COMPSCI4062&5063: Cyber Security Fundamentals

Topic 4: Cryptography I

Dongzhu Liu

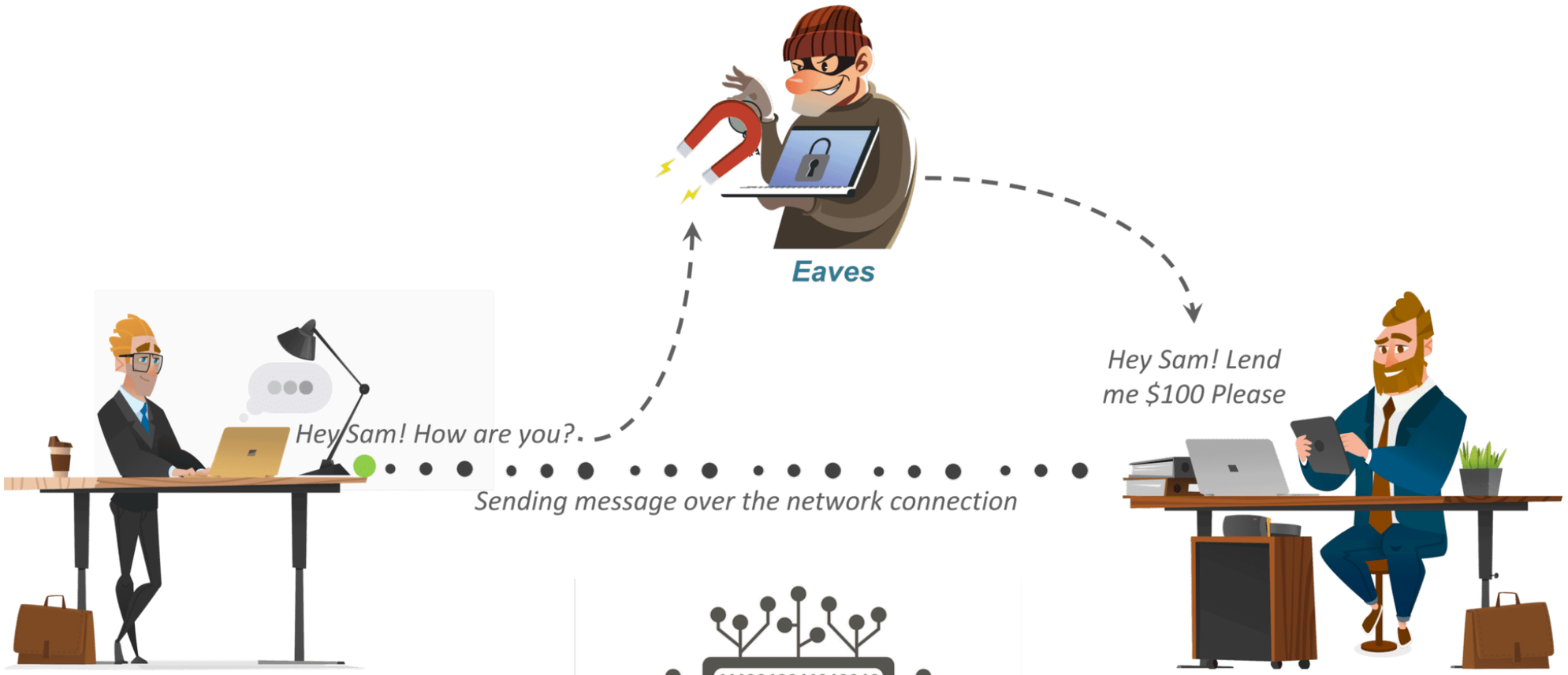
Email: dongzhu.liu@glasgow.ac.uk
Office: SAWB 510 (b)

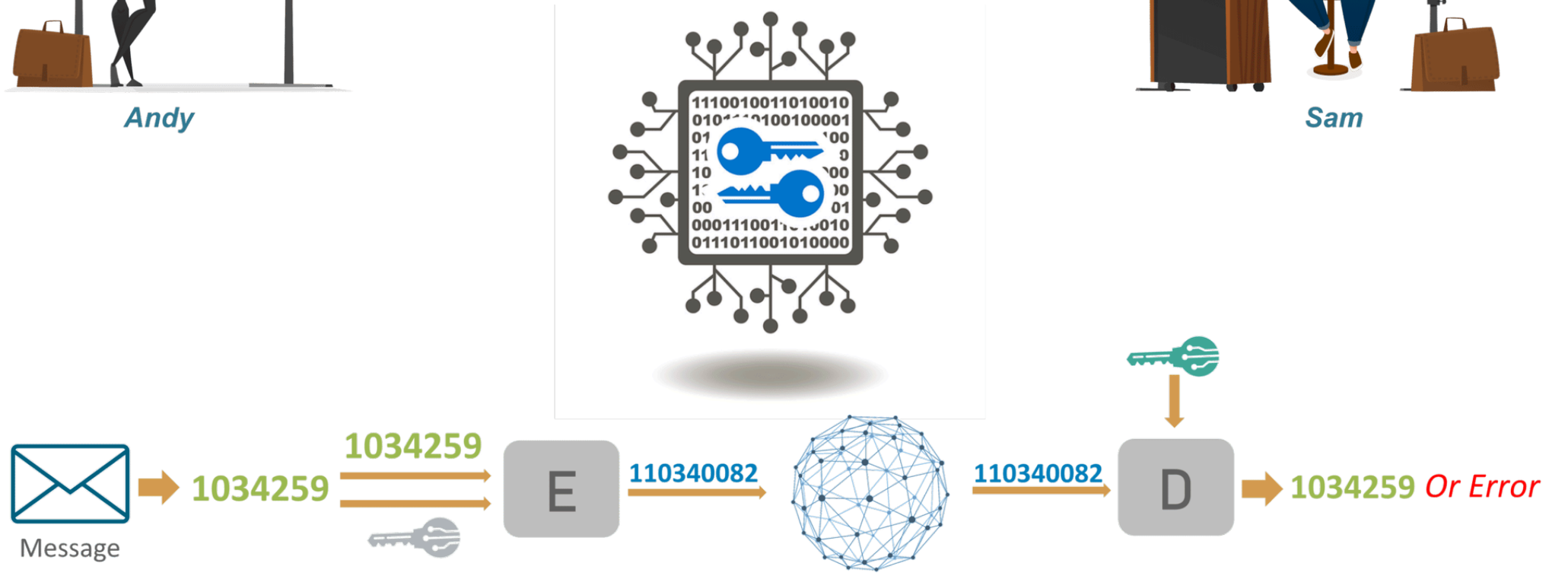
Overview

- Cryptography
  - Context
  - Ingredients
  - Classification
  - Attacks
  - Symmetric Encryption: Block Cipher
    - DES/Triple DES (Feistel Cipher Structure)
    - AES
- Symmetric Encryption: Stream Cipher
  - RC4
- Cipher Block Modes of Operation

Reading: Chapter 20 in Book “Computer Security Principles and Practice (Third Edition)” by William Stallings and Lawrie Brown

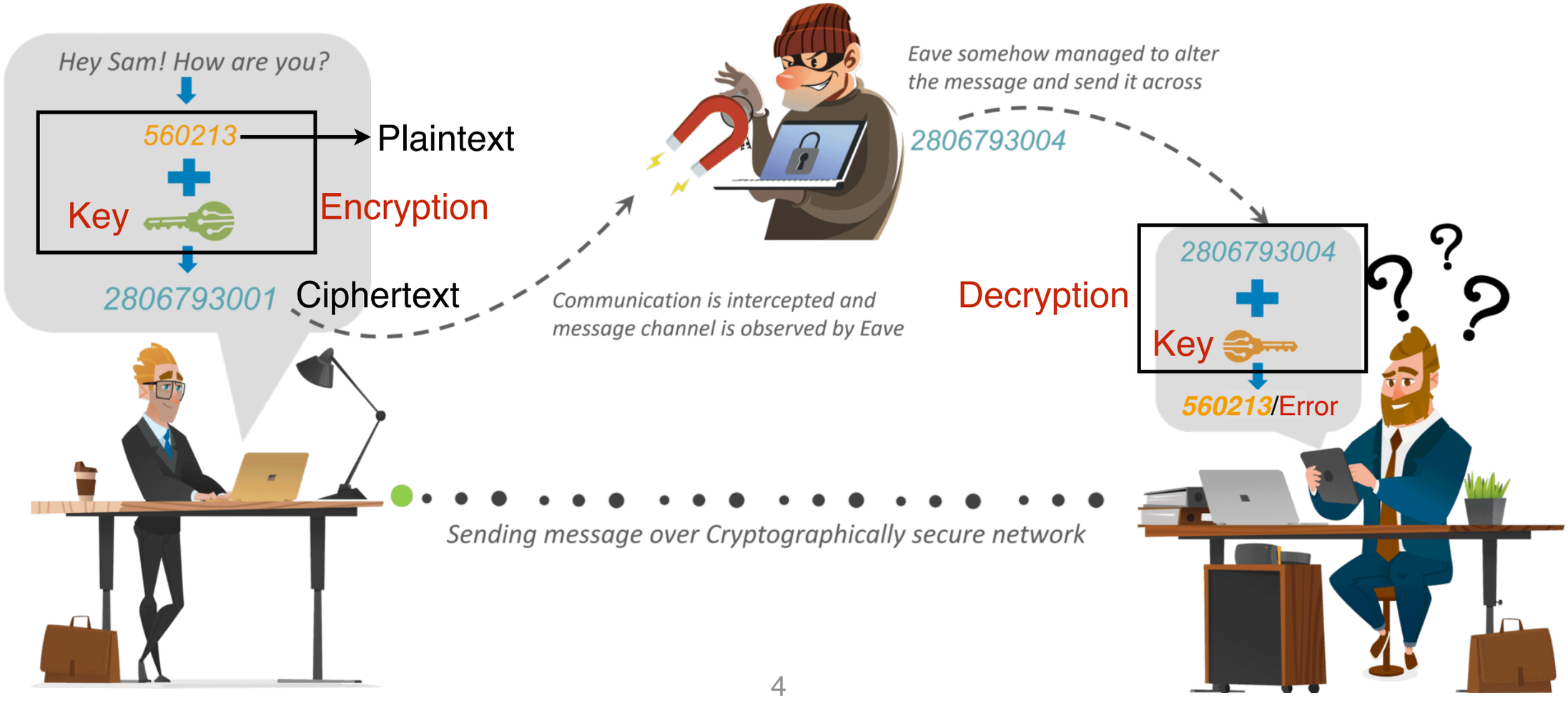
Cryptography: Context





Cryptography: Ingredients

- Plaintext: original message
- Encryption algorithm: substitution/transformations on the plain text
- Secret key: algorithm input, substitution/transformations depends on the key
- Ciphertext: algorithm output, depends on plain text and secret key
- Decryption algorithm: reverse of encryption

