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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Lecture 4

Information & Communication Security (SS 16)

Cryptography I

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Agenda

- Introduction
- Classical cryptosystems
  - General concept
  - Substitution ciphers
    - Caesar cipher
    - Vigenére cipher
    - One time pad
  - AES
  - Advantages and Problems
- Public key cryptography

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Cryptography

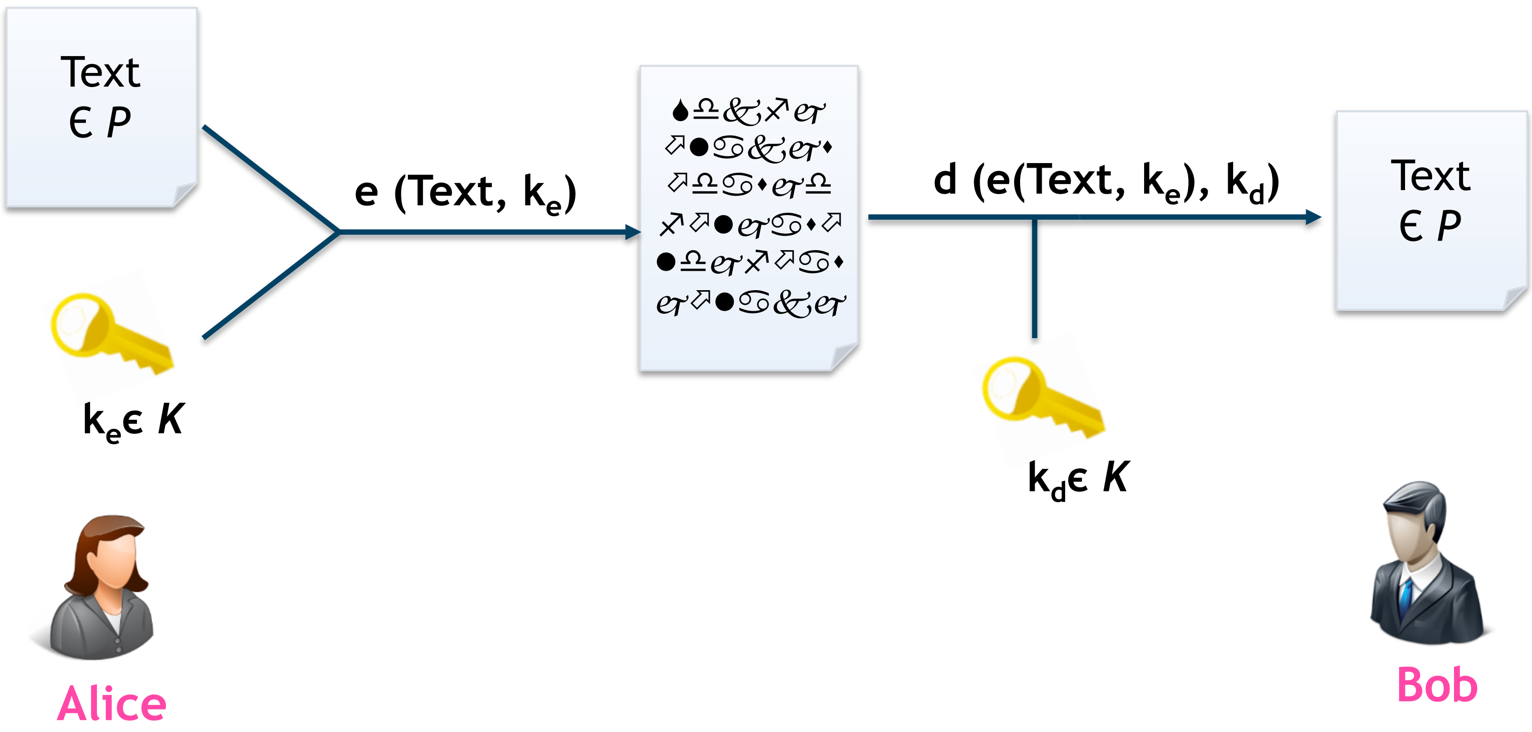
Cryptosystem

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

- A set ***P*** of plaintexts
- A set ***K*** of keys
- A set ***C*** of ciphertexts
- A set ***E*** of enciphering functions, with ***E: P x K -> C***
- A set D of deciphering functions, with ***D: C x K -> P***

[Bi2005]

