CS405 – Computer Security

Lab04 – Block Ciphers

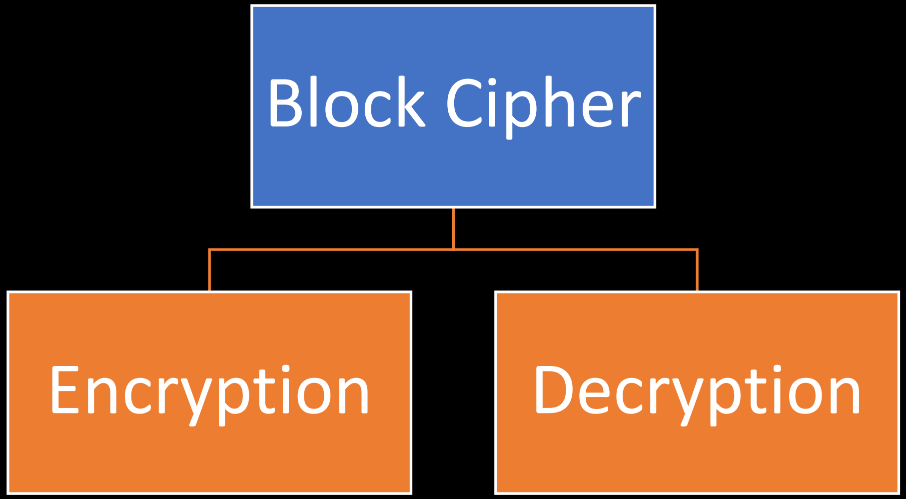
Content

Content
Introduction
Constructing Block Ciphers
Modes of Operation
Advanced Encryption Standard
Simon and Speck Ciphers

Introduction

What is a block cipher?

- A type of cipher that is combined with a mode of operation to process data in blocks.



$E(K, P) = C$ $\quad\quad$ $D(K, C) = P$

Introduction

- Secure block cipher = pseudorandom permutation (PRP).
  - PRP is a function to shuffle the input.
- Security objectives:
  - Cannot produce any ciphertext without a key
  - Cannot discover any pattern in plaintext/ciphertext
  - Indistinguishable from random permutation
  - Impossible to recover the secret key
  - Cannot recover plaintext from ciphertext without the key.

Introduction

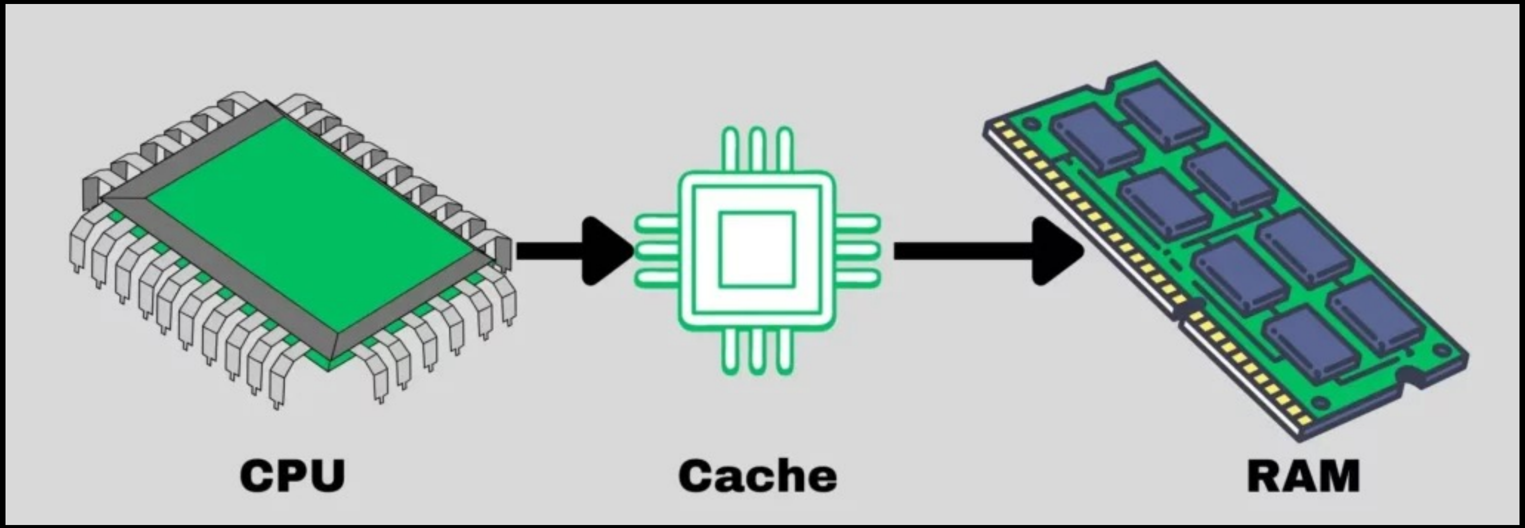
- A block cipher depends on two value:
  - **Block size:** the length of single unit processed by the PRP of the cipher.
  - **Key size:** the length of the key used in encryption and decryption.

- Most block ciphers have either 64-bit or 128-bit blocks
  - DES's blocks have 64 (2^6) bits
  - AES's blocks have 128 (2^7) bits.

- What is the ideal block size?

Introduction

- A block size should not be too large to minimize memory footprint.
- Blocks of 64, 128, 256 bits are short enough.
  - Such size can fit into the registers of most CPUs.
  - Allow efficient implementations.



Introduction

- While blocks shouldn't be too large, they also shouldn't be too small.
- Short block sizes make the cipher susceptible to codebook attacks.
    - An attack on a block cipher, where you generate every possible plaintext and consequently every possible ciphertext for a fixed key.
    - KPA model.

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	E0	F7	6	1A	23	3E	47	5C	6E	79	83	9B	A2	B2	CE	D8
1	F6	5	19	22	3D	46	5B	6D	78	82	9A	A1	B1	CD	D7	EF
2	4	18	21	3C	45	5A	6C	77	81	99	A0	B0	CC	D6	EE	F5
3	17	20	3B	44	59	6B	76	80	98	AF	BF	CB	D5	ED	F4	3
4	2F	3A	43	58	6A	75	8F	97	AE	BE	CA	D4	EC	F3	2	16
5	39	42	57	69	74	8E	96	AD	BD	C9	D3	EB	F2	1	15	2E
6	41	56	68	73	8D	95	AC	BC	C8	D2	EA	F1	0	14	2D	38
7	55	67	72	8C	94	AB	BB	C7	D1	E9	F0	F	13	2C	37	40
8	66	71	8B	93	AA	BA	C6	D0	E8	FF	E	12	2B	36	4F	54
9	70	8A	92	A9	B9	C5	DF	E7	FE	D	11	2A	35	4E	53	65
A	89	91	A8	B8	C4	DE	E6	FD	C	10	29	34	4D	52	64	7F
B	90	A7	B7	C3	DD	E5	FC	B	1F	28	33	4C	51	63	7E	88
C	A6	B6	C2	DC	E4	FB	A	1E	27	32	4B	50	62	7D	87	9F
D	B5	C1	DB	E3	FA	9	1D	26	31	4A	5F	61	7C	86	9E	A5
E	C0	DA	E2	F9	8	1C	25	30	49	5E	60	7B	85	9D	A4	B4
F	D9	E1	F8	7	1B	24	3F	48	5D	6F	7A	84	9C	A3	B3	CF

Content

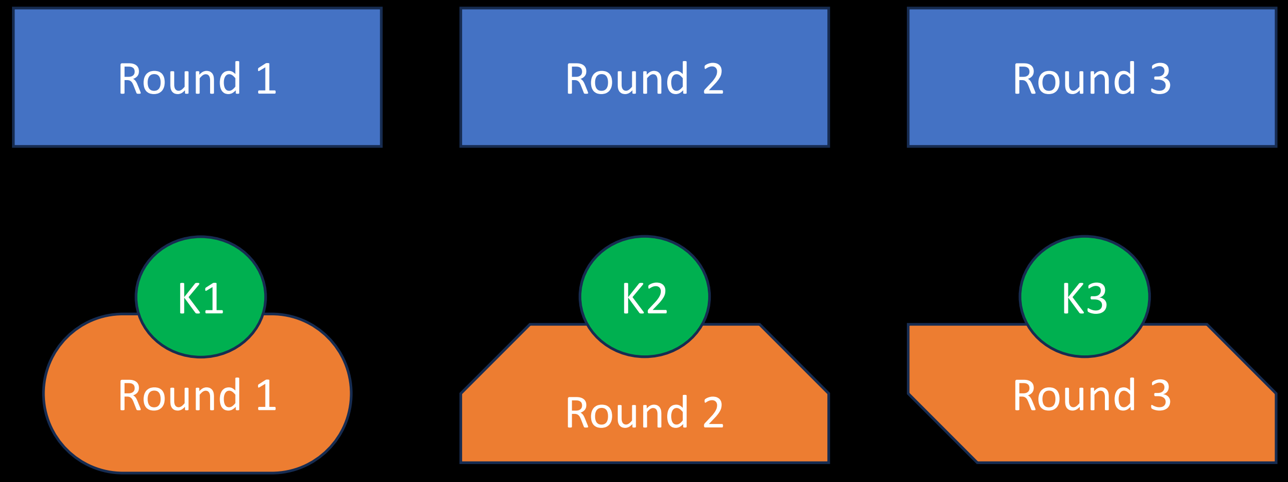
Content
Introduction
Constructing Block Ciphers
Modes of Operation
Advanced Encryption Standard
Simon and Speck Ciphers

Constructing Block Ciphers

- Encryption: performing a sequence of rounds.
  - Each round performs weak operations on its own.
  - More rounds → strong cipher.
- A block cipher with three rounds: $\boldsymbol{R_3}\left(\boldsymbol{R_2}\left(\boldsymbol{R_1}(P)\right)\right)$
- To decrypt, each round should have an inverse: $\boldsymbol{iR_1}\left(\boldsymbol{iR_2}\left(\boldsymbol{iR_3}(C)\right)\right)$

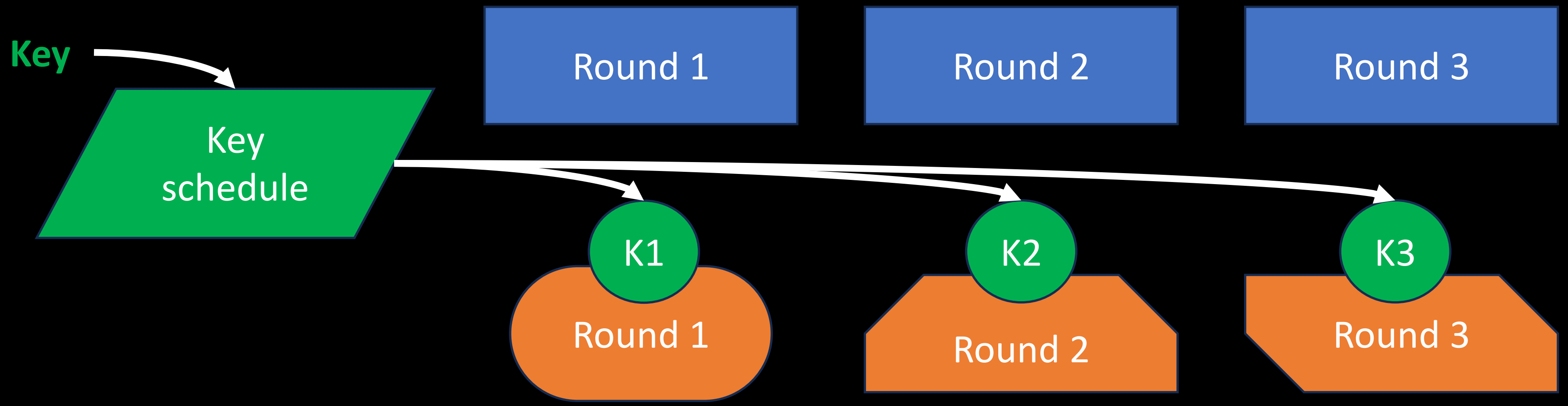
Constructing Block Ciphers

- The round functions are identical, but they are parameterized by a value called the *round key*.
  - Different keys → different rounds.



Constructing Block Ciphers

- The round functions are identical, but they are parameterized by a value called the *round key*.
  - Different keys → different rounds.
- Round keys are derived from the main key, K, using a key schedule algorithm.



Constructing Block Ciphers

- Identical rounds → *slide attack*.
- Slide attacks look for two plaintext/ciphertext pairs (P1, C1) and (P2, C2), where P2 = **R**(P1) if **R** is the cipher's round.
  - Knowing the input/output of a single round helps recovering the key.

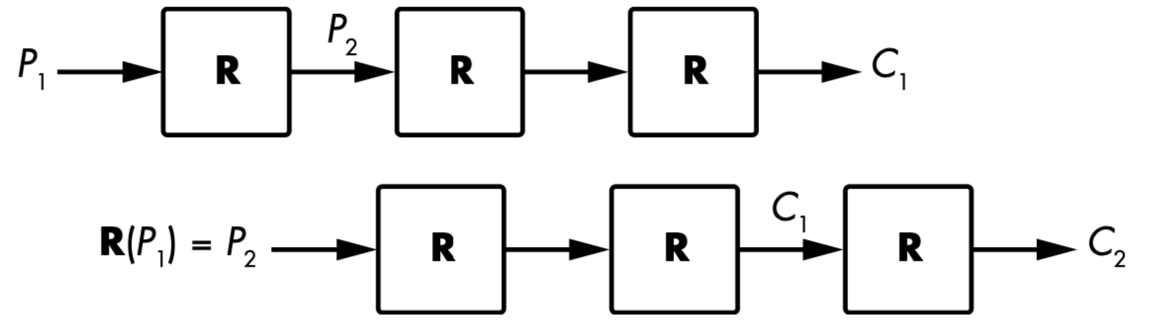
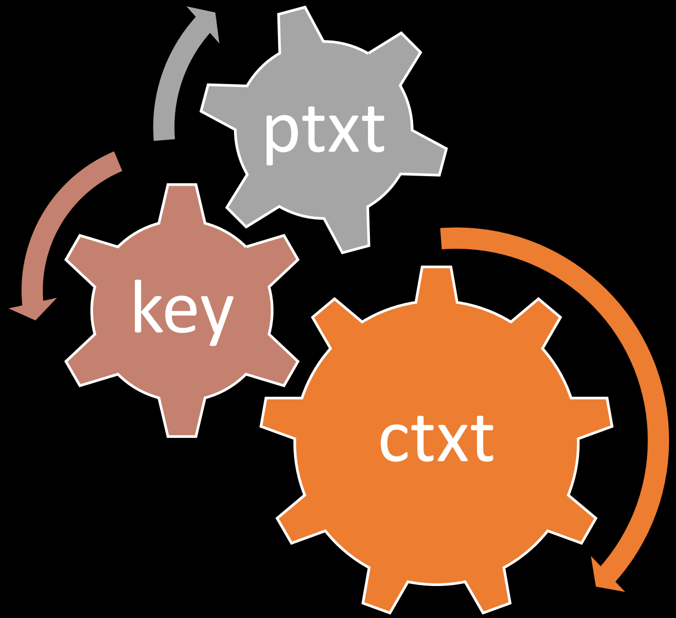


Figure 4-1: The principle of the slide attack, against block ciphers with identical rounds

https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=62e452197f49c29e499342d978e562999c09cbbf

