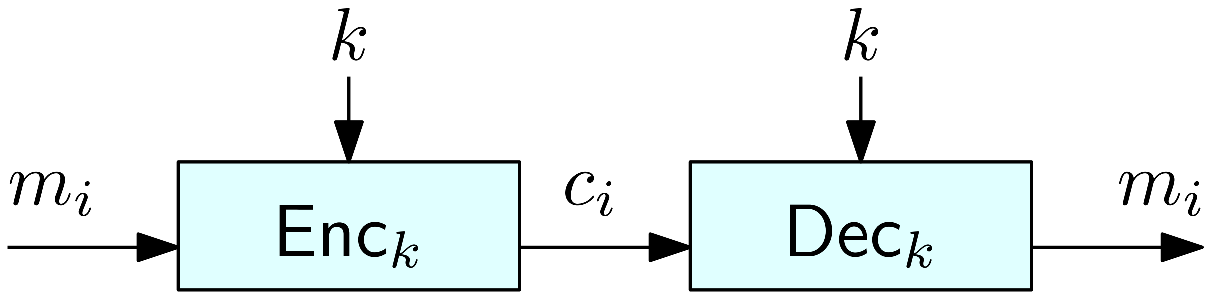

$$\mathsf{Dec}_k(\mathsf{Enc}_k(m_i)) \;= \mathsf{Dec}_k((m_i + k) \bmod 26) \qquad \text{(definition of } \mathsf{Enc}_k\text{)}$$

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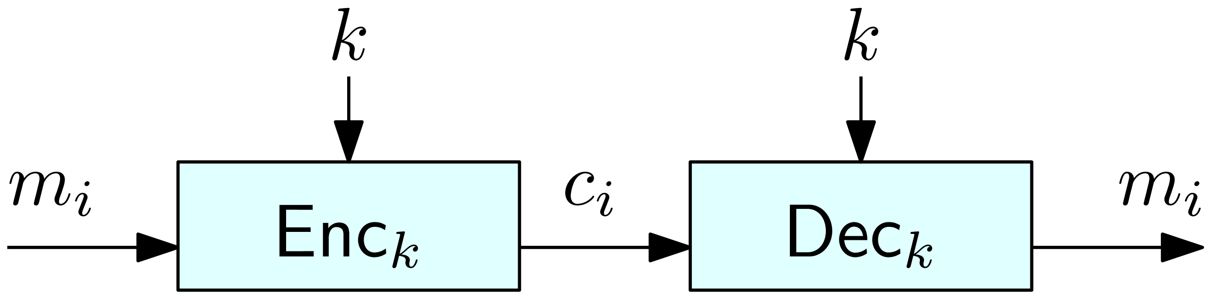
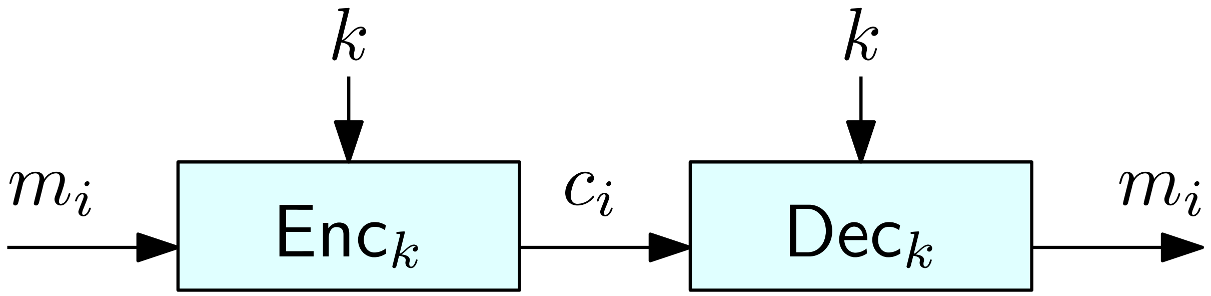


$$\begin{aligned}\mathsf{Dec}_k(\mathsf{Enc}_k(m_i)) &= \mathsf{Dec}_k((m_i + k) \bmod 26) && \text{(definition of Enc}_k\text{)}\\ &= (((m_i + k) \bmod 26) - k) \bmod 26 && \text{(definition of Dec}_k\text{)}\end{aligned}$$

Shift ciphers

Correctness:



We need to prove that $\mathsf{Dec}_k(\mathsf{Enc}_k(m)) = m$

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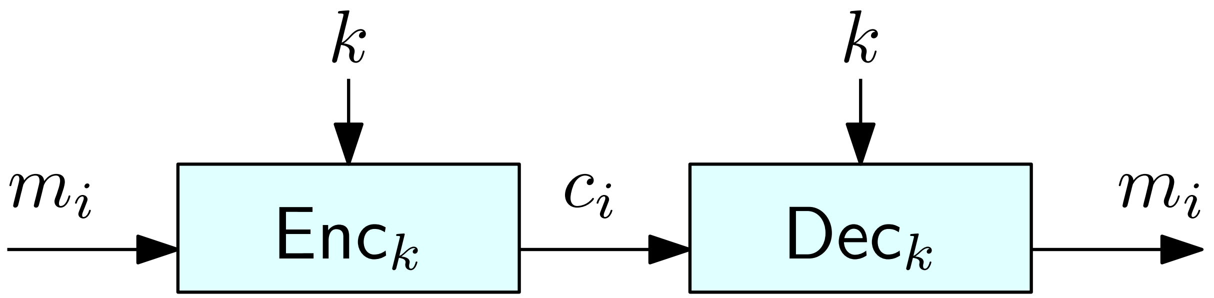
$$\begin{aligned}
\mathsf{Dec}_k(\mathsf{Enc}_k(m_i)) &= \mathsf{Dec}_k((m_i + k) \bmod 26) && \text{(definition of Enc}_k\text{)} \\
&= (((m_i + k) \bmod 26) - k) \bmod 26 && \text{(definition of Dec}_k\text{)} \\
&= (m_i + k - k) \bmod 26 && \text{(properties of mod)}
\end{aligned}$$

Shift ciphers

Correctness:



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&= (((m_i + k) \bmod 26) - k) \bmod 26 && \text{(definition of } \mathsf{Dec}_k\text{)} \\
&= (m_i + k - k) \bmod 26 && \text{(properties of } \mathrm{mod}\text{)} \\
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Shift ciphers

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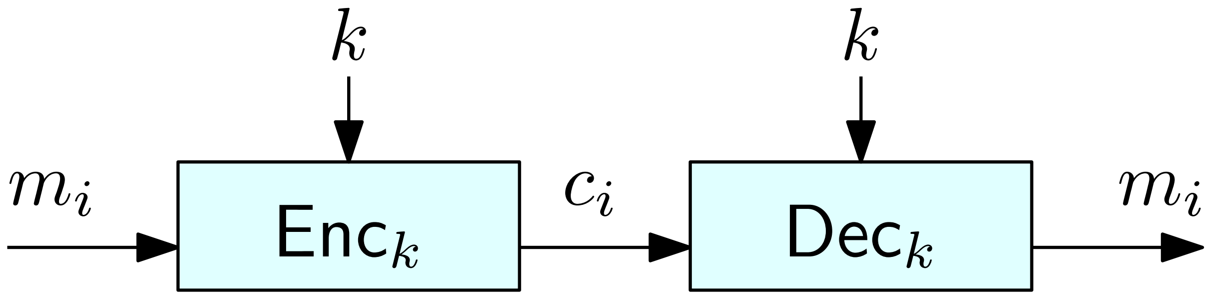

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\mathsf{Dec}_k(\mathsf{Enc}_k(m_i)) &= \mathsf{Dec}_k((m_i + k) \bmod 26) && \text{(definition of Enc}_k\text{)} \\
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&= (m_i + k - k) \bmod 26 && \text{(properties of mod)} \\
&= m_i \bmod 26 \\
&= m_i && (m_i < 26)
\end{aligned}$$

Shift ciphers

Are shift ciphers secure?

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How many keys are there? $|\mathcal{K}| = 26$

We can use a **brute-force** (or **exhaustive search**) attack

In a brute-force attack, the adversary systematically tries all possible keys until the correct one is found.

Shift ciphers

Brute-force attack:

$$
\begin{aligned}
\mathsf{Dec}_{0}(c) &= \texttt{X J S I M J Q U} \\
\mathsf{Dec}_{1}(c) &= \texttt{W I R H L I P T} \\
\mathsf{Dec}_{2}(c) &= \texttt{V H Q G K H O S} \\
\mathsf{Dec}_{3}(c) &= \texttt{U G P F J G N R} \\
\mathsf{Dec}_{4}(c) &= \texttt{T F O E I F M Q} \\
\mathsf{Dec}_{5}(c) &= \texttt{S E N D H E L P} \\
\mathsf{Dec}_{6}(c) &= \texttt{R D M C G D K O} \\
&\vdots \\
\mathsf{Dec}_{24}(c) &= \texttt{Z L U K O L S W} \\
\mathsf{Dec}_{25}(c) &= \texttt{Y K T J N K R V}
\end{aligned}
$$

Shift ciphers

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$$\mathsf{Dec}_3(c) = \texttt{U G P F J G N R}$$

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$$\boxed{\mathsf{Dec}_5(c) = \texttt{S E N D H E L P}}$$

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$$\vdots$$

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$$\vdots$$

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Sufficient key-space principle: Any cipher should use a "large enough" key space to prevent brute-force attacks

(Monoalphabetic) Substitution ciphers

The key is now a permutation π of the alphabet $\Sigma = \{\mathtt{A}, \mathtt{B}, \ldots, \mathtt{Z}\}$

$\mathcal{K} = \{\pi : \Sigma \to \Sigma \mid \pi \text{ is a pemutation}\}$

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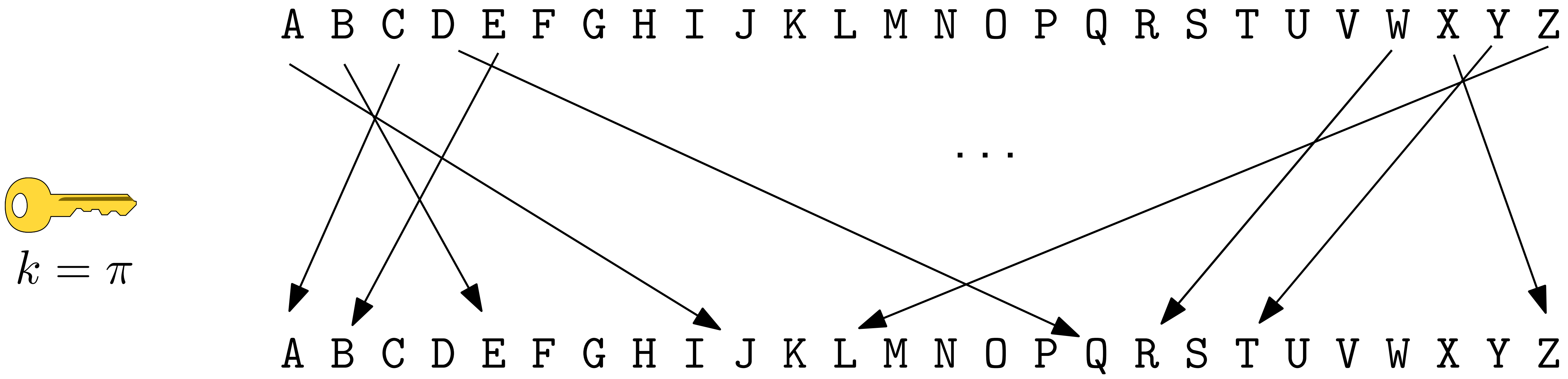
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
. . .
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

$k = \pi$

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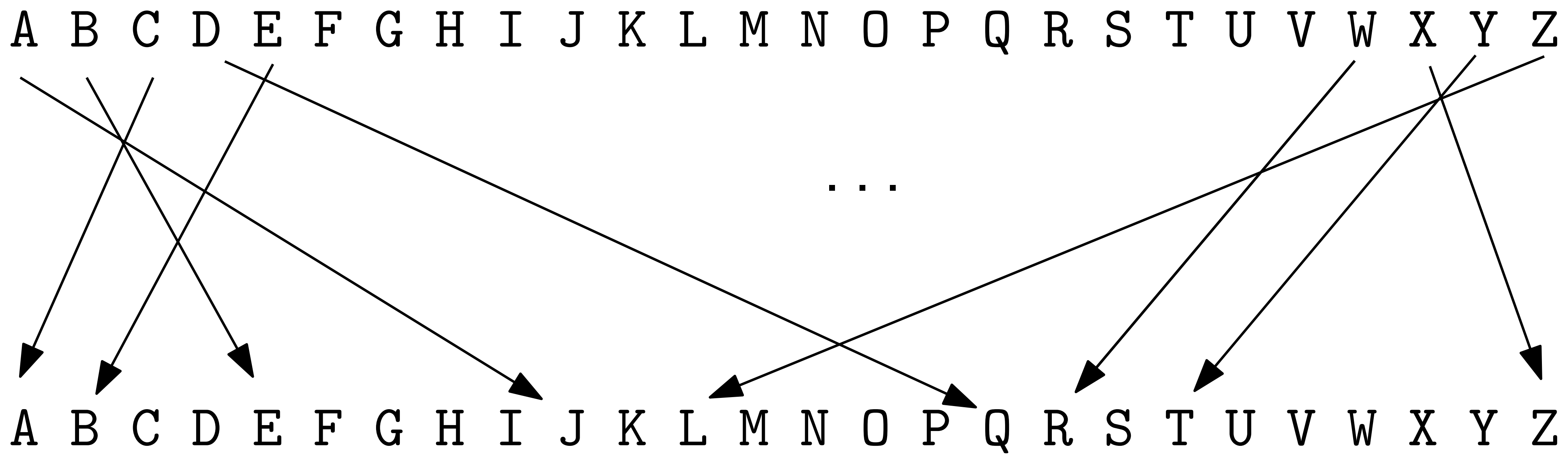


A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

. . .

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

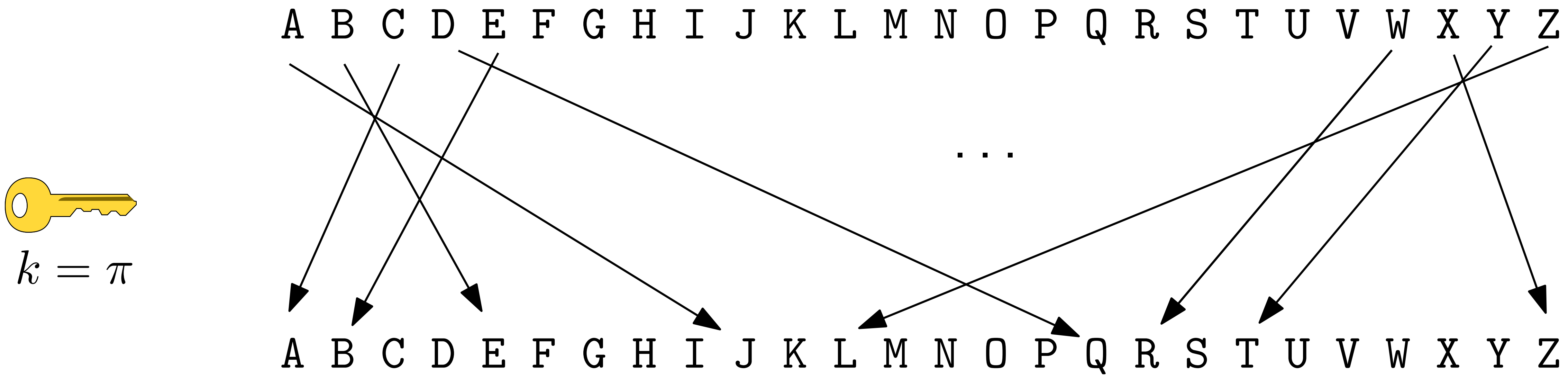
To encrypt a message, replace each character m_i in the plaintext with $k(m_i) = \pi(m_i)$

$\mathsf{Enc}_k(m) = k(m_1) \| k(m_2) \| \ldots \| k(m_\ell)$

(Monoalphabetic) Substitution ciphers

The key is now a permutation π of the alphabet $\Sigma = \{\mathtt{A}, \mathtt{B}, \ldots, \mathtt{Z}\}$

$\mathcal{K} = \{\pi : \Sigma \to \Sigma \mid \pi \text{ is a pemutation}\}$


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
. . .
$k = \pi$
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

To encrypt a message, replace each character m_i in the plaintext with $k(m_i) = \pi(m_i)$

$\mathsf{Enc}_k(m) = k(m_1) \| k(m_2) \| \ldots \| k(m_\ell)$

To decrypt a message, replace each character c_i of the ciphertext with $k^{-1}(c_i) = \pi^{-1}(c_i)$

$\mathsf{Dec}_k(m) = k^{-1}(c_1) \| k^{-1}(c_2) \| \ldots \| k^{-1}(c_\ell)$

(Monoalphabetic) Substitution ciphers

$$\underbrace{\begin{array}{cccccccccccccccccccccccccc}
\mathtt{A} & \mathtt{B} & \mathtt{C} & \mathtt{D} & \mathtt{E} & \mathtt{F} & \mathtt{G} & \mathtt{H} & \mathtt{I} & \mathtt{J} & \mathtt{K} & \mathtt{L} & \mathtt{M} & \mathtt{N} & \mathtt{O} & \mathtt{P} & \mathtt{Q} & \mathtt{R} & \mathtt{S} & \mathtt{T} & \mathtt{U} & \mathtt{V} & \mathtt{W} & \mathtt{X} & \mathtt{Y} & \mathtt{Z} \\
\mathtt{J} & \mathtt{E} & \mathtt{A} & \mathtt{Q} & \mathtt{B} & \mathtt{Y} & \mathtt{D} & \mathtt{P} & \mathtt{V} & \mathtt{F} & \mathtt{K} & \mathtt{I} & \mathtt{N} & \mathtt{H} & \mathtt{M} & \mathtt{X} & \mathtt{U} & \mathtt{S} & \mathtt{W} & \mathtt{C} & \mathtt{O} & \mathtt{G} & \mathtt{R} & \mathtt{Z} & \mathtt{T} & \mathtt{L}
\end{array}}_{k}$$

$$m = \mathtt{AWAITORDERS}$$

$$\Big\downarrow\ \mathsf{Enc}_k(m)$$

(Monoalphabetic) Substitution ciphers

$$\underbrace{\begin{array}{cccccccccccccccccccccccccc}
\mathtt{A} & \mathtt{B} & \mathtt{C} & \mathtt{D} & \mathtt{E} & \mathtt{F} & \mathtt{G} & \mathtt{H} & \mathtt{I} & \mathtt{J} & \mathtt{K} & \mathtt{L} & \mathtt{M} & \mathtt{N} & \mathtt{O} & \mathtt{P} & \mathtt{Q} & \mathtt{R} & \mathtt{S} & \mathtt{T} & \mathtt{U} & \mathtt{V} & \mathtt{W} & \mathtt{X} & \mathtt{Y} & \mathtt{Z} \\
\mathtt{J} & \mathtt{E} & \mathtt{A} & \mathtt{Q} & \mathtt{B} & \mathtt{Y} & \mathtt{D} & \mathtt{P} & \mathtt{V} & \mathtt{F} & \mathtt{K} & \mathtt{I} & \mathtt{N} & \mathtt{H} & \mathtt{M} & \mathtt{X} & \mathtt{U} & \mathtt{S} & \mathtt{W} & \mathtt{C} & \mathtt{O} & \mathtt{G} & \mathtt{R} & \mathtt{Z} & \mathtt{T} & \mathtt{L}
\end{array}}_{k}$$

$$m = \mathtt{A\ W\ A\ I\ T\ O\ R\ D\ E\ R\ S}$$

$$\Big\downarrow\ \mathsf{Enc}_k(m)$$

$$c = \mathtt{J\ R\ J\ V\ C\ M\ S\ Q\ B\ S\ W}$$

(Monoalphabetic) Substitution ciphers

$$\underbrace{\begin{array}{cccccccccccccccccccccccccc} \texttt{A} & \texttt{B} & \texttt{C} & \texttt{D} & \texttt{E} & \texttt{F} & \texttt{G} & \texttt{H} & \texttt{I} & \texttt{J} & \texttt{K} & \texttt{L} & \texttt{M} & \texttt{N} & \texttt{O} & \texttt{P} & \texttt{Q} & \texttt{R} & \texttt{S} & \texttt{T} & \texttt{U} & \texttt{V} & \texttt{W} & \texttt{X} & \texttt{Y} & \texttt{Z} \\ \texttt{J} & \texttt{E} & \texttt{A} & \texttt{Q} & \texttt{B} & \texttt{Y} & \texttt{D} & \texttt{P} & \texttt{V} & \texttt{F} & \texttt{K} & \texttt{I} & \texttt{N} & \texttt{H} & \texttt{M} & \texttt{X} & \texttt{U} & \texttt{S} & \texttt{W} & \texttt{C} & \texttt{O} & \texttt{G} & \texttt{R} & \texttt{Z} & \texttt{T} & \texttt{L} \end{array}}_{k}$$

$$\begin{tikzcd} m = \texttt{A W A I T O R D E R S} \arrow[d, "\mathsf{Enc}_k(m)"] \\ c = \texttt{J R J V C M S Q B S W} \end{tikzcd}$$

$$c = \texttt{B H B N T Q M R H}$$

$$\Big\downarrow \; \mathsf{Dec}_k(c)$$

(Monoalphabetic) Substitution ciphers

$$\underbrace{\begin{array}{cccccccccccccccccccccccccc} \texttt{A} & \texttt{B} & \texttt{C} & \texttt{D} & \texttt{E} & \texttt{F} & \texttt{G} & \texttt{H} & \texttt{I} & \texttt{J} & \texttt{K} & \texttt{L} & \texttt{M} & \texttt{N} & \texttt{O} & \texttt{P} & \texttt{Q} & \texttt{R} & \texttt{S} & \texttt{T} & \texttt{U} & \texttt{V} & \texttt{W} & \texttt{X} & \texttt{Y} & \texttt{Z} \\ \texttt{J} & \texttt{E} & \texttt{A} & \texttt{Q} & \texttt{B} & \texttt{Y} & \texttt{D} & \texttt{P} & \texttt{V} & \texttt{F} & \texttt{K} & \texttt{I} & \texttt{N} & \texttt{H} & \texttt{M} & \texttt{X} & \texttt{U} & \texttt{S} & \texttt{W} & \texttt{C} & \texttt{O} & \texttt{G} & \texttt{R} & \texttt{Z} & \texttt{T} & \texttt{L} \end{array}}_{k}$$

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$$\begin{tikzcd} c = \texttt{B H B N T Q M R H} \arrow[d, "\mathsf{Dec}_k(c)"] \\ m = \texttt{E N E M Y D O W N} \end{tikzcd}$$

(Monoalphabetic) Substitution ciphers

How many keys are there?