Example

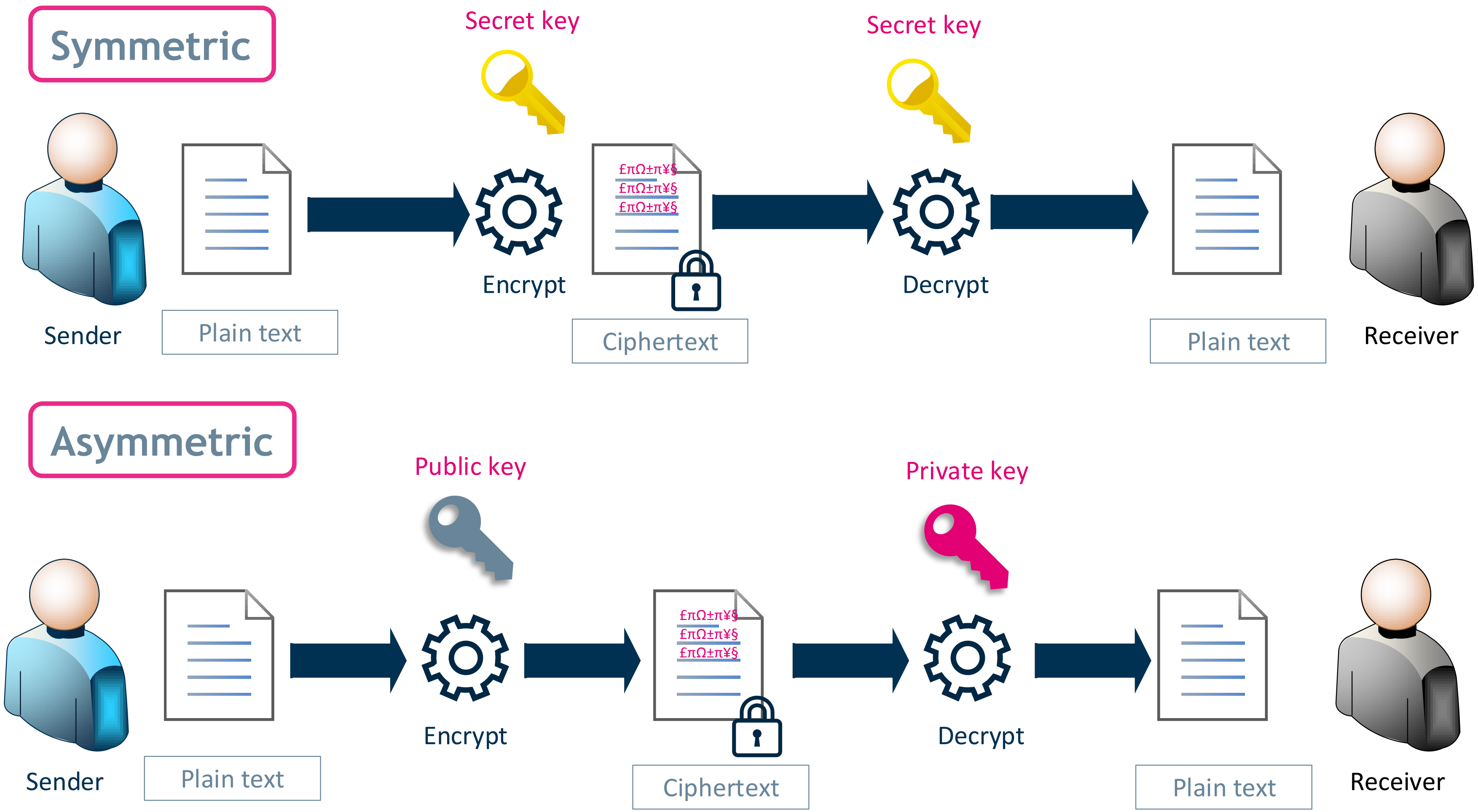


Cryptographic Systems (I)

- 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

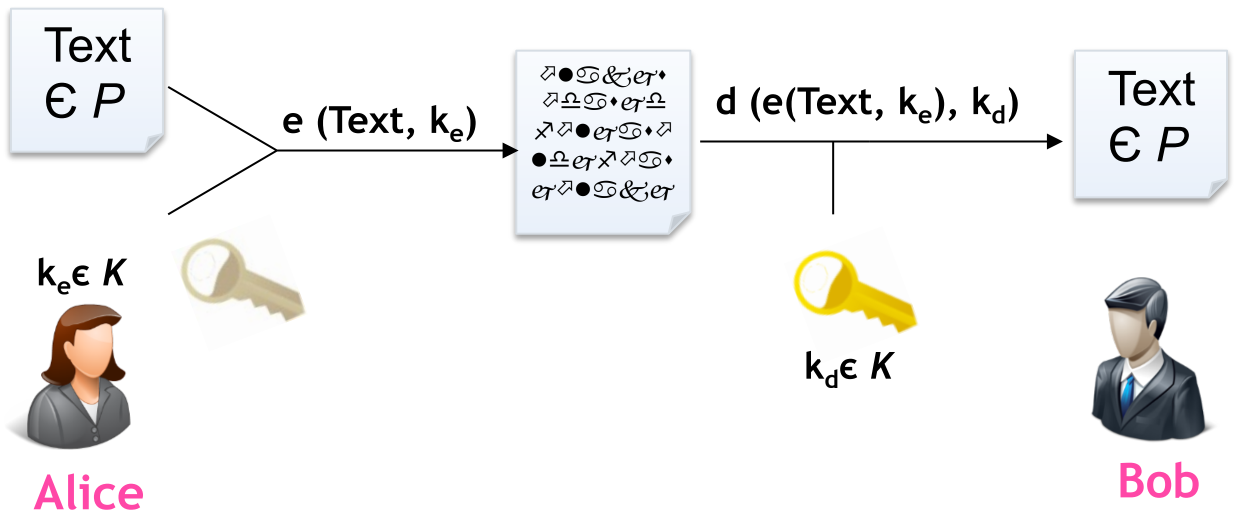
In practice mostly hybrid systems

Cryptographic Systems (II)



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 $\boldsymbol{k_e}$



Cryptography – Important Concepts

- 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)

