Stream Ciphers and Block Ciphers

2MMC10 Cryptology – Fall 2015

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Introduction

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- **Public-key crypto:**
  - Pair of keys: public key for encryption, private key for decryption.

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- **Symmetric-key crypto:**
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What are the respective advantages, disadvantages, use-cases..?

Introduction: Symmetric-Key Crypto

Stream Cipher vs. Block Cipher:

- **Idea of a stream cipher:** partition the text into small (e.g. 1bit) blocks; encoding of each block depends on the previous blocks.
  $\rightarrow$ A different "key" is generated for each block.

Introduction: Symmetric-Key Crypto

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- **Idea of a stream cipher:** partition the text into small (e.g. 1bit) blocks; encoding of each block depends on the previous blocks.
  $\rightarrow$ A different "key" is generated for each block.
- **Idea of a block cipher:** partition the text into "large" (e.g. 128bit) blocks; encode each block independently.
  $\rightarrow$ The same "key" is used for each block.

Introduction: Symmetric-Key Crypto

Stream Ciphers:

- symmetric-key cipher,
- state-driven: operates on arbitrary message length,
- commonly used stream ciphers: A5/1 and A5/2 (GSM), RC4 (SSL, WEP), eSTREAM Project.

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Encrypt the *message stream* with the *key stream* to a *cipher stream*.

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Given key K and initial state $c_{-1} \ldots c_{-t}$:

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An n-bit block cipher is a function $E : \{0,1\}^n \times \mathfrak{K} \to \{0,1\}^n$.
For each fixed key $K \in \mathfrak{K}$ the map

$$E_K : \{0,1\}^n \to \{0,1\}^n, M \mapsto E_K(M)$$

is invertible (bijective) with inverse $E_K^{-1} : \{0,1\}^n \to \{0,1\}^n$.

From Block Ciphers to Stream Ciphers

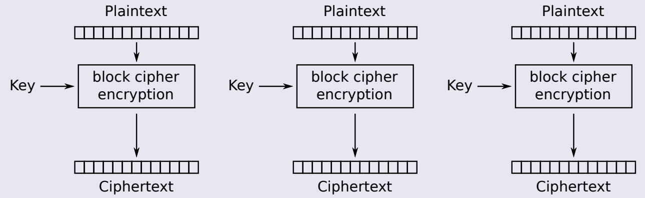
Modes of Operation:

- electronic codebook (ECB) mode,
- cipher-block chaining (CBC) mode,
- cipher feedback (CFB) mode,
- output feedback (OFB) mode,
- counter (CTR) mode.

Modes of Operation

Electronic Codebook (ECB) Mode:

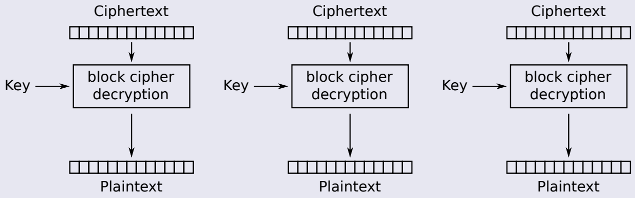
- Encryption:
  obtain ciphertext $C_1, \ldots, C_t$ as
  $C_i = E_K(M_i), \; i = 1 \ldots t$



Electronic Codebook (ECB) mode encryption

Electronic Codebook (ECB) Mode:

- Decryption:
  obtain plaintext $M_1, \ldots, M_t$ as
  $M_i = E_K^{-1}(C_i),\; i = 1 \ldots t$



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- Decryption:
  obtain plaintext $M_1, \ldots, M_t$ as

Plaintext Plaintext Plaintext

Electronic Codebook (ECB) mode decryption

Modes of Operation

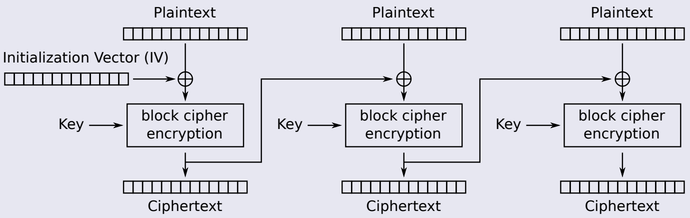
Properties of ECB:

- Considered insecure if applied to more than one block!
- Each block of ciphertext C_i depends only on message block M_i,
- encryption and decryption can be performed in parallel,
- allows random read access for decryption,
- requires padding of input to a multiple of block size.