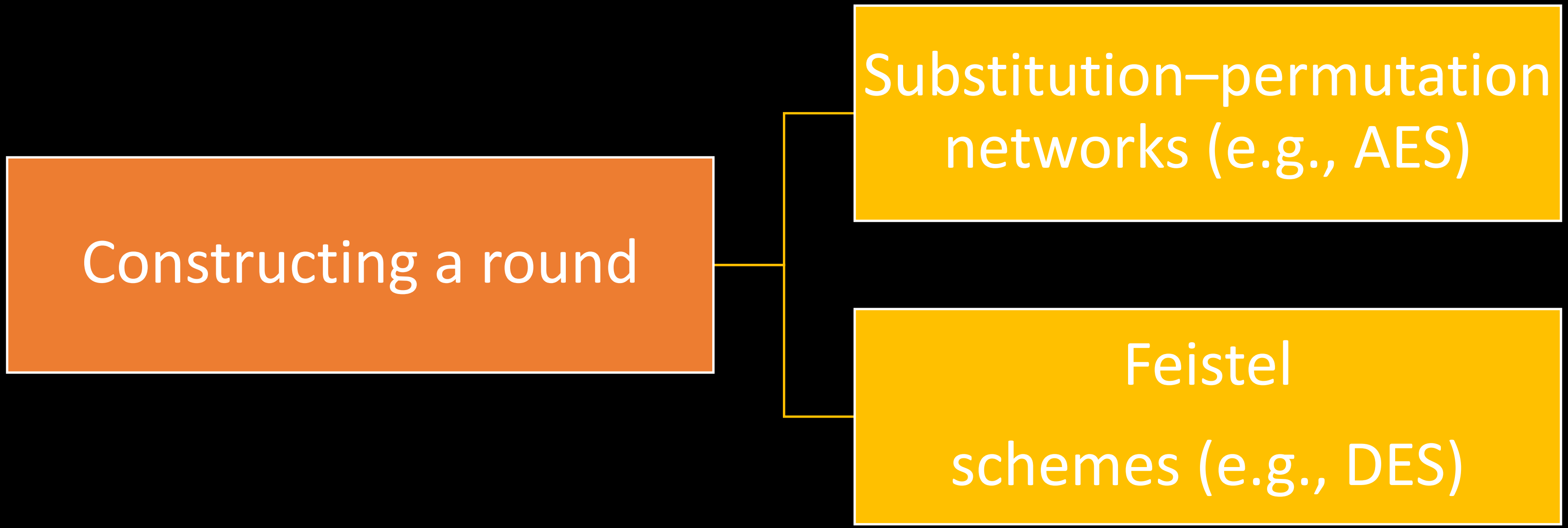
Constructing Block Ciphers

- Properties of block ciphers:
  - **Confusion**: the input (plaintext and key) undergoes complex transformations.
  - **Diffusion**: the transformations depend equally on all bits of the input.
    - Changing 1 bit plaintext changes half of the ciphertext



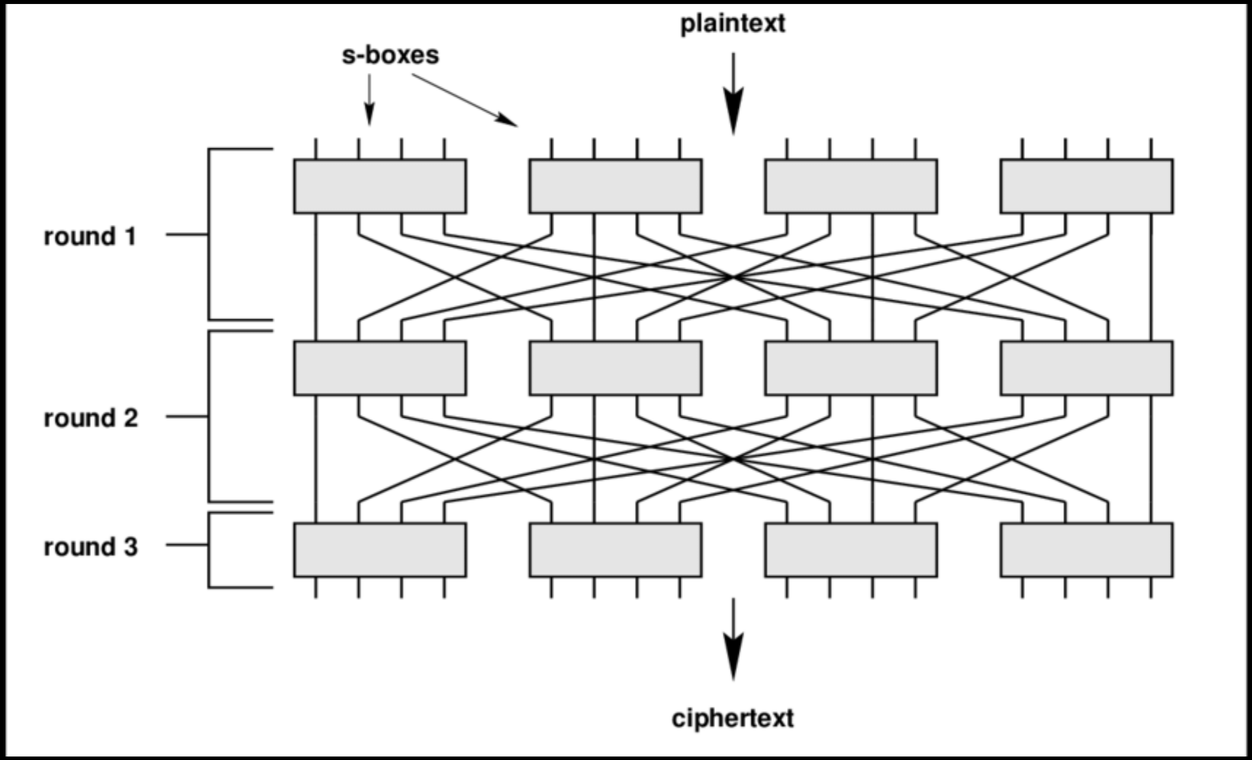
Constructing Block Ciphers

- Two techniques to construct rounds



Constructing Block Ciphers

- A Substitution-Permutation Network (SPN):
  - takes in blocks of plaintext and keys,
  - applies substitution layers (S-boxes) and permutation layers.



Constructing Block Ciphers

- Substitution boxes are lookup tables that transform chunks of 4 or 8 bits.
  - Example, DES S-Box:

0	1	0	1	0

Column

Row

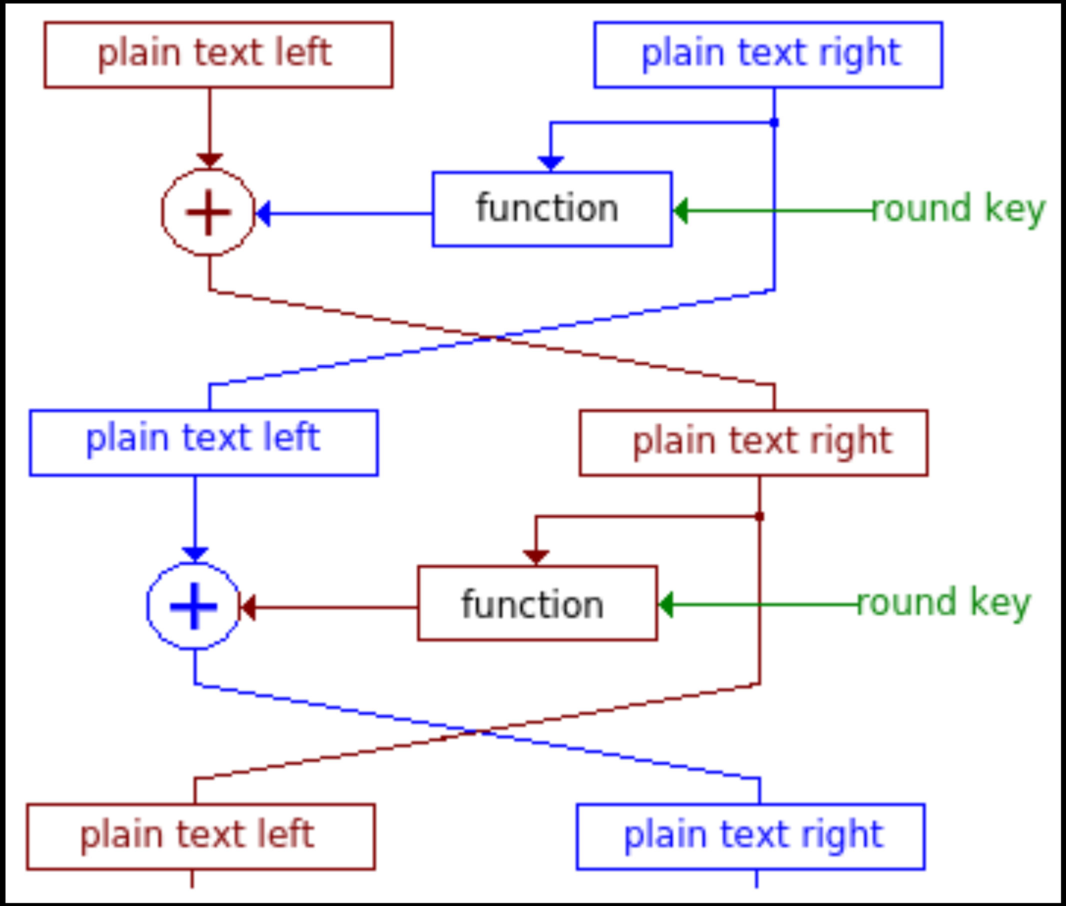
	x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	$S(x)$	10	3	11	22	17	4	1	8	12	28	23	18	26	6	31	20
1		15	24	29	13	14	19	30	5	25	27	7	0	16	21	2	9

5-bit Input	Row	Column	Mapping Value	5-bit Output
01010	(0) 0	(1010) 10	23 (10111)	10111

- S-boxes must be designed carefully:
  - Cryptographically secure
  - No statistical bias

Constructing Block Ciphers

- Feistel Schemes works as follows:
  1. Split the ciphertext block into two halves, L and R.
  2. Set L to L $\oplus$ F(R), where F is a round function.
  3. Swap the values of L and R.
  4. Go to step 2 and repeat a certain number of times.
  5. Merge L and R into the one output block.



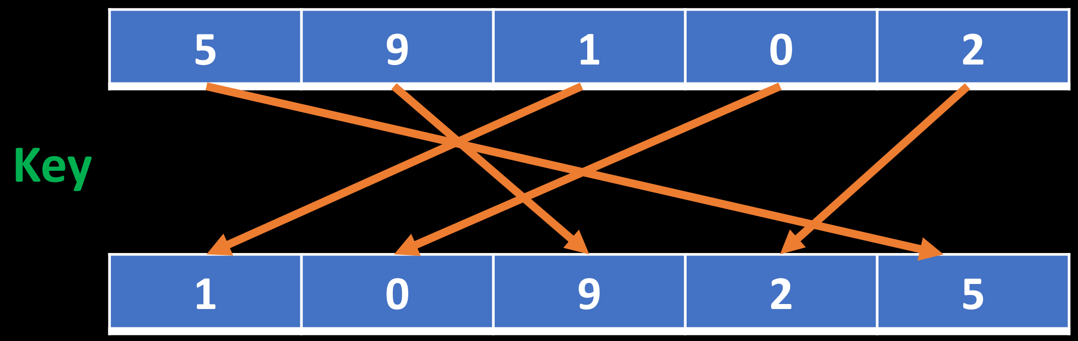
Constructing Block Ciphers

- In a Feistel scheme, the F function can be:
  - Pseudorandom permutation (PRP)
  - Pseudorandom function (PRF)

Property	Pseudorandom Permutation (PRP)	Pseudorandom Function (PRF)
Output	Pseudorandom output	
Mapping	Shuffles the data and creates a unique mapping. Must be unique. E.g., PRP(0xAB) $\neq$ PRP(0xCD)	Transforms the input based on random function. Doesn't have to be unique. E.g., PRF(0xAB) = PRF(0xCD)
Invertibility	Always invertible with respect to the key.	Not necessarily invertible.
Key	Both use a secret key to transform the plaintext	

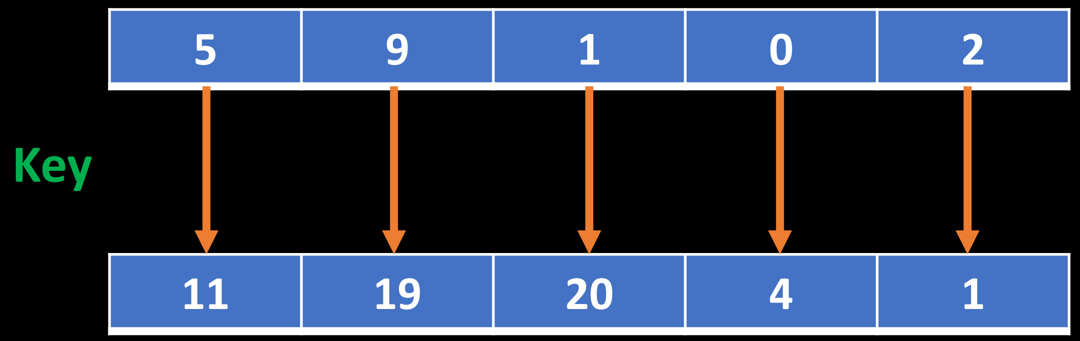
Constructing Block Ciphers

- In a Feistel scheme, the F function can be:
  - Pseudorandom permutation (PRP) – bijective.



Constructing Block Ciphers

- In a Feistel scheme, the F function can be:
  - Pseudorandom function (PRF)

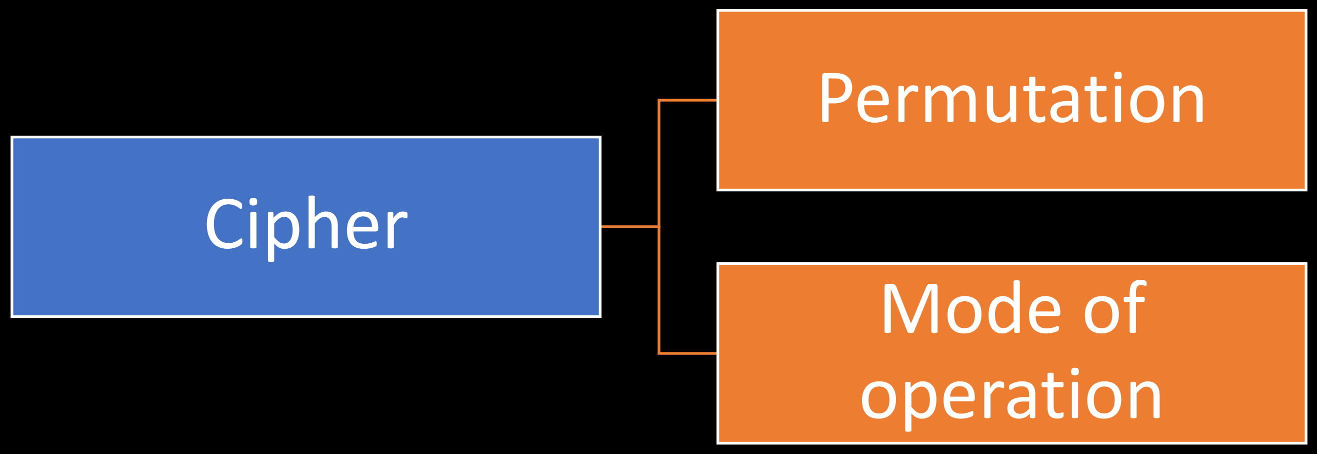


Content

Content
Introduction
Constructing Block Ciphers
Modes of Operation
Advanced Encryption Standard
Simon and Speck Ciphers

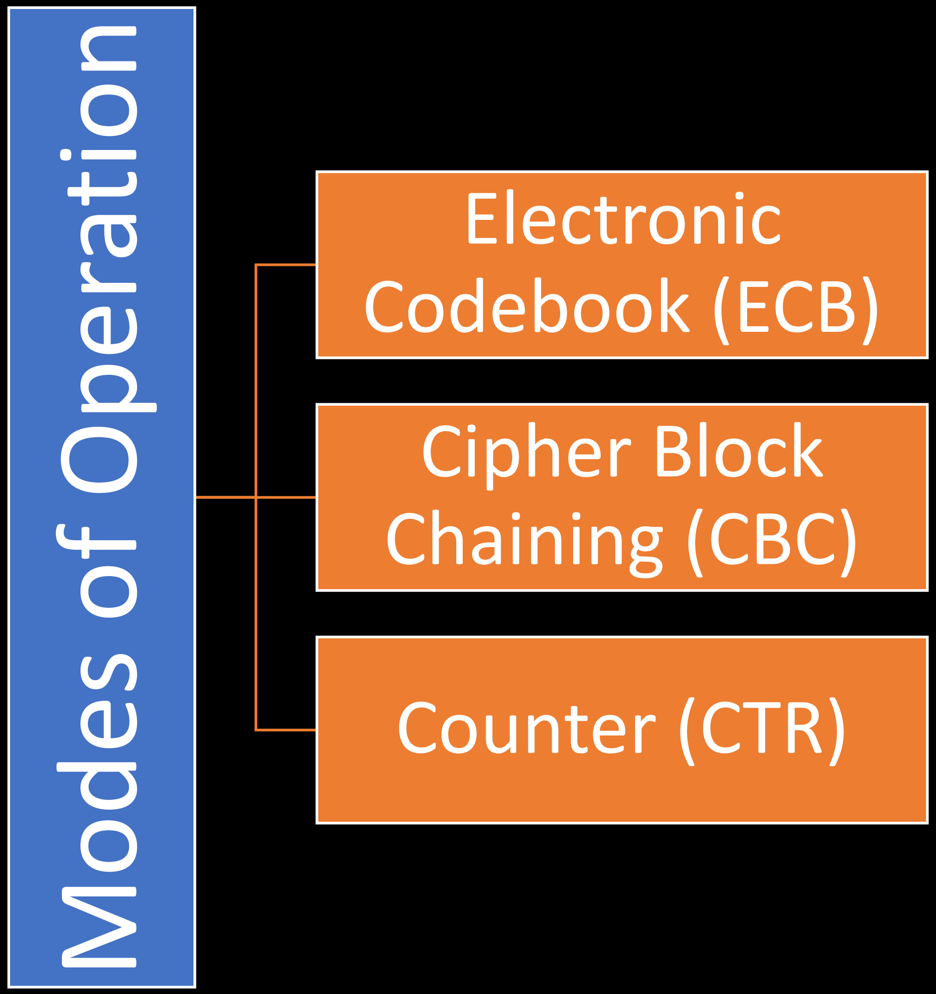
Modes of Operation

- Encryption schemes combine a permutation with a mode of operation to handle messages of any length.



