Cryptographic Systems in Operation

Software Security

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Objectives of today's exercise

- ➜ Understanding the concepts *stream cipher* and *block cipher*
- ➜ Getting to know key criteria for evaluating operation modes such as *self-synchronization*, *error expansion* and *random access*
- ➜ Being able to describe fundamental modes of operation, e.g. *ECB*, *CBC*, *CFB*, *OFB* and *CTR*

Basic Terms

What are the problems with the practical use of encryption methods? How can operation modes help to solve these problems?

Block Cipher

- Encryption and decryption of strings with a *fixed* length

Stream Cipher

- Encryption and decryption of strings with a *variable* length
- Messages are encoded as a sequence of characters

Remarks

- Distinction is not always clear and depends on the used alphabet

  ➜ **Example**

  - for the alphabet $\{0, 1\}$ DES is a block cipher
  - for the alphabet $\{0, 1, 2, \ldots, 2^{64} - 1\}$ DES is a stream cipher

Deterministic vs. Indeterministic Cipher

What are the problems with the practical use of encryption methods?
How can operation modes help to solve these problems?

Deterministic Block Cipher

- Ciphertext blocks and plaintext blocks have the *same length*
- Identical input parameters always result in the *same ciphertext*

Indeterministic Block Cipher

- Ciphertext blocks will be *longer* than the plaintext blocks
- Identical input parameters result in *different ciphertexts*

Synchronous vs. Self-Synchronizing Cipher

What is the difference between a synchronous and a selfsynchronizing mode?

Synchronous Stream Cipher

- Encryption of a character depends on *all preceding characters*

Self-Synchronizing Stream Cipher

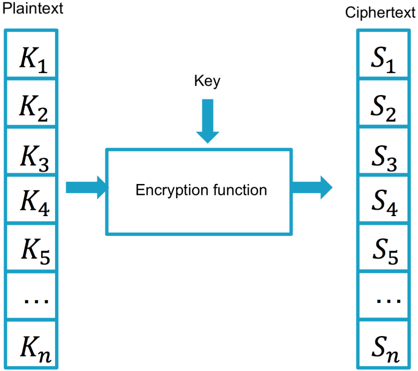
- Encryption of a character depends only on a *certain number of preceding characters*
- Regular re-synchronization mechanism is implemented

Classification of Operation Modes

What are the problems with the practical use of encryption methods?
How can operation modes help to solve these problems?

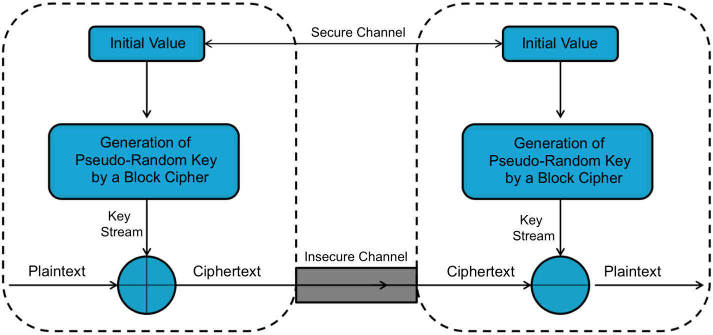
- Operation mode of the block cipher determines how the encryption of (long) plain texts is implemented
- Classification
  1. Block cipher is used to *encrypt a message directly*
  2. Block cipher is used to *generate a pseudo-random key stream*, which is used to encrypt the message by a stream cipher
- The basic concept of an operation mode is usually independent of the used block cipher (encryption system)

How to encrypt a message by a block cipher directly?



- ➜ The last block will be filled with *padding*
- ➜ We assume that the plaintext is fully available at the beginning of encryption

How to encrypt a message by a block cipher indirectly?



