CS458/CS558 Introduction to Computer Security

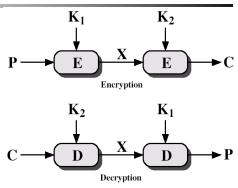
Double-DES?

- Could use 2 DES encrypts on each block
  $C = E(K2, E(K1, P))$
- Issue of reduction to single stage
  - Would it be possible to find a key K3 such that
    $E(K2, E(K1, P)) = E(K3, P)$
  - Answer: NO - proved in 1992

Double-DES?

- Meet-in-the-middle attack
  - Works whenever use a cipher twice
  - Based on the observation:

If $C = E(K2, E(K1, P))$,
then $X = E(K1,P) = D(K2,C)$



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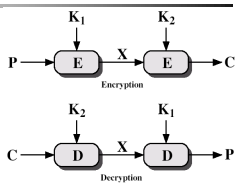
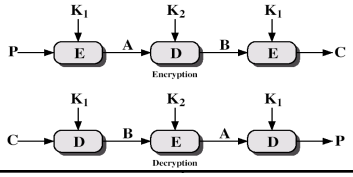


- Encrypt P for all 2^{56} keys. Store the result in a table and then sort the table.
- Decrypt C with 2^{56} keys and check the result against the table for a match.
- If a match occurs, then test the two resulting keys against some more known plaintext-ciphertext pairs.

Triple-DES with Two-Keys

- An obvious counter to the meet-in-the-middle attack is to use three stages of encryption with 3 different keys → requiring key length 168-bits
- Can use 2 keys with E-D-E sequence
  - $C = E(K1, D(K2, E(K1,P)))$
  - The only advantage of the use of decryption for the second stage is: if $K1=K2$ then can work with single DES



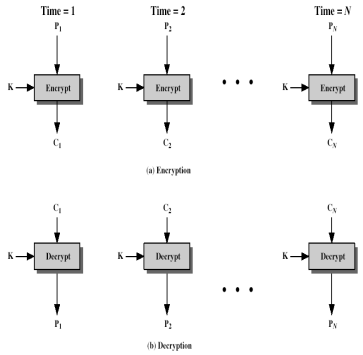
Triple-DES with Three-Keys

- No current known practical attacks
  - Brute-force: 2^{112}
  - Differential cryptanalysis: > 10^{52} plaintext-ciphertex pairs
- Can use Triple-DES with 3 Keys to avoid these
  - $C = E(K3, D(K2, E(K1, P)))$
- Has been adopted by some Internet applications, eg PGP, S/MIME

Section 6 Block Cipher Modes of Operation

Electronic Codebook Mode (ECB)

- The message is divided into blocks.
- Plaintext is handled one block at a time and each block is encrypted using the same key.

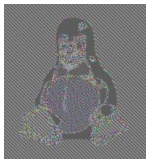


Advantages and Limitations of ECB

- Each block is encrypted independently of the other blocks
- Ideal for a short amount of data, e.g. transmit a DES key securely.
- For lengthy mesg, the ECB mode may not be secure.
  - The same n-bit block of plaintext, if it appears more than once in the mesg., always produces the same ciphertext - does not hide data patterns well.

Example: Disadvantage of ECB

- A pixel-map version of the image on the left was encrypted with ECB mode and with other modes.



Encrypted using ECB mode

Example: Disadvantage of ECB

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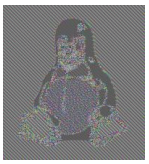
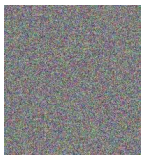
Original



Encrypted using ECB mode



Encrypted using other modes

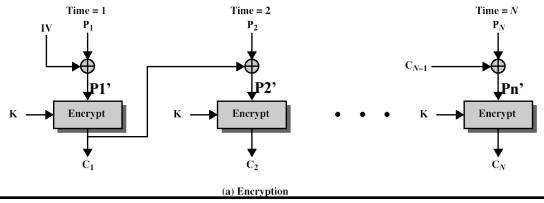
Advantages and Limitations of ECB

- Weakness is due to the encrypted message blocks being independent
  - Would like a technique in which the same plaintext block, if repeated, produces different ciphertext block.