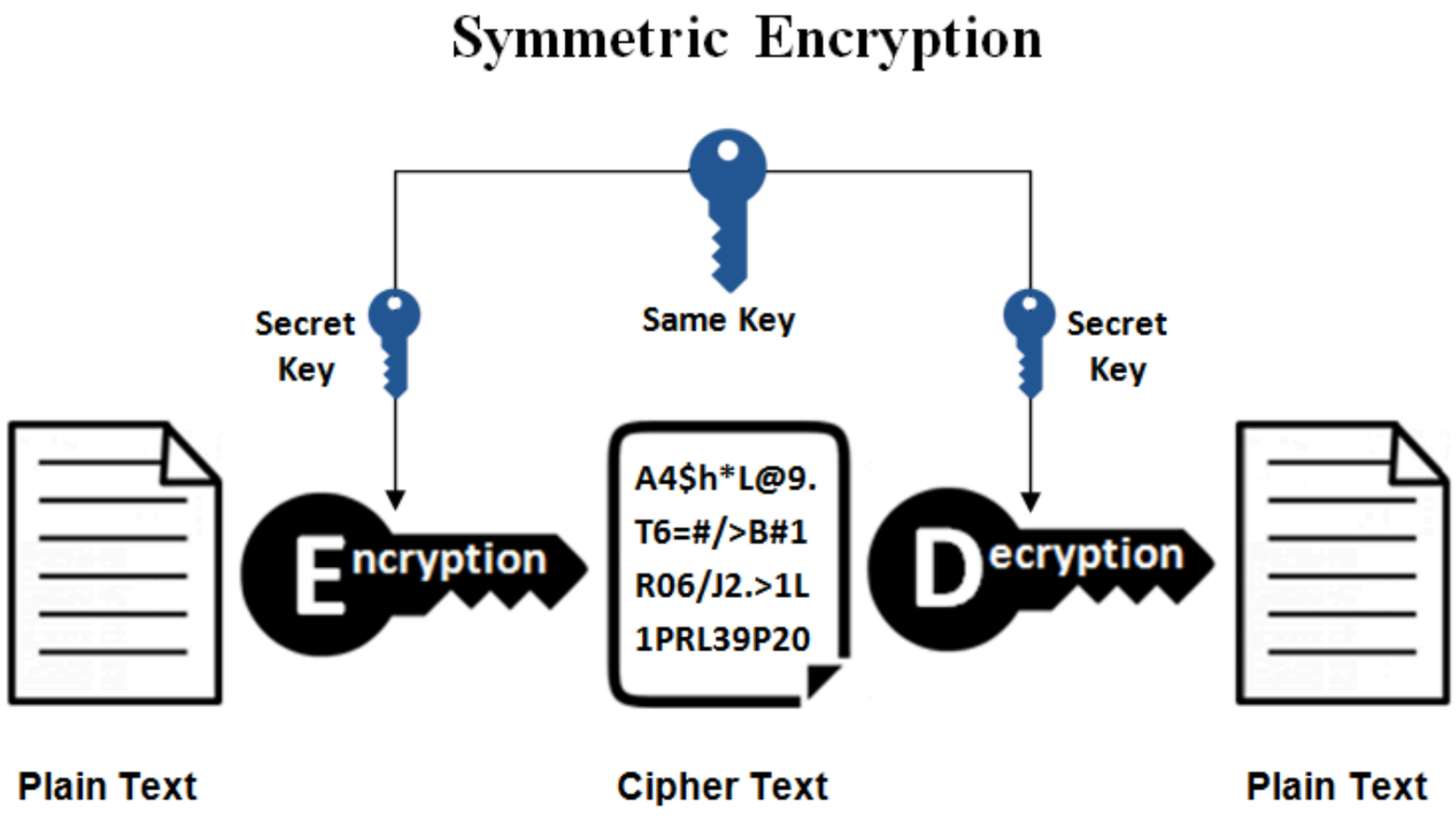


Cryptography: Classification

- The type of operations used for transforming plaintext to cipher text
  - Substitution: each element in the plaintext is mapped into another element
  - Transposition: elements in the plaintext are rearranged

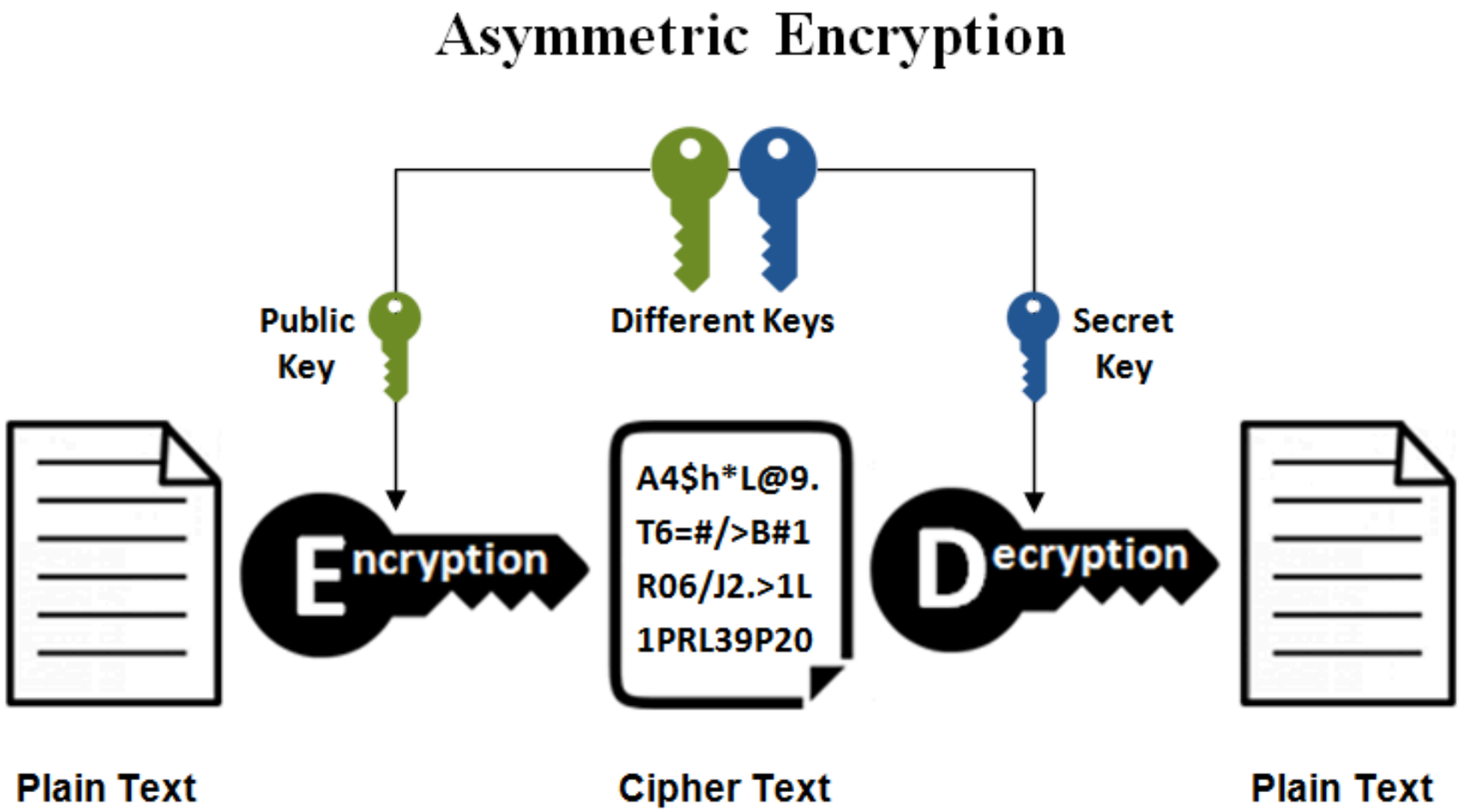
    Fundamental requirement: No information be lost
- The way in which the plaintext is processed
  - Block cipher: processes the input of one block of elements at a time
  - Stream cipher: processes the input elements continuously
- The number of keys used
  - Same key at sender and receiver — **Symmetric Encryption**
  - Different keys at sender and receiver — **Asymmetric Encryption**

Symmetric Encryption



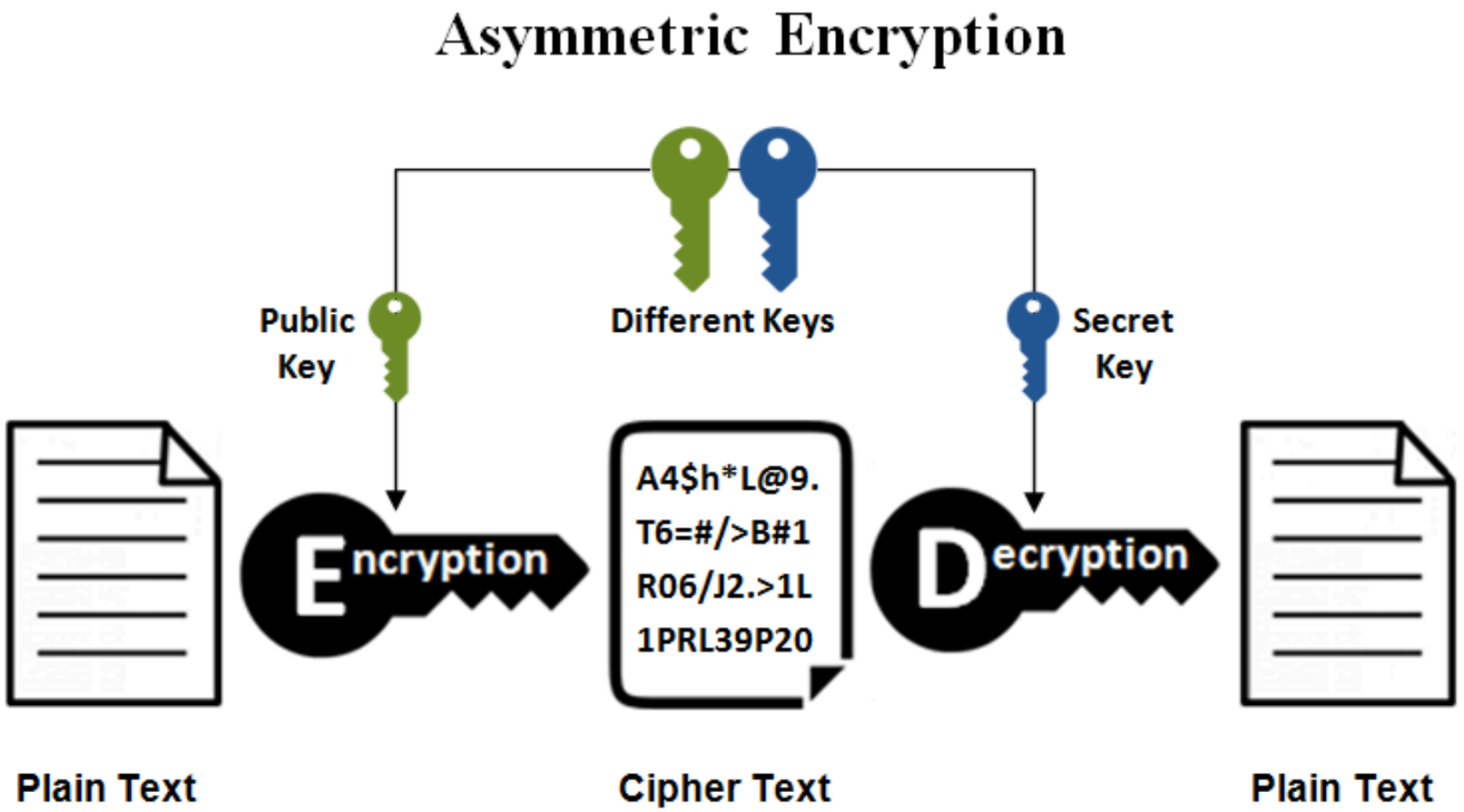
- Communication overhead to share the key
- To receive information from multiple sender, the secret key is shared among them, or create different keys for each sender.

