

# Information & Communication Security (SS 2022)

## Cryptography I

Prof. Dr. Kai Rannenberg

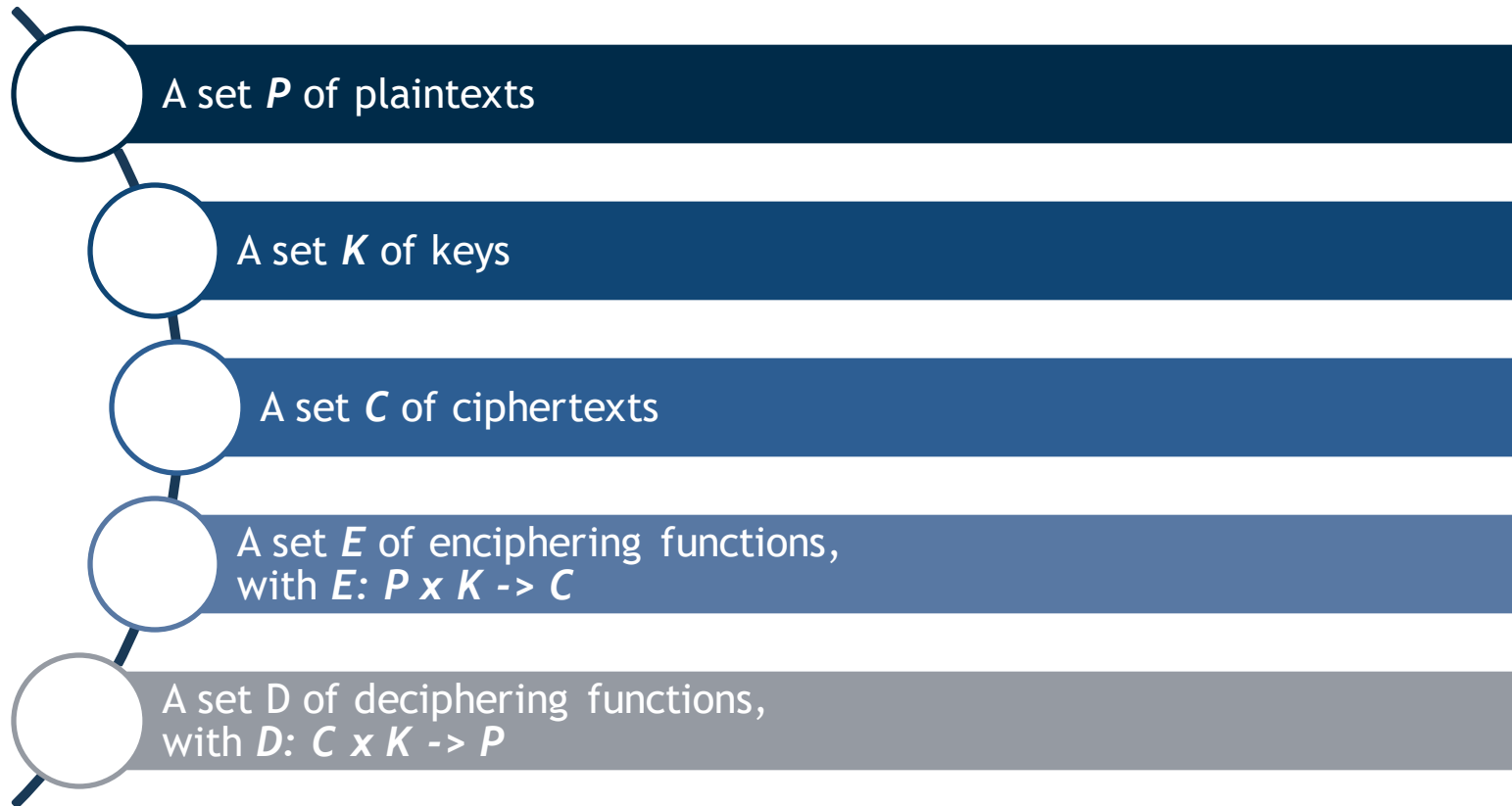
Chair of Mobile Business & Multilateral Security  
Goethe University Frankfurt a. M.

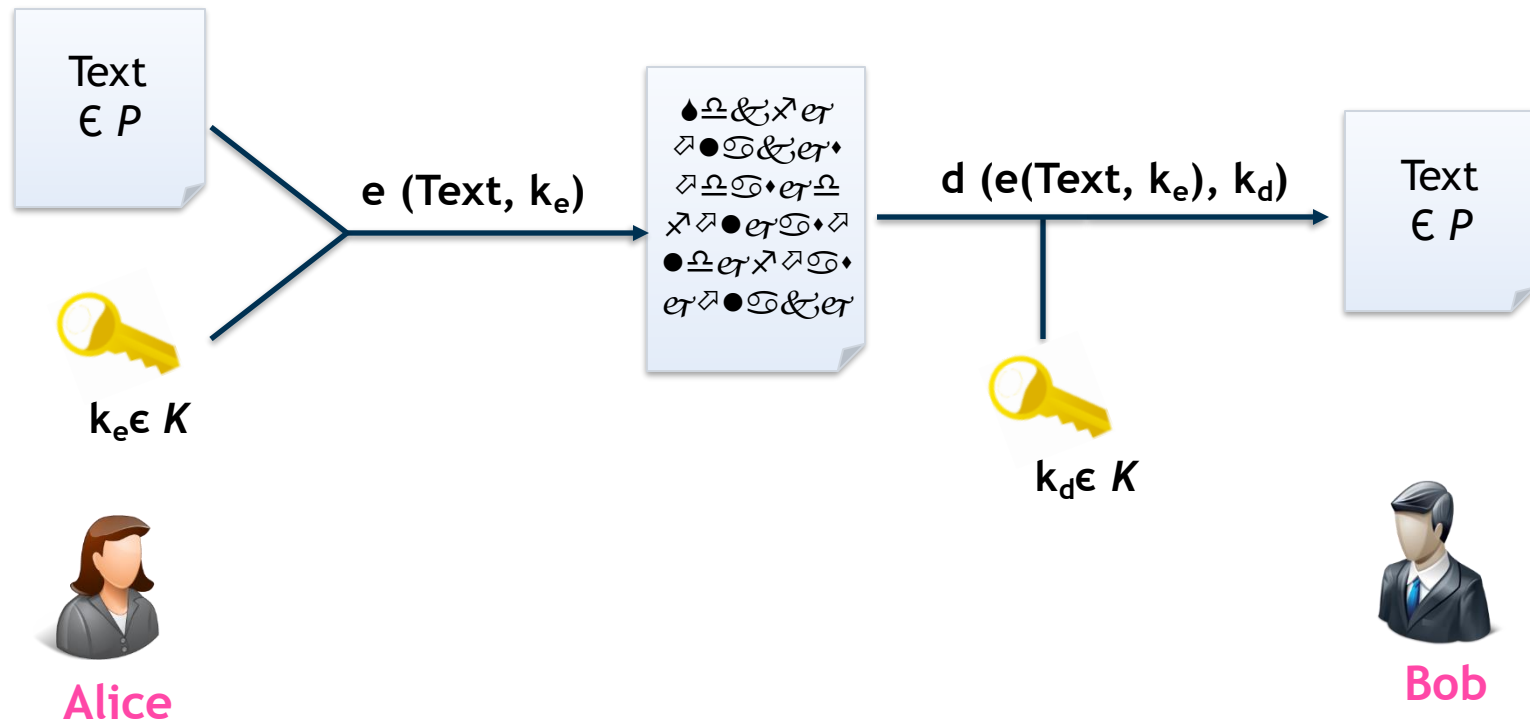
- Introduction
- Symmetric Key Cryptography
  - General Process
  - Substitution Ciphers
    - Caesar Cipher
    - Vigenère Cipher
    - One Time Pad
  - AES
    - Advantages and Problems
- Public Key Cryptography
- Outlook and Post-Quantum Cryptography