Modes of Operation

- Basic modes of operation



Modes of Operation – ECB

- ECB is the simplest, the dumpiest.

1. Takes plaintext blocks $P_1, P_2, \ldots, P_N$
2. Processes each independently by computing $C_1 = E(K, P_1), C_2 = E(K, P_2)$

- Insecure mode.

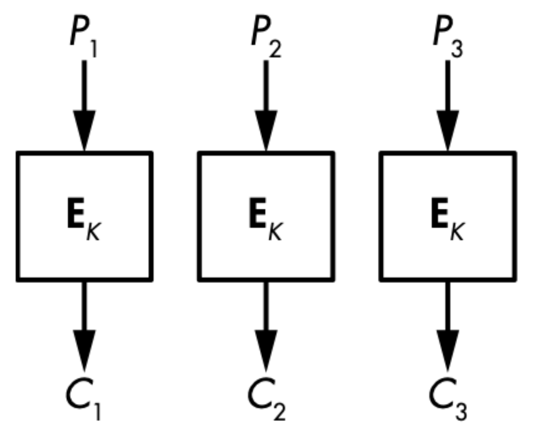


Figure 4-6: The ECB mode

Modes of Operation – ECB

- ECB is not semantically secure
    - **Identical plaintext** blocks results in **identical ciphertext** blocks.

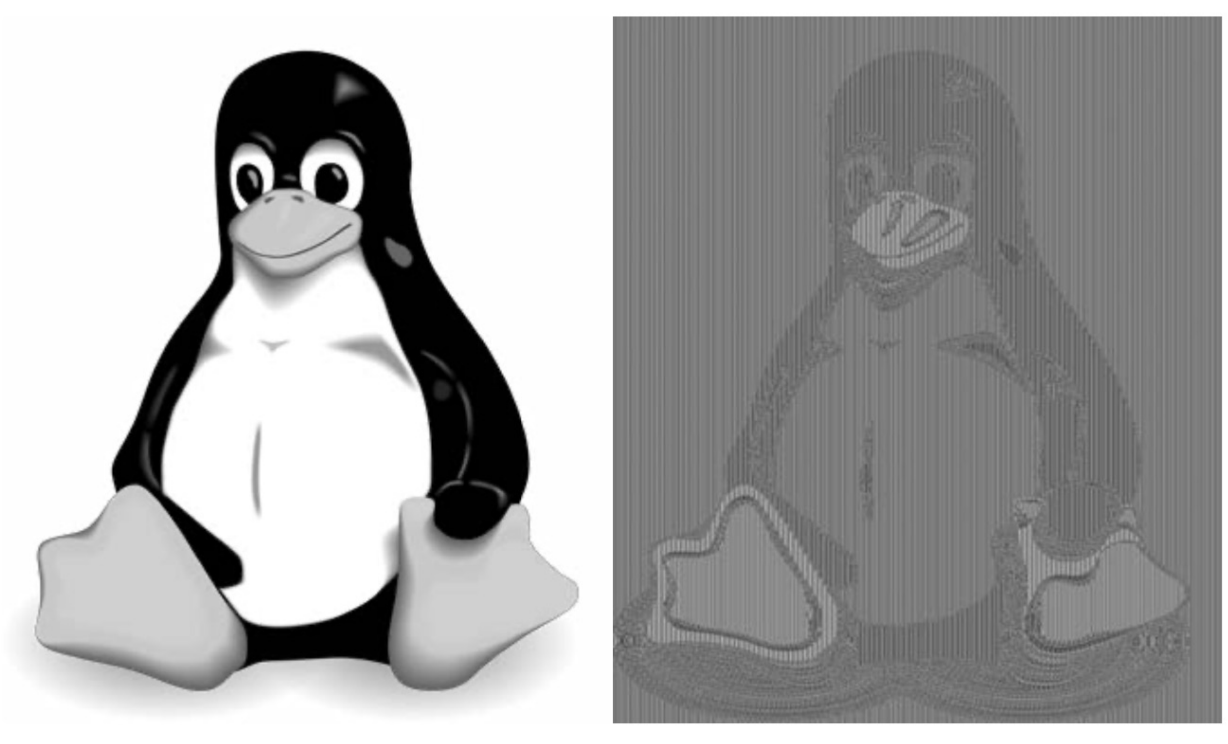


Figure 4-7: The original image (left) and the ECB-encrypted image (right)

Modes of Operation – CBC

- CBC makes each ciphertext block dependent on all the previous blocks.
  - Ensures that identical plaintext blocks won't be identical ciphertext blocks.

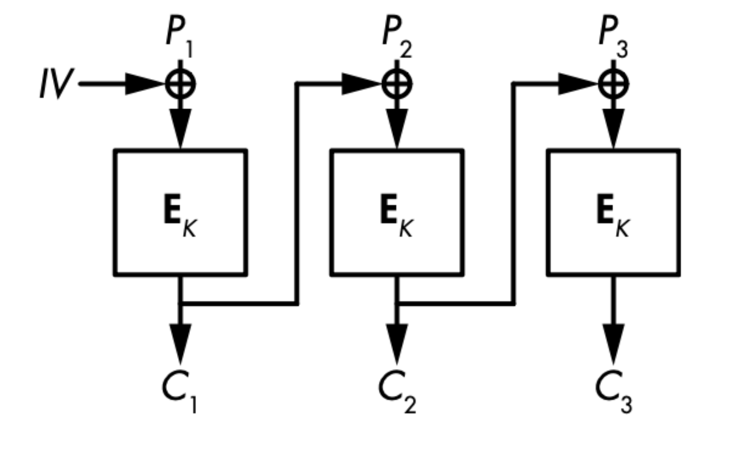
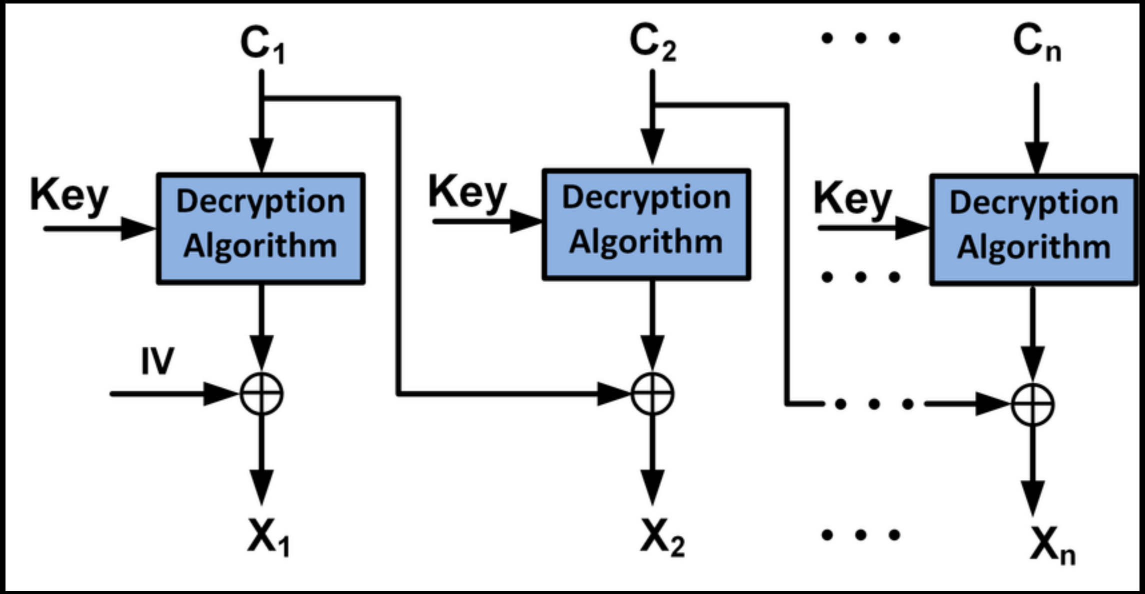


Figure 4-8: The CBC mode

- $C_i = E(K, P_i \oplus C_{i-1})$
- When encrypting the first block, P_1, CBC takes a random initial value (IV)

Modes of Operation – CBC

- Decryption needs to know the IV used to encrypt, so it's sent along with the ciphertext, in the clear.
- Decryption can be parallelized.



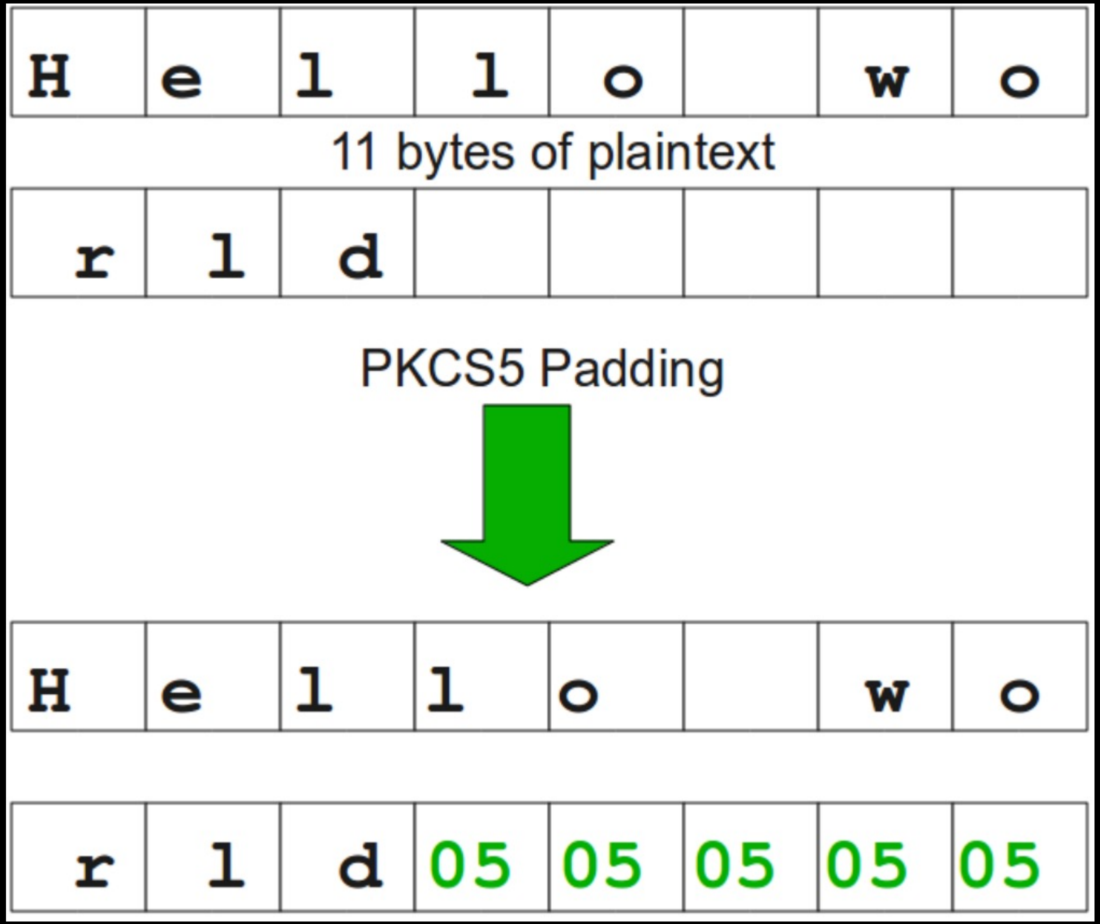
Modes of Operation – CBC

- Two ways to align the plaintext to the block size in CBC mode.

Padding	Ciphertext stealing
• Add extra bytes to fill the last block • $01, 02\ 02, 03\ 03\ 03, \dots,$ fifteen $0f$ • If ptxt aligns to blocks, pad with sixteen 10 • Vulnerable to padding oracle attack • Increase the ciphertext size	• Extend the last block with bits from the previous ciphertext block, and then encrypts the resulting block. • No increase in ctxt size • Not vulnerable to padding oracle attack • NIST has three implementation variants of the CBC-CS mode