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If we tried 100 billion keys per second, we would need about 100 million years to find the right permutation k

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Observation (informal): A large keyspace is not a sufficient condition for a cipher to be secure

Substitution ciphers

Suppose that we somehow have deciphered a small portion of the ciphertext

We can replace each known ciphertext symbol x with its plaintext $k^{-1}(x)$ and then use the partially decrypted message to make further guesses about k

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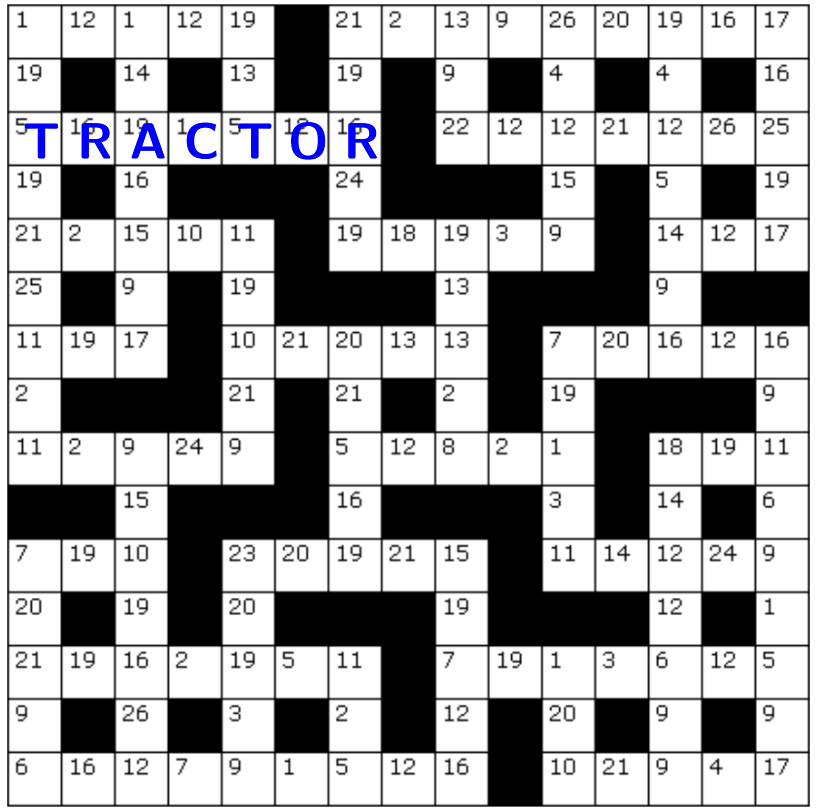
A similar example: codebreaker word puzzle



1	12	1	12	19	■	21	2	13	9	26	20	19	16	17
19	■	14	■	13	■	19	■	9	■	4	■	4	■	16
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12	12	21	12	26	25
19	■	16	■	■	■	24	■	■	■	15	■	5	■	19
21	2	15	10	11	■	19	18	19	3	9	■	14	12	17
25	■	9	■	19	■	■	■	13	■	■	■	9	■	■
11	19	17	■	10	21	20	13	13	■	7	20	16	12	16
2	■	■	■	21	■	21	■	2	■	19	■	■	■	9
11	2	9	24	9	■	5	12	8	2	1	■	18	19	11
■	■	15	■	■	■	16	■	■	■	3	■	14	■	6
7	19	10	■	23	20	19	21	15	■	11	14	12	24	9
20	■	19	■	20	■	■	■	19	■	■	■	12	■	1
21	19	16	2	19	5	11	■	7	19	1	3	6	12	5
9	■	26	■	3	■	2	■	12	■	20	■	9	■	9
6	16	12	7	9	1	5	12	16	■	10	21	9	4	17

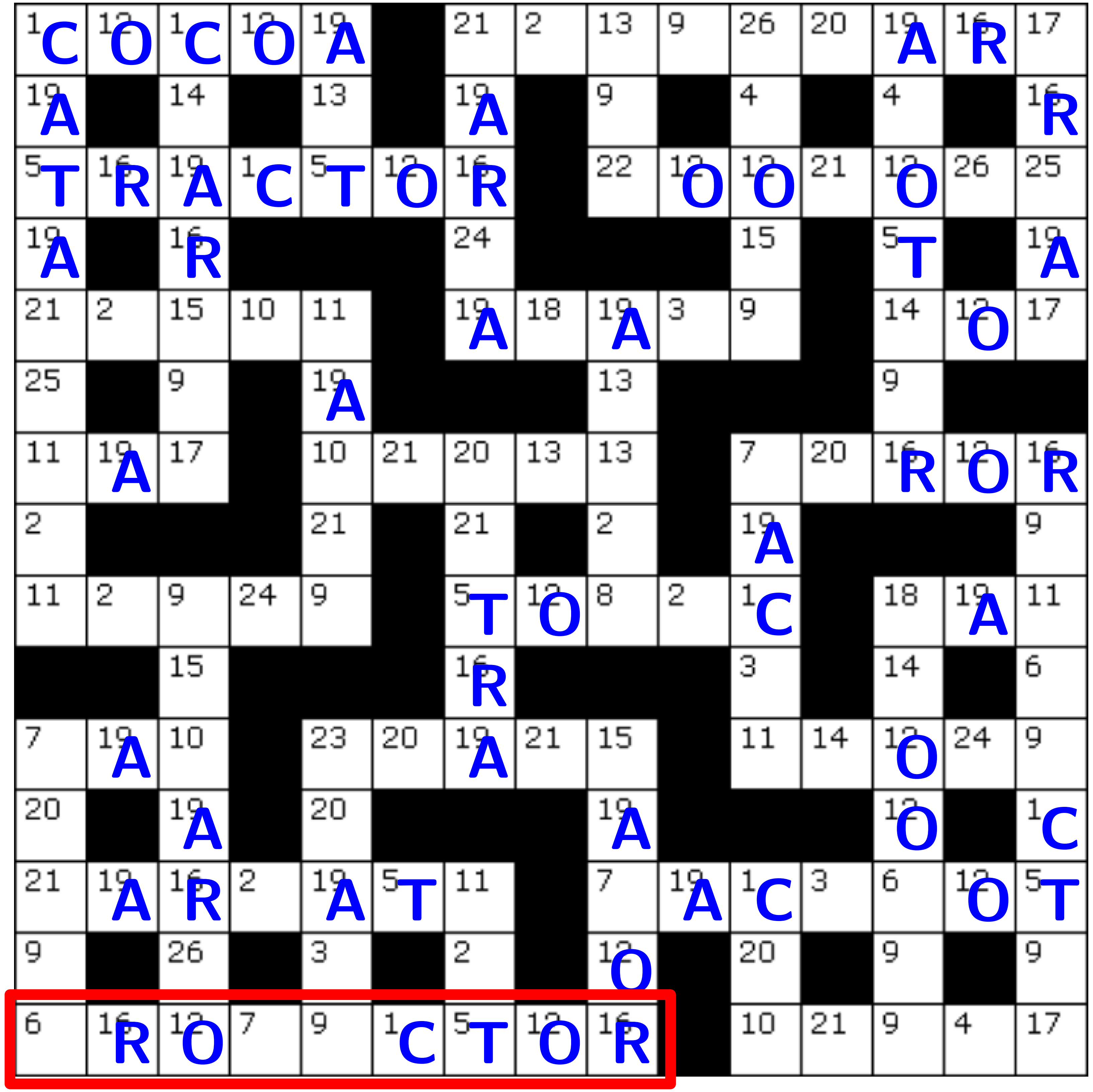
Substitution ciphers

1	12	1	12	19	■	21	2	13	9	26	20	19	16	17
19	■	14	■	13	■	19	■	9	■	4	■	4	■	16
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12	12	21	12	26	25
19	■	16	■	■	■	24	■	■	■	15	■	5	■	19
21	2	15	10	11	■	19	18	19	3	9	■	14	12	17
25	■	9	■	19	■	■	■	13	■	■	■	9	■	■
11	19	17	■	10	21	20	13	13	■	7	20	16	12	16
2	■	■	■	21	■	21	■	2	■	19	■	■	■	9
11	2	9	24	9	■	5	12	8	2	1	■	18	19	11
■	■	15	■	■	■	16	■	■	■	3	■	14	■	6
7	19	10	■	23	20	19	21	15	■	11	14	12	24	9
20	■	19	■	20	■	■	■	19	■	■	■	12	■	1
21	19	16	2	19	5	11	■	7	19	1	3	6	12	5
9	■	26	■	3	■	2	■	12	■	20	■	9	■	9
6	16	12	7	9	1	5	12	16	■	10	21	9	4	17

Substitution ciphers

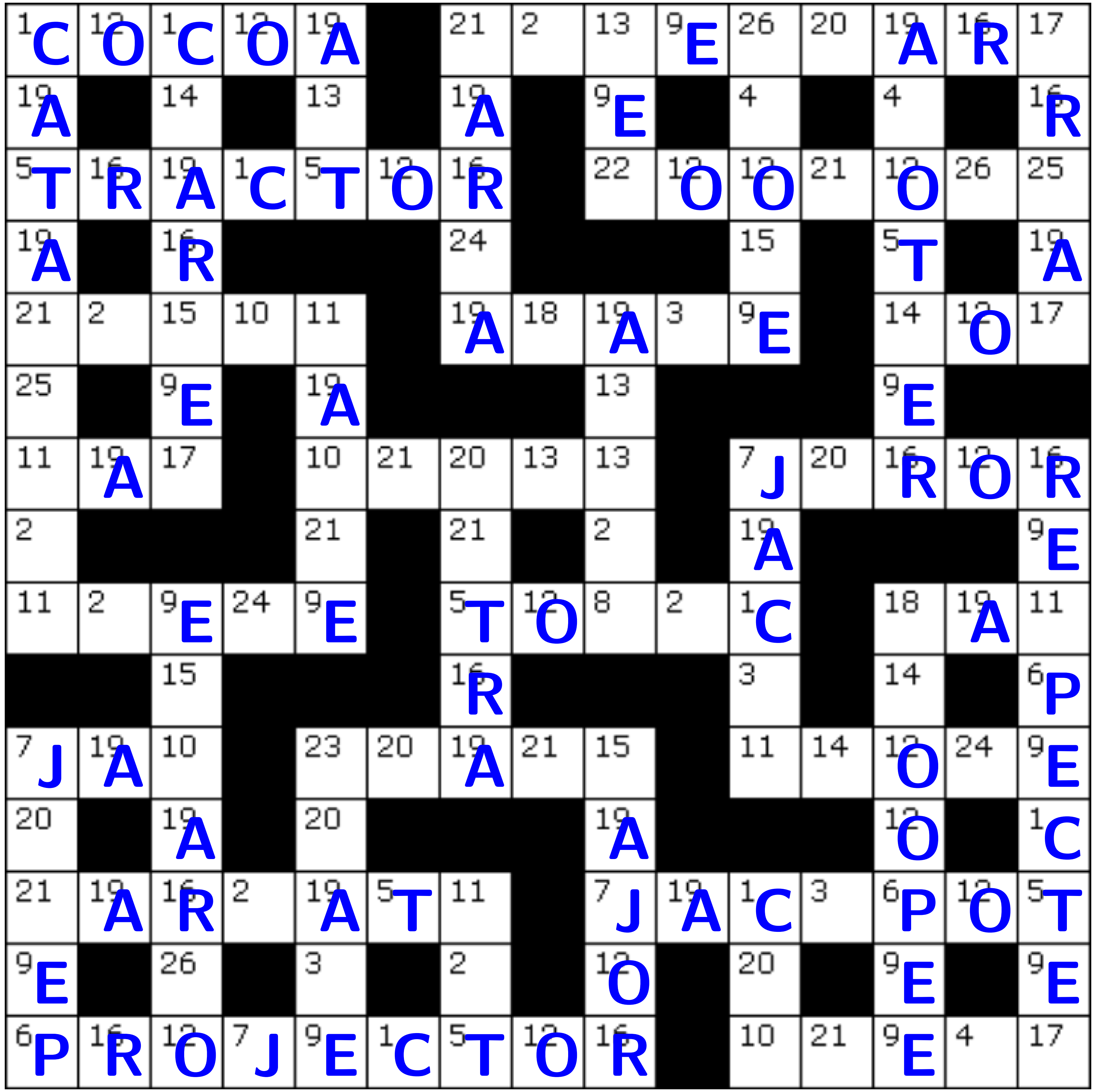
1 C	12 O	1 C	12 O	19 A	■	21	2	13	9	26	20	19 A	16 R	17
19 A	■	14	■	13	■	19 A	■	9	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21	12 O	26	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21	2	15	10	11	■	19 A	18	19 A	3	9	■	14	12 O	17
25	■	9	■	19 A	■	■	■	13	■	■	■	9	■	■
11	19 A	17	■	10	21	20	13	13	■	7	20	16 R	12 O	16 R
2	■	■	■	21	■	21	■	2	■	19 A	■	■	■	9
11	2	9	24	9	■	5 T	12 O	8	2	1 C	■	18	19 A	11
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6
7	19 A	10	■	23	20	19 A	21	15	■	11	14	12 O	24	9
20	■	19 A	■	20	■	■	■	19 A	■	■	■	12 O	■	1 C
21	19 A	16 R	2	19 A	5 T	11	■	7	19 A	1 C	3	6	12 O	5 T
9	■	26	■	3	■	2	■	12 O	■	20	■	9	■	9
6	16 R	12 O	7	9	1 C	5 T	12 O	16 R	■	10	21	9	4	17

Substitution ciphers



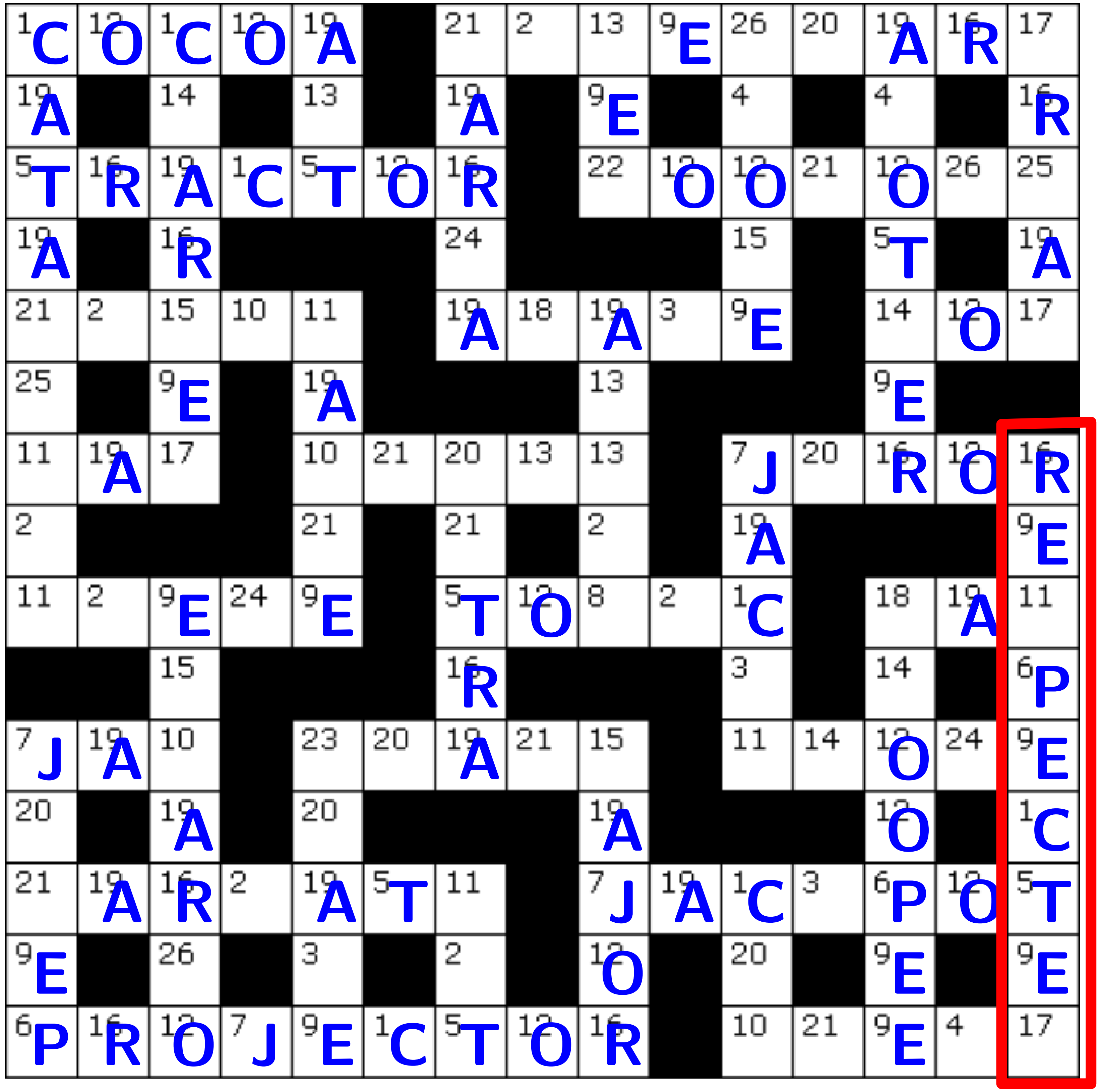
1 C	12 O	1 C	12 O	19 A	■	21	2	13	9	26	20	19 A	16 R	17
19 A	■	14	■	13	■	19 A	■	9	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21	12 O	26	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21	2	15	10	11	■	19 A	18	19 A	3	9	■	14	12 O	17
25	■	9	■	19 A	■	■	■	13	■	■	■	9	■	■
11	19 A	17	■	10	21	20	13	13	■	7	20	16 R	12 O	16 R
2	■	■	■	21	■	21	■	2	■	19 A	■	■	■	9
11	2	9	24	9	■	5 T	12 O	8	2	1 C	■	18	19 A	11
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6
7	19 A	10	■	23	20	19 A	21	15	■	11	14	12 O	24	9
20	■	19 A	■	20	■	■	■	19 A	■	■	■	12 O	■	1 C
21	19 A	16 R	2	19 A	5 T	11	■	7	19 A	1 C	3	6	12 O	5 T
9	■	26	■	3	■	2	■	12 O	■	20	■	9	■	9
6	16 R	12 O	7	9	1 C	5 T	12 O	16 R	■	10	21	9	4	17

Substitution ciphers



1 C	12 O	1 C	12 O	19 A	■	21	2	13	9 E	26	20	19 A	16 R	17
19 A	■	14	■	13	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21	12 O	26	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21	2	15	10	11	■	19 A	18	19 A	3	9 E	■	14	12 O	17
25	■	9 E	■	19 A	■	■	■	13	■	■	■	9 E	■	■
11	19 A	17	■	10	21	20	13	13	■	7 J	20	16 R	12 O	16 R
2	■	■	■	21	■	21	■	2	■	19 A	■	■	■	9 E
11	2	9 E	24	9 E	■	5 T	12 O	8	2	1 C	■	18	19 A	11
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6 P
7 J	19 A	10	■	23	20	19 A	21	15	■	11	14	12 O	24	9 E
20	■	19 A	■	20	■	■	■	19 A	■	■	■	12 O	■	1 C
21	19 A	16 R	2	19 A	5 T	11	■	7 J	19 A	1 C	3	6 P	12 O	5 T
9 E	■	26	■	3	■	2	■	12 O	■	20	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10	21	9 E	4	17

Substitution ciphers

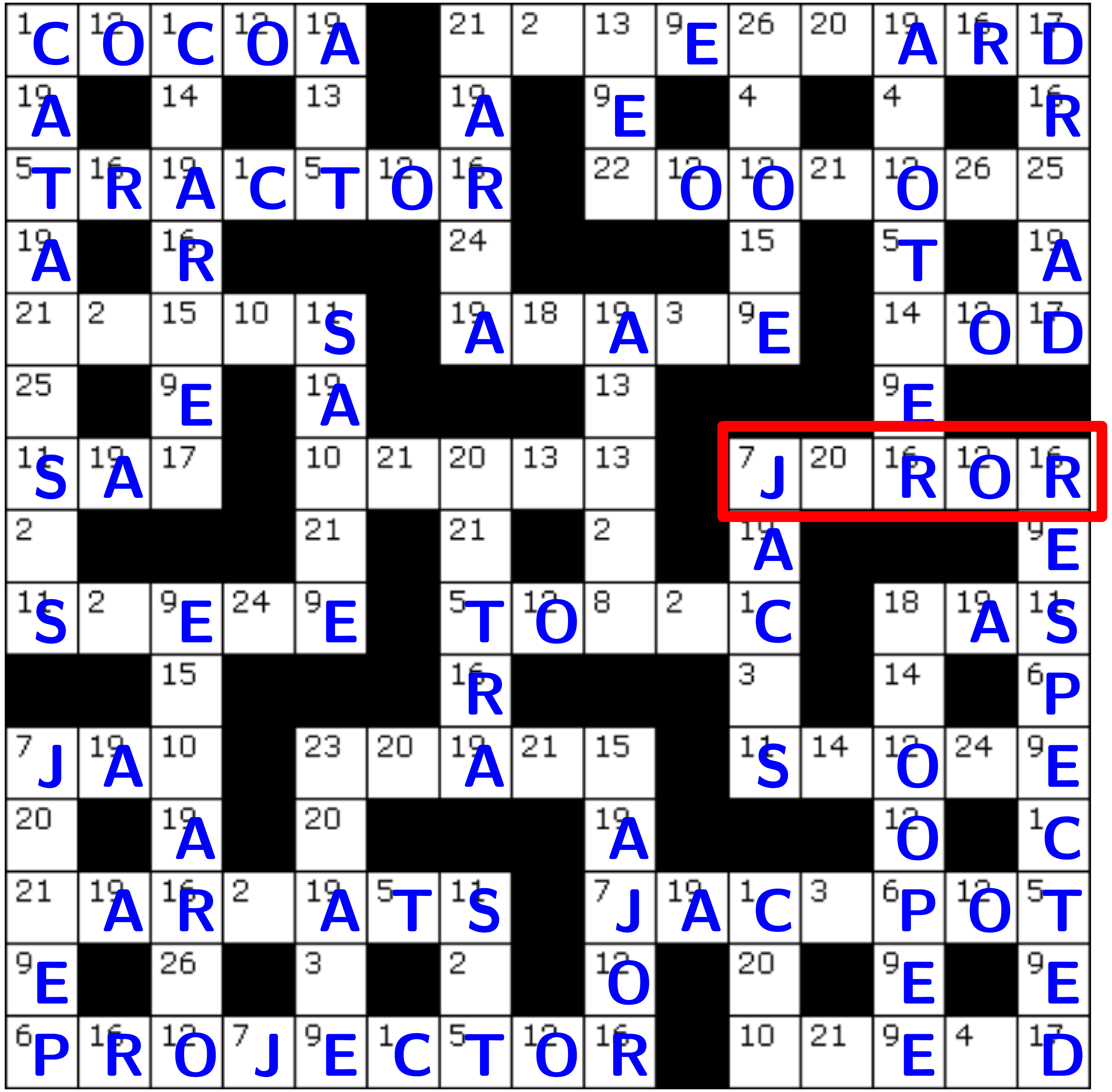


1 C	12 O	1 C	12 O	19 A	■	21	2	13	9 E	26	20	19 A	16 R	17
19 A	■	14	■	13	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21	12 O	26	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21	2	15	10	11	■	19 A	18	19 A	3	9 E	■	14	12 O	17
25	■	9 E	■	19 A	■	■	■	13	■	■	■	9 E	■	■
11	19 A	17	■	10	21	20	13	13	■	7 J	20	16 R	12 O	16 R
2	■	■	■	21	■	21	■	2	■	19 A	■	■	■	9 E
11	2	9 E	24	9 E	■	5 T	12 O	8	2	1 C	■	18	19 A	11
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6 P
7 J	19 A	10	■	23	20	19 A	21	15	■	11	14	12 O	24	9 E
20	■	19 A	■	20	■	■	■	19 A	■	■	■	12 O	■	1 C
21	19 A	16 R	2	19 A	5 T	11	■	7 J	19 A	1 C	3	6 P	12 O	5 T
9 E	■	26	■	3	■	2	■	12 O	■	20	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10	21	9 E	4	17

Substitution ciphers

1 C	12 O	1 C	12 O	19 A	■	21	2	13	9 E	26	20	19 A	16 R	17 D
19 A	■	14	■	13	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21	12 O	26	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21	2	15	10	11 S	■	19 A	18	19 A	3	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13	■	■	■	9 E	■	■
11 S	19 A	17	■	10	21	20	13	13	■	7 J	20	16 R	12 O	16 R
2	■	■	■	21	■	21	■	2	■	19 A	■	■	■	9 E
11 S	2	9 E	24	9 E	■	5 T	12 O	8	2	1 C	■	18	19 A	11 S
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6 P
7 J	19 A	10	■	23	20	19 A	21	15	■	11 S	14	12 O	24	9 E
20	■	19 A	■	20	■	■	■	19 A	■	■	■	12 O	■	1 C
21	19 A	16 R	2	19 A	5 T	11 S	■	7 J	19 A	1 C	3	6 P	12 O	5 T
9 E	■	26	■	3	■	2	■	12 O	■	20	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10	21	9 E	4	17 D

Substitution ciphers



1 C	12 O	1 C	12 O	19 A	■	21	2	13	9 E	26	20	19 A	16 R	17 D
19 A	■	14	■	13	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21	12 O	26	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21	2	15	10	11 S	■	19 A	18	19 A	3	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13	■	■	■	9 E	■	■
11 S	19 A	17	■	10	21	20	13	13	■	7 J	20	16 R	12 O	16 R
2	■	■	■	21	■	21	■	2	■	19 A	■	■	■	9 E
11 S	2	9 E	24	9 E	■	5 T	12 O	8	2	1 C	■	18	19 A	11 S
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6 P
7 J	19 A	10	■	23	20	19 A	21	15	■	11 S	14	12 O	24	9 E
20	■	19 A	■	20	■	■	■	19 A	■	■	■	12 O	■	1 C
21	19 A	16 R	2	19 A	5 T	11 S	■	7 J	19 A	1 C	3	6 P	12 O	5 T
9 E	■	26	■	3	■	2	■	12 O	■	20	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10	21	9 E	4	17 D

Substitution ciphers

1 C	12 O	1 C	12 O	19 A	■	21	2	13	9 E	26	20 U	19 A	16 R	17 D
19 A	■	14	■	13	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21	12 O	26	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21	2	15	10	11 S	■	19 A	18	19 A	3	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13	■	■	■	9 E	■	■
11 S	19 A	17	■	10	21	20 U	13	13	■	7 J	20 U	16 R	12 O	16 R
2	■	■	■	21	■	21	■	2	■	19 A	■	■	■	9 E
11 S	2	9 E	24	9 E	■	5 T	12 O	8	2	1 C	■	18	19 A	11 S
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6 P
7 J	19 A	10	■	23	20 U	19 A	21	15	■	11 S	14	12 O	24	9 E
20 U	■	19 A	■	20 U	■	■	■	19 A	■	■	■	12 O	■	1 C
21	19 A	16 R	2	19 A	5 T	11 S	■	7 J	19 A	1 C	3	6 P	12 O	5 T
9 E	■	26	■	3	■	2	■	12 O	■	20 U	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10	21	9 E	4	17 D