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Ciphertext  
Public  
Enigma  
Asymmetric  
AES  
functions  
Code  
Hash  
Key  
RSA  
Symmetric  
Plaintext  
Substitution  
writing  
Cipher  
Secret

*A Cryptosystem is a 5-tuple  $(P, K, C, E, D)$*





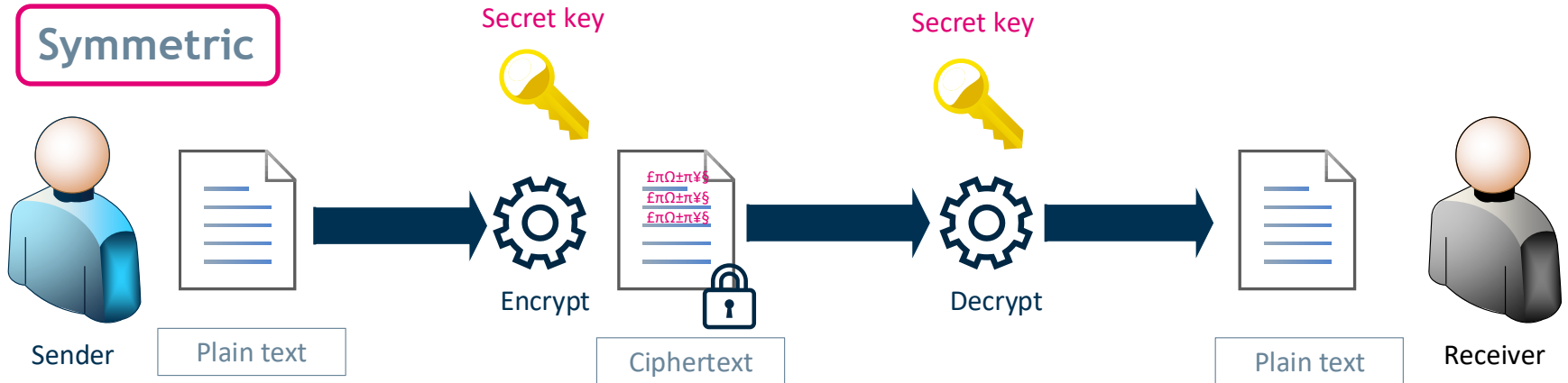
# Cryptographic Systems (I)

- Intention
  - Confidentiality (secrecy of messages):  
**encryption systems**
  - Integrity (protection from undetected manipulation) and accountability:  
**authentication systems** and **digital signature systems**
- Key distribution
  - Symmetric:  
Both partners have the same key.
  - Asymmetric:  
Different (but related) keys for encryption and decryption

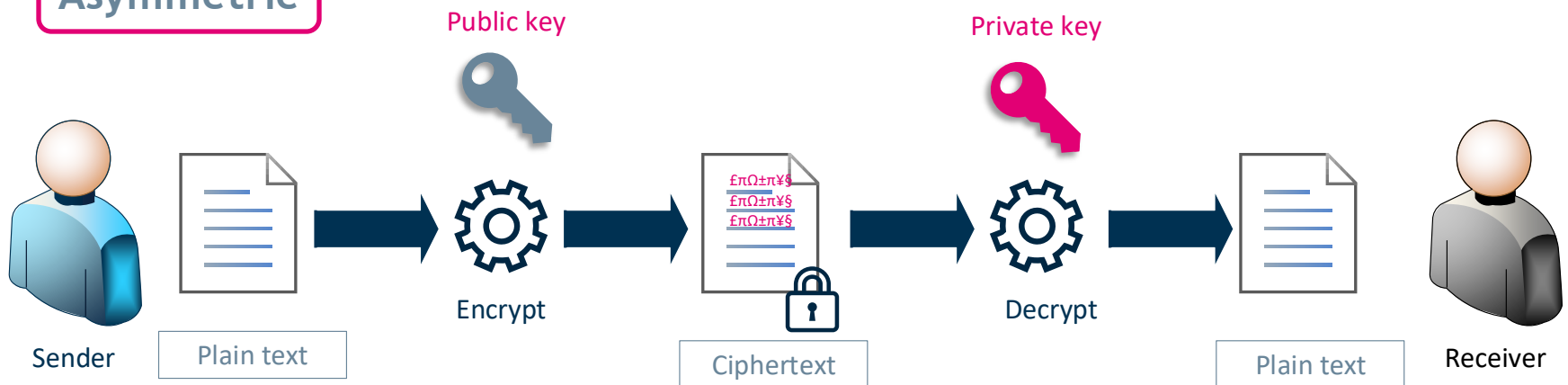
*In practice mostly hybrid systems*

# Cryptographic Systems (II)

## Symmetric



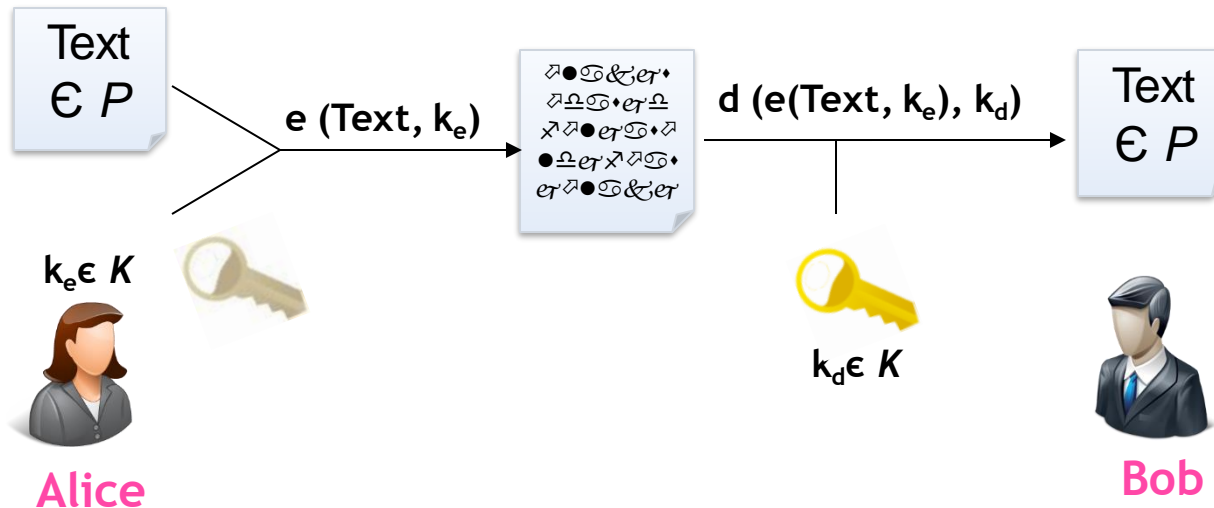
## Asymmetric





# Kerckhoffs' Principle

- The principle (first stated in 1883):
  - The secret lies within the key and not within the algorithm;
  - Thus "Security through obscurity" is not a sustainable solution.
- In our small example:
  - Separation of algorithm  $e$  and key  $k_e$