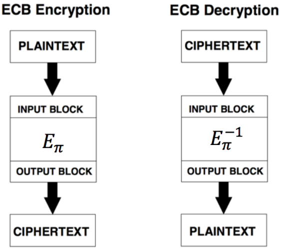
- ➜ Plaintext does not have to be fully available at the beginning of encryption
- ➜ An arbitrarily small block size for the encryption is possible

Operation Mode

– Electronic Codebook (ECB) –

ECB – Electronic Codebook

- Procedure for block ciphers, very naively implemented
- Splitting the plaintext into blocks of equal size
- Filling of the last block (*Padding*) is usually necessary
- Encryption and decryption of a block is *completely independent of other blocks*



Quelle: NIST

Encryption

$c_j = E_\pi(m_j)$ for $j = 1..n$

Decryption

$m_j = E_\pi^{-1}(c_j)$ for $j = 1..n$

ECB – Example

Assumption

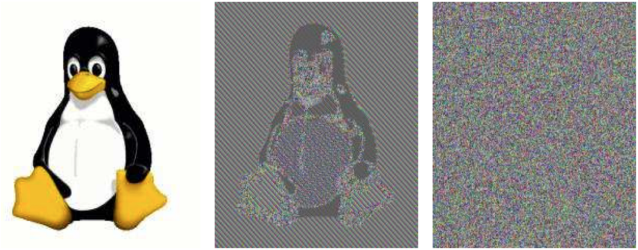
- Block size: $b = 4$
- Plaintext: $m = 101100010100101$ (15 Bits)
- Encryption function: here $E_\pi \mathrel{\widehat{=}}$ Permutation on bits
  ➜ in practice a modern encryption system is used, e.g. AES
- Key: $(1 \to 4),(2 \to 1),(3 \to 2),(4 \to 3)$ – just a *left shift*

Calculation

1. Splitting into blocks, including *Padding*
   $m_1 = 1011,\ m_2 = 0001,\ m_3 = 0100,\ m_4 = 1010$
2. Encryption
   $c_1 = E_\pi(1011) = 0111,\ c_2 = E_\pi(0001) = 0010,\ \ldots$
   ➜ $c = 0111\ 0010\ 1000\ 0101$

Disadvantages of the ECB Mode

➜ Same plaintext blocks are represented by the same ciphertext blocks, i.e. regularities in plaintext are also recognizable in the ciphertext



Original | Encrypted by ECB mode | Encrypted by another operation mode

➜ Note, the Bundestrojaner studied by the Chaos Computer Club in 2011 was implemented by AES & ECB

Why is the Electronic Codebook Mode (ECB) considered insecure and should not be used?

Evaluation of the ECB Mode

Why is the Electronic Codebook Mode (ECB) considered insecure and should not be used?

Advantages

+ Encryption and decryption can be parallelized
+ Errors in one block do not affect other blocks
+ Indeterministic block ciphers can be used

Disadvantages

- Regularities of the plaintext are recognizable in the ciphertext

  ➜ It is not recommended to use ECB

Neutral

+/- Self-synchronizing operation mode

Operation Mode

– Cipher Block Chaining (CBC) –

CBC – Cipher Block Chaining

- Split the plaintext into n blocks of the same size
- Use XOR to connect a plaintext block and the corresponding ciphertext block of the previous step and apply the encryption function E_π to the result.
- Use for the first plaintext block the initialization vector IV

Encryption

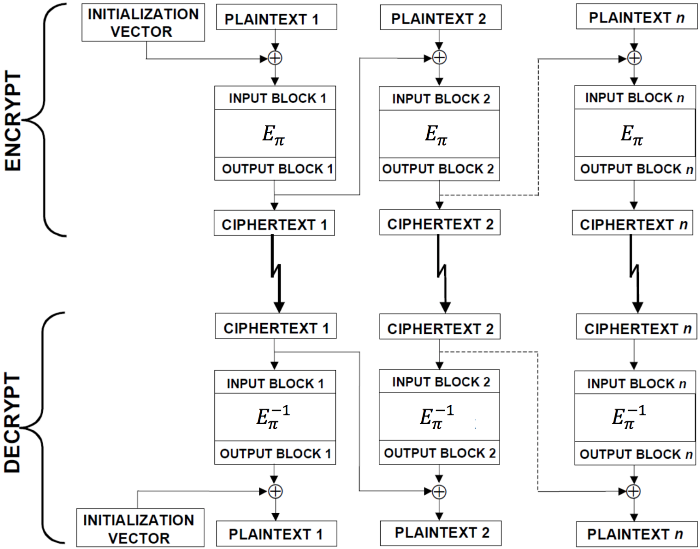
$$c_1 = E_\pi(m_1 \oplus IV)$$
$$c_j = E_\pi(m_j \oplus c_{j-1}) \text{ for } j = 2 \mathinner{..} n$$