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Attacks

- 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 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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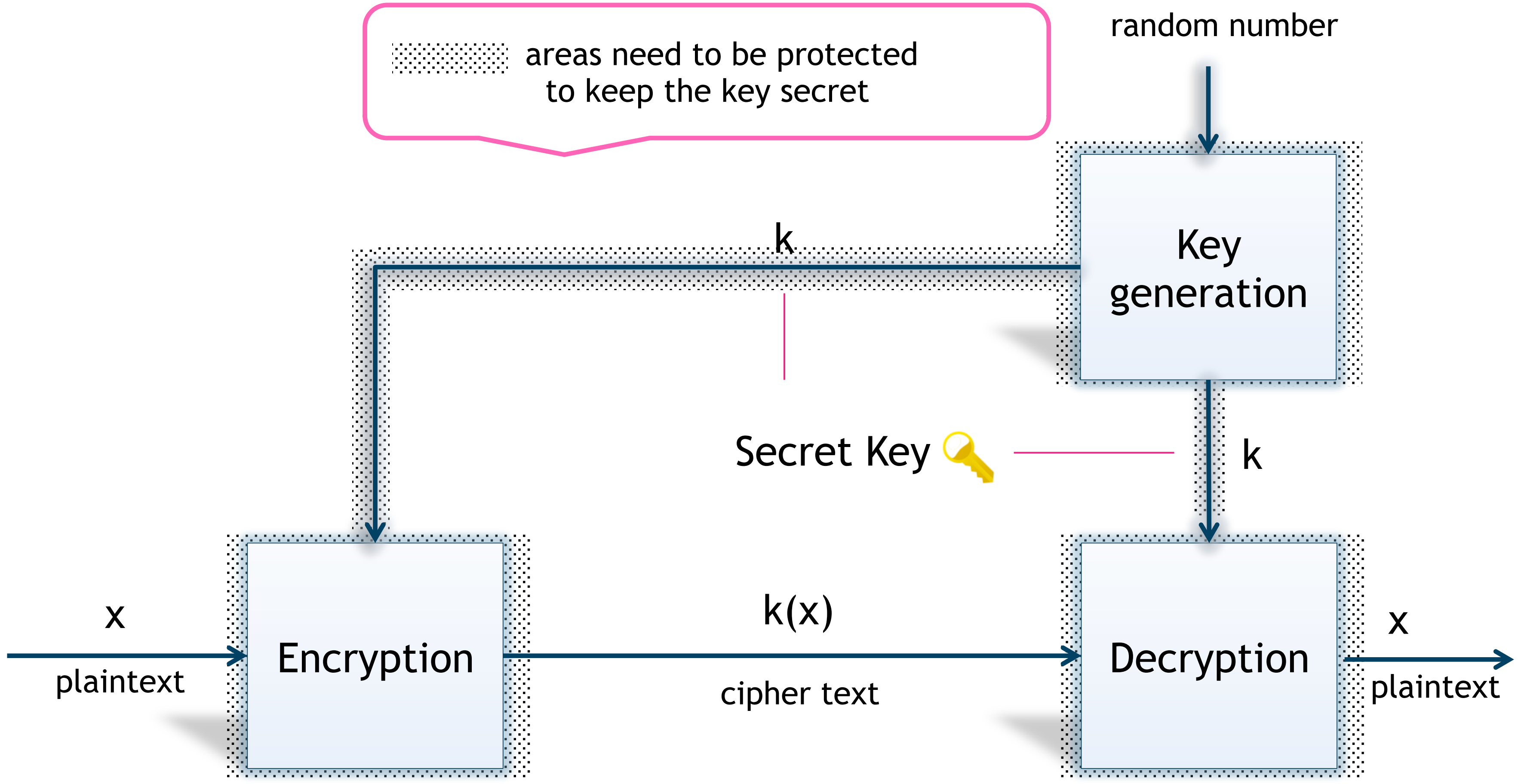
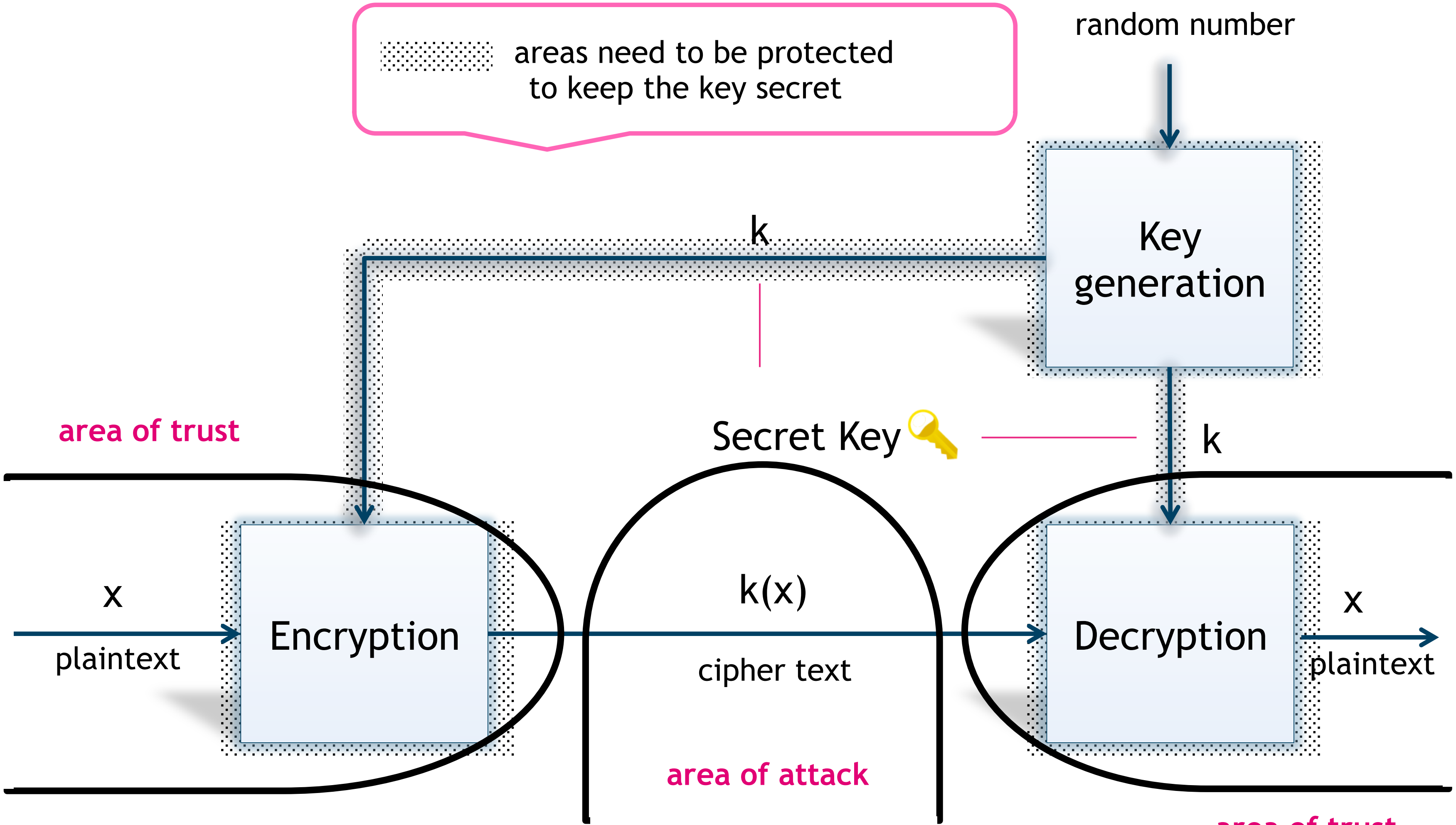
Symmetric Encryption Systems