# Cryptography - Important Concepts

- Shannon's perfect secrecy
  - All plaintexts have the same probability for a given ciphertext.
- One-Time Pad - Shannon / Vernam
  - Theoretically completely unbreakable, but highly impractical
- Shannon's concepts: Confusion and Diffusion
  - Relation between  $M$ ,  $C$ , and  $K$  should be as complex as possible ( $M$  = message,  $C$  = cipher,  $K$  = key)
  - Every ciphertext character should depend on as many plaintext characters and as many characters of the encryption key as possible.
  - "Avalanche effect" (small modification, big impact)
- Trapdoor function (one-way function)
  - Fast in one direction, not in the opposite direction (without secret information)
  - Knowing the secret allows the function to work in the opposite direction (access to the trapdoor).

- In a *ciphertext only* attack, the adversary has only the ciphertext. Her goal is to find the corresponding plaintext. If possible, she may try to find the key, too.
- In a *known plaintext* attack, the adversary has the plaintext and the ciphertext that was enciphered. Her goal is to find the key that was used.
- In a *chosen plaintext* attack, the adversary may ask that specific plaintexts be enciphered. She is given the corresponding ciphertexts. Her goal is to find the key that was used.

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# Symmetric Key Cryptography

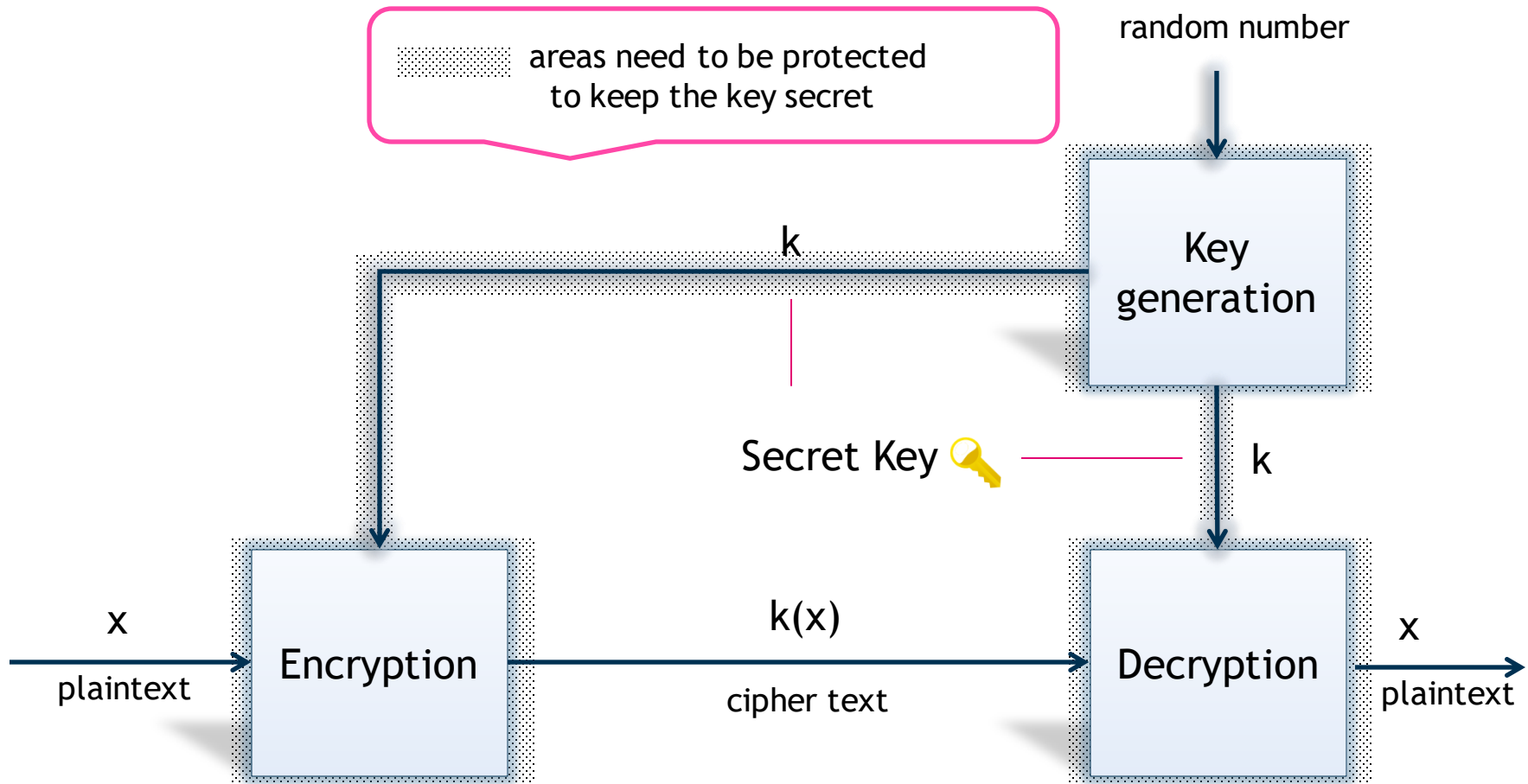
## Symmetric Encryption Systems

### Applications & Examples

- Classical cryptosystems are usually based on symmetric encryption systems.
- Typical applications
  - confidential storage of user data
  - transfer of data between 2 users who negotiate a key via a secure channel
- Examples
  - Vernam-Code (one-time pad, Gilbert Vernam)
    - key length = length of the plaintext (information theoretically secure)
  - DES: Data Encryption Standard
    - key length 56 bit, so  $2^{56}$  different keys
  - AES: Advanced Encryption Standard (Rijndael, [NIST])
    - 3 alternatives for key length: 128, 192 und 256 bit