Decryption

$$m_1 = E_\pi^{-1}(c_1) \oplus IV$$
$$m_j = E_\pi^{-1}(c_j) \oplus c_{j-1} \text{ for } j = 2 \mathinner{..} n$$

Why could be Cipher Block Chaining (CBC) a better alternative? What are the disadvantages of this operation mode?

How does the CBC operation mode work?



CBC – Example (Encryption)

Assumption

- Plaintext blocks:
  $m_1 = 1011, m_2 = 0001,\ m_3 = 0100,\ m_4 = 1010$
- Encryption function: $E_\pi \mathrel{\widehat{=}}$ Permutation of Bits
- Key: $(1 \to 4),(2 \to 1),(3 \to 2),(4 \to 3)$ – just a *left shift*
- Initialization vector: $IV = 1010$

Calculation

- Steps

$$\begin{aligned} c_1 &= E_\pi(m_1 \oplus IV) = E_\pi(0001) = 0010 \\ c_2 &= E_\pi(m_2 \oplus c_1) = E_\pi(0011) = 0110 \\ c_3 &= E_\pi(m_3 \oplus c_2) = E_\pi(0010) = 0100 \\ c_4 &= E_\pi(m_4 \oplus c_3) = E_\pi(1110) = 1101 \end{aligned}$$

- Result

$$c = 0010\ 0110\ 0100\ 1101$$

CBC – Example (Decryption)

Assumption

- Ciphertext blocks:
  $c_1 = 0010,\ c_2 = 0110,\ c_3 = 0110,\ c_4 = 1101$
- Encryption function: $E_\pi \mathrel{\widehat{=}}$ Permutation of Bits
- Key: $(1 \to 4),(2 \to 1),(3 \to 2),(4 \to 3)$ – just a *left shift*
- Initialization vector: $IV = 1010$

Calculation

- Steps

$$
\begin{aligned}
m_1 &= E_\pi^{-1}(c_1) \oplus IV = 0001 \oplus 1010 = 1011 \\
m_2 &= E_\pi^{-1}(c_2) \oplus c_1 = 0011 \oplus 0010 = 0001 \\
m_3 &= E_\pi^{-1}(c_3) \oplus c_2 = 0010 \oplus 0110 = 0100 \\
m_4 &= E_\pi^{-1}(c_4) \oplus c_3 = 1110 \oplus 0100 = 1010
\end{aligned}
$$

- Result

$$m = 1011\ 0001\ 0100\ 1010$$

CBC – Error Propagation

Assumption

- Ciphertext block with *transmission error*
  $c_1 = 0011,\ c_2 = 0110,\ c_3 = 0110,\ c_4 = 1101$
- Encryption function: $E_\pi \mathrel{\widehat{=}}$ Permutation of Bits
- Key: $(1 \to 4),(2 \to 1),(3 \to 2),(4 \to 3)$ – just a *left shift*
- Initialization vector: $IV = 1010$

Why could be Cipher Block Chaining (CBC) a better alternative? What are the disadvantages of this operation mode?

Decryption

- Steps

$$
\begin{aligned}
m_1 &= E_\pi^{-1}(c_1) \oplus IV = 1001 \oplus 1010 = 0011\\
m_2 &= E_\pi^{-1}(c_2) \oplus c_1 = 0011 \oplus 0011 = 0000\\
m_3 &= E_\pi^{-1}(c_3) \oplus c_2 = 0010 \oplus 0110 = 0100\\
m_4 &= E_\pi^{-1}(c_4) \oplus c_3 = 1110 \oplus 0100 = 1010
\end{aligned}
$$

- Result

$$m = 0011\ 0000\ 0100\ 1010$$

Evaluation of CBC

Why could be Cipher Block Chaining (CBC) a better alternative? What are the disadvantages of this operation mode?