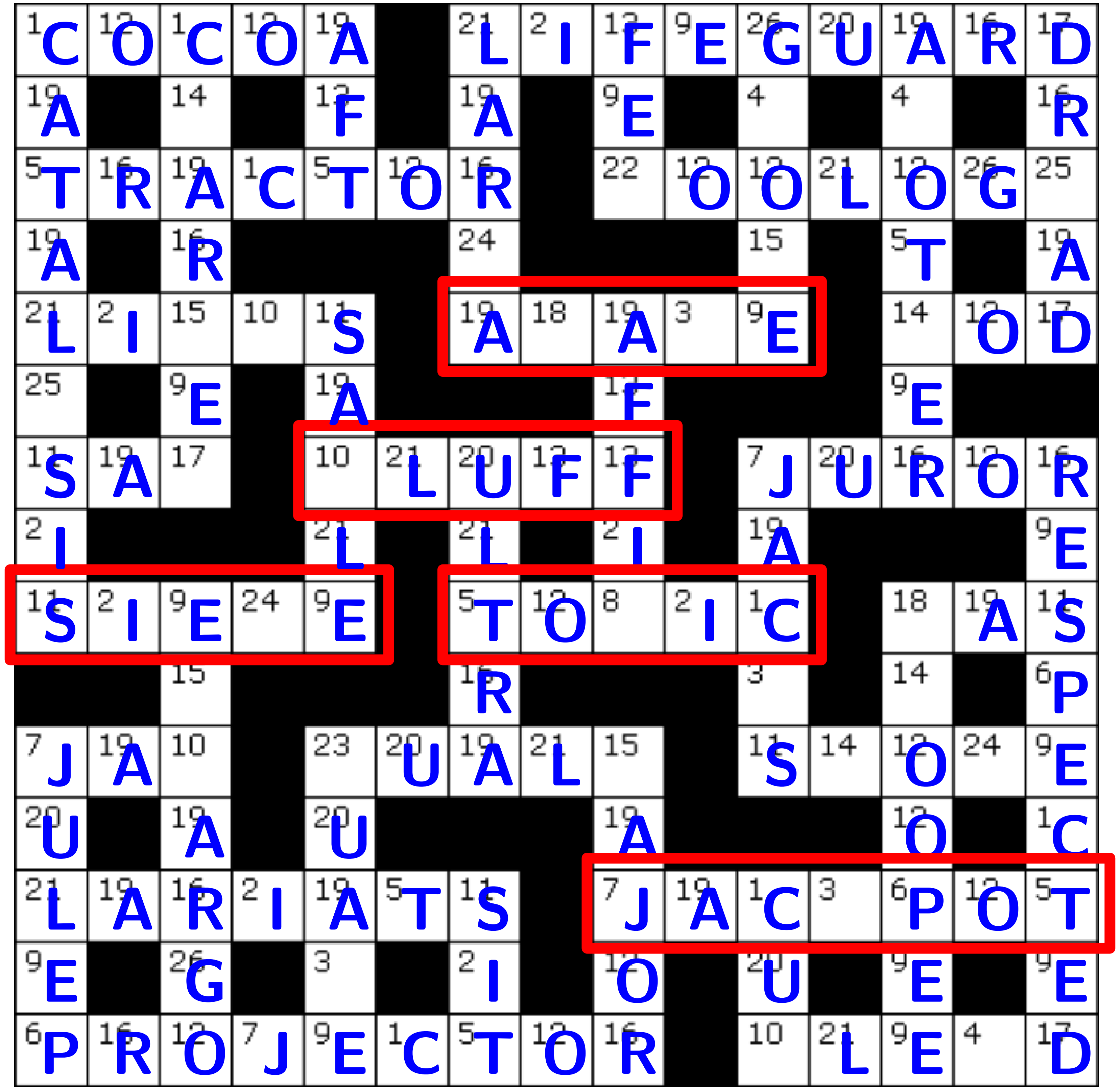
Substitution ciphers

1 C	12 O	1 C	12 O	19 A	■	21	2	13	9 E	26	20 U	19 A	16 R	17 D
19 A	■	14	■	13	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21	12 O	26	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21	2	15	10	11 S	■	19 A	18	19 A	3	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13	■	■	■	9 E	■	■
11 S	19 A	17	■	10	21	20 U	13	13	■	7 J	20 U	16 R	12 O	16 R
2	■	■	■	21	■	21	■	2	■	19 A	■	■	■	9 E
11 S	2	9 E	24	9 E	■	5 T	12 O	8	2	1 C	■	18	19 A	11 S
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6 P
7 J	19 A	10	■	23	20 U	19 A	21	15	■	11 S	14	12 O	24	9 E
20 U	■	19 A	■	20 U	■	■	■	19 A	■	■	■	12 O	■	1 C
21	19 A	16 R	2	19 A	5 T	11 S	■	7 J	19 A	1 C	3	6 P	12 O	5 T
9 E	■	26	■	3	■	2	■	12 O	■	20 U	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10	21	9 E	4	17 D

Substitution ciphers

1 C	12 O	1 C	12 O	19 A	■	21 L	2 I	13 F	9 E	26 G	20 U	19 A	16 R	17 D
19 A	■	14	■	13 F	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21 L	12 O	26 G	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21 L	2 I	15	10	11 S	■	19 A	18	19 A	3	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13 F	■	■	■	9 E	■	■
11 S	19 A	17	■	10	21 L	20 U	13 F	13 F	■	7 J	20 U	16 R	12 O	16 R
2 I	■	■	■	21 L	■	21 L	■	2 I	■	19 A	■	■	■	9 E
11 S	2 I	9 E	24	9 E	■	5 T	12 O	8	2 I	1 C	■	18	19 A	11 S
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6 P
7 J	19 A	10	■	23	20 U	19 A	21 L	15	■	11 S	14	12 O	24	9 E
20 U	■	19 A	■	20 U	■	■	■	19 A	■	■	■	12 O	■	1 C
21 L	19 A	16 R	2 I	19 A	5 T	11 S	■	7 J	19 A	1 C	3	6 P	12 O	5 T
9 E	■	26 G	■	3	■	2 I	■	12 O	■	20 U	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10	21 L	9 E	4	17 D

Substitution ciphers

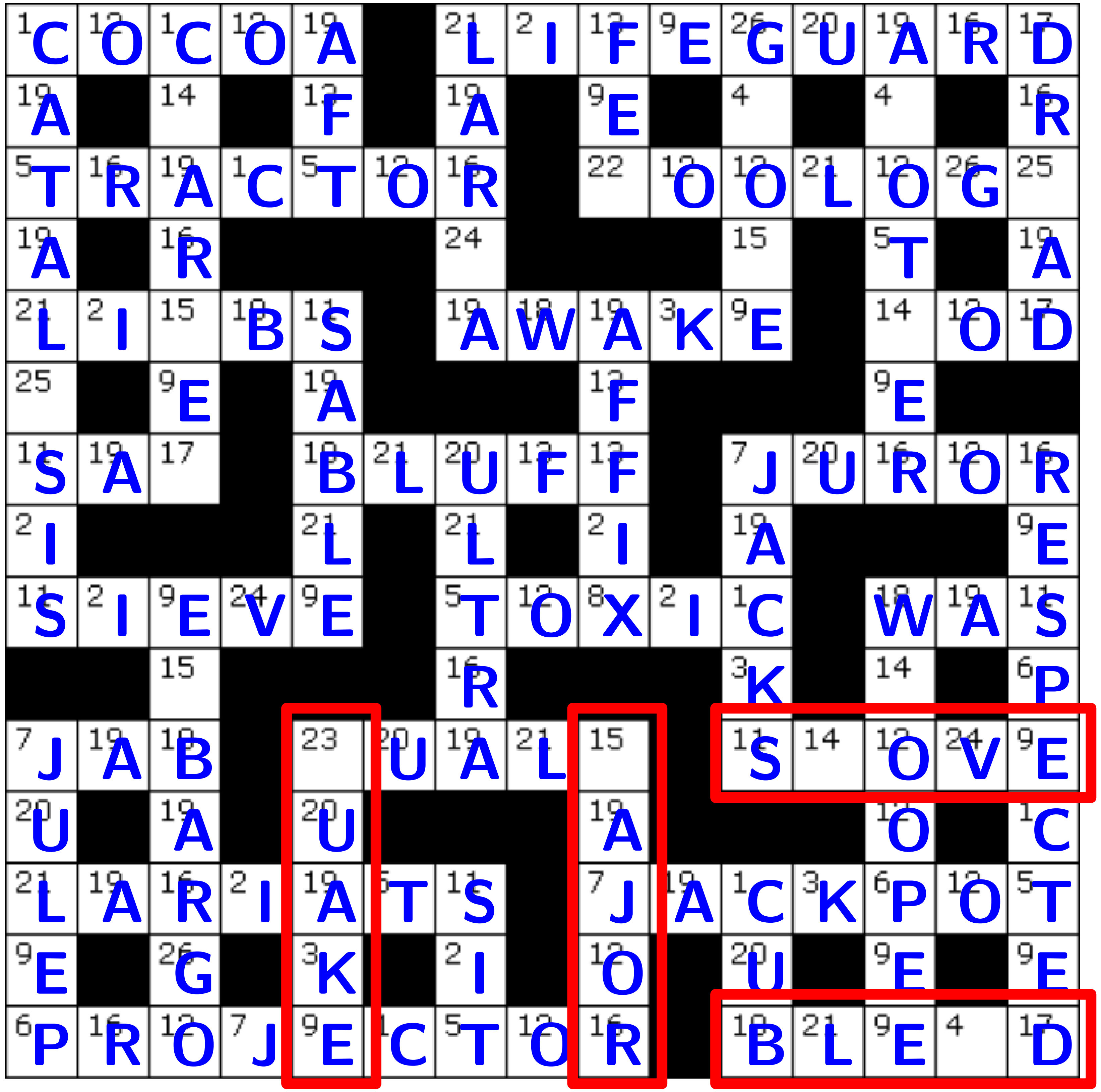


1 C	12 O	1 C	12 O	19 A	■	21 L	2 I	13 F	9 E	26 G	20 U	19 A	16 R	17 D
19 A	■	14	■	13 F	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21 L	12 O	26 G	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21 L	2 I	15	10	11 S	■	19 A	18	19 A	3	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13 F	■	■	■	9 E	■	■
11 S	19 A	17	■	10	21 L	20 U	13 F	13 F	■	7 J	20 U	16 R	12 O	16 R
2 I	■	■	■	21 L	■	21 L	■	2 I	■	19 A	■	■	■	9 E
11 S	2 I	9 E	24	9 E	■	5 T	12 O	8	2 I	1 C	■	18	19 A	11 S
■	■	15	■	■	■	16 R	■	■	■	3	■	14	■	6 P
7 J	19 A	10	■	23	20 U	19 A	21 L	15	■	11 S	14	12 O	24	9 E
20 U	■	19 A	■	20 U	■	■	■	19 A	■	■	■	12 O	■	1 C
21 L	19 A	16 R	2 I	19 A	5 T	11 S	■	7 J	19 A	1 C	3	6 P	12 O	5 T
9 E	■	26 G	■	3	■	2 I	■	12 O	■	20 U	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10	21 L	9 E	4	17 D

Substitution ciphers

1 C	12 O	1 C	12 O	19 A	■	21 L	2 I	13 F	9 E	26 G	20 U	19 A	16 R	17 D
19 A	■	14	■	13 F	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21 L	12 O	26 G	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21 L	2 I	15	10 B	11 S	■	19 A	18 W	19 A	3 K	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13 F	■	■	■	9 E	■	■
11 S	19 A	17	■	10 B	21 L	20 U	13 F	13 F	■	7 J	20 U	16 R	12 O	16 R
2 I	■	■	■	21 L	■	21 L	■	2 I	■	19 A	■	■	■	9 E
11 S	2 I	9 E	24 V	9 E	■	5 T	12 O	8 X	2 I	1 C	■	18 W	19 A	11 S
■	■	15	■	■	■	16 R	■	■	■	3 K	■	14	■	6 P
7 J	19 A	10 B	■	23	20 U	19 A	21 L	15	■	11 S	14	12 O	24 V	9 E
20 U	■	19 A	■	20 U	■	■	■	19 A	■	■	■	12 O	■	1 C
21 L	19 A	16 R	2 I	19 A	5 T	11 S	■	7 J	19 A	1 C	3 K	6 P	12 O	5 T
9 E	■	26 G	■	3 K	■	2 I	■	12 O	■	20 U	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10 B	21 L	9 E	4	17 D

Substitution ciphers

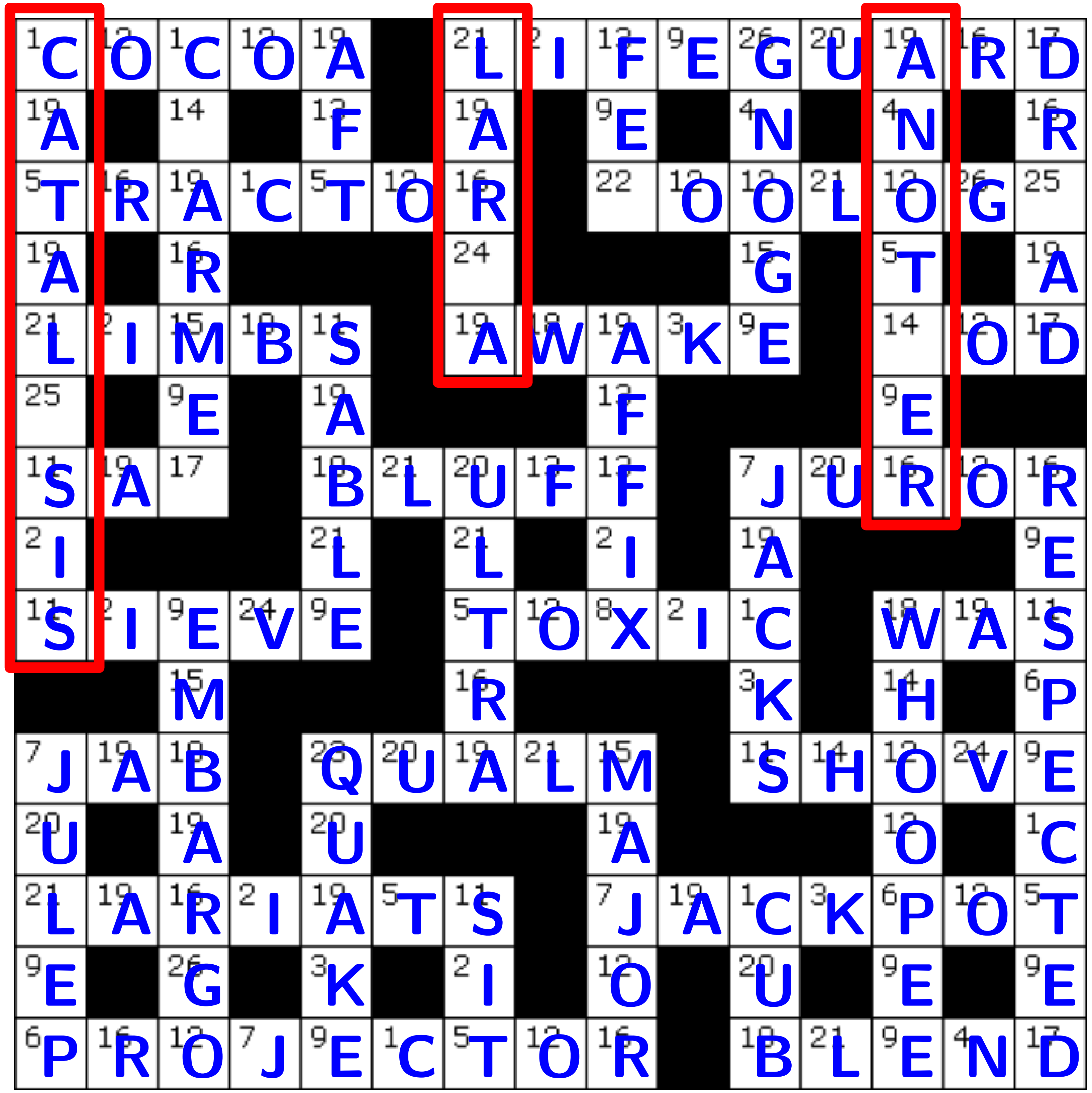


1 C	12 O	1 C	12 O	19 A	■	21 L	2 I	13 F	9 E	26 G	20 U	19 A	16 R	17 D
19 A	■	14	■	13 F	■	19 A	■	9 E	■	4	■	4	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21 L	12 O	26 G	25
19 A	■	16 R	■	■	■	24	■	■	■	15	■	5 T	■	19 A
21 L	2 I	15	10 B	11 S	■	19 A	18 W	19 A	3 K	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13 F	■	■	■	9 E	■	■
11 S	19 A	17	■	10 B	21 L	20 U	13 F	13 F	■	7 J	20 U	16 R	12 O	16 R
2 I	■	■	■	21 L	■	21 L	■	2 I	■	19 A	■	■	■	9 E
11 S	2 I	9 E	24 V	9 E	■	5 T	12 O	8 X	2 I	1 C	■	18 W	19 A	11 S
■	■	15	■	■	■	16 R	■	■	■	3 K	■	14	■	6 P
7 J	19 A	10 B	■	23	20 U	19 A	21 L	15	■	11 S	14	12 O	24 V	9 E
20 U	■	19 A	■	20 U	■	■	■	19 A	■	■	■	12 O	■	1 C
21 L	19 A	16 R	2 I	19 A	5 T	11 S	■	7 J	19 A	1 C	3 K	6 P	12 O	5 T
9 E	■	26 G	■	3 K	■	2 I	■	12 O	■	20 U	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10 B	21 L	9 E	4	17 D

Substitution ciphers

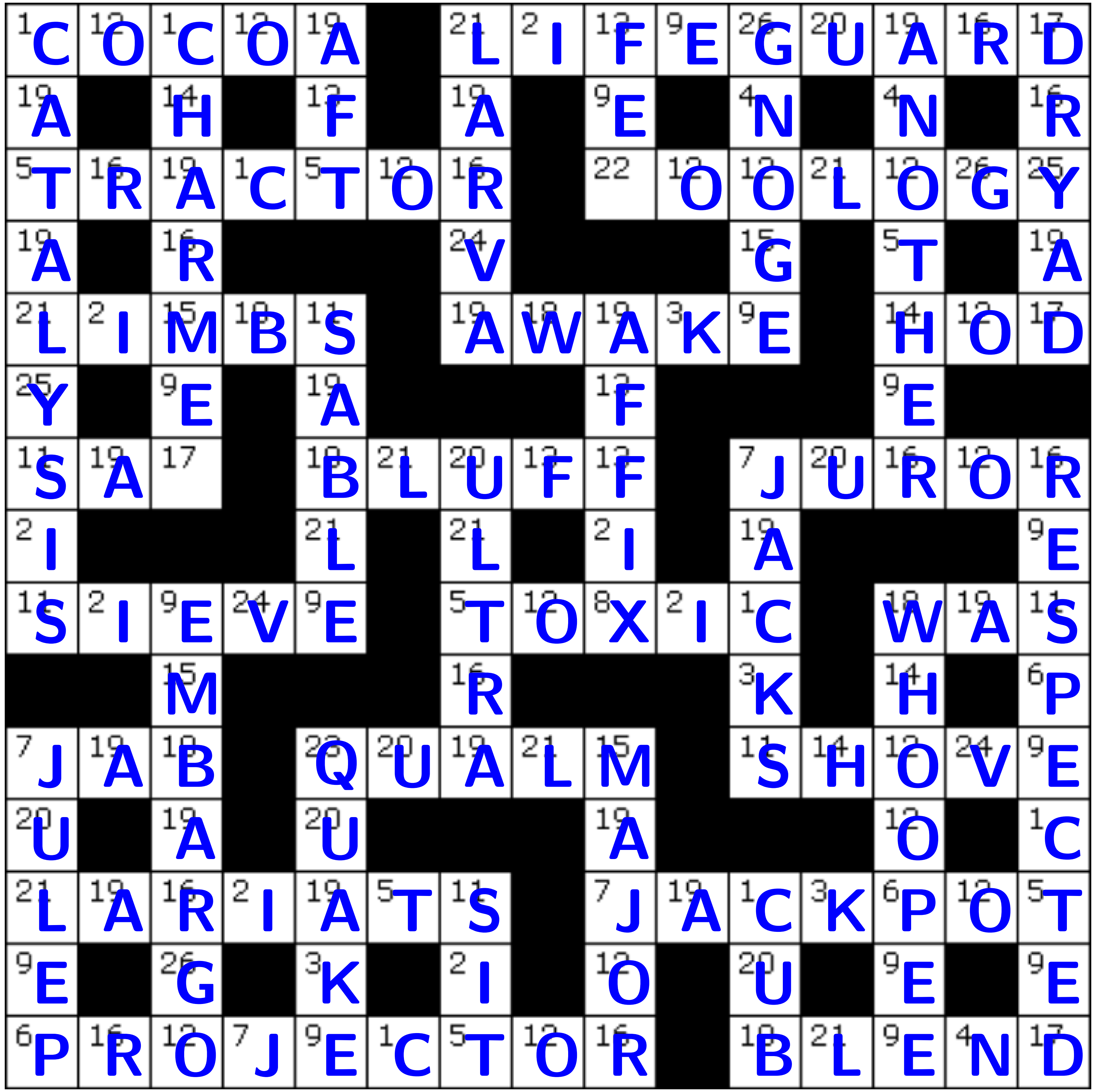
1 C	12 O	1 C	12 O	19 A	■	21 L	2 I	13 F	9 E	26 G	20 U	19 A	16 R	17 D
19 A	■	14	■	13 F	■	19 A	■	9 E	■	4 N	■	4 N	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21 L	12 O	26 G	25
19 A	■	16 R	■	■	■	24	■	■	■	15 G	■	5 T	■	19 A
21 L	2 I	15 M	10 B	11 S	■	19 A	18 W	19 A	3 K	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13 F	■	■	■	9 E	■	■
11 S	19 A	17	■	10 B	21 L	20 U	13 F	13 F	■	7 J	20 U	16 R	12 O	16 R
2 I	■	■	■	21 L	■	21 L	■	2 I	■	19 A	■	■	■	9 E
11 S	2 I	9 E	24 V	9 E	■	5 T	12 O	8 X	2 I	1 C	■	18 W	19 A	11 S
■	■	15 M	■	■	■	16 R	■	■	■	3 K	■	14 H	■	6 P
7 J	19 A	10 B	■	23 Q	20 U	19 A	21 L	15 M	■	11 S	14 H	12 O	24 V	9 E
20 U	■	19 A	■	20 U	■	■	■	19 A	■	■	■	12 O	■	1 C
21 L	19 A	16 R	2 I	19 A	5 T	11 S	■	7 J	19 A	1 C	3 K	6 P	12 O	5 T
9 E	■	26 G	■	3 K	■	2 I	■	12 O	■	20 U	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10 B	21 L	9 E	4 N	17 D

Substitution ciphers



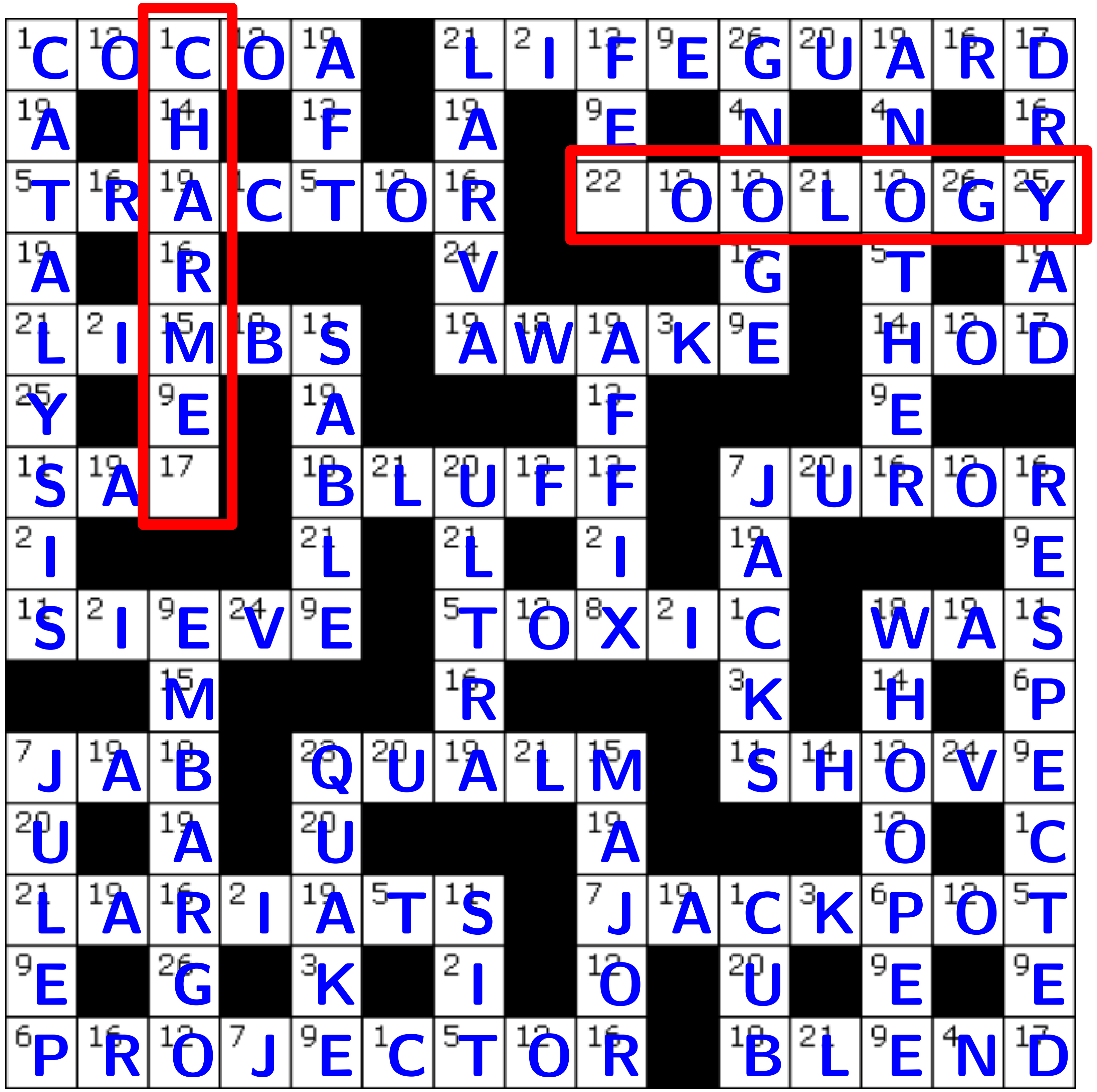
1 C	12 O	1 C	12 O	19 A	■	21 L	2 I	13 F	9 E	26 G	20 U	19 A	16 R	17 D
19 A	■	14	■	13 F	■	19 A	■	9 E	■	4 N	■	4 N	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21 L	12 O	26 G	25
19 A	■	16 R	■	■	■	24	■	■	■	15 G	■	5 T	■	19 A
21 L	2 I	15 M	10 B	11 S	■	19 A	18 W	19 A	3 K	9 E	■	14	12 O	17 D
25	■	9 E	■	19 A	■	■	■	13 F	■	■	■	9 E	■	■
11 S	19 A	17	■	10 B	21 L	20 U	13 F	13 F	■	7 J	20 U	16 R	12 O	16 R
2 I	■	■	■	21 L	■	21 L	■	2 I	■	19 A	■	■	■	9 E
11 S	2 I	9 E	24 V	9 E	■	5 T	12 O	8 X	2 I	1 C	■	18 W	19 A	11 S
■	■	15 M	■	■	■	16 R	■	■	■	3 K	■	14 H	■	6 P
7 J	19 A	10 B	■	23 Q	20 U	19 A	21 L	15 M	■	11 S	14 H	12 O	24 V	9 E
20 U	■	19 A	■	20 U	■	■	■	19 A	■	■	■	12 O	■	1 C
21 L	19 A	16 R	2 I	19 A	5 T	11 S	■	7 J	19 A	1 C	3 K	6 P	12 O	5 T
9 E	■	26 G	■	3 K	■	2 I	■	12 O	■	20 U	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10 B	21 L	9 E	4 N	17 D