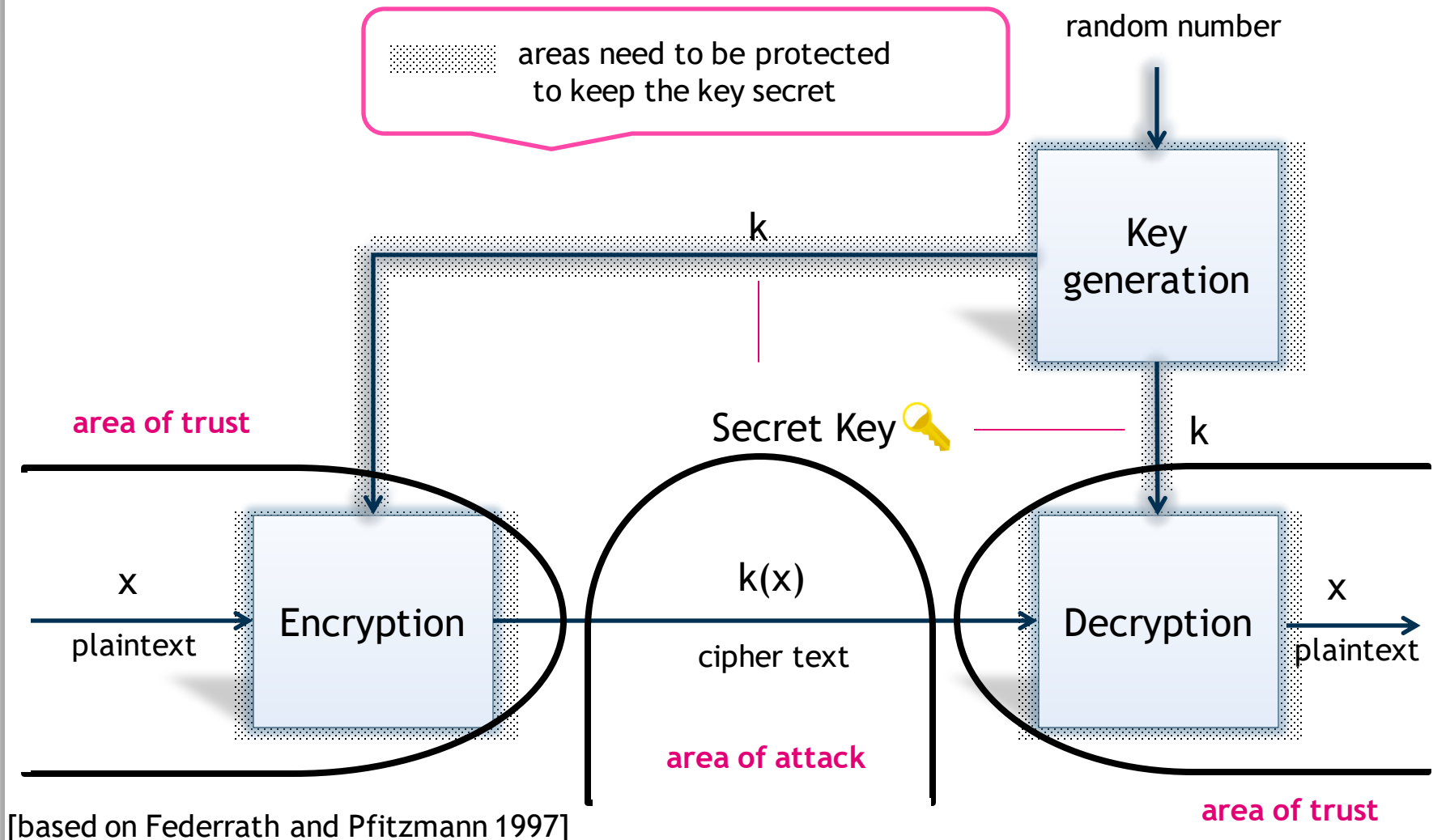
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# Symmetric Key Cryptography General Process



[based on Federrath and Pfitzmann 1997]

# Symmetric Key Cryptography General Process





# Symmetric Key Cryptography

## General Process

- **Keys have to be kept secret (*secret key crypto system*).**
- It must not be possible to infer on the plaintext or the keys used from the encrypted text (ideally encrypted text is not distinguishable from a numerical random sequence).
- Each key shall be equally probable.
- In principle each system with limited key length is breakable by testing all possible keys.
- ***Publication of encrypting and decrypting functions (algorithms) is considered as good style and is trust-building.***
- **Security of cryptosystems should base on the strength of chosen key lengths.**

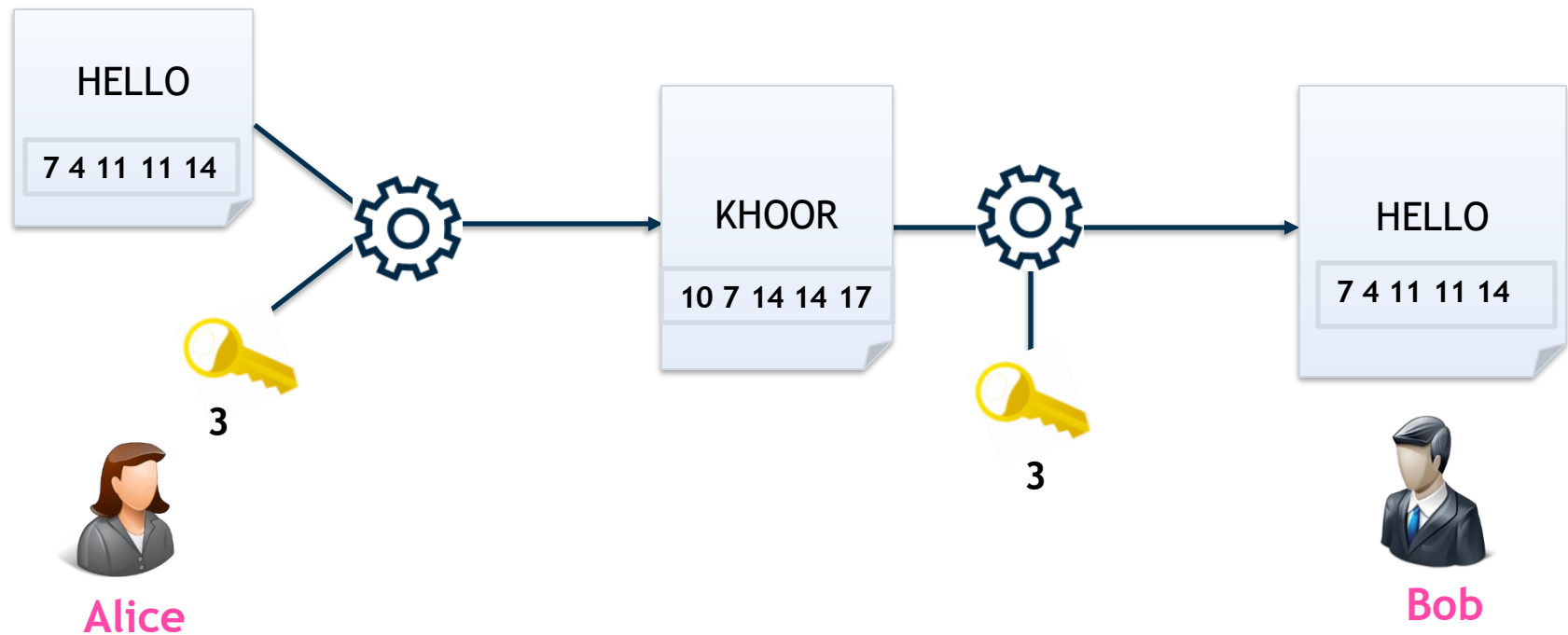
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A	B	C	D	E	F	G	H	I	J	K	L	M
0	1	2	3	4	5	6	7	8	9	10	11	12

N	O	P	Q	R	S	T	U	V	W	X	Y	Z
13	14	15	16	17	18	19	20	21	22	23	24	25

- We assign a **number** for every **character**.
- This enables us to calculate with letters as if they were numbers.

