Chair for Network Architectures and Services
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Network Security

Chapter 2
Basic Building Blocks
2.1 Symmetric Cryptography

Acknowledgments

This course is based to a significant extend on slides provided by Günter Schäfer, author of the **book "Netzsicherheit - Algorithmische Grundlagen und Protokolle"**, available in German from **dpunkt Verlag**. The English version of the book is entitled “Security in Fixed and Wireless Networks: An Introduction to Securing Data Communications” and is published by Wiley is also available. We gratefully acknowledge his support.

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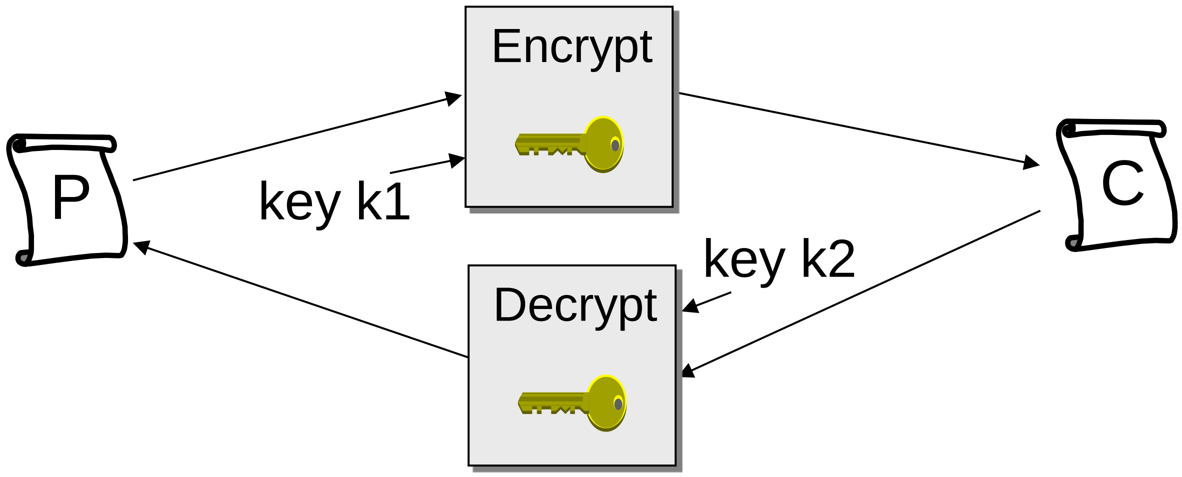
Basic Terms: Plaintext and Ciphertext

- Plaintext P
  - The original readable content of a message (or data).
  - P = „This is network security“
- Ciphertext C
  - The encrypted version of the plaintext.
  - C = „ad 5c 66 d3 55 be 00 88 8c 82 41 d2 75 3d 93 da fe d0 12 20 ac c1 2c e6 64 60 b4 82 2c 87 03 b2 “



In case of symmetric cryptography, k1 = k2.

Cryptographic algorithms: overview

- *Encryption*: transforms plaintext data into ciphertext
  - $C = Enc_K(P)$
  - $P = Dec_K(C)$
  - The identity: $P = Dec_K(Enc_K(P))$

- *Signing*: computes a *check value* or *digital signature*
  - Verifies that the signed data was not tampered with
  - Integrity

- Categories of cryptographic algorithms:
  - *Symmetric cryptography* using 1 key for en-/decryption
  - *Asymmetric cryptography* using 2 different keys for en-/decryption
  - *Cryptographic hash functions* using 0
  - *Message Authentication Codes* using 1 key for signing and verification

Basic Terms: Block cipher and Stream cipher

- Both ciphers require a symmetric key *k*

- Block cipher
  - A cipher that encrypts / decrypts inputs of length *n* to outputs of length *n*
  - Block length *n*
- Stream cipher
  - Generates a random bitstream, called *key stream*
  - Ciphertext = key stream $\oplus$ plaintext

Basic Terms: Block cipher and Stream cipher

Ponies indicate that this slide is intended for your personal postprocessing at home.

- Both ciphers require a symmetric key *k*
- Block cipher
  - A cipher that encrypts / decrypts inputs of length *n* to outputs of length *n*
  - Block length *n*
  - Many modern symmetric ciphers are block ciphers
    e.g. AES, DES, Twofish, …
  - For example, AES 128 uses a block length of 128 bit
- Stream cipher
  - Generates a random bitstream, called *key stream* from the key *k*
  - Ciphertext = key stream ⊕ plaintext
  - ⊕ denotes the XOR operation
  - Popular stream cipher: RC4 (which is no longer considered secure)

Attacking cryptography (1): brute force attack

- Given: *C*
- Unknown: *P, K*

- *brute force attack:* try all keys until an intelligible plaintext is found
- On average, half of all possible keys will have to be tried.

Average Time Required for Exhaustive Key Search

Key Size [bit]	Number of keys	Time required at 1 encryption / µs	Time required at 10^6 encryption/µs
32	$2^{32} = 4.3 * 10^9$	2^{31} µs = 35.8 minutes	2.15 milliseconds
56	$2^{56} = 7.2 * 10^{16}$	2^{55} µs = 1142 years	10.01 hours
128	$2^{128} = 3.4 * 10^{38}$	2^{127} µs = $5.4 * 10^{24}$ years	$5.4 * 10^{18}$ years

1 encryption / µs: 100 Clock cycles of a 100 MHz processor
10^6 encryptions / µs: Clock cycles using 500 parallel 2GHz processors

Attacking cryptography (2): How large is large?

Reference Numbers Comparing Relative Magnitudes	
Reference	**Magnitude**
Seconds in a year	$\approx 3 * 10^{7}$
Seconds since creation of solar system	$\approx 2 * 10^{17}$
Clock cycles per year (3 GHz computer)	$\approx 1 * 10^{17}$
Binary strings of length 64	$2^{64} \approx 1.8 * 10^{19}$
Binary strings of length 128	$2^{128} \approx 3.4 * 10^{38}$
Binary strings of length 256	$2^{256} \approx 1.2 * 10^{77}$
Number of 75-digit prime numbers	$\approx 5.2 * 10^{72}$
Electrons in the universe	$\approx 8.37 * 10^{77}$

Attacking cryptography (3): Cryptanalysis

- Definition: *Cryptanalysis* is the process of attempting to discover the plaintext
  and / or the key

- Types of cryptanalysis:
  - *Ciphertext only:* hope that specific patterns of the plaintext have remained in the ciphertext (frequencies of letters, digraphs, etc.)
  - *Known ciphertext / plaintext pairs*
  - *Chosen plaintext* or *chosen ciphertext*
  - *Differential cryptanalysis*, *linear cryptanalysis*

2.1 Symmetric Cryptography

A perfect symmetric cipher: One-Time-Pad

- Assumption: Alice and Bob share a perfectly random bitstream *otp*.

- Key = *otp*

- Encryption:
  - $C = P \oplus otp$
- Decryption:
  - $P = C \oplus otp$

- Requirement
  - *Key must have same size as message.*
  - *Key must only be used once.*

- Cryptanalysis for One-Time-Pad
  - Ciphertext only: No attack possible as *any possible plaintext* can be generated with the ciphertext.
  - Pairs of ciphertext and plaintext don’t help
  - The ciphertext is perfectly random

Real-world ciphers

- Strengths of otp
  - C of length *n* can be decrypted to any P of length *n*
  - Only knowledge of *k* reveals the right P
  - otp is a **perfect cipher**
- Drawbacks of otp
  - length(key) = length(message)
  - Usually length(key) << length(message)
  - Key must only be used once
- Real- world ciphers
  - Key *k* of fixed length
  - Key *k* is reused for several messages
- Implications
  - The number of possible decryptions of C is smaller

Brute Force attacks on non-perfect ciphers

- Message of length m
  - → 2^m possible messages
- Key of length k
  - → 2^k possible keys
  - → 2^k possible decryptions of message
- Usually: $k \ll m$

- Brute Force: Ciphertext only
  - → if the decryption is intelligible, with high probability *k* is found

- Further advantages for the attacker
  - no perfect randomness of C

- The attacker might be able to break non-perfect ciphers
  - or at least find the most likely plaintext and key

Basic cryptographic Principles

- Substitution
  - Individual characters are exchanged by other characters

  Types of substitution
  - simple substitution: operates on single letters
  - polygraphic substitution: operates on larger groups of letters
  - monoalphabetic substitution: uses fixed substitution over the entire message
  - polyalphabetic substitution: uses different substitutions at different sections of a message

- Transposition
  - The position of individual characters changes (Permutation)

Transposition: scytale

- Known as early as 7th century BC
- Principle:
  - Wrap parchment strip over a wooden rod of a fixed diameter and write letters along the rod.
  - Unwrap a strip and “transmit”
  - To decrypt, wrap a received over a wooden rod of the same diameter and read off the text.

