ECE 443/518 – Computer Cyber Security
Lecture 04 Block Ciphers, Modes of Operation

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Outline

Reading Assignment

- This lecture: UC 3, 4 except 4.3, 5.1 – 5.1.5
- Next lecture (9/3): Go Introduction
  - Please install VSCode and Go following the instructions on: `https://docs.microsoft.com/en-us/azure/developer/go/configure-visual-studio-code`

Outline

Block Ciphers

DES and AES

Modes of Operation

Overview

- Substitution cipher $\rightarrow$ OTP (unconditional security) $\rightarrow$ Stream ciphers (CSPRNG)
- How about cryptanalysis based on statistics?
- Simple substitution cipher maps letters to letters.
  - If there is only 26 letters, collecting a few thousands letters (e.g. allow each letter to appear 100 times on average) of ciphertext will reveal substantial amount of statistics.
- For plaintext and ciphertext as bytes, need a few tens of thousand of bytes so each byte appear 100 times on average.
- What about substition on larger blocks of bits?
  - E.g. 64-bit blocks: every block appears once on average in $2^{64} * 8$ bytes – seems longer than any practical message.
  - Need to study more to be a secure cipher.

Block Ciphers

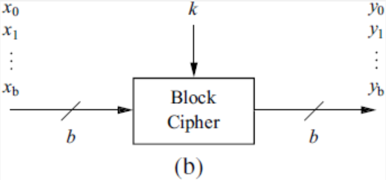


Fig.2 (Paar and Pelzl)

- Shared secret key k.
- Plaintext x as bit blocks of fixed size.
- Each block is encrypted via a block cipher and then concatenated into the ciphertext y.

Discussions

- We first focus on block encryption and decryption, i.e. both x and y are fixed-length bit strings.
  - Popular block lengths in bit: 64, 128, 256, ...
- A substitution cipher with 64-bit blocks need $(2^{64})!$ keys.
  - Generate random permutations if keys are chosen uniformly.
  - But not practical to store or transmit such keys.
- A block cipher only supports a subset of the permutations.
  - Still able to resit brute-force if the key space is large enough.
  - Key space depends on key sizes: 64-bit, 128-bit, ...
- With modern cryptanalysis, a strong block cipher should resist known-plaintext attack and beyond.
  - E.g. allow attackers to have access to $e_k()$ or $d_k()$ (without knowing k directly).

Outline

Block Ciphers

DES and AES

Modes of Operation

History of Data Encryption Standard (DES)

- 1972: NBS (now NIST) request for proposals for a standardized cipher in the USA
  - Motivated by demands for encryption in commercial applications.
  - Before this, cryptography and cryptanalysis are considered so crucial for national security that it had to be kept secret.
- 1974: proposal from IBM received
- 1977: NBS release Data Encryption Standard (FIPS PUB 46)
  - IBM cipher modified by NSA.
- 1990's: key space too small (2^{56}) to resist brute-force attack
  - Moore's law: computers become much more powerful
  - Triple DES proposed as a remedy
- 2001: NIST publish Advanced Encryption Standard (AES)
  - This is what you should use instead of DES as of now.

History of Advanced Encryption Standard (AES)

- 1997: NIST call for proposals
  - 128-bit block with 128, 192, and 256 bits keys
  - Efficiency in software and hardware
  - Open selection process
- 1998: 15 candidate algorithms, from several countries
- 1999: 5 finalist algorithms
  - Mars, RC6, Rijndael, Serpent, Twofish
- 2000: Rijndael announced as the winner
- 2001: Advanced Encryption Standard (AES) (FIPS PUB 197)
- 2003: NSA announced that it allows AES to encrypt classified documents up to the level SECRET, and up to the TOP SECRET level for 192 or 256-bit keys.