Asymmetric Encryption



- Public key is freely available to anyone who is a sender
- Encryption by public key can only be decrypted by secrete key
- What about encryption by secret key?

Asymmetric Encryption



- Public key is freely available to anyone who is a sender
- Encryption by public key can only be decrypted by secrete key
- Encryption by secret key can be decrypted by anyone who has public key (DON'T encrypt message by secret key)

Types of Attacks on Encrypted Messages

Type of Attack	Known to Cryptanalyst
Ciphertext only	• Encryption algorithm • Ciphertext to be decoded
Known plaintext	• Encryption algorithm • Ciphertext to be decoded • One or more plaintext-ciphertext pairs formed with the secret key
Chosen plaintext	• Encryption algorithm • Ciphertext to be decoded • Plaintext message chosen by cryptanalyst, together with its corresponding cipher-text generated with the secret key
Chosen ciphertext	• Encryption algorithm • Ciphertext to be decoded • Purported ciphertext chosen by cryptanalyst, together with its corresponding decrypted plaintext generated with the secret key
Chosen text	• Encryption algorithm • Ciphertext to be decoded • Plaintext message chosen by cryptanalyst, together with its corresponding cipher-text generated with the secret key • Purported ciphertext chosen by cryptanalyst, together with its corresponding decrypted plaintext generated with the secret key

Easier (defend)

Harder (defend)

Types of Attacks on Encrypted Messages

- Ciphertext only attack
  - Encryption algorithm
  - Ciphertext to be decoded

How to decrypt the message?

Types of Attacks on Encrypted Messages

- Ciphertext only attack
  - Encryption algorithm
  - Ciphertext to be decoded

Brute force approach: try all possible keys until an intelligible translation of the cipher text into plaintext is obtained.

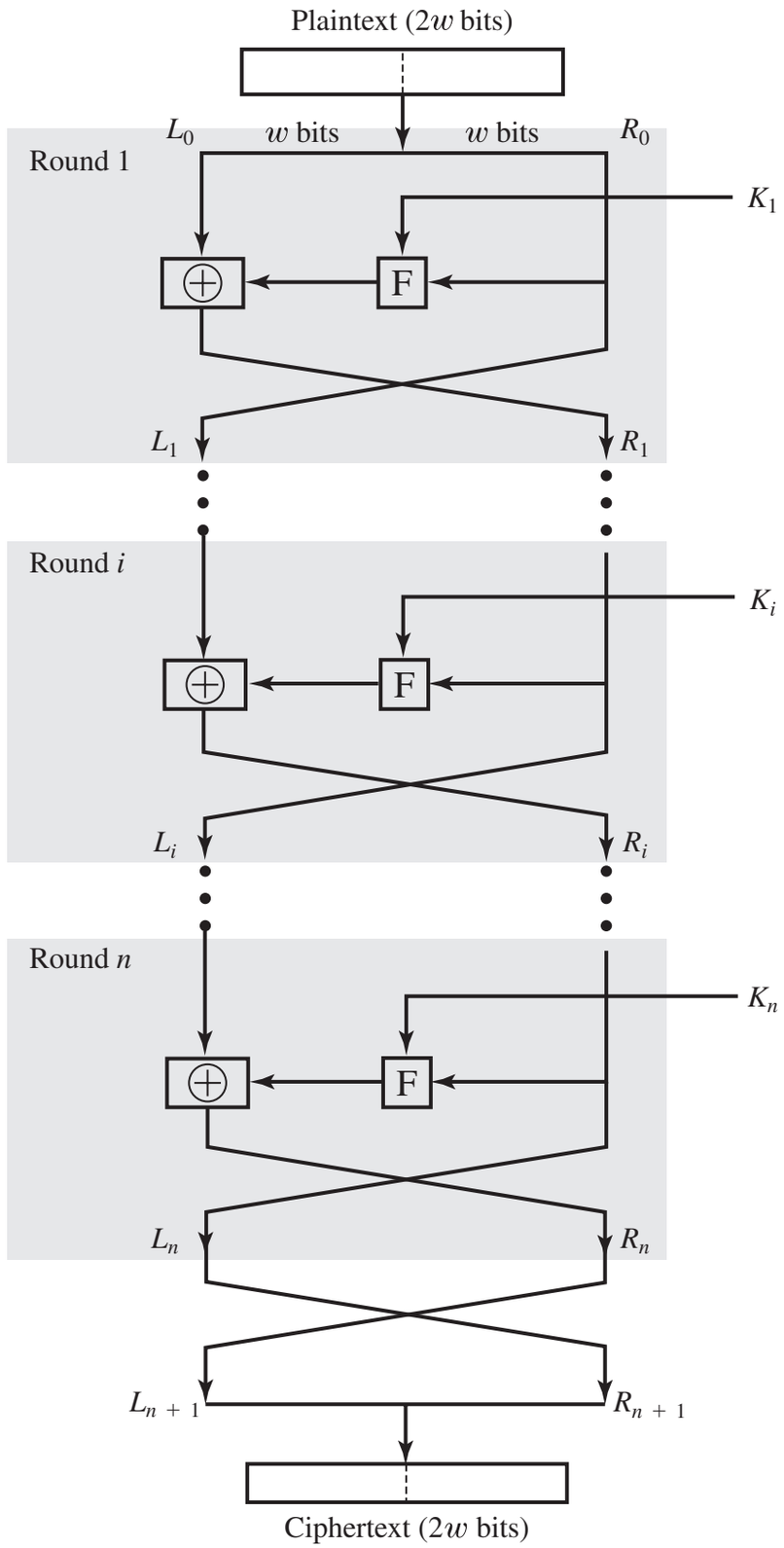
Impractical if the key space is large!

- **Computationally Secure**
  - The cost of breaking the cipher exceeds the value of the encrypted information
  - The time required to break the cipher exceeds the useful lifetime of the information

  Unfortunately, it is very difficult to estimate the amount of effort required to cryptanalyze ciphertext successfully.

Symmetric Encryption: Feistel Cipher Structure

- A structure for symmetric block encryption algorithm
  - The plaintext block is divided into two halves, L_0 and R_0
  - The two halves of the data pass through n rounds of processing and then combine to produce the ciphertext block.
  - The subkeys K_i are different from each other
  - Applying a round function F to the right half of the data and then taking the XOR of the output of F and the left half of the data (substitution on the left half)

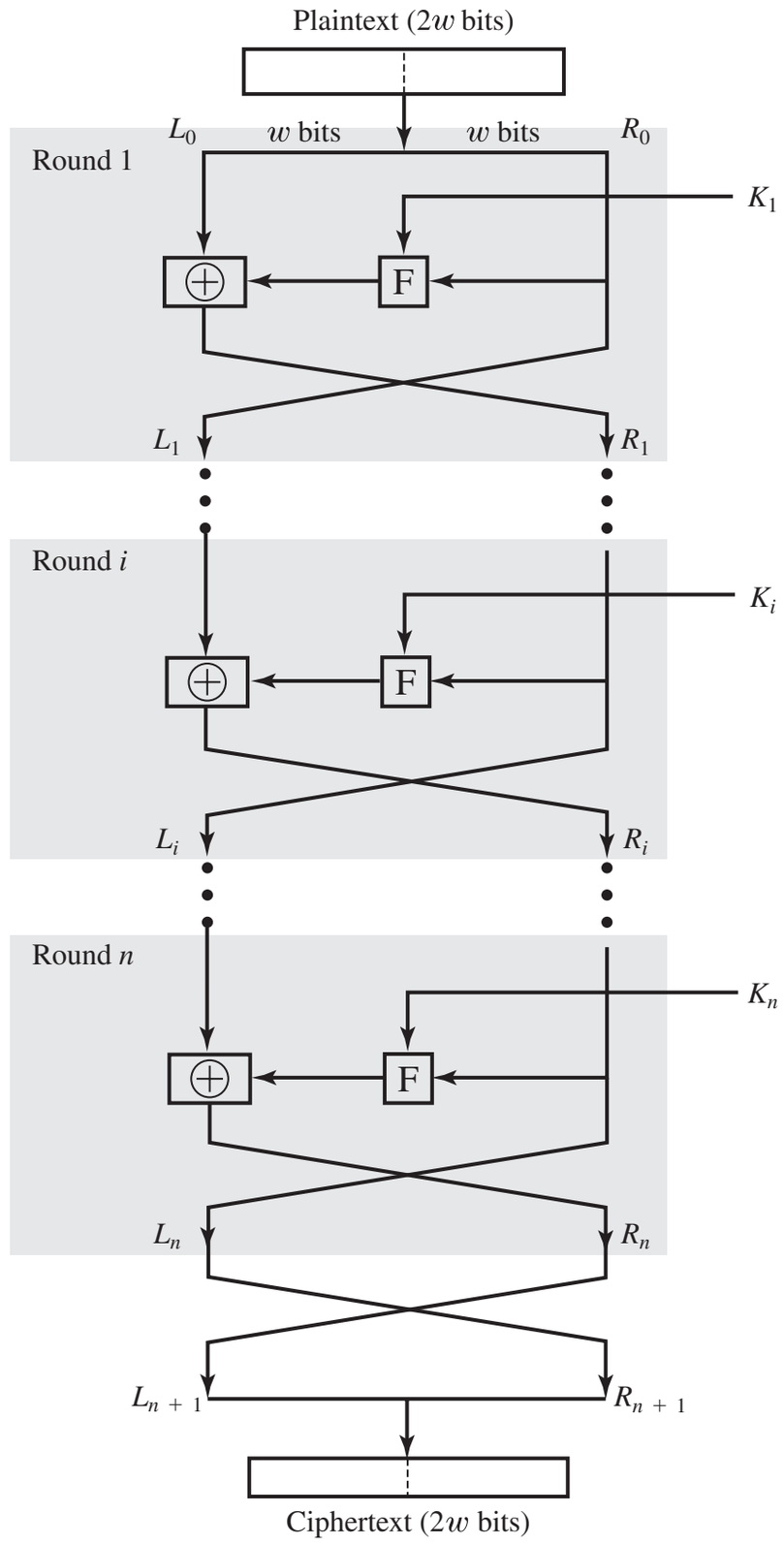


Symmetric Encryption: Design Features

- Block Size: larger block sizes mean greater security but reduced encryption/decryption speed. A block size of 128 bits is a reasonable tradeoff and is nearly universal among recent block cipher designs.
- Key Size: similar to block size, most common key length 128 bits.
- Number of rounds: a single round offers inadequate security but that multiple rounds offer increasing security. A typical size is 16 rounds.
- Subkey generation algorithm: greater complexity in this algorithm should lead to greater difficulty of cryptanalysis.
- Rond function: similar to subkey generation
- Fast software encryption/decryption: In many cases, encryption is embedded in applications or utility functions in such a way as to preclude a hardware implementation. Accordingly, the speed of execution of the algorithm becomes a concern.
- Ease of Analysis: if the algorithm can be concisely and clearly explained, it is easier to analyze that algorithm for cryptanalytic vulnerabilities and therefore develop a higher level of assurance as to its strength.