[based on Federrath and Pfitzmann 1997]

Symmetric Encryption Systems



[based on Federrath and Pfitzmann 1997]

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Symmetric Encryption Systems

- **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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Caesar Cipher

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.

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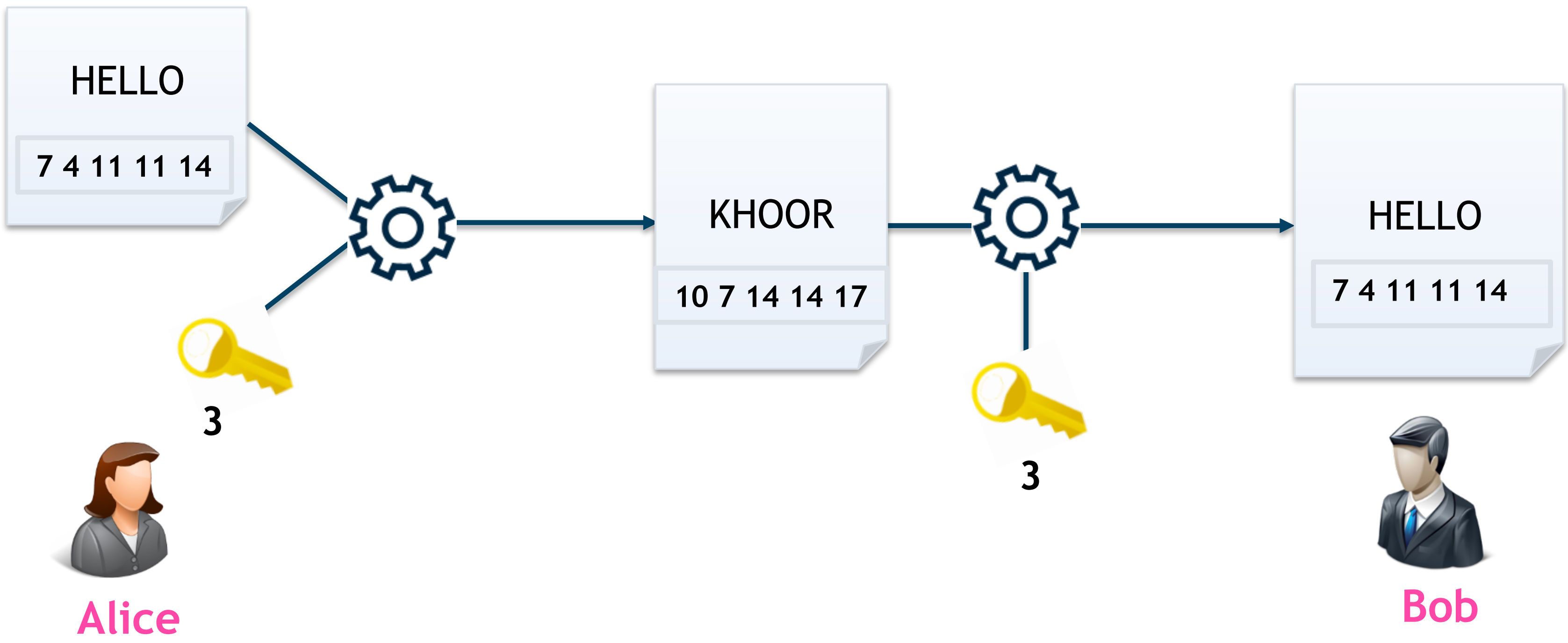
Caesar Cipher

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

Example


HELLO
7 4 11 11 14
3
Alice
KHOOR
10 7 14 14 17
3
HELLO
7 4 11 11 14
Bob

Some Attacks

- 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”

Assessment

- 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)

[www.oxforddictionaries.com/words/what-is-the-frequency-of-the-letters-of-the-alphabet-in-english]

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Vigenére Cipher

- The Vigenére 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.

