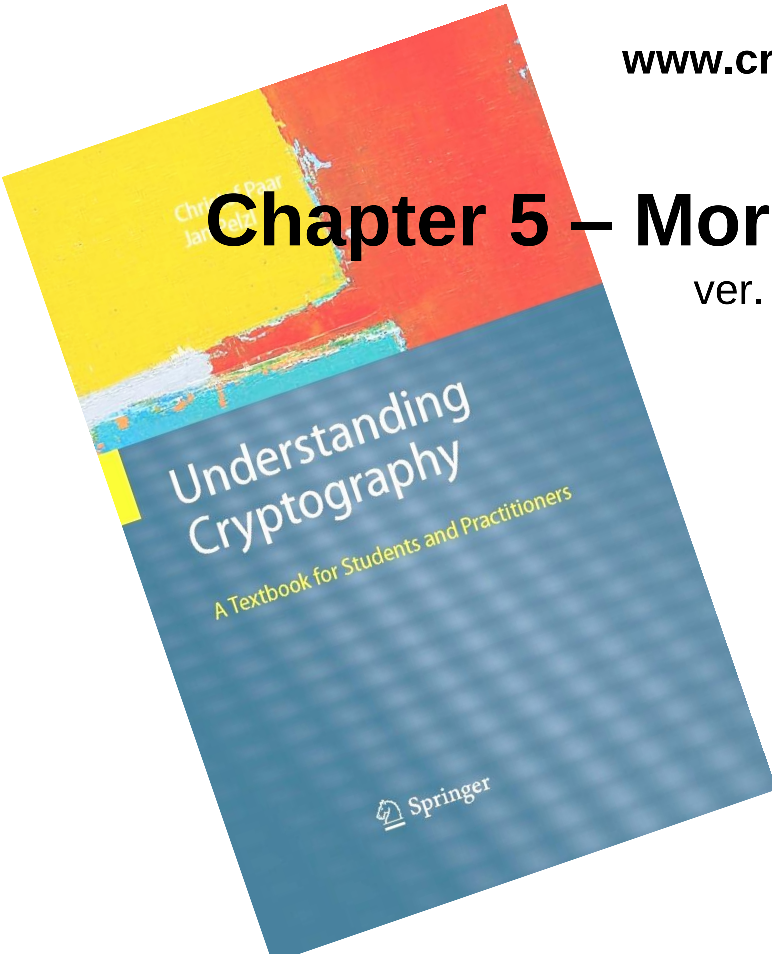
Understanding Cryptography – A Textbook for Students and Practitioners

by Christof Paar and Jan Pelzl

www.crypto-textbook.com



Chapter 5 – More About Block Ciphers

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These slides were originally prepared by Amir Moradi, Christof Paar and Jan Pelzl. Later, they were modified by Tomas Fabsic for purposes of teaching I-ZKRY at FEI STU.

Homework

- Read Section 5.1 (you can skip subsections 5.1.3, 5.1.4 and 5.1.6).

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Content of this Chapter

- Encryption with Block Ciphers for Confidentiality: Modes of Operation
  - Electronic Code Book mode (ECB)
  - Cipher Block Chaining mode (CBC)
  - Counter mode (CTR)

Block Ciphers

- A block cipher is much more than just an encryption algorithm, it can be used ...
  - to build different types of block-based encryption schemes
  - to realize stream ciphers
  - to construct hash functions
  - to make message authentication codes
  - to build key establishment protocols
  - to make a CSPRNG
  - ...

Encryption with Block Ciphers for Confidentiality

- There are several ways of encrypting long plaintexts, e.g., an e-mail or a computer file, with a block cipher ("modes of operation")
  - Electronic Code Book mode (ECB)
  - Cipher Block Chaining mode (CBC)
  - Counter mode (CTR)
- All of the above modes have only one goal – **confidentiality (dôvernosť)**.
- Confidentiality:
  - The content of the message is hidden from illegitimate parties.

Encryption with Block Ciphers for Authenticity and Integrity

- Other important goals in cryptography:
  - Is the message really coming from the original sender? (**authenticity**)
  - Was the ciphertext altered during transmission? (**integrity)**
- Modes providing authenticity and integrity (Chapter 13):
  - CBC-MAC
  - Cipher-based MAC (CMAC)
- Modes providing both confidentiality and authenticity and integrity (Chapter 13):
  - Cipher Block Chaining-Message Authentication Code (CCM)
  - Galois Counter mode (GCM)
- Today, **CCM and GCM are the most recommended modes** when confidentiality is needed!