AES Encryption

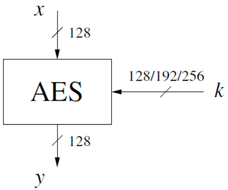


Fig. 4.1 AES input/output parameters

key lengths	# rounds = n_r
128 bit	10
192 bit	12
256 bit	14

Table 4.1

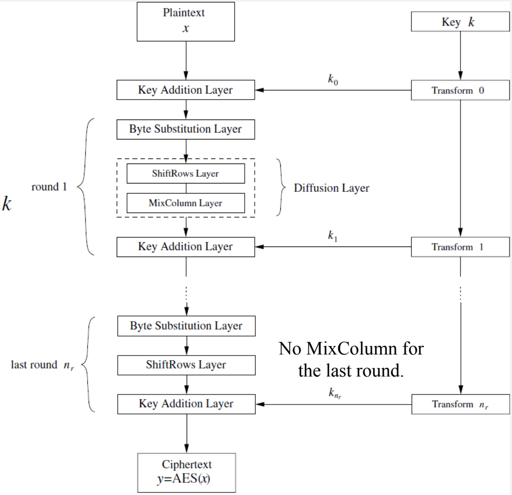


Fig. 4.2 AES encryption block diagram

(Paar and Pelzl)

- Round keys are always 128 bits.

AES Decryption

- Need to invert all layers.
  - Need extra resource though the basic structure is similar.
- Key schedule remains the same.
  - The order to apply subkeys are reversed.

AES Implementations

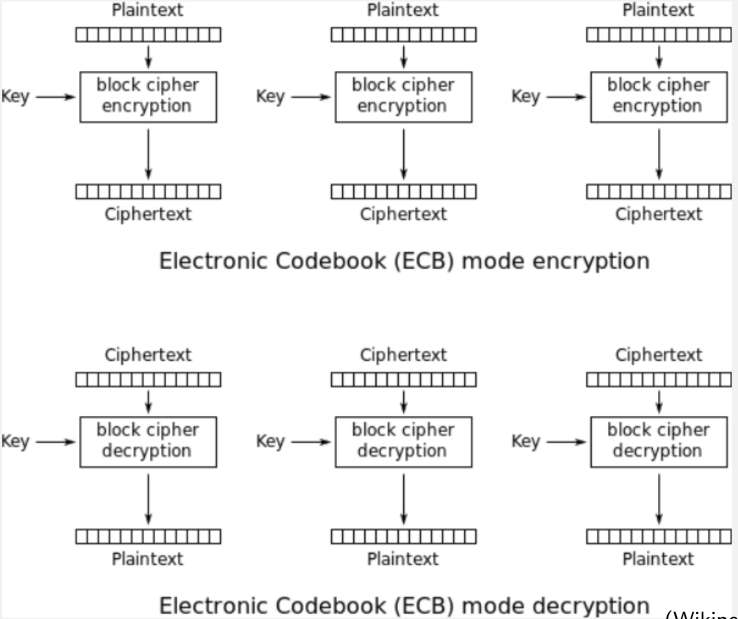
- A lot of literatures as references.
- Hardware
  - ASIC or FPGA
  - Optimized for throughput, e.g. for 400Gb/s and beyond networking, or power/area, e.g. for IoT devices.
- Software
  - Purely software: table lookup
  - Hardware acceleration: e.g. AES-NI for x86 CPUs
  - Don't implement it by yourself, use a library for correctness, security, and performance.

Outline

Should we apply AES as it is directly to messages?

- What if the message is longer than 128 bits?
- What if the message is not exactly 128 bits?
- Any other concerns?
- What about other block ciphers?

Electronic Code Book (ECB)