[Bi2005]

Vigenére 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

[Bi2005]

Assessment Vigenére Cipher

- For many years, the Vigenére 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 Vigenére cipher is quite easily breakable.
- *Example: The Caesar cipher is a Vigenére cipher with a period of 1.*

[Bi2005]

Example Vigenére Cipher

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

- Plaintext:
- Key:
- Ciphertext:

T	H	E	B	O	Y	H	A	S	T	H	E	B	A	G
V	I	G	V	I	G	V	I	G	V	I	G	V	I	G
O	P	K	W	W	E	C	I	Y	O	P	K	W	I	M

[Bi2005]

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Example

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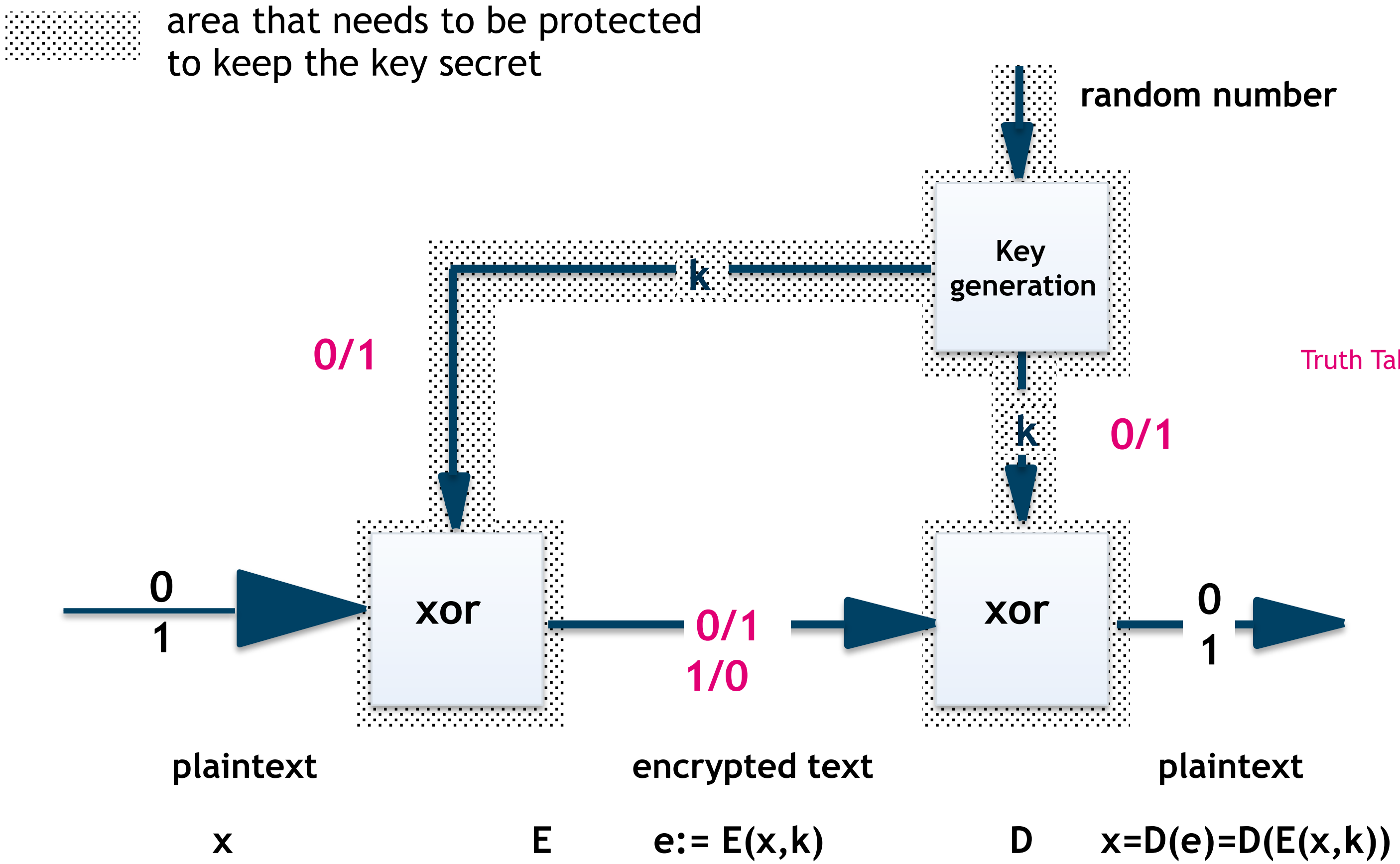
One Time Pad

- Invented by Gilbert Vernam
- The one-time pad is basically a Vigenére 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



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]

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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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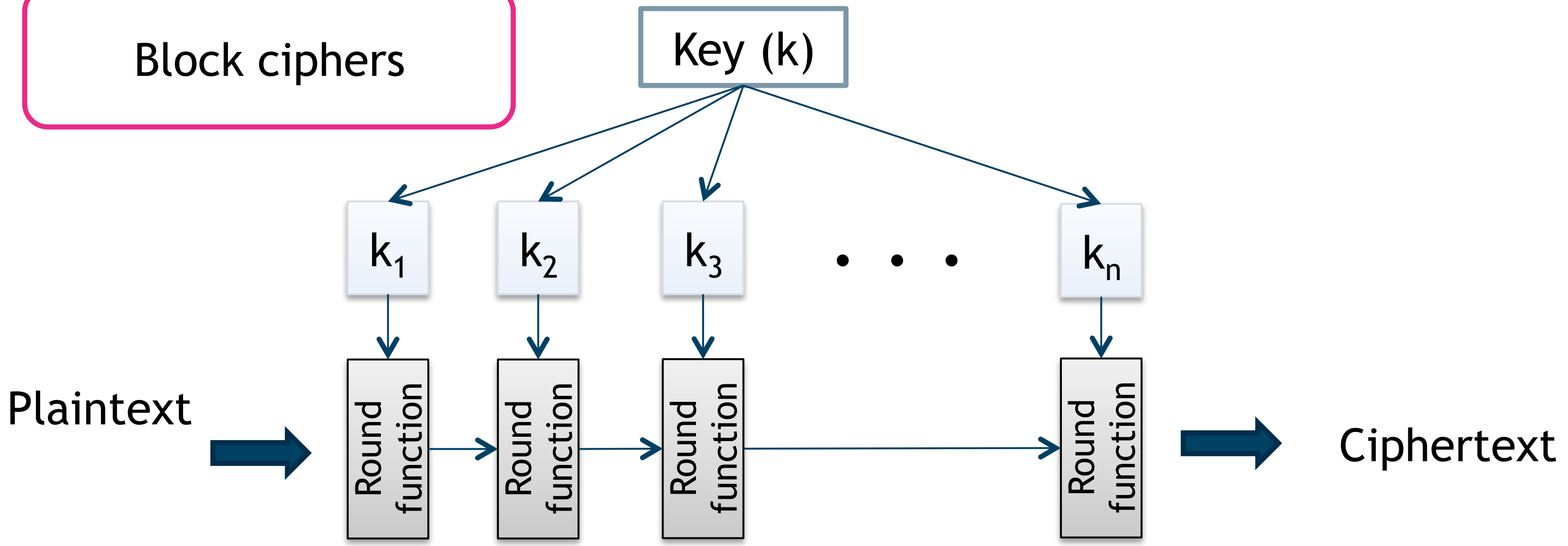
Advanced Encryption Standard (AES) - History