Advantages

+ Decryption can be parallelized
+ Regularities of the plaintext will be not recognizable in the ciphertext
+ Indeterministic block ciphers can be used

Disadvantages

- Encryption can't be parallelized
- Error of a block effects the successor block

Neutral

+/- Self-synchronizing operation mode

What is the problem with error propagation? Which operation mode is not sensitive to this problem?

Operation Mode

– Cipher Feedback (CFB) –

CFB – Cipher Feedback

General Procedure

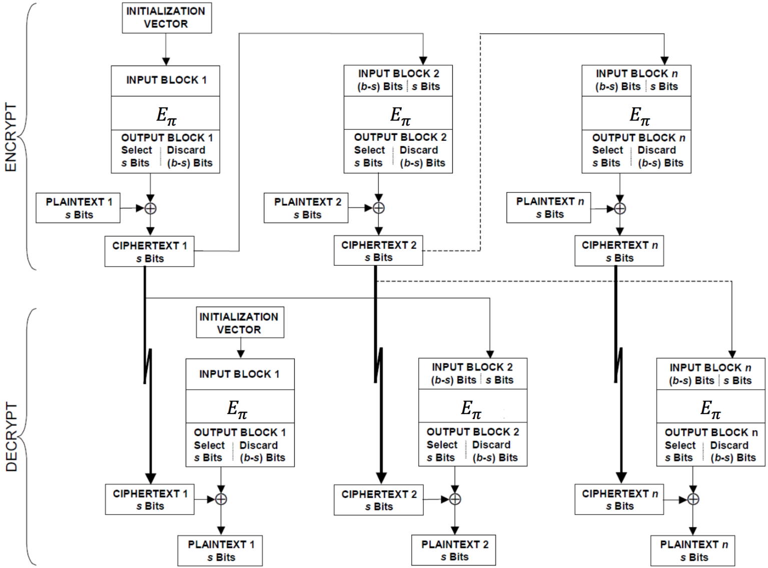
- Length s of the unit to be encrypted can be shorter than the block length b of the used encryption system
- The ciphertext of the previous block is encrypted by E_π and the result and the plaintext block will be connected by XOR
- The first plaintext block is encrypted with the initialization vector IV, which (at least) should have the length b

Calculation

➜ Set $I_1 = IV$ and perform the following steps for each j with $1 \leq j \leq n$

1. Set $O_j = E_\pi(I_j)$
2. Set t_j to the first s bits of O_j
3. Set $c_j = m_j \oplus t_j$ for encryption
   Set $m_j = c_j \oplus t_j$ for decryption
4. Set I_{j+1} to the last b bits of the concatenation of I_j and c_j

How does the CFB operation mode work?



CFB – Example (Encryption)

Assumption

- $s = 3$ and $b = 4$
- Plaintext blocks: $m_1 = 101$, $m_2 = 100$, $m_3 = 010$
- Encryption function: $E_\pi \mathrel{\widehat{=}}$ Permutation of Bits
- Key: $(1 \to 4),(2 \to 1),(3 \to 2),(4 \to 3)$ – just a *left shift*
- Initialization vector: $IV = 1010$

Calculation

j	I_j	O_j	t_j	m_j	c_j
1	1010	0101	010	101	111
2	0111	1110	111	100	011
3	1011	0111	011	010	001

CFB – Example (Decryption)

Assumption

- $s = 3$ and $b = 4$
- Ciphertext blocks: $c_1 = 111$, $c_2 = 011$, $c_3 = 001$
- Encryption function: $E_\pi \mathrel{\widehat{=}}$ Permutation of Bits
- Key: $(1 \rightarrow 4),(2 \rightarrow 1),(3 \rightarrow 2),(4 \rightarrow 3)$ – just a *left shift*
- Initialization vector: $IV = 1010$

Calculation

j	I_j	O_j	t_j	c_j	m_j
1	1010	0101	010	111	101
2	0111	1110	111	011	100
3	1011	0111	011	001	010

CFB – Error Propagation (Decryption)