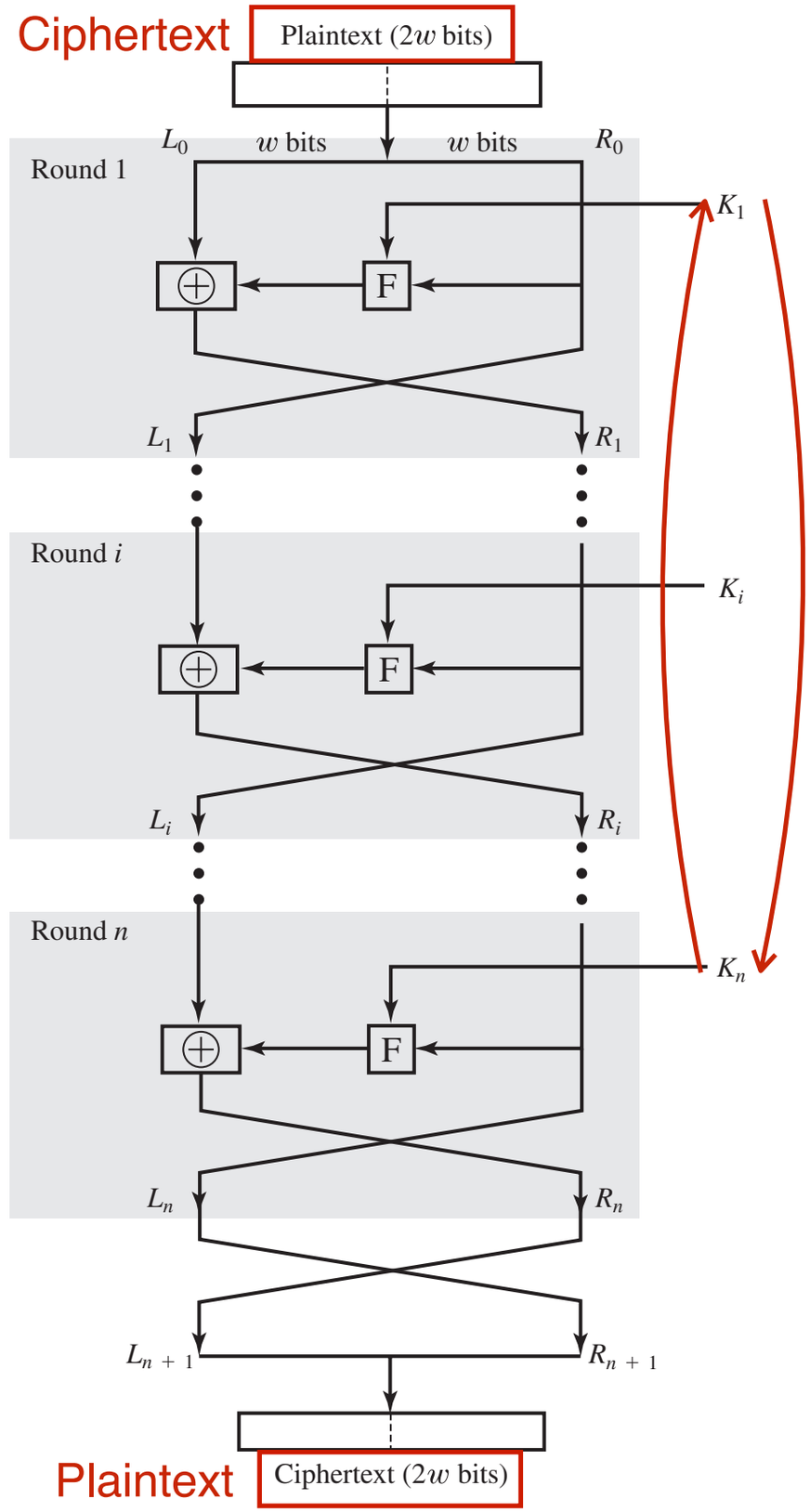
Symmetric Encryption: DES

- Data Encryption Standard
  - Symmetric block cipher
  - Plaintext 64 bits, longer plaintext are processed in 64-bit blocks
  - Key 56 bits
  - 16 rounds of processing
  - 16 subkeys are generated from the original key



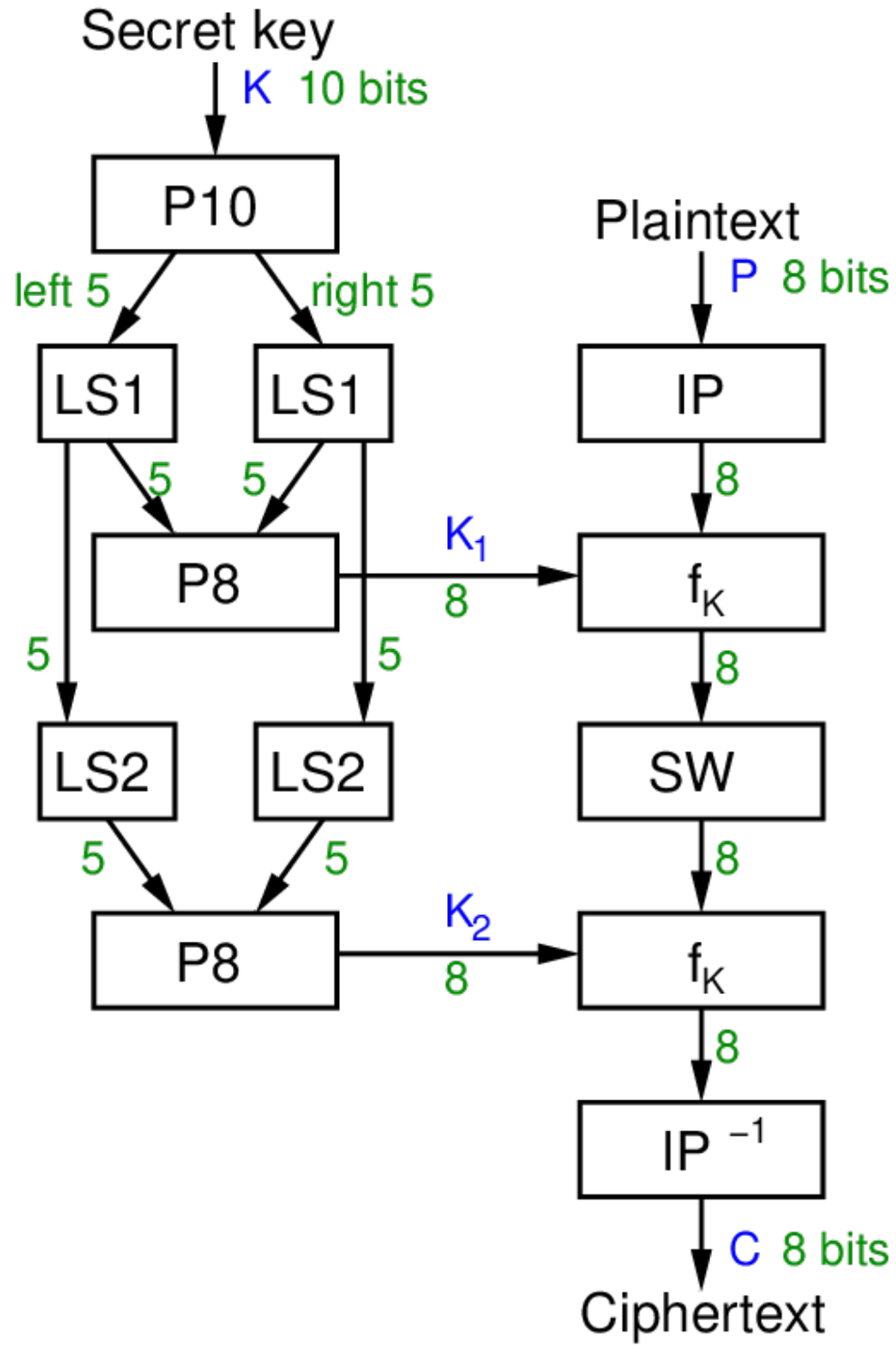
Symmetric Encryption: DES

- Decryption DES
  - Use the ciphertext as input to the DES algorithm
  - Use the subkeys K_i in reverse order



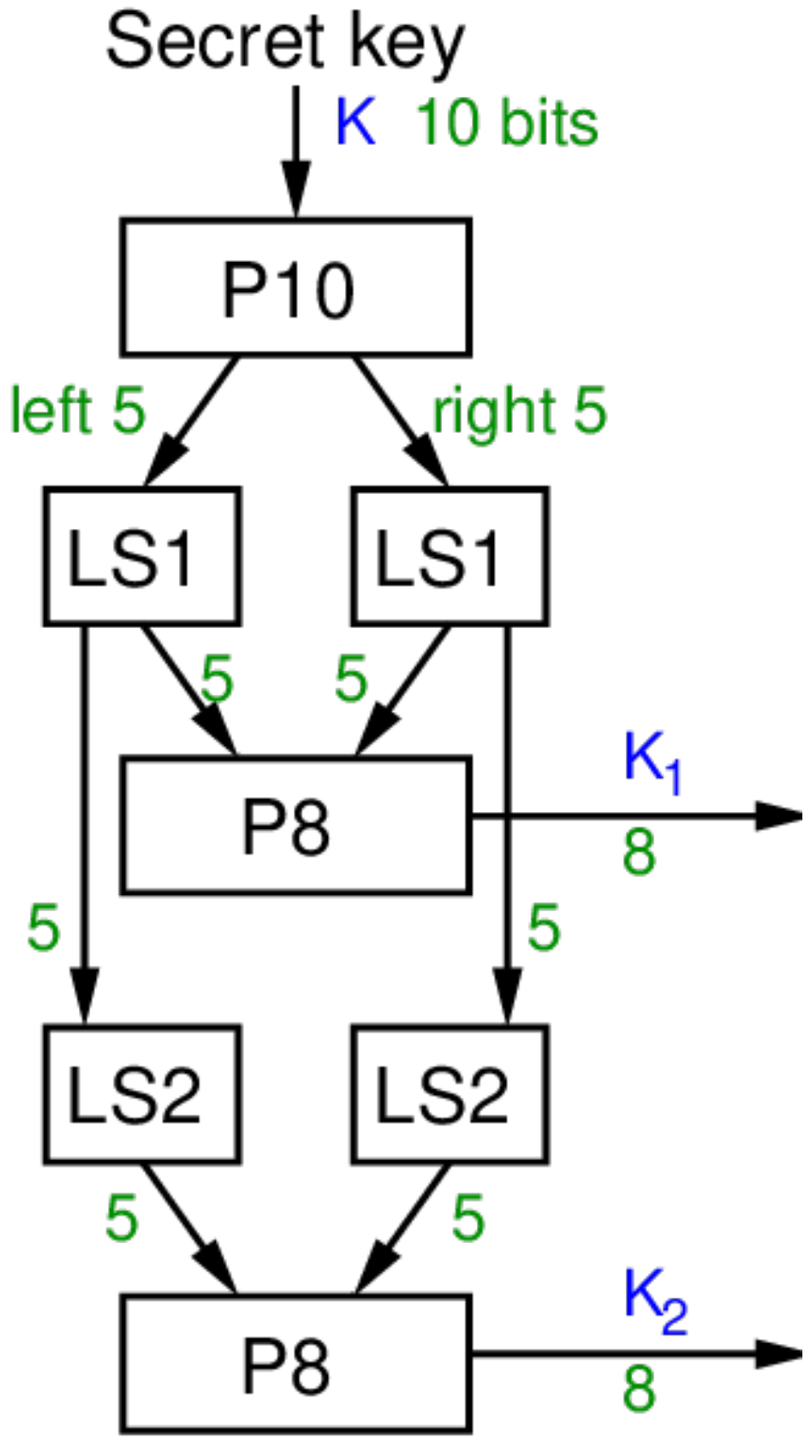
Symmetric Encryption: DES

- A simplified example for DES
  - Plaintext 8 bits
  - Ciphertext 8 bits
  - Key 10 bits
  - Rounds 2
  - Subkeys generated using permutations and left shifts
  - Encryption: initial permutation, round function, switch halves
  - Decryption: Same as encryption, except round keys used in opposite order