Cipher Block Chaining (CBC)

- The input to the encryption algorithm is the XOR (⊕) of the current plaintext block and the preceding ciphertext block. ($A \oplus A = 0, 0 \oplus A = A$)
- Each ciphertext block is dependent on all plaintext blocks processed up to that point.

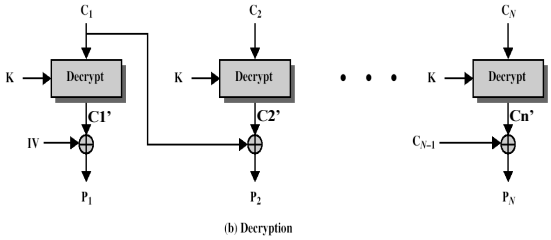
$C_j = E(K,[C_{j-1} \oplus P_j]), C_0 = IV$



Cipher Block Chaining (CBC)

- For decryption, each cipher block is passed through the decryption alg.. The result is XORed with the preceding ciphertext block to produce the plaintext.

$P_j = C_{j-1} \oplus D(K,C_j), C_0 = IV$



Cipher Block Chaining (CBC)

- How to prove that the decryption process is correct?

Encryption: $C_j = E(K,[C_{j-1} \oplus P_j]), C_0 = IV$

Decryption: $P_j = C_{j-1} \oplus D(K,C_j), C_0 = IV$

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Proof:

$A \oplus A = 0$

$0 \oplus A = A$

$$\begin{aligned} P_j &= C_{j-1} \oplus D(K,C_j) \\ &= C_{j-1} \oplus D(K, E(K,[C_{j-1} \oplus P_j])) \\ &= C_{j-1} \oplus C_{j-1} \oplus P_j \\ &= 0 \oplus P_j \\ &= P_j \end{aligned}$$

Message Padding

- At end of message must handle a possible last block, which is not as large as block size of cipher

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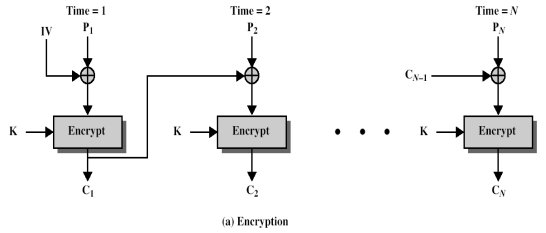
- At end of message must handle a possible last block, which is not as large as block size of cipher
  - Pad either with known non-data value (eg nulls)
  - Or pad last block along with count of pad size
    - eg. [b1 b2 b3 0 0 0 0 5] - 3 data bytes, 5 bytes pad+count

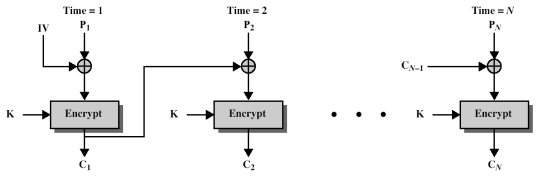
Advantages and Limitations of CBC

- Advantage:
  - Avalanche effect: A ciphertext block depends on all blocks before it - any change to one block affects all the following ciphertext blocks



Advantages and Limitations of CBC

- Disadvantage:
  - Encryption is sequential (i.e., cannot be parallelized)
  - Need Initialization Vector (IV)
    - Which must be known to sender & receiver
    - IV must either be a fixed value or be sent encrypted in ECB mode before rest of message

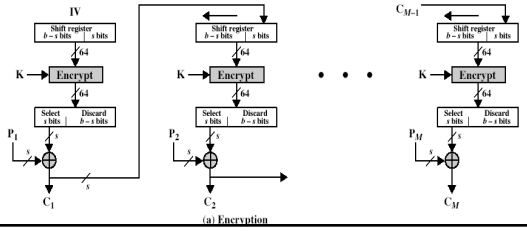


Cipher FeedBack Mode (CFB)

- When the data unit is smaller than the block size (e.g. data is only available a bit/byte at a time).
- Convert DES into a stream cipher and can be used to encrypt any number of bits
  - Property of stream cipher: the ciphertext is of the same length as the plaintext.
  - Eliminates the need to pad a mesg.