Assumption

- $s = 3$ and $b = 4$
- Ciphertext blocks with *transmission error*
  $c_1 = 110$, $c_2 = 011$, $c_3 = 001$
- Encryption function: $E_\pi \mathrel{\widehat{=}}$ Permutation of Bits
- Key: $(1 \to 4),(2 \to 1),(3 \to 2),(4 \to 3)$ – just a *left shift*
- Initialization vector: $IV = 1010$

Calculation

j	I_j	O_j	t_j	c_j	m_j
1	1010	0101	010	110	100
2	0110	1100	110	011	101
3	0011	0110	011	001	010

Evaluation of CFB

Advantages

+ Decryption can be parallelized
+ Regularities of the plaintext will be not recognizable in the ciphertext
+ The length of the encryption units can be smaller than the block size of the used encryption system

Disadvantages

- Encryption can't be parallelized
- Error of a block effects $1 + \frac{b}{s}$ successor blocks
- Indeterministic block ciphers are not supported

Neutral

+/- Self-synchronizing operation mode

Operation Mode

– Output Feedback (OFB) –

OFB – Output Feedback

General Procedure

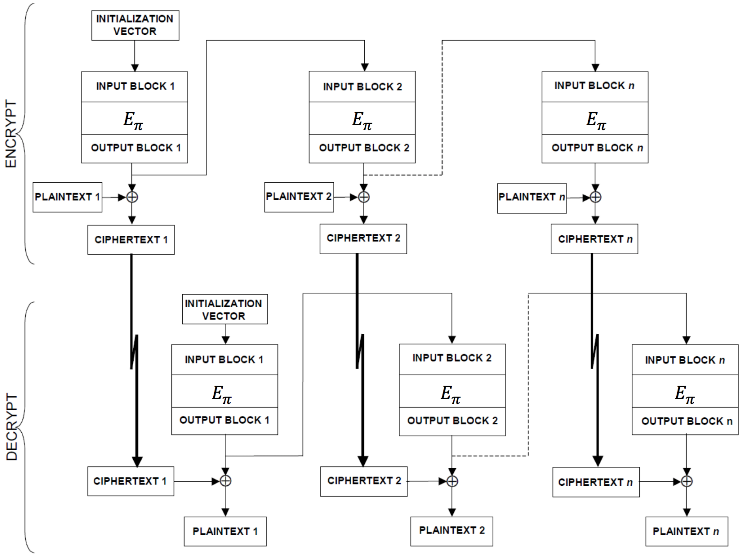
- Length s of the unit to be encrypted can be shorter than the block length b of the used encryption system
- The generated pseudo-random key stream depends only on the IV and the used main key
- Both encryption and decryption depend only on the position, not on the previous message

Calculation

➜ Set $I_1 = IV$ and perform the following steps for all j with $1 \leq j \leq n$

1. Set $O_j = E_\pi(I_j)$
2. Set t_j to the first s bits of O_j
3. Set $c_j = m_j \oplus t_j$ for encryption,
   Set $m_j = c_j \oplus t_j$ for decryption
4. Set $I_{j+1} = O_j$

How does the OFB operation mode work?



OFB – Example (Encryption)

Assumption

- $s = 3$ and $b = 4$
- Plaintext blocks: $m_1 = 101$, $m_2 = 100$, $m_3 = 010$
- Encryption function: $E_\pi \mathrel{\widehat{=}}$ Permutation of Bits
- Key: $(1 \rightarrow 4)$,$(2 \rightarrow 1)$,$(3 \rightarrow 2)$,$(4 \rightarrow 3)$ – just a *left shift*
- Initialization vector: $IV = 1010$

Calculation

j	I_j	O_j	t_j	m_j	c_j
1	1010	0101	010	101	111
2	0101	1010	101	100	001
3	1010	0101	010	010	000

OFB – Example (Decryption)

Assumption

- $s = 3$ and $b = 4$
- Ciphertext blocks: $c_1 = 111$, $c_2 = 001$, $c_3 = 000$
- Encryption function: $E_\pi \mathrel{\widehat{=}}$ Permutation of Bits
- Key: $(1 \to 4),(2 \to 1),(3 \to 2),(4 \to 3)$ – just a *left shift*
- Initialization vector: $IV = 1010$

