Legacy Encryption Downgrade Attacks against LibrePGP and CMS

Work in the scope of Project 480 – "PQC@Thunderbird"

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Plaintext manipulation attacks against LibrePGP AEAD

Plaintext recovery for low entropy blocks in LibrePGP OCB Packets

Legacy Mode Downgrade Attacks against AES Key Wrap

Conclusion

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- Goal: decryption of messages
- Asymmetric
  - Bleichenbacher's padding oracle attack against RSA with PKCS#1 v1.5 padding
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- Symmetric
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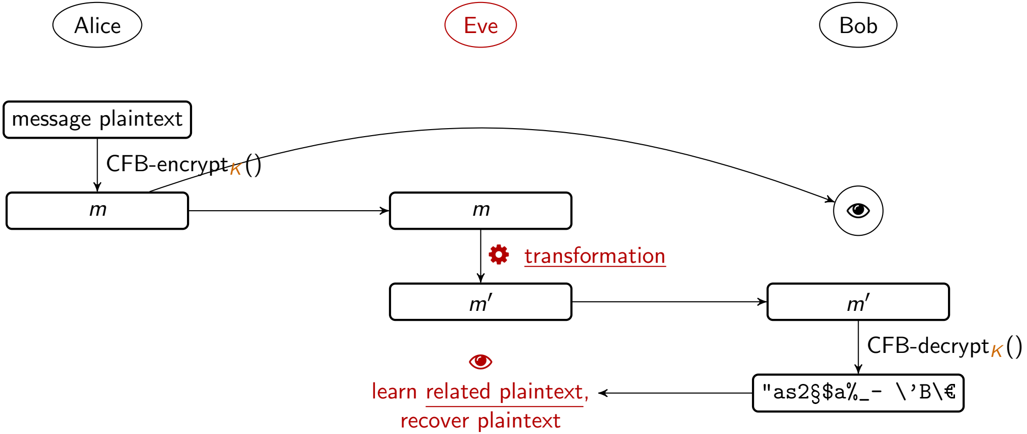
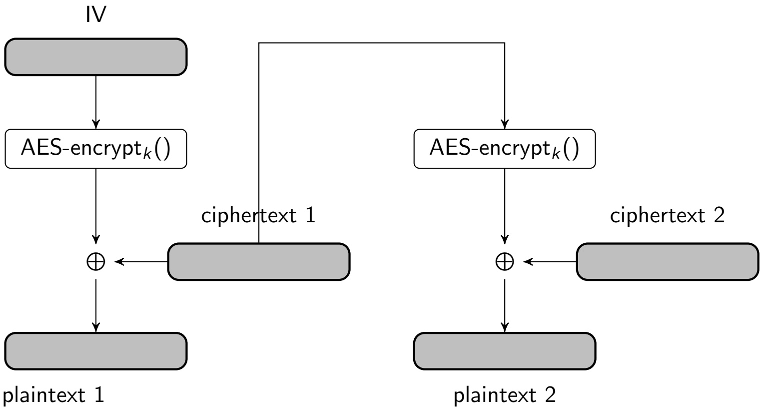
Decryption Oracle Attack against OpenPGP SED Packets



CFB decryption and its malleability



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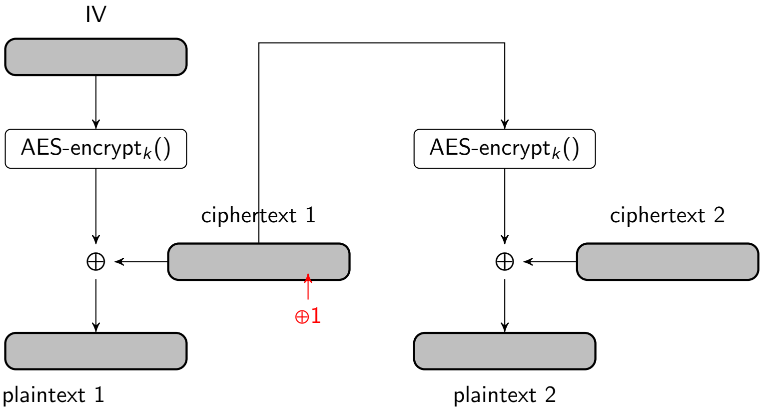

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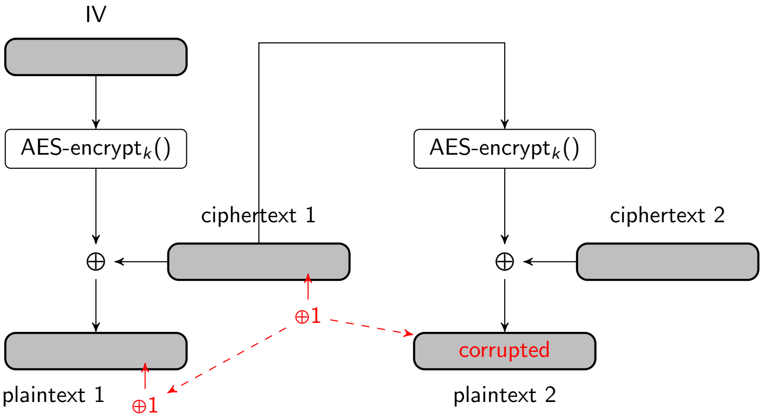

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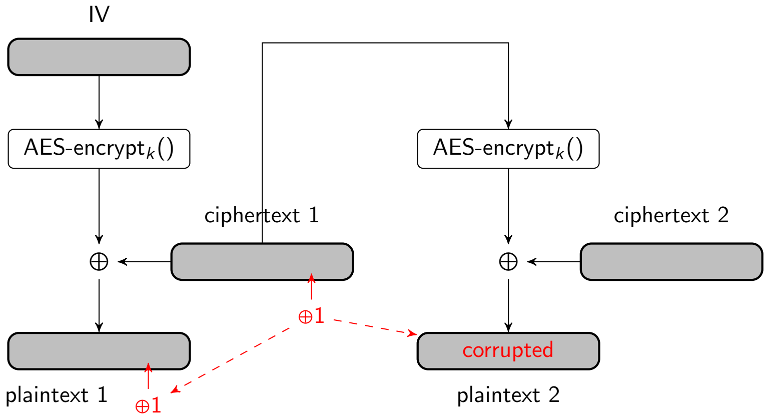
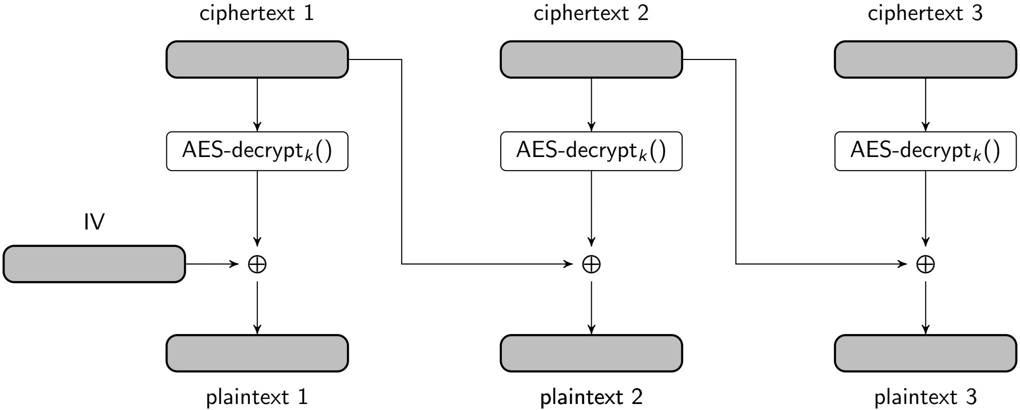


ability to mask actual
plaintext in a reversible way

CBC decryption and its malleability



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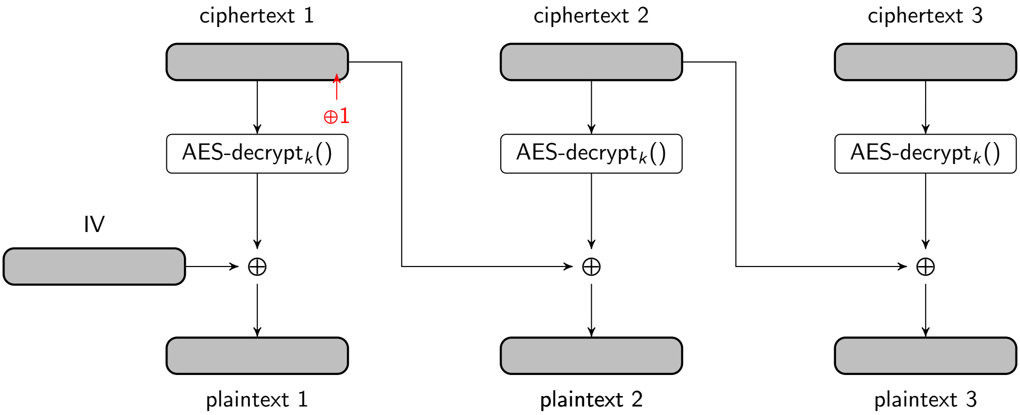

