Block Ciphers II

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Cryptology 1 (2021/22)

Content

Confidentiality modes – ECB, CBC, OFB, CFB, CTR

Padding
- Padding oracle attack
- Ciphertext stealing

Authenticated encryption – CCM, GCM

Other constructions
- Format-preserving encryption
- Encryption of block devices

Theoretical security of block ciphers

Modes of operation

- plaintext usually much longer than the block length
- modes of operation can provide:
  - confidentiality (and not authenticity) …"traditional" modes
  - authenticity (and not confidentiality)
  - confidentiality & authenticity (authenticated encryption)
  - confidentiality for block-oriented storage devices (e.g. disks)
  - key wrapping
  - format-preserving encryption, …
- varying requirements (speed, security properties, ability to parallelize, availability of RNG, etc.) $\Rightarrow$ different modes

Confidentiality modes

- the most important confidentiality modes: ECB, CBC, OFB, CFB, CTR
- e.g. see NIST SP 800-38A: *Recommendation for Block Cipher Modes of Operation: Methods and Techniques*
- None of these modes provide protection against accidental or adversarial modifications of ciphertext!
- however, the effect of ciphertext modification on resulting plaintext varies among modes

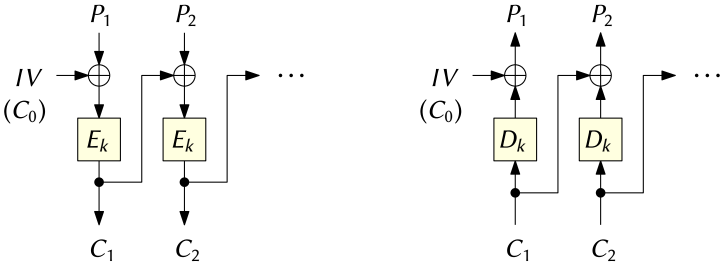
ECB (Electronic Codebook)

encrypt: $C_i = E_k(P_i)$

decrypt: $P_i = D_k(C_i)$

- the simplest mode
- data leaks: $C_i = C_j \iff P_i = P_j$
- easy to rearrange the ciphertexts blocks (permute, duplicate, …)
- encryption and decryption trivially parallelizable
- easy to perform a seek (random access)
- bit changes do not propagate (single block affected)

CBC (Cipher Block Chaining) 1

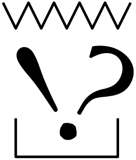


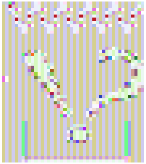
encrypt: $C_i = E_k(P_i \oplus C_{i-1})$

decrypt: $P_i = D_k(C_i) \oplus C_{i-1}$

- IV (initialization vector) – secrecy not required, usually appended as C_0
- popular mode (e.g. AES-128 CBC was mandatory in TLS 1.2, RFC 5246)
- parallelizable decryption but not encryption
- bit change in plaintext or IV propagates to the rest of the ciphertext
- bit change in the ciphertext affects only two plaintext blocks

Visual comparison of ECB and CBC (AES-128)





ECB

CBC

CBC 2

- "self-synchronizing" after losing a ciphertext block
- similarly to ECB, plaintext should be a multiple of block length
  - padding, ciphertext stealing
- IV should be unpredictable (e.g. $IV = E_k(\mathrm{msg}_{\mathrm{seq}})$, random, ...)
  - otherwise, in CPA scenario, an attacker gets an $E_k(\cdot)$ oracle
  - since $C_1 = E_k(IV \oplus P_1)$, predictable IV allows him/her to adjust P_1
  - the attacker with $E_k(\cdot)$ access can test any plaintext block

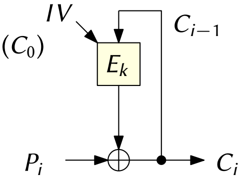
CBC 3

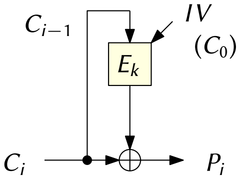
- data leak (birthday & two-time pad):

$$C_i = C_j \quad \Rightarrow \quad E_k(P_i \oplus C_{i-1}) = E_k(P_j \oplus C_{j-1})$$
$$P_i \oplus P_j = C_{i-1} \oplus C_{j-1}$$

- Sweet32 attack (2016): ciphers with block length 64 bits and large amount of data encrypted using the same key (TLS, OpenVPN)
  - 64 bit block $\Rightarrow$ collision expected after $\approx 2^{32}$ blocks (32 GiB)
- limit number of blocks encrypted with a single key