  → Key is the diameter of the rod

- Example:

```
troops
headii
nthewe             thnsm predd opoah nrlod eeeis iedus
stneed      ⇨
moresu
pplies
```

- Weakness:
  - Easy to break by finding a suitable matrix transposition.

Monoalphabetic substitution: Atbash

Jeremiah 25:25

And all the kings of the north, far and near, one with another, and all the kingdoms of the world, which are upon the face of the earth: and the king of Sheshach shall drink after them.

Atbash code: reversed Hebrew alphabet.

A Aleph א	B Beth ב	G Gimel ג	D Daleth ד	H He ה	WVFY Waw ו	Z Zajin ז	H Chet ח	T Tet ט	IJ Jod י	K Kaph כ ך	L Lamed ל	M Mem מ ם	N Nun נ ן	X Samech ס	O Ajin ע	P Pe פ ף	Z Sade צ ץ	Q Koph ק	R Resch ר	S Sin ש	T Taw ת
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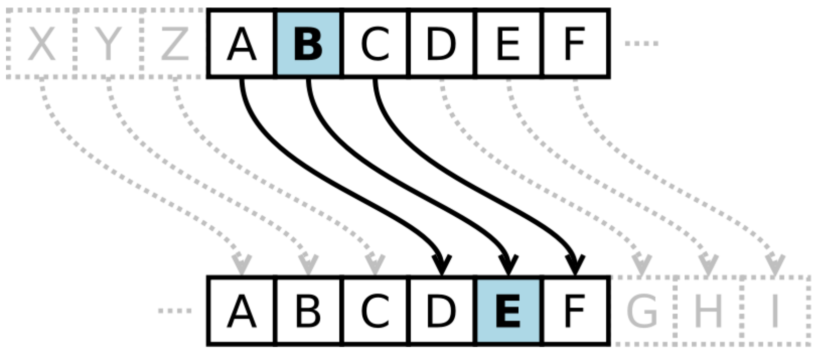
Sheshach ⇨ כ ך ש ש ⇨ ל ב ב ⇨ Babel

Monoalphabetic substitution: Caesar cipher

- Caesar code: left shift of alphabet by 3 positions.



- Example (letter of Cicero to Caesar):

  MDEHV RSNQNRQNV PHDH XHVXNPRQNZP

  HABES OPINIONIS MEAE TESTIMONIUM

- Weakness: a limited number of possible substitutions. Easy to break by brute force!

Now on the bit level

Plaintext	P = 1 1 0 1 1 0 0 1
Key	k = 1 0 0 1
Ciphertext	C = ?

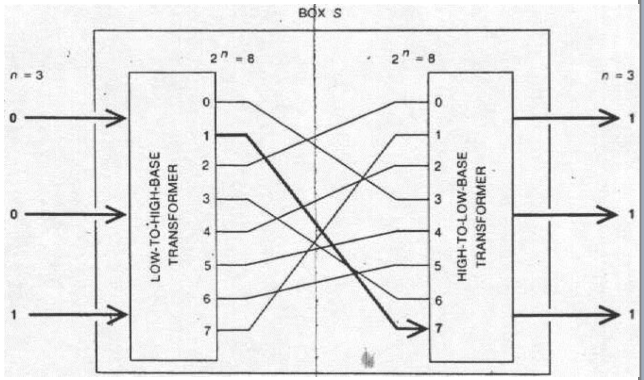
$C = P \oplus k = 11011001 \oplus 10011001 = 01000000$

Why is this not as secure as the OTP?

Modern cryptography: S and P-boxes

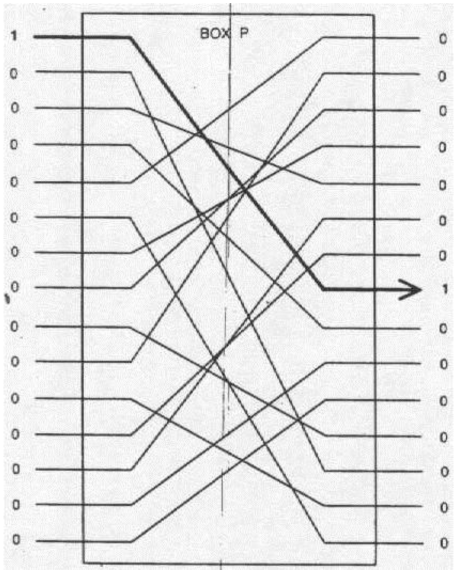
S-box:

- Block-wise **substitution** of binary digits.
  - Can be static or depend on key
  - Input and output size can be different
  - Can be implemented as a large table with all inputs and their predefined outputs
- Resistant to attacks for sufficiently large block size; e.g. for n=128 it provides 2^{128} possible mappings.



P-box:

- Block-wise **permutation** of binary digits.
- Realizes a simple **transposition** cipher with maximal entropy.
- Problem: straightforward attacks exist.

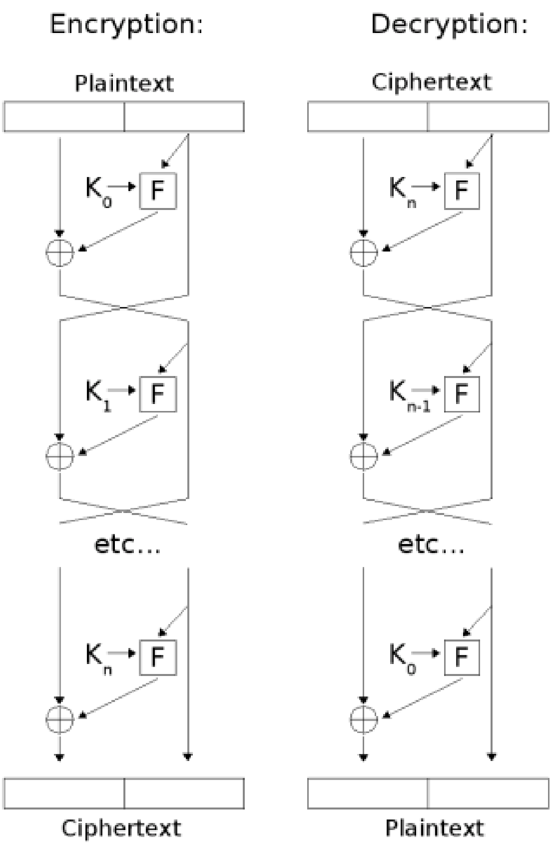


A product cipher of S and P-boxes

- A product cipher is a combination of simple ciphers (e.g. S-box and P-box).
- Rounds: This combination may be applied multiple times.
- Multiple rounds provide a cryptographically strong polyalphabetic substitution.
- Combination of substitution with transposition provides protection against specific attacks (frequency analysis).
- Follows the theoretical principles outlined by C. Shannon in 1949: combines “confusion” with “diffusion” to attain maximal entropy of a cipher text.
  - *Confusion*: cipher text statistics depend in a very complex way on plaintext statistics (approach: substitution in different rounds)
    - e.g. make the number of 1s and 0s in ciphertext seem independent of their numbers in plaintext
  - *Diffusion*: each digit in plaintext and in key influence many digits of cipher text (approach: many rounds with transposition)

Feistel ciphers (Feistel network)

- A multiple-round scheme with separate keys per round.
- Goal: Encrypt plaintext block $P = L_0 \mid R_0$
- Function $f(K_i,R_{i-1})$ is algorithm-specific, usually a combination of permutations and substitutions.
- Invertible via a reverse order of rounds.
- 3 rounds suffice to achieve a pseudorandom permutation.
- 4 rounds suffice to achieve a strong pseudorandom permutation (i.e. it remains pseudorandom to an attacker with an oracle access to its inverse permutation).
- A foundation for a large number of modern symmetric ciphers: DES, Lucifer, Blowfish, RC5, Twofish, etc.