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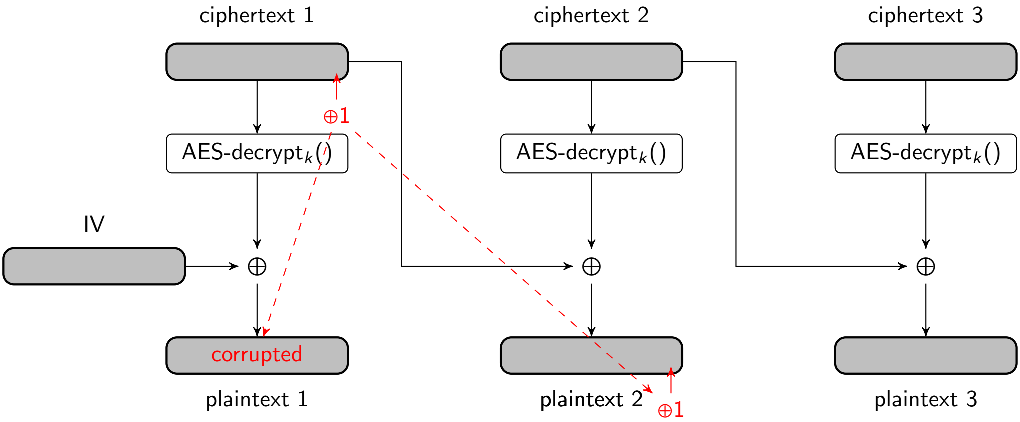

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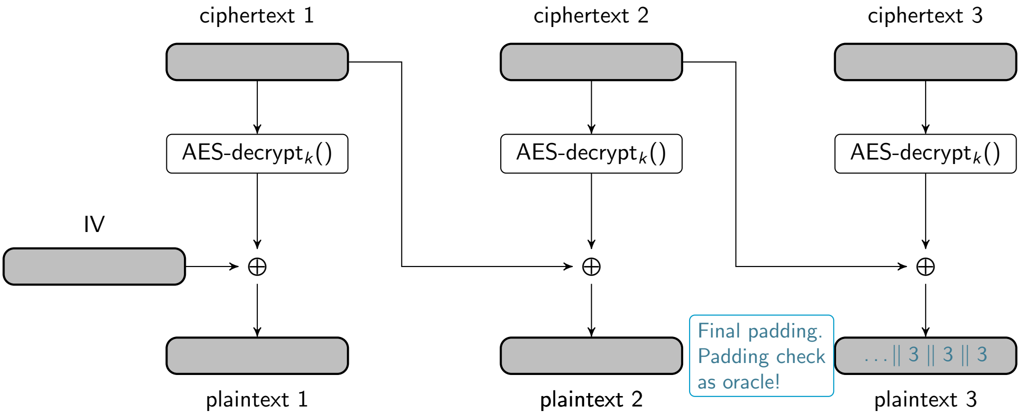

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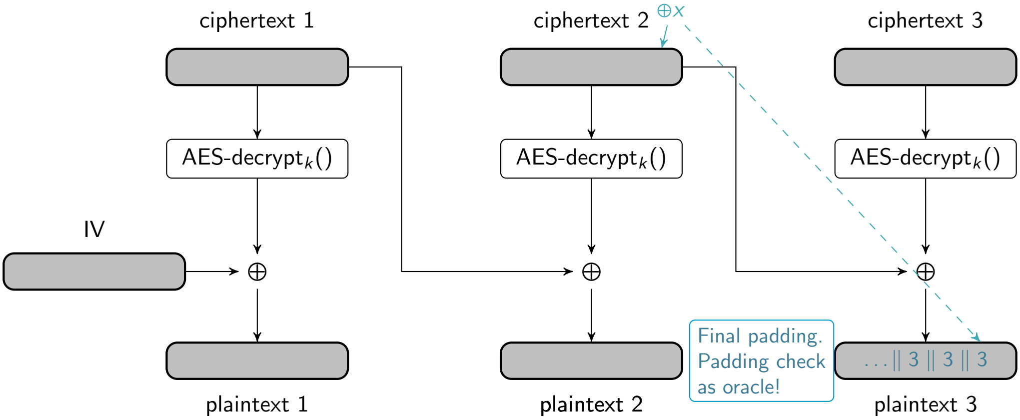

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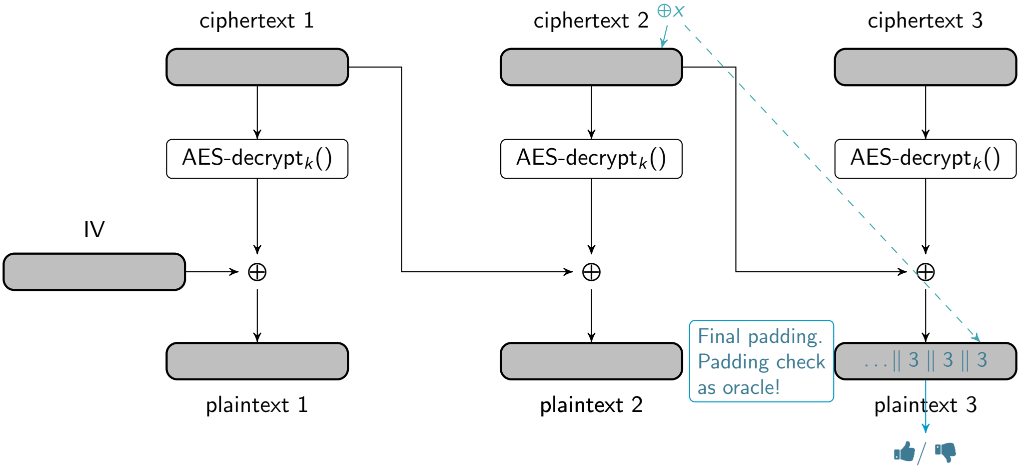

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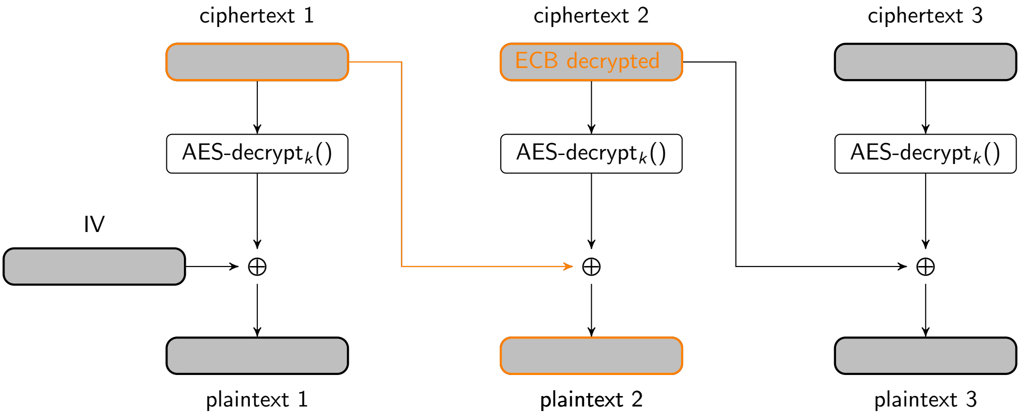

CBC decryption oracle = ECB decryption oracle

Decryption oracle attacks against modern cipher modes

MTG

- Classical oracle attacks
  - ◎ target ciphertext: CFB
  - 🔓 ciphertext decrypted by the oracle: CFB
- Oracle attacks using downgrades
  - ◎ target ciphertext: AEAD or AES Key Wrap
  - 🔓 ciphertext decrypted by the oracle: CFB (or CBC)