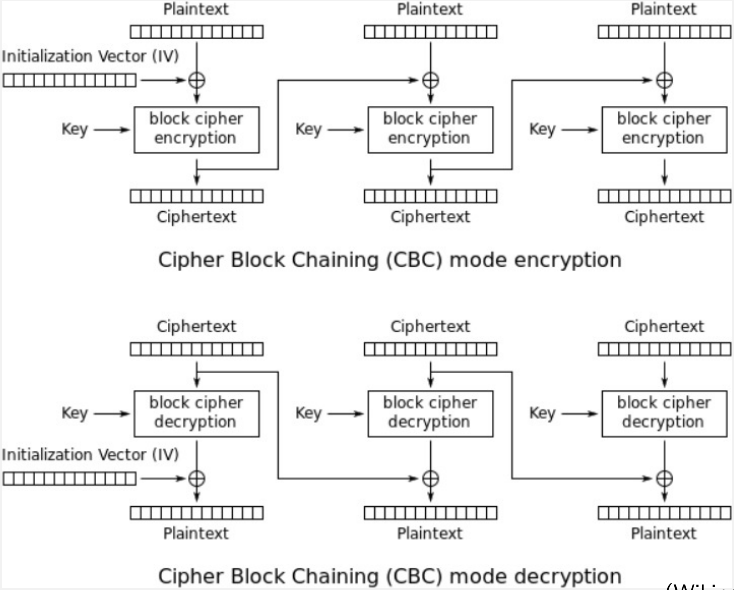


(Wikipedia)

Discussions

- A substitution cipher based on a block cipher like AES.
- Padding: when message size is not multiples of block size
  - Alice appends additional bits that Bob will identify.
  - E.g. 1 followed by necessary number of 0's.
- Oscar the passive adversary
  - Known-plaintext attack using padding.
  - Traffic analysis possible since same plaintext blocks always encrypts to same ciphertext blocks.
- Can be parallelized as long as the message is available.

Cipher Block Chaining (CBC)

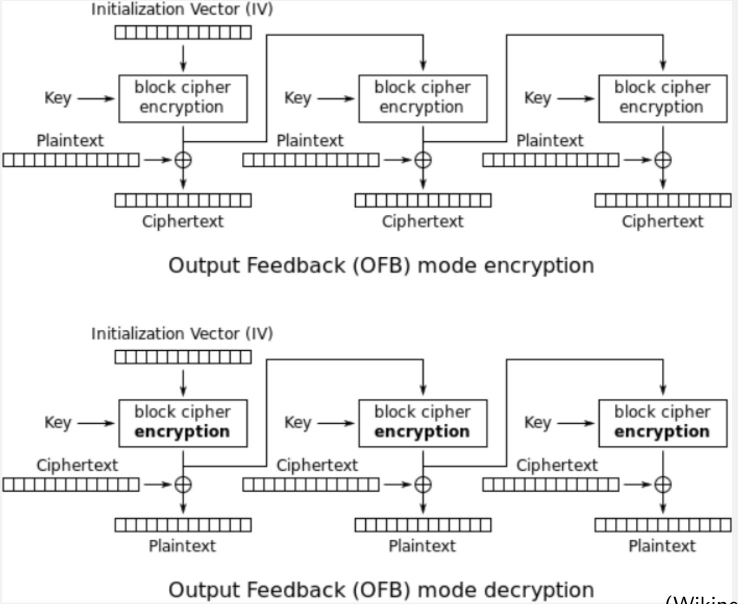


(Wikipedia)

Discussions

- "Randomize" plaintext blocks
  - Use previous ciphertext blocks.
  - Use an initialization vector (IV) for the first plaintext block.
- Choice of IV
  - Probabilistic encryption: different IVs results in different ciphertexts even if the plaintext and the key are the same.
  - A.k.a nonce – a number used only once.
  - Usually randomly chosen and transmitted before ciphertext.
    - Oscar will see it.
    - If that's a concern, Alice could just encrypt IV.
- Only decryption can be parallelized.

Output Feedback (OFB)