Substitution ciphers



1 C	12 O	1 C	12 O	19 A	■	21 L	2 I	13 F	9 E	26 G	20 U	19 A	16 R	17 D
19 A	■	14 H	■	13 F	■	19 A	■	9 E	■	4 N	■	4 N	■	16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R	■	22	12 O	12 O	21 L	12 O	26 G	25 Y
19 A	■	16 R	■	■	■	24 V	■	■	■	15 G	■	5 T	■	19 A
21 L	2 I	15 M	10 B	11 S	■	19 A	18 W	19 A	3 K	9 E	■	14 H	12 O	17 D
25 Y	■	9 E	■	19 A	■	■	■	13 F	■	■	■	9 E	■	■
11 S	19 A	17	■	10 B	21 L	20 U	13 F	13 F	■	7 J	20 U	16 R	12 O	16 R
2 I	■	■	■	21 L	■	21 L	■	2 I	■	19 A	■	■	■	9 E
11 S	2 I	9 E	24 V	9 E	■	5 T	12 O	8 X	2 I	1 C	■	18 W	19 A	11 S
■	■	15 M	■	■	■	16 R	■	■	■	3 K	■	14 H	■	6 P
7 J	19 A	10 B	■	23 Q	20 U	19 A	21 L	15 M	■	11 S	14 H	12 O	24 V	9 E
20 U	■	19 A	■	20 U	■	■	■	19 A	■	■	■	12 O	■	1 C
21 L	19 A	16 R	2 I	19 A	5 T	11 S	■	7 J	19 A	1 C	3 K	6 P	12 O	5 T
9 E	■	26 G	■	3 K	■	2 I	■	12 O	■	20 U	■	9 E	■	9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R	■	10 B	21 L	9 E	4 N	17 D

Substitution ciphers



1 C	12 O	1 C	12 O	19 A		21 L	2 I	13 F	9 E	26 G	20 U	19 A	16 R	17 D
19 A		14 H		13 F		19 A		9 E		4 N		4 N		16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R		22	12 O	12 O	21 L	12 O	26 G	25 Y
19 A		16 R				24 V				13 G		5 T		19 A
21 L	2 I	15 M	10 B	11 S		19 A	18 W	19 A	3 K	9 E		14 H	12 O	17 D
25 Y		9 E		19 A				13 F				9 E		
11 S	19 A	17		10 B	21 L	20 U	13 F	13 F		7 J	20 U	16 R	12 O	16 R
2 I				21 L		21 L		2 I		19 A				9 E
11 S	2 I	9 E	24 V	9 E		5 T	12 O	8 X	2 I	1 C		18 W	19 A	11 S
		15 M				16 R				3 K		14 H		6 P
7 J	19 A	10 B		23 Q	20 U	19 A	21 L	15 M		11 S	14 H	12 O	24 V	9 E
20 U		19 A		20 U				19 A				12 O		1 C
21 L	19 A	16 R	2 I	19 A	5 T	11 S		7 J	19 A	1 C	3 K	6 P	12 O	5 T
9 E		26 G		3 K		2 I		12 O		20 U		9 E		9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R		10 B	21 L	9 E	4 N	17 D

Substitution ciphers

1 C	12 O	1 C	12 O	19 A		21 L	2 I	13 F	9 E	26 G	20 U	19 A	16 R	17 D
19 A		14 H		13 F		19 A		9 E		4 N		4 N		16 R
5 T	16 R	19 A	1 C	5 T	12 O	16 R		22 Z	12 O	12 O	21 L	12 O	26 G	25 Y
19 A		16 R				24 V				15 G		5 T		19 A
21 L	2 I	15 M	10 B	11 S		19 A	18 W	19 A	3 K	9 E		14 H	12 O	17 D
25 Y		9 E		19 A				13 F				9 E		
11 S	19 A	17 D		10 B	21 L	20 U	13 F	13 F		7 J	20 U	16 R	12 O	16 R
2 I				21 L		21 L		2 I		19 A				9 E
11 S	2 I	9 E	24 V	9 E		5 T	12 O	8 X	2 I	1 C		18 W	19 A	11 S
		15 M				16 R				3 K		14 H		6 P
7 J	19 A	10 B		23 Q	20 U	19 A	21 L	15 M		11 S	14 H	12 O	24 V	9 E
20 U		19 A		20 U				19 A				12 O		1 C
21 L	19 A	16 R	2 I	19 A	5 T	11 S		7 J	19 A	1 C	3 K	6 P	12 O	5 T
9 E		26 G		3 K		2 I		12 O		20 U		9 E		9 E
6 P	16 R	12 O	7 J	9 E	1 C	5 T	12 O	16 R		10 B	21 L	9 E	4 N	17 D

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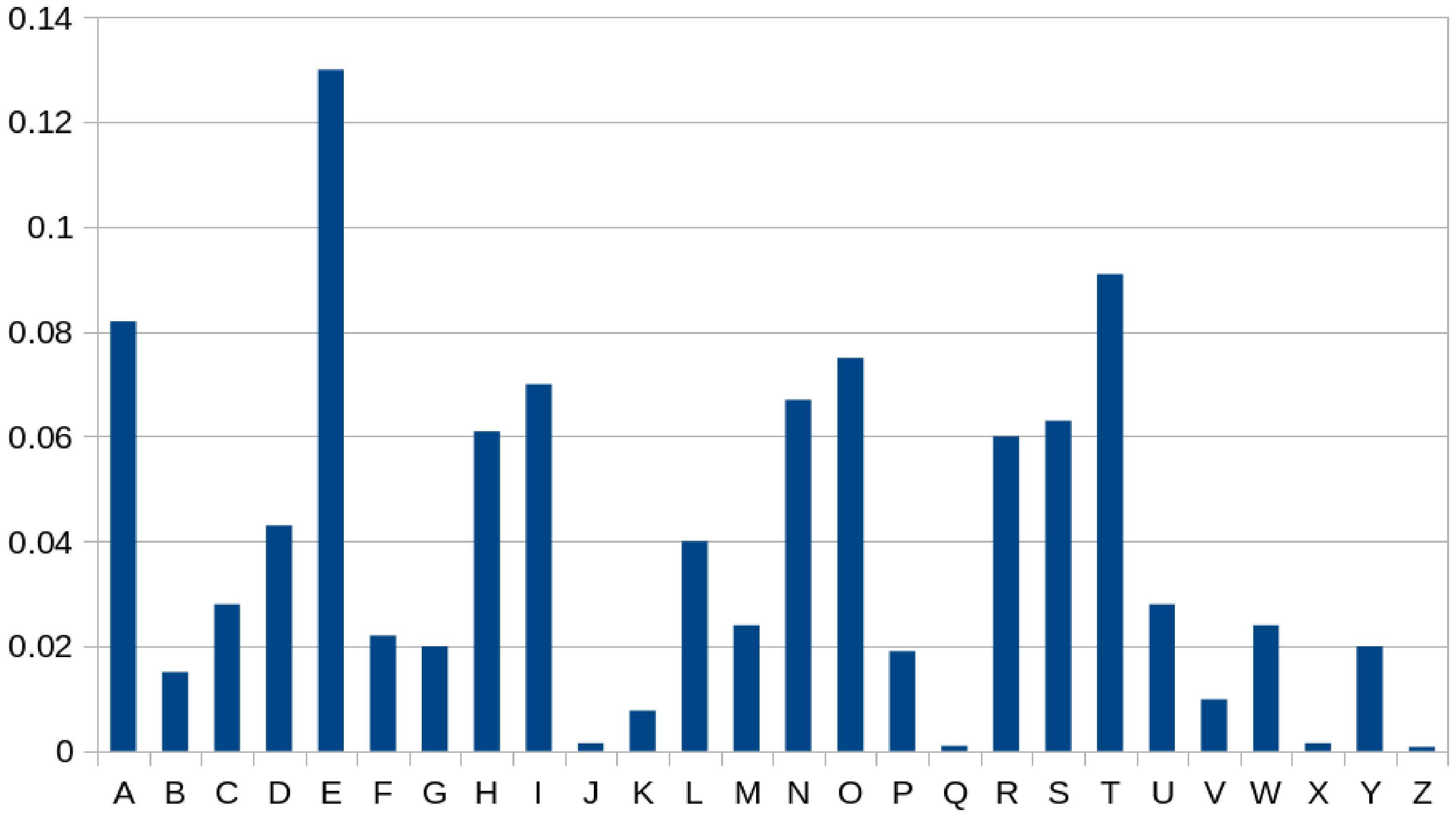
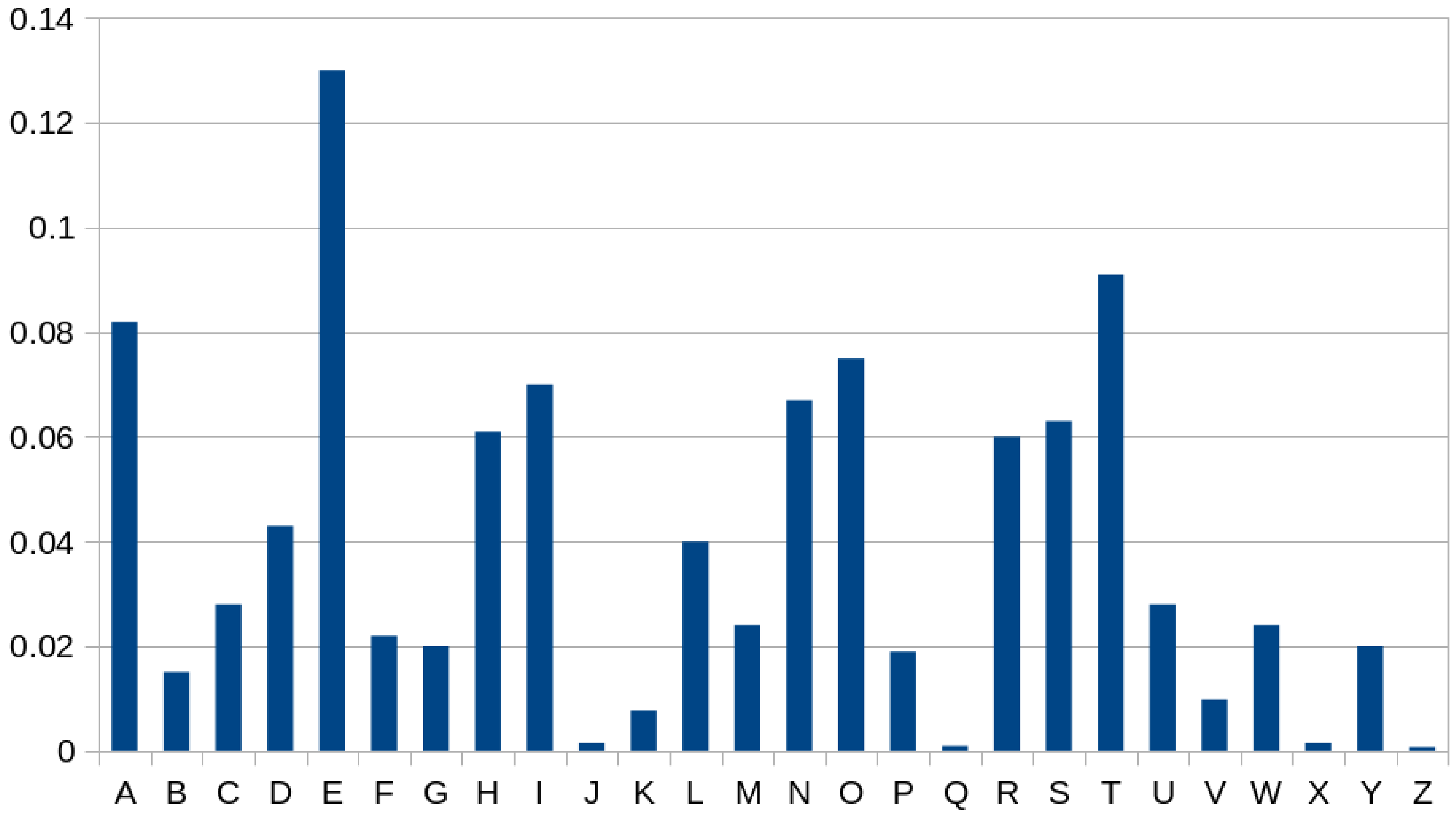


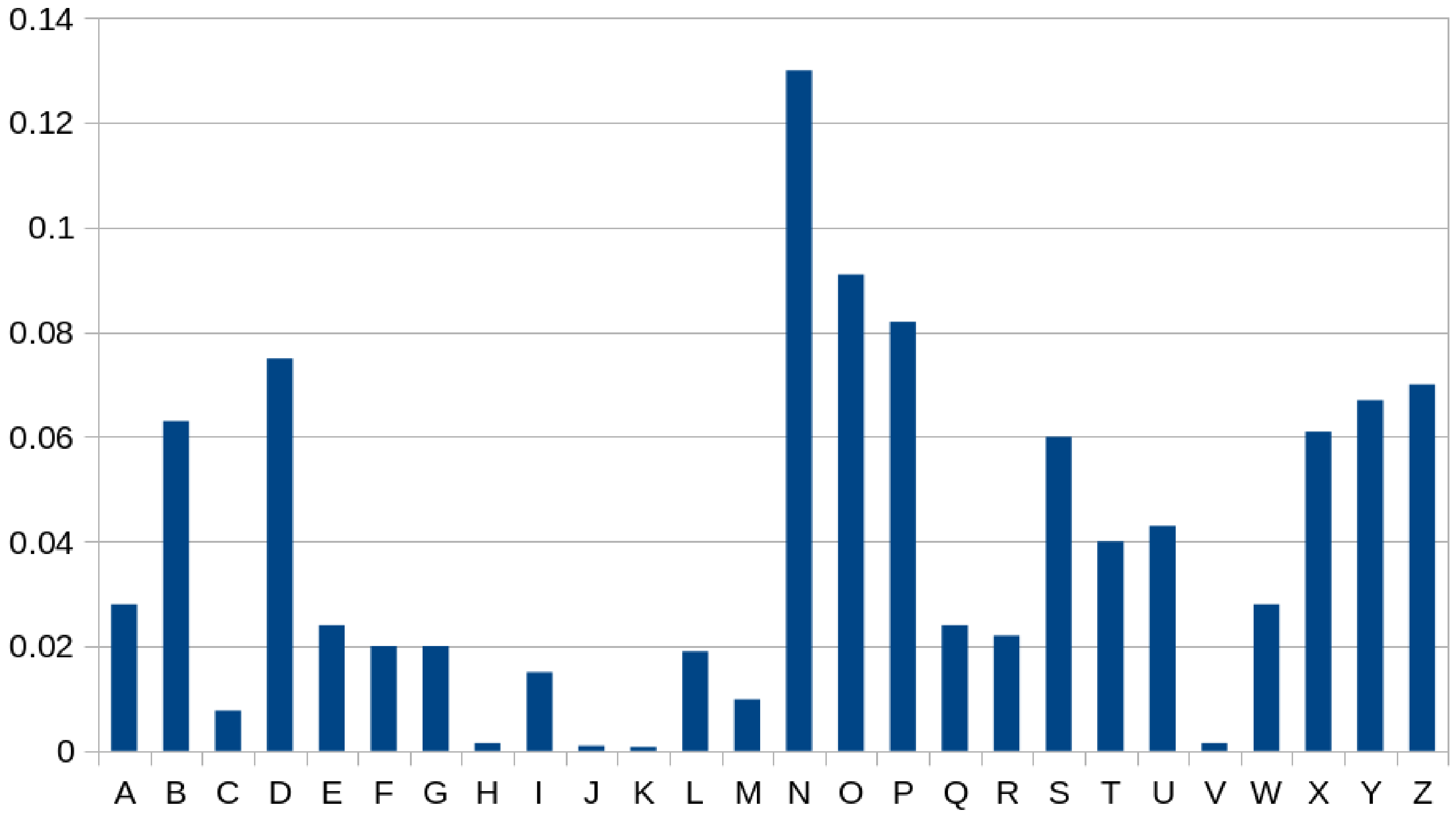
Substitution ciphers

Compare the expected frequencies in the message language with the observed frequencies in the ciphertext

Expected



Observed (in the ciphertext)



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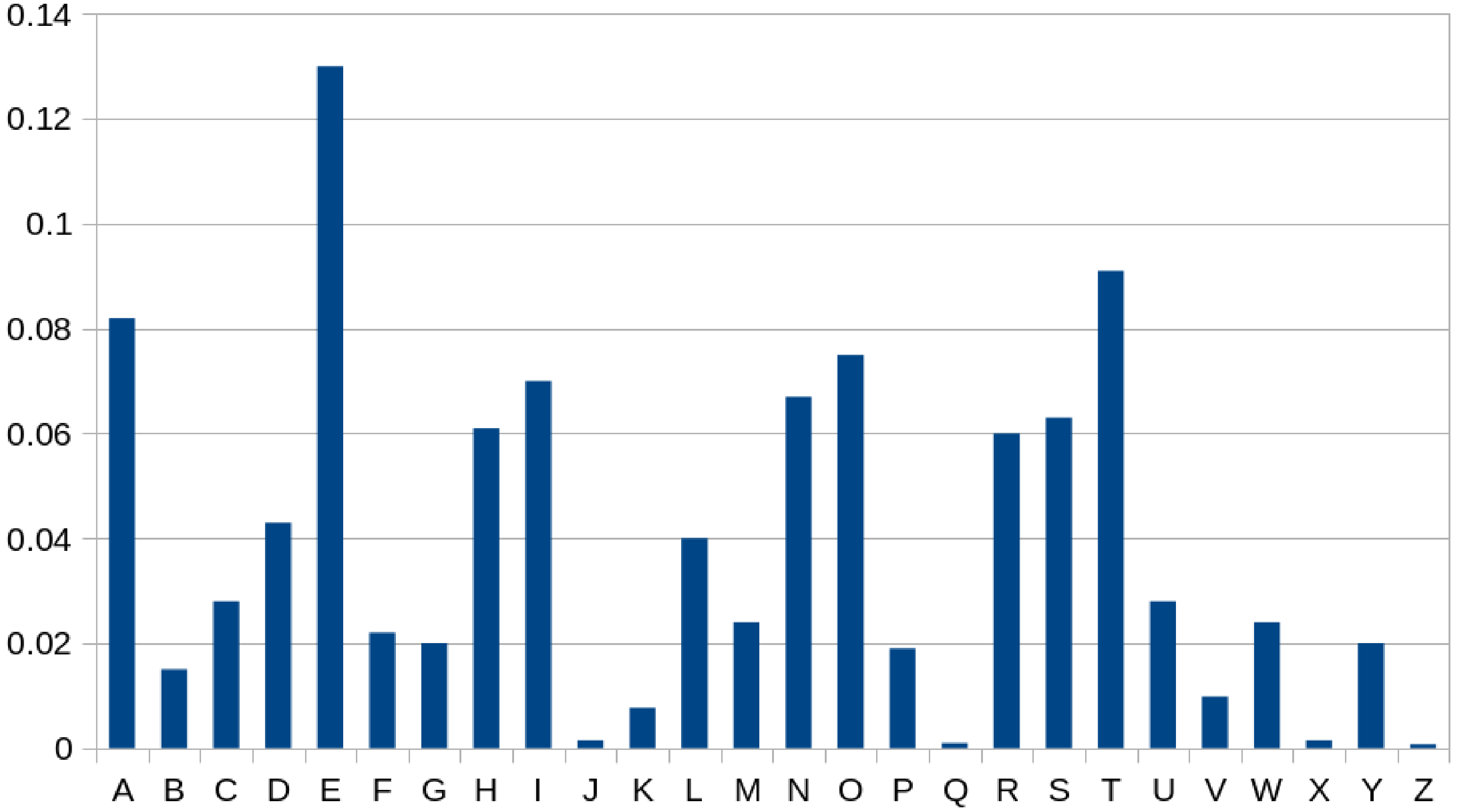
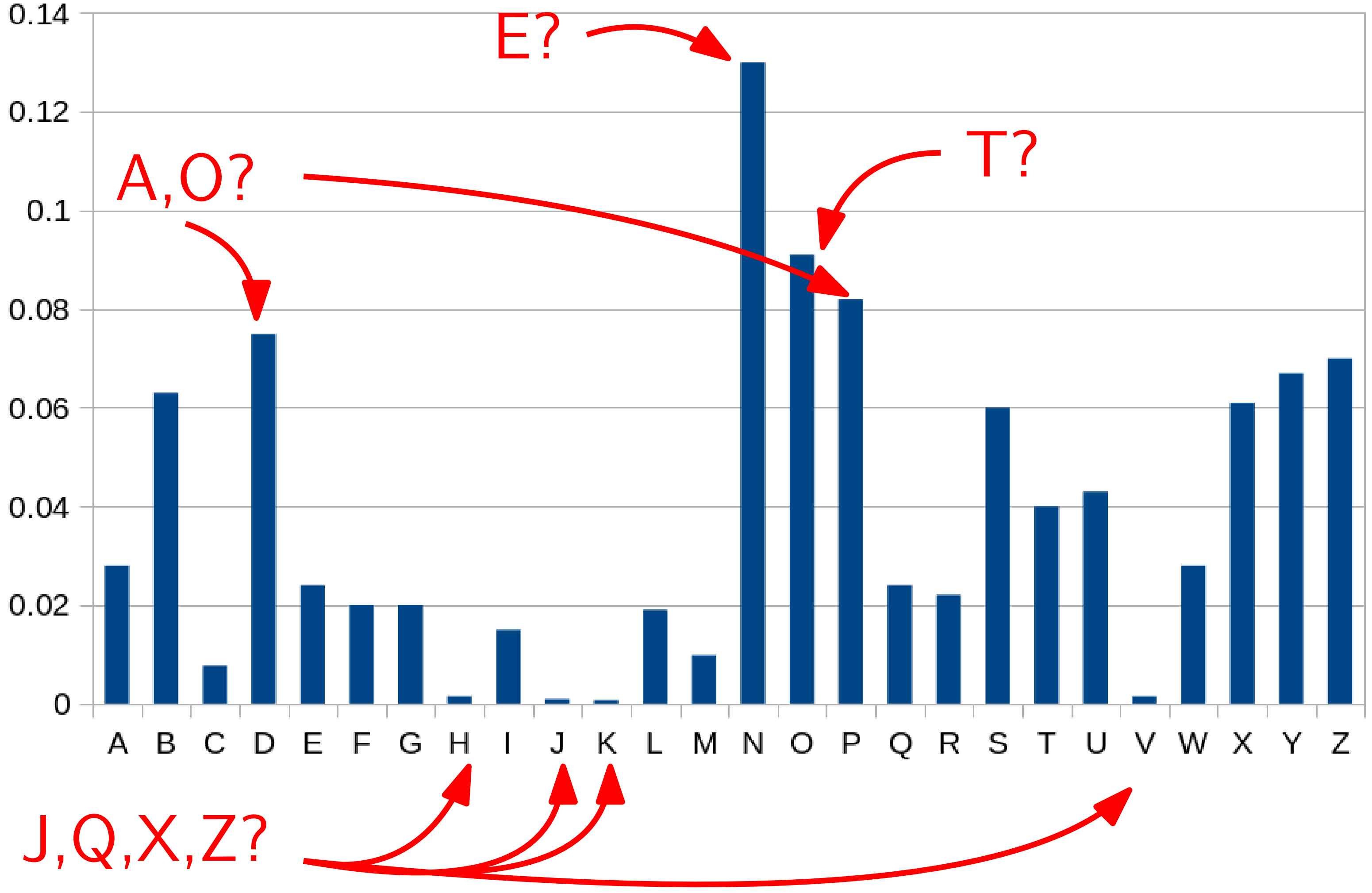