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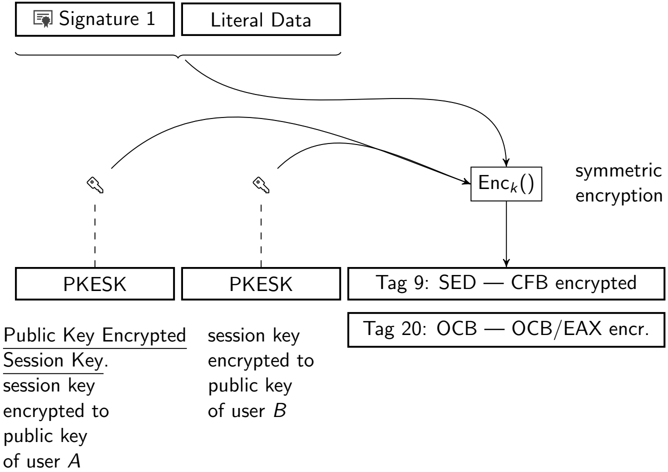
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Literal Data
Enc$_k$()
symmetric encryption
PKESK
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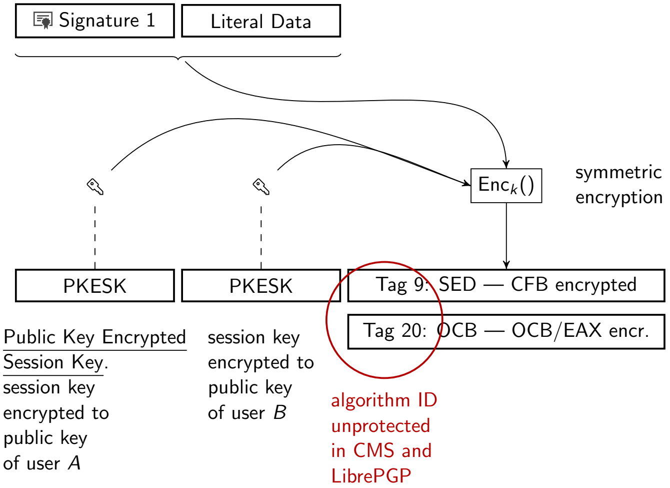
Tag 9: SED — CFB encrypted
Tag 20: OCB — OCB/EAX encr.
Public Key Encrypted Session Key.
session key encrypted to public key of user *A*
session key encrypted to public key of user *B*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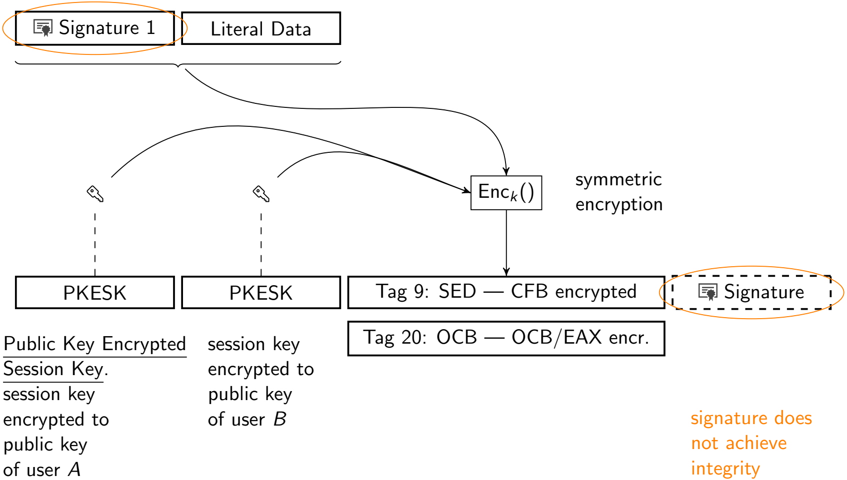

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signature does not achieve integrity

Decryption Oracle Attacks against Cryptographic Message Syntax (CMS)

- CMS realizes two AES-based AEAD modes
  - AES-CCM
  - AES-GCM
- both perform encryption using CTR-mode
- Legacy encryption mode in CMS: CBC
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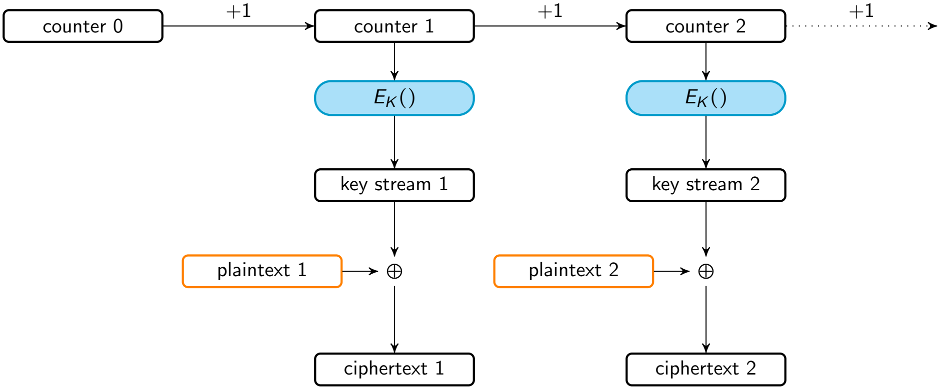
Revealing low entropy blocks in plaintext



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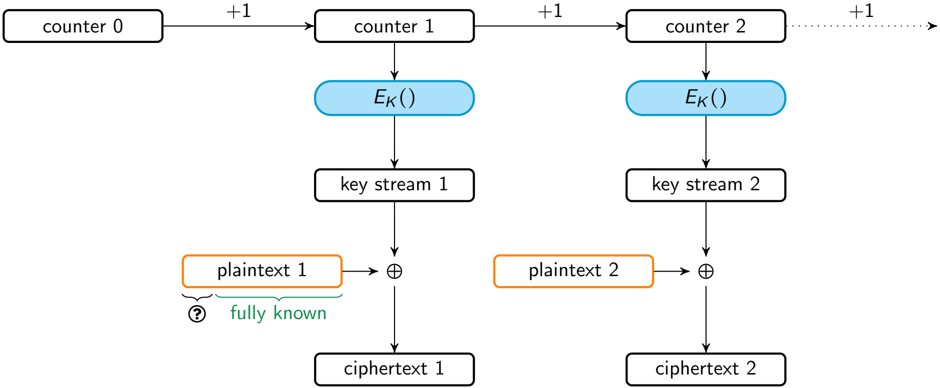

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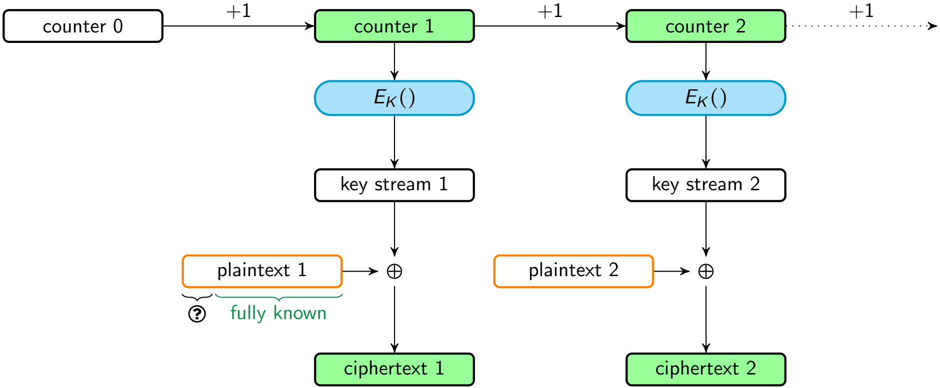

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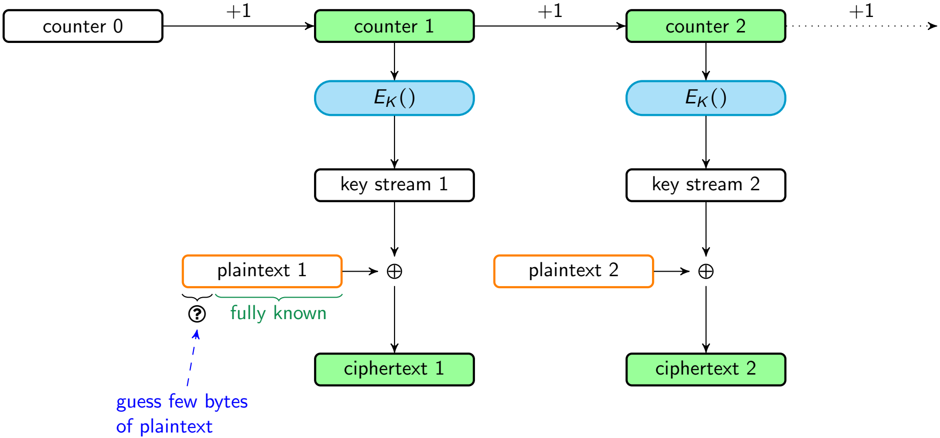

