Block Ciphers

Gianluca Dini
Dept. of Ingegneria dell'Informazione
University of Pisa
gianluca.dini@unipi.it

Version: 2024-03-04

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Block Ciphers

GENERAL CONCEPTS

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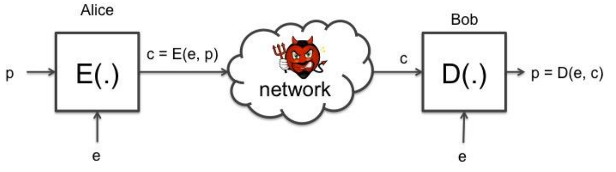
Block cipher

- Block ciphers break up the plaintext in blocks of fixed length *n* bits and encrypt one block at time



- E_k: $\{0,1\}^n \rightarrow \{0,1\}^n$ D_k: $\{0,1\}^n \rightarrow \{0,1\}^n$
- E is a keyed permutation: $E(k, p) = E_k(p) = Enc_k(p)$
- $E_K(\cdot)$ is a permutation

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Permutation

- E_k is a permutation
  - E_K is efficiently computable
  - E_k is bijective
    - Surjective (or onto)
    - Injective (or one-to-one)
  - E_k^{-1} is efficiently computable

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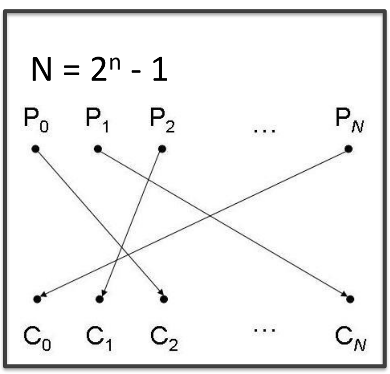
Examples

- Block ciphers
  - DES n = 64 bits, k = 56 bits
  - 3DES n = 64 bits, k = 168 bits
  - AES n = 128 bits k = 128, 192, 256 bits

Random permutations



A possible random permutation π

- Let $Perm_n$ be the set of all permutations π: $\{0,1\}^n \rightarrow \{0,1\}^n$
- $|Perm_n| = 2^n!$
- A true random cipher
  - implements all the permutations in $Perm_n$
  - uniformly selects a permutation $\pi \in Perm_n$ at random

True Random Cipher

- A True random cipher is perfect
- A true random cipher implements all possible Random permutations ($2^n!$)
  - Need a uniform random key for each permutation (naming)
    - key size := $\log_2 (2^n!) \approx (n - 1.44)\, 2^n$
      - Exponential in the block size!
      - The block size cannot be small to avoid a dictionary attack
- A true random cipher cannot be implemented

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Pseudorandom permutations

- Consider a *family of permutations* parametrized by $\kappa \in K = \{0, 1\}^k$, $E_\kappa: \{0,1\}^n \rightarrow \{0,1\}^n$
- A E_κ is a *pseudorandom permutation* (PRP) if it is indistinguishable from a uniform random permutation by a limited adversary
- $| \{E_\kappa\} | = 2^k << |Perm_n|$, with $|\kappa| = k$
- A block cipher is a practical instantiation of a PRP

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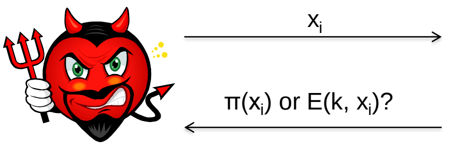
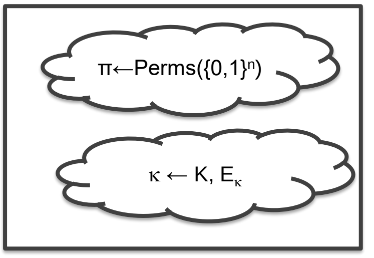
Practical block cipher

- In practice, the encryption function corresponding to a randomly chosen key should appear as a randomly chosen permutation to a limited adversary





- Oracle access
  - adversary cannot look into the box

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Exhaustive key search attack

- The attack
  - Given a pair (pt, ct), check whether ct == E_{ki}(pt), i = 0, 1, …, $2^k – 1$
    - Known-plaintext attack
    - Time complexity: $O(2^k)$
- False positives
  - Do you expect that just one key k maps pt into ct?
  - How many keys (false positives) do we expect to map pt into ct?
  - How do you discriminate the good one?

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Exhaustive key search

- False positives
  - Do you expect that just one key k maps pt into ct?
  - How many keys (false positives) do we expect to map pt into ct?
  - How do you discriminate the good one?

False positives

- Problem: Given (ct, pt) s.t. ct = E_{k*}(pt) for a given k*, determine the number of keys that map pt into ct
- Solution.
  - Given a certain key k, P(k) = Pr[E_k(pt) == ct] = $1/2^n$
  - The *expected* number of keys that map pt into ct is $2^k \times 1/2^n = 2^{k-n}$

False positives

- Example 1 – DES with n = 64 and k = 56
  - On average 2^{-8} keys map pt into ct
  - One pair (pt, ct) is sufficient for an exhaustive key search
- Example 2 – Skipjack with n = 64 and k = 80
  - On average 2^{16} keys map pt into ct
  - Two or more plaintext-ciphertext pairs are necessary for an exhaustive key search