Cipher-Block Chaining (CBC) Mode:

Use a (non-secret) initialization vector (IV) of length n bits.

- Encryption:
  obtain ciphertext $C_1, \ldots, C_t$ as
  $C_i = E_K(M_i \oplus C_{i-1}),\ i = 1 \ldots t,\ C_0 = IV$



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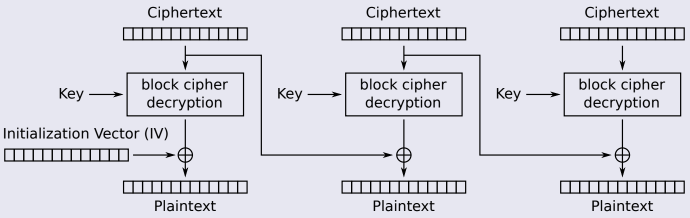

Cipher Block Chaining (CBC) mode decryption

Properties of CBC:

- The last ciphertext block C_t depends all message blocks $M_1, \ldots, M_t$,
- encryption can *not* be performed in parallel but decryption can,
- *no* random read access for decryption,
- requires padding of input to a multiple of block size.

Modes of Operation

Cipher Feedback (CFB) Mode:

Use a (non-secret) initialization vector (IV) of length n bits.

- Encryption:
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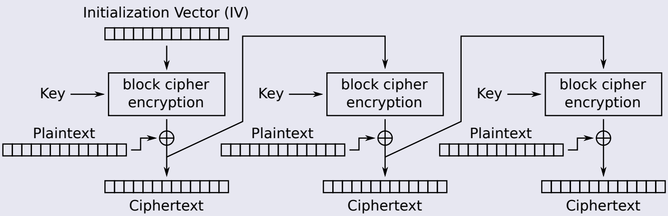

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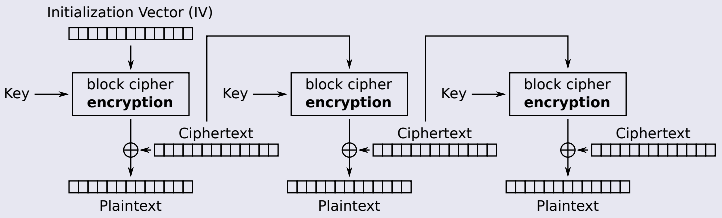

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Modes of Operation

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- The last ciphertext block C_t depends all message blocks $M_1, \ldots, M_i$,
- encryption can *not* be performed in parallel but decryption can,
- *no* random access for decryption,
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- Two messages encrypted with the same key must use a different IV!

Modes of Operation

Output Feedback (OFB) Mode:

Use a (non-secret) initialization vector (IV) of length n bits.

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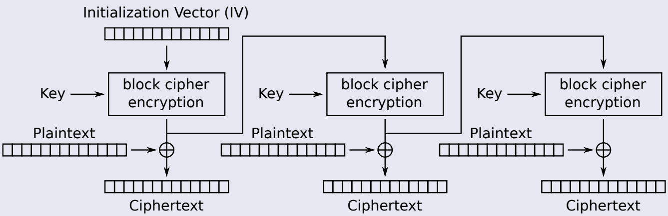

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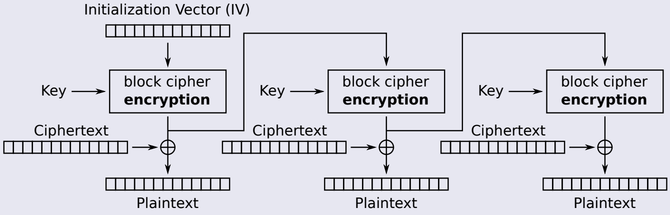

Output Feedback (OFB) mode decryption

Modes of Operation

Properties of OFB:

- Each block of ciphertext C_i depends only on message block M_i,
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Modes of Operation

Counter (CTR) Mode:

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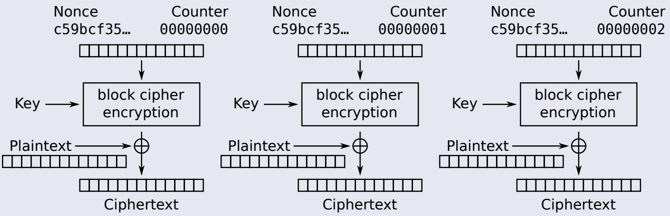