- For  $k \in \{0..25\}$  we have:
  - An encryption function:
    - $e: x \rightarrow (x+k) \bmod 26$
  - A decryption function:
    - $d: x \rightarrow (x-k) \bmod 26$
  - In this case  $k_e = k_d$



- In case of a known plaintext attack it is trivial to get the key used.
- There are only 26 possible keys. This cipher is therefore vulnerable to a **brute force attack**.
- This cipher is also vulnerable to a **statistical ciphertext-only attack**.

# Assessment of Caesar Cipher

- Of course this is a very simple form of encryption.
- The encryption and decryption algorithms are very easy and fast to compute.
- It uses a very limited key space ( $n=26$ ).
- Therefore, the encryption is very easy and fast to compromise.

# Can We Make it More Secure?

- Use a permutation of the alphabet as the key.
- Example:

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

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

- “HELLO” -> “ITSSG”



- Use of permutations increases the key space.
- Therefore, a **brute force attack** becomes more difficult.
- The encryption and decryption are not much harder to compute.
  - Table lookup
- Still vulnerable to a **statistical ciphertext-only attack**.

# Statistical Ciphertext-only Attack

- Use statistical frequency of occurrence of single characters to figure out the key.
- Language dependent
- Frequencies of character pairs (bigrams) may also be used

E	11.1607%	M	3.0129%
A	8.4966%	H	3.0034%
R	7.5809%	G	2.4705%
I	7.5448%	B	2.0720%
O	7.1635%	F	1.8121%
T	6.9509%	Y	1.7779%
N	6.6544%	W	1.2899%
S	5.7351%	K	1.1016%
L	5.4893%	V	1.0074%
C	4.5388%	X	0.2902%
U	3.6308%	Z	0.2722%
D	3.3844%	J	0.1965%
P	3.1671%	Q	0.1962%

(English)

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- The Vigenère cipher chooses a sequence of keys, represented by a string.
- The key letters are applied to successive plaintext characters.
- When the end of the key is reached, the key starts over.
- The length of the key is called the *period* of the cipher.

# Vigenère Tableau

	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

## Example

- Let the message be "THE BOY HAS THE BAG"
- and let the KEY be "VIG"

PT= T H E B O Y H A S T H E B A G

K= V I G V I G V I G V I G V I G

CT= O P K W W E C I Y O P K W I M

# Assessment Vigenère Cipher

- For many years, the Vigenère cipher was considered unbreakable.
- Then a Prussian cavalry officer named Kasiski noticed that repetitions occur when characters of the key appear over the same characters in the plaintext.
- The number of characters between successive repetitions is a multiple of the period (key length).
- Given this information and a short period the Vigenère cipher is quite easily breakable.
- *Example: The Caesar cipher is a Vigenère cipher with a period of 1.*

# Example Vigenère Cipher

- Let the message be „THE BOY HAS THE BAG “ and let the key be „VIG “:

■ Plaintext:	T	H	E	B	O	Y	H	A	S	T	H	E	B	A	G
■ Key:	V	I	G	V	I	G	V	I	G	V	I	G	V	I	G
■ Ciphertext:	O	P	K	W	W	E	C	I	Y	O	P	K	W	I	M

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

## Example

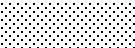
- Let the message be "HELLO"
- and let the KEY be "SEC"
- a=ZINLO
- b=ZINDS
- c=ZENNO



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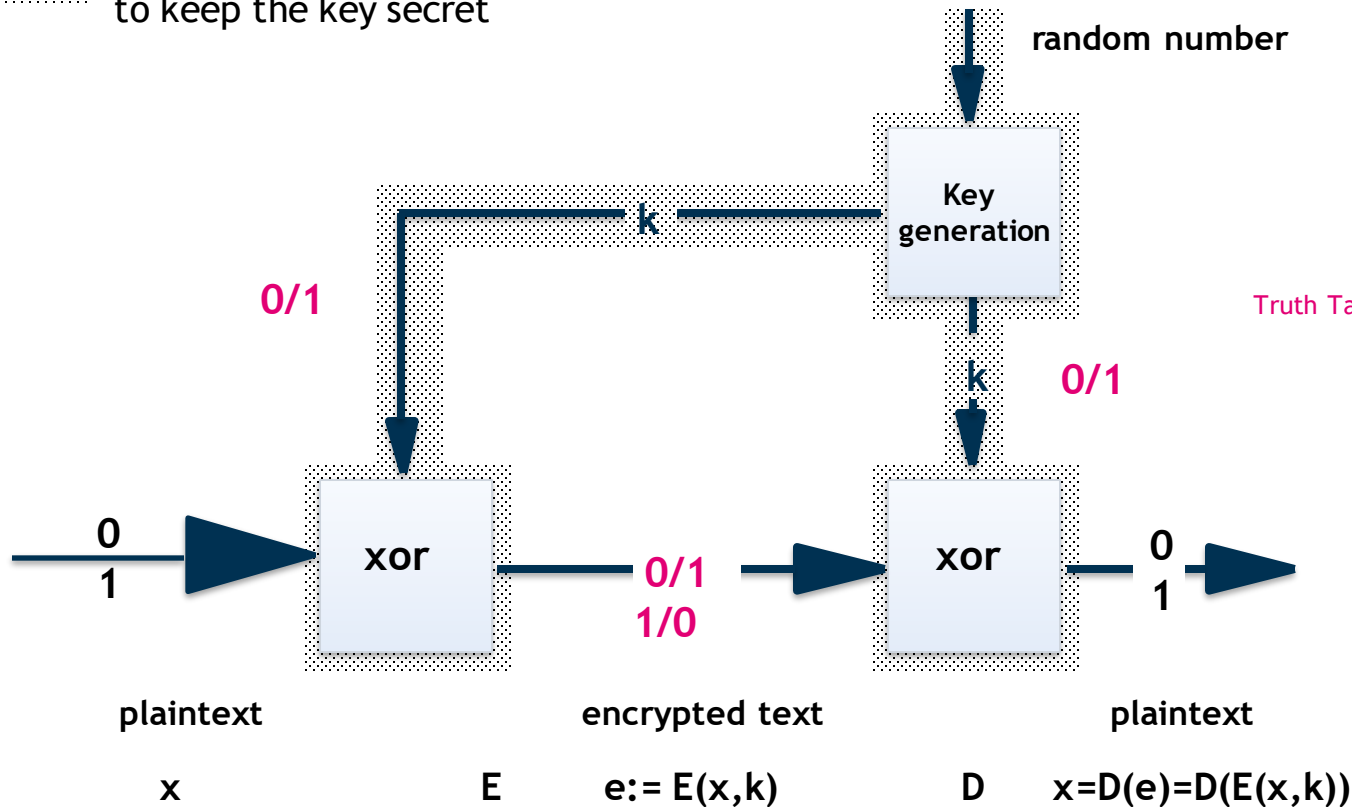
- Invented by Gilbert Vernam
- The one-time pad is basically a Vigenère cipher.
- The length of the key is as long as the length of the plaintext.
- Therefore, there are no periodic reoccurrences.
- The key is randomly chosen and only used once.
- Every key has the same probability.