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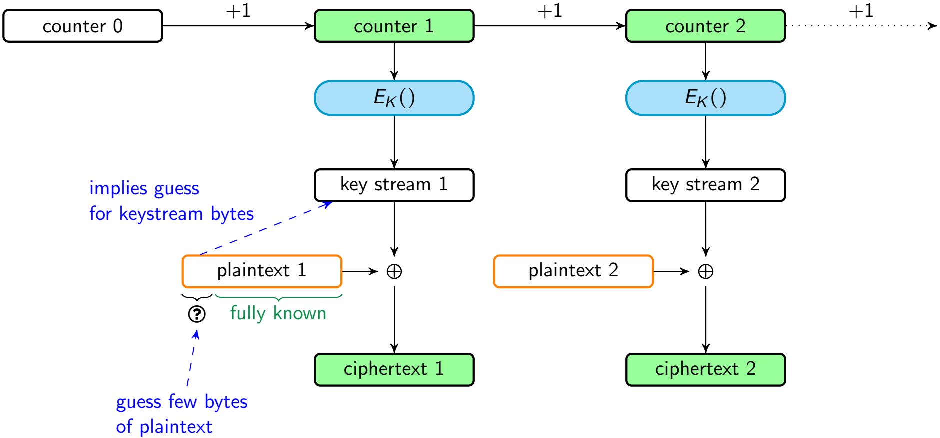

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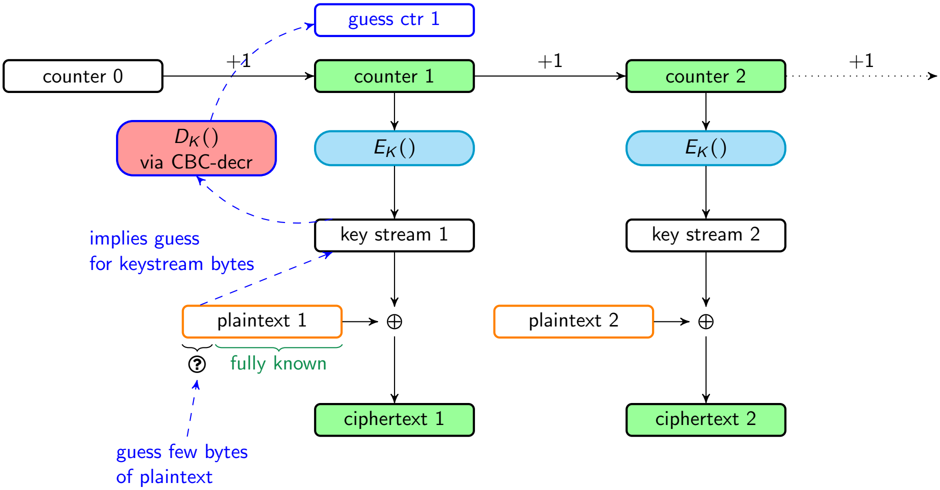

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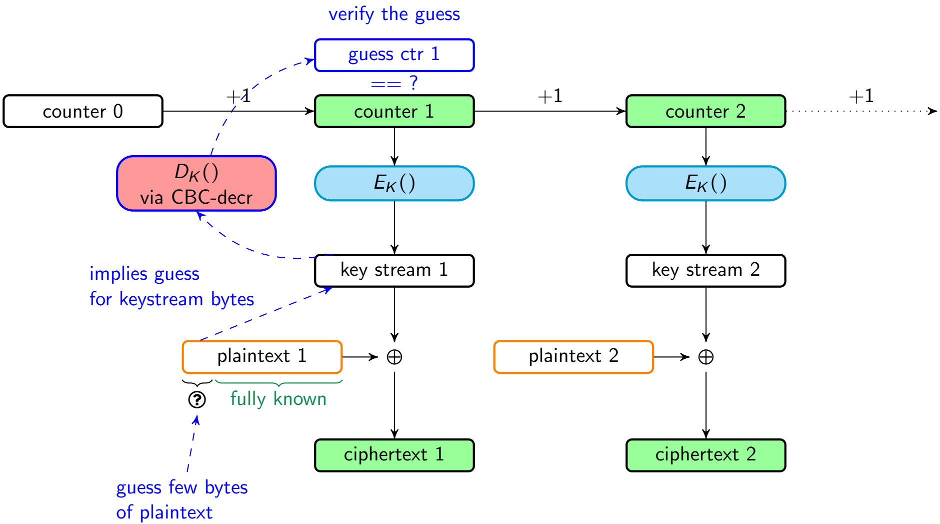

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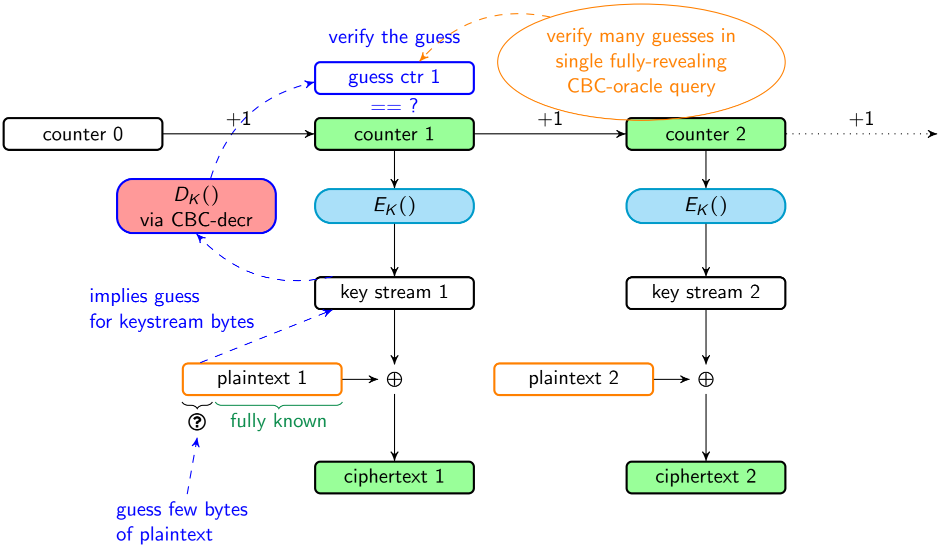

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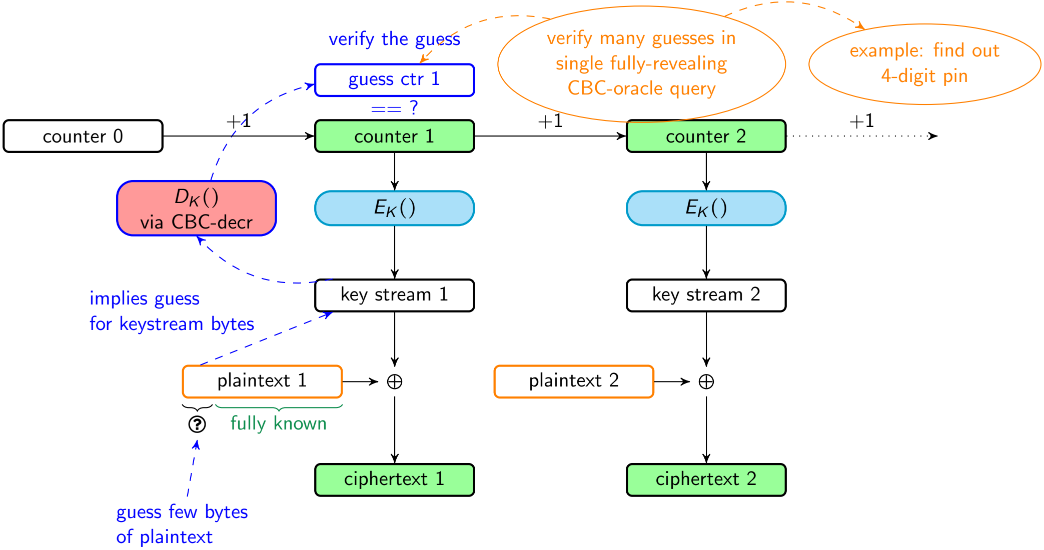