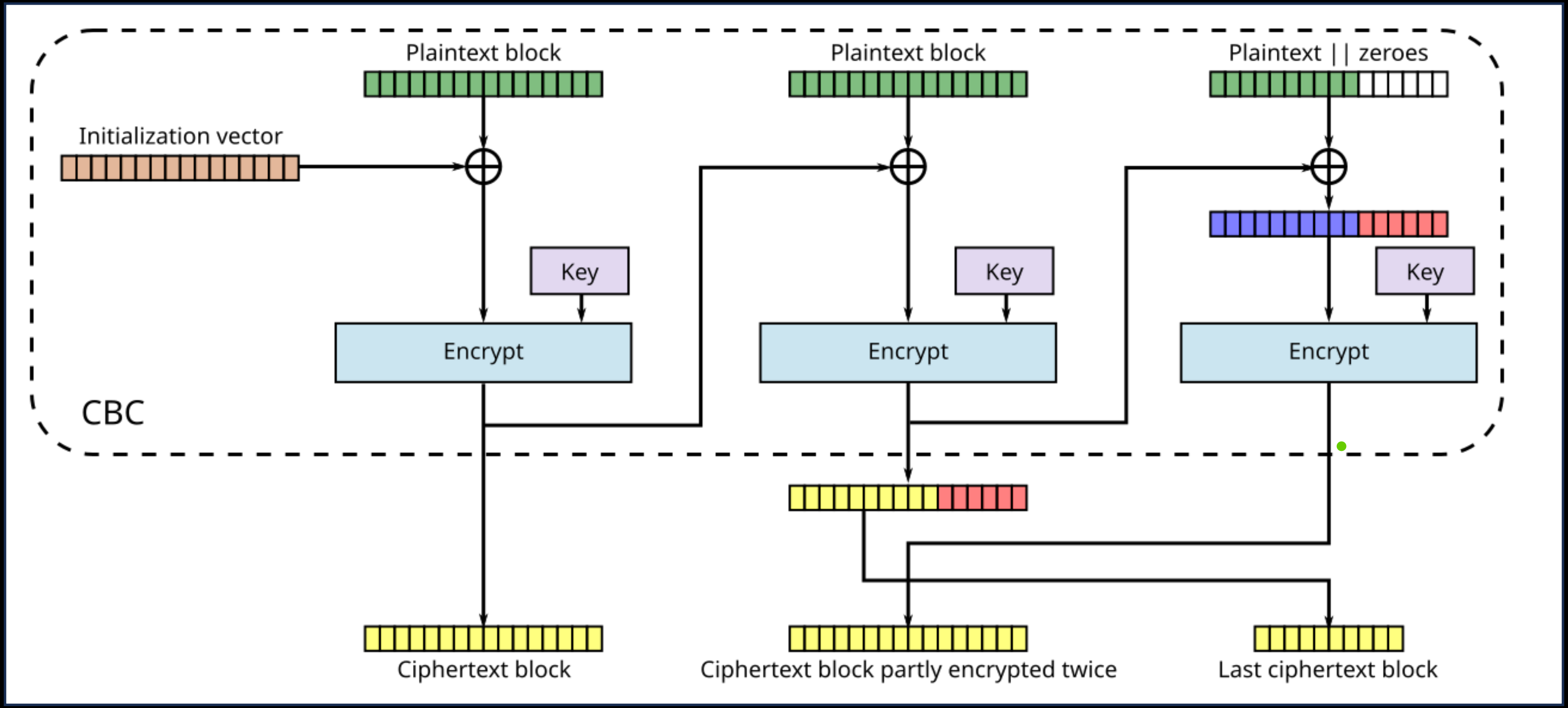
Modes of Operation – CBC

- Padding



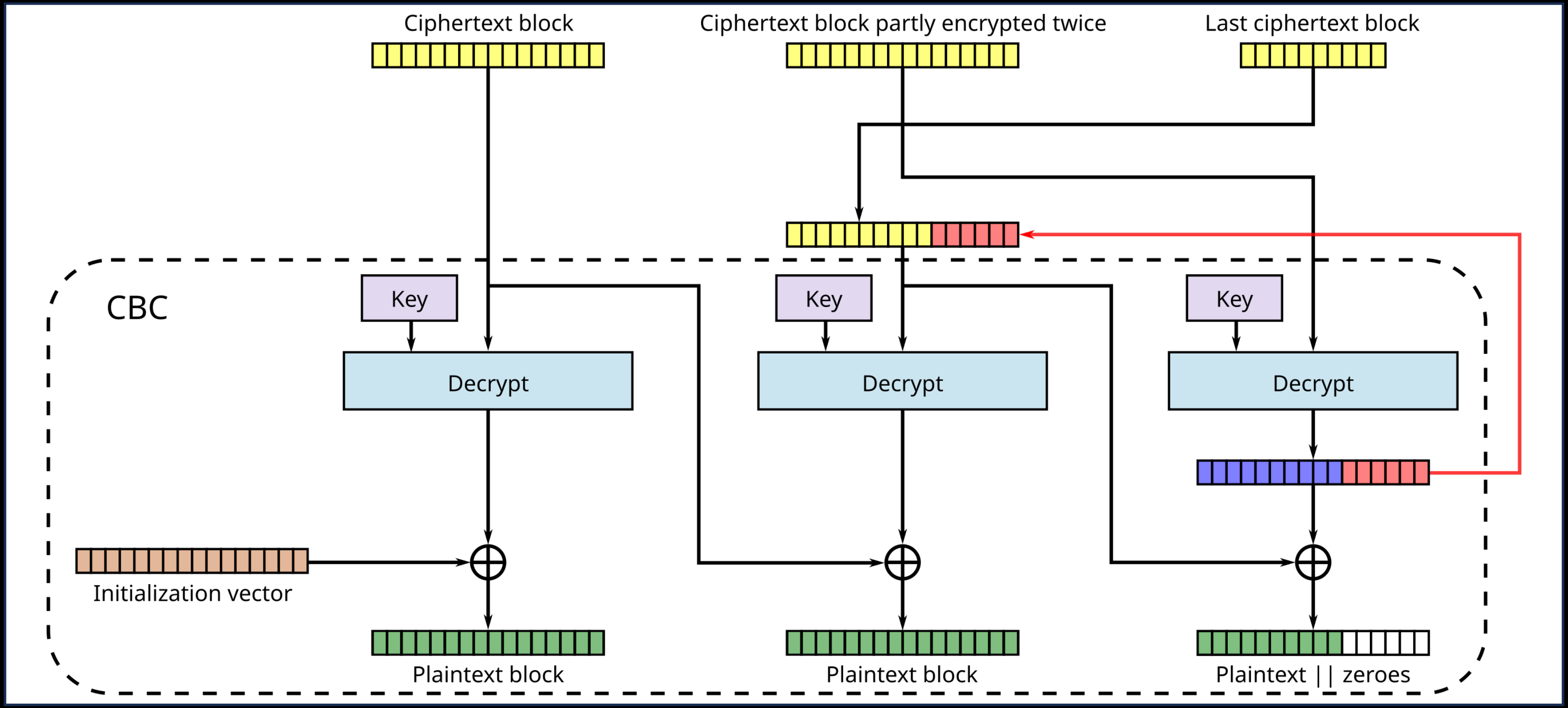
Modes of Operation – CBC

- Encryption in CBC-CS



Modes of Operation – CBC

- Decryption in CBC-CS



Modes of Operation – CBC

- Example: assume we are encrypting ptxt="ABCD", the block size is 3 bytes, IV=123, and the key is K.