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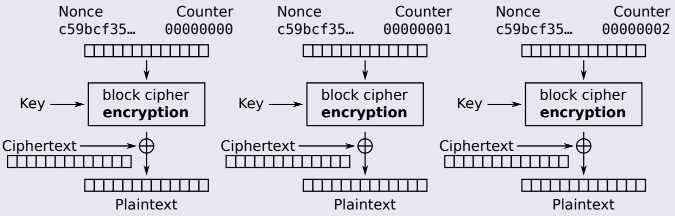

Counter (CTR) mode decryption

Properties of CTR:

- Each block of ciphertext C_i depends only on message block M_i,
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Most widely used modes are CBC and CTR.

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"NSA worked closely with IBM to strengthen the algorithm against all except brute force attacks and to strengthen substitution tables, called S-boxes. Conversely, NSA tried to convince IBM to reduce the length of the key from 64 to 48 bits. Ultimately they compromised on a 56-bit key."

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- **Nov. 2008:** The successor of COPACOBANA, the RIVYERA machine reduces the average time to less than one single day.

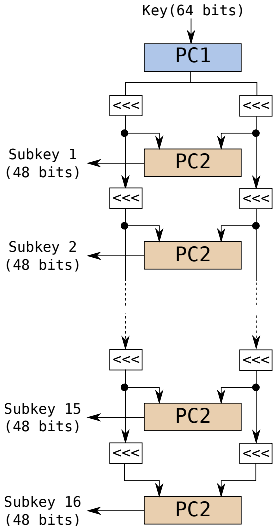
An Example for Block Ciphers: DES

Overall structure:

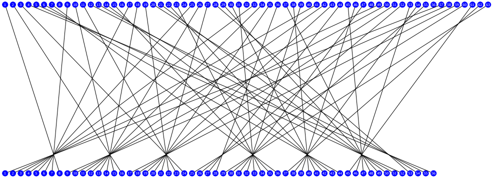
DES uses a 64-bit key with 8 parity bits, hence effectively 56-bits.

- Key schedule: Expand 56-bit key into 16 subkeys.
- Message processing: en-/decode message in 16 rounds.

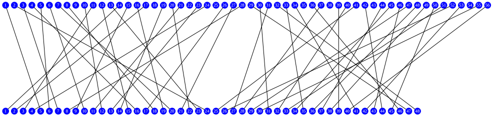
DES: Key Schedule



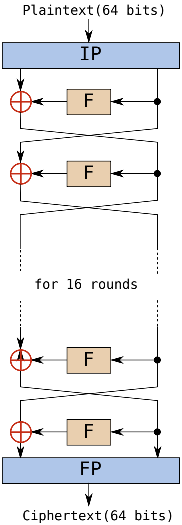
PC1: 64-bit $\longrightarrow 2 \times$ 28-bit



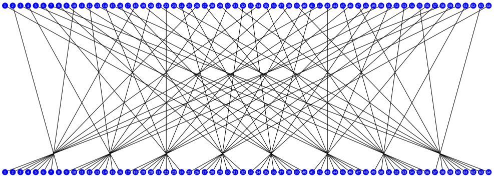
PC2: $2 \times$ 28-bit $\longrightarrow$ 48-bit



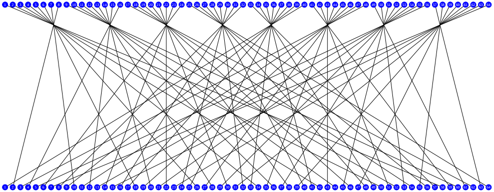
DES: Message En-/decoding



Initial permutation:



Final permutation:



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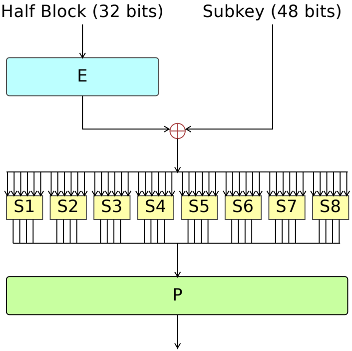
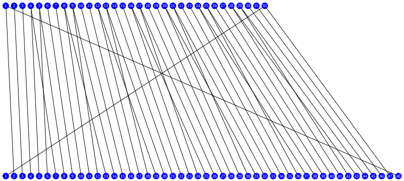
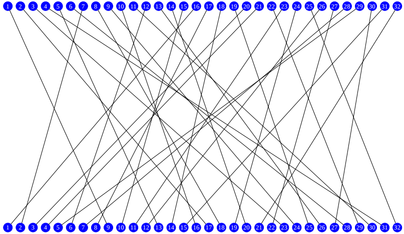


Expansion function:



Permutation:



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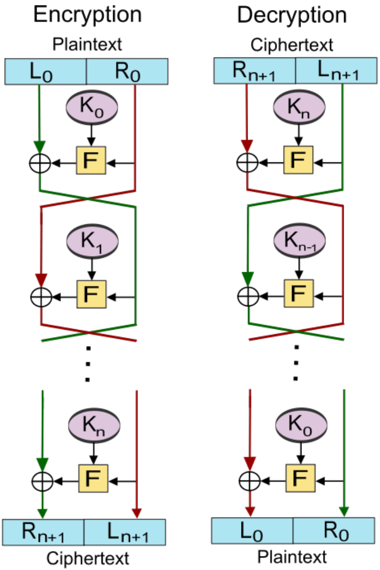

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Limited Security!

- Option 1 provides about 112-bits of security.
- Option 2 provides about 80-bits of security.
- Option 3 does *not* provide security.

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- **April 2000:** AES3 conference.
- **October 2nd, 2000:** NIST announces Rijndael as winner.

An Example for Block Ciphers: AES

Parameters:

- fixed block size of 128bit,
- variable key size (in bits): AES-128, AES-192, AES-256.

Animation:

http://poincare.matf.bg.ac.rs/~ezivkovm/nastava/rijndael_animacija.swf

Rijndael S-box:

For y in $GF(2^8) = GF(2)[x]/(x^8 + x^4 + x^3 + x + 1)$ compute

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} z_0 \\ z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \\ z_7 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 0 \end{bmatrix}$$

with $z = y^{-1}$.

An Example for Block Ciphers: AES

Rijndael S-box:

	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
00	63	7c	77	7b	f2	6b	6f	c5	30	01	67	2b	fe	d7	ab	76
10	ca	82	c9	7d	fa	59	47	f0	ad	d4	a2	af	9c	a4	72	c0
20	b7	fd	93	26	36	3f	f7	cc	34	a5	e5	f1	71	d8	31	15
30	04	c7	23	c3	18	96	05	9a	07	12	80	e2	eb	27	b2	75
40	09	83	2c	1a	1b	6e	5a	a0	52	3b	d6	b3	29	e3	2f	84
50	53	d1	00	ed	20	fc	b1	5b	6a	cb	be	39	4a	4c	58	cf
60	d0	ef	aa	fb	43	4d	33	85	45	f9	02	7f	50	3c	9f	a8
70	51	a3	40	8f	92	9d	38	f5	bc	b6	da	21	10	ff	f3	d2
80	cd	0c	13	ec	5f	97	44	17	c4	a7	7e	3d	64	5d	19	73
90	60	81	4f	dc	22	2a	90	88	46	ee	b8	14	de	5e	0b	db
a0	e0	32	3a	0a	49	06	24	5c	c2	d3	ac	62	91	95	e4	79
b0	e7	c8	37	6d	8d	d5	4e	a9	6c	56	f4	ea	65	7a	ae	08
c0	ba	78	25	2e	1c	a6	b4	c6	e8	dd	74	1f	4b	bd	8b	8a
d0	70	3e	b5	66	48	03	f6	0e	61	35	57	b9	86	c1	1d	9e
e0	e1	f8	98	11	69	d9	8e	94	9b	1e	87	e9	ce	55	28	df
f0	8c	a1	89	0d	bf	e6	42	68	41	99	2d	0f	b0	54	bb	16

An Example for Block Ciphers: AES

Optimizations for 32-bit Architectures:

- Lookup tables $T_0, \ldots, T_3$ combining all steps.

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High-Speed Implementations:

- NaCl: `http://nacl.cr.yp.to/features.html`
- `http://cryptojedi.org/crypto/index.shtml#aesbs`

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