# Example One Time Pad

 area that needs to be protected to keep the key secret

$X_i$	$S_i$	$Y_i$
0	0	0
0	1	1
1	0	1
1	1	0

Truth Table of the XOR operation



[based on Federrath and Pfitzmann 1997]

# Example

PT=	0	1	1	0
k=	1	0	1	1

$X_i$	$S_i$	$Y_i$
0	0	0
0	1	1
1	0	1
1	1	0

Truth Table of the XOR operation

a=	1	1	1	1
b=	1	0	1	1
c=	1	1	0	1

# Assessment One Time Pad

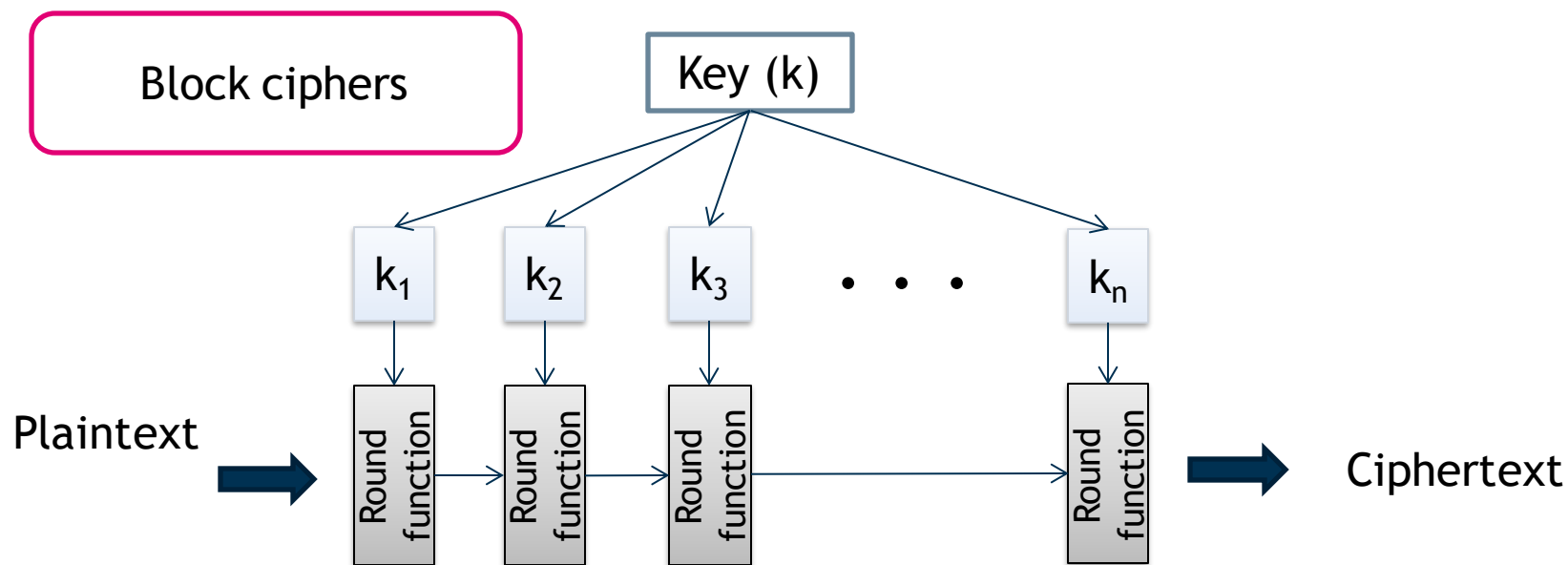
- The one time pad is unbreakable by ciphertext only attacks.
  - Example: Let the ciphertext be “FGHA” .
  - Since we know the key length is at least 4 and the probability of every possible key is equal, the plaintext can be any 4-letter word possible.
- In a known plaintext attack we can deduct the key.
  - Then we know which key was used to encrypt the message we already know.
  - But the next message is encrypted with a different key, because every key is only used once.
- The same applies to a chosen plaintext attack.
- **The one-time pad is information theoretically secure and provably impossible to break.**

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# Advanced Encryption Standard (AES) - History

- The Data Encryption Standard (DES) was designed to encipher sensitive but not classified data.
- The standard has been issued in 1977.
- In 1998, a design for a computer system and software that could break any DES-enciphered message within a few days was published.
- By 1999, it was clear that the DES no longer provided the same level of security it had 10 years earlier, and the search was on for a new, stronger cipher.
- AES Rijndael was a winner of U.S. National Institute of Standards and Technology bid for advanced encryptions.
- AES has been approved for Secret or even Top Secret information by the NSA.

[Bi05]



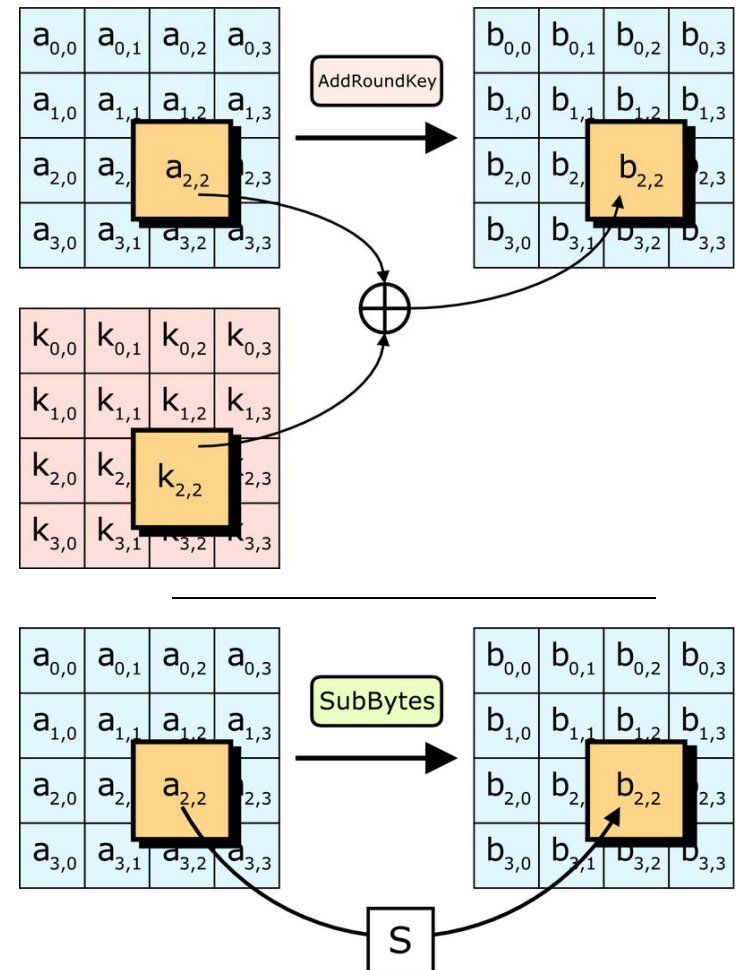
- Variable **number of rounds (10, 12, 14)**
- Depending on **key size (128-bit, 192-bit, 256-bit)**.