Symmetric Encryption: DES

- A simplified example for DES
  - Key generation
  - Original key: 1 0 1 0 0 0 0 0 1 0
  - After P10: 1 0 0 0 0 0 1 1 0 0
  - Left 5: 1 0 0 0 0 Right 5: 0 1 1 0 0
  - LS1(left 5): 0 0 0 0 1 LS1(right 5): 1 1 0 0 0
  - Input P8: 0 0 0 0 1 1 1 0 0 0
  - K1: 1 0 1 0 0 1 0 0



P10 (permutate)

```
Input : 1 2 3 4 5 6 7 8 9 10

Output: 3 5 2 7 4 10 1 9 8 6
```

P8 (select and permutate)

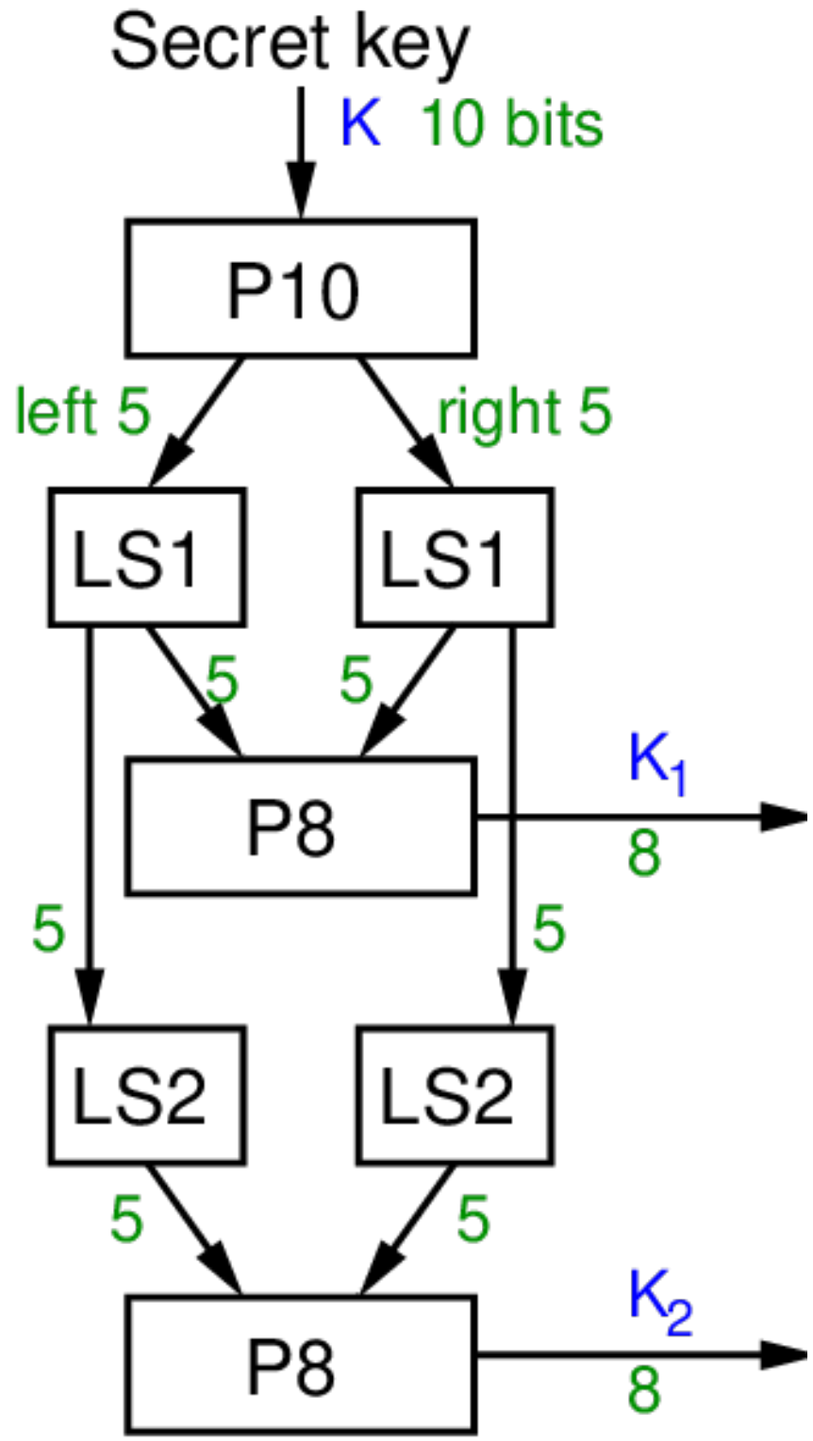
```
Input : 1 2 3 4 5 6 7 8 9 10

Output: 6 3 7 4 8 5 10 9
```

LS1: Circular left shift by 1 position
LS2: Circular left shift by 2 position

Symmetric Encryption: DES

- A simplified example for DES
  - Key generation
  - LS1(left 5): 0 0 0 0 1 LS1(right 5): 1 1 0 0 0
  - Exercise: How to get K2?



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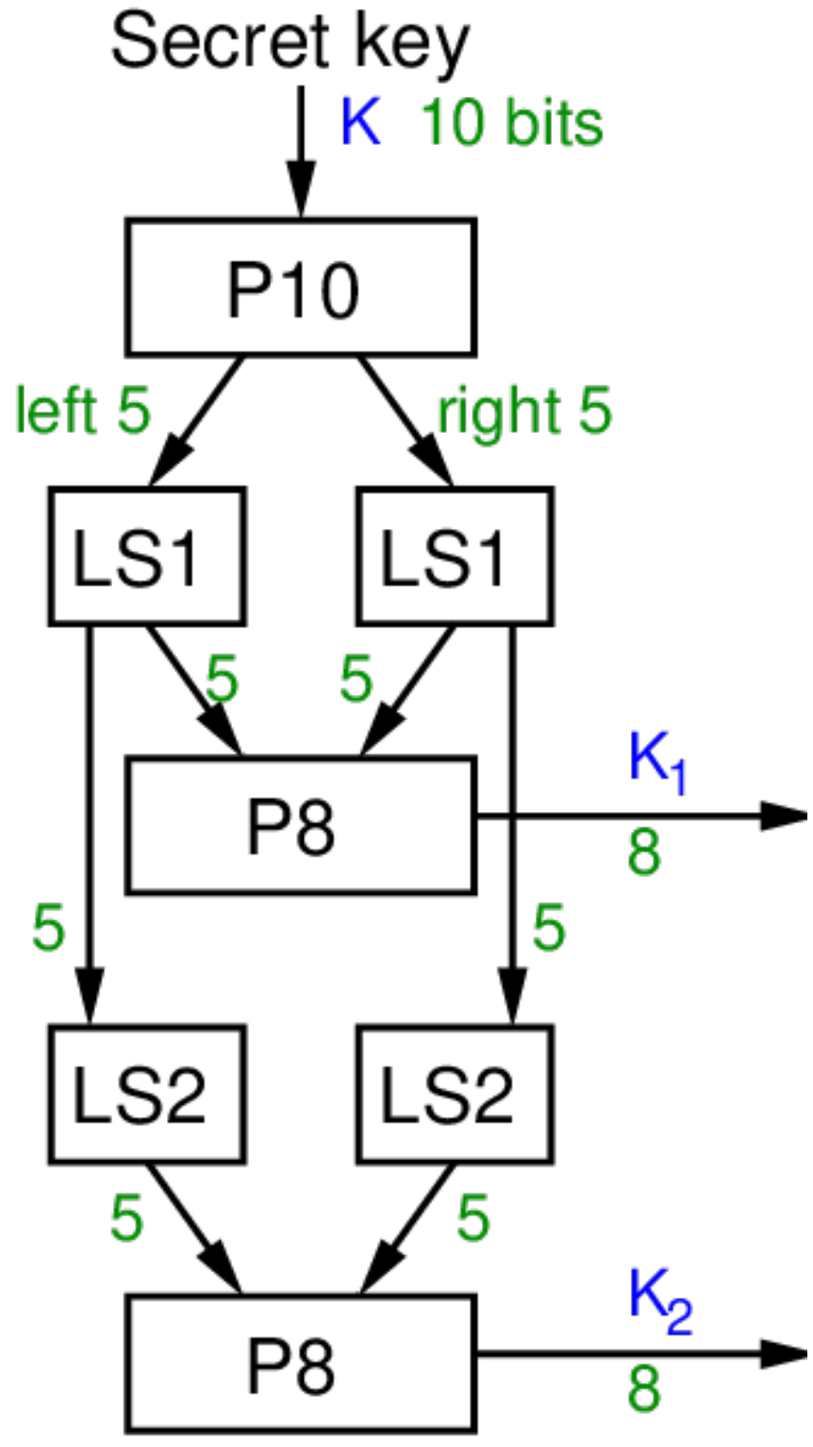
Symmetric Encryption: DES

- A simplified example for DES
  - Key generation
  - LS1(left 5): 0 0 0 0 1 LS1(right 5): 1 1 0 0 0
  - LS2 (left 5): 0 0 1 0 0 LS2(right 5): 0 0 0 1 1
  - Input P8: 0 0 1 0 0 0 0 0 1 1
  - K2: 0 1 0 0 0 0 1 1