- 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]

AES - Functionality

Block ciphers



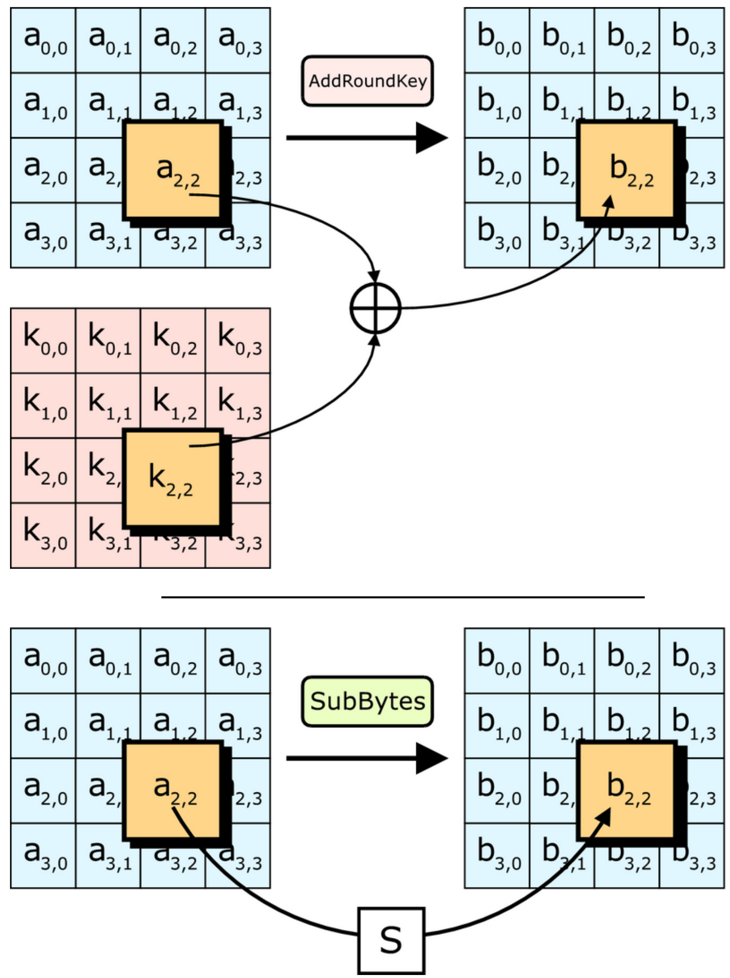
- Variable **number of rounds (10, 12, 14)**
- Depending on **key size (128-bit, 192-bit, 256-bit)**.

[Bi2005]

Encryption Round (1)

AES

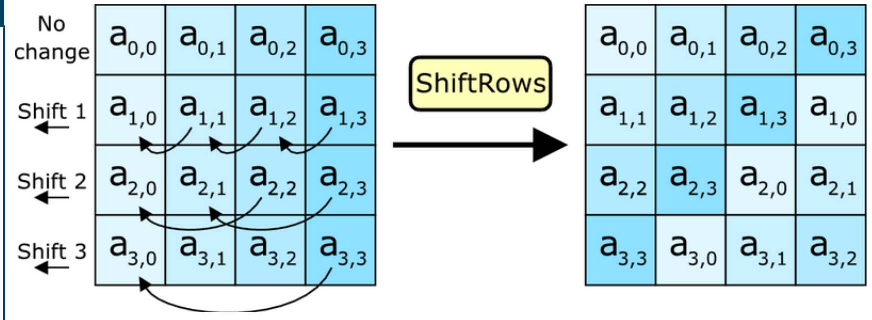
- AddRoundKey
  - XOR (mix bits of) current state a and round key
  - Round key k derived using key schedule
- SubBytes
  - Substitution using a lookup table (S-Box)

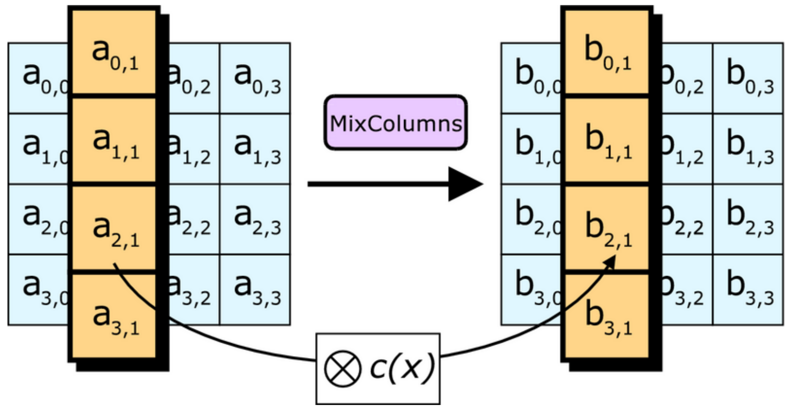


Encryption Round (2)