Modes of Operation – CBC

ABC

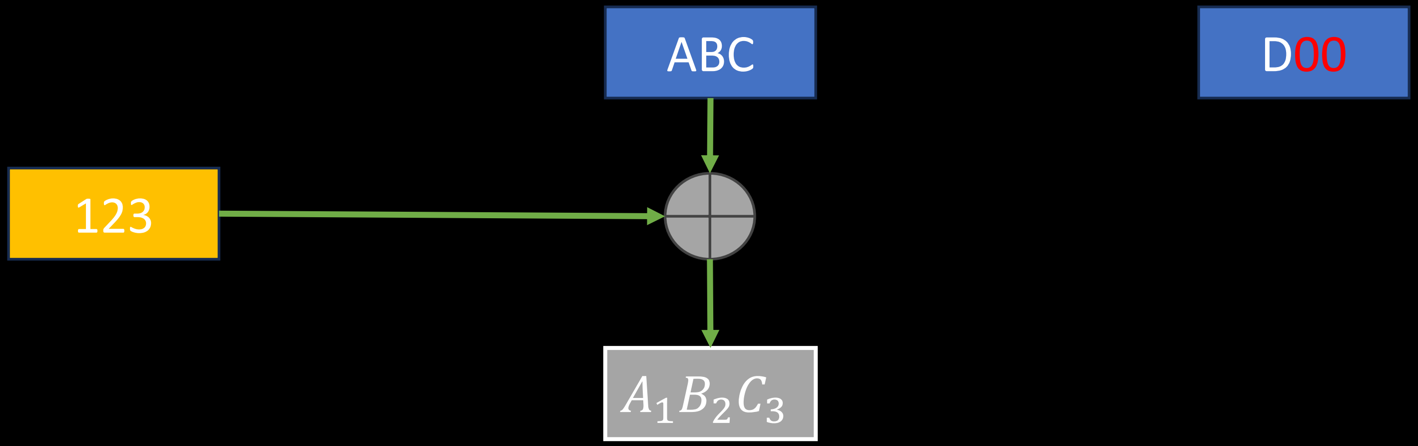
D

Modes of Operation – CBC

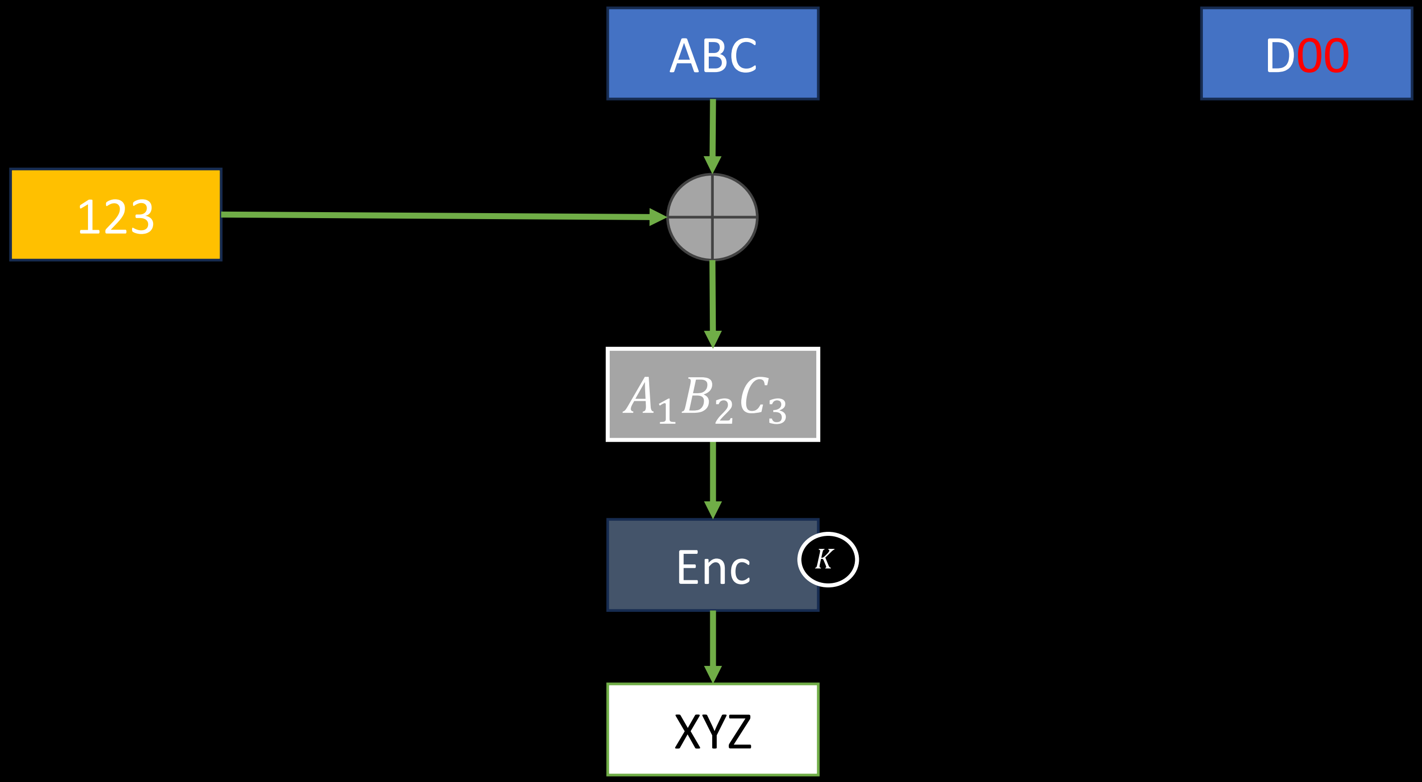
ABC

D00

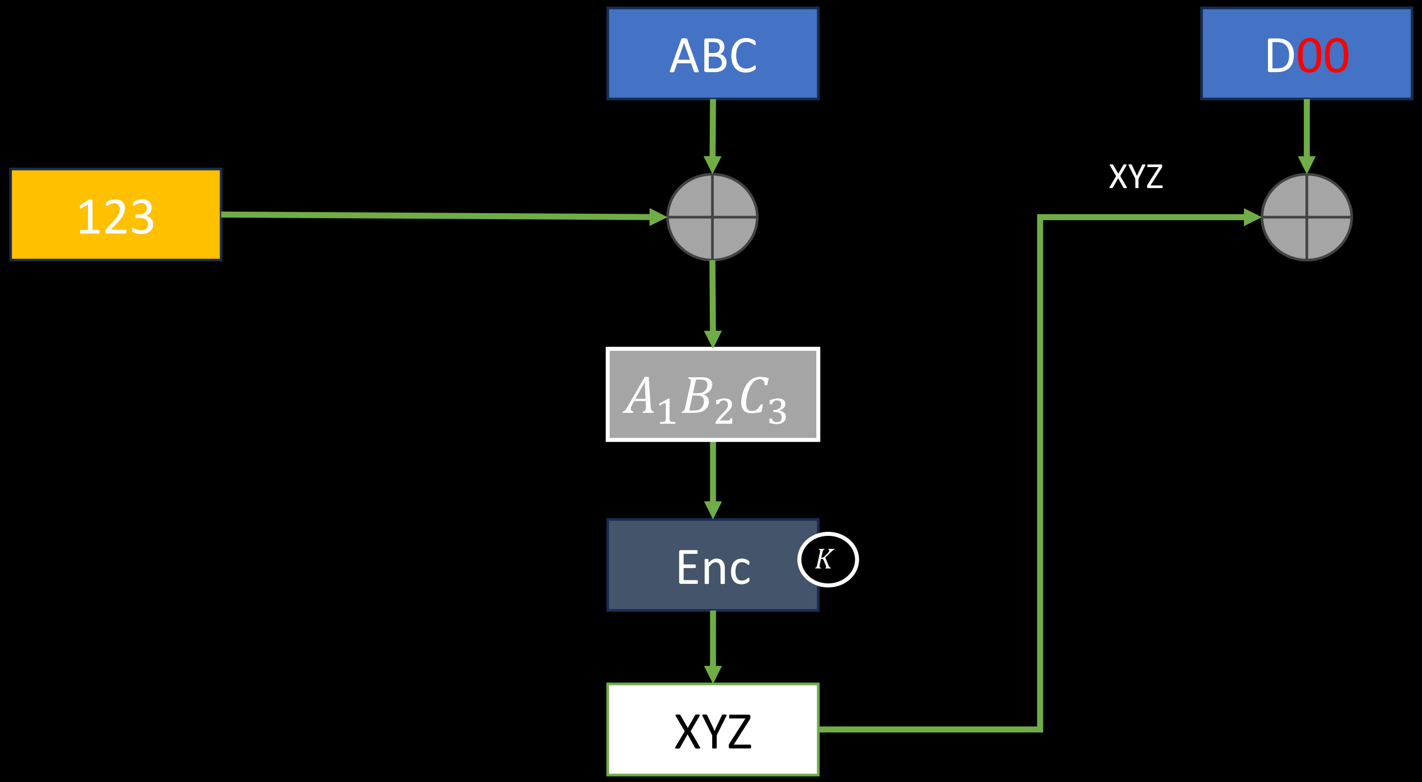
Modes of Operation – CBC



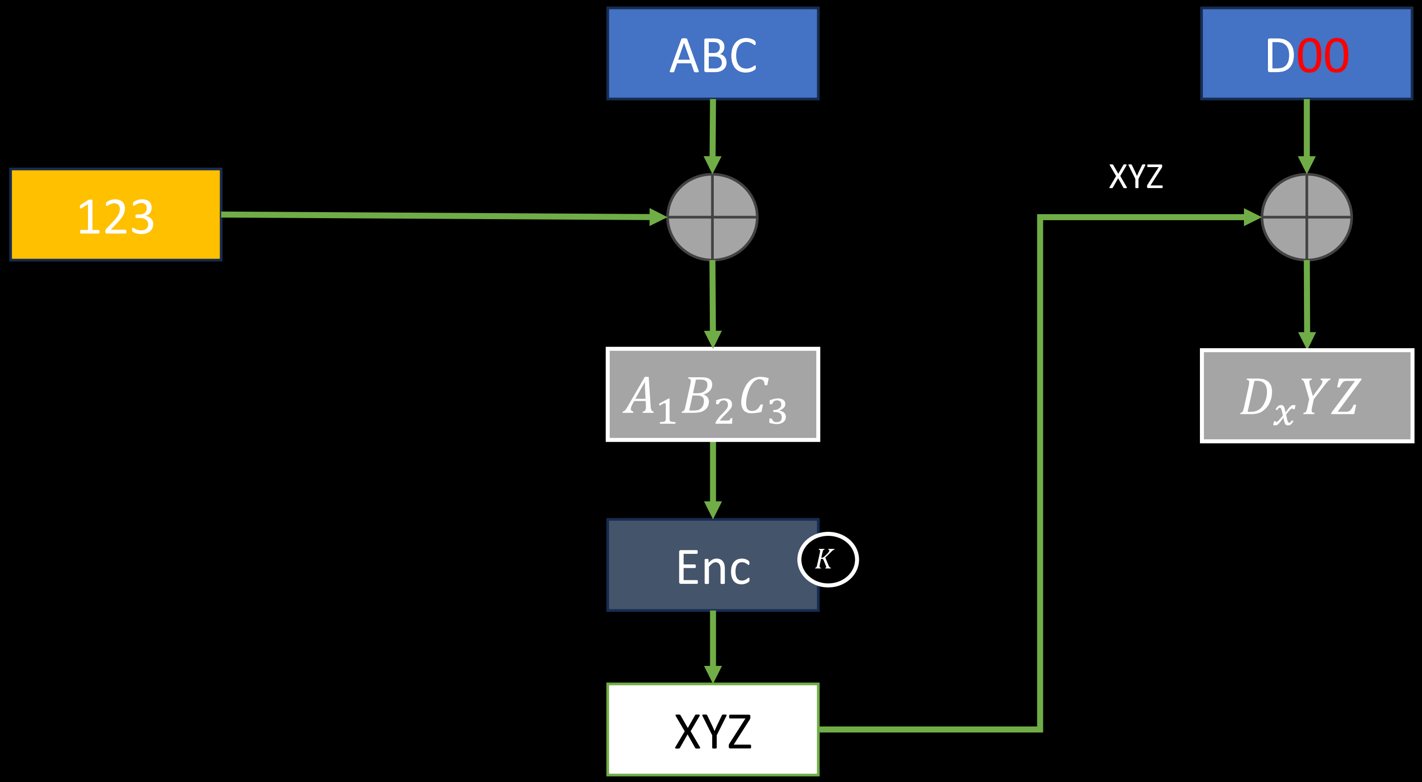
Modes of Operation – CBC



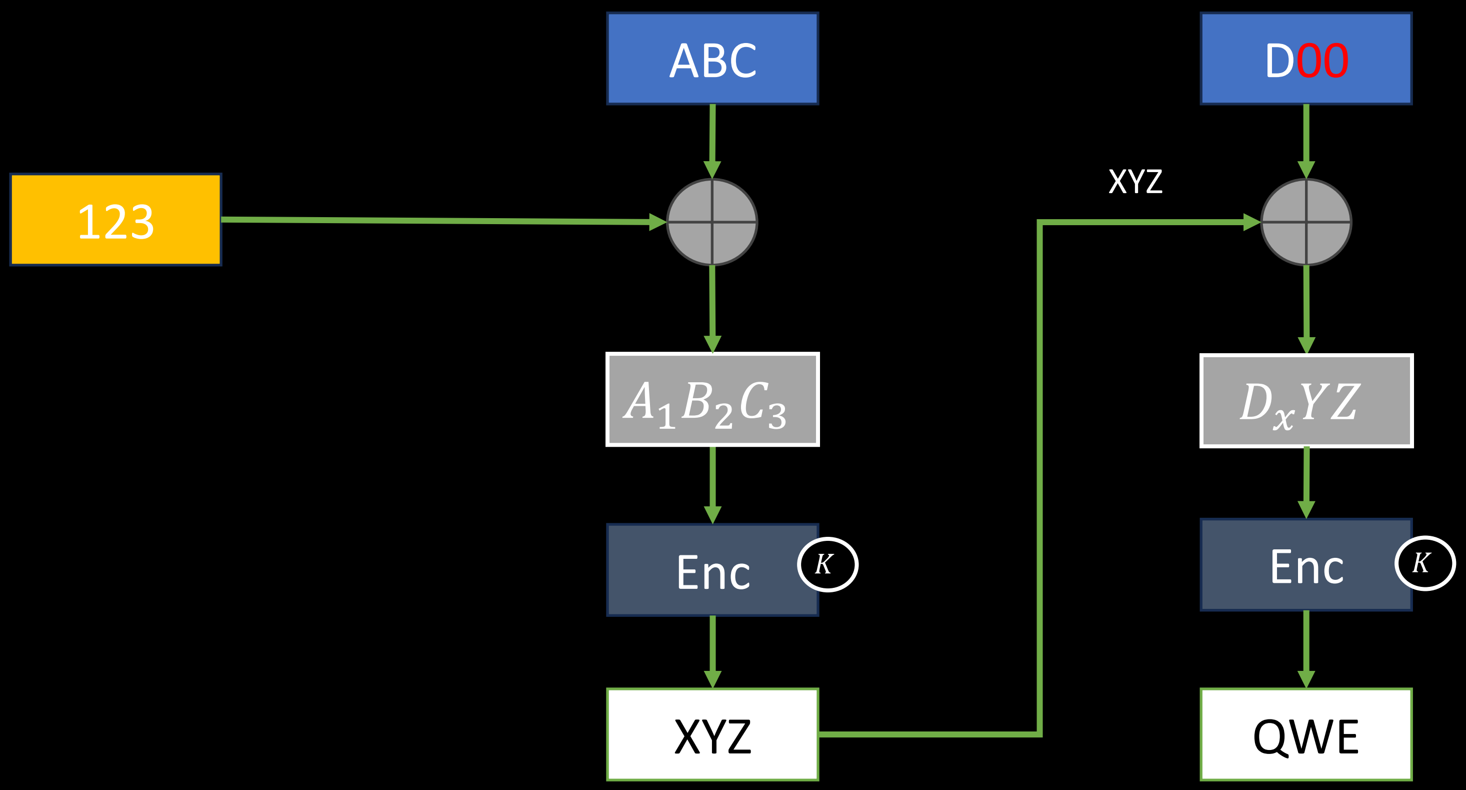
Modes of Operation – CBC



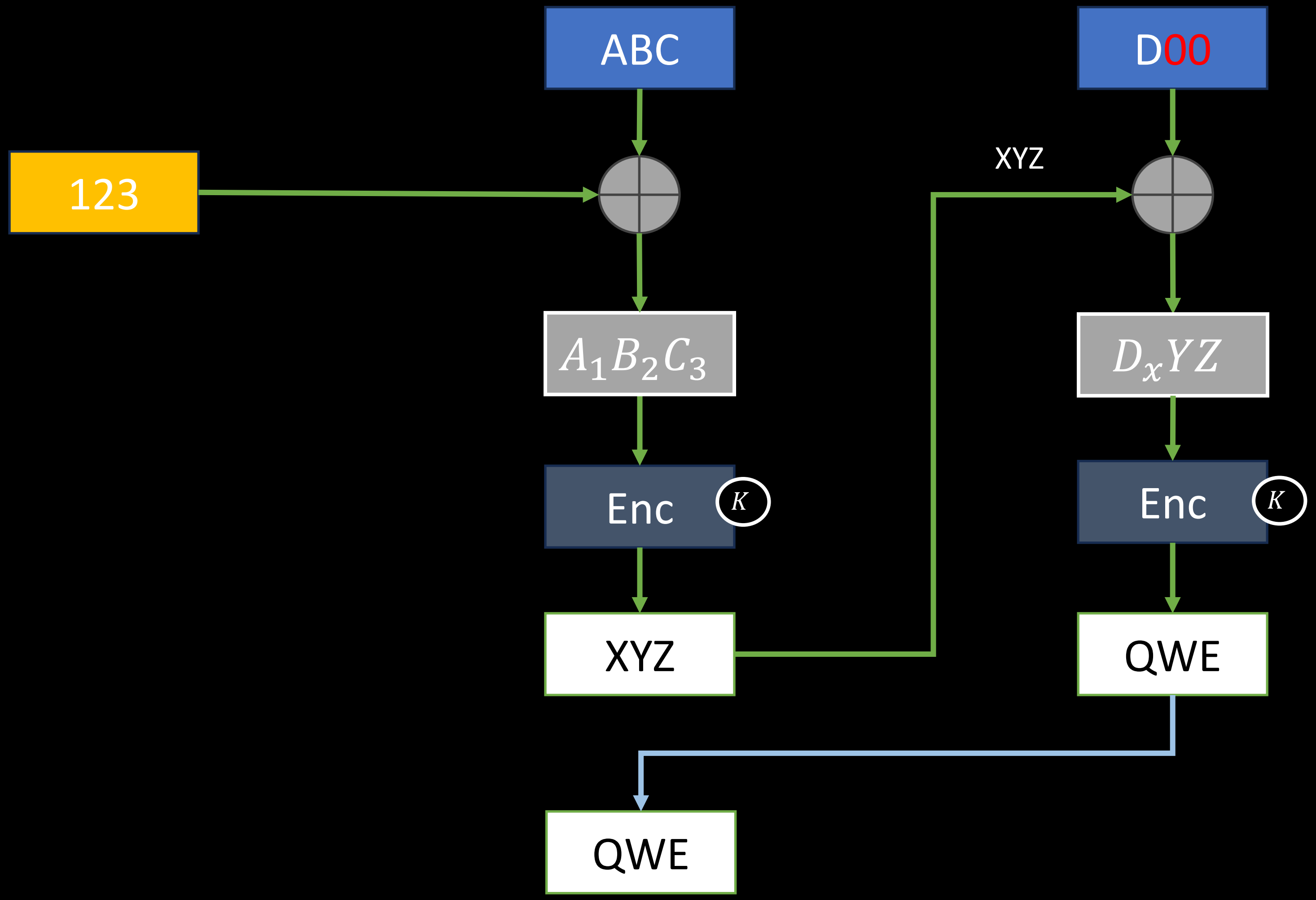
Modes of Operation – CBC



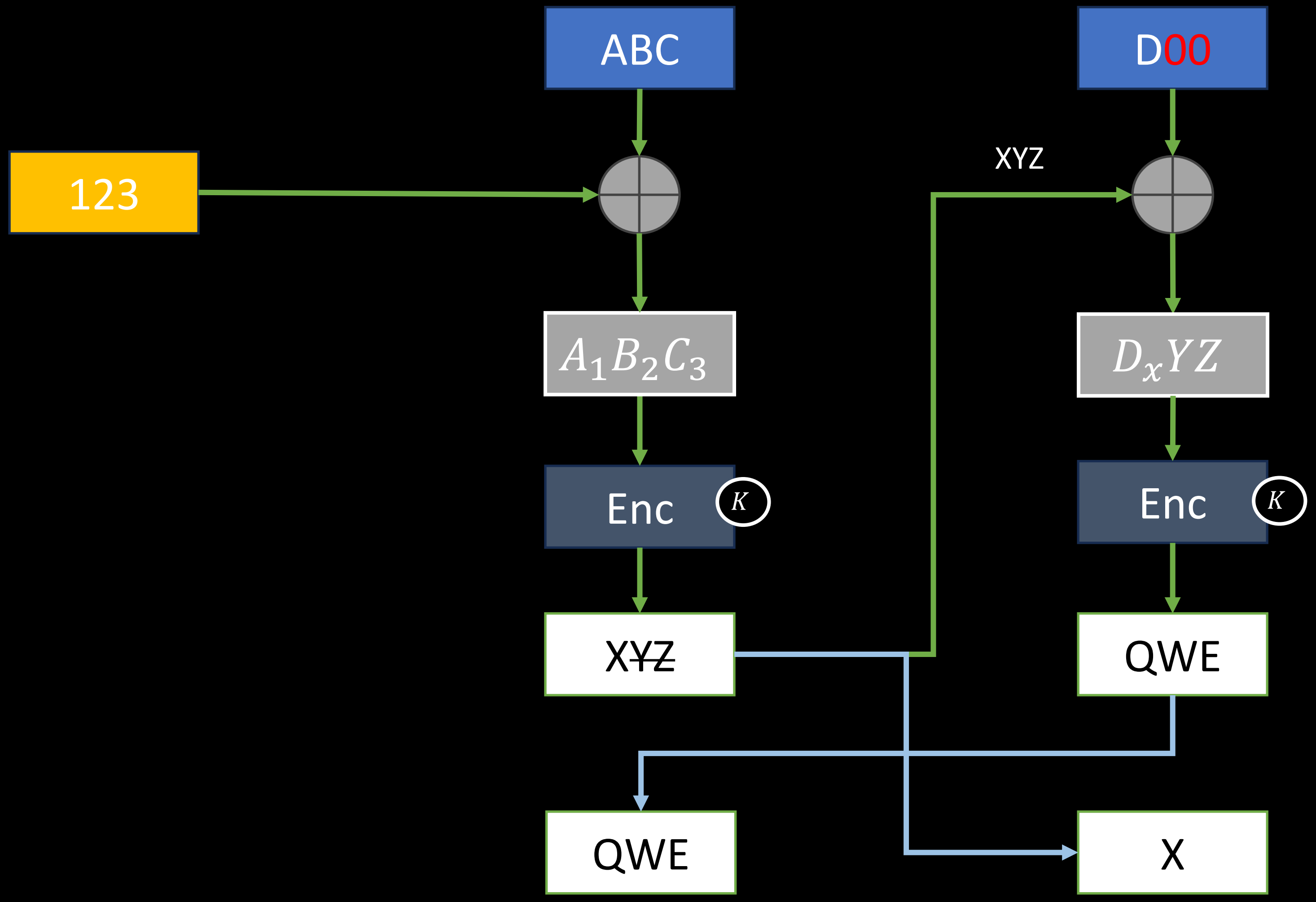
Modes of Operation – CBC



Modes of Operation – CBC



Modes of Operation – CBC

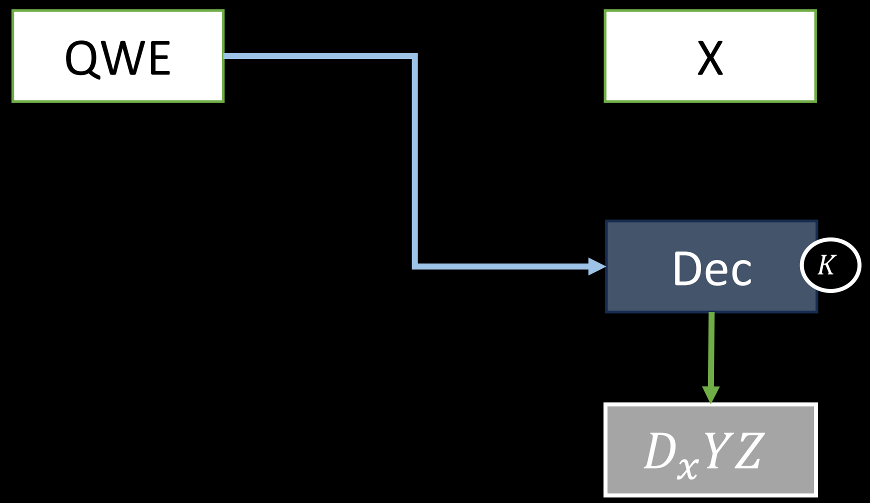


Modes of Operation – CBC

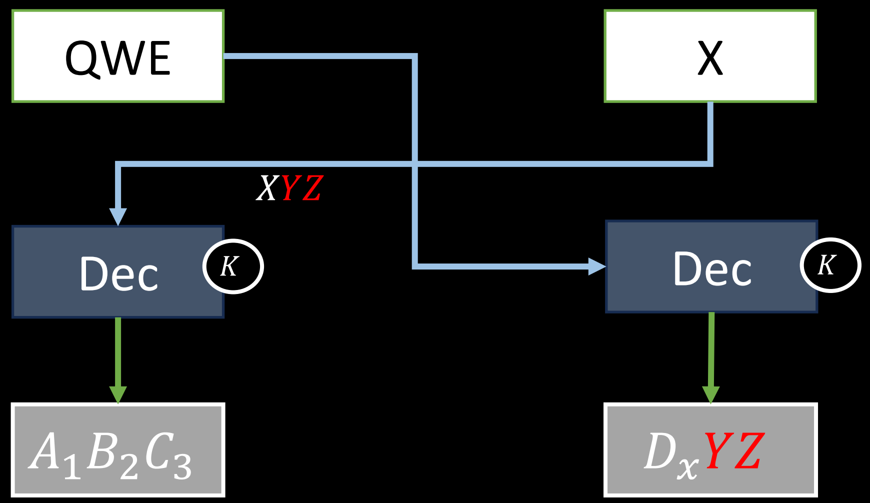
QWE

X

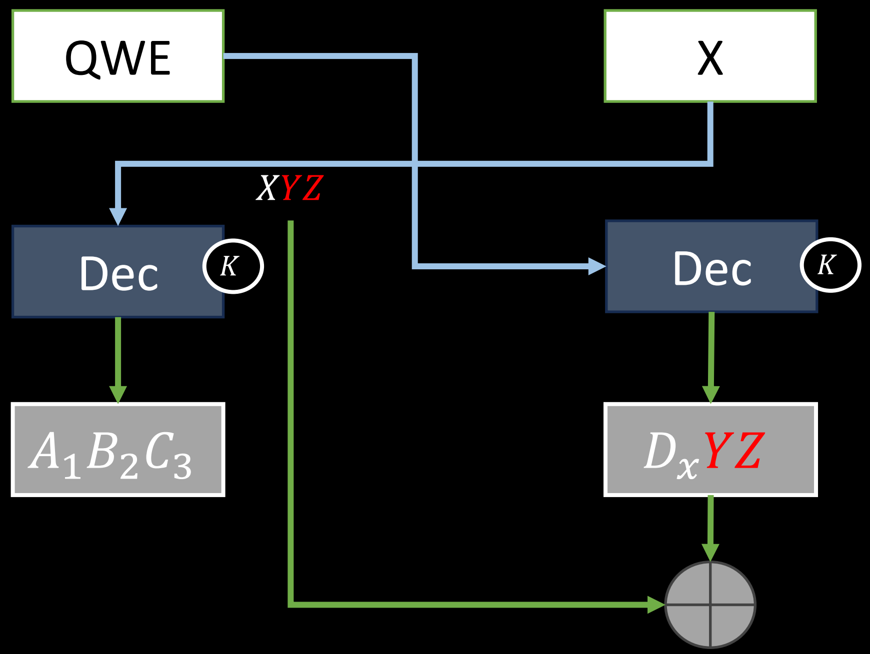
Modes of Operation – CBC



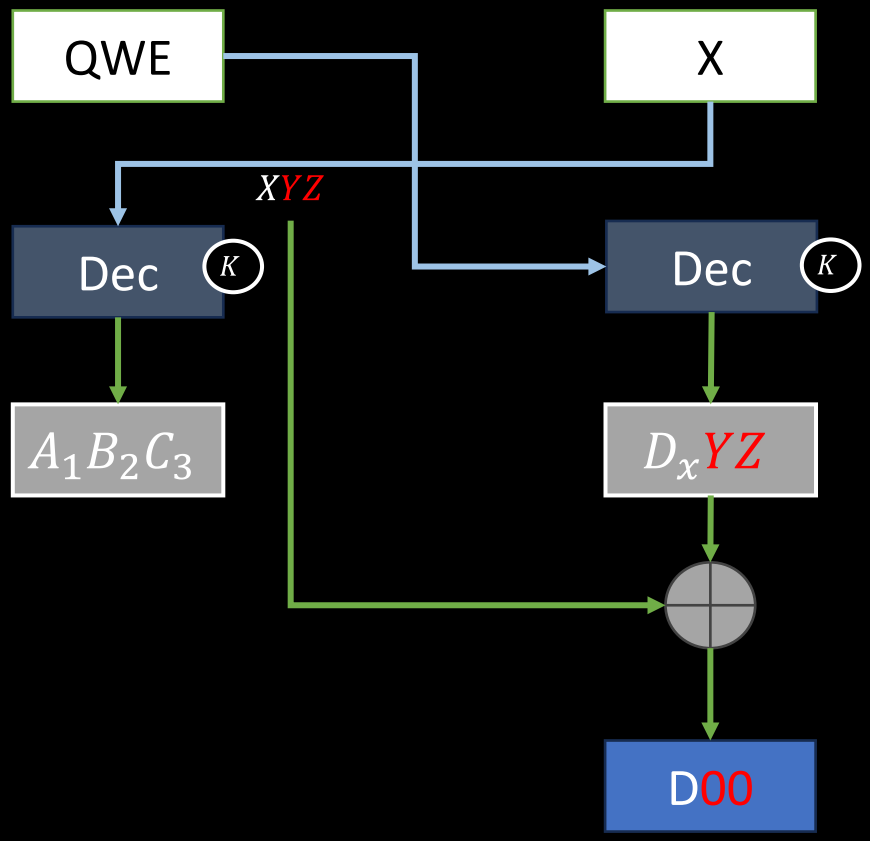
Modes of Operation – CBC



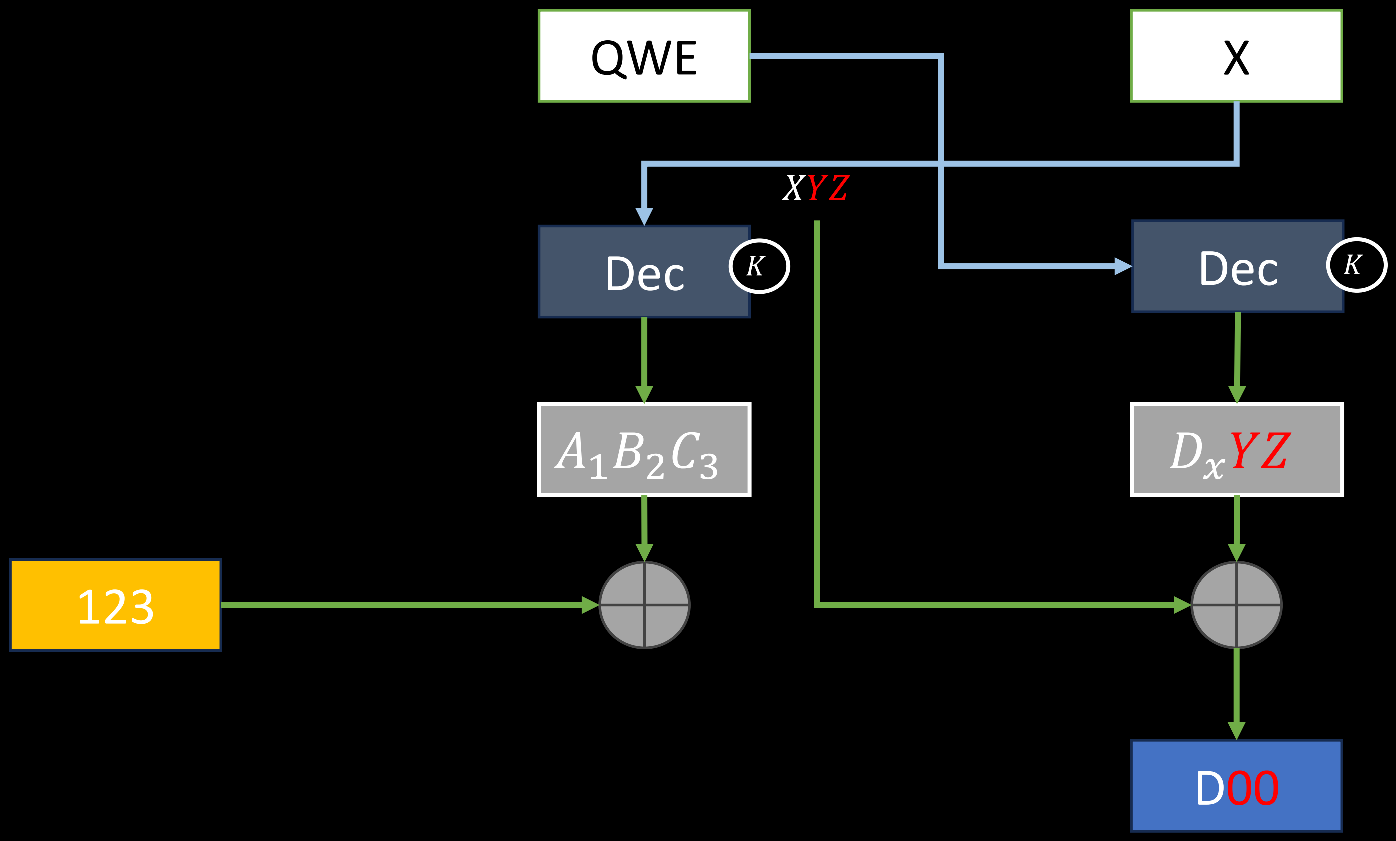
Modes of Operation – CBC



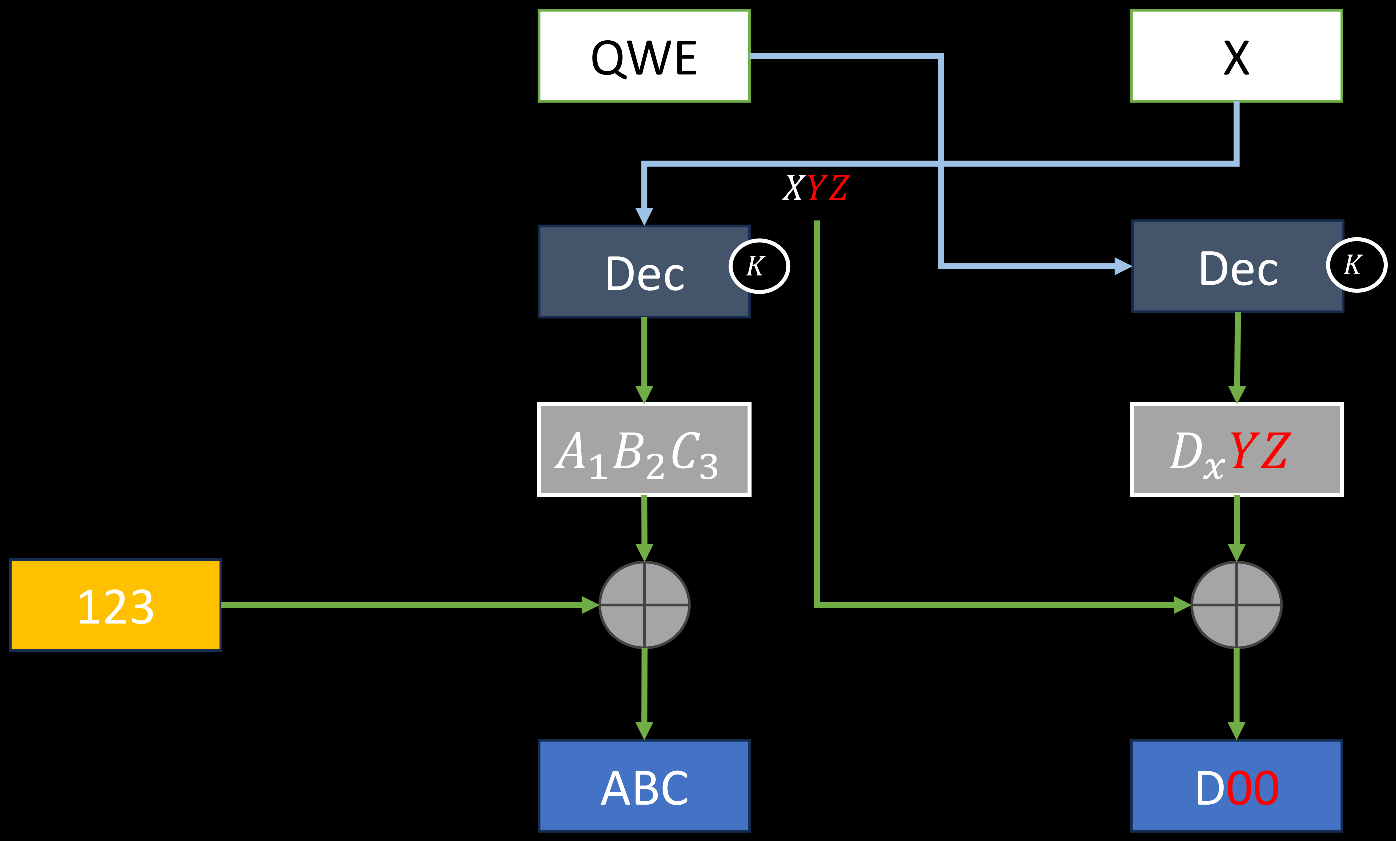
Modes of Operation – CBC



Modes of Operation – CBC



Modes of Operation – CBC



Modes of Operation – CTR

- In CTR mode, a cipher encrypts blocks composed of a **counter** and a **nonce**.
    - **Counter**: an integer incremented for each block.
        - Blocks in a message use different counters.
        - Different messages can use the same counter sequence (1, 2, 3, …).
    - **Nonce**: a number used only once.
        - The same for all blocks in a single message.
        - No two messages should use the same nonce.
        - Sent along with the key (not secret).
- The encryption of $Nonce||CTR$ is XORed with the plaintext.

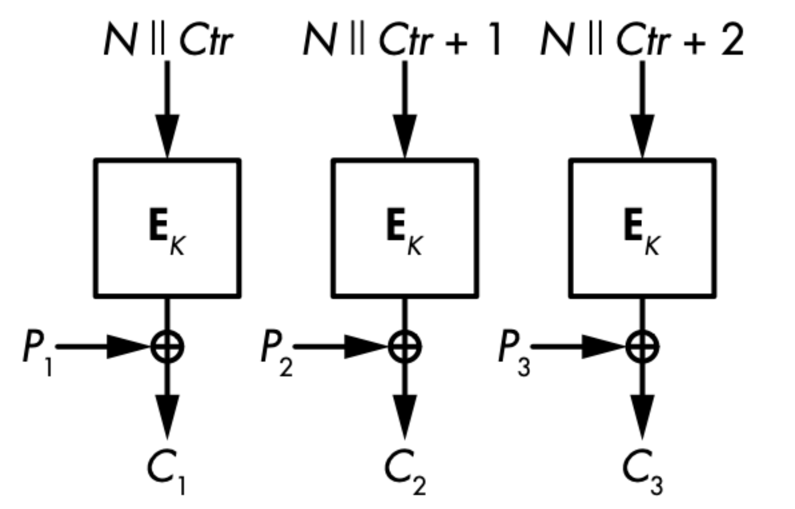


Figure 4-10: The CTR mode