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  - **Electronic Code Book mode (ECB)**
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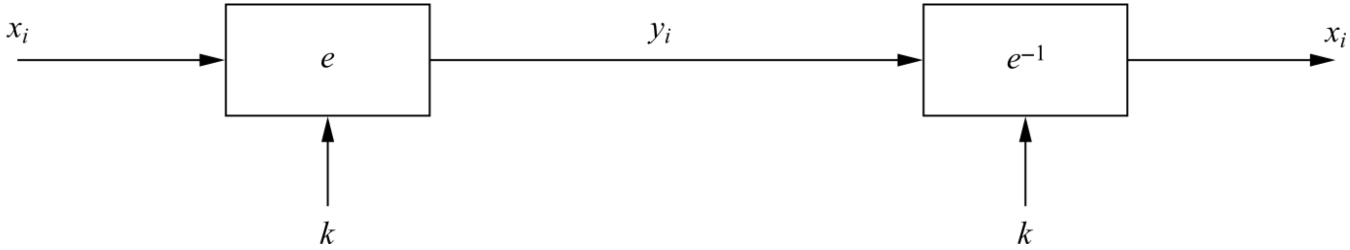
Electronic Code Book mode (ECB)

- $e_k(x_i)$ denote the encryption of a b-bit plaintext block x_i with key k
- $e_k^{-1}(y_i)$ denote the decryption of b-bit ciphertext block y_i with key k
- Messages which exceed b bits are partitioned into b-bit blocks
- **Each Block is encrypted separately**



Encryption: $y_i = e_k(x_i),\ \ i \geq 1$

Decryption: $x_i = e_k^{-1}(y_i) = e_k^{-1}(e_k(x_i)),\ \ i \geq 1$

ECB: advantages/disadvantages

- Advantages
  - no block synchronization between sender and receiver is required
  - bit errors caused by noisy channels only affect the corresponding block but not succeeding blocks
  - Block cipher operating can be parallelized
    - advantage for high-speed implementations

- **Disadvantages**
  - **ECB encrypts highly deterministically!**
    - identical plaintexts result in identical ciphertexts
      - an attacker recognizes if the same message has been sent twice
    - plaintext blocks are encrypted independently of previous blocks
      - an attacker may reorder ciphertext blocks which results in valid plaintext

Substitution Attack on ECB

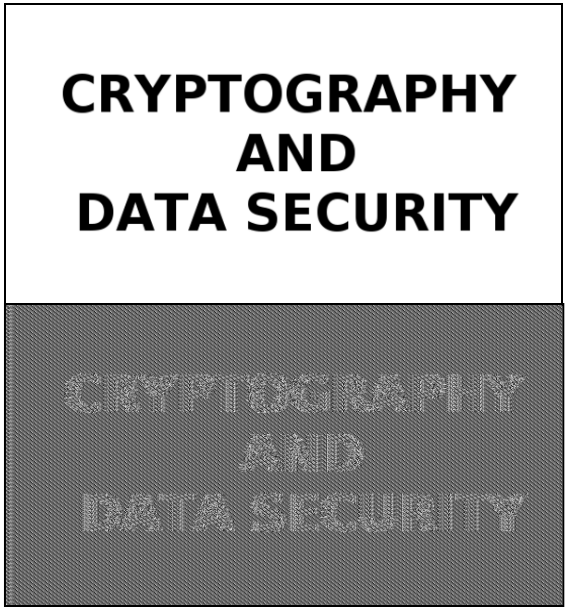
- Once a particular plaintext to ciphertext block mapping $x_i \rightarrow y_i$ is known, a sequence of ciphertext blocks can easily be manipulated
- Suppose an *electronic bank transfer*

Block #	1	2	3	4	5
	Sending Bank A	Sending Account #	Receiving Bank B	Receiving Account #	Amount $

  - the encryption key between the two banks does not change too frequently
  - The attacker sends $1.00 transfers from his account at bank A to his account at bank B repeatedly
    - He can check for ciphertext blocks that repeat, and he stores blocks 1,3 and 4 of these transfers
  - He now simply replaces block 4 of other transfers with the block 4 that he stored before
    - *all transfers* from some account of bank A to some account of bank B are redirected to go into the attacker's B account!

Example of encrypting bitmaps in ECB mode

- Identical plaintexts are mapped to identical ciphertexts



- Statistical properties in the plaintext are preserved in the ciphertext

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Cipher Block Chaining mode (CBC)

- There are two main ideas behind the CBC mode:
  - The encryption of all blocks are “chained together”
    - ciphertext y_i depends not only on block x_i but on all previous plaintext blocks as well
  - The encryption is randomized by using an initialization vector (IV)