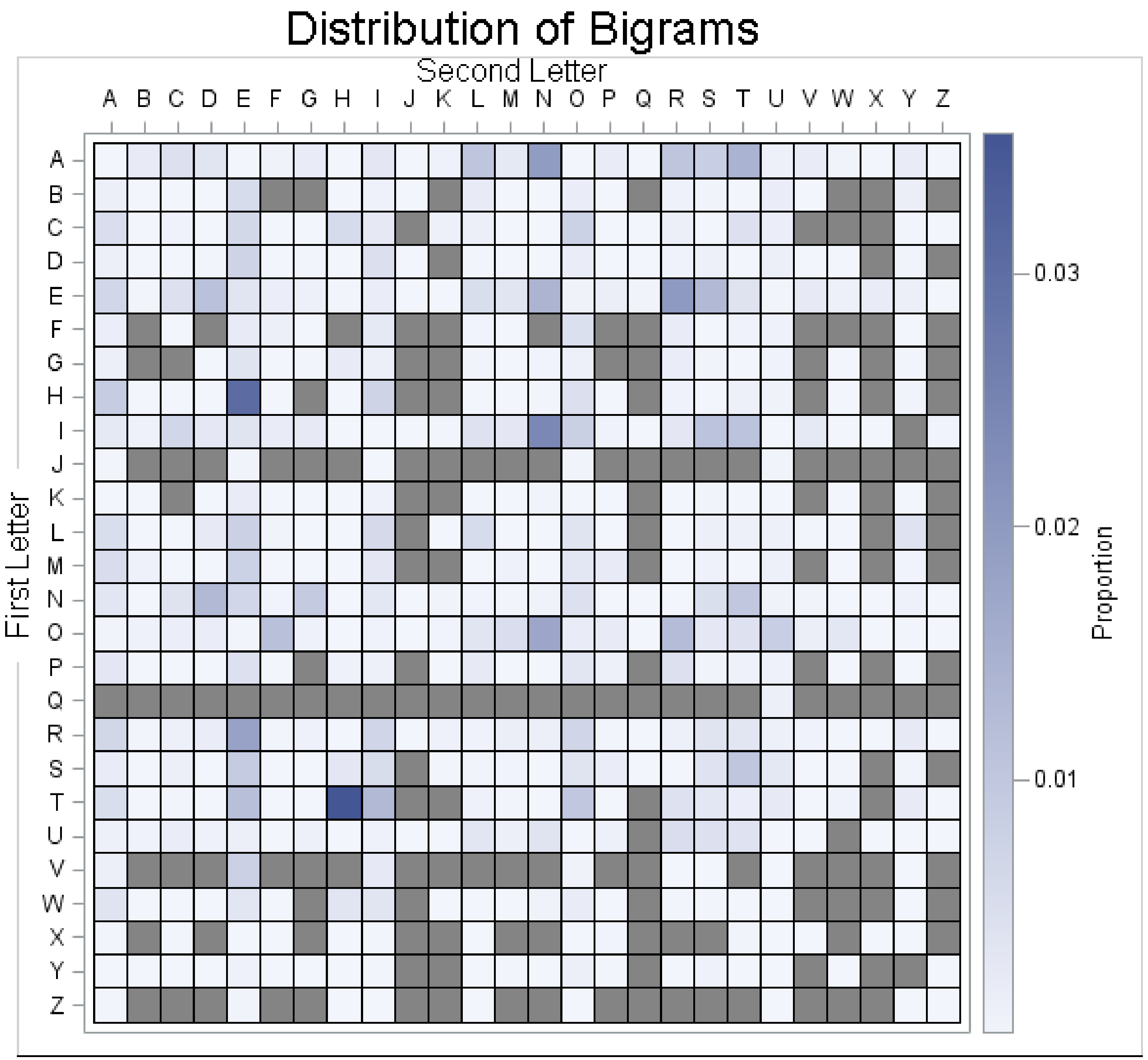
Observed (in the ciphertext)



Guess part of the key and use the guesses to break the cipher (as shown before)

Substitution ciphers

The same analysis can be repeated for bigrams, trigrams, etc



Vigenère cipher

Monoalphabetic substitution ciphers are vulnerable to frequency analysis

Blaise de Vigenère
(1523 - 1596)

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$$s_i = \begin{cases} 0 & \text{if } k_i = \text{A} \\ 1 & \text{if } k_i = \text{B} \\ 2 & \text{if } k_i = \text{C} \\ \ldots & \\ 25 & \text{if } k_i = \text{Z} \end{cases}$$

Blaise de Vigenère
(1523 - 1596)

Vigenère cipher

Monoalphabetic substitution ciphers are vulnerable to frequency analysis

Idea: mix up the letter frequencies by using different shift ciphers for different positions of the plaintext

The key $k = k_0, k_1, \ldots, k_{t-1}$ is a (non empty) string in $\{A, B, \ldots, Z\}^t$, for some t

The generic i-th character k_i of the key corresponds to the shift $s_i \in \{0, \ldots, 25\}$ of the i-th shift cipher

$$s_i = \begin{cases} 0 & \text{if } k_i = \text{A} \\ 1 & \text{if } k_i = \text{B} \\ 2 & \text{if } k_i = \text{C} \\ \ldots & \\ 25 & \text{if } k_i = \text{Z} \end{cases}$$

The generic i-th character m_i of the message $m = m_0 m_1 \ldots m_{\ell-1}$ is encrypted using a shift cipher with shift $s_{i \bmod t}$

Blaise de Vigenère
(1523 - 1596)

Vigenère cipher

$\mathcal{M} = \{A, \ldots, Z\}^*$

$\mathcal{K} = \{A, \ldots, Z\}^t$

$\mathcal{C} = \{A, \ldots, Z\}^*$

Vigenère cipher

$\mathcal{M} = \{A, \ldots, Z\}^*$

$\mathcal{K} = \{A, \ldots, Z\}^t$

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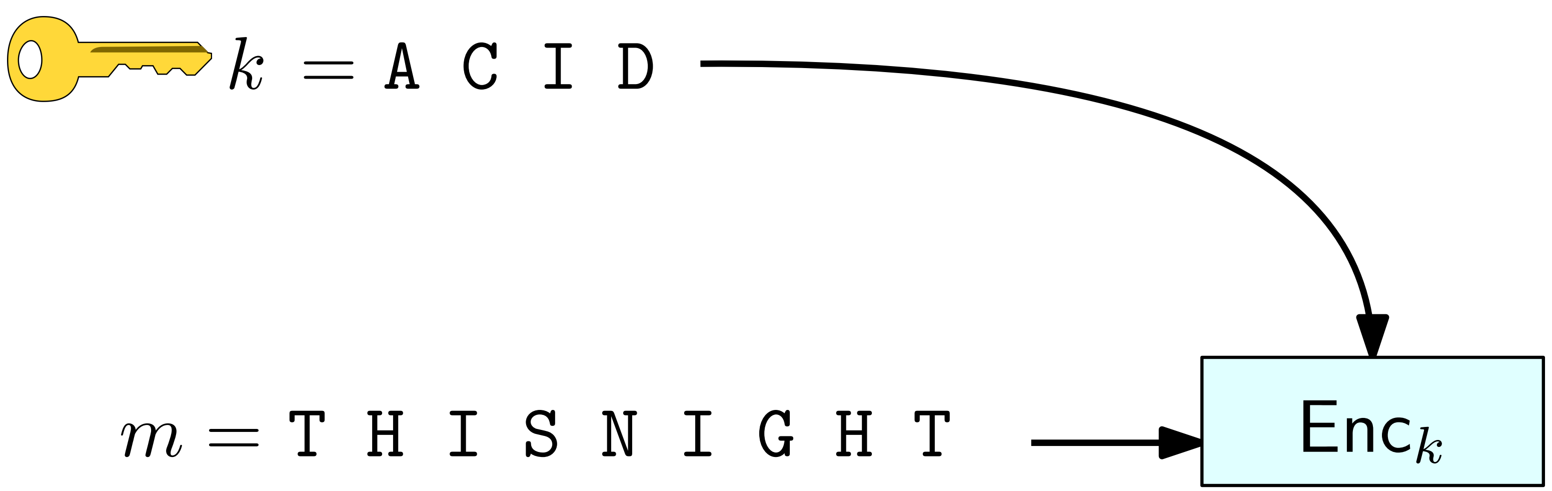

k = A C I D

m = T H I S N I G H T

Enc_k

Vigenère cipher

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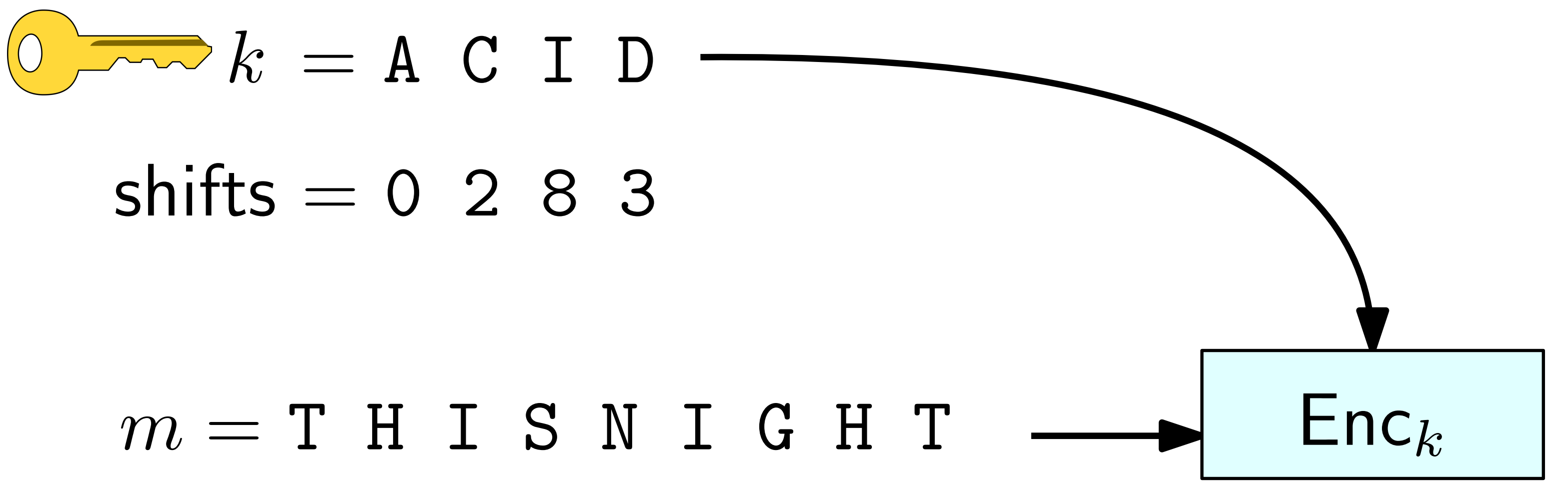


k = A C I D

shifts = 0 2 8 3

m = T H I S N I G H T

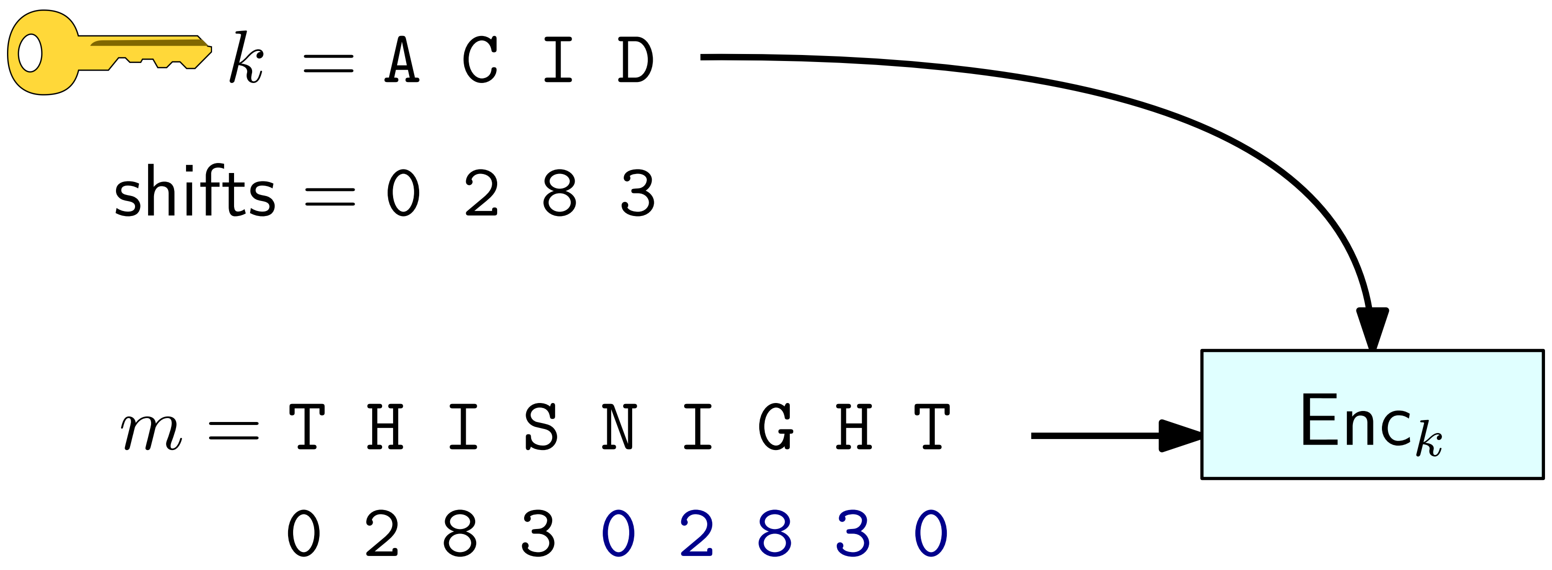
Enc_k

Vigenère cipher

$\mathcal{M} = \{A, \ldots, Z\}^*$

$\mathcal{K} = \{A, \ldots, Z\}^t$

$\mathcal{C} = \{A, \ldots, Z\}^*$



k = A C I D

shifts = 0 2 8 3

m = T H I S N I G H T

0 2 8 3 0 2 8 3 0

Enc_k

Vigenère cipher

$\mathcal{M} = \{A, \ldots, Z\}^*$

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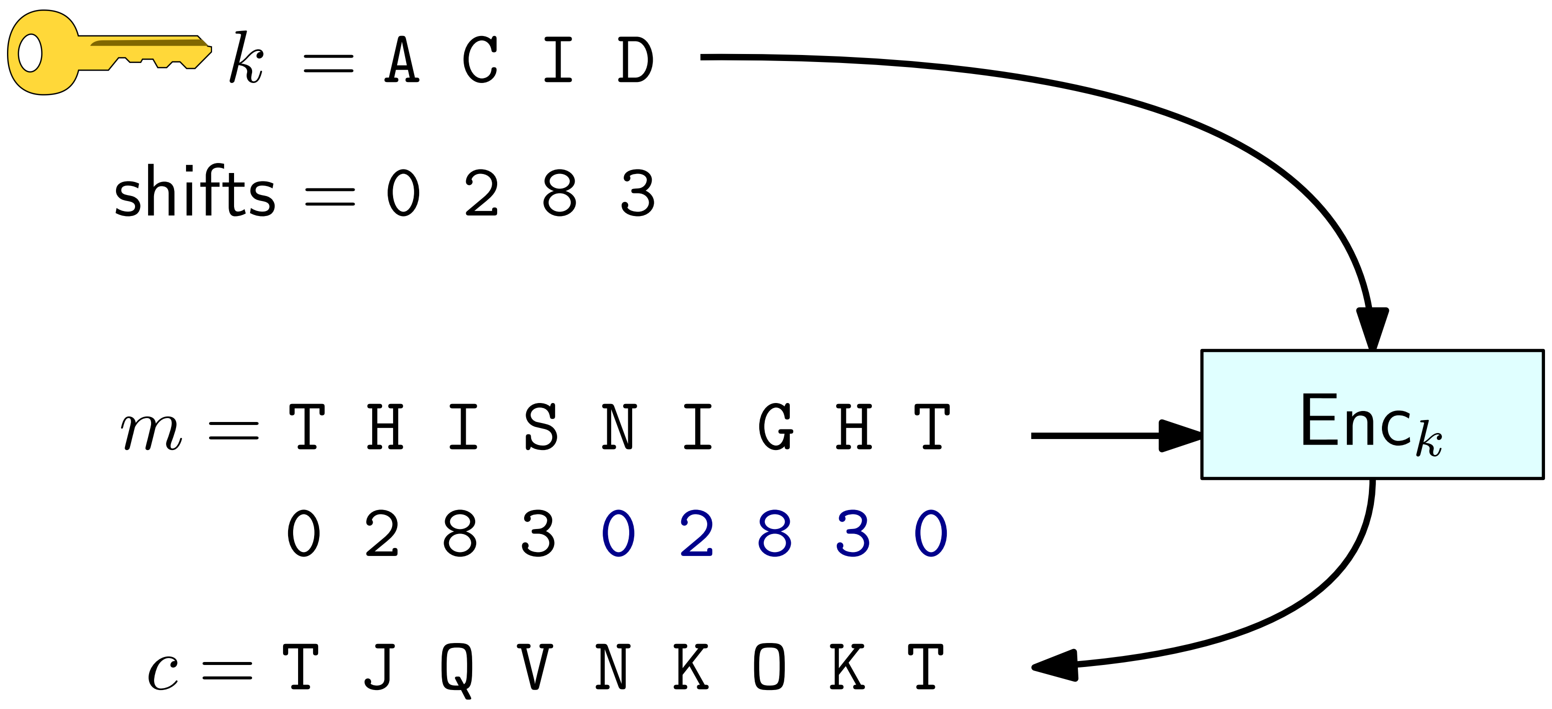

k = A C I D

shifts = 0 2 8 3

m = T H I S N I G H T

0 2 8 3 0 2 8 3 0

c = T J Q V N K O K T

Enc_k

Vigenère cipher

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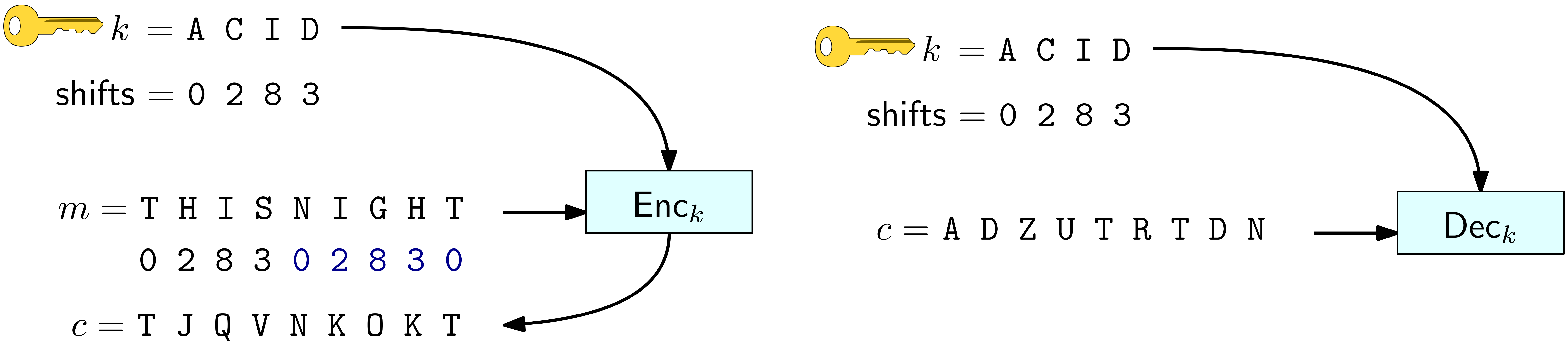
$\mathcal{K} = \{A, \dots, Z\}^t$