False positives

- Consider now t pairs (pt_i, ct_i), i = 1, 2,…, t
  - Given k, $Pr[E_k(pt_i) = ct_i$, for all i = 1, 2,…, t] = $1/2^{tn}$
  - Expected number of keys that map pt_i into ct_i, for all i = 1, 2, …, t, is $2^k/2^{tn} = 2^{k-tn}$
- Example 3 – Skypjack with k = 80, n = 64, t = 2
  - The expected number of keys is = $2^{80-2\times64} = 2^{-48}$
  - Two pairs are sufficient for an exhaustive key search

False positives

- THEOREM
  - Given a block cipher with a key lenght of *k* bits and a block size of *n* bits, as well as *t* plaintext-ciphertext pairs, $(pt_1, ct_1),\dots, (pt_t, ct_t)$, the expected number of false keys which encrypt all plaintexts to the corresponding ciphertexts is 2^{k-tn}
- FACT
  - Two input-output pairs are generally enough for exhaustive key search

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Block ciphers

EXERCISES

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Exercise 1 - Exhaustive key search

- Exhaustive key search is a known-plaintext attack
- However, the adversary can mount a cyphertext-only attack if (s)he has some knowledge on PT

Exercise 1 – exhaustive key search

- Assume DES is used to encrypt 64-bit blocks of 8 ASCII chars, with one bit per char serving as parity bit
- How many CT blocks the adversary needs to remove false positives with a probability smaller than ε?

Exercise 2 - dictionary attack

- Consider a block cipher k and n.
- The adversary has collected D pairs (pt_i, ct_i), i = 1,…, D, with D << 2^n
- Now the adversary reads C newly produced cyphertexts ct^*_j, j = 1,…, C.
- Determine the value of C s.t. the Pr[Exists j, j = 1, 2,… C, s.t. c^*_j is in the dictionary] = P

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Exercise 3 - Rekeying

- An adversary can successfully perform an exhaustive key search in a month.
- Our security policy requires that keys are changed every hour.
- What is the probability P that, in a month, the adversary is able to find any key before it is changed?
  - For simplicity assume that every month is composed of 30 days.
- What if we refresh key every minute?

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Symmetric Encryption

MULTIPLE ENCRYPTION AND KEY WHITENING

Increasing the Security of Block Ciphers

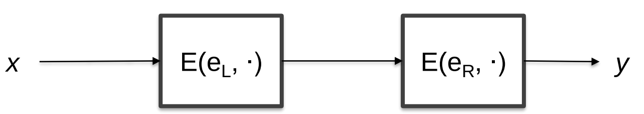
- DES is a secure cipher, no efficient cryptanalys is known
- DES does not define a group
- DES key has become too short
- Can we improve the security of DES?
- Yes, by means of two techniques
  - Multiple encryption
  - Key whitening

DES does not define a group

- If DES were a group then $\forall k_1, k_2 \in \mathcal{K}, \exists k_3 \in \mathcal{K}$ s.t. $\forall x \in \mathcal{M}, E_{k_2}\left(E_{k_1}(x)\right) = E_{k_3}(x)$
- So, double (multiple) encryption would be useless
- Furthermore, DES would be vulnerable to Meet-in-the-Middle attack that runs in 2^{28}

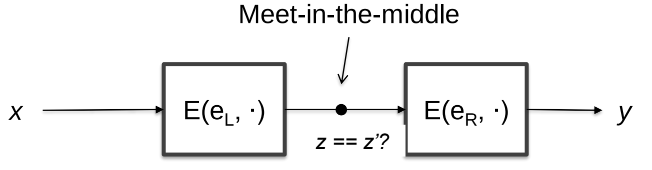
Two-times Encryption (2E)

- y = 2E((e_L, e_R), m) = E(e_R, E(e_L, x))
  - key size is 2k bits
  - Brute force attack requires 2^{2k} steps
  - 2E is two times slower than E
- Is it really secure?
- Meet-in-the-middle attack



Meet-in-the-middle attack

- Attack Sketch
  1. Build a table T containing $z = E(e_L, x)$ for all possible keys e_L. Keep T sorted according to z.
  2. Check whether $z' = D(e_R, y)$ is contained in the table T, for all possible key e_R.
     1. If z' in contained in T then (e_L, e_R) maps x into y with e_L s.t. $T[e_L] = z'$.



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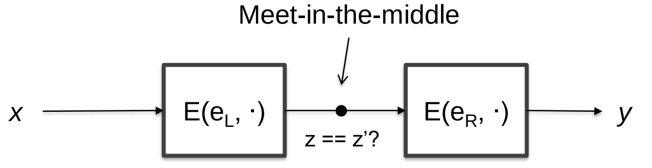
Meet-in-the-middle attack

- Attack complexity
  - Storage complexity
    - Storage necessary for table T ≈ $O(2^k)$
  - Time complexity
    - Time complexity for step 1 + Time complexity for step 2 = Time for building and sorting the table + Time for searching in a sorted table = $k\,2^k + k\,2^k \approx O(2^k)$



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Two-times DES

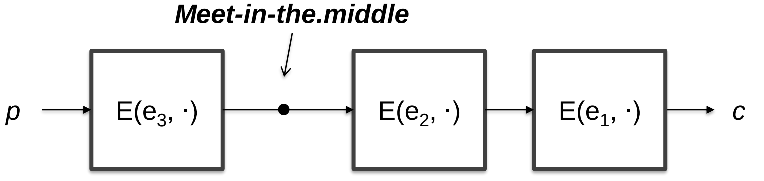
- 2DES
  - Time complexity: 2^{56} (doable nowadays!)
  - Space complexity: 2^{56} (lot of space!)
  - 2DES brings no advantage

Triple DES (3DES)

- EDE scheme
  - Standard ANSI X9.17 and ISO 8732
  - $Y = 3E((e_1, e_2, e_3), x) = E(e_1, D(e_2, E(e_3, x)))$
    - If $e_1 = e_2 = e_3$, 3DES becomes DES
      - backward compatibility
  - Key size = 168-bits
  - 3 times slower than DES
  - Simple attack ≈ 2^{118}

3DES – meet-in-the-middle attack

- Time = 2^{112} (undoable!)
- Space = 2^{56} (lot of space!)