Modes of Operation – CTR

- Nonces must be <u>unique</u>, but not necessarily random.

- To ensure uniqueness:
  - Some techniques include a timestamp within a random nonce.
  - Update the counter for every plaintext you encrypt.

- Advantage: faster than any mode.
  - More than parallelizable.
  - Start encrypting before knowing the message by picking a nonce and computing the stream that you'll later XOR with the plaintext.

Content

Advanced Encryption Standard

- AES is a symmetric block cipher.
  - Fixed block size, 128 bits.
  - Key size: 128 (most common), 192, 256 bits.

- It processes a 16-byte block as a 2D array.

- Transforms the bytes, rows, and columns to produce the final ciphertext

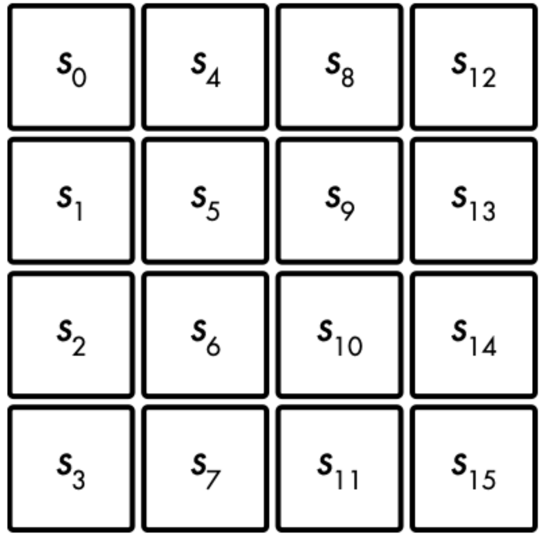
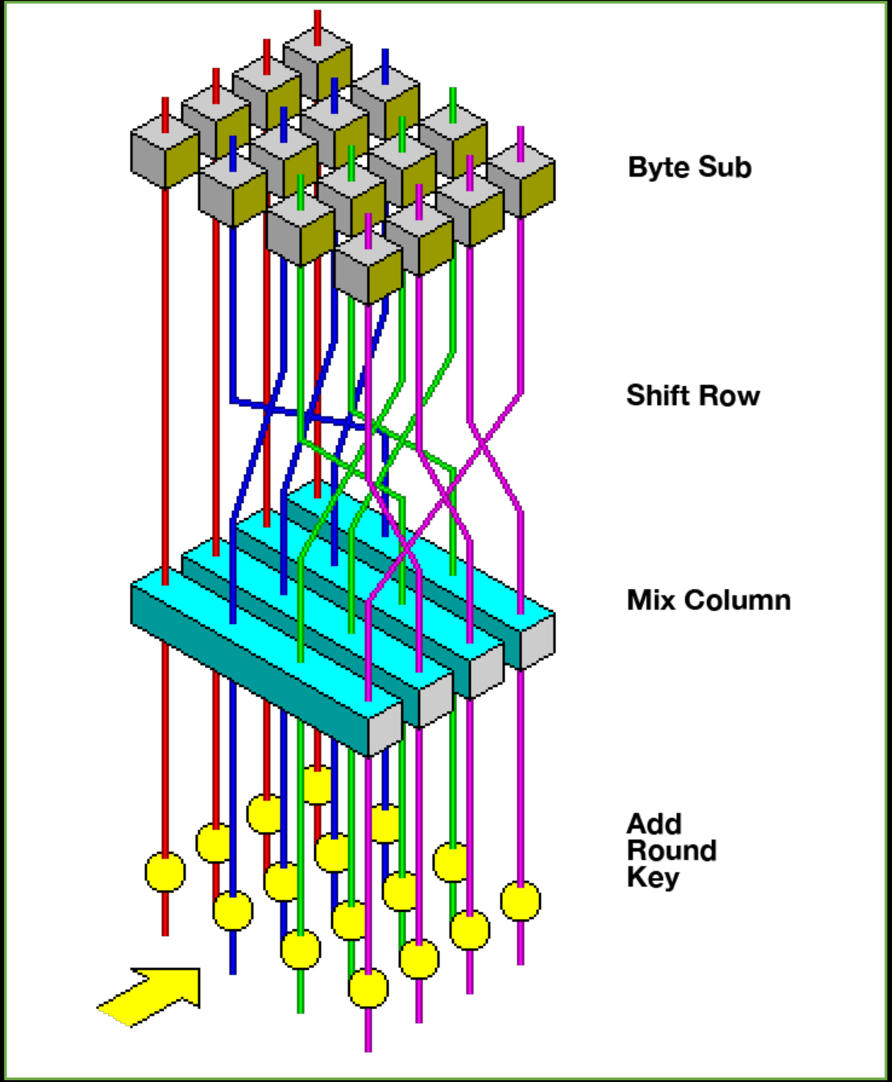


Figure 4-3: The internal state of AES viewed as a 4 × 4 array of 16 bytes

Advanced Encryption Standard

- AES uses an SPN structure.
  - 128-bit key → 10 rounds.
  - 192-bit key → 12 rounds.
  - 256-bit key → 14 rounds.
- Each round consists of:
  - **SubBytes**: Replaces each byte (s0, s1, . . . , s15) with another byte according to an S-box.
  - **ShiftRows**: shift the last three row cyclically a certain number of steps.
  - **MixCols**: a linear mixing operations on the columns of the state.
  - **AddRoundKey**: XORs a round key to the internal state.



Advanced Encryption Standard

- In a full-AES implementation:
  - We start by **AddRoundKey** with the ptxt
  - The last round does not include **MixColumns**.

- Substitution layers → **SubBytes** operations.

- Permutation layers → **ShiftRows** + **MixColumns** operations.