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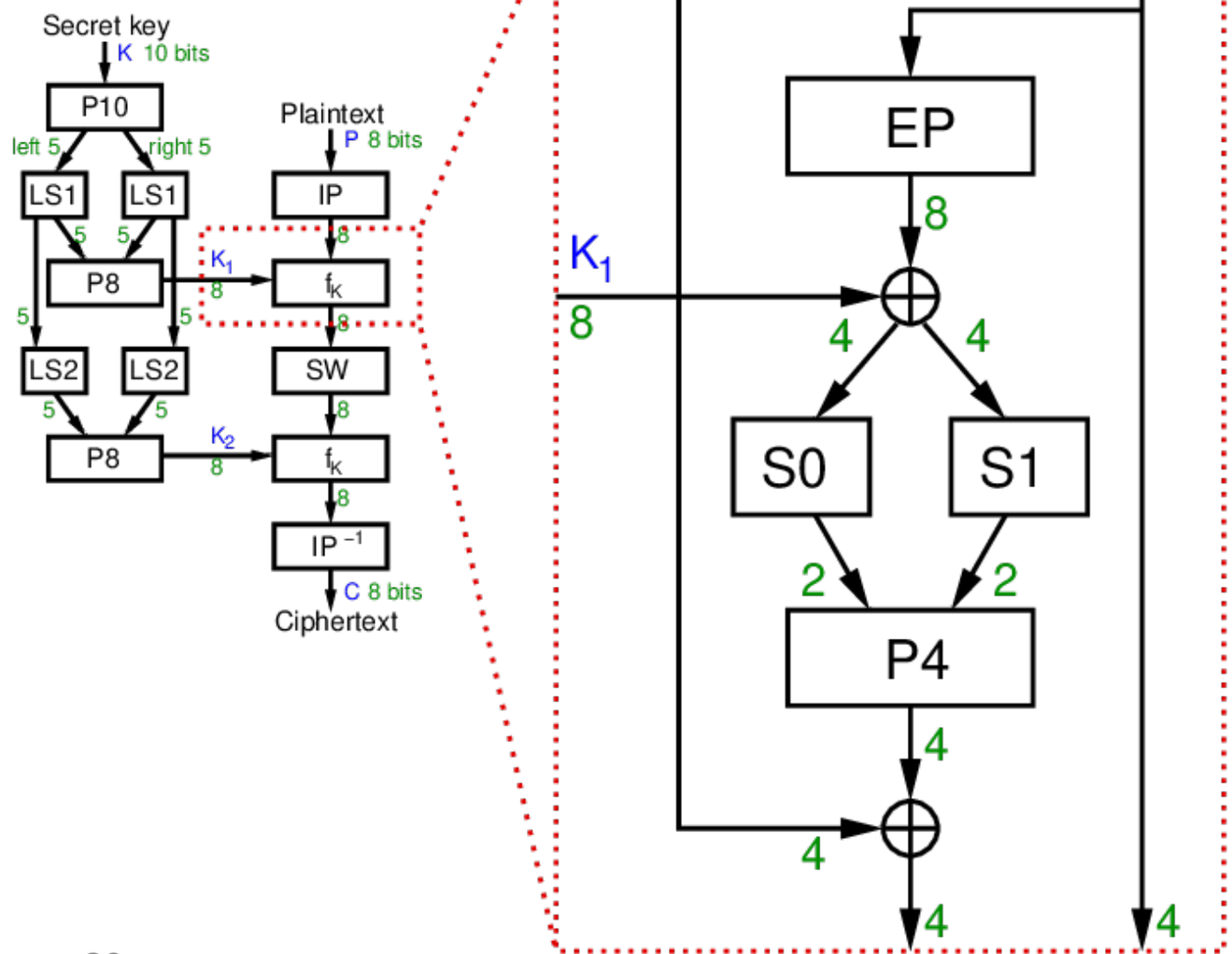
Symmetric Encryption: DES

- A simplified example for DES
  - Encryption: plaintext 0 1 1 1 0 0 1 0
  - K1: 1 0 1 0 0 1 0 0 K2: 0 1 0 0 0 0 1 1



IP (initial permutation)

```
Input : 1 2 3 4 5 6 7 8

Output: 2 6 3 1 4 8 5 7
```

IP-1: inverse of IP, such that X = IP-1(IP(X))

EP (expand and permutate)

```
Input : 1 2 3 4

Output: 4 1 2 3 2 3 4 1
```

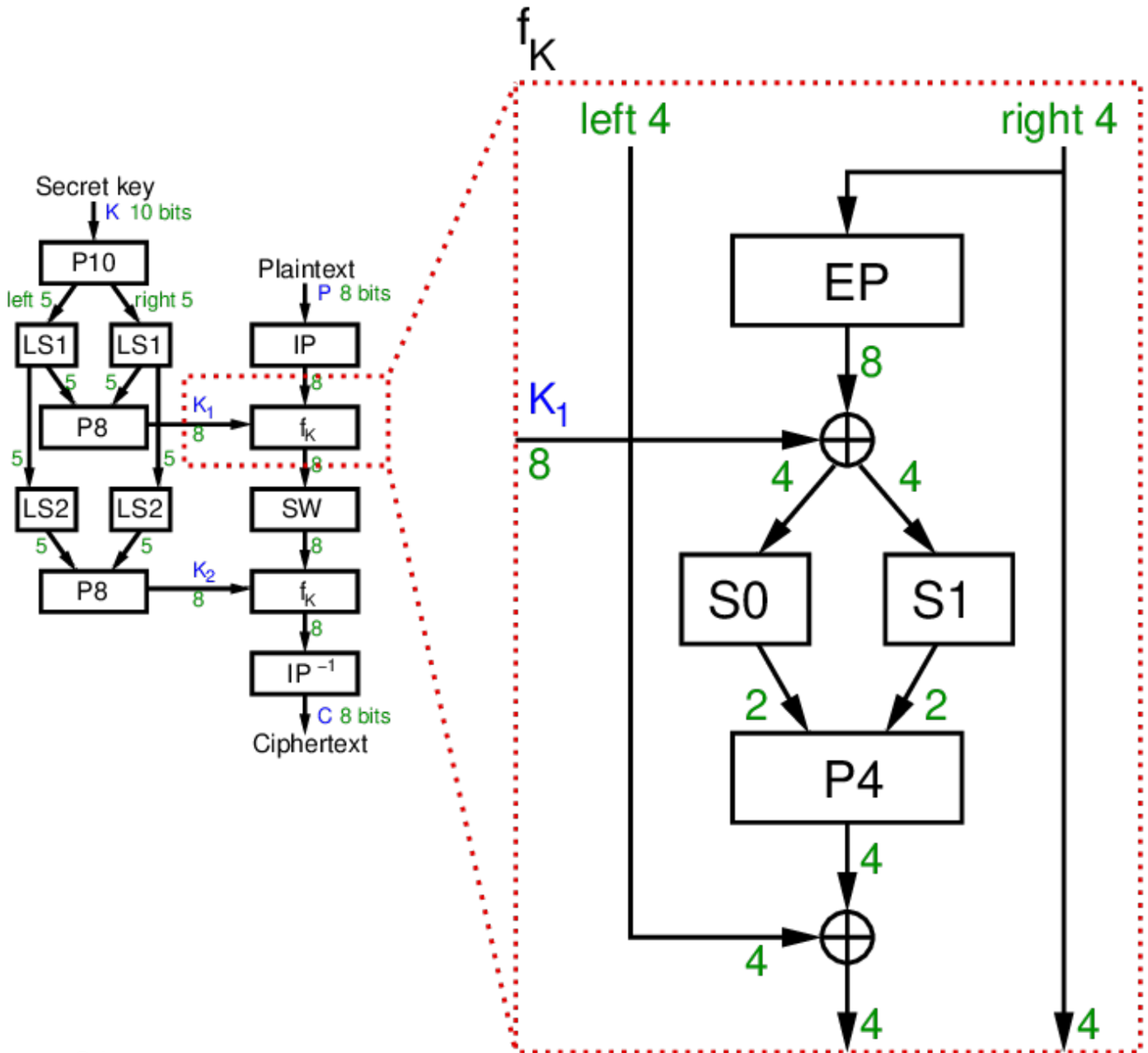
P4 (permutate)

```
Input : 1 2 3 4

Output: 2 4 3 1
```

Symmetric Encryption: DES

- A simplified example for DES
  - Encryption: plaintext 0 1 1 1 0 0 1 0
  - IP: 1 0 1 0 1 0 0 1
  - EP: 1 1 0 0 0 0 1 1
  - XOR K1 (1 0 1 0 0 1 0 0):
    - 0 1 1 0 0 1 1 1



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Input : 1 2 3 4
Output: 4 1 2 3 2 3 4 1
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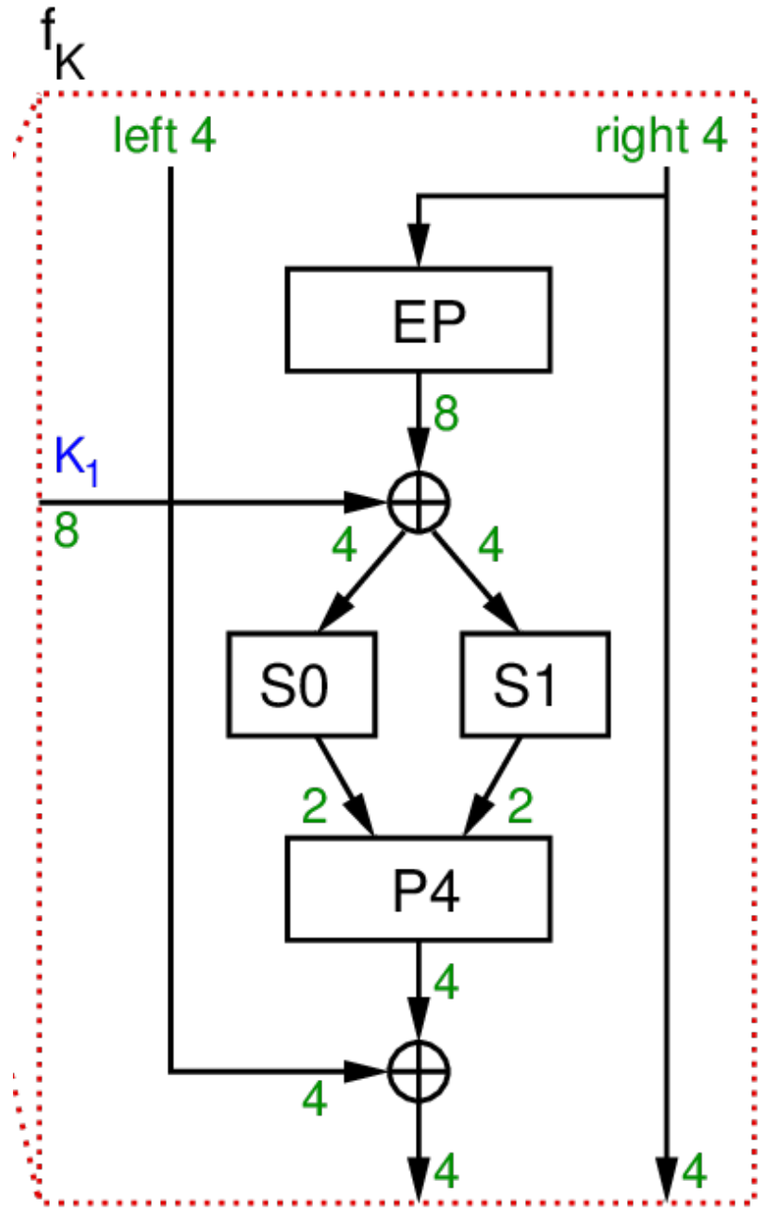
XOR truth table

Input		Output
A	B	
0	0	0
0	1	1
1	0	1
1	1	0

Symmetric Encryption: DES

- A simplified example for DES
  - Output XOR: 0 1 1 0 0 1 1 1
  - Input S0: 0 1 1 0
  - S0: row index (1st, 4th digit) —> 00 and column index (2nd, 3rd digit) —> 11
  - Output S0: 10



S-DES S-Boxes

- S-DES (and DES) perform substitutions using S-Boxes
- S-Box considered as a matrix: input used to select row/column; selected element is output
- 4-bit input: $bit_1, bit_2, bit_3, bit_4$
- $bit_1 bit_4$ specifies row (0, 1, 2 or 3 in decimal)
- $bit_2 bit_3$ specifies column
- 2-bit output

$$S0 = \begin{bmatrix} 01 & 00 & 11 & 10 \\ 11 & 10 & 01 & 00 \\ 00 & 10 & 01 & 11 \\ 11 & 01 & 11 & 10 \end{bmatrix} \quad S1 = \begin{bmatrix} 00 & 01 & 10 & 11 \\ 10 & 00 & 01 & 11 \\ 11 & 00 & 01 & 00 \\ 10 & 01 & 00 & 11 \end{bmatrix}$$

Symmetric Encryption: DES

- A simplified example for DES
  - Output XOR: 0 1 1 0 0 1 1 1
  - Input S1: 0 1 1 1
  - Exercise: Output S1?