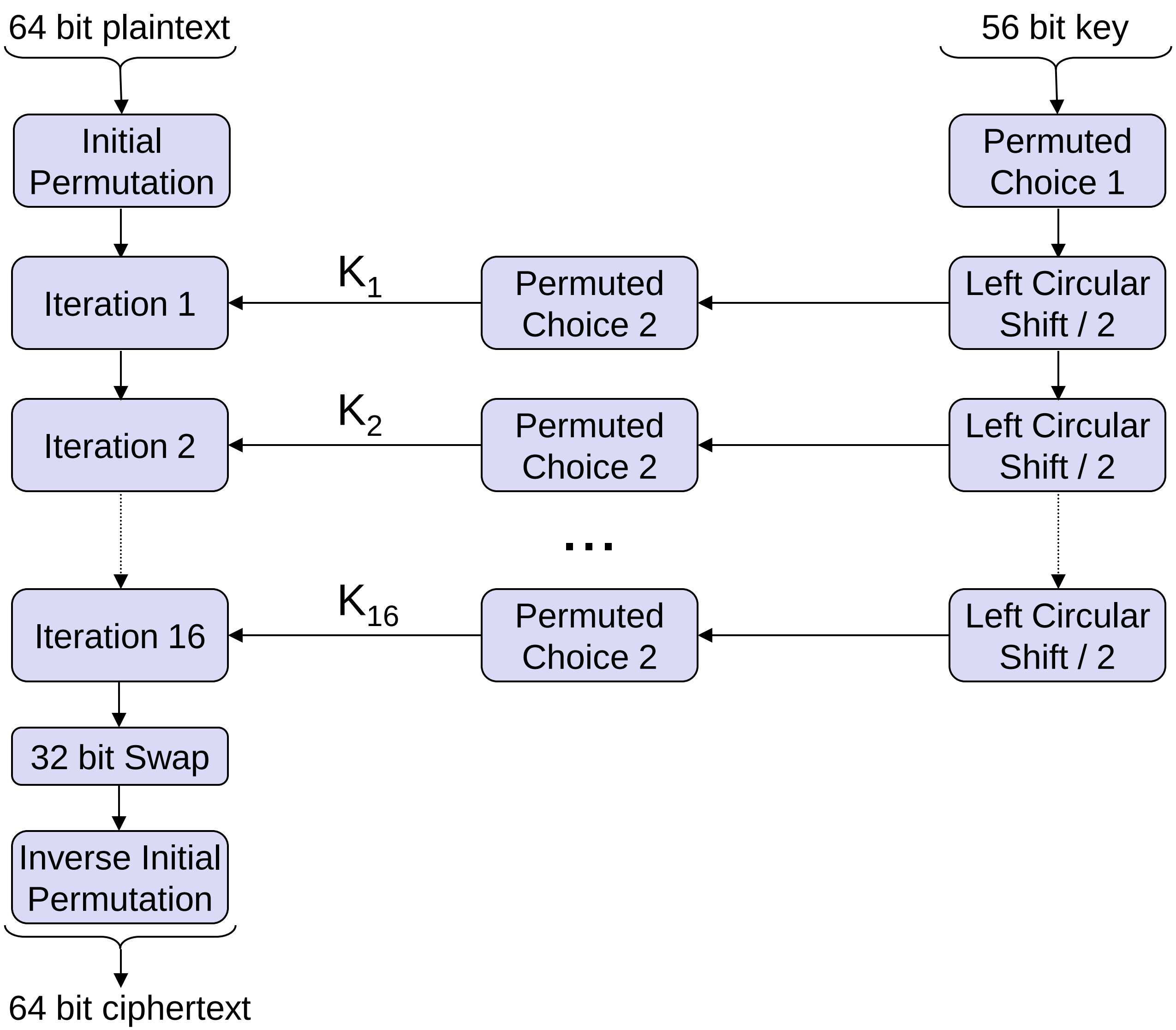
Feistel Cipher

Data Encryption Standard (DES)

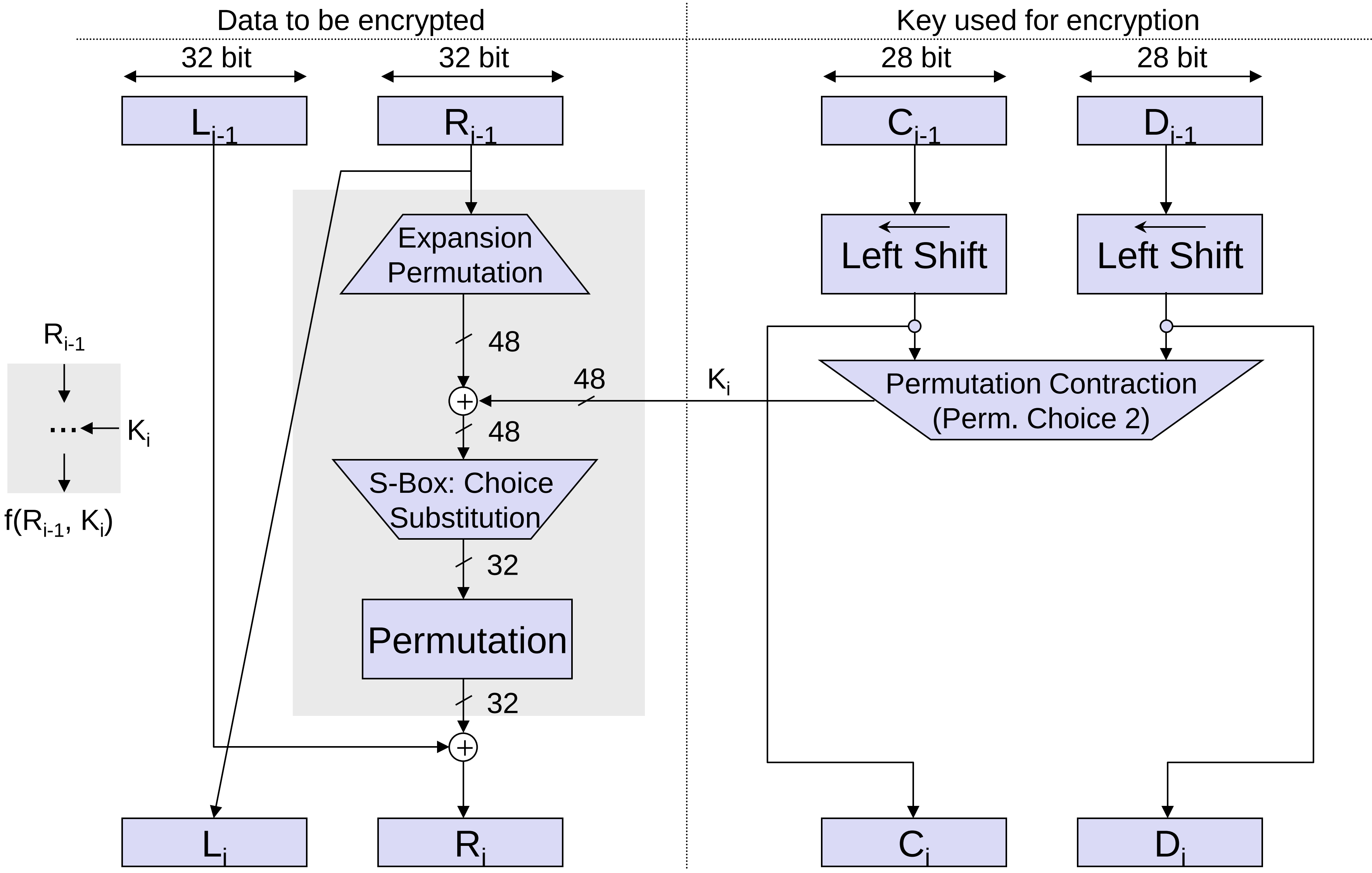
- Data Encryption Standard - DES
- Standardized 1977
- We will look at this cipher as example