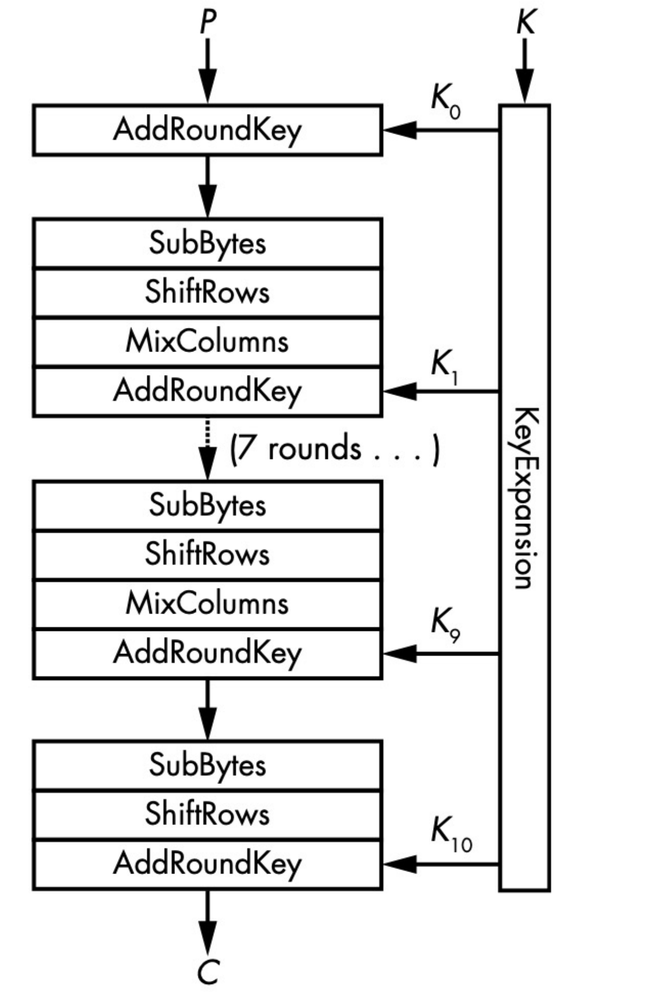


Figure 4-4: The internal operations of AES

Advanced Encryption Standard

KeyExpansion: the key schedule algorithm.

- Takes the master 16-bytes key
- Creates the round keys.
    - Each subkey is 16 bytes.
- **Drawback**: given one of the round keys, an attacker can recover other round keys and the master key.
    - A single round key can be recovered through a side-channel attack.

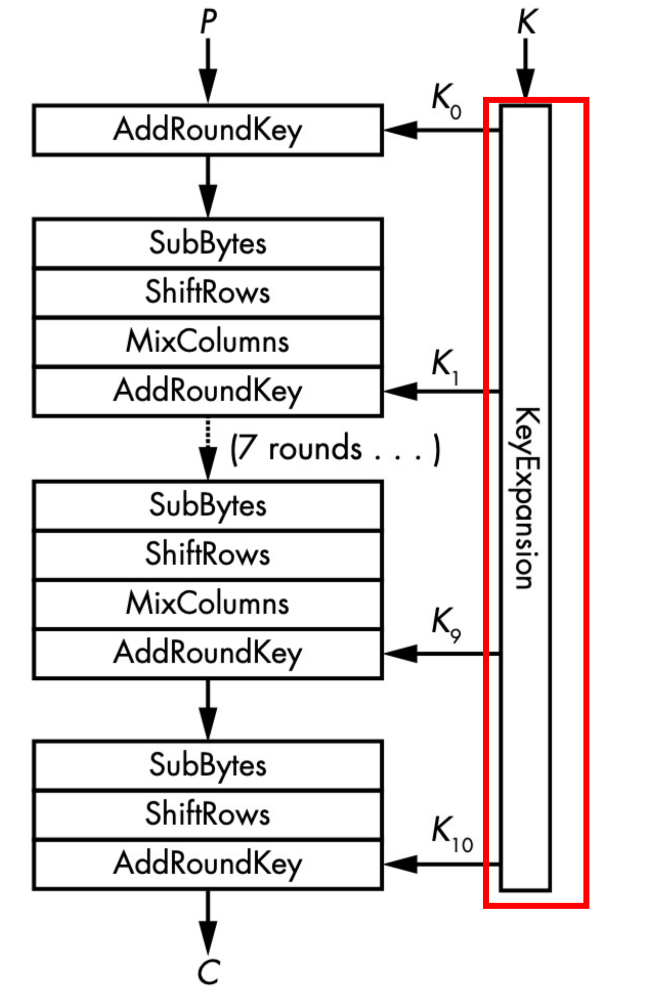
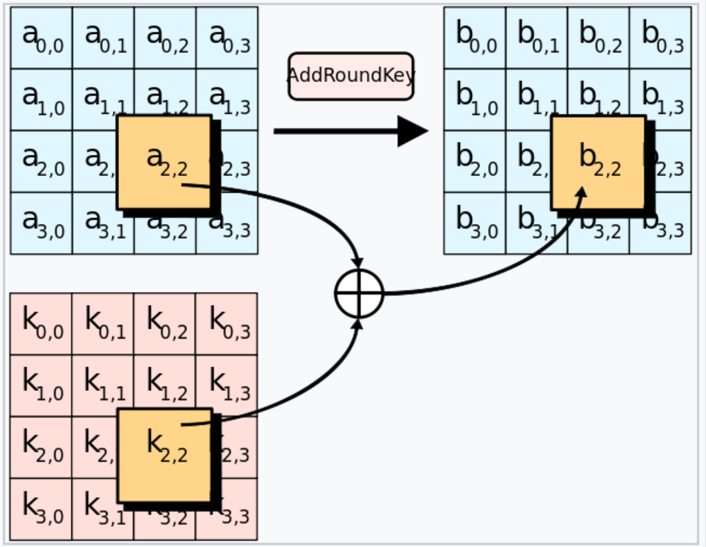


Figure 4-4: The internal operations of AES

Advanced Encryption Standard

AddRoundKey

- Combine the key with the internal state.
- XORs each byte from the key with a byte from the internal state.



In the AddRoundKey step, each byte of the state is combined with a byte of the round subkey using the XOR operation (⊕).

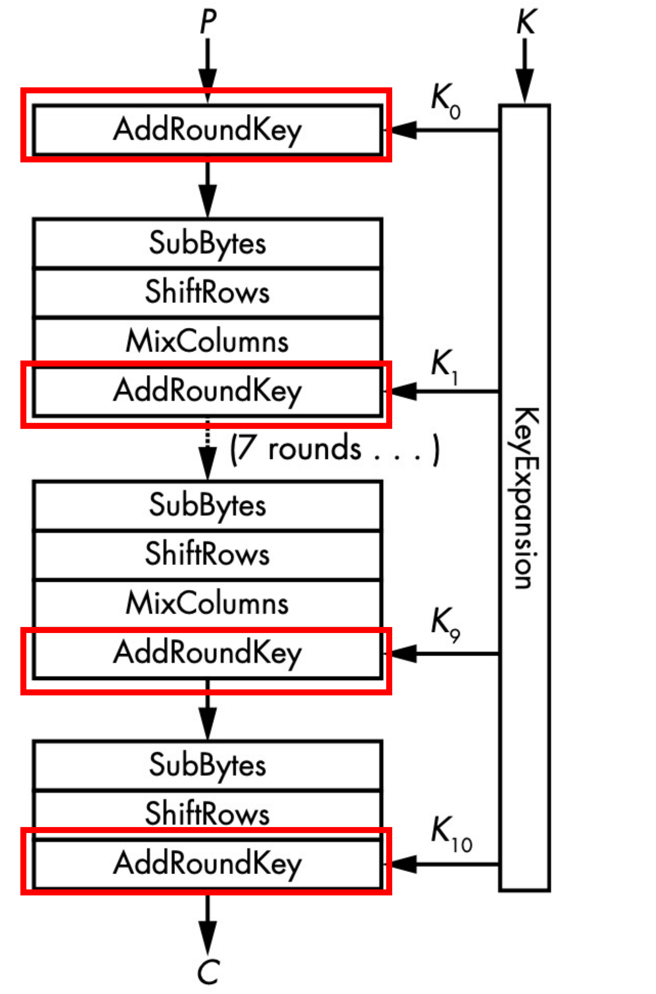
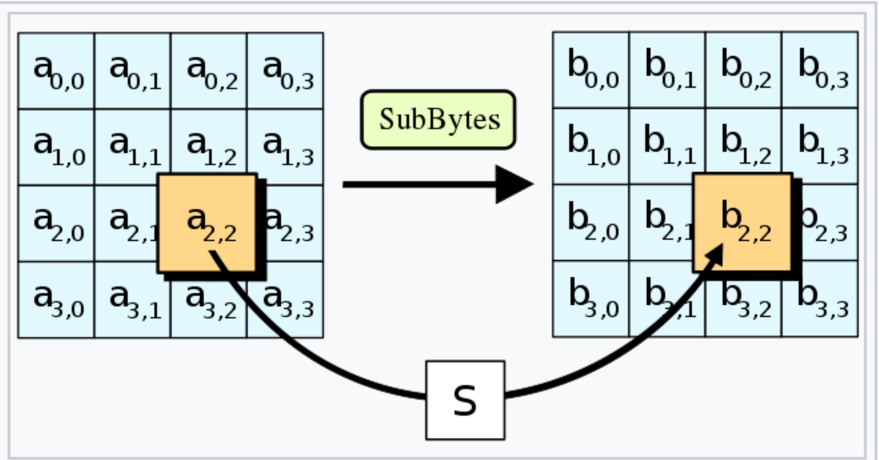


Figure 4-4: The internal operations of AES

Advanced Encryption Standard

SubBytes

- Each byte in the state array is replaced with another byte using an 8-bit substitution box.



In the `SubBytes` step, each byte in the state is replaced with its entry in a fixed 8-bit lookup table, S; $b_{ij} = S(a_{ij})$.

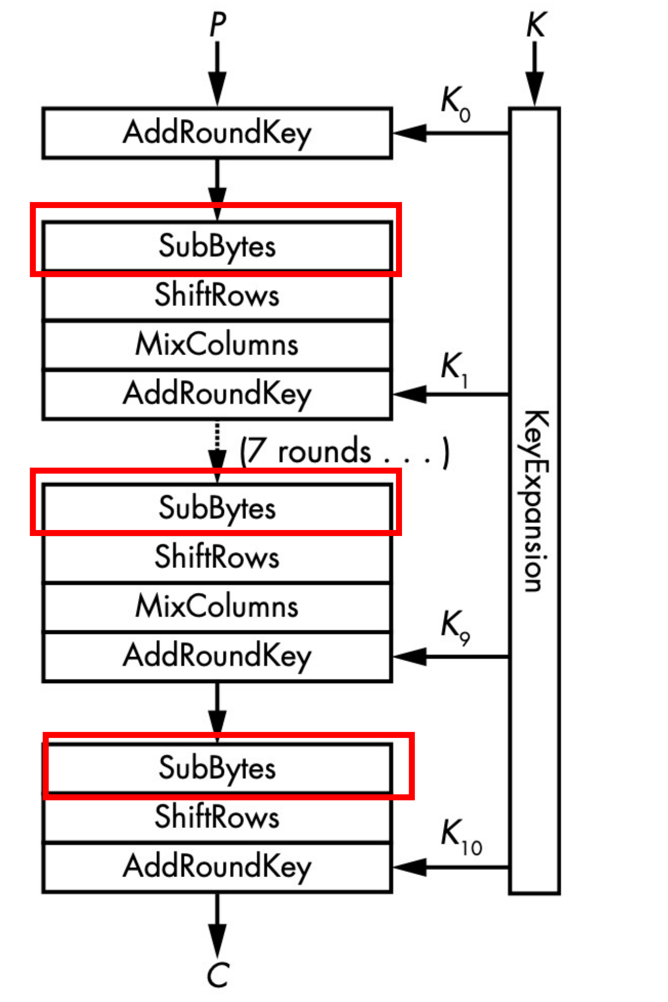
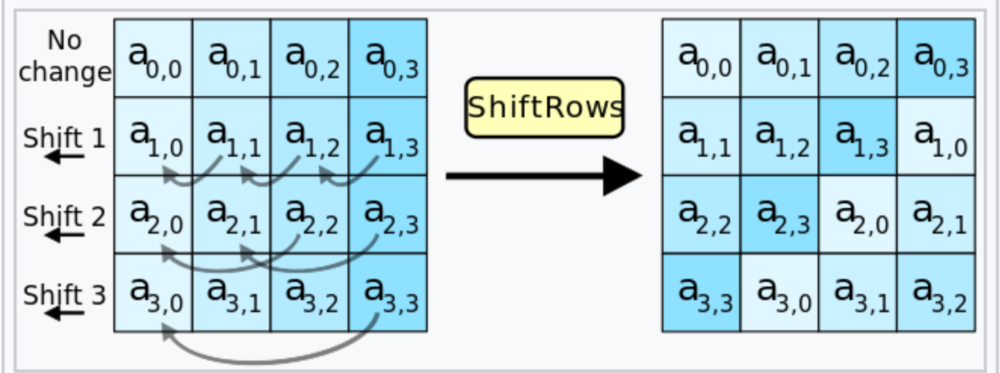


Figure 4-4: The internal operations of AES

Advanced Encryption Standard

ShiftRows

- Cyclically shift the bytes in each row by a certain offset.



In the ShiftRows step, bytes in each row of the state are shifted cyclically to the left. The number of places each byte is shifted differs incrementally for each row.

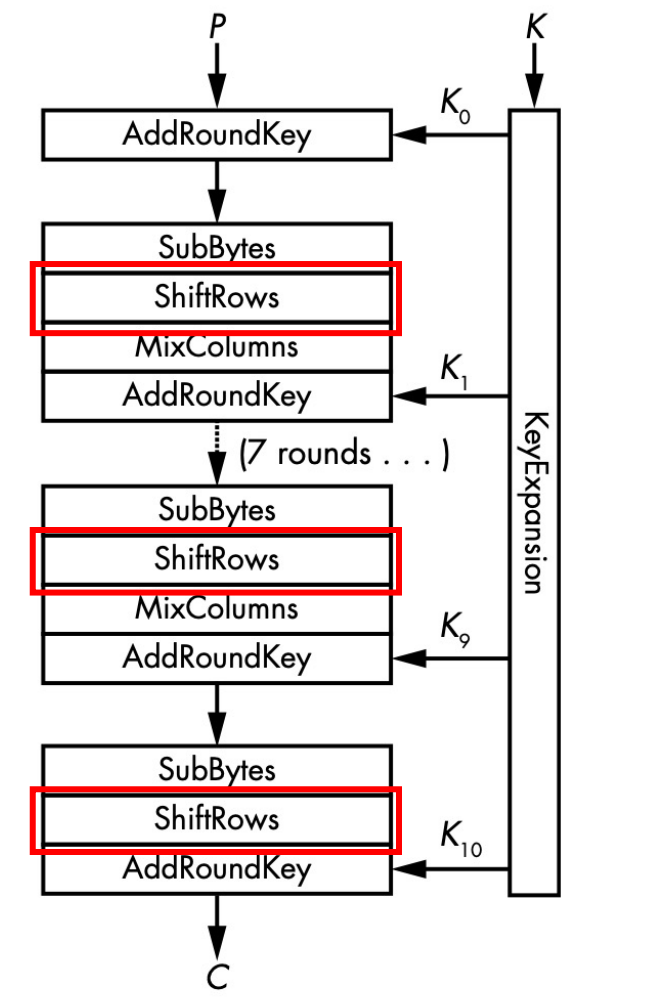


Figure 4-4: The internal operations of AES

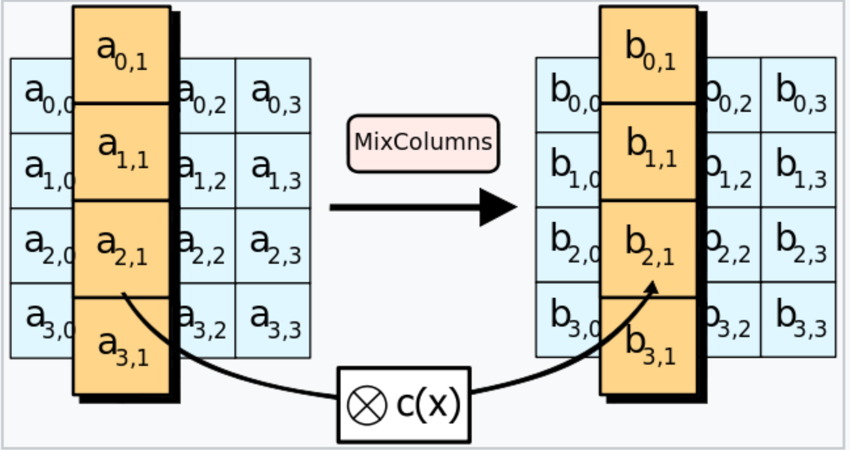
Advanced Encryption Standard

MixColumns

- The four bytes of each column of the state are combined using an invertible linear transformation.

$$\begin{bmatrix} b_{0,j} \\ b_{1,j} \\ b_{2,j} \\ b_{3,j} \end{bmatrix} = \begin{bmatrix} 2 & 3 & 1 & 1 \\ 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 3 \\ 3 & 1 & 1 & 2 \end{bmatrix} \begin{bmatrix} a_{0,j} \\ a_{1,j} \\ a_{2,j} \\ a_{3,j} \end{bmatrix}$$

$$0 \leq j \leq 3$$



In the MixColumns step, each column of the state is multiplied with a fixed polynomial $c(x)$.