CBC padding oracle

- CBC operates only on full plaintext blocks
- padding needed
- padding in CMS:
  - *13 bytes of content* || 0x3 || 0x3 || 0x3
- padding oracle:
  - if decrypting party reveals whether padding was incorrect
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Countermeasure for CMS

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- draft-ietf-lamps-cms-cek-hkdf-sha256
- defines new algorithm identifier for symmetric which indicates use of prior key HKDF derivation
- ```
  cea-CEKHKDFSHA256 CONTENT-ENCRYPTION ::= {
      IDENTIFIER id-alg-cek-hkdf-sha256
      PARAMS TYPE ContentEncryptionAlgorithmIdentifier ARE required
      SMIME-CAPS { IDENTIFIED BY id-alg-cek-hkdf-sha256 } }
  ```
  - PRK = HKDF-Extract(salt, IKM)
  - DEK = HKDF-Expand(PRK, AlgorithmID, OKM_SIZE)
- Cross-algorithm attack: derived key is different
  ```

Introduction

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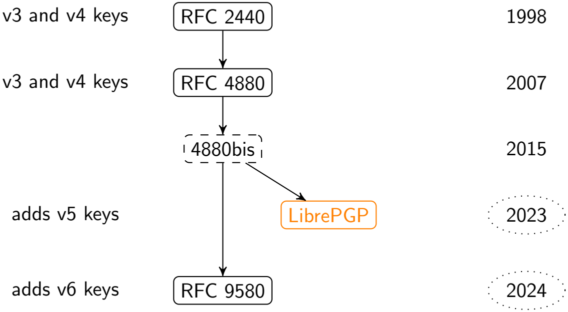
Plaintext recovery for low entropy blocks in LibrePGP OCB Packets

Legacy Mode Downgrade Attacks against AES Key Wrap

Conclusion

Cross-Algorithm Attacks against LibrePGP AEAD

MTG



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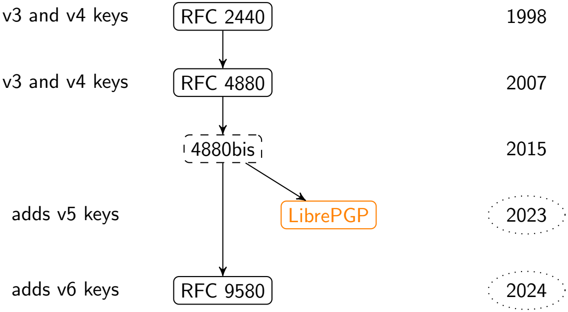

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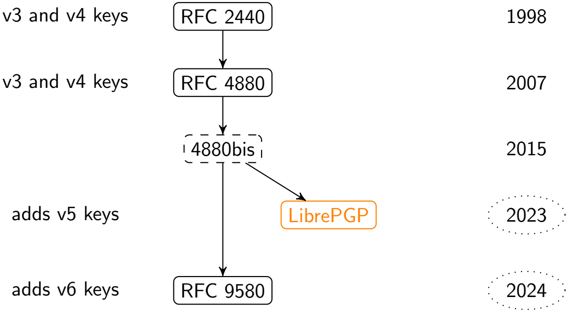

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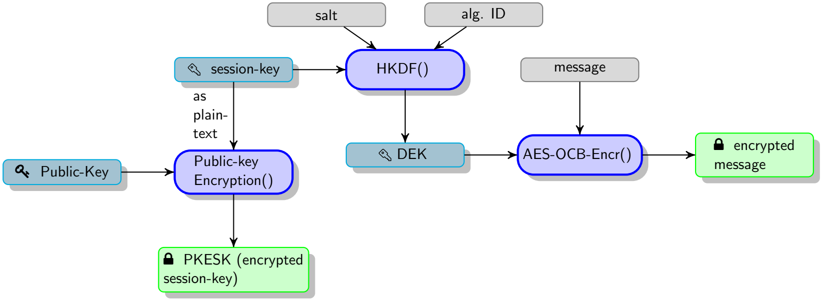

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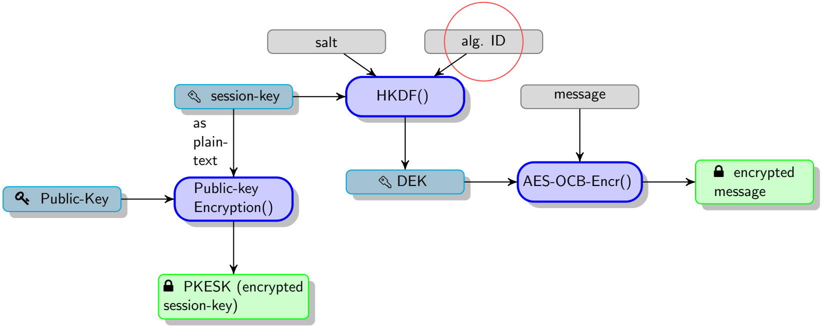

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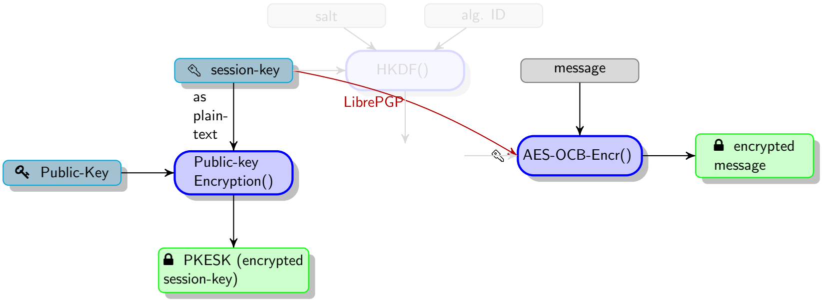

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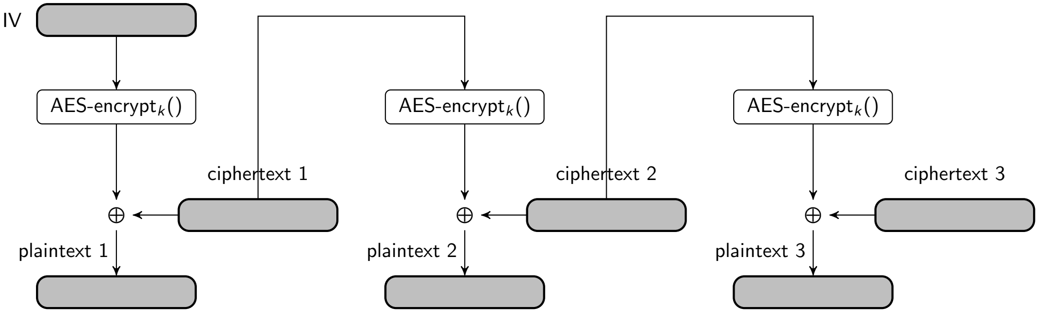
CFB decryption oracle as an ECB encryption oracle



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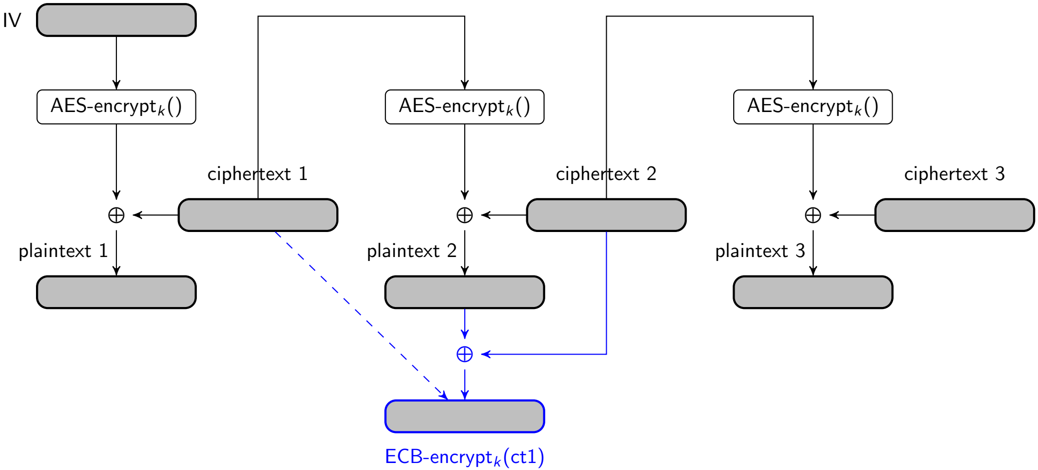

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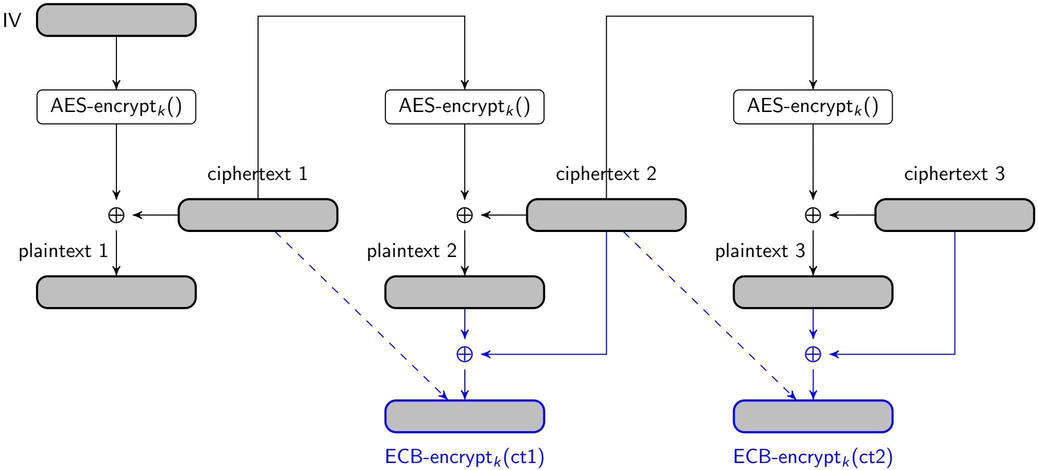

What we can do with an OpenPGP SED decryption Oracle

- An SED decryption oracle can be used to decrypt SED packages (legacy attack)
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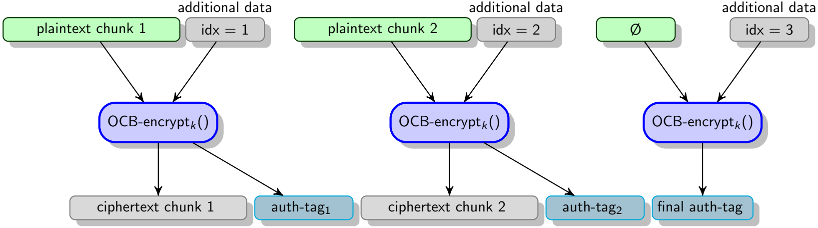

OCB Encryption

- OCB encryption uses only block cipher (e.g. AES) block-encryption
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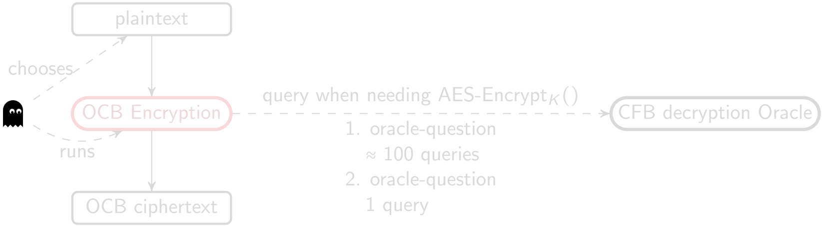

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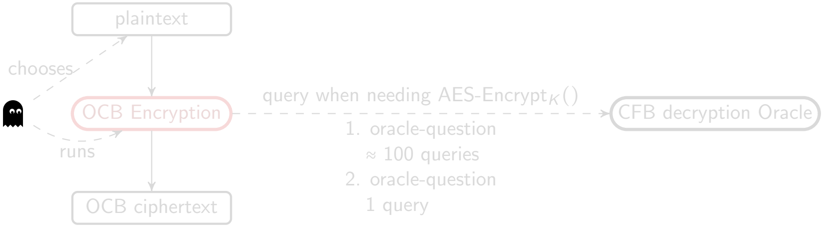

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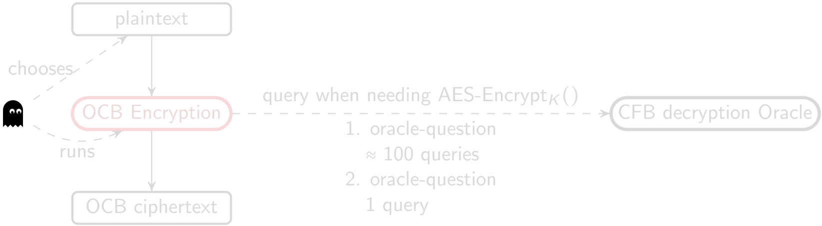

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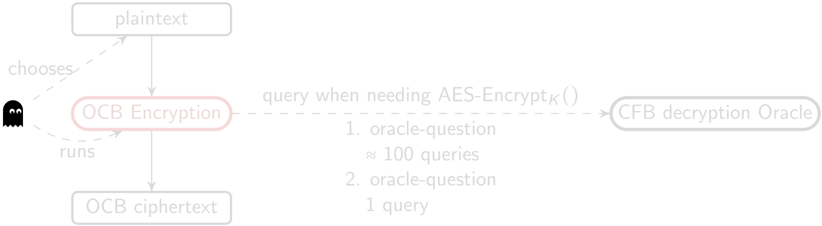

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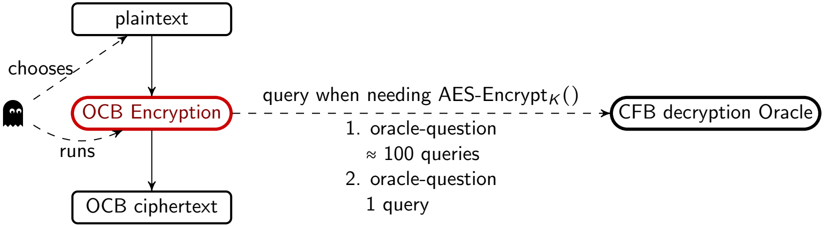

procedure OCB-ENCRYPT($k \in \{0,1\}^{\mathrm{keylen}}, N \in \{0,1\}^{120}, A \in \{0,1\}^*, P \in \{0,1\}^*$)

  $\tilde{m} = \lfloor |P|/128 \rfloor$