False positives for multiple encryption

- THEOREM
  - Given there are r subsequent encyptions with a block cipher with a key lenght of k bits and a block size of n bits, as well as t plaintext-ciphertext pairs, $(pt_1, ct_2),\ldots, (pt_t, ct_t)$, the expected number of false keys which encrypt all plaintext to the corresponsig ciphertext is $2^{rk - tn}$

Limitations of 3DES

- 3DES resists brute force but
  - It is not efficient regarding software implementation
  - It has a short block size (n = 64)
    - A drawback if you want to make a hash function from 3DES, for example
  - Key lengths of 256+ are necessary to resist quantum computing attack

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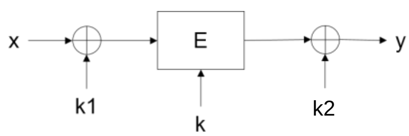
Key whitening

- Considerations
  - KW is not a “cure” for weak ciphers
- Applications
  - DESX: a variant of DES
  - AES: uses KW internally
- Performance
  - Negliglible overhead w.r.t. E (Just two XOR’s!)



Definition 5.3.1 Key whitening for block ciphers
Encryption: $y = e_{k,k_1,k_2}(x) = e_k(x \oplus k_1) \oplus k_2$.
Decryption: $x = e^{-1}_{k,k_1,k_2}(x) = e_k^{-1}(y \oplus k_2) \oplus k_1$

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Key whitening

- Attacks
  - Brute-force attack
    - Time complexity: 2^{k+2n} encryption ops
  - Meet-in-the-middle:
    - Time complexity 2^{k+n}
    - Storage complexity: 2^n data sets
  - The most efficient attack
    - If the adversary can collect 2^m pt-ct pairs, then time complexity becomes 2^{k+n-m}
      - The adversary cannot control m (rekeying)
    - Example: DES (m = 32)
      - Time complexity 2^{88} encryptions (nowadays, out of reach)
      - Storage complexity 2^{32} pairs = 64 GBytes of data (!!!)

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Symmetric Encryption

ENCRYPTION MODES

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Encryption Modes

- A block cipher encrypts PT in fixed-size *n*-bit blocks
- When the PT len exceeds n bits, there are several modes to use the block cipher
  - Electronic Codebook (ECB)
  - Cipher-block Chaining (CBC)

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Other encryption modes

- Other encryption modes
  - To build a stream cipher out of a block cipher
    - Cipher Feedback mode (CFB)
    - Output Feedback mode (OFB)
    - Counter mode (CTR)
  - Authenticated encryption
    - Galois Counter mode (GCM, CCM, …)
  - and many others (e.g., CTS, …)
- Block ciphers are very versatile components

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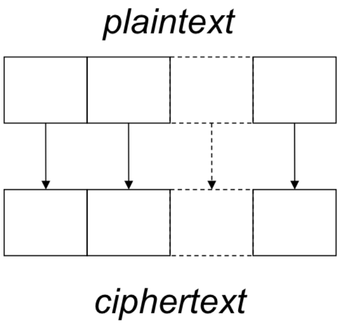
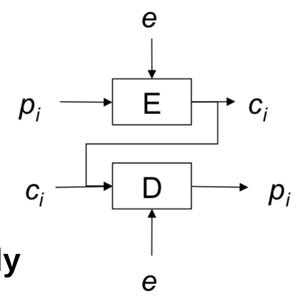
Electronic codebook



$$\forall 1 \le i \le t, c_i \leftarrow E(e, p_i)$$
$$\forall 1 \le i \le t, p_i \leftarrow D(e, c_i)$$



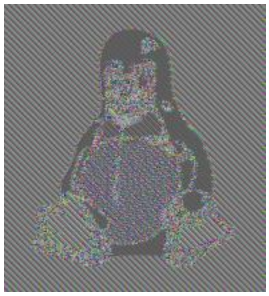
PT blocks are encrypted separately

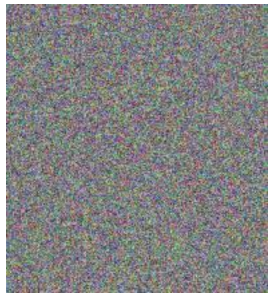
ECB - properties

- PROS
  - No error propagation
    - One or more bits in a single CT block affects decryption of that block only
  - Enc & Dec can be parallelized
- CONS (it is insecure)
  - Blocks are encrypted separately
    - Identical PT results in identical CT
      - ECB doesn't hide data pattern
      - ECB allows traffic analysis
    - ECB allows block re-ordering and substitution