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-ede	250 ms
RIJNDEAL (AES)	65 ms

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

[J. Buchmann: Lecture Public Key Infrastrukturen, FG Theoretische Informatik, TU-Darmstadt]

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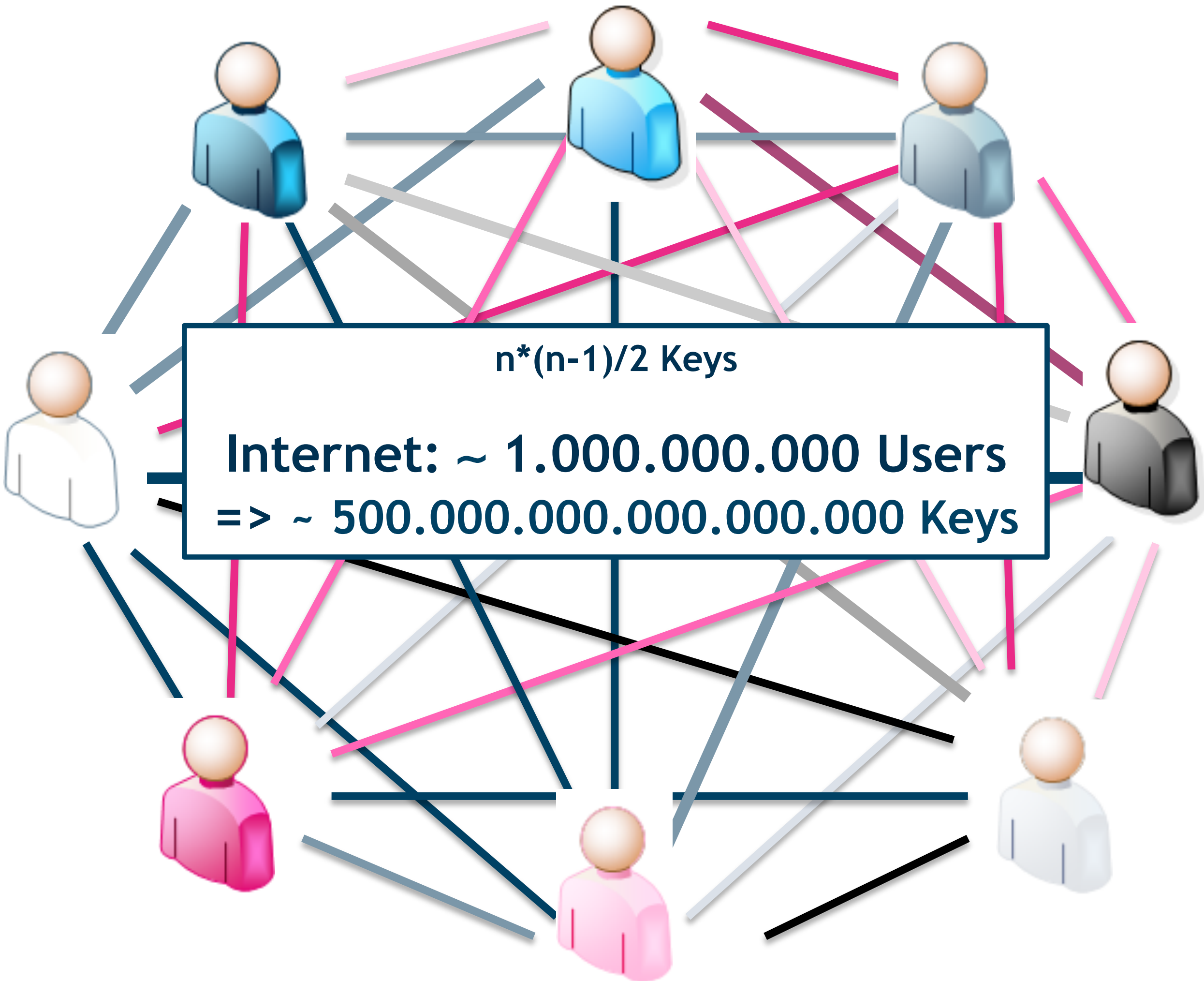
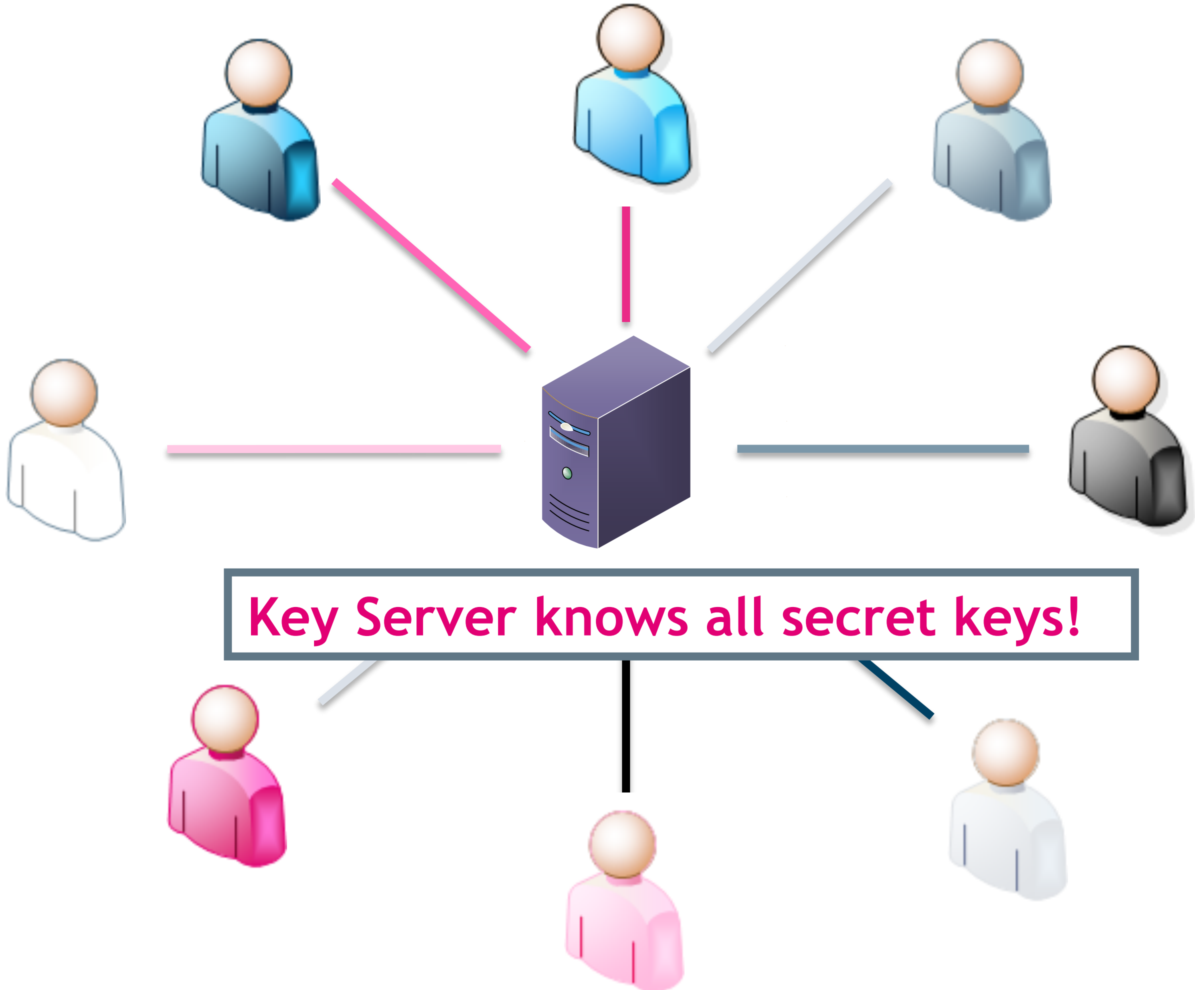
Disadvantage: Key Exchange