- Warning: DES is no longer used as of today
  1. The key length is too small
  2. DES is comparably slow

DES – Algorithm Outline



DES – Single Iteration



DES – Security

- Main weakness: key length:
  - As a 56 bit key can be searched in 10.01 hours when being able to perform 10^6 encryptions / μs (which is feasible today), DES can no longer be considered as sufficiently secure
- *Differential cryptanalysis:*
  - In 1990 E. Biham and A. Shamir published a cryptoanalysis method for DES
  - It looks specifically for differences in ciphertexts whose plaintexts have particular differences and tries to guess the correct key
  - The basic approach needs **chosen plaintext** together with its **ciphertext**
  - DES with 16 rounds is immune against this attack, as the attack needs 2^{47} chosen plaintexts or (when “converted” to a known plaintext attack) 2^{55} known plaintexts.
  - The designers of DES told in the 1990s that they knew about this kind of attacks in the 1970’s and that the S-boxes were designed accordingly

Extending the Key-Length of DES by Multiple Encryption

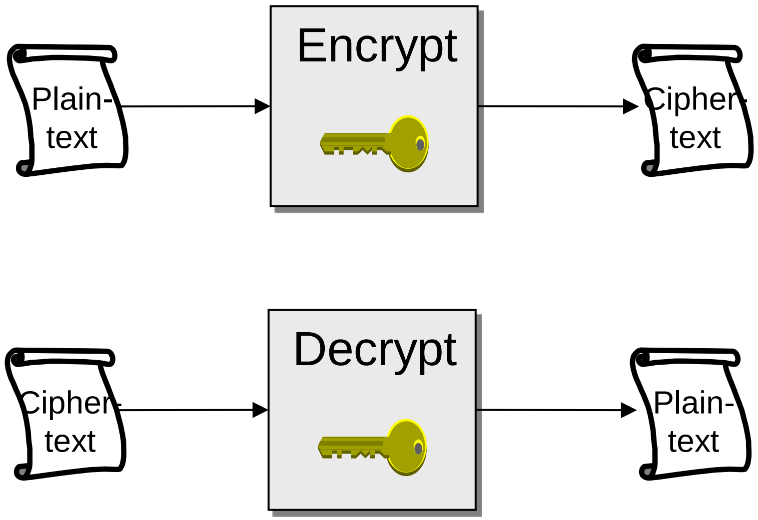
- Triple encryption scheme, as proposed by W. Tuchman in 1979:
  - $C = Enc_{K3}\, Dec_{K2}\, Enc_{K1}\, (P)$
  - The use of the decryption function *Dec* in the middle allows to use triple encryption devices with peers that only own single encryption devices by setting K1 = K2 = K3 (backwards compatibility with DES)
  - Triple encryption can be used with two or three different keys
    - Two keys: set K1 = K3
    - Three pairwise distinct keys
  - There are no known practical attacks against this scheme up to now
  - Drawback: the performance is only 1/3 of that of single encryption, so it should be a better idea to use a different cipher, which offers a bigger key-length right away
- Double encryption is not a feasible option – there is an attack against it (Meet-in-the-middle-attack)

State-of-the-art symmetric cryptography

- Advanced Encryption Standard (AES)
- Standardized 2001
- Key and block lengths
  - Key Length: 128, 192, or 256 bit
  - Block Length: 128, 192, or 256 bit
- Fast
  - Roughly 3 times the speed of DES (200 MBit/s vs. 80 MBit/s)
  - Hardware support in modern CPUs (Intel AES-NI)
  - Modern CPUs: > 2GB/s
- Hardware implementations for embedded devices available
- Secure
  - There are attacks, but AES is still practically secure
  - AES seems to be the best we have, and it is among the most researched algorithms

Symmetric Encryption (revisited)

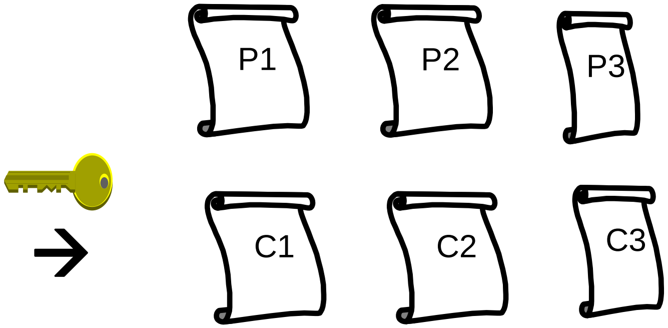
- General description:
  - The same key $K_{A,B}$ is used for enciphering and deciphering of messages:



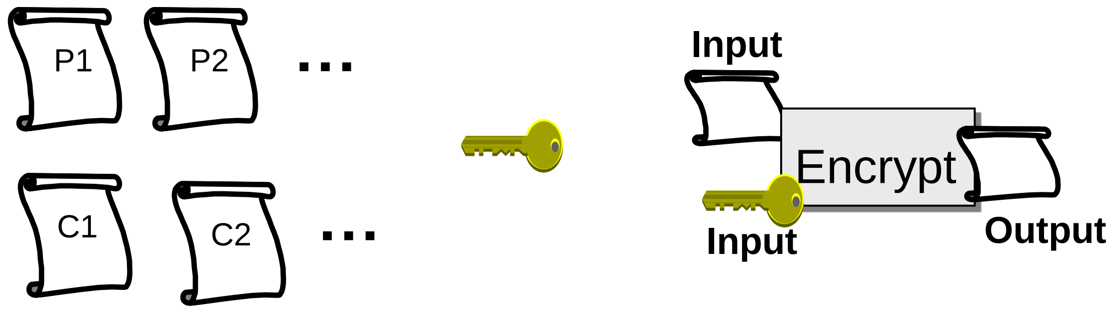
- Notation
  - If *P* denotes the plaintext message, $Enc_{K_{A,B}}(P)$ denotes the cipher text. The following holds: $Dec_{K_{A,B}}(Enc_{K_{A,B}}(P)) = P$
- Symmetric encryption
  - $Enc_{K_{A,B}}$ is at least an injective, often a bijective function
  - $Dec_{K_{A,B}}$ is the inverse function of $Enc_{K_{A,B}}$ is $Dec_{K_{A,B}} = (Enc_{K_{A,B}})^{-1}$
- Examples: DES, 3DES, AES, Twofish, RC4

Using Block Ciphers

- Problem
  - Block ciphers operate on a block size *b*. For example, b=128bit
  - We want to encrypt and decrypt a plaintext of larger length
- Solution
  - A plaintext *P* is segmented in blocks $p_1, p_2, \ldots p_n$ each of length *b.*
  - The last block may need padding to be of length *b*
  - The ciphertext *c* is the combination of $c_1, c_2, \ldots p_n$ where c_i denotes the result of the encryption of the i^{th} block of the plaintext message