Encryption (first block): $y_1 = e_k(x_1 \oplus \text{IV})$

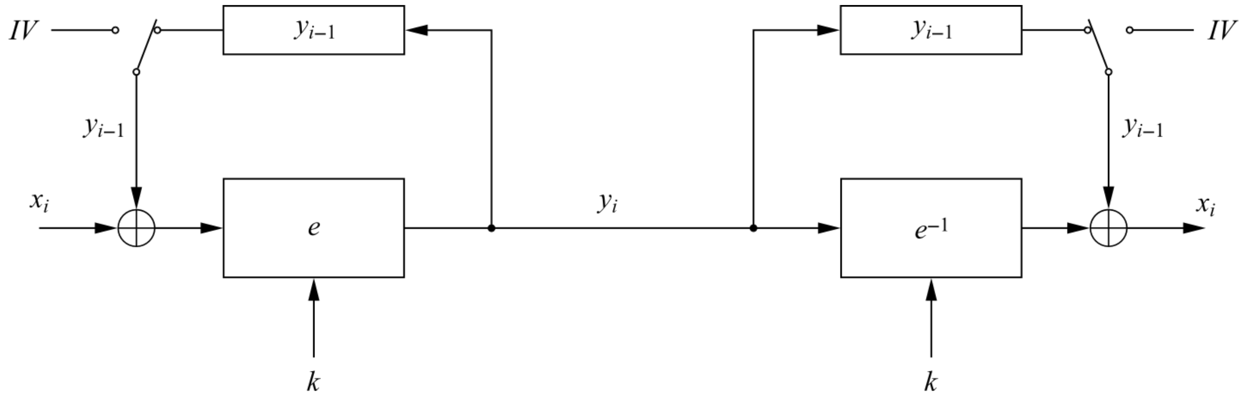
Encryption (general block): $y_i = e_k(x_i \oplus y_{i-1}), \; i \geq 2$

Decryption (first block): $x_1 = e_k^{-1}(y_1) \oplus \text{IV}$

Decryption (general block) : $x_i = e_k^{-1}(y_i) \oplus y_{i-1}, \; i \geq 2$

Cipher Block Chaining mode (CBC)

- For the first plaintext block x_1 there is no previous ciphertext
  - an IV is added to the first plaintext to make each CBC encryption nondeterministic
  - the first ciphertext y_1 depends on plaintext x_1 and the IV
- The second ciphertext y_2 depends on the IV, x_1 *and* x_2
- The third ciphertext y_3 depends on the IV and x_1, x_2 *and* x_3, and so on



Substitution Attack on CBC

- Suppose the last example (*electronic bank transfer*)
- If the IV is properly chosen for every wire transfer, the attack will not work at all
- If the IV is kept the same for several transfers, the attacker would recognize the transfers from his account at bank A to back B
- If we choose a new IV every time we encrypt, the CBC mode becomes a probabilistic encryption scheme, i.e., two encryptions of the same plaintext look entirely different
- It is not needed to keep the IV *secret*!
- Typically, the IV should be a non-secret nonce (value used only once)

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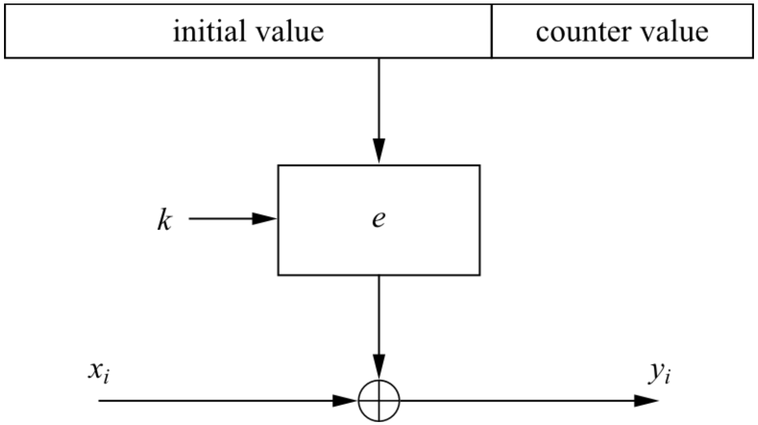
Counter mode (CTR)

- It uses a block cipher as a **stream cipher**
- The key stream is computed in a blockwise fashion
- The input to the block cipher is a counter which assumes a different value every time the block cipher computes a new key stream block



- can be parallelized since the 2^{nd} encryption can begin before the 1^{st} one has finished
- IV and counter value do not have to be secret

Encryption: $y_i = e_k(\text{IV} \,||\, \text{CTR}_i) \oplus x_i, \quad i \geq 1$

Decryption: $x_i = e_k(\text{IV} \,||\, \text{CTR}_i) \oplus y_i, \quad i \geq 1$

Lessons Learned

- There are many different ways to encrypt with a block cipher.
- Some modes of operation turn a block cipher into a stream cipher.
- The straightforward ECB mode has security weaknesses, independent of the underlying block cipher.
- The counter mode allows parallelization of encryption and is thus suited for highspeed implementations.