ECB doesn't hide data patterns


Plaintext


ECB encrypted


Non-ECB encrypted

ECB – block attack

- Bank transaction that transfers a customer C's amount of money D from bank B1 to bank B2
  - Bank B1 debits D to C
  - Bank B1 sends the "credit D to C" message to bank B2
  - Upon receiving the message, Bank B2 credits D to C
- Credit message format
  - Src bank: M (12 byte)
  - Rcv banck: R (12 byte)
  - Customer: C (48 byte)
  - Bank account number: N (16 byte)
  - Amount of money: D (8 byte)
- Cipher: n = 64 bit; ECB mode

ECB – block attack

- Mr. Lou Cipher is a client of the banks and wants to make a fraud
- Attack aim
  - To replay Bank B1's message "credit 100$ to Lou Cipher" many times
- Attack strategy
  - Lou Cipher activates multiple transfers of 100$ so that multiple messages "credit 100$ to Lou Cipher" are sent from B1 to B2
  - The adversary identifies at least one of these messages
  - The adversary replies the message several times

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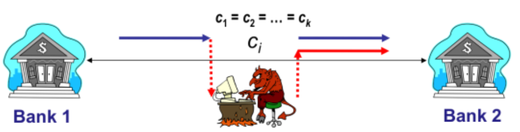
ECB – block attack

- The fraud
  1. Mr. Lou Cipher performs k equal transfers
     - credit 100$ to Lou Cipher → c1
     - credit 100$ to Lou Cipher → c2
     - ...
     - credit 100$ to Lou Cipher → c_k
  2. Then, he searches for "his own" CTs, namely k equal CTs!
  3. Finally he replies one of these cryptograms (many times)



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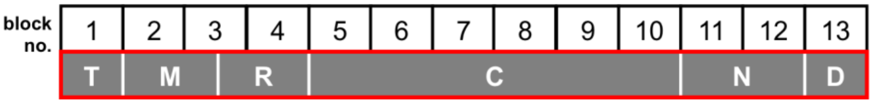
ECB – block attack

- The message lacks any notion of time so it can be easily replied
- An 8-byte timestamp field T (block #1) is added to the message to prevent replay attacks
- A replied message can now be discarded



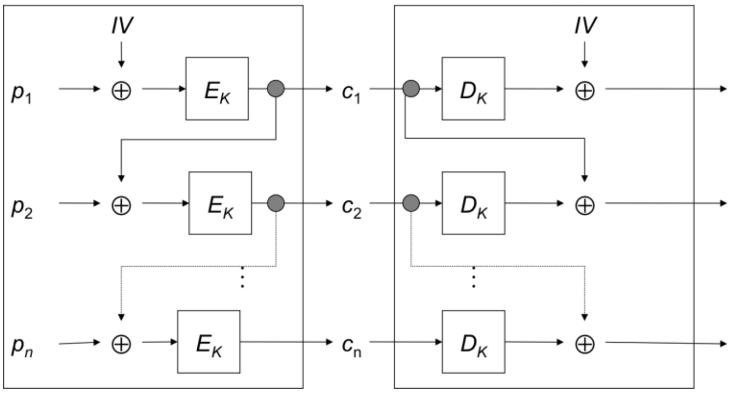
ECB – block attack

- However, Mr Lou Cipher can still perform the attack
  1. Identify "his own" CTs by inspecting blocks #2-#13
  2. Select any his-own-CT
  3. Substitute block #1 of his-own-CT with block #1 of any intercepted "fresh" block
  4. Replay the resulting CT

Cipher block chaining (CBC)

Encryption: $c_0 \leftarrow IV. \forall 1 \le i \le t, c_i \leftarrow E_k\left(p_i \oplus c_{i-1}\right)$

Decryption: $c_0 \leftarrow IV. \forall 1 \le i \le t, p_i \leftarrow c_{i-1} \oplus D_k\left(c_i\right)$



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CBC – properties (→)

- CBC mode is CPA-secure
- CBC-Enc is *randomized* by using IV (nonce)
  - Identical ciphertext results from the same PT under the same key and IV
- Chaining dependencies: c_i depends on p_i and the preceding PT block
- CT-block reordering affects decryption
- Cyphertext expansion is just one block

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CBC – properties

- IV can be sent in the clear but its integrity must be guaranteed
- CBC suffers from Error propagation
  - Bit errors in c_i affect p_i and p_{i+1} (*error propagation*)
- Only CBC-dec can be parallelized

CBC – block attack

- If Bank A chooses a random IV for each wire transfer the attack will not work
- However, if Lou Cipher substitutes blocks #5–10 and #13, bank B would decrypt *account number* and *deposit amount* to random numbers => this is highly undesirable!
- Encryption itself is not sufficient, we need additional mechanisms (MDC, MAC, digsig) to protect integrity

Chosen-Plaintext Attack (Informal)

- CPA Attack
  - Attacker *makes* the sender to encrypt $x_1, \ldots, x_t$
    - The attacker may influence or control encryption
  - The sender encrypts and transmits $y_1 = E_k(x_1), \ldots, y_t = E_k(x_t)$
  - Later on, the sender encrypts x and transmits $y = E_k(m)$
- CPA-security guarantees that the adversary cannot learn anything about x
- The encryption scheme must be randomized