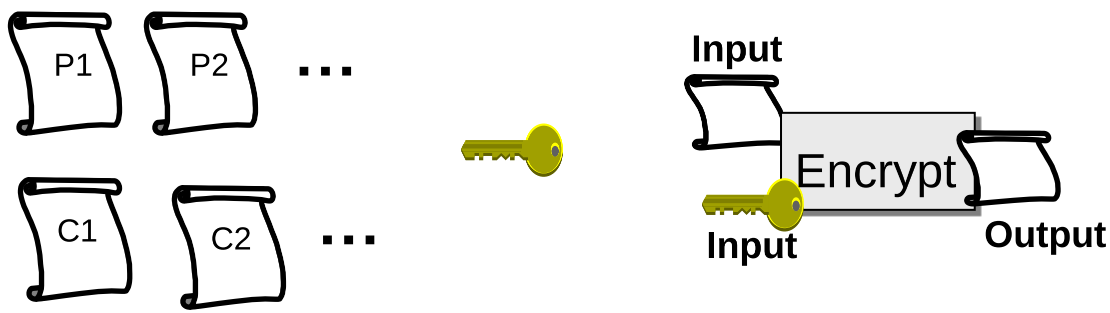


Modes of Encryption



- Modes of Encryption
  - Ways to combine encryption algorithm with the plaintext blocks and key and maybe additional input to generate the ciphertext blocks

Modes of Encryption



- Modes of Encryption
  - Ways to combine encryption algorithm with the plaintext blocks and key and maybe additional input to generate the ciphertext blocks
- Modes where the plaintext is input to the block cipher. Examples:
  - Electronic Code Book Mode (ECB), Cipher Block Chaining Mode (CBC)
- Modes where the plaintext is XORed with the output of a block cipher
  - A pseudorandom stream of bits, called *key stream,* is generated from the symmetric key *K* and a specific input per block,
    e.g. Enc_K(“Block 1”), Enc_K(“Block 2”), Enc_K(“Block 3”), …
  - Examples
    - Output Feedback Mode (OFB), Counter Mode (CTR)

Properties of modes of encryption

- *Error propagation*
  - characterizes the effects of bit-errors during transmission of ciphertext

- *Synchronization*
  - characterizes the effects of lost ciphertext data units

Properties of modes of encryption

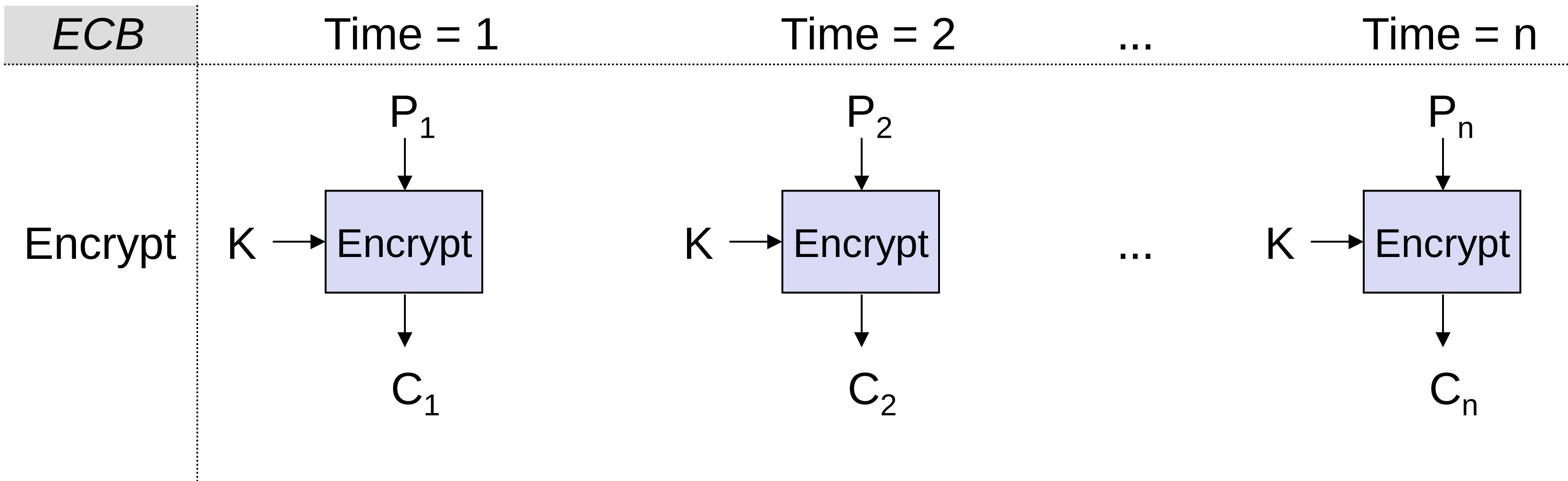
- Plaintext messages p_1, p_2, ... and ciphertext messages c_1, c_2, ...
- The following properties of the mode of encryption and cipher are of interest

- *Error propagation* characterizes the effects of bit-errors during transmission of ciphertext
  - Affects reconstructed plaintext $p_1´$, $p_2´$, ...
  - Depending on the mode of encryption, there may be one or more erroneous bits in the reconstructed plaintext per erroneous ciphertext bit

- *Synchronization* characterizes the effects of lost ciphertext data units
  - Affects reconstructing the plaintext
  - Some modes of encryption cannot recover from lost ciphertext and need therefore explicit re-synchronization in case of lost messages
  - Other modes of encryption do automatically re-synchronize after 0 to n (n depending on the algorithm) ciphertext bits

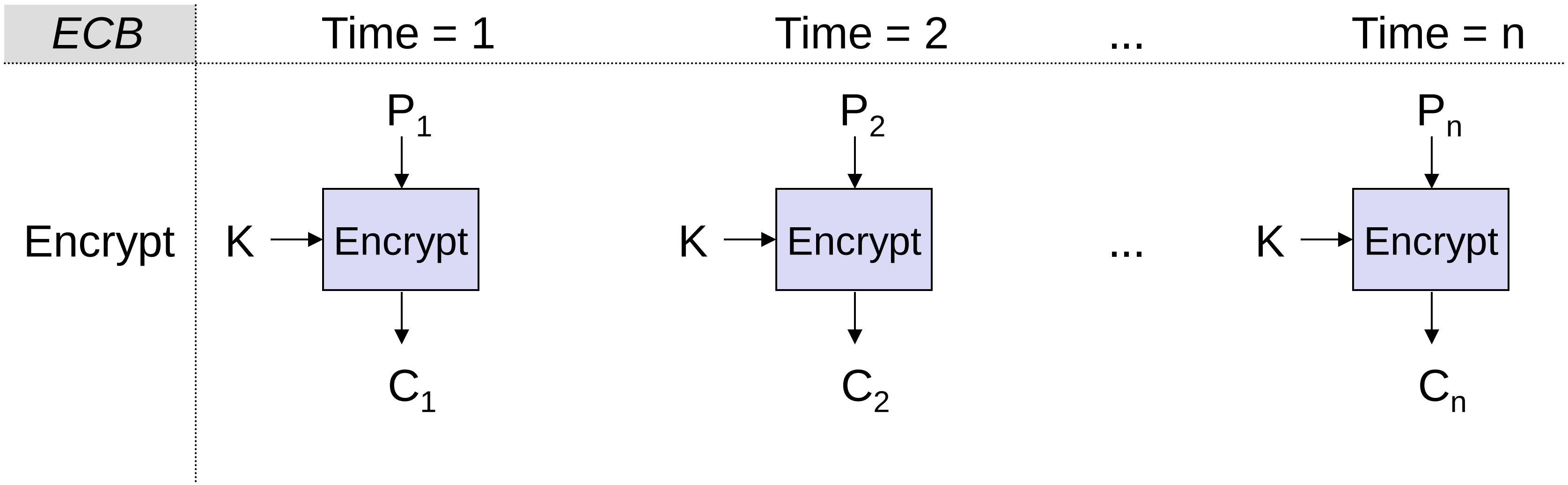
Modes of Encryption – ECB

- *Electronic Code Book Mode (ECB):*
  - Every block p_i is encrypted independently
    $c_i = Enc_K(p_i)$



Modes of Encryption – ECB

- *Electronic Code Book Mode (ECB):*
  - A bit error in one ciphertext block c_i results in a completely wrongly recovered plaintext block p_i' (subsequent blocks are not affected)
  - Loss of synchronization does not have any effect if integer multiples of the block size *b* are lost.
    If any other number of bits are lost, explicit re-synchronization is needed.
  - Drawback: identical plaintext blocks are encrypted to identical ciphertext!