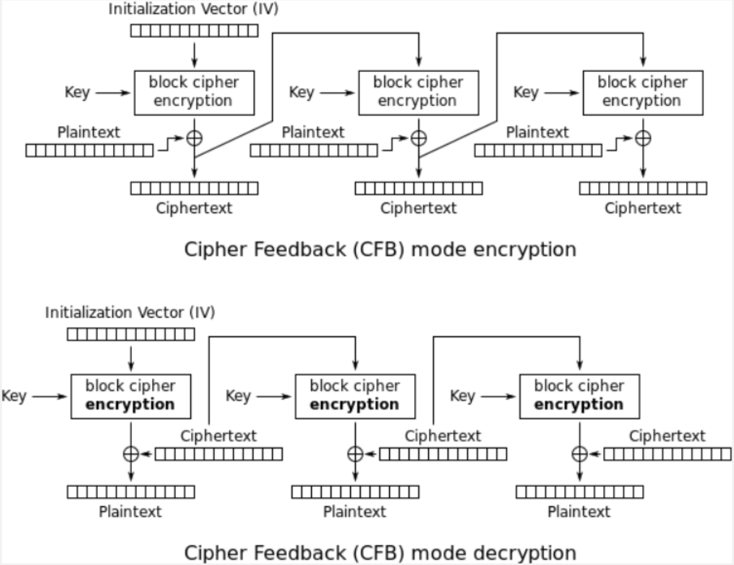


(Wikipedia)

Discussions

- A stream cipher based on a block cipher.
  - Random IV guarantees probabilistic encryption.
  - Resist known-plaintext attack as long as the block cipher can resist known-plaintext attack.
- Only need encryption from the block cipher.
  - No need to implement decryption – save hardware resource.
- Cannot be parallelized.
  - Key stream can be precomputed as long as storage permits.

Cipher Feedback (CFB)

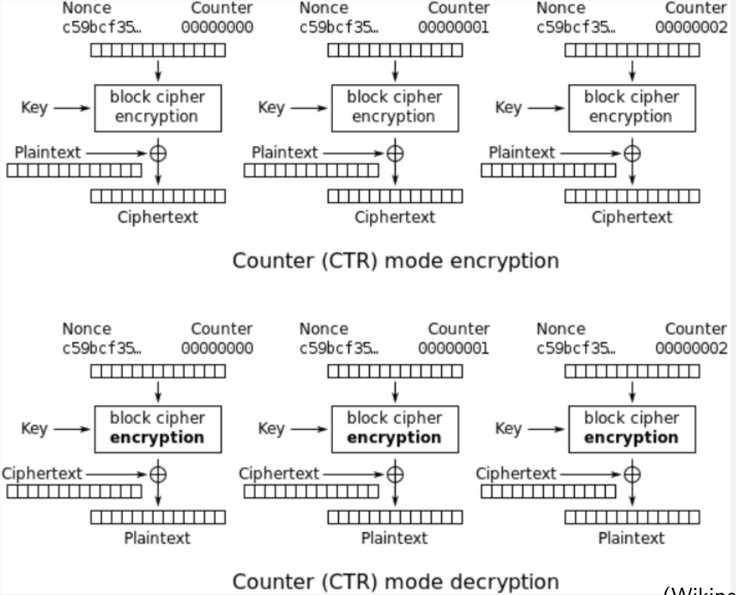


(Wikipedia)

Discussions

- An asynchronous stream cipher as the key stream depends on both key and previou ciphertext (and plaintext).
  - Otherwise very similar to OFB.
- Only need encryption from the block cipher.
- Decryption can be parallelized.

Counter Mode (CTR)



(Wikipedia)

Discussions

- A stream cipher that can be fully parallelized.
  - Resist known-plaintext attack as long as the block cipher can resist known-plaintext attack.
- Only need encryption as OFB and CFB.
- There is a limitation on message size for a given IV.
  - OFB also has limitation on message size, although it should be much longer.

Active Adversaries and Integrity

- We introduce passive adversaries to address confidentiality.
- For integrity, we could address it by active adversaries.
  - They can modify or even insert messages.
  - E.g. reorder/substitute/modify/create blocks.
- With the ability to manipulate ciphertext, active adversaries could even
  - Break confidentiality by side-channel attack.
  - Break higher level protocols by replay attack.
- None of the modes of operation can guarantee integrity.
  - No matter how secure the underlying block cipher is.
  - E.g. if reordering and substitution attacks are applied to ECB, all blocks will decrypt correctly but may mean things completely different when combined together.

Summary

- Block ciphers
- DES and AES
- Modes of operation