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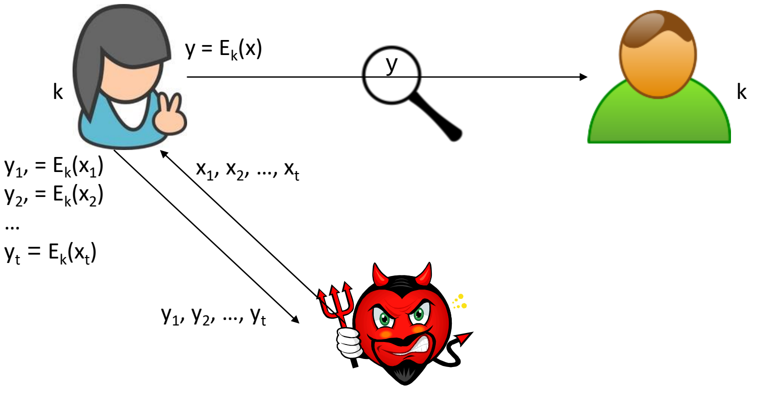
CPA model



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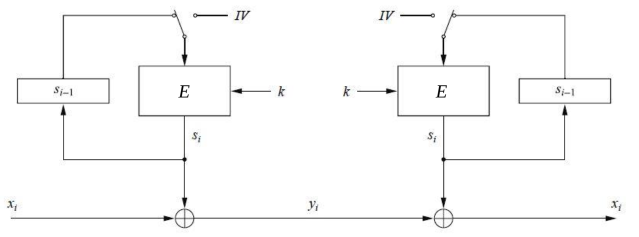
Block Ciphers: How to transform a block cipher into a stream cipher

MORE ENCRYPTION MODES: OFB, CFB, CTR

Block cipher vs stream cipher

- Stream ciphers do not require padding
- Stream ciphers can operate in real-time

Output Feedback Mode (OFB)



Let e() be a block cipher of block size b; let x_i, y_i and s_i be bit strings of length b; and IV be a nonce of length b.
Encryption (first block): $s_1 = e_k(IV)$ *and* $y_1 = s_1 \oplus x_1$
Encryption (general block): $s_i = e_k(s_{i-1})$ *and* $y_i = s_i \oplus x_i, \quad i \geq 2$
Decryption (first block): $s_1 = e_k(IV)$ *and* $x_1 = s_1 \oplus y_1$
Decryption (general block): $s_i = e_k(s_{i-1})$ *and* $x_i = s_i \oplus y_i, \quad i \geq 2$

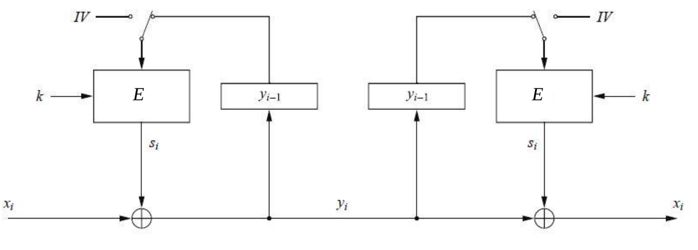
Output Feedback Mode (OFB)

- OFB builds a stream cipher out of a block cipher
- The key stream is generated block-wise
- OFB is a *synchronous* stream cipher, i.e., key stream is a function of K and IV, only
  - ➔ precomputation of key stream is possible
- The receiver does not use decryption
- If |last pt block| < block, keystream bits are discarded

Output Feedback Mode (OFB)

- IV should be a nonce ➔ OFB non-deterministic
- No error propagation
- OFB suffers from malleability

Cipher Feedback Mode (CFB)



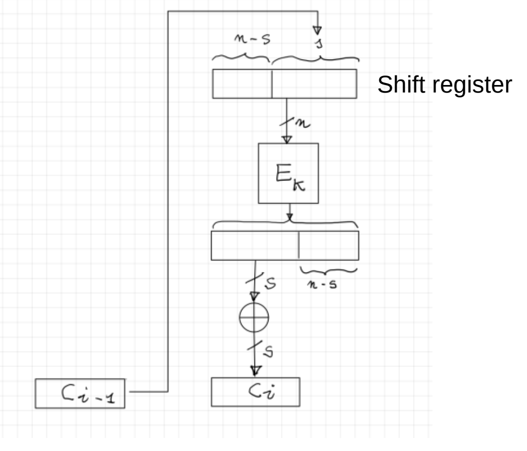
Definition 5.1.4 Cipher feedback mode (CFB)
Let $e()$ be a block cipher of block size b; let x_i and y_i be bit strings of length b; and IV be a nonce of length b.
Encryption (first block): $y_1 = e_k(IV) \oplus x_1$
Encryption (general block): $y_i = e_k(y_{i-1}) \oplus x_i, \quad i \geq 2$
Decryption (first block): $x_1 = e_k(IV) \oplus y_1$
Decryption (general block): $x_i = e_k(y_{i-1}) \oplus y_i, \quad i \geq 2$

Cipher Feedback Mode (CFB)

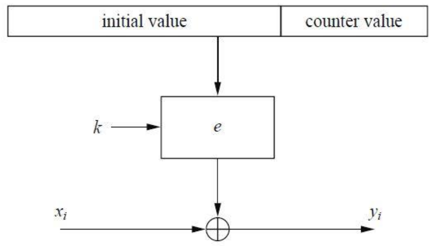
- OFB builds a stream cipher out of a block cipher
- CFB is an *asynchronous* stream cipher as the key stream is also a function of the CT
- Key stream is generated block-wise
- IV is a nonce and makes CFB nondeterministic
- Enc is sequential, Dec may be parallelized
- CFB may operate on pt/ct smaller than a block
  - Sizeof(pt/ct) = s ≤ n (cipher block size)

Cipher Feedback Mode (CFB)

Pt/ct character size s < block size n



Counter Mode (CTR)