Modes of Encryption – ECB

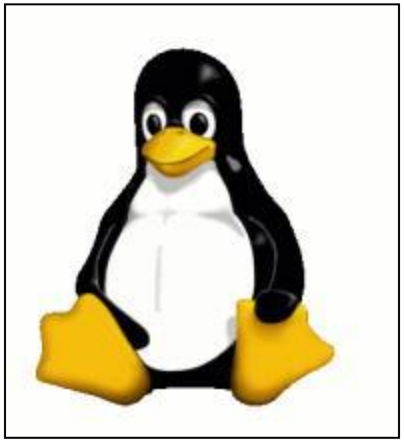
- If $p_i = p_j$ then $c_i = c_j$

- The string “This is network.This is network.Security” with AES-128 key = "AliceBob“

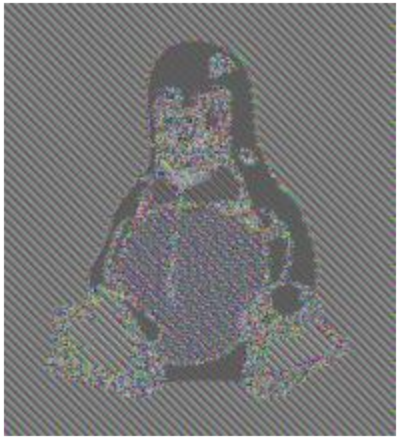
2d	3c	ab	1b	a0	80	77	ec	e8	1d	56	0d	09	2b	f6	77
2d	3c	ab	1b	a0	80	77	ec	e8	1d	56	0d	09	2b	f6	77
16	ea	2c	19	97	e7	40	db	06	a0	35	93	49	5c	37	0b

- Why is it important for this example to use AES with blocklength 128?