  parse P as $P_1 \| P_2 \| \dots \| P_{\tilde{m}} \| P_*$ where $|P_i| = 128$ for each $1 \le i \le \tilde{m}$ and $0 \le |P_*| < 128$

  compute values L_*, $L_\$$, and L_i for $0 \le i$ (dbl. in GF(2^{128}) using $E_k([0]^{128})$)

  ...

  $f = E_k(\mathcal{N}[1:122] \| [0]^6)$ // "Ktop"

  ...

  $G_0 = \dots$ // inital mask

  $s_0 = [0]^{128}$ // "Checksum"

Setup $L_{\dots}$ and G_0 values

  for $1 \le i \le \tilde{m}$ **do**

    $G_i = G_{i-1} \oplus L_{\mathrm{ntz}(i)}$

    $C_i = G_i \oplus E_k(P_i \oplus G_i)$

    $s_i = s_{i-1} \oplus P_i$

Encryption loop with input and output whitening

  end for

  if $|P_*| > 0$ **then**

    $\tilde{n} \leftarrow \tilde{m} + 1$

    ...

    $u = E_k(G_{\tilde{n}})$ // "Pad"

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Special case of non-full final plaintext block

  else

    $\tilde{n} \leftarrow \tilde{m}$

  end if

  $T = E_k(s_{\tilde{n}} \oplus G_{\tilde{n}} \oplus L_\$) \oplus \mathrm{HASH}(K, A)$ ← Compute the auth. tag

  return $C = C_1 \| C_2 \| \dots \| C_{\tilde{n}} \| T[1:\mathrm{taglen}]$

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1st question to ECB oracle

Special case of non-full final plaintext block

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1st question to ECB oracle

2nd question to ECB oracle

2nd encr. call only

OCB Hash

procedure $\text{OCB-Hash}(\text{key } k \in \{0,1\}^{|\mathrm{K}|}, \text{ additional data } A \in \{0,1\}^*)$
    $L_* = E_k([0]^{128})$
    $L_\$ = \mathrm{ocbDouble}(L_*)$
    $L_0 = \mathrm{ocbDouble}(L_\$)$
    $L_i = \mathrm{ocbDouble}(L_{i-1})$ for any integer $i > 0$
    $m = \lfloor |A|/128 \rfloor$
    parse A as $A_1 \parallel A_2 \parallel \ldots \parallel A_m \parallel A_*$ where $|A_i| = 128$ for each $1 \leq i \leq m$ and $0 \leq |A_*| < 128$
    $F_0 = [0]^{128}$ // Offset
    for i ← 1 to m **do**
        $F_i = F_{i-1} \oplus L_{\mathrm{ntz}(i)}$
    end for
    if $|A_*| > 0$ **then**
        $n \leftarrow m + 1$
        $F_n = F_m \oplus L_*$
        $A_n = (A_* \parallel 1 \parallel [0]^{127-|A_*|})$
    else
        $n \leftarrow m$
    end if
    $S_0 = [0]^{128}$ // Sum
    for i ← 1 to n **do**
        $S_i = S_{i-1} \oplus E_k(A_i \oplus F_i)$
    end for
    return $S = S_n$
end procedure

Summary: LibrePGP OCB ciphertext manipulation

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  - implement CFB encryption
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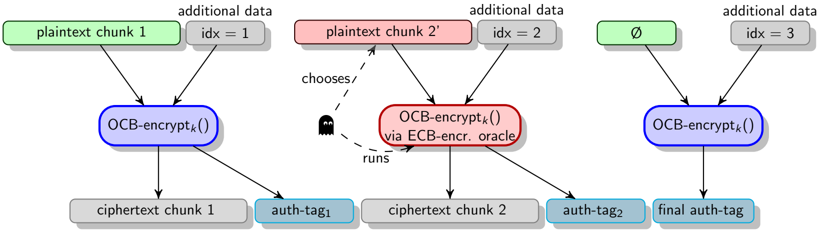
Insertion of LibrePGP AEAD chunk



It's not that simple: expected plaintext structure in SED (CFB) oracle

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Availability and exploitability of SED decryption

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- GnuPG (CLI) in default configuration
  - outputs the SED plaintext
  - non-zero exit code and warning (stderror)