Definition 5.1.5 Counter mode (CTR)
Let $e()$ be a block cipher of block size b, and let x_i and y_i be bit strings of length b. The concatenation of the initialization value IV and the counter CTR_i is denoted by $(IV||CTR_i)$ and is a bit string of length b.
***Encryption**:* $y_i = e_k(IV||CTR_i) \oplus x_i, \quad i \geq 1$
***Decryption**:* $x_i = e_k(IV||CTR_i) \oplus y_i, \quad i \geq 1$

Counter Mode (CTR)

- CTR prevents two-time pad (keystream reuse)
- CTR can be parallelized
- Counter can be a regular counter or a more complex functions, e.g., LFSR
- Ciphertext expansion is just one block
  - Output y_0, y_1, …, y_t with y_0 = (IV|ctr_0) being the *expansion block*
  - IV|ctr_0 does not have to be kept secret
  - Can be transmitted together with ct y_i

CTR is CPA-secure

- A block cipher is a good approximation of a PRP (PRF), so the sequence $E_k(iv|ctr_0+1)$, …, $E_k(iv|ctr_0+t)$ is pseudorandom
  - Two-time pad may occur when $(iv|ctr_0+i)$ wraps around ➔ limit to the maximum number of messages you can encrypt
  - Two-time pad may occur when $(iv|ctr_0+i) = (iv'|ctr_0'+ j)$ but the probability of this event is exponentially small

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Block Ciphers: How to avoid ciphertext expansion

MORE ENCRYPTION MODES: CTS

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Ciphertext Stealing (CTS) mode

- CTS allows encrypting PT that is not evenly divisible into blocks without resulting in any ciphertext expansion
- sizeof(ciphertext) = sizeof(plaintext)
- CTS operates on the last two blocks
  - **Intuition**: a portion of the 2nd-last CT block *is stolen* to pad the last PT block

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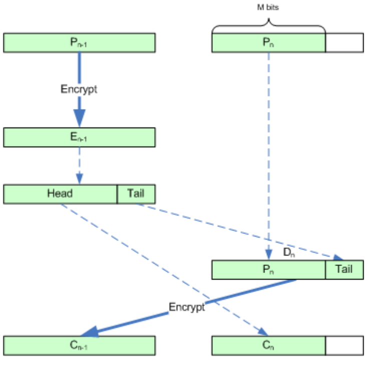
Ciphertext stealing (CTS)

- CTS + ECB mode



Picture taken from Wikipedia

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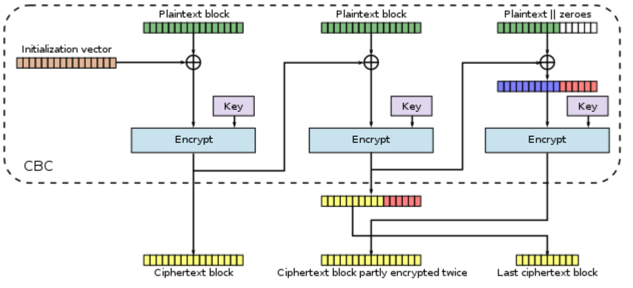
Ciphertext stealing (CTS)

- CTS + CBC mode



Picture taken from Wikipedia

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Block Ciphers

PADDING

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The need for a padding scheme

Naïve (wrong) solution: Pad the message with zeroes to the right, without ambiguous boundaries

Problem: What if the message was a NULL-terminated string?

At the receiving side: Was it a NULL-terminated string or a 7-bytes pt?

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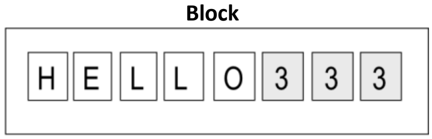
The PKCS #5 padding scheme

- Padding is necessary when PT len is not an integer multiple of the block

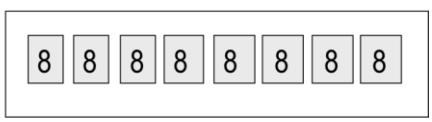
If PT len is NOT a block multiple
- We need b padding bytes
- Fill each padding byte by b

Example: b = 3 then append 0x030303

Block



If PT is a block multiple
Padding = block
Fill each padding block by 8



Padding causes *ciphertext expansion*

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PKCS #5: encryption

- Let L be the block length (in bytes) of the cipher
- Let b be the # of blocks that need to be appended to the plaintext to get its length a multiple of L
  - $1 \leq b \leq L$
- Before encryption
  - Append b (encoded in 1 byte), b times
    - i.e., if b = 3, append 0x030303

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PKCS #5: decryption

- After decryption, say the final byte has value b
  - If b = 0 or b > L, return “error”
  - If the trailing b bytes are not all equal to b, return “error”
  - Strip off the trailing b bytes and output the left as the message

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PKCS #7

- Difference between PKCS#5 and PKCS#7
  - PKCS#5: padding is defined for 8-byte block sizes (RFC 2898)
  - PKCS#7: padding is defined for block of any size ranging from 1 to 255 bytes (RFC 2315)

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Block Ciphers

PADDING ORACLE ATTACK

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Padding Oracle Attack

- The attacker
  - intercepts y and wants to obtain x (*ciphertext-only attack*)
  - modifies y into y' and submits to the receiver
- The receiver (the padding oracle)
  - Receiver decrypts y' and returns "error", if x' is not properly formatted
- On padding oracles
  - Frequently present in web applications
  - Error, receiver timing, receiver behaviour,…