S-DES S-Boxes

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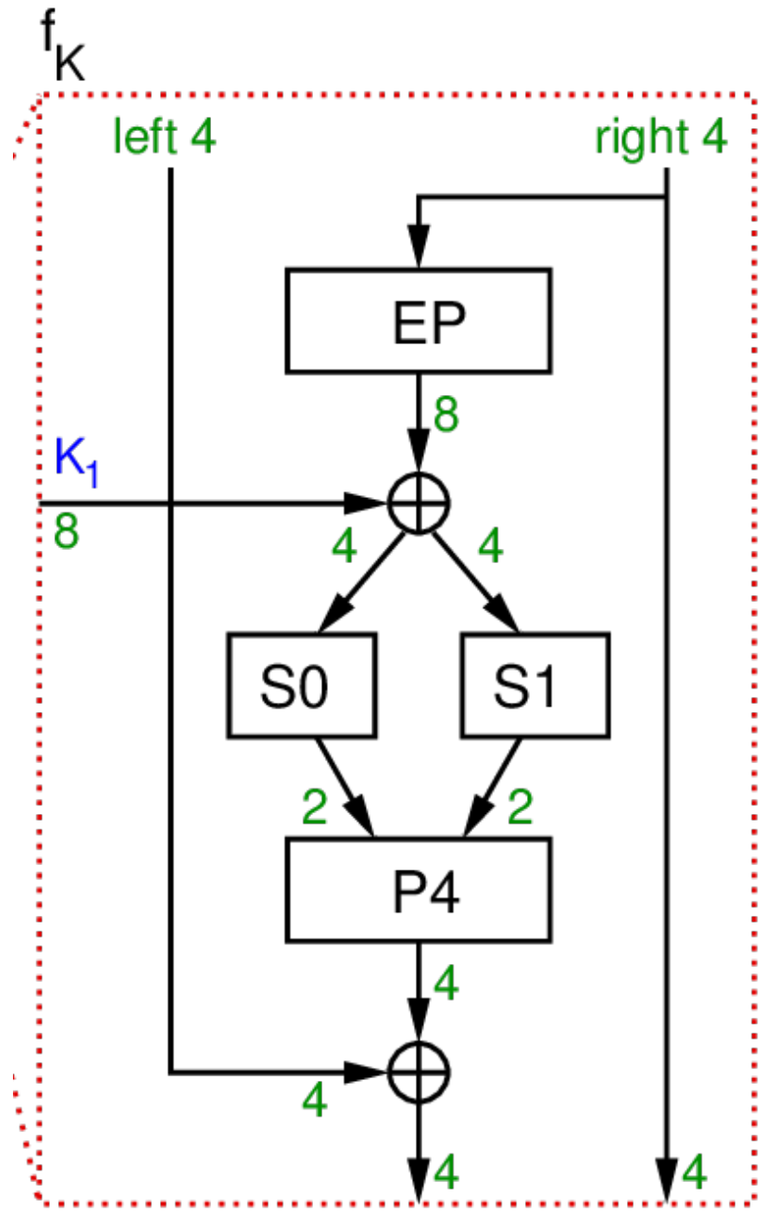
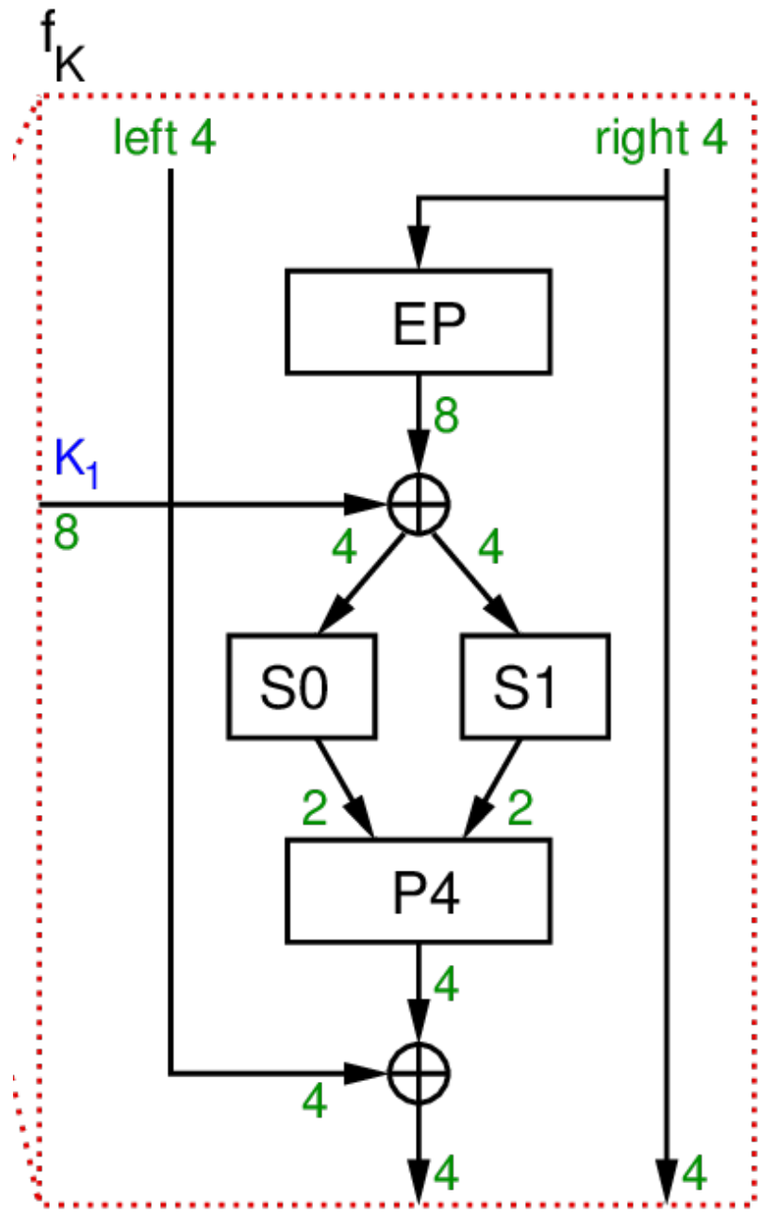


Symmetric Encryption: DES

- A simplified example for DES
  - Output XOR: 0 1 1 0 0 1 1 1
  - Input S1: 0 1 1 1
  - S1: row 01 and column 11
  - Output S1: 11



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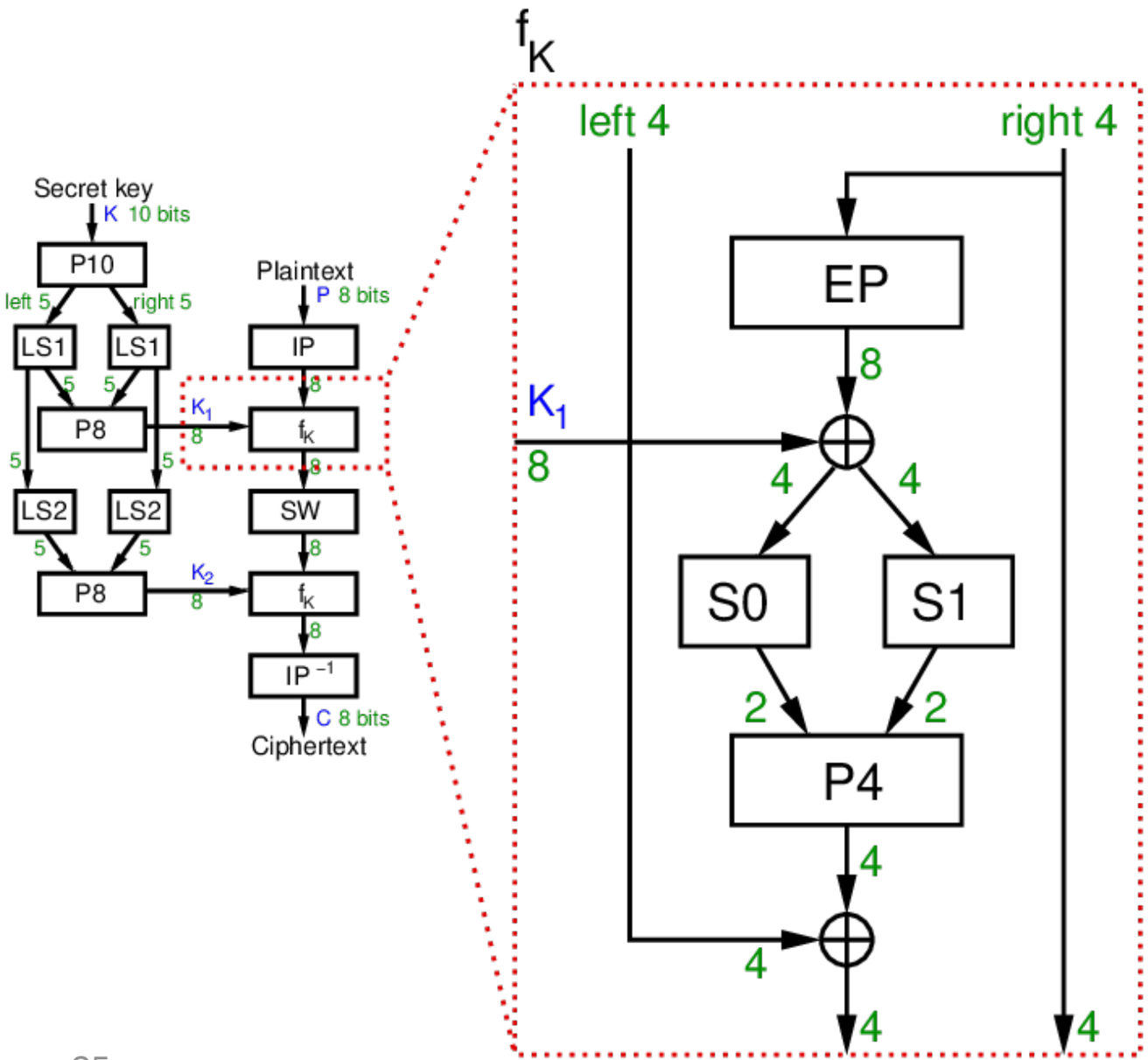
Symmetric Encryption: DES

- A simplified example for DES
  - S0: 10 S1: 11
  - P4: 0 1 1 1
  - IP: 1 0 1 0 1 0 0 1
  - P4 XOR (1 0 1 0): 1 1 0 1
  - left: 1101 right: 1001