CFB (Cipher Feedback)





encrypt: $C_i = P_i \oplus E_k(C_{i-1})$

decrypt: $P_i = C_i \oplus E_k(C_{i-1})$

- parallelizable decryption but not encryption; D_k not needed
- bit change in plaintext or IV propagates to the rest of the ciphertext
- bit change in the ciphertext affects only two plaintext blocks
- self-synchronizing after full ciphertext block is lost
  - ciphertext block and its predecessor are needed to decrypt correctly
  - there is a variant for more granular losses

CFB 2

- plaintext length does not need to be a multiple of block length
- *IV* should be unique for each plaintext
- repeated *IV*:
  - two-time pad for the first blocks:

$$C_1 \oplus C_1' = E_k(IV) \oplus P_1 \oplus E_k(IV) \oplus P_1' = P_1 \oplus P_1'$$

  - for constant *IV* we have an encryption oracle in CPA scenario; 2nd block (C_2):

$$C_2 = E_k(\underbrace{E_k(IV) \oplus P_1}_{C_1}) \oplus P_2$$

choosing $P_1' = C_1 \oplus P_1 \oplus X$ and arbitrary P_2' yields

$$C_2' = E_k(E_k(IV) \oplus C_1 \oplus P_1 \oplus X) \oplus P_2' = E_k(X) \oplus P_2'$$

thus $E_k(X) = C_2' \oplus P_2'$

CFB8 variant of CFB mode and Zerologon

- Zerologon (CVE-2020-1472, Tom Tervoort) compromising domain admin in AD
- problems with cryptography in Netlogon protocol
- AES-CFB8
- CFB8 mode (P_i and C_i denote bytes):

$$
\begin{aligned}
C_1 &= E_k(IV[0 \dots 15])[0] \oplus P_1 \\
C_2 &= E_k(IV[1 \dots 15]C_1)[0] \oplus P_2 \\
C_3 &= E_k(IV[2 \dots 15]C_1C_2)[0] \oplus P_3 \\
&\dots \\
C_{i+1} &= E_k(C[i-15, \dots, i])[0] \oplus P_{i+1}
\end{aligned}
$$

CFB8 variant of CFB mode and Zerologon 2

- function in Netlogon implementation used all-zero IV (always)
- consider all-zero plaintext
  - 1/256 of all keys lead to all-zero ciphertext
- client authenticates by encrypting his own challenge with a session key
  - the attacker chooses all-zero challenge
  - session-key is unknown
  - the attacker succeeds with probability 1/256
  - if unsuccessful try again (session-key will change since it depends on server challenge as well)
- the attack require more than this, but this is the core problem

OFB (Output Feedback)

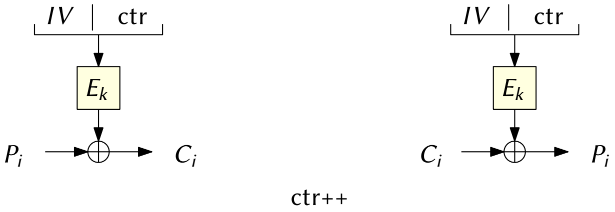
$$R_i = E_k(R_{i-1})$$

encrypt: $C_i = P_i \oplus R_i$

decrypt: $P_i = C_i \oplus R_i$

- synchronous stream cipher; D_k not needed
- IV should be unique for each plaintext
- neither encryption nor decryption can be parallelized
- single bit change in plaintext/ciphertext causes single bit change in ciphertext/plaintext (easy to flip plaintext bits)

CTR (Counter)



encrypt: $C_i = P_i \oplus E_k(IV \,|\, \text{ctr})$ decrypt: $P_i = C_i \oplus E_k(IV \,|\, \text{ctr})$

- inputs to E_k should not overlap (otherwise …two-time pad)
- similar to OFB (synchronous stream cipher)
- similar properties of changing ciphertext bits
- easy to perform a seek (random access)
- easy to encrypt and decrypt in parallel

Padding

- ECB and CBC assume: $n \mid |\text{plaintext}|$
  (i.e. n divides the length of plaintext)
- padding required (various paddings used):
  - bit padding – append 1 (always) and necessary number of 0's:
    $$\text{msg} \;\|\; 1000\ldots0$$
  - byte padding (PKCS #7, CMS (RFC 5652)):
    $$\begin{array}{lll} \text{msg} \,\|\, 01 & \text{if } n \mid |\text{msg}| + 1 & \\ \text{msg} \,\|\, 03\ 03\ 03 & \text{if } n \mid |\text{msg}| + 3 & \\ \text{msg} \,\|\, 10\ 10 \ldots 10 & \text{if } n \mid |\text{msg}| & (\text{for } n = 128) \end{array}$$
  - similarly for TLS 1.2 (RFC 5246): 00; 02 02 02; 0F 0F …0F
- padding $\Rightarrow |\text{ciphertext}| > |\text{plaintext}|$
- padding should be verified after decryption
- "stream" modes like OFB, CTR or CFB do not need padding
  - $|\text{ciphertext}| = |\text{plaintext}|$