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Main idea of the attack

- For simplicity, let the ciphertext be a two-block ciphertext (IV, y), with $y = E_k(x)$
  - So, at the receiving site, $x = D_k(y) \oplus IV$
- Message x is well formatted (padding)
- Main intuition
  - If the attacker changes the i-th byte of IV, this causes a predictable change (only) to the i-th byte of x

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The attack – step 1 – padding lenght

$D_k(y)$	yy	yy	yy	yy	yy	yy	yy	yy
					⊕			
IV	AB	01	4F	21	00	7C	02	9E
					=			
x	XX	XX	XX	XX	XX	XX	XX	XX

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The attack – step 2 – determine pt

$D_k(y)$	yy	yy	yy	yy	yy	yy	yy	yy	
					⊕				
IV	AB	01	4F	21	00	7C	02	9E	←9F = 9E⊕06⊕07
					=				
x	XX	XX	06	06	06	06	06	06	←07

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The attack – step 2 – determine pt

$D_k(y)$	yy	yy	yy	yy	yy	yy	yy	yy
				$\oplus$				
IV	AB	01	4E	20	01	7D	03	9F
				=				
x	XX	XX	07	07	07	07	07	07

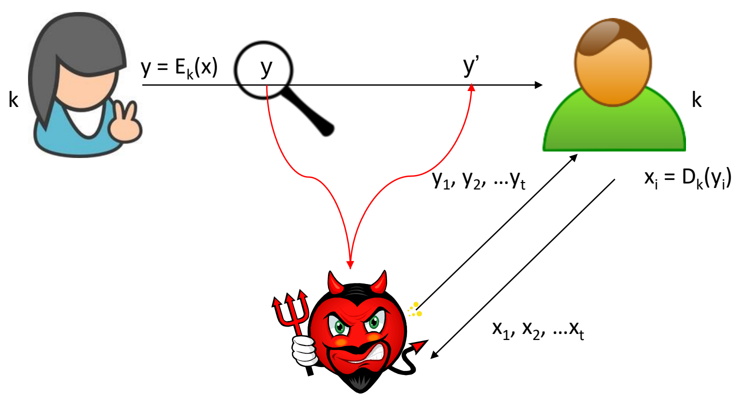
The attack – step 2 – determine pt

$D_k(y)$	yy	yy	yy	yy	yy	yy	yy	yy
				$\oplus$				
IV	AB	41	4E	20	01	7D	03	9F
				=				
x	XX	07	07	07	07	07	07	07

Attack complexity

- At most L tries to learn the # of padding bytes
- At most $2^8 = 256$ tries to learn each plaintext byte

CCA model



Chosen-ciphertext attack

- Now the attacker becomes active
- The CCA
  - The attacker intercepts y = $E_k(x)$ and modifies it into y’
  - The receiver decrypts y’ and returns (the attacker) either x’ or some information about x’
  - The adversary can derive either x or some information about x
- CCA and malleability
  - CCA-security implies non-malleability

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CCA-security

- Chosen-ciphertext attacks represent a significant, real-world threat
- Modern encryption schemes are designed to be CCA-secure

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XTS-AES MODE

XTS-AES Mode for Block-Oriented Storage Devices

- IEEE Std 1619-2007
  - Standard describes an encryption mode for data stored in sector-based devices where the threat model includes possible access to stored data by the adversary
  - Has received widespread industry support
- Approved as an additional block cipher mode of operation by NIST in 2010

Assumptions

- Hard disk organized in tracks and sectors
- A sector is the read/write unit
- Sector size is typically 512 byte
- A sector may be divided up in blocks
- Encryption
  - Use all the space
  - Depends only on a) Cleartext, b) Encryption key, c) Sector number and block number

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XTS-AES – Requirements (→)

- The requirements for encrypting stored data, also referred to as “data at rest”, differ somewhat from those for transmitted data
- The ciphertext is freely available for an attacker
- The data layout is not changed on the storage medium and in transit
- Data are accessed in fixed sized blocks, independently from each other

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XTS-AES – Requirements (→)

- Encryption is performed in 16-byte blocks, independently from each other
- There are no other metadata used, except the location of the data blocks within the whole data set
- The same plaintext is encrypted to different ciphertexts at different locations, but always to the same ciphertext when written to the same location again

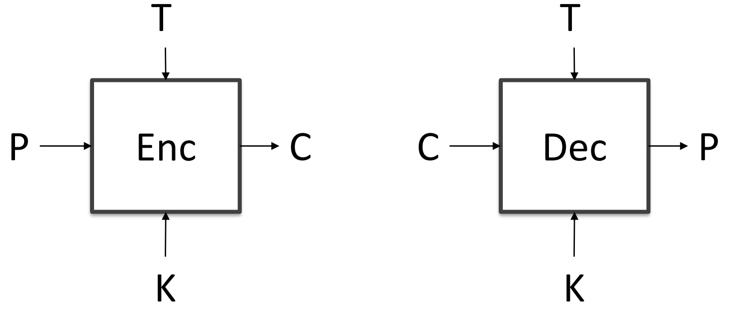
XTS-AES – Requirements (↓)

- A standard conformant device can be constructed for decryption of data encrypted by another standard conformant device