```
gpg: WARNING: message was not integrity protected
gpg: decryption forced to fail!
```

- RNP
  - supports SED unrestricted
  - implements quick-check
    - omitted detail: OpenPGP SED CFB encryption uses two-step CFB encryption
    - Quick-check (redundancy test): requires the equality of two 2-byte pairs at the start of the plaintext
    - random ciphertext fails this check with 2^{-16}
    - Quick check is vulnerability in itself!

Two-step CFB encryption in SED Packet

procedure $\mathrm{SED\text{-}D\textsc{ec}}_K(H \parallel B_1 \parallel \ldots \parallel B_m)$ with $H \in \{0,1\}^{144}$ and $B_i \in \{0,1\}^{128}$

  $Y \leftarrow \mathrm{CFB\text{-}\textsc{decrypt}}_K([0]^{128}, H)$ // $Y \in \{0,1\}^{128+16}$

  if have quick-check AND $Y[96:127] \neq Y[128:143]$ **then**

    Abort with error

  end if

  $\mathrm{IV} \leftarrow H[16:143]$

  return $\mathrm{CFB\text{-}\textsc{decrypt}}_K(\mathrm{IV}, B_1 \parallel \ldots \parallel B_m)$

end procedure

OpenPGP plaintext format

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- decrypted plaintext must be either
  - Literal Data (LIT) Packet
  - (Compressed Data)
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Random appearance of LIT Packet in SED (CFB) oracle

- Attacker's ciphertext will decrypt to plaintexts with random appearance
- Plaintext must by chance be decodable as LIT Packet

- Problems:
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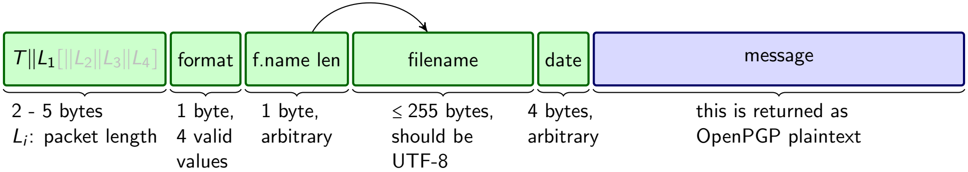

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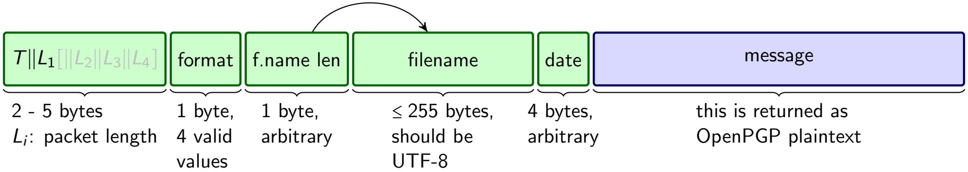
Random appearance of LIT Packet in SED (CFB) oracle

- Attacker's ciphertext will decrypt to plaintexts with random appearance
- Plaintext must by chance be decodable as LIT Packet



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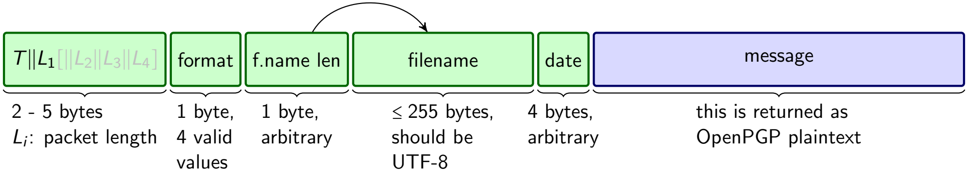

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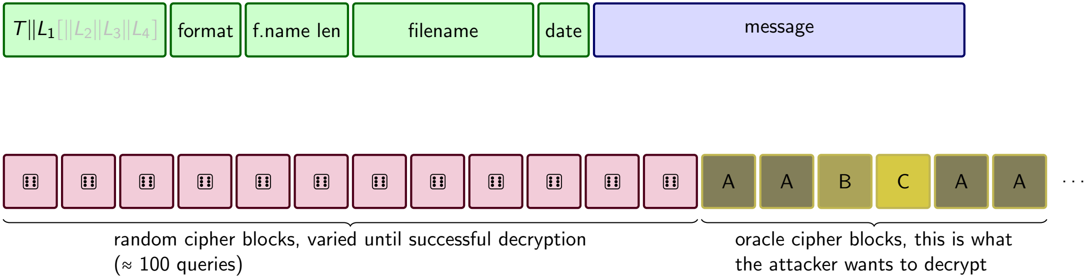

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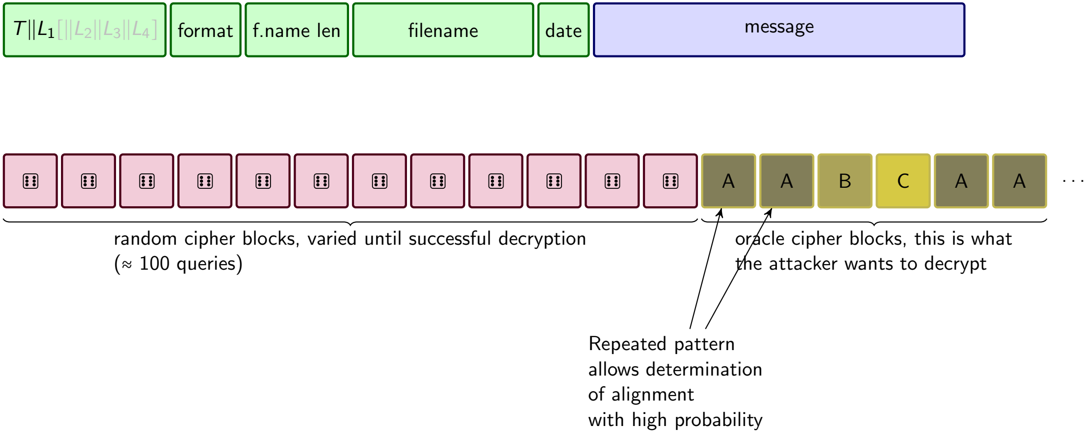

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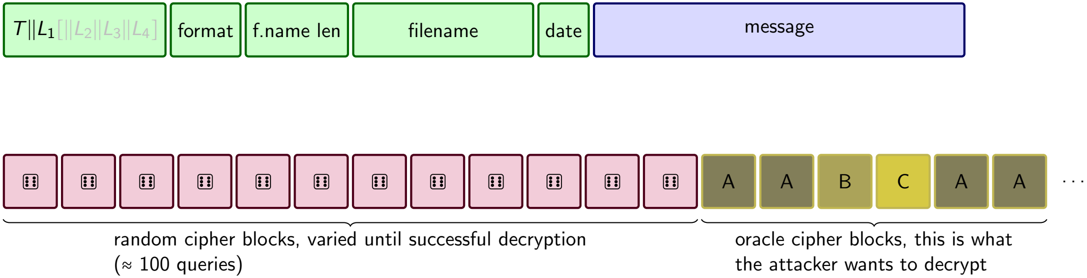
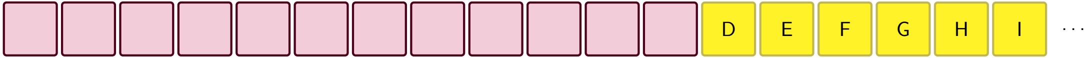
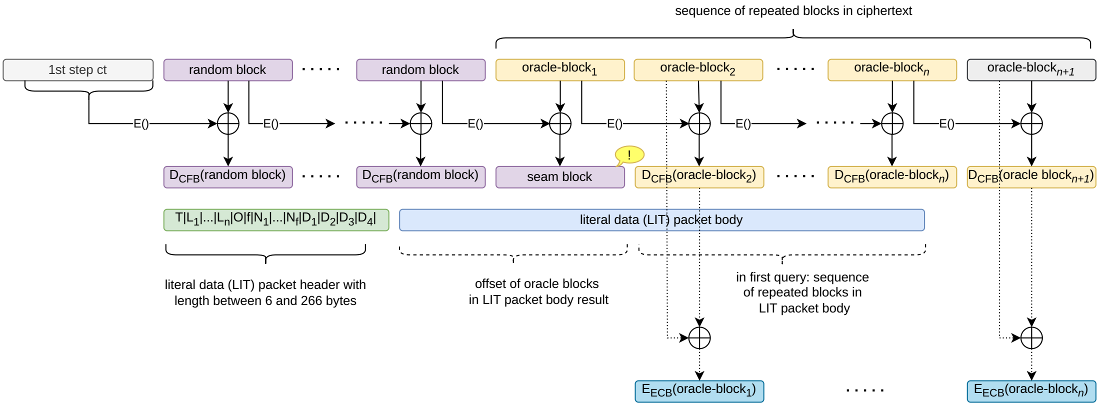


2n question: single query reusing the leading "random" blocks (offset now known):





sequence of repeated blocks in ciphertext
1st step ct
random block
random block
oracle-block$_1$
oracle-block$_2$
oracle-block$_n$
oracle-block$_{n+1}$
E()
E()
E()
E()
E()
E()
D_{CFB}(random block)
D_{CFB}(random block)
seam block
!
D_{CFB}(oracle-block$_2$)
D_{CFB}(oracle-block$_n$)
D_{CFB}(oracle block$_{n+1}$)
T|L$_1$|...|L$_n$|O|f|N$_1$|...|N$_f$|D$_1$|D$_2$|D$_3$|D$_4$|
literal data (LIT) packet body
literal data (LIT) packet header with length between 6 and 266 bytes
offset of oracle blocks in LIT packet body result
in first query: sequence of repeated blocks in LIT packet body
E_{ECB}(oracle-block$_1$)
E_{ECB}(oracle-block$_n$)

Summary of LibrePGP AEAD OCB Chunk Encryption Attack

- Exploit legacy SED Packet decryption to encrypt OCB chunk under same key
- Challenge: valid LIT packet must appear in decrypted data
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  - 1st oracle-question:
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OCB encryption

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- compute mask values:
  - $E_k([0]^{128})$ // 1st oracle-question
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- AES Key Wrap in NIST SP 800-38F, RFC 3394
- Key encryption with 64-bit “integrity check register”
- AES Key Wrap decryption / unwrap uses only $D_k()$
- CMS defines AES Key Wrap
  - Legacy encryption mode: CBC
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- Key encryption with 64-bit "integrity check register"
- AES Key Wrap decryption / unwrap uses only $D_k()$
- CMS defines AES Key Wrap
  - Legacy encryption mode: CBC
  - CBC decryption uses block $D_k()$
    - is oracle for AES Key Wrap decryption
- was observed already by Jager et al.

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```
Inputs:  Ciphertext, (n+1) 64-bit values {C0, C1, ..., Cn}, and
           Key, K (the KEK).
Outputs: Plaintext, n 64-bit values {P1, P2, ..., Pn}.

1) Initialize variables.
   Set A[s] = C[0] where s = 6n
   For i = 1 to n
       R[s][i] = C[i]
c2) Calculate the intermediate values.
   For t = s to 1
       A[t-1] = MSB(64, AES-1(K, ((A[t] ^ t) | R[t][n]))
       R[t-1][1] = LSB(64, AES-1(K, ((A[t]^t) | R[t][n]))
       For i = 2 to n
           R[t-1][i] = R[t][i-1]
3) Output the results.
   If A[0] is an appropriate initial value (see 2.2.3),
   Then
       For i = 1 to n
           P[i] = R[0][i]
   Else
       Return an error
```