[adopted from J. Buchmann: Lecture Public Key Infrastrukturen, FG Theoretische Informatik, TU-Darmstadt]

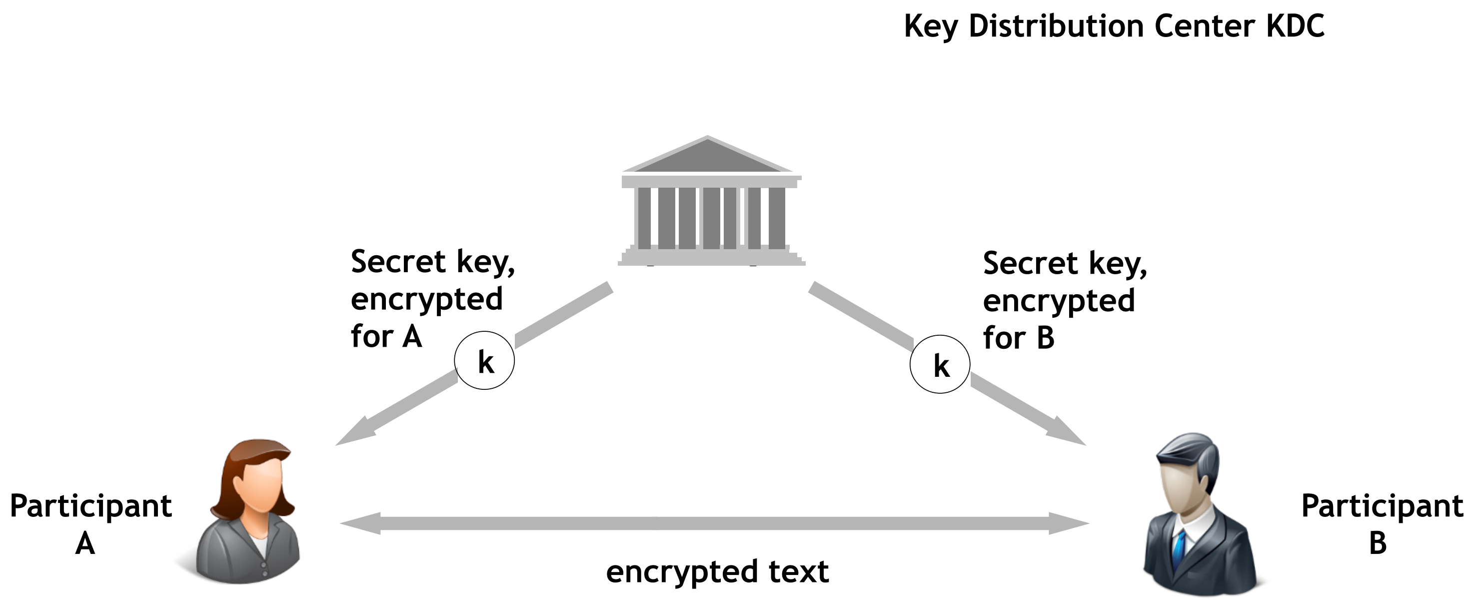
A Possible Solution



[J. Buchmann: Lecture Public Key Infrastrukturen, FG Theoretische Informatik, TU-Darmstadt]

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!



Remark

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]

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