Calculation

j	I_j	O_j	t_j	c_j	m_j
1	1010	0101	010	111	101
2	0101	1010	101	001	100
3	1010	0101	010	000	010

Evaluation of OFB

Advantages

+ Regularities of the plaintext will be not recognizable in the ciphertext
+ The length of the encryption units can be smaller than the block size of the used encryption system

Disadvantages

- Encryption and decryption cannot be parallelized, but the key stream can be calculated in advance
- Result is a symmetric stream cipher, independent of the encryption system used, which could be asymmetric
- Indeterministic block ciphers are not supported

Neutral

+/- Synchronous operation mode

Operation Mode

– Counter Mode (CTR) –

CTR – Counter Mode

General Procedure

- Input of the key function is a counter value $T_1, T_2 \dots T_n$, whereby T_j is unique
- Input is combined with a nonce for a single block

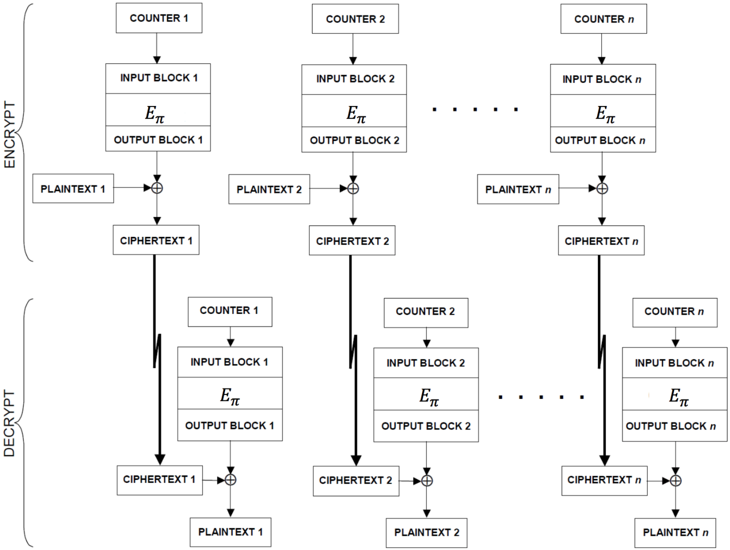
Encryption

1. Set $O_j = E_\pi(T_j)$ for $j = 1, 2, \dots n$
2. Set $c_j = m_j \oplus O_j$ for $j = 1, 2, \dots n - 1$
3. Set $c_n = m_n \oplus O_n$, whereby for an incomplete block m_n only required bits of O_n will be used

Decryption

1. Set $O_j = E_\pi(T_j)$ for $j = 1, 2, \dots n$
2. Set $m_j = c_j \oplus O_j$ for $j = 1, 2, \dots n - 1$
3. Set $m_n = c_n \oplus O_n$, whereby for an incomplete block c_n only required bits of O_n will be used

How does the CTR operation mode work?



Evaluation of CTR

Advantages

+ Encryption and decryption can be parallelized
+ Regularities of the plaintext will be not recognizable in the ciphertext
+ The length of the encryption units can be smaller than the block size of the used encryption system

Disadvantages

- Indeterministic block ciphers are not supported
- Counter functions are predictable, therefore it is better to use an extension of CTR, e.g. the GCM (Galois Counter Mode)

Neutral

+/- Synchronous mode

Comparison

	ECB	CBC	CFB	OFB	CTR
usage of indeterministic block ciphers	+ possible		- impossible		
asymmetrical block cipher produces	- asymmetrical stream cipher		- symmetrical stream cipher		
length of encryptable units	- specified by block length		+ arbitrary		
error expansion	inside one block	2 blocks	≤ 1 + b/s blocks	none with falsification	
synchrony	self-synchronized			synchronous	
random access	yes	only with decryption		no	yes
parallelizeable	yes	only with decryption		no	yes
calculation of the block cipher in advance	no		for one block at a time	yes	