Padding oracle attack 1

- implementation issue
- our assumptions:
  - CBC mode
  - we can recognize correct/incorrect padding, e.g. a server behaves differently (observable error, timing differences, …)
- goal: decrypt ciphertext block C, i.e. compute $Y = D_k(C)$
- the attack:
  - try ciphertexts (assume 16-byte block, X is a random 15-byte value): $(X \| 00) \| C$, $(X \| 01) \| C$, …, $(X \| 7A) \| \mathrm{C}$, …, $(X \| \mathrm{FF}) \| \mathrm{C}$, until we find a ciphertext with valid padding
  - probably the corresponding plaintext ends with byte 01, and we can compute Y_{15}, e.g. $(7\mathrm{A} \oplus Y_{15}) = 01 \Rightarrow Y_{15} = 7\mathrm{B}$

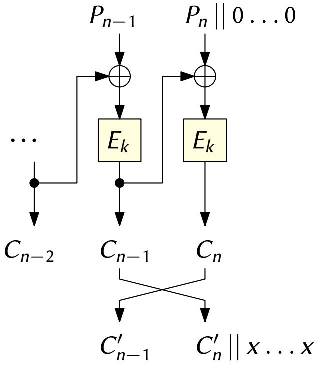
Padding oracle attack 2

- the attack (cont.):
  - set the last byte of the first block to get 02 as the final byte of the plaintext: $b \oplus Y_{15} = 02$, i.e. $b = 79$
  - try ciphertexts (X is a random 14-byte value):
    $(X \parallel 00 \parallel 79) \parallel C, (X \parallel 01 \parallel 79) \parallel C, \ldots,$
    $(X \parallel \mathrm{B2} \parallel 79) \parallel \mathrm{C}, \ldots, (X \parallel \mathrm{FF} \parallel 79) \parallel \mathrm{C},$
    until we find a ciphertext with valid padding (this time: 02 02)
  - we can compute Y_{14}, e.g. $(\mathrm{B2} \oplus Y_{14}) = 02 \Rightarrow Y_{14} = \mathrm{B0}$

    …similarly for other bytes
- a variant used against SSL/TLS implementations (Lucky Thirteen, 2013)

Ciphertext stealing 1

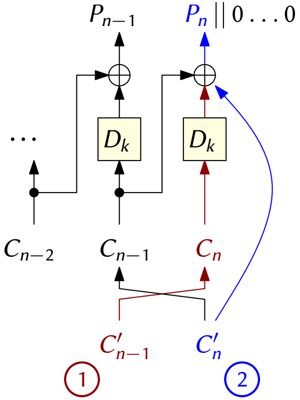
- method of avoiding padding for CBC or ECB modes
- ciphertext stealing for CBC mode encryption:



plaintext: ... P_{n-2}, P_{n-1}, P_n
ciphertext: ... C_{n-2}, C'_{n-1}, C'_n

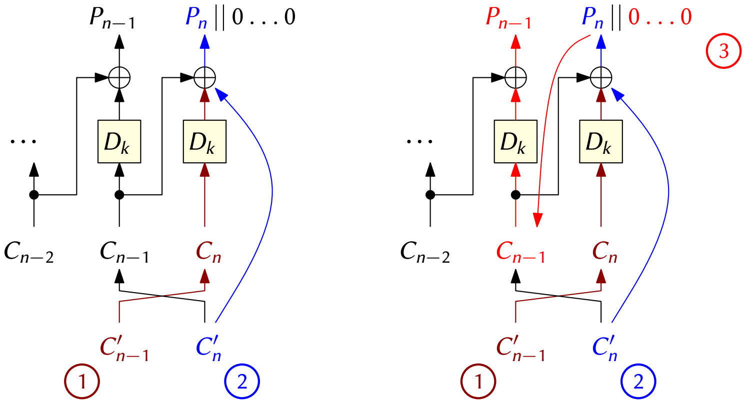
Ciphertext stealing 2

- decrypting CBC ciphertext stealing:



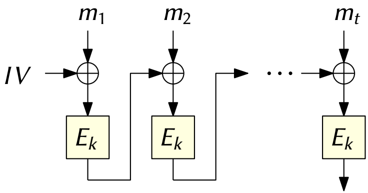
Ciphertext stealing 2

- decrypting CBC ciphertext stealing:



Authenticated encryption

- modes providing confidentiality & authenticity of data
- e.g. CCM (Counter with CBC-MAC), GCM (Galois/Counter Mode)
- CCM (idea):
  - plaintext encrypted using CTR mode
  - authentication tag computed as CBC-MAC
  - authenticate-then-encrypt (single key is used)
  - two-pass scheme (two E transforms for each input block)



Authenticated encryption – GCM

- faster than CCM
- simplified GCM:
  - single key is used
  - plaintext encrypted using CTR mode (starting with $\mathrm{inc}(J_0)$, an incremented "pre-counter block", derived from IV, e.g. $J_0 = \mathrm{IV} \,||\, 0^{31} \,||\, 1$)
  - authentication tag computed as follows: $\mathrm{CTR}_K(\mathrm{GHASH}_H(A, C)) = E_K(J_0) \oplus \mathrm{GHASH}_H(A, C)$
  - A – additional authenticated data, C – ciphertext
  - $H = E_K(0)$
  - $A \,||\, C \;\mapsto\; X_1, \ldots, X_{n-1}, \underbrace{\mathrm{len}(A) \,||\, \mathrm{len}(C)}_{X_n}$

$$\boxed{\begin{array}{l} Y_0 = 0,\; Y_i = (Y_{i-1} \oplus X_i) \bullet H \\ \mathrm{GHASH}_H(A, C) \leftarrow Y_n \end{array}}$$

  - $\bullet$ is multiplication in $\mathrm{GF}(2^{128})$ (generated by $x^{128} + x^7 + x^2 + x + 1$)
  - IV must be unique for a given key (otherwise "forbidden attack")

Format-preserving encryption

- goal: encrypt fixed-length string over some alphabet while preserving the length and the format of data
  - examples: credit card numbers, social security numbers, ...
- various proposals; the most important are FFX schemes
- based on Feistel structure
- see NIST SP 800-38G for recommended modes (and details)
- we present a very simplified (illustration) variant of FFX
- notation:
  - r – radix, the size of input alphabet
  - input plaintext X (string in base r) of length n (even)
  - AES-128 – underlying block cipher; no tweak
  - PRF – pseudorandom function (based on AES)

Simplified FFX variant

1. $A \,||\, B \leftarrow X$ (left and right halves)
2. $P =$ constants $||\, r \,||\, n$
3. for i from 0 to 9: (10 rounds of Feistel structure)
   3.1 $R = \mathrm{PRF}_k(P \,||\, i \,||\, B)$
   3.2 $S = R \,||\, \mathrm{AES}_k(R \oplus 1) \,||\, \mathrm{AES}_k(R \oplus 2)$ ... (sufficiently long)
   3.3 $C = (A + S) \bmod r^{n/2}$
   3.4 $A = B$
   3.5 $B = C$
4. return $A \,||\, B$

- omitted – all conversions from strings to bytes (and back)

XTS – encryption of block devices

- XEX-based Tweaked CodeBook mode (TCB) with CipherText Stealing (CTS)
- encryption of disks (block storage devices), e.g. File Vault 2, VeraCrypt, Bitlocker, etc.
- IEEE standard; approved by NIST

$$C_i = E_{k_1}(P_i \oplus T_n) \oplus T_n; \qquad T_n = E_{k_2}(n) \bullet a^i$$

where

- k_1, k_2 are two independent keys
- n – data unit number (e.g. 512B in VeraCrypt)
- i – block number in particular data unit
- $\bullet$ – multiplication in $GF(2^{128})$ (defined by $x^{128} + x^7 + x^2 + x + 1$)
- a – a primitive element in $GF(2^{128})$ (corresponds to polynomial x)

Theoretical security of block ciphers

- just an idea is presented
- E is an n-bit cipher
- attacker A (distinguisher)
- two different scenarios — A with oracle access to
  - $E_k(\cdot)$ and $E_k^{-1}(\cdot)$ for fixed, randomly chosen k
  - π and π^{-1} for randomly chosen permutation on $\{0, 1\}^n$
- block cipher is strong pseudorandom permutation if for any (efficient) attacker A the probability of distinguishing these scenarios is negligible
- "standard model" (other models of security exist, e.g. "ideal cipher" model – random independent permutation for every key)