$\mathcal{C} = \{A, \dots, Z\}^*$



$k =$ A C I D

shifts $=$ 0 2 8 3

$m =$ T H I S N I G H T

0 2 8 3 0 2 8 3 0

$c =$ T J Q V N K O K T

Enc$_k$

$k =$ A C I D

shifts $=$ 0 2 8 3

$c =$ A D Z U T R T D N

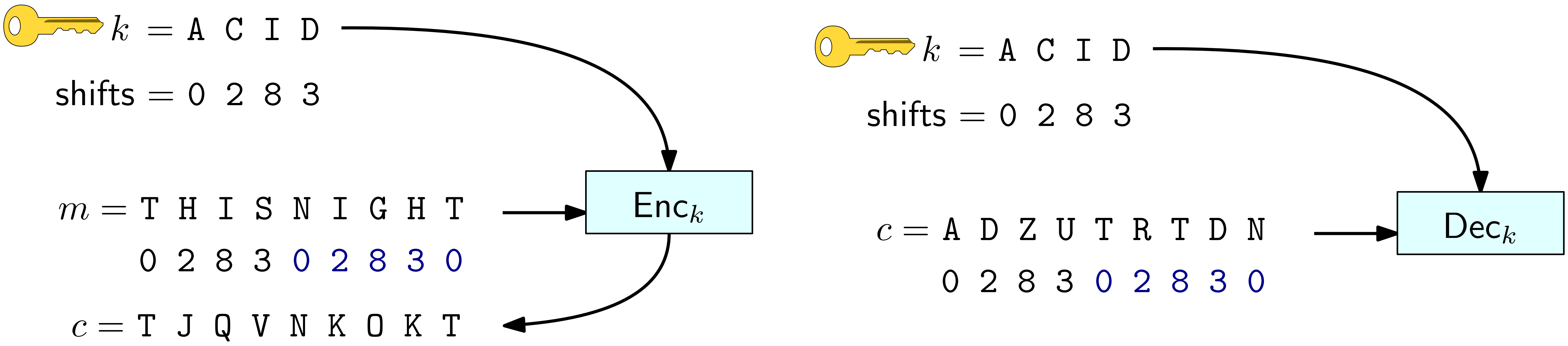
Dec$_k$

Vigenère cipher

$\mathcal{M} = \{A, \ldots, Z\}^*$

$\mathcal{K} = \{A, \ldots, Z\}^t$

$\mathcal{C} = \{A, \ldots, Z\}^*$



k = A C I D

shifts = 0 2 8 3

$m =$ T H I S N I G H T

0 2 8 3 0 2 8 3 0

Enc$_k$

$c =$ T J Q V N K O K T

k = A C I D

shifts = 0 2 8 3

$c =$ A D Z U T R T D N

0 2 8 3 0 2 8 3 0

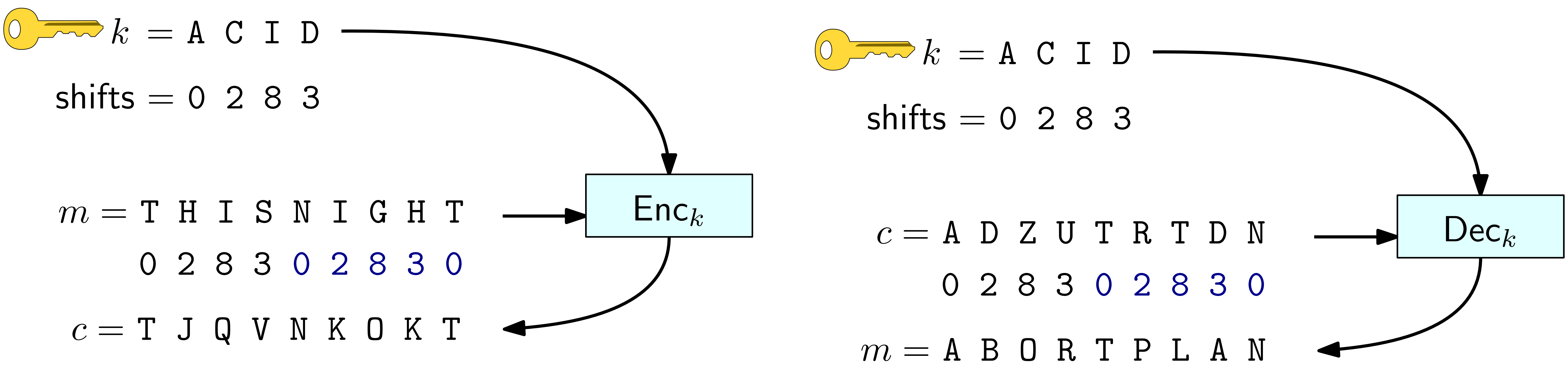
Dec$_k$

Vigenère cipher

$\mathcal{M} = \{A, \ldots, Z\}^*$

$\mathcal{K} = \{A, \ldots, Z\}^t$

$\mathcal{C} = \{A, \ldots, Z\}^*$



k = A C I D

shifts = 0 2 8 3

m = T H I S N I G H T

0 2 8 3 0 2 8 3 0

c = T J Q V N K O K T

k = A C I D

shifts = 0 2 8 3

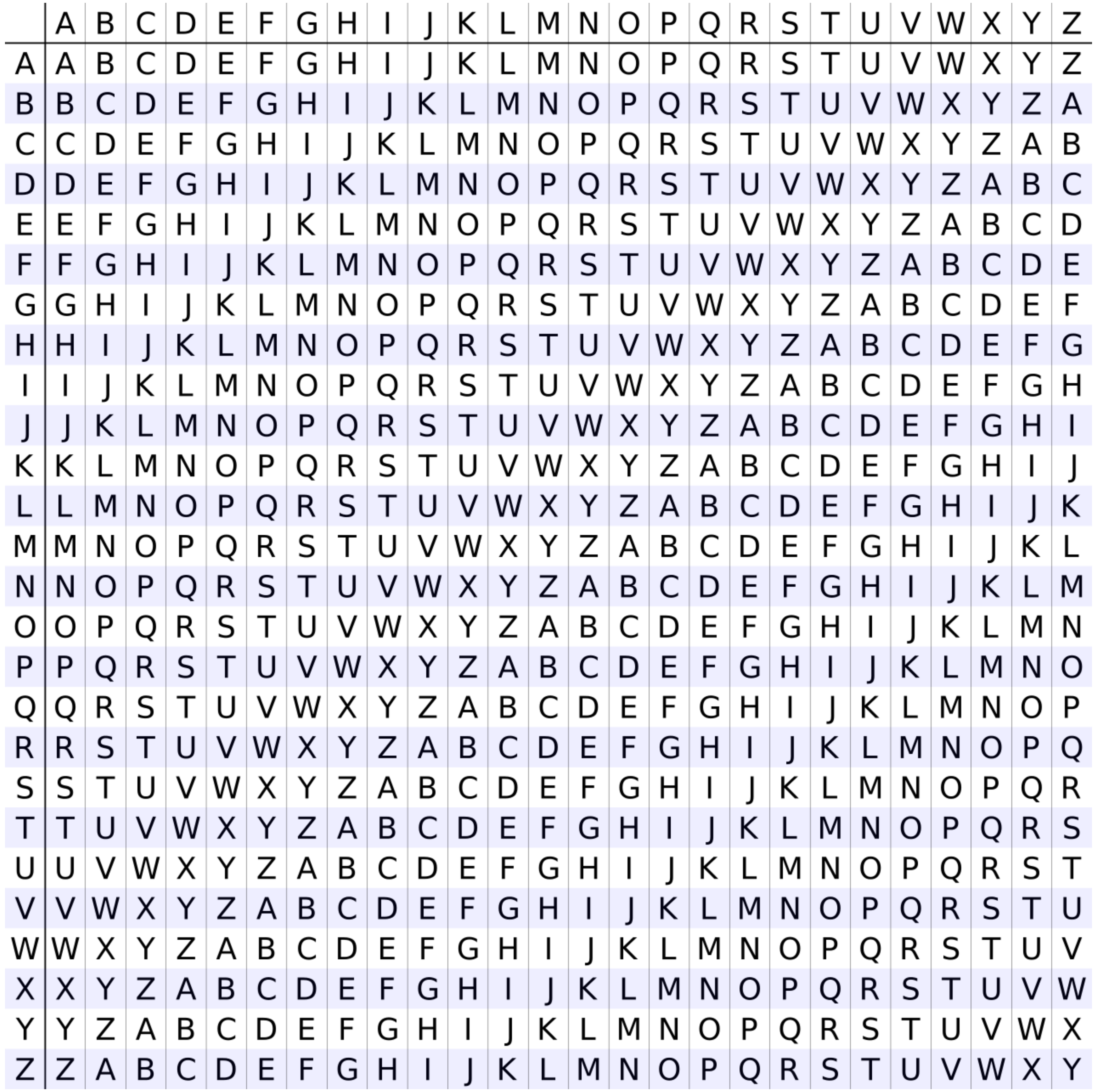
c = A D Z U T R T D N

0 2 8 3 0 2 8 3 0

m = A B O R T P L A N

Vigenère cipher

A table called “tabula recta” can be used to aid encryption and decryption

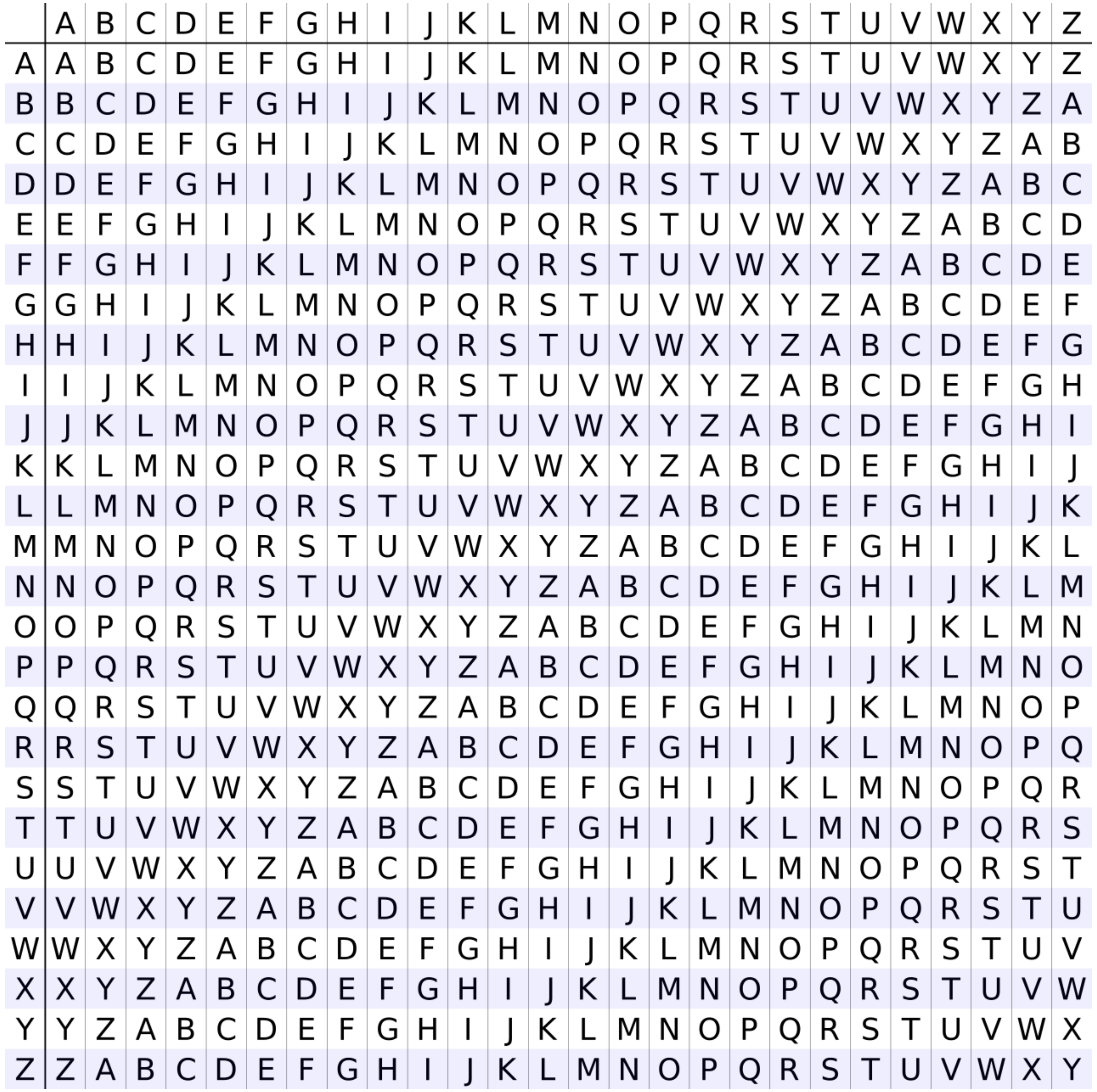


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T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

Vigenère cipher

A table called "tabula recta" can be used to aid encryption and decryption

E.g., to encrypt the plaintext character `K` with the shift corresponding to the key character `F`, look up the letter at the intersection of the row labeled `K` and the column labeled `F` (or vice-versa)



	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

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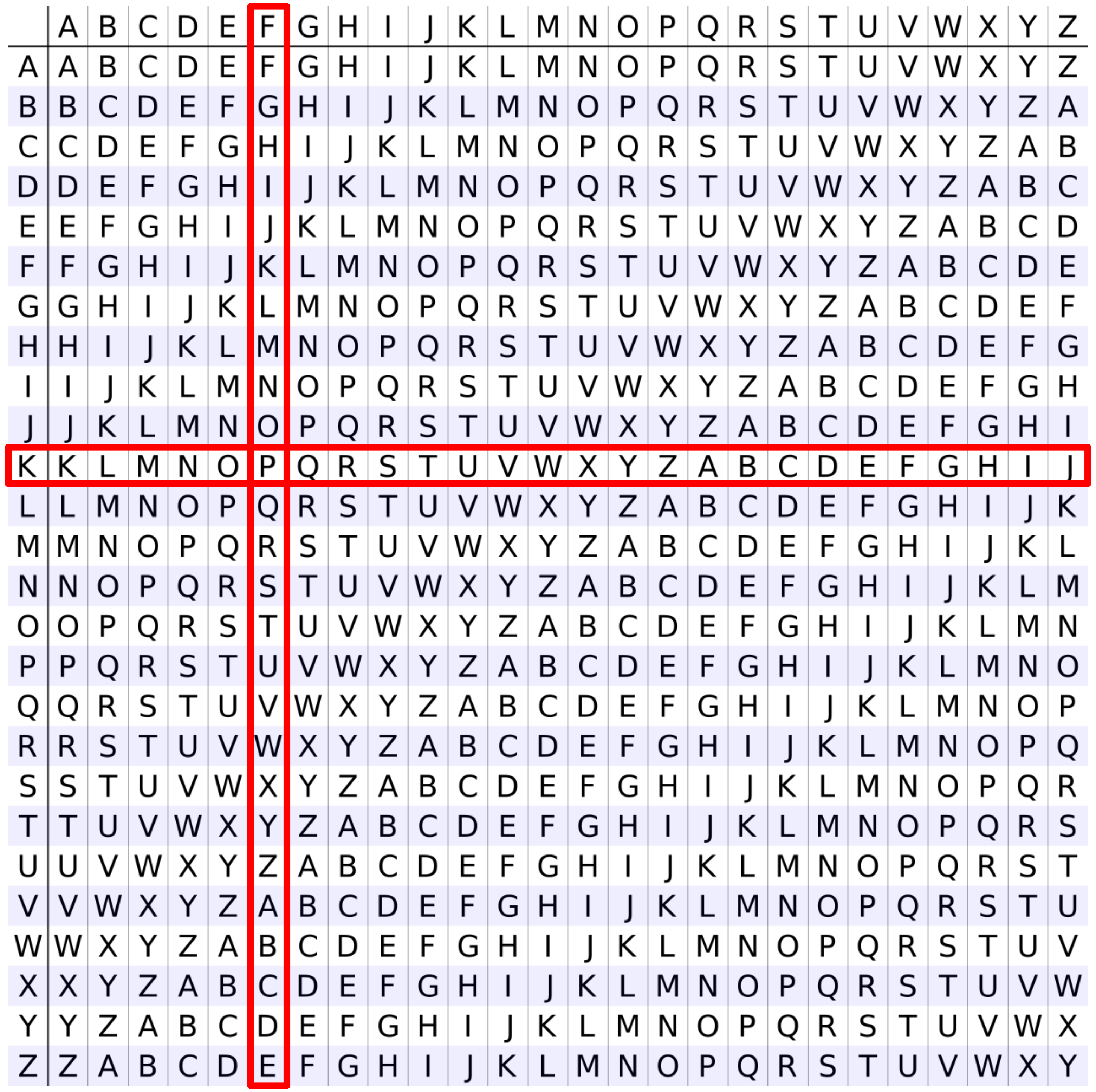

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T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

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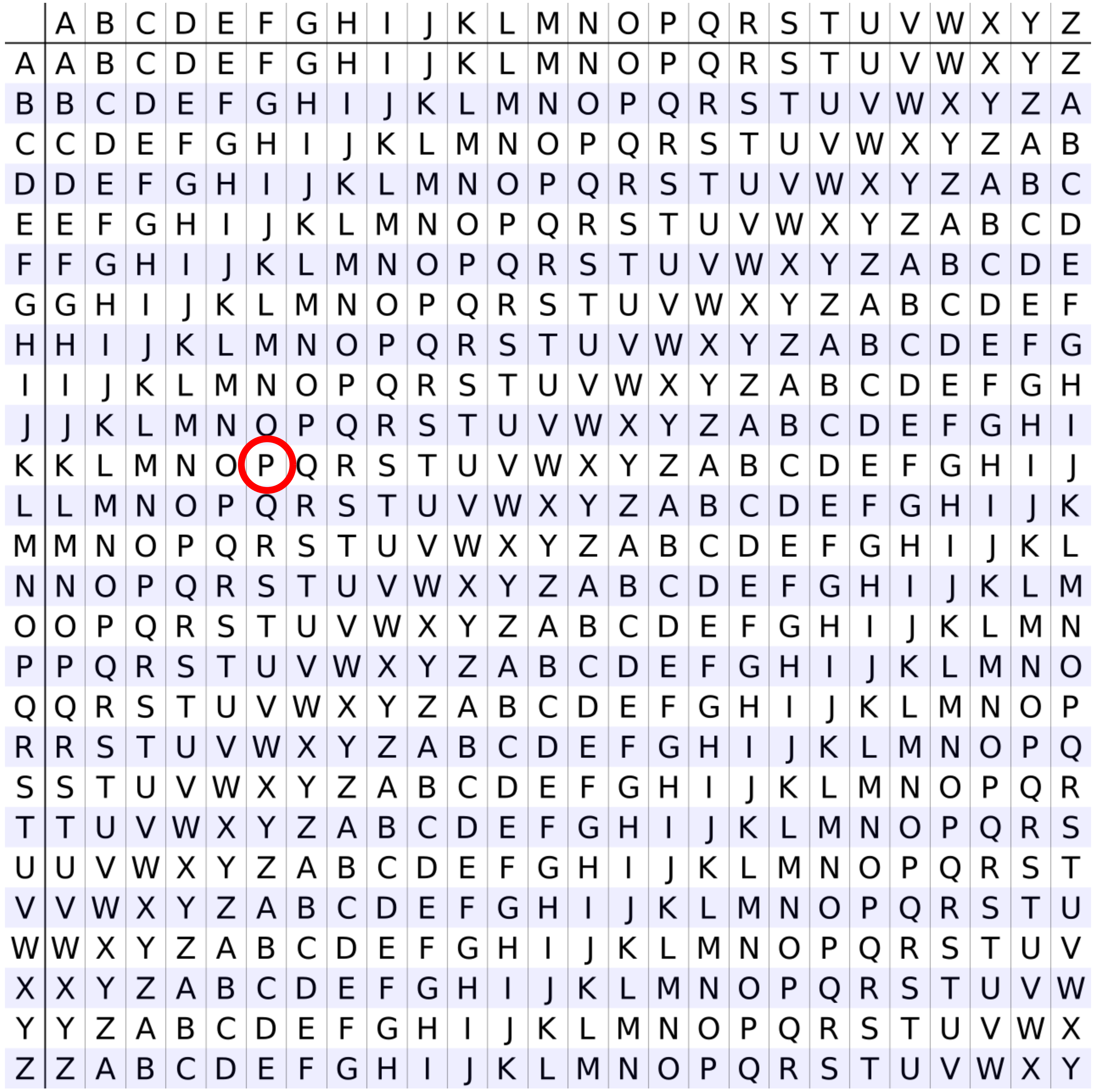

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T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

Vigenère cipher

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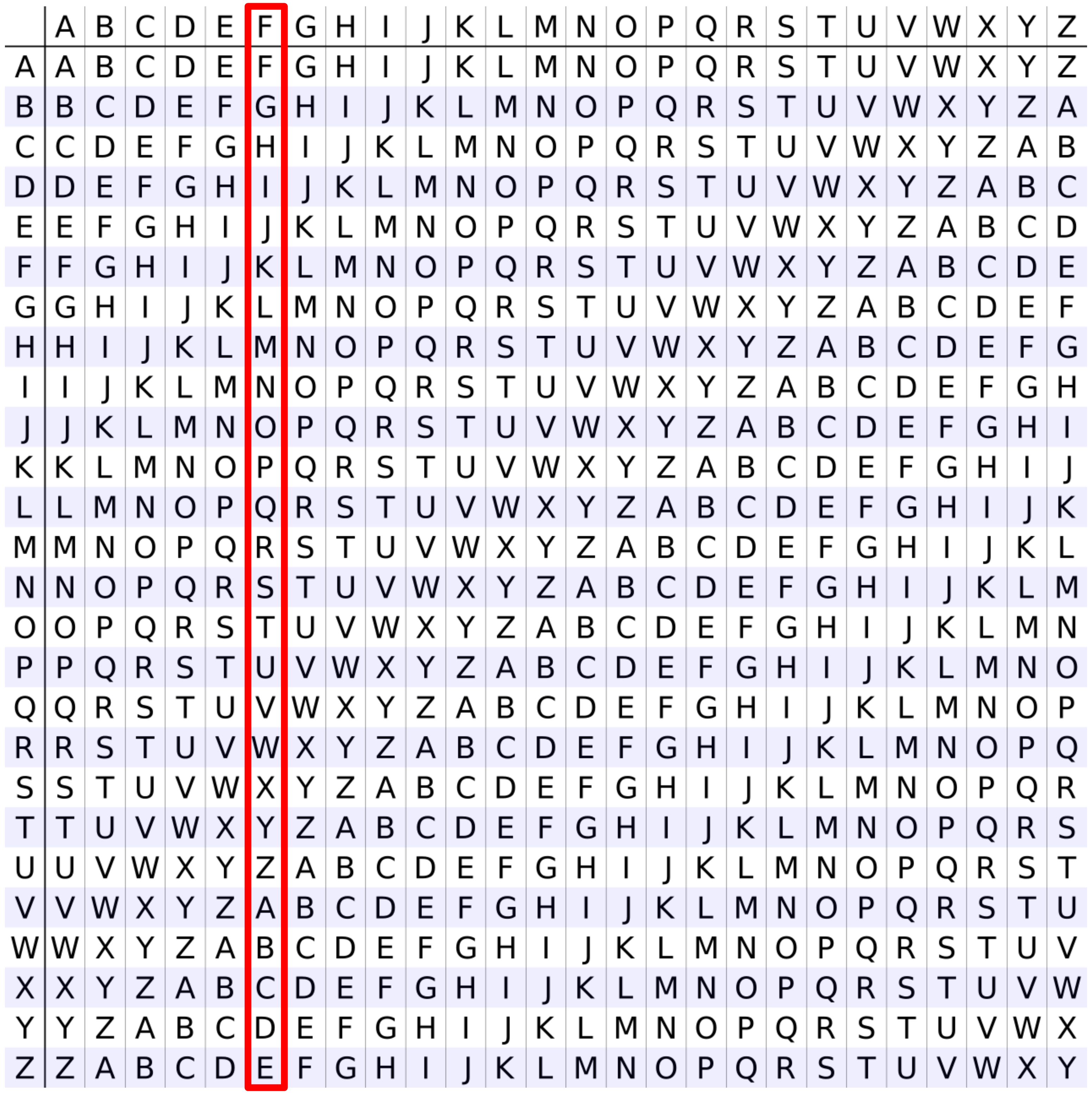

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T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

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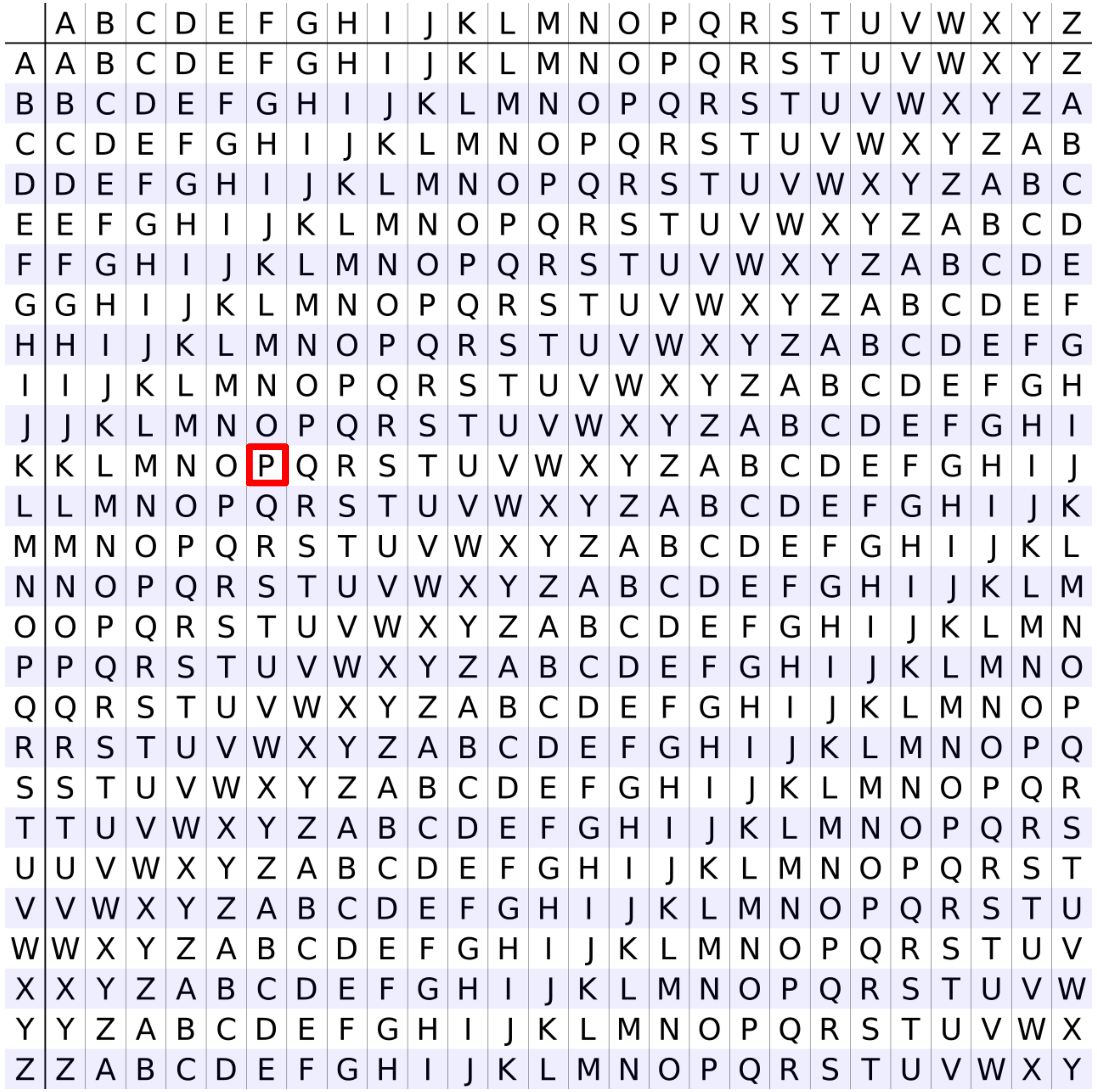

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T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

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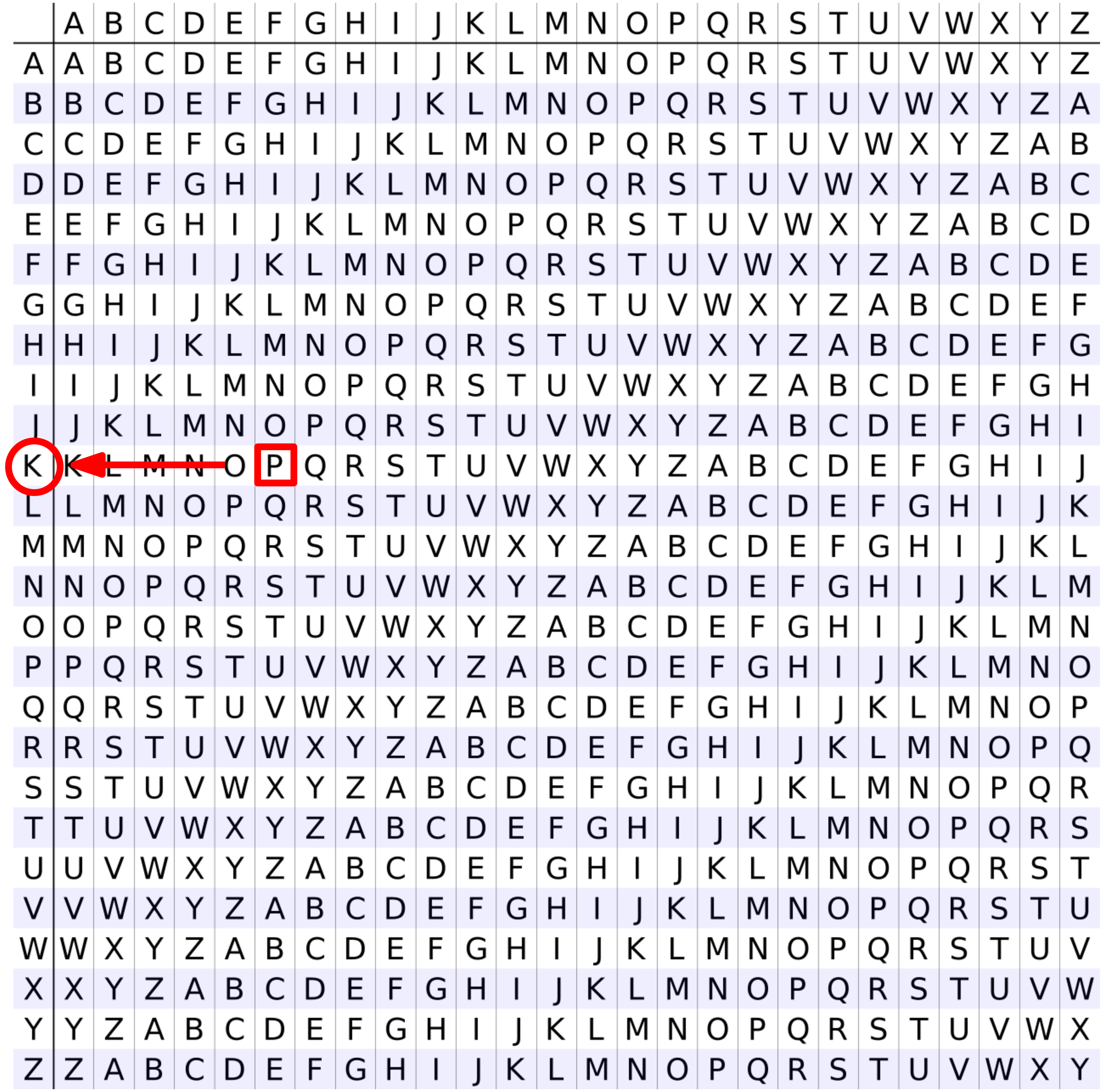

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T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

Vigenère cipher

Is Vigenère cipher secure?