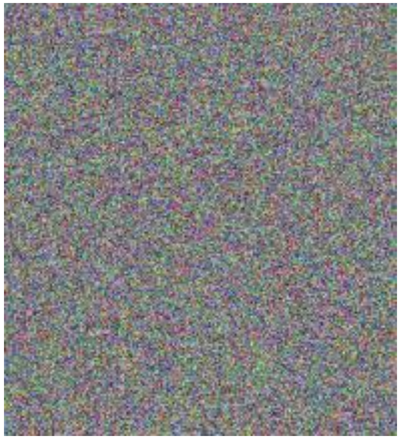
Modes of Encryption – ECB



Original

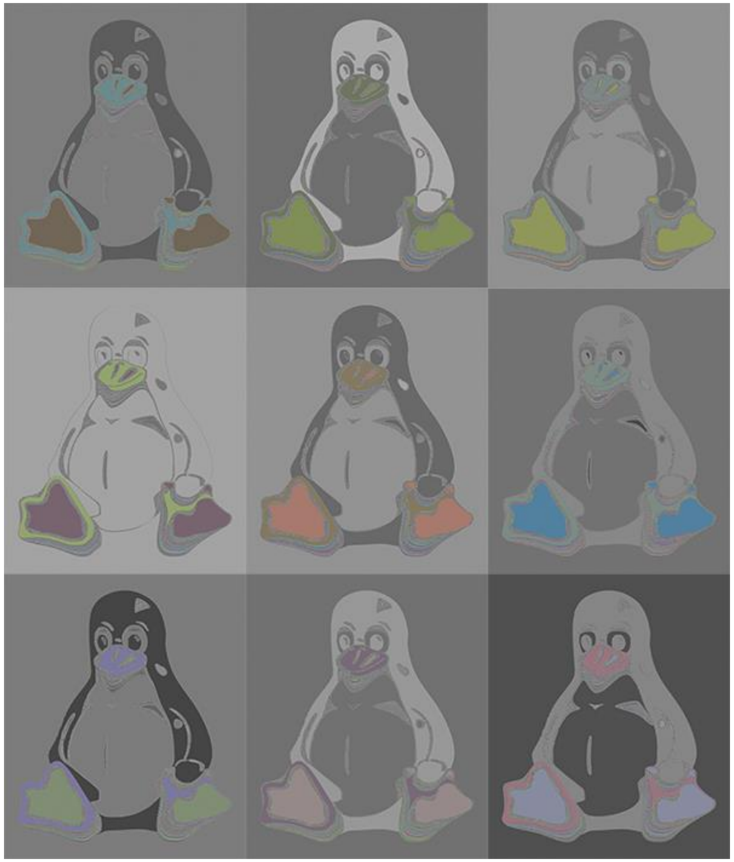


Encrypted using ECB mode



Encrypted using other modes

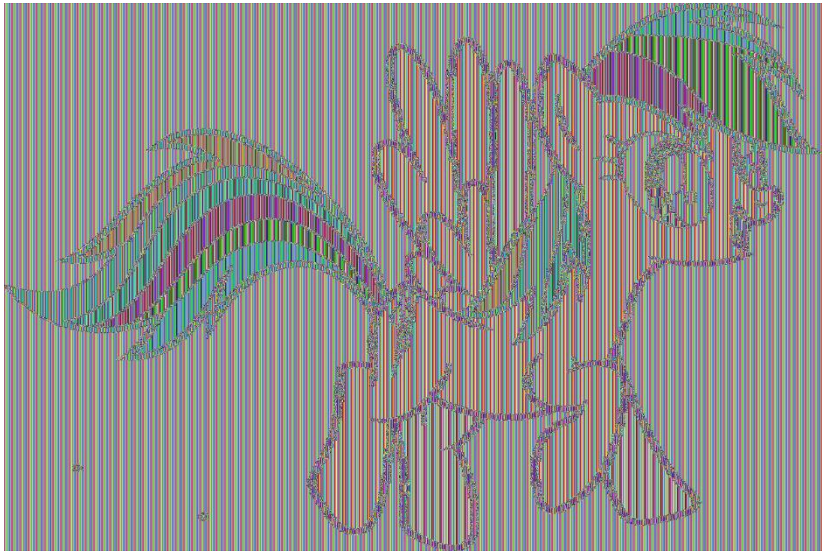
Source: http://www.wikipedia.org/



Fun with fixed *P* and varying keys

Source: https://filippo.io/the-ecb-penguin/

Modes of Encryption – ECB



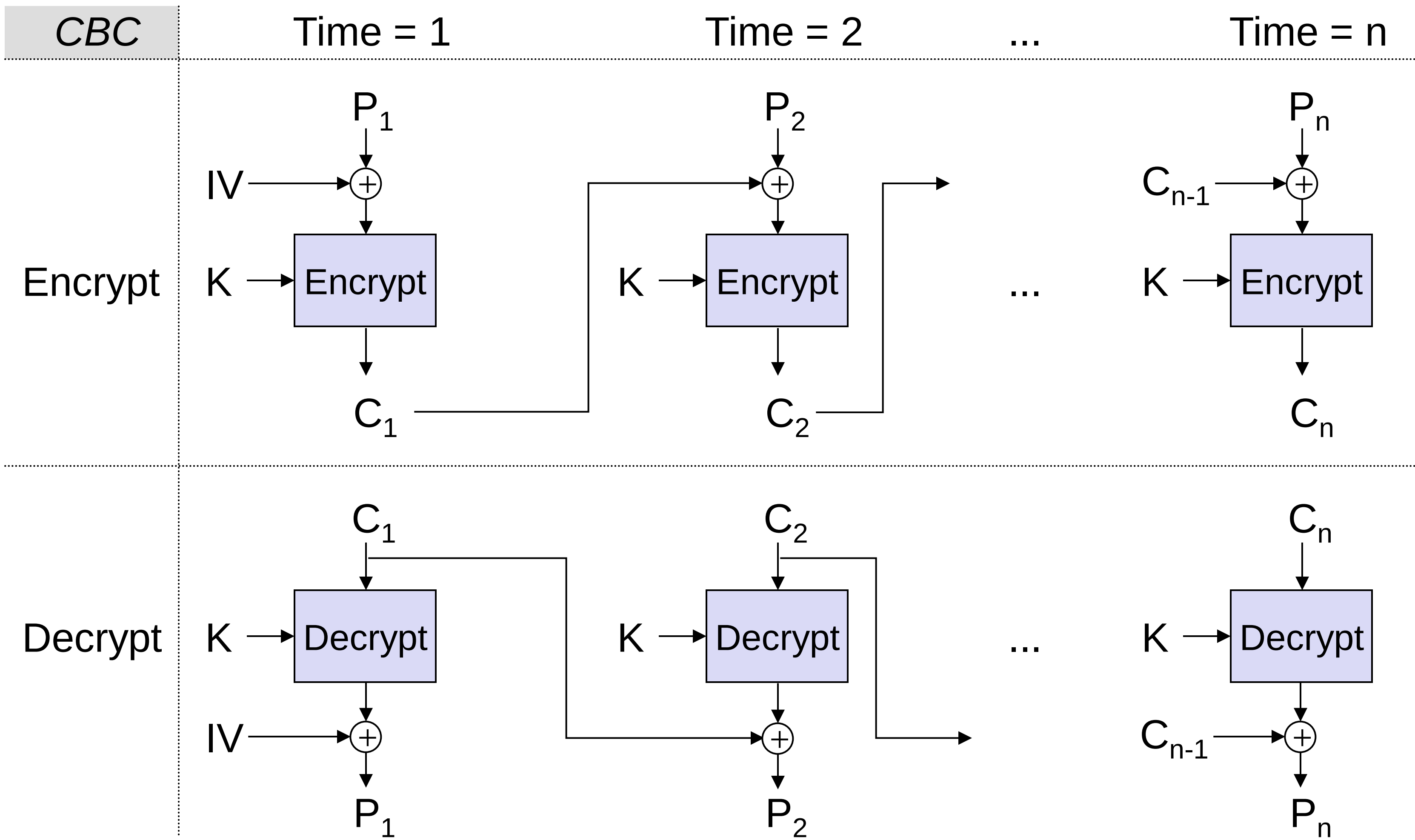
Does not only work with penguins

Modes of Encryption – CBC

- *Cipher Block Chaining Mode (CBC)*

- Before encrypting a plaintext block, it is ⊕ with the preceding ciphertext block
- An initial value, called *Initialization Vector (IV)* is required

Modes of Encryption – CBC



- *Cipher Block Chaining Mode (CBC):*

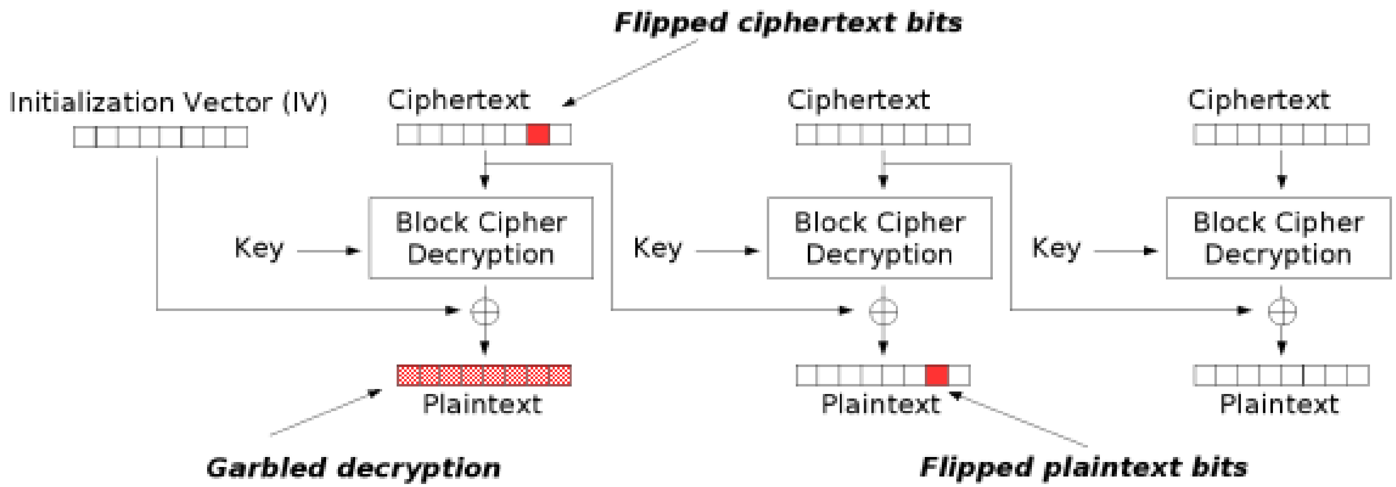
  - $c_i = Enc_K(c_{i-1} \oplus p_i)$
  - $p_i' = c_{i-1} \oplus Dec_K(K, c_i)$
  - $c_0 = \text{IV}$

  Both parties need to agree on an *Initialization Vector (IV)*
  IV may be public

- Identical plaintext blocks are encrypted to non-identical ciphertext

CBC Error Propagation and Synchronization

- Error Propagation
  - p_i' depends on c_{i-1} and c_i
  - One distorted ciphertext block results in two distorted plaintext blocks