# Encryption Round (1)

## AES

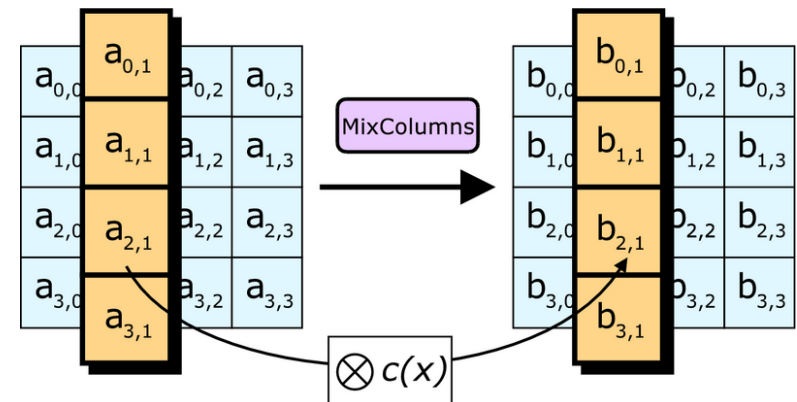
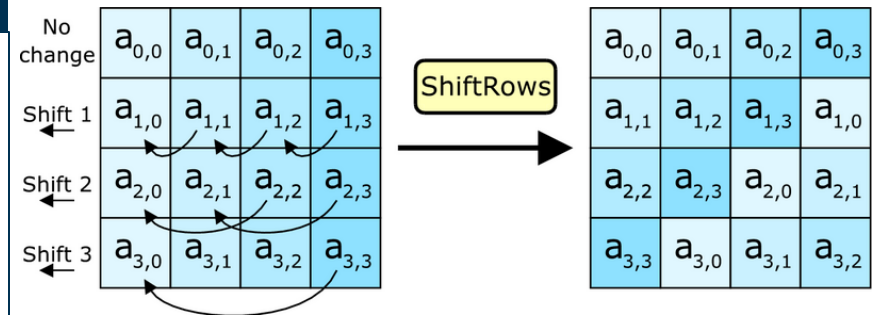
- AddRoundKey
  - XOR (mix bits of) current state  $a$  and round key
  - Round key  $k$  derived using key schedule
- SubBytes
  - Substitution using a lookup table (S-Box)



# Encryption Round (2)

## AES

- ShiftRows
  - Shift each row by row index
- MixColumns
  - 4 key bytes combined into each column using polynomial multiplication modulo  $2^8$  [in  $GF(2^8)$ ]
  - GF = Galois field = finite field



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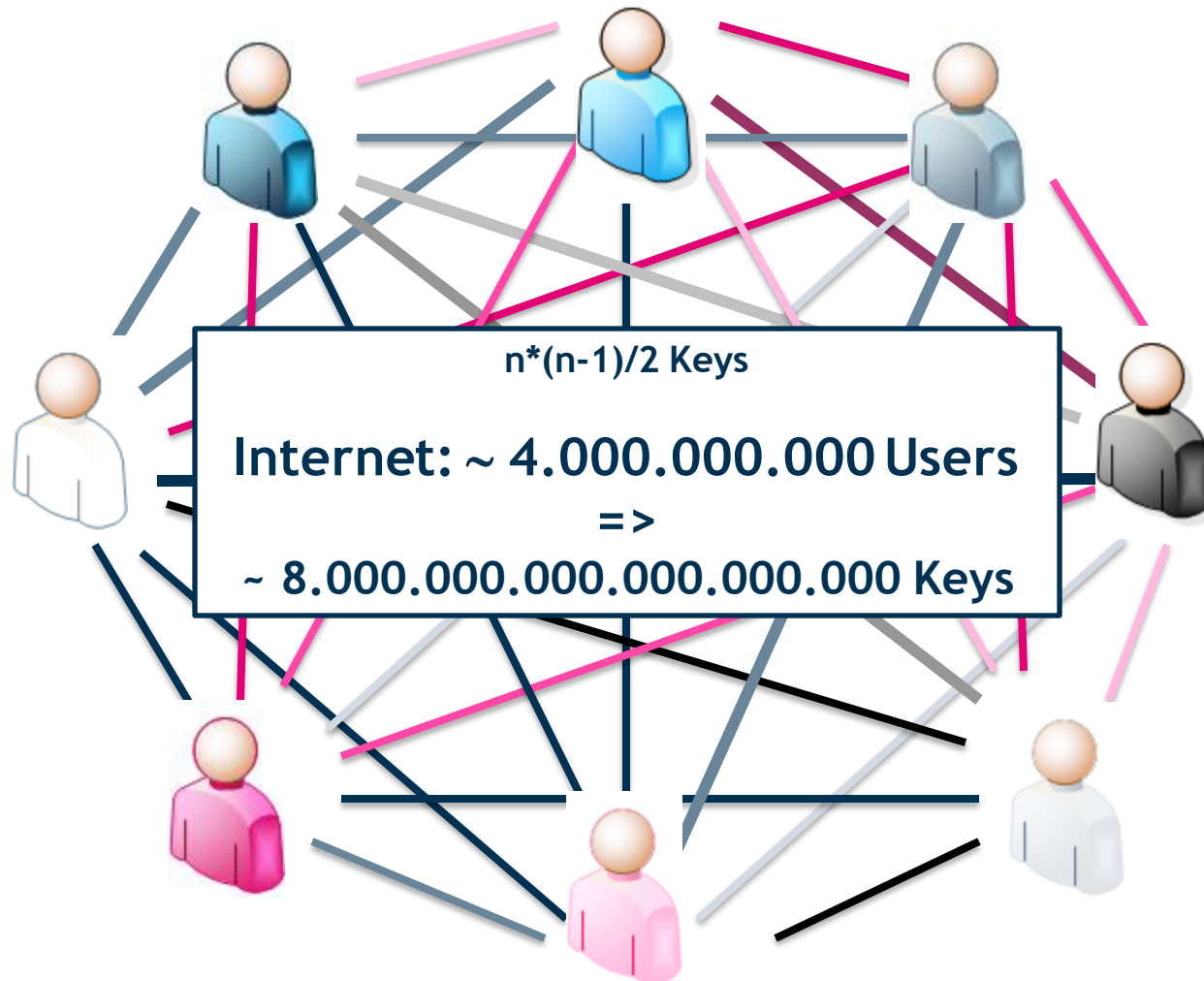
# Symmetric Encryption