Number of oracle-questions

- assume 128-bit key:
  - $n = 2$
  - loop iterations: $s = 6 \times 2 = 12$
  - 12 oracle queries
- full plaintext (wrapped key) recovery
- CBC padding oracle might be leveraged

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Summary

	Attacked AEAD mode & direction	oracle type	Exploited legacy mode	Nb questions	Nb queries
CMS	AES-CCM, AES-GCM decr (low entropy block)	inverse	CBC	1	1
	AES Key Wrap decr.	direct		≥ 12	≥ 12
LibrePGP	OCB encr	direct	CFB	2	≈ 100
	OCB decr (low entropy block)	inverse			

Conclusion

- Cryptographic design errors in CMS and LibrePGP
  - email probably not affected (efail countermeasures should prevent this)
  - Thunderbird seems not affected according to test
- Countermeasure
  - note: signatures don't protect the integrity of a message
  - CMS: yes, new RFC (key derivation)
    - new mechanism, must be implemented and used
  - LibrePGP:
    - disable SED decryption
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  - OpenPGP (RFC 9580):
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Thank you for your attention

Dr. Falko Strenzke
falko.strenzke@mtg.de
+49 6151 8000-24

MTG AG
www.mtg.de

AEAD in RFC 9580

```
           +-----------------------+    +--------------+
           | decrypted session key|    | salt value  |
           +-----------------------+    +-----+--------+       +------------------------+
                    |                         |                |  packet tag            |                 *****************
                    |                         v (SALT)         |  version number        |                 * RFC 9580 AEAD  *
                    | (IKM)  +--------------------+  (INFO)    |  cipher algo octet     |                 * key derivation *
                    +-------->|        HKDF        | <----------|  AEAD algo octet       |                 *****************
                             +--------------------+            |  chunk size            |
                                        |                      |                        |
                                        | M + N - 64 bits      +------------------------+
                                        v
                      +-----------------+---------------+
                      | leftmost M bits | N - 64 bits    |
                      +-----------------+---------------+
                              |                   |
                              |                   |
                              |                   |
                              |                   |
                              |                   |                +---------------------+
                              |                   +----------------| 64 bit chunk number |
                        (KEY) |     +-------------+                +---------------------+
                              |     | (INIT. VEC.                  +------------------+                     +--------------------------------------
                              v     v  / NONCE )         +---------| plaintext chunk | ...             ... | (empty str., AD incl. plaint. size)
                           +------------------+ <-----------+      +------------------+                     +--------------------------------------
                           | AEAD encrypt.    |
                           +------------------+ --------+
                                           ^             |         +------------------+ +------------+     +---------------------+
         +--------------------+            |             +--------> | ciphertext chunk | | auth. tag | ... | final auth. tag     |
         | packet tag         |            |                       +------------------+ +------------+     +---------------------+
         | version nr.        |            |                                                        ^
         | cipher algo octet  |            |                                                        |
         | AEAD algo octet    | (ADD. DATA) |                                                further ciphertext
         | chunk size         |-------------+                                                chunks with tags
         |                    |
         +--------------------+
```