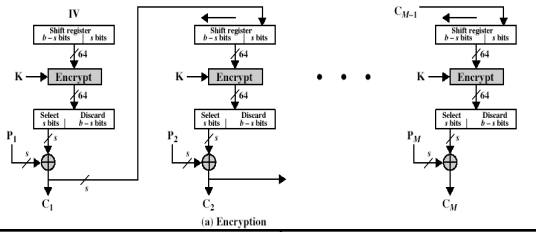
Cipher FeedBack Mode (CFB): Encryption

- E.g. The unit of transmission is s bits.
  - 64-bit shift register is initially set to some initialization vector (IV).
  - The leftmost s bits of the output of the encryption function is XORed with the first unit of plaintext P1 to produce C1.



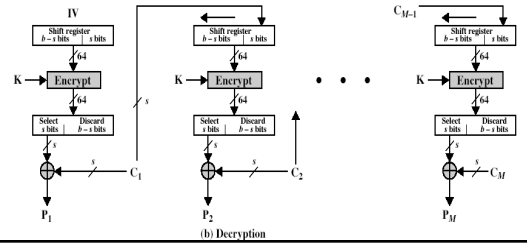
Cipher FeedBack Mode (CFB): Encryption

- E.g. the unit of transmission is s bits.
  - The contents of the shift register are shifted left by s bits and C1 is placed in the rightmost s bits of the shift register.
  - Continue this process until all plaintext units have been encrypted.



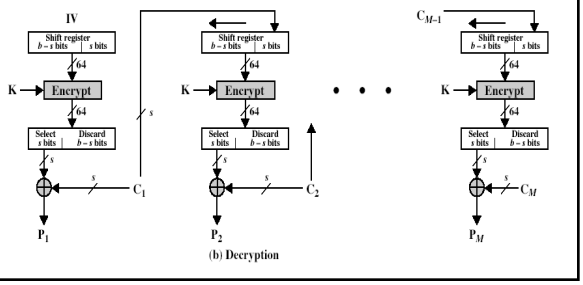
Cipher FeedBack Mode (CFB): Decryption

- E.g. the unit of transmission is s bits.
  - Same scheme as encryption, except that the received ciphertext unit is XORed with the output of the encryption function to produce the plaintext unit.



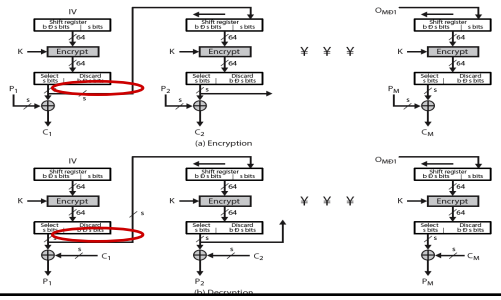
Cipher FeedBack Mode (CFB): Decryption

- Question: how to prove that the decryption is correct?



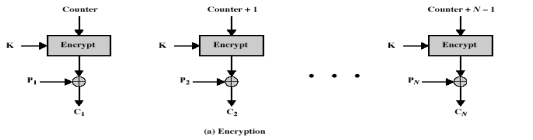
Output FeedBack (OFB)

- In OFB, the output of the encryption function is fed back to the shift register, while in CFB, the ciphertext unit is fed back to the register.



Counter (CTR)

- The counter is initialized to some value and then incremented by 1 for each subsequent block.
- The counter can be any simple function which produces a sequence which is guaranteed not to repeat for a long time



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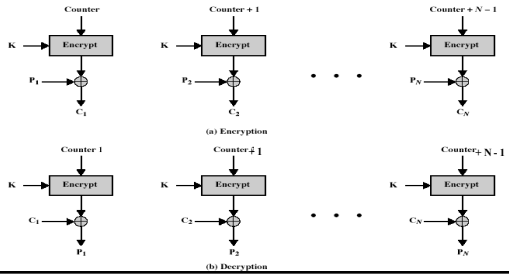

Advantages of CTR

- Efficiency
  - Encryption/decryption can be done in parallel on multiple blocks of plaintext or ciphertext
  - The execution of the encryption algorithm does not depend on the plaintext and ciphertext - can preprocess in advance.
  - Uses: high-speed network encryptions
- Random access to encrypted data blocks
- Provable security (good as other modes)