Advantage: Algorithms are very fast

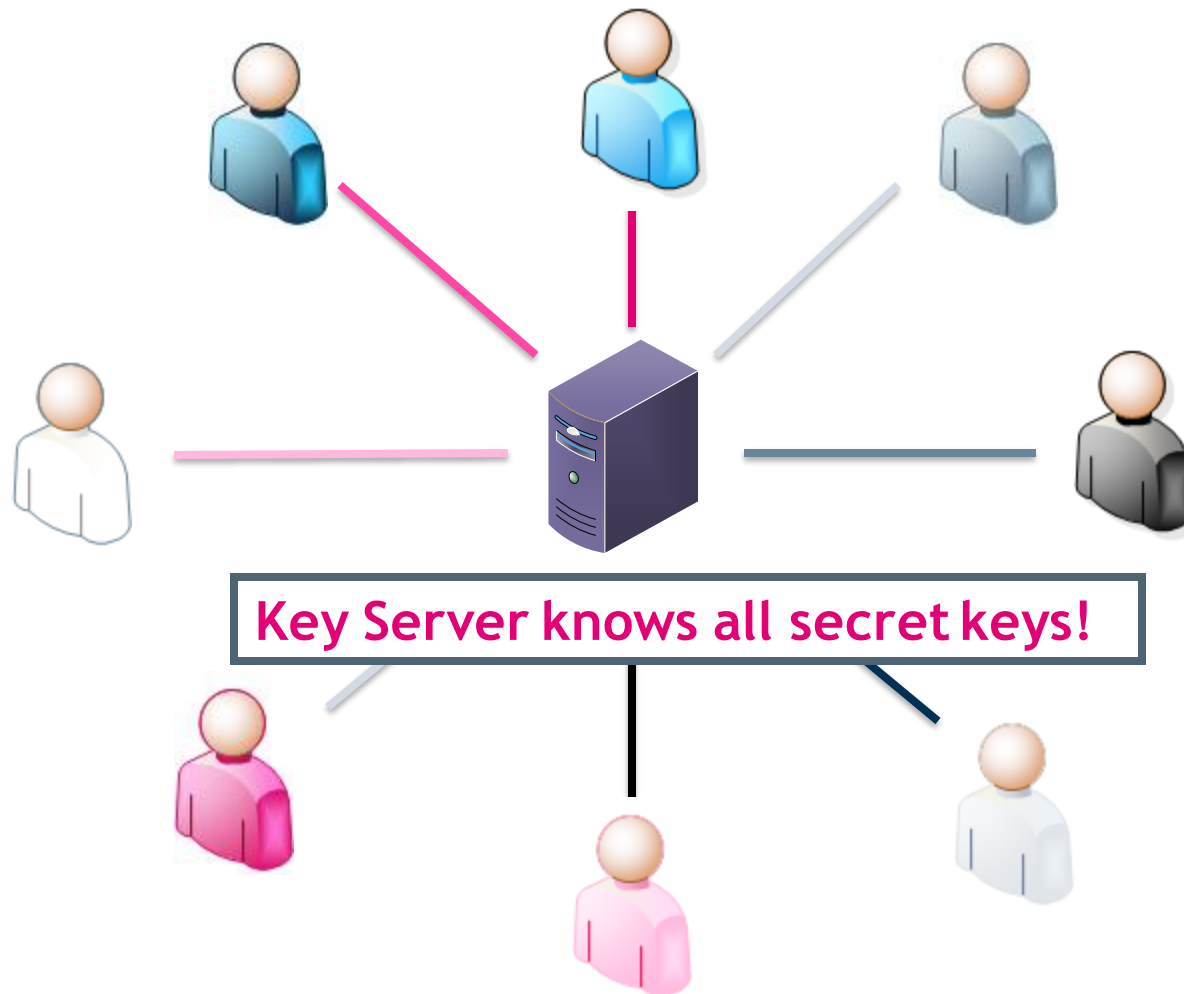
Algorithm	Performance*
RC6	78 ms
SERPENT	95 ms
IDEA	170 ms
MARS	80 ms
TWOFISH	100 ms
DES-edc	250 ms
RIJNDEAL (AES)	65 ms

\* Encryption of 1 MB on a Pentium 2.8 GHz, using the FlexiProvider Java)

# Disadvantage: Key Exchange

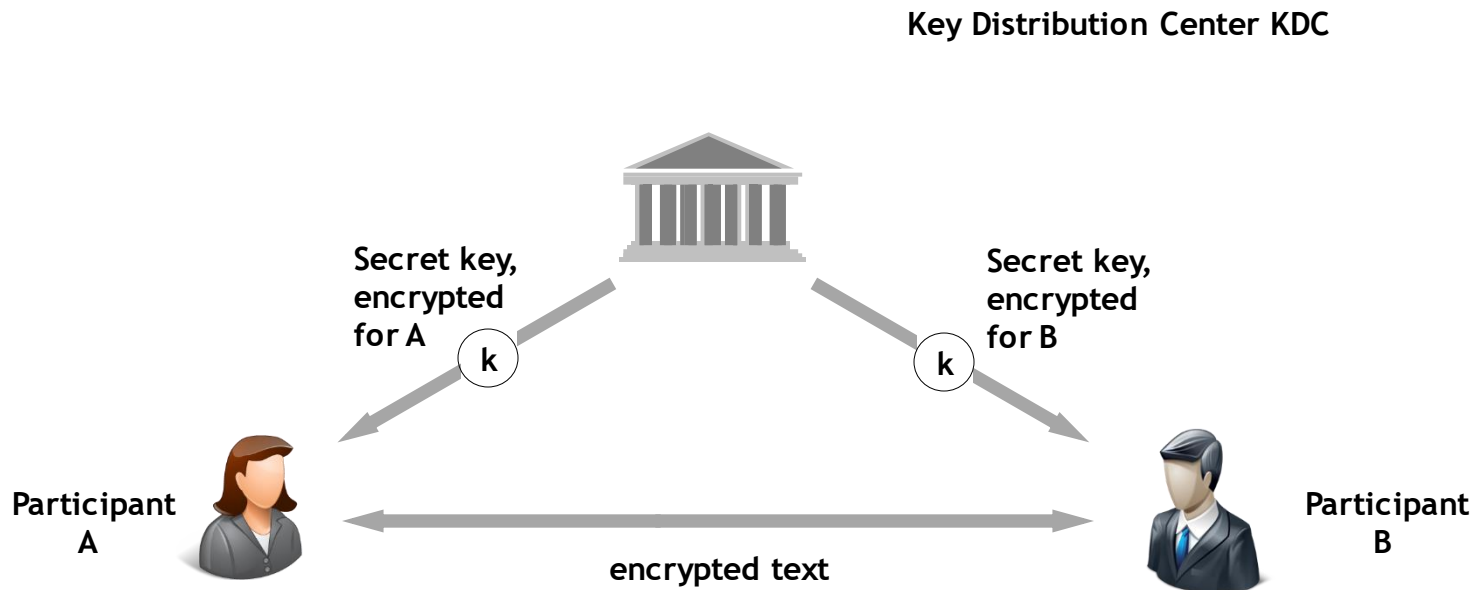


# A Possible Solution



# Key Management in Symmetric Encoding Systems

- One key per communication pair is necessary.
- Secure agreement and transfer are also challenging.
- A center for key distribution is possible but this party then knows all secret keys!



Roger Needham / Butler Lampson

“Anybody who asserts that a problem is readily solved by encryption, understands neither encryption nor the problem.”



[Marshall Symposium 1998] [Randell 2004]



- **[Knospe2019]** Knospe, Heiko. *A Course in Cryptography*. Vol. 40. American Mathematical Soc., 2019. p. 35.
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- **[The Marshall Symposium]** **The Marshall Symposium**: Address Roger Needham, May 29, 1998, Rackham School of Graduate Studies, University of Michigan  
[web.archive.org/web/20081201182254/http://www.si.umich.edu/marshall/docs/p201.htm](http://web.archive.org/web/20081201182254/http://www.si.umich.edu/marshall/docs/p201.htm), accessed 2015-04-15.
- **[Randell 2004]** Randell, B. (2004) *Brief Encounters*; Pp. 229-235 in: Andrew Herbert, Karen Spärck Jones: *Computer Systems: Theory, Technology, and Applications*; New York, Springer 2004
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