CTR and CB are inadequate

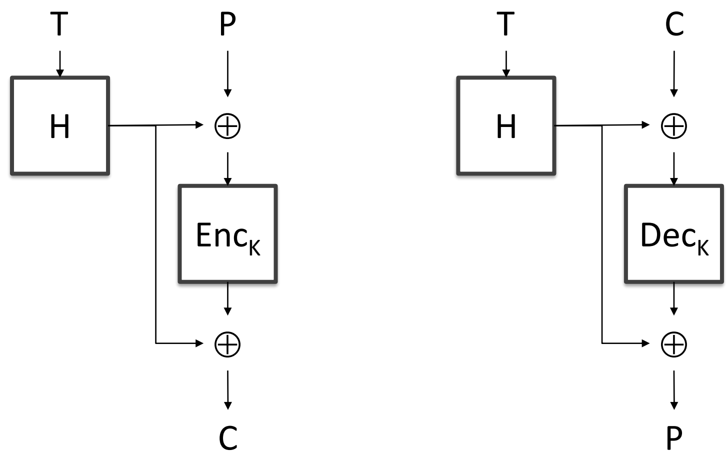
- CTR is malleable
- CBC (with IV = location)
  - Only the first block depends on location
  - Malleable

Tweakable Block Ciphers



- T is public
- K provides security while T provides variability

Tweakable Block Ciphers



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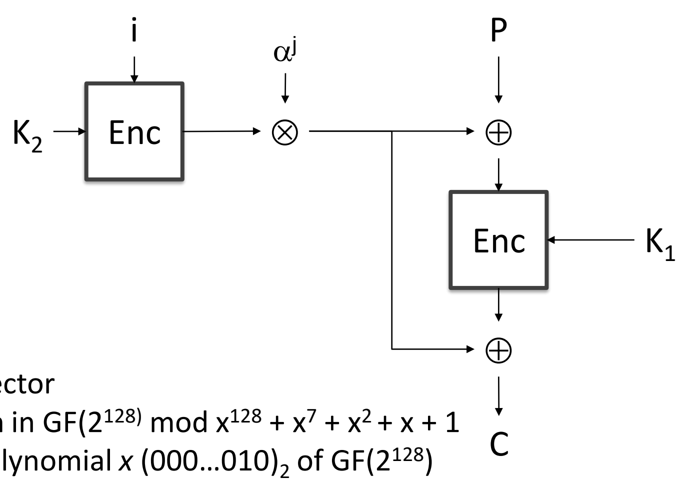
XTS-AES: block encryption



- Enc/Dec = AES
- Tweak = i, j
- i: sector
- j: block in the sector
- $\otimes$ multiplication in $GF(2^{128})$ mod $x^{128} + x^7 + x^2 + x + 1$
- α = primitive polynomial x $(000\ldots010)_2$ of $GF(2^{128})$

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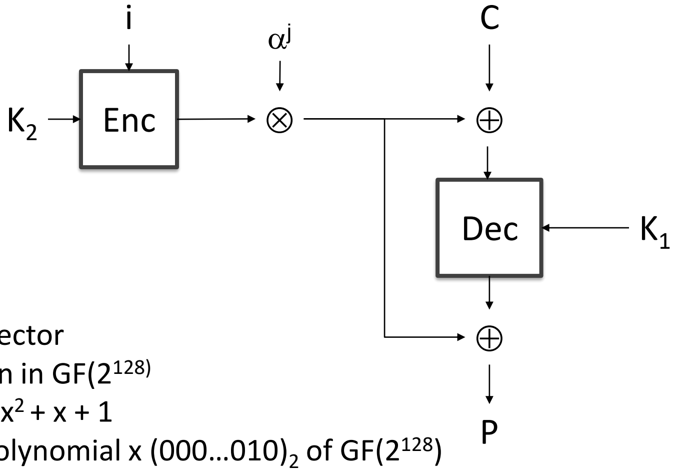
XTS-AES: block decryption



- Enc/Dec = AES
- Tweak = i, j
- i: sector
- j: block in the sector
- $\otimes$ multiplication in GF(2^{128}) mod $x^{128} + x^7 + x^2 + x + 1$
- α = primitive polynomial x $(000\ldots010)_2$ of GF(2^{128})

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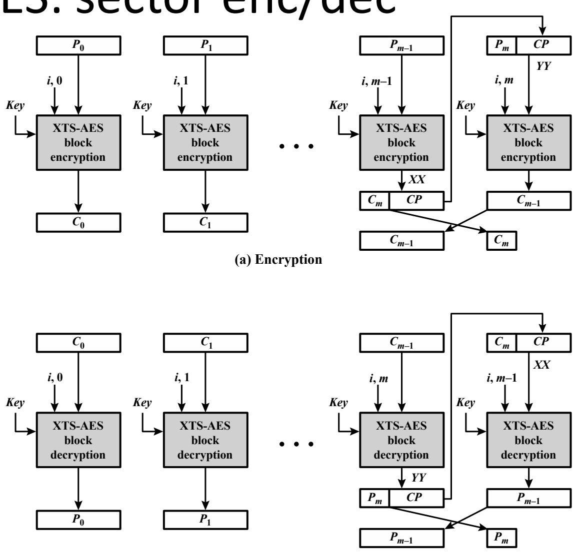
XTS-AES: sector enc/dec



(a) Encryption

(b) Decryption

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Implementations

- Software
  - BestCrypt, dm-crypt, FreeOTFE, TrueCrypt, DiskCryptor, FreeBSD e OpenBSD+
  - Nativo in Mac OS X Lion (nel FileVault)
  - BitLocker di Windows 10
- Hardware
- SPYRUS Hydra PC Digital Attaché
- Kingston DataTraveler 5000