Vigenère cipher

Is Vigenère cipher secure? It has been considered secure for centuries...

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Suppose that the adversary is somehow able to figure out what the length t of the key is

E.g.: $t = 4$

$c =$

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

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$$
\begin{array}{rl}
c = & \boxed{\mathtt{A}}\ \mathtt{M\ A\ P}\ \boxed{\mathtt{A}}\ \mathtt{A\ U\ H}\ \boxed{\mathtt{K}}\ \mathtt{G\ O\ O}\ \boxed{\mathtt{T}}\ \mathtt{W\ F\ I}\ \boxed{\mathtt{O}}\ \mathtt{G\ G\ G}\ \boxed{\mathtt{T}}\ \mathtt{B\ T} \\
 & \mathtt{Q}\ \boxed{\mathtt{I}}\ \mathtt{N\ N\ A}\ \boxed{\mathtt{V}}\ \mathtt{S\ M\ B}\ \boxed{\mathtt{T}}\ \mathtt{K\ Q\ O}\ \boxed{\mathtt{M}}\ \mathtt{O\ I\ W}\ \boxed{\mathtt{C}}\ \mathtt{P\ C\ T}\ \boxed{\mathtt{W}}\ \mathtt{T} \\
 & \mathtt{U\ O}\ \boxed{\mathtt{I}}\ \mathtt{F\ A\ G}\ \boxed{\mathtt{O}}\ \mathtt{G\ T\ I}\ \boxed{\mathtt{M}}\ \mathtt{O\ U\ C}\ \boxed{\mathtt{F}}\ \mathtt{P\ B\ T}\ \boxed{\mathtt{W}}\ \mathtt{T\ B\ N}\ \boxed{\mathtt{P}} \\
 & \mathtt{W\ C\ P}\ \boxed{\mathtt{C}}\ \mathtt{Q\ B\ S}\ \boxed{\mathtt{J}}\ \mathtt{D\ G\ F}\ \boxed{\mathtt{A}}\ \mathtt{U\ O\ W}\ \boxed{\mathtt{B}}\ \mathtt{O\ E\ E}\ \boxed{\mathtt{K}}\ \mathtt{D\ A\ E} \\
 & \boxed{\mathtt{R}}\ \mathtt{K\ R\ E}\ \boxed{\mathtt{M}}\ \mathtt{L\ K\ B}\ \boxed{\mathtt{F}}\ \mathtt{P\ R\ O}\ \boxed{\mathtt{O}}\ \mathtt{T\ J\ C}\ \boxed{\mathtt{C}}\ \mathtt{S\ U\ O}\ \boxed{\mathtt{O}}\ \mathtt{F\ S} \\
 & \mathtt{I}\ \boxed{\mathtt{Q}}\ \mathtt{I\ W\ U}\ \boxed{\mathtt{R}}\ \mathtt{B\ N\ F}\ \boxed{\mathtt{W}}\ \mathtt{M\ B\ T}\ \boxed{\mathtt{G}}\ \mathtt{A\ A\ U}\ \boxed{\mathtt{I}}\ \mathtt{E\ W\ D}\ \boxed{\mathtt{F}}\ \mathtt{L} \\
 & \mathtt{Z\ L}\ \boxed{\mathtt{S}}\ \mathtt{F\ C\ Q}\ \boxed{\mathtt{Z}}\ \mathtt{O}
\end{array}
$$

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& \mathtt{Q}\;\boxed{\mathtt{I}}\boxed{\mathtt{N}}\;\mathtt{N}\;\mathtt{A}\;\boxed{\mathtt{V}}\boxed{\mathtt{S}}\;\mathtt{M}\;\mathtt{B}\;\boxed{\mathtt{T}}\boxed{\mathtt{K}}\;\mathtt{Q}\;\mathtt{O}\;\boxed{\mathtt{M}}\boxed{\mathtt{O}}\;\mathtt{I}\;\mathtt{W}\;\boxed{\mathtt{C}}\boxed{\mathtt{P}}\;\mathtt{C}\;\mathtt{T}\;\boxed{\mathtt{W}}\boxed{\mathtt{T}} \\
& \mathtt{U}\;\mathtt{O}\;\boxed{\mathtt{I}}\boxed{\mathtt{F}}\;\mathtt{A}\;\mathtt{G}\;\boxed{\mathtt{O}}\boxed{\mathtt{G}}\;\mathtt{T}\;\mathtt{I}\;\boxed{\mathtt{M}}\boxed{\mathtt{O}}\;\mathtt{U}\;\mathtt{C}\;\boxed{\mathtt{F}}\boxed{\mathtt{P}}\;\mathtt{B}\;\mathtt{T}\;\boxed{\mathtt{W}}\boxed{\mathtt{T}}\;\mathtt{B}\;\mathtt{N}\;\boxed{\mathtt{P}} \\
& \boxed{\mathtt{W}}\;\mathtt{C}\;\mathtt{P}\;\boxed{\mathtt{C}}\boxed{\mathtt{Q}}\;\mathtt{B}\;\mathtt{S}\;\boxed{\mathtt{J}}\boxed{\mathtt{D}}\;\mathtt{G}\;\mathtt{F}\;\boxed{\mathtt{A}}\boxed{\mathtt{U}}\;\mathtt{O}\;\mathtt{W}\;\boxed{\mathtt{B}}\boxed{\mathtt{O}}\;\mathtt{E}\;\mathtt{E}\;\boxed{\mathtt{K}}\boxed{\mathtt{D}}\;\mathtt{A}\;\mathtt{E} \\
& \boxed{\mathtt{R}}\boxed{\mathtt{K}}\;\mathtt{R}\;\mathtt{E}\;\boxed{\mathtt{M}}\boxed{\mathtt{L}}\;\mathtt{K}\;\mathtt{B}\;\boxed{\mathtt{F}}\boxed{\mathtt{P}}\;\mathtt{R}\;\mathtt{O}\;\boxed{\mathtt{O}}\boxed{\mathtt{T}}\;\mathtt{J}\;\mathtt{C}\;\boxed{\mathtt{C}}\boxed{\mathtt{S}}\;\mathtt{U}\;\mathtt{O}\;\boxed{\mathtt{O}}\boxed{\mathtt{F}}\;\mathtt{S} \\
& \mathtt{I}\;\boxed{\mathtt{Q}}\boxed{\mathtt{I}}\;\mathtt{W}\;\mathtt{U}\;\boxed{\mathtt{R}}\boxed{\mathtt{B}}\;\mathtt{N}\;\mathtt{F}\;\boxed{\mathtt{W}}\boxed{\mathtt{M}}\;\mathtt{B}\;\mathtt{T}\;\boxed{\mathtt{G}}\boxed{\mathtt{A}}\;\mathtt{A}\;\mathtt{U}\;\boxed{\mathtt{I}}\boxed{\mathtt{E}}\;\mathtt{W}\;\mathtt{D}\;\boxed{\mathtt{F}}\boxed{\mathtt{L}} \\
& \mathtt{Z}\;\mathtt{L}\;\boxed{\mathtt{S}}\boxed{\mathtt{F}}\;\mathtt{C}\;\mathtt{Q}\;\boxed{\mathtt{Z}}\boxed{\mathtt{O}}
\end{aligned}$$

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

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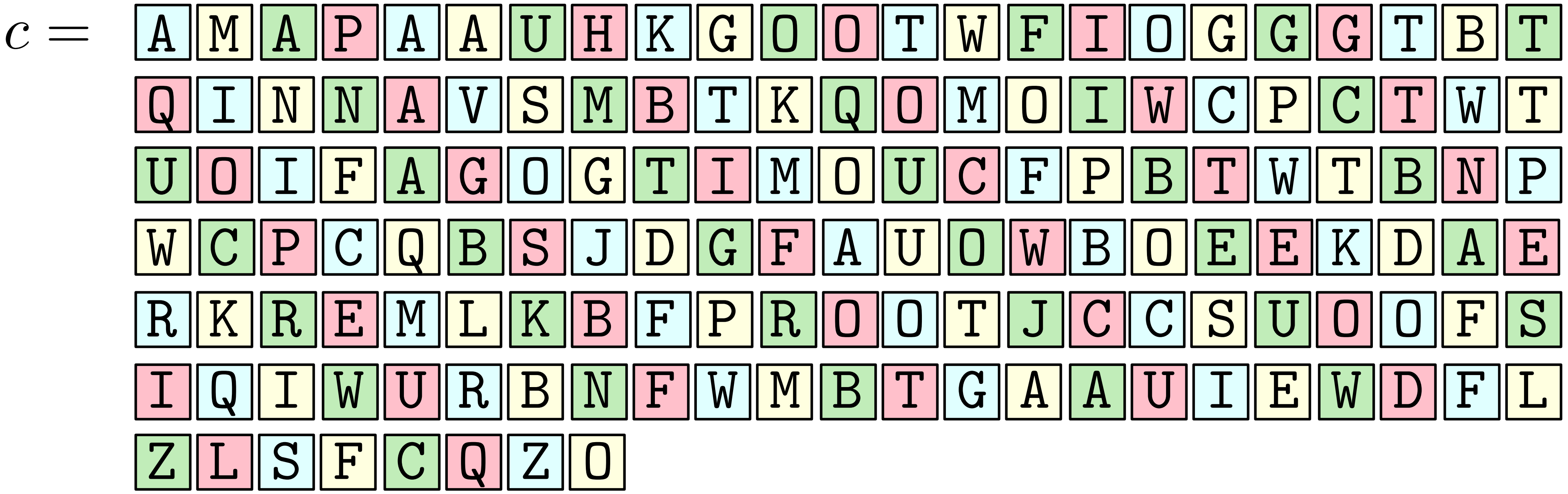

$c =$

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

The ciphertext can be decomposed into n ciphertext $c^{(1)}, c^{(2)}, \ldots, c^{(t)}$.

Each $c^{(i)}$ is encrypted using the same shift

Each ciphertext can be attacked separately (but we cannot simply bruteforce them)

Breaking the Vigenère cipher

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- Consider some (unknown) sequence of characters that appears frequently in the plaintext (for example the word "the")

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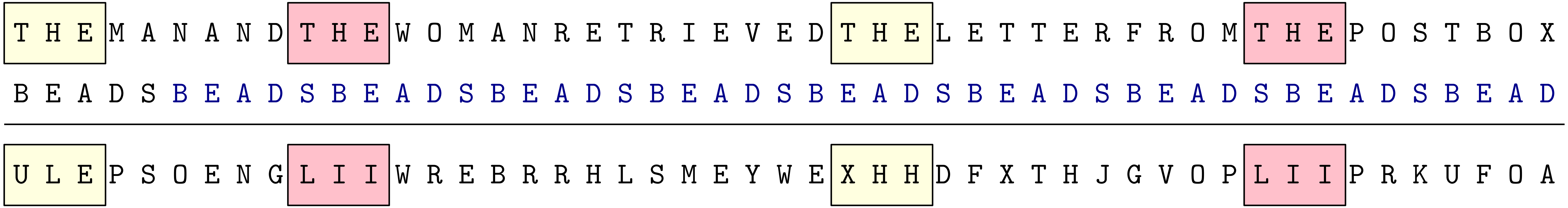

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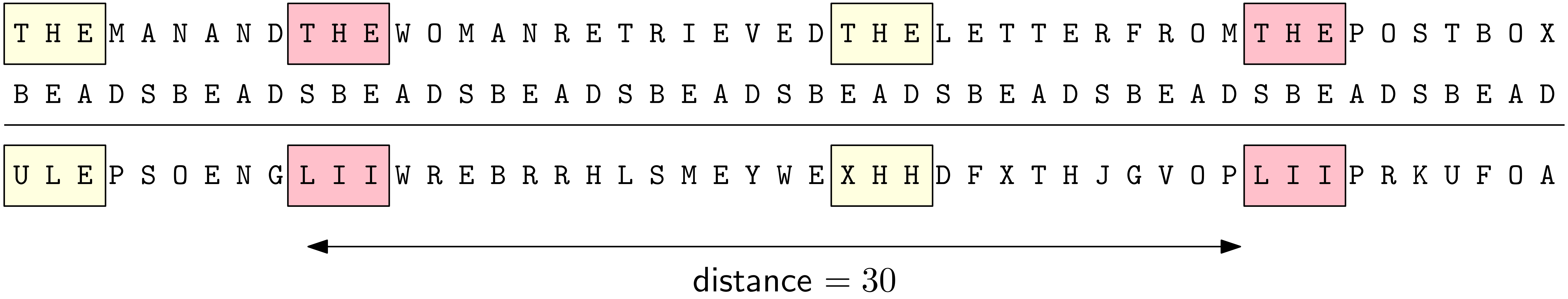

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distance $= 30$

Obs: The distance between repeated patterns in the ciphertext is likely to be a multiple of the key length

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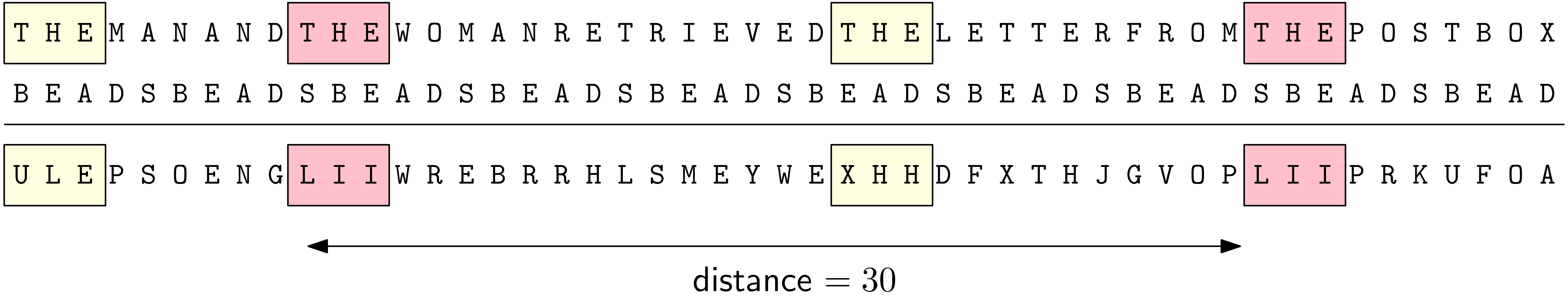

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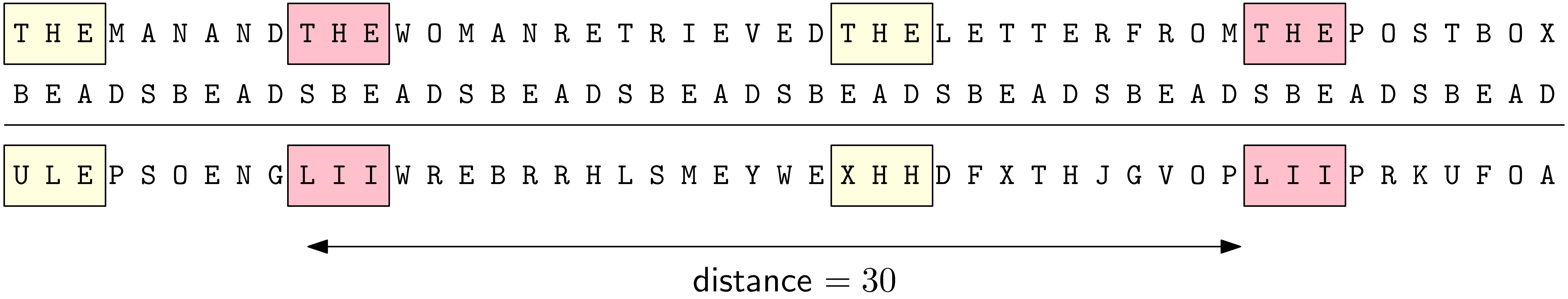

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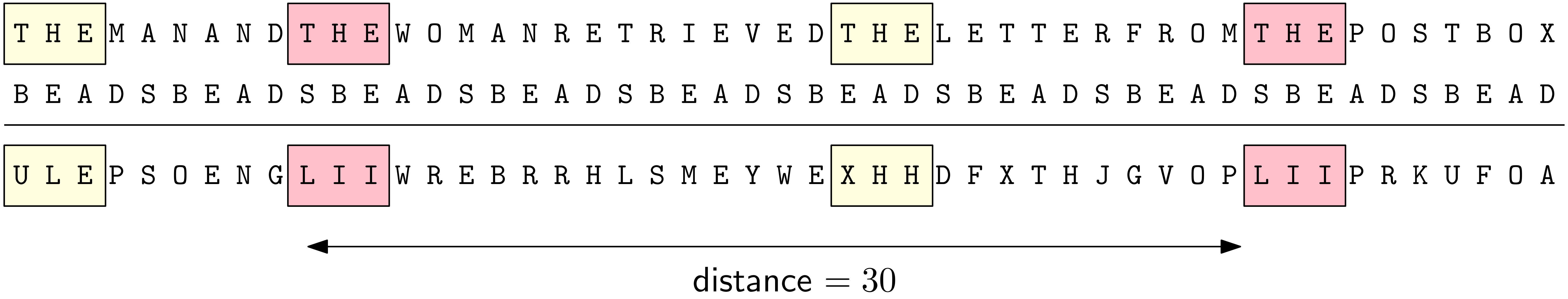

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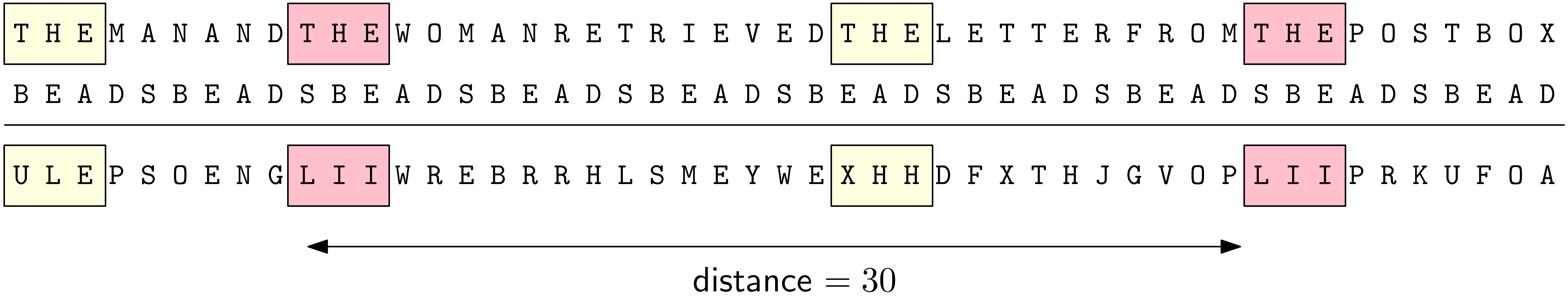

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In the example the key length t is 5 and the distance between patterns is 30

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- **Option 1:** brute-force (guess n and try decrypting the n shift ciphers)
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Index of coincidence method

Let p_j be the expected frequency of the j-th letter $(j = 0. \dots, 25)$ in the language of the plaintext

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$\implies S_\tau \approx \sum_{j=0}^{25} \left(\frac{1}{26}\right)^2 \approx 0.038$

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The smallest value of τ such that $S_\tau \approx 0.065$ is probably the length of the key

This can be validated by repeating the check for other values of i

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Compute $I_j = \sum_{i=0}^{25} p_i q_{(i+j)} \bmod 26$ for all possible shifts j and choose the one for which I_j is closest to 0.065.

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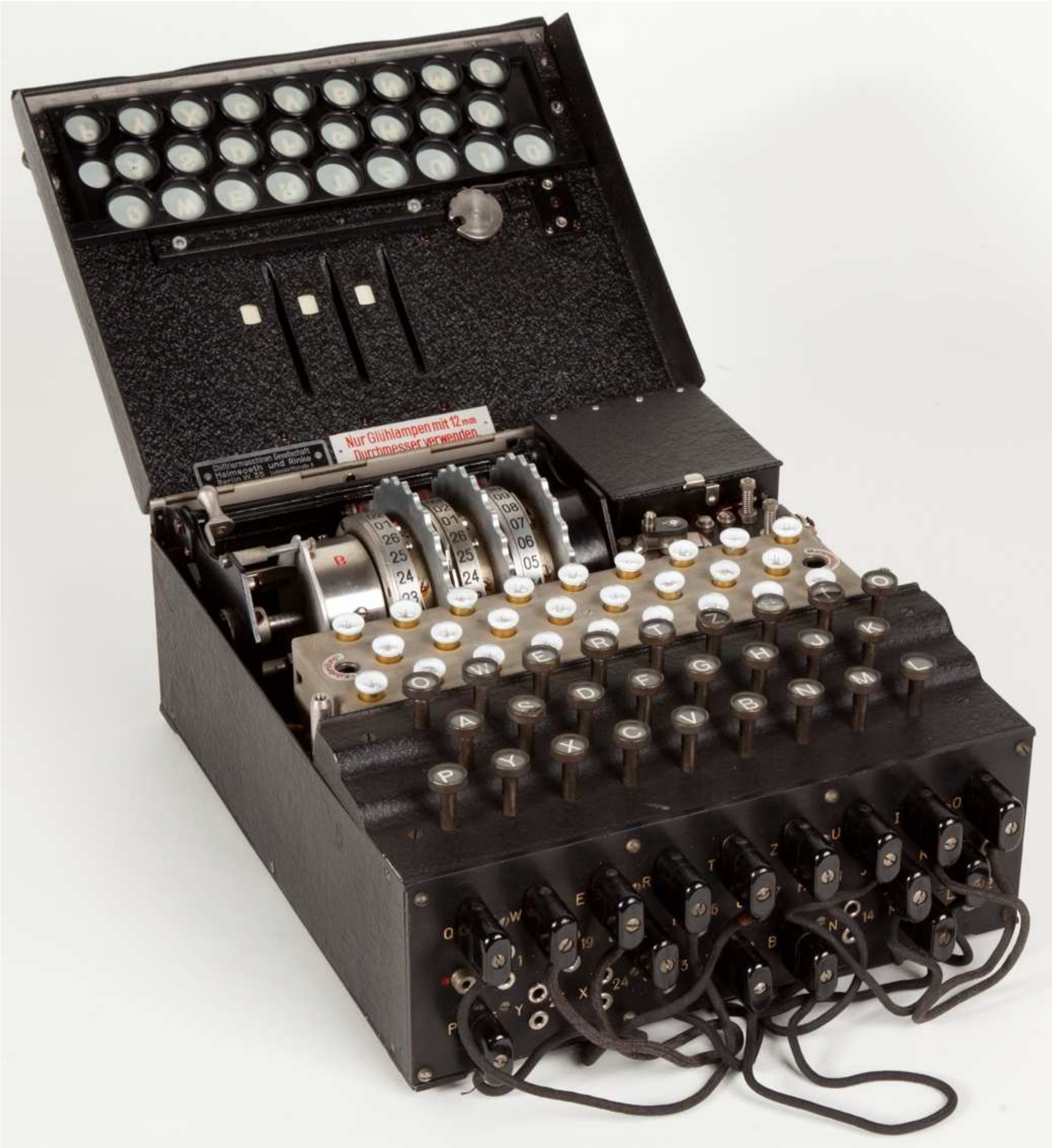