Modification attack or transmission error for CBC

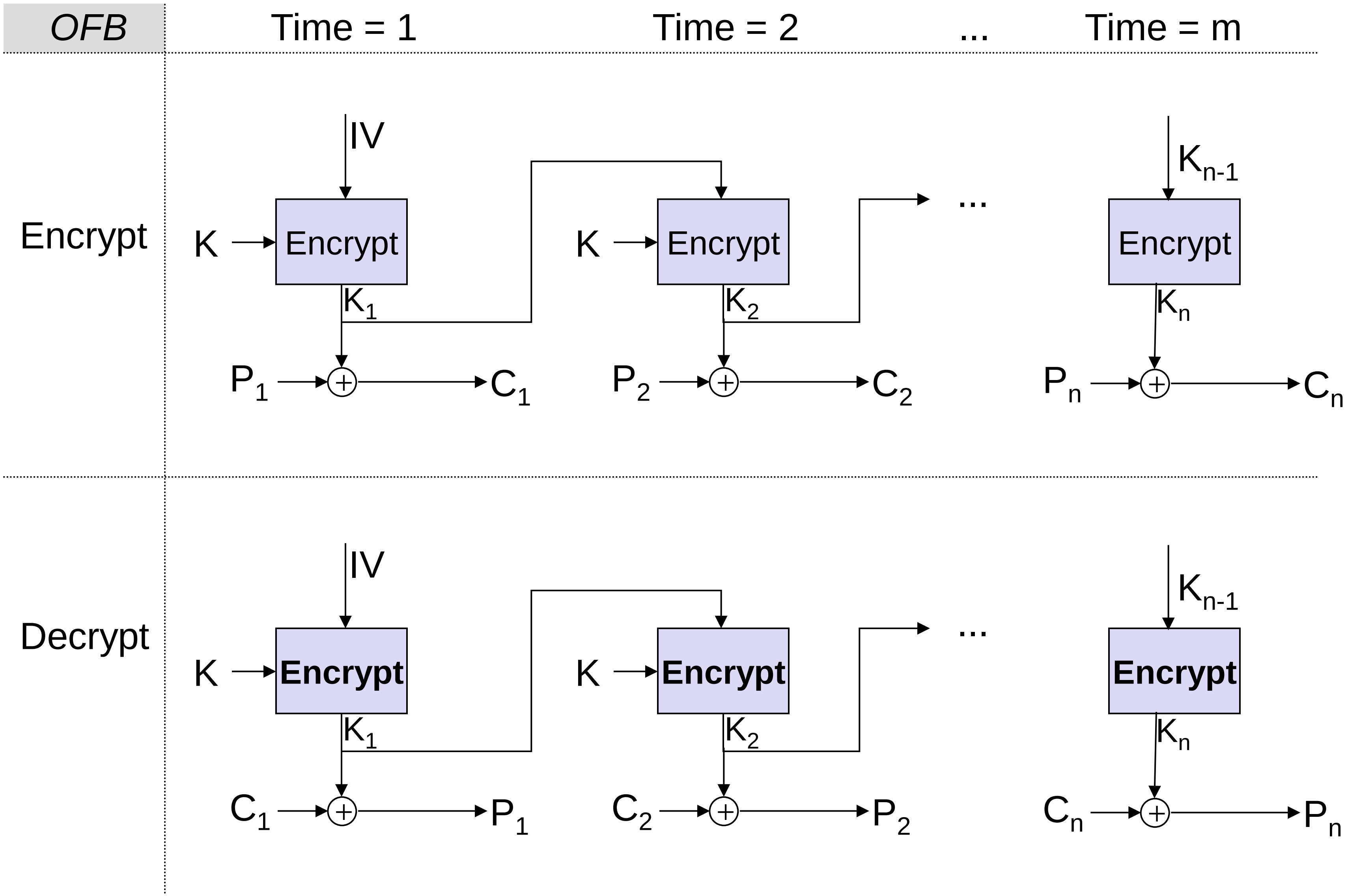
Source: http://www.wikipedia.org/

- Synchronization
  - If the number of lost bits is a multiple integer of *b*, one additional block p_{i+1} is misrepresented before synchronization is re-established.
  - If any other number of bits are lost explicit re-synchronization is needed.

Modes of Encryption – OFB

- *Output Feedback Mode (OFB):*
  - The block encryption algorithm is used to generate a key stream that depends only on K and IV
    - $K_0 = IV$
    - $K_i = Enc_K(K_{i-1})$
    - $C_i = P_i \oplus K_i$
  - The plaintext blocks are XORed with the pseudo-random sequence to obtain the ciphertext and vice versa

Modes of Encryption – OFB



Modes of Encryption – OFB

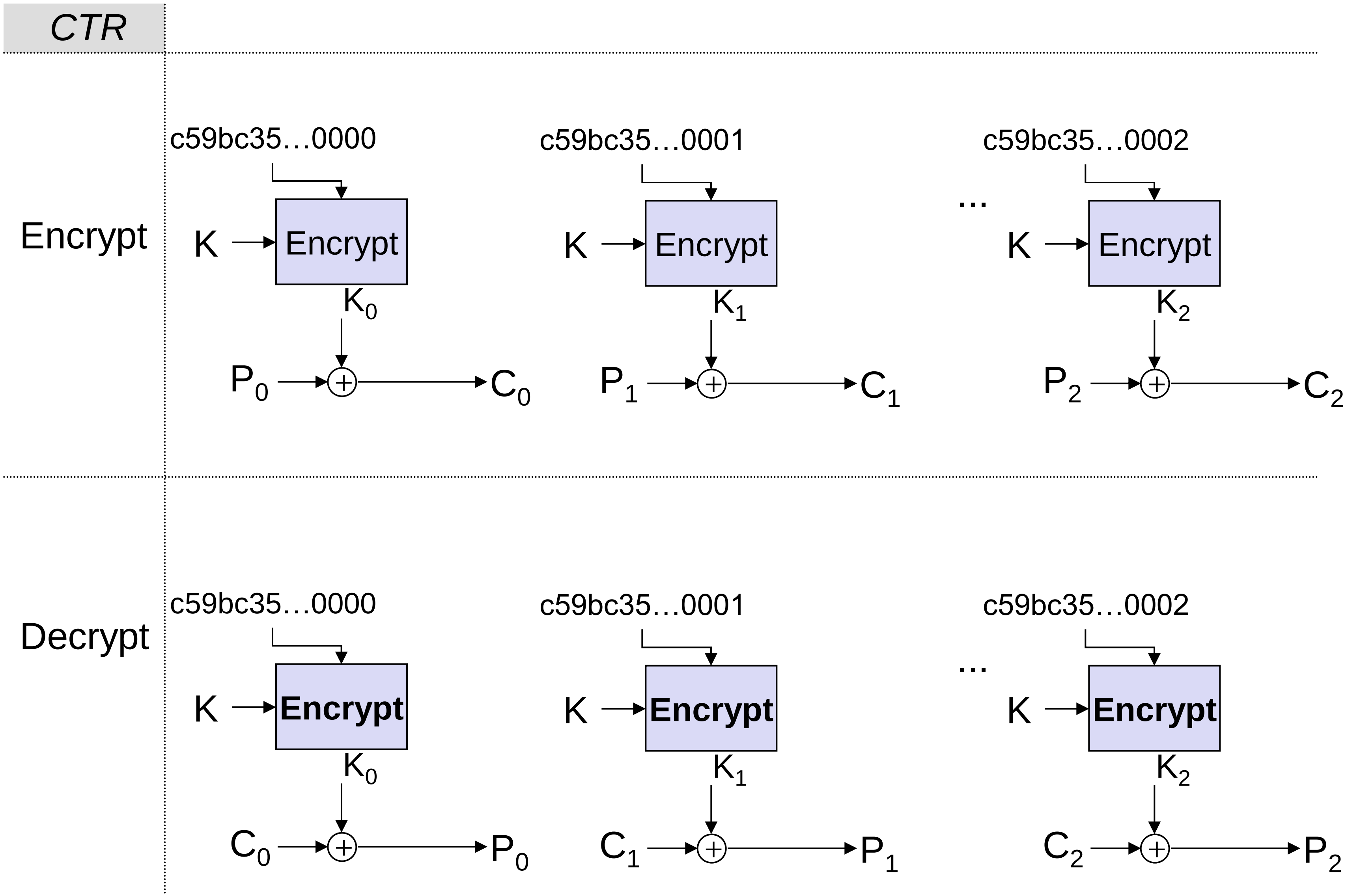
- Properties of OFB:
  - Error propagation:
    - Single bit errors result only in single bit errors ⇒ no error multiplication
  - Synchronisation:
    - If some bits are lost explicit re-synchronization is needed
  - Advantage:
    - The pseudo-random sequence can be pre-computed in order to keep the impact of encryption to the end-to-end delay low
  - Drawbacks:
    - It is easily possible for an attacker to manipulate specific bits of the plaintext

Modes of Encryption - CTR

- *Counter Mode (CTR)*
  - The block encryption algorithm is used to generate a key stream that depends on K and a counter function ctr_i .
  - The counter function can be simply an increment modulo 2^w, where w is a convenient register width, e.g.
    - $ctr_i = Nonce \mathbin{||} i$
  - The counter function does not provide any security other than the uniqueness of the input to the block cipher function E
  - The plaintext blocks are XORed with the pseudo-random sequence to obtain the ciphertext and vice versa
  - Putting everything together:
    - $K_i = Enc_K(Nonce \mathbin{||} i)$
    - $C_i = P_i \oplus K_i$

Modes of Encryption - CTR

CTR



Modes of Encryption - CTR

- Properties of CTR:
  - Error propagation:
    - Single bit errors result only in single bit errors $\Rightarrow$ no error multiplication
  - Synchronisation:
    - If some bits are lost explicit re-synchronization is needed.
  - Advantage:
    - The key stream can be pre-computed in order to keep the impact of encryption to the end-to-end delay low.
    - The computation of the key stream can be parallelized.
  - Drawbacks:
    - It is easily possible for an attacker to manipulate specific bits of the plaintext

Additional References

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