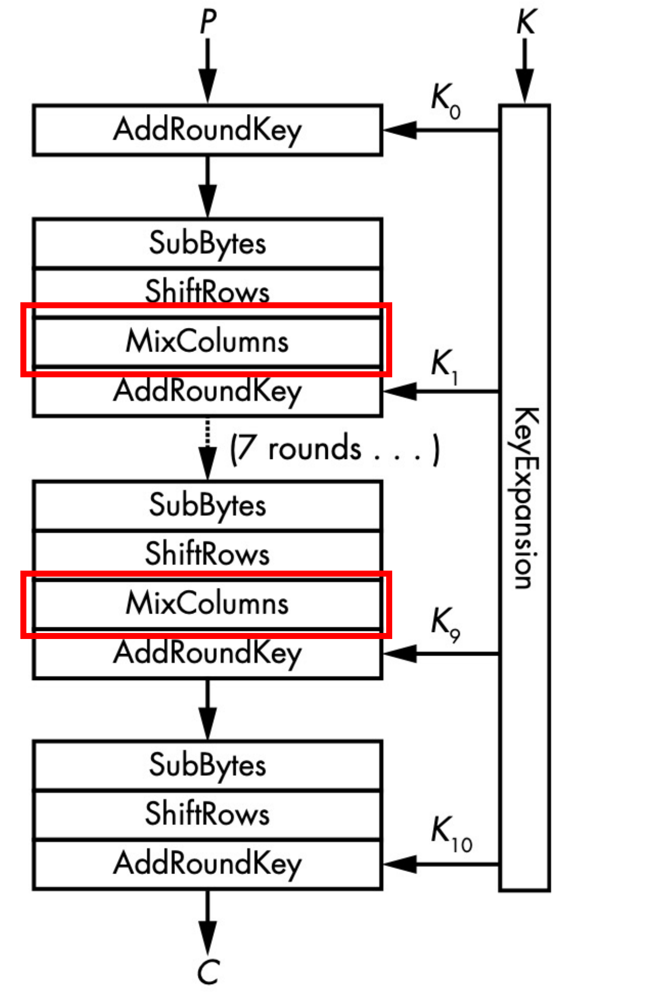
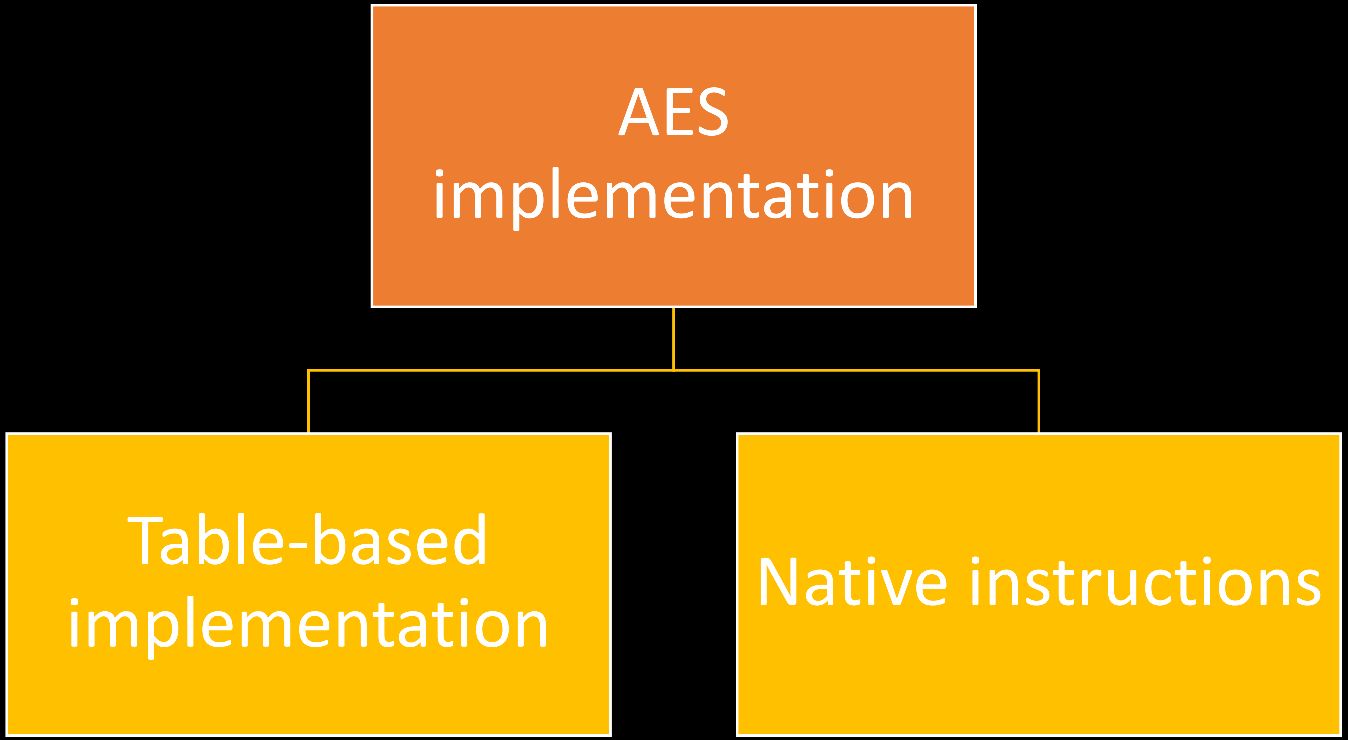


Figure 4-4: The internal operations of AES

Advanced Encryption Standard

- Real-world implementation of AES is different from the algorithm.
- Fast AES software uses special techniques:



Advanced Encryption Standard

Table- based implementations:

- Instead of SubBytes-ShiftRows-MixColumns, use a hardcoded table.
  - The table is hardcoded into the program.
  - Loaded in memory during runtime.
  - Perform lookups to the table to transform a given byte.
- Vulnerable to cache-timing attacks.
  - Exploits timing variations when a program access elements in cache memory.
  - Timings leak information about which element was accessed, which in turn leaks information on the secrets involved.
  - Difficult to avoid.

Advanced Encryption Standard

Table- based implementations:

```
    /* round 1: */
    t0 = Te0[s0 >> 24] ^ Te1[(s1 >> 16) & 0xff] ^ Te2[(s2 >> 8) & 0xff] ^ Te3[s3 & 0xff] ^ rk[ 4];
    t1 = Te0[s1 >> 24] ^ Te1[(s2 >> 16) & 0xff] ^ Te2[(s3 >> 8) & 0xff] ^ Te3[s0 & 0xff] ^ rk[ 5];
    t2 = Te0[s2 >> 24] ^ Te1[(s3 >> 16) & 0xff] ^ Te2[(s0 >> 8) & 0xff] ^ Te3[s1 & 0xff] ^ rk[ 6];
    t3 = Te0[s3 >> 24] ^ Te1[(s0 >> 16) & 0xff] ^ Te2[(s1 >> 8) & 0xff] ^ Te3[s2 & 0xff] ^ rk[ 7];
    /* round 2: */
    s0 = Te0[t0 >> 24] ^ Te1[(t1 >> 16) & 0xff] ^ Te2[(t2 >> 8) & 0xff] ^ Te3[t3 & 0xff] ^ rk[ 8];
    s1 = Te0[t1 >> 24] ^ Te1[(t2 >> 16) & 0xff] ^ Te2[(t3 >> 8) & 0xff] ^ Te3[t0 & 0xff] ^ rk[ 9];
    s2 = Te0[t2 >> 24] ^ Te1[(t3 >> 16) & 0xff] ^ Te2[(t0 >> 8) & 0xff] ^ Te3[t1 & 0xff] ^ rk[10];
    s3 = Te0[t3 >> 24] ^ Te1[(t0 >> 16) & 0xff] ^ Te2[(t1 >> 8) & 0xff] ^ Te3[t2 & 0xff] ^ rk[11];
--snip--
```

Listing 4-2: The table-based C implementation of AES in OpenSSL

Advanced Encryption Standard

Native implementation (AES-NI):

- Solve the problem of cache-timing attacks on AES software implementations.
- Example: $AESENC$ instruction will execute a round on a given block.
  - 10X faster than software.
- Assuming $xmm5$ to $xmm15$ registers hold the subkeys, and $xmm0$ has ptxt block.

```
PXOR       %xmm5,  %xmm0
AESENC     %xmm6,  %xmm0
AESENC     %xmm7,  %xmm0
AESENC     %xmm8,  %xmm0
AESENC     %xmm9,  %xmm0
AESENC     %xmm10, %xmm0
AESENC     %xmm11, %xmm0
AESENC     %xmm12, %xmm0
AESENC     %xmm13, %xmm0
AESENC     %xmm14, %xmm0
AESENCLAST %xmm15, %xmm0
```

Listing 4-3: AES native instructions

Advanced Encryption Standard

- Implement AES using $pycryptodome$

Content

Content
Introduction
Constructing Block Ciphers
Modes of Operation
Advanced Encryption Standard
Simon and Speck Ciphers

Simon & Speck Ciphers

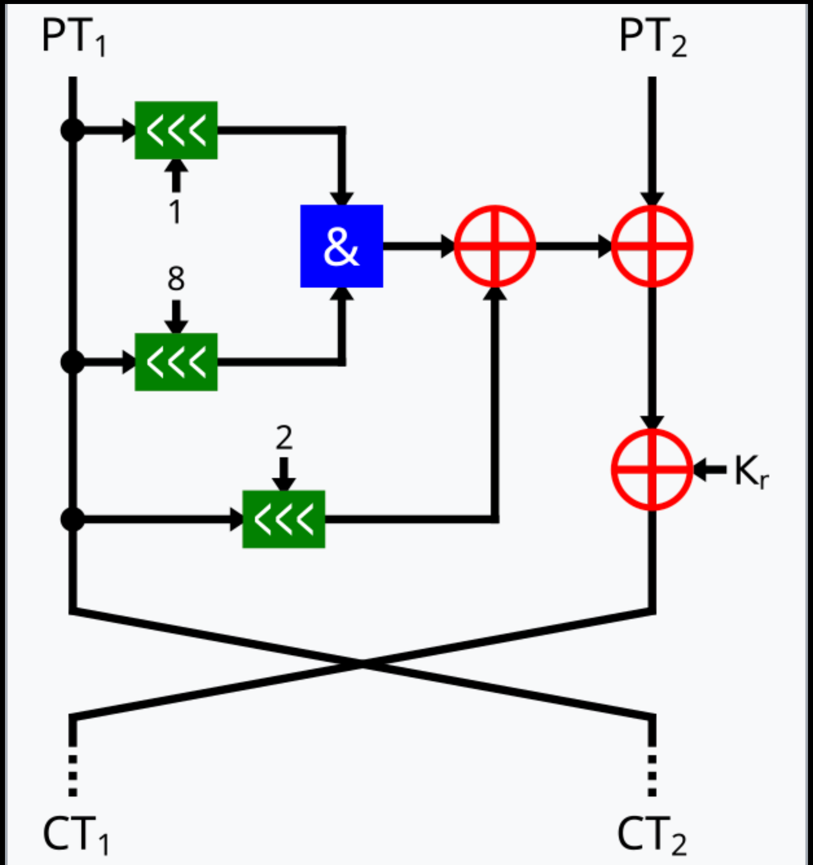
- A family of block ciphers released by the National Security Agency (NSA).
  - Simon is optimized for hardware implementation.
  - Speck is optimized for software implementation.

- Both are based on Feistel structure.

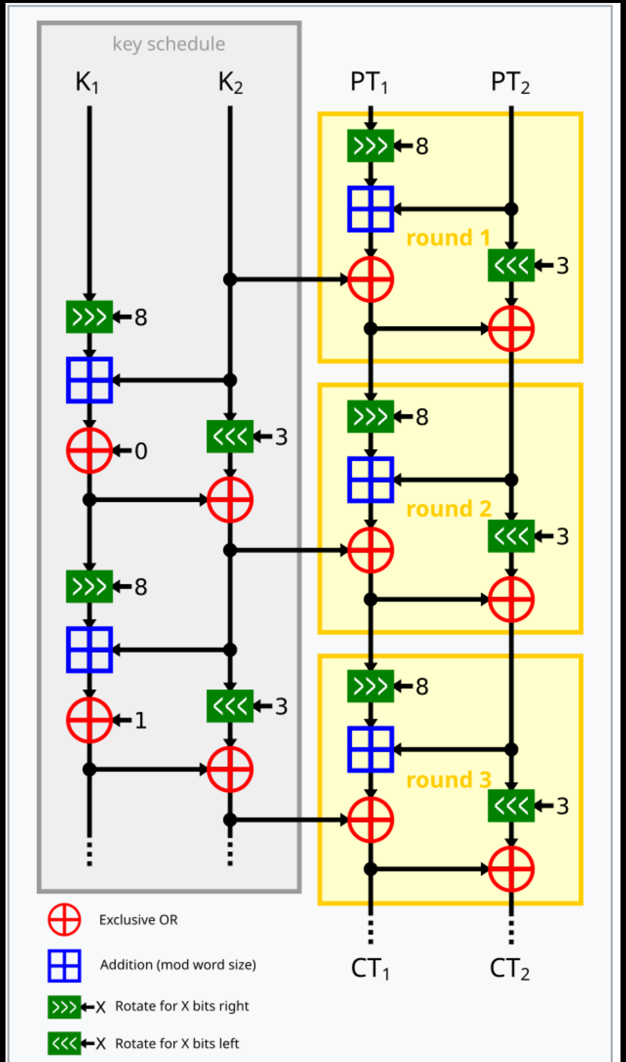
- Basic operations:
  - Modular addition and subtraction
  - Bitwise XOR and AND
  - Circular shifts

Simon & Speck Ciphers

- Simon and Speck rounds



One round of Simon



3 rounds of Speck with 2-word key schedule

Simon & Speck Ciphers

- Supported block and key sizes

block size	key sizes
32	64
48	72, 96
64	96, 128
96	96, 144
128	128, 192, 256

Table 2: SIMON and SPECK parameters.

Simon & Speck Ciphers

- Security evaluation:
  - Simon: 48/72 (67%)
  - Speck: 128/128 (53%)

size	alg	rounds		ref
		total	attacked	
32/64	SIMON	32	23 (72%)	[24]
	SPECK	22	14 (64%)	[29]
48/72	SIMON	36	24 (67%)	[24]
	SPECK	22	14 (64%)	[29]
48/96	SIMON	36	25 (69%)	[24]
	SPECK	23	15 (65%)	[29]
64/96	SIMON	42	30 (71%)	[24]
	SPECK	26	18 (69%)	[29]
64/128	SIMON	44	31 (70%)	[24]
	SPECK	27	19 (70%)	[29]
96/96	SIMON	52	37 (71%)	[61, 24]
	SPECK	28	16 (57%)	[29]
96/144	SIMON	54	38 (70%)	[24]
	SPECK	29	17 (59%)	[29]
128/128	SIMON	68	49 (72%)	[61, 24]
	SPECK	32	17 (53%)	[29]
128/192	SIMON	69	51 (74%)	[24]
	SPECK	33	18 (55%)	[3, 29]
128/256	SIMON	72	53 (74%)	[24]
	SPECK	34	19 (56%)	[29]

Table 1: Security of SIMON and SPECK.

TASK

- Is it safe to use CBC mode with a constant IV? Why or why not? Explain with a code example.
- Encrypt the following image using AES-ECB, AES-CBC, AES-CTR mode.
  - Process the image as grayscale.
  - Your code should show the result of the three modes.

TASK

Challenge: You've been tasked with decrypting a flag encrypted with AES-128 in CBC mode. But, there's more to it than just AES. This isn't your typical AES encryption challenge. The secret flag has been encrypted using a weak AES key. The key is 16 bytes long, but the catch is that each byte of the key is identical, and it's derived from a random value.

- The ciphertext is shown below
- Hint: check the class’s code for how a key was generated.

```
b'\xb5W\xae"k(u\x18*"e\xf1\x98\x17\xa0\xe6\xc2\xd1\xf6\x98i\xa5[>\x02\xf1\xb6\xd5\x
db;\xc4ZJ\xc0\xf1\xa0\x0b*\xa5\xfej%\xb8\x1e\x07\xb3\x02\x16’
```