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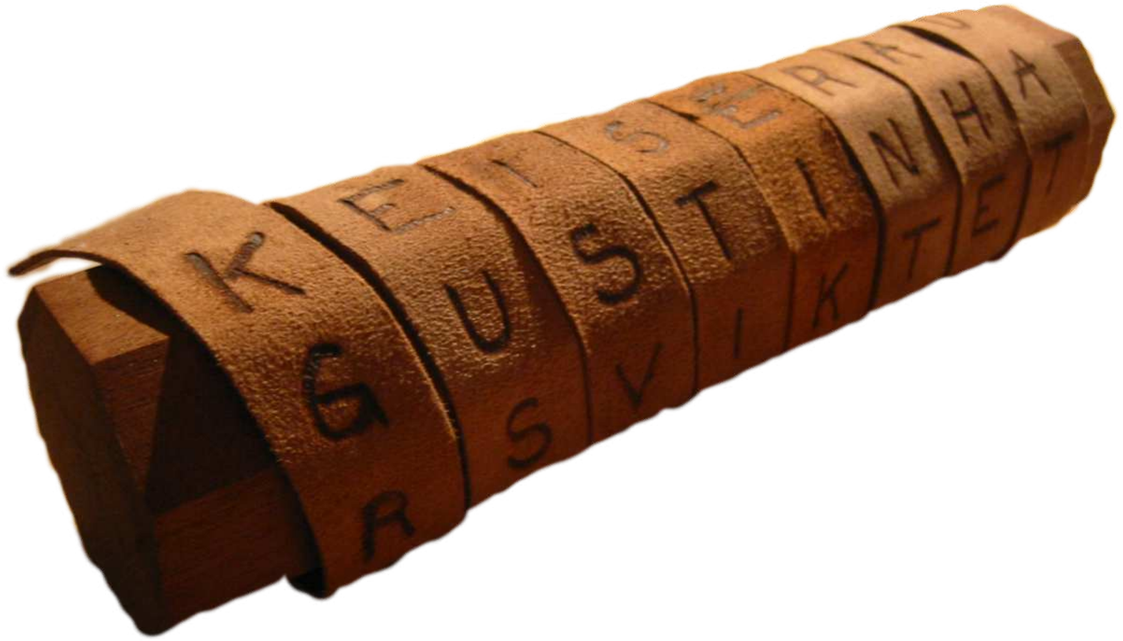
Marian Adam Rejewski

Alan Mathison Turing

Scytale cipher

A way used to encrypt a message using a rod (the scytale, or skytale) and a strip of parchment



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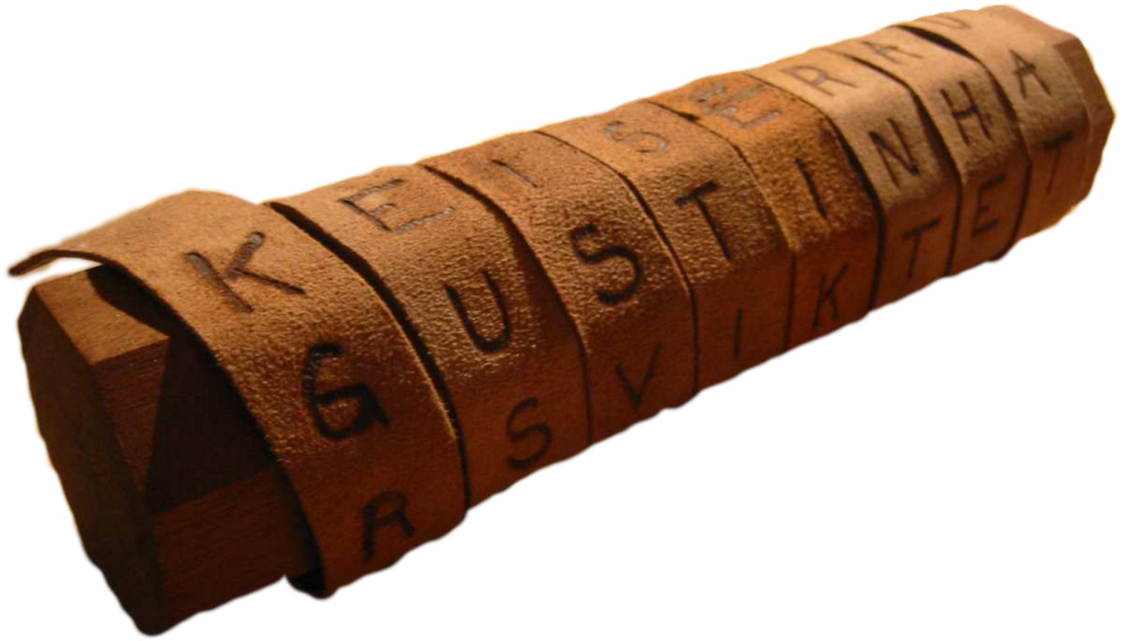

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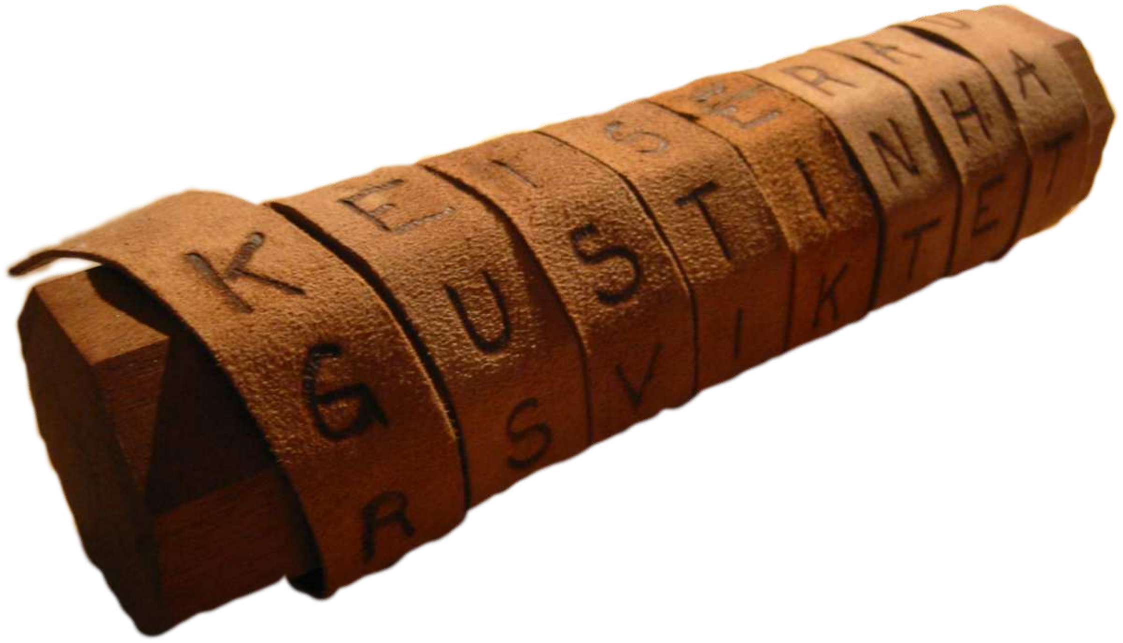

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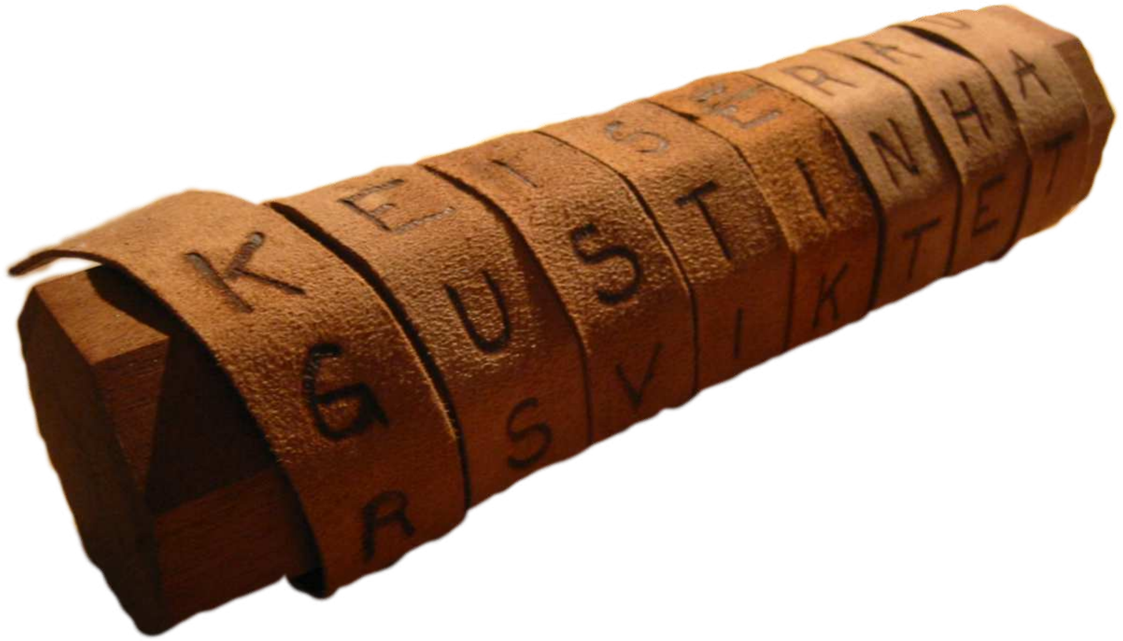

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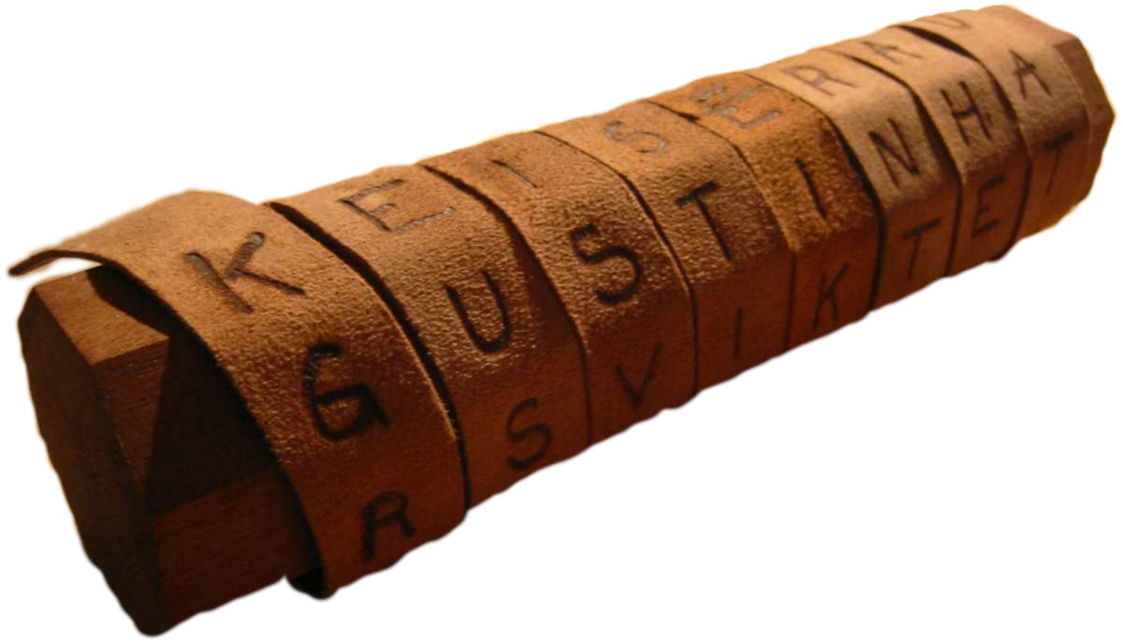

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To decrypt the ciphertext, simply wind it around a rod of the same diameter

Breaking the scytale cipher

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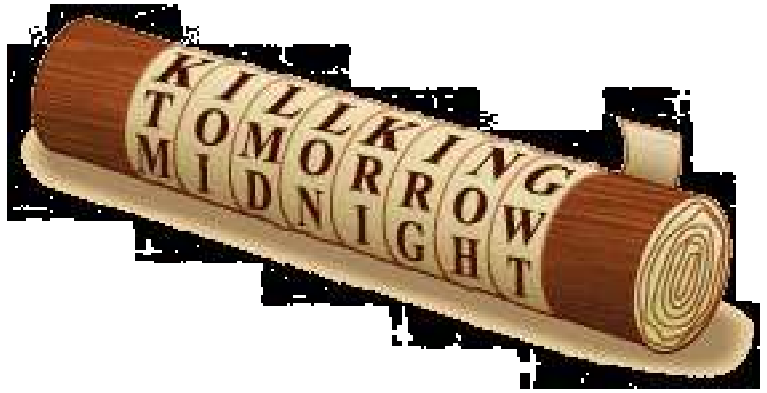
Wind the parchment around a cone

Look for the portion of the cone where letters start to line up and produce sensible words

The corresponding diameter is the key!

Scytale cipher

What is the effect of winding the parchment around the scytale on the order of the characters in the plaintext?



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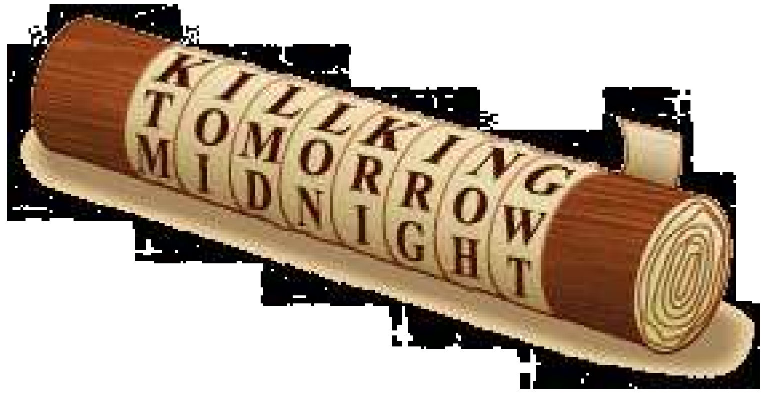

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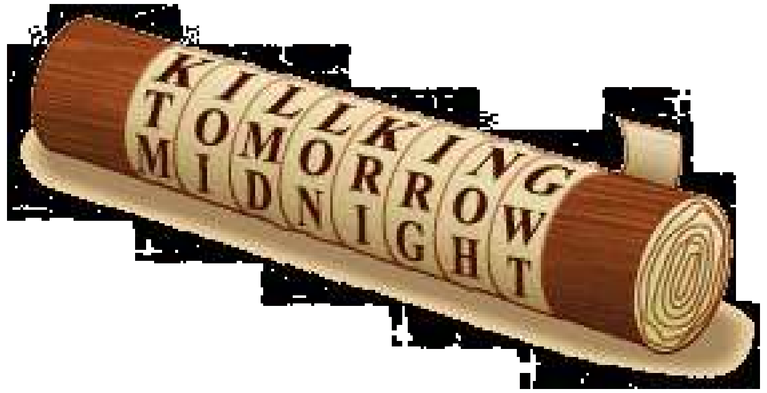

$$m = \begin{array}{cccccccc} \texttt{K} & \texttt{I} & \texttt{L} & \texttt{L} & \texttt{K} & \texttt{I} & \texttt{N} & \texttt{G} \\ \texttt{T} & \texttt{O} & \texttt{M} & \texttt{O} & \texttt{R} & \texttt{R} & \texttt{O} & \texttt{W} \\ \texttt{M} & \texttt{I} & \texttt{D} & \texttt{N} & \texttt{I} & \texttt{G} & \texttt{H} & \texttt{T} \end{array}$$

Scytale cipher

What is the effect of winding the parchment around the scytale on the order of the characters in the plaintext?

$m =$ `K I L L K I N G T O M O R R O W M I D N I G H T`

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KILLKING
TOMORROW
MIDNIGHT

$$m = \begin{bmatrix} \mathtt{K} & \mathtt{I} & \mathtt{L} & \mathtt{L} & \mathtt{K} & \mathtt{I} & \mathtt{N} & \mathtt{G} \\ \mathtt{T} & \mathtt{O} & \mathtt{M} & \mathtt{O} & \mathtt{R} & \mathtt{R} & \mathtt{O} & \mathtt{W} \\ \mathtt{M} & \mathtt{I} & \mathtt{D} & \mathtt{N} & \mathtt{I} & \mathtt{G} & \mathtt{H} & \mathtt{T} \end{bmatrix}$$

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The scytale cipher is a (specific type of) transposition cipher!

(Columnar) Transposition ciphers

The plaintext is arranged in a matrix with n columns (and the appropriate number of rows)

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T	O	M	O	R	R
O	W	A	T	T	H
E	D	O	C	K	

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\mathtt{O} & \mathtt{W} & \mathtt{A} & \mathtt{T} & \mathtt{T} & \mathtt{H} \\
\mathtt{E} & \mathtt{D} & \mathtt{O} & \mathtt{C} & \mathtt{K} & \boxed{\mathtt{X}}
\end{array}$$

The message might or might not be padded with random characters (X in this case) to fill the last row.

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E.g., if the permutation is $4, 2, 1, 6, 5, 3$, then the ciphertext is:

$c =$ M G O T C H I O W D T T T O E E S R H X E I R T K E N M A O

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What is the key?

(Columnar) Transposition ciphers

What is the key? 🔑 The pair (n, π)

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- If the ciphertext has ℓ characters, then the original matrix had ℓ/n rows

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\end{array}$$

The plaintext can be found by reading the rows in order (left to right, top to bottom)

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Are columnar transposition ciphers secure?

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(if the transposition cipher is regular, look at the divisors of the ciphertext's length)

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- Write down the columns, in some arbitrary order (the permutation π is unknown)

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```

- Look for anagrams (that simultaneously yield intelligible text on multiple rows)

Other transposition ciphers

To make cryptanalysis harder, a double (irregular) transposition cipher is often used:

- Pick two sub-keys $k_1 = (n_1, \pi_1)$ and $k_2 = (n_2, \pi_2)$ $\qquad k = (k_1, k_2)$

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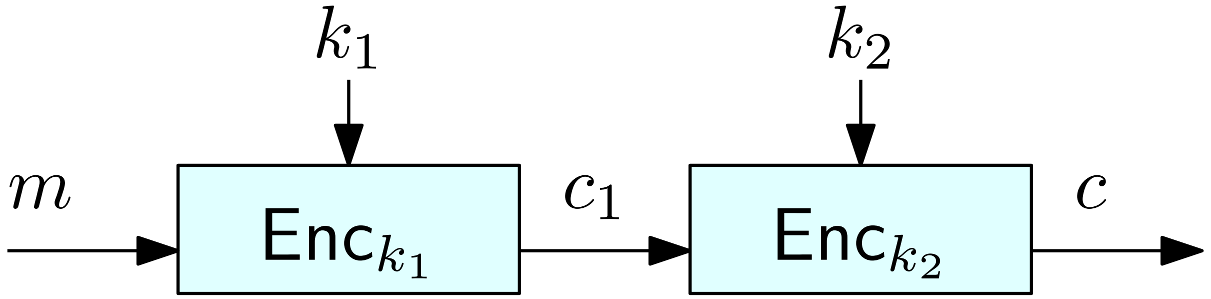

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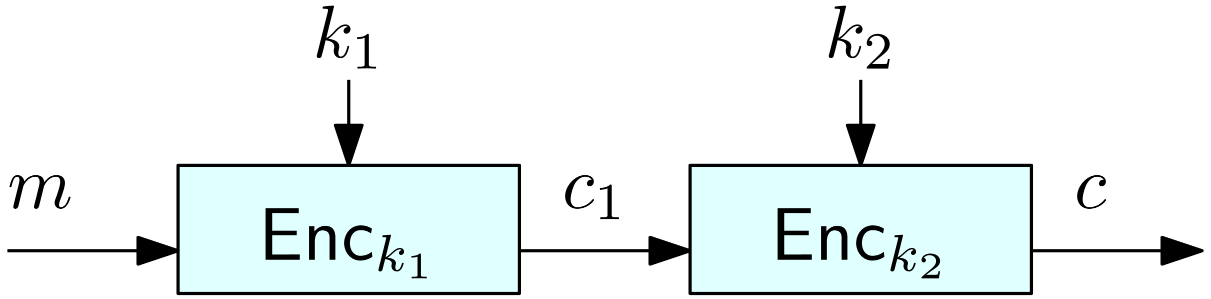

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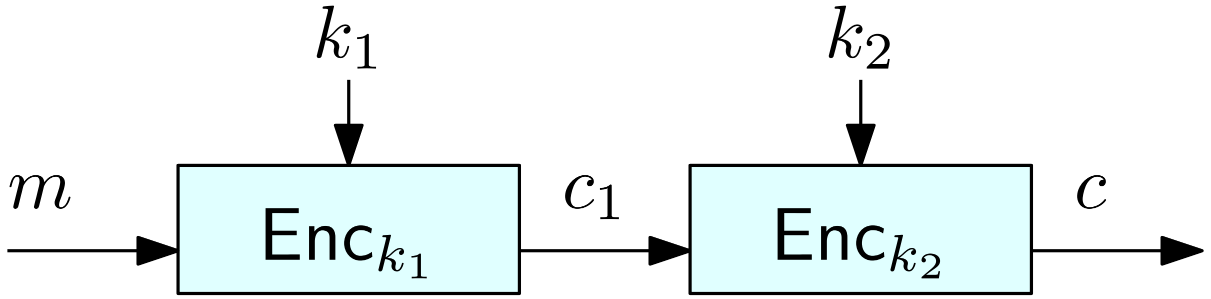
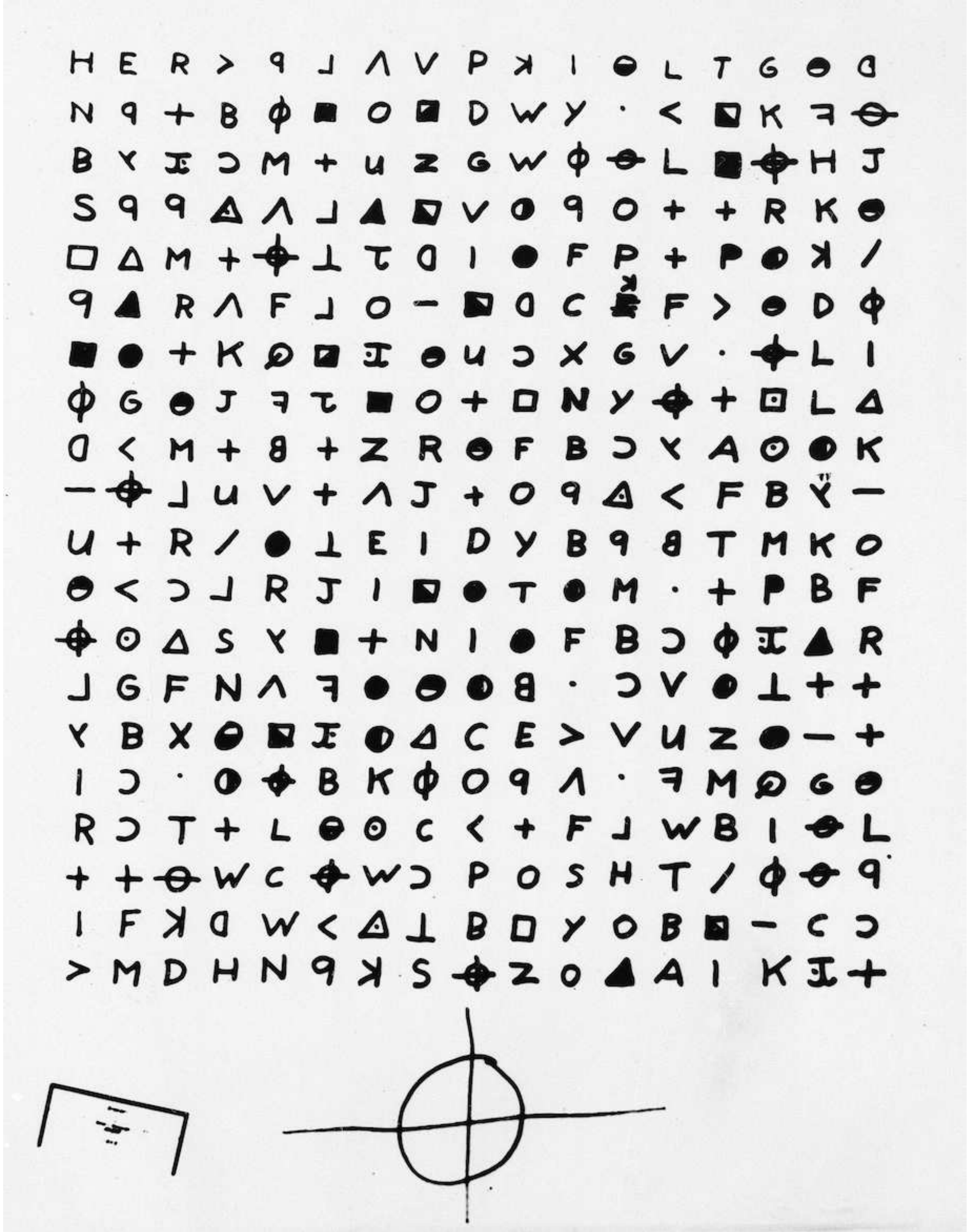


- Among the "manual" ciphers, the double transposition cipher is easy to carry out but hard to break
- Many other (more complex) transposition ciphers have been used

Other transposition ciphers

The Zodiac Z-340 cipher remained unsolved for 51 years!



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- If a part of the plaintext is somehow known or guessed, this can be used to recover the key (known plaintext attack, key recovery attack)

Are there even secure ciphers?

What does secure mean?