P4 (permutate)

```
Input : 1 2 3 4

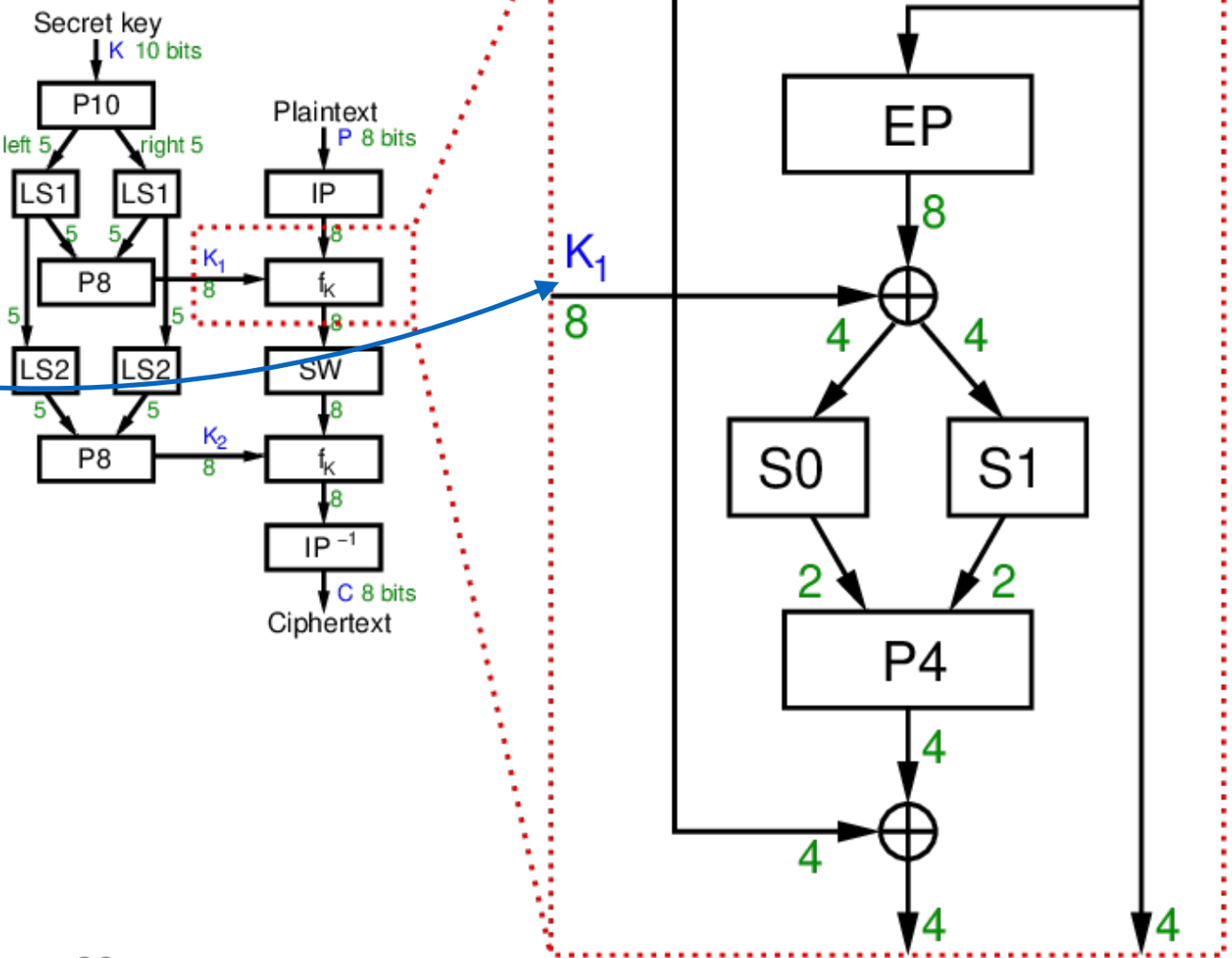
Output: 2 4 3 1
```

XOR truth table

Input		Output
A	B	
0	0	0
0	1	1
1	0	1
1	1	0

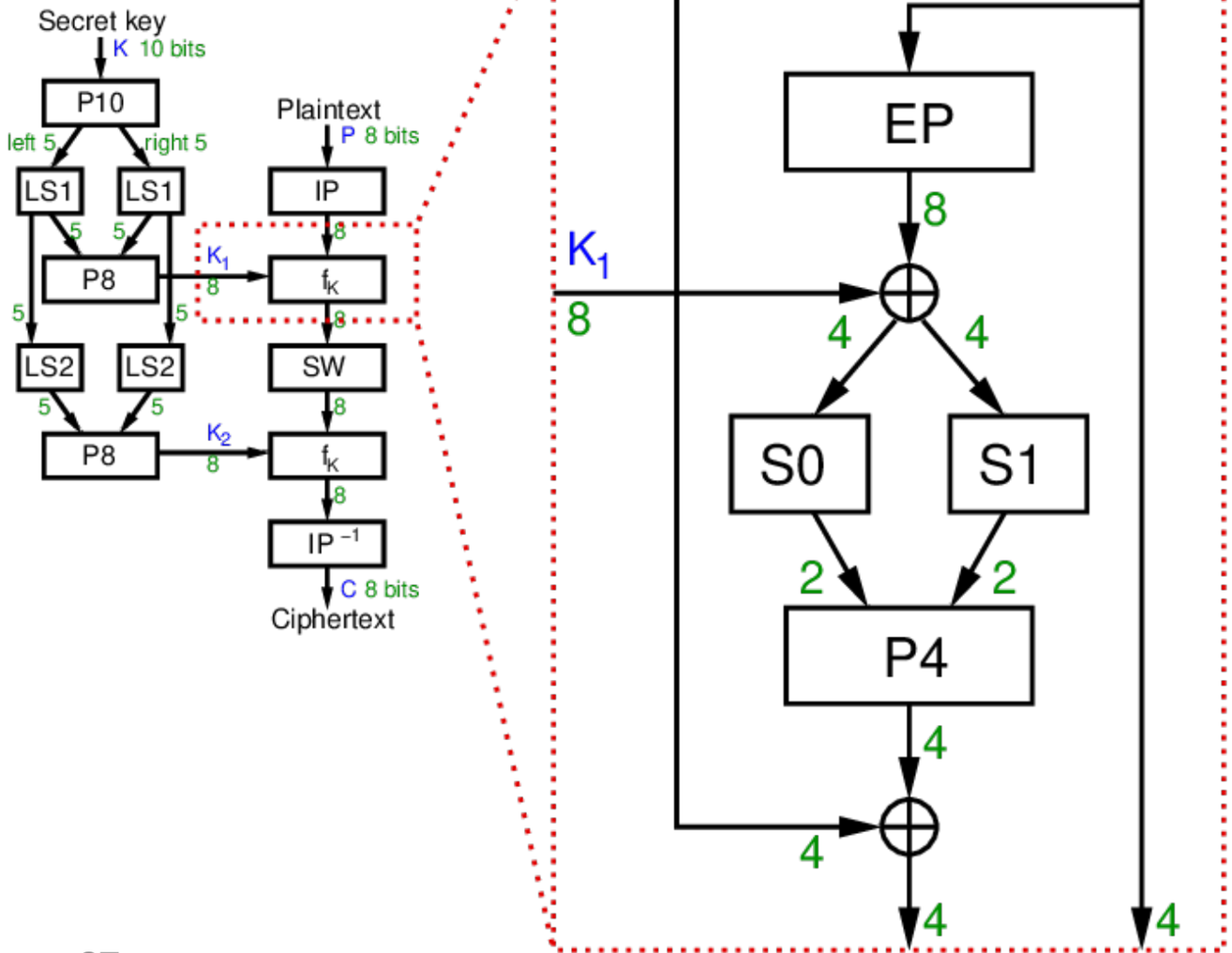
Symmetric Encryption: DES

- A simplified example for DES
  - left: 1101 right: 1001
  - Swap: 1001 1101
  - Exercise: Output of round 2?
    - K2: 0 1 0 0 0 0 1 1



Symmetric Encryption: DES

- A simplified example for DES
  - left: 1101 right: 1001
  - Swap: 1001 1101
  - Output f2: 1 1 1 0 1 1 0 1
  - Ciphertext: 0 1 1 1 0 1 1 1



IP (initial permutation)

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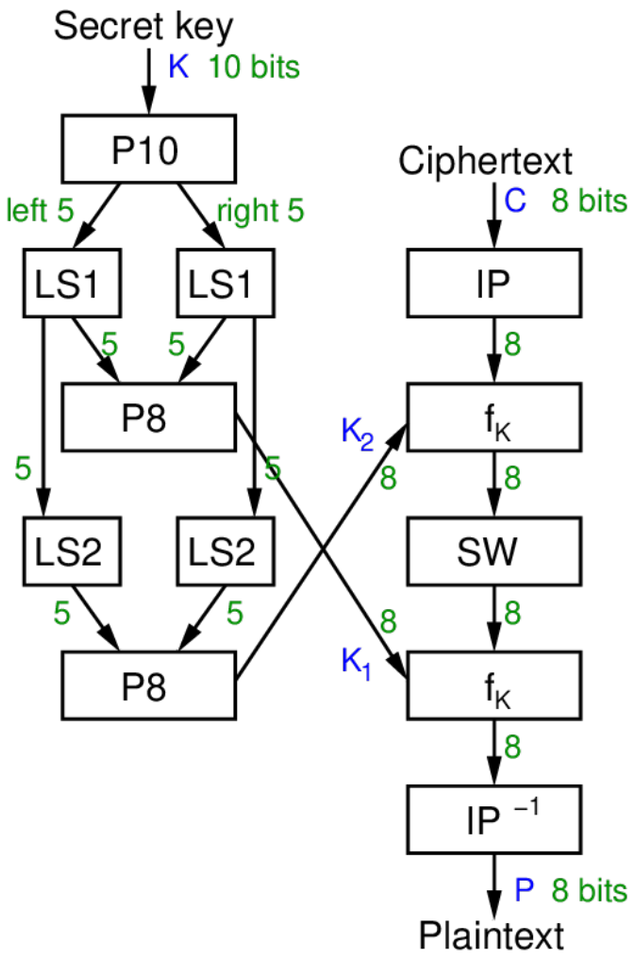
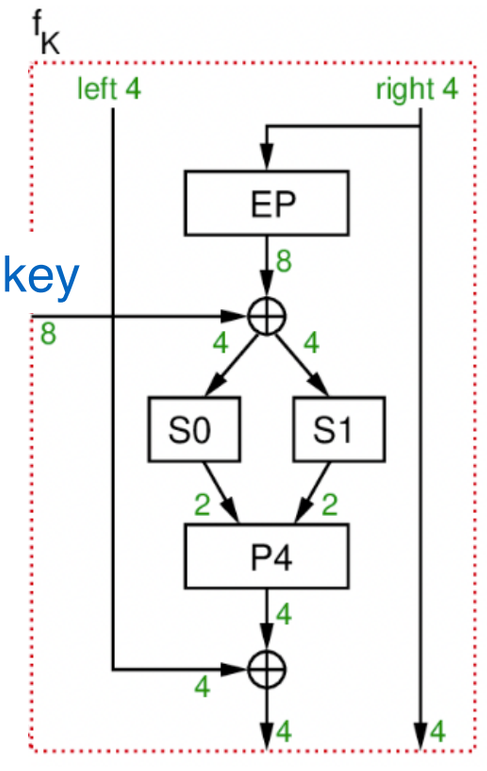
IP-1: inverse of IP, such that X = IP-1(IP(X))

Symmetric Encryption: DES

- A simplified example for DES
  - Decryption ciphertext: 0 1 1 1 0 1 1 1
  - K1: 10100100 K2: 01000011
  - Exercise: Can you recover plaintext 0 1 1 1 0 0 1 0?





EP (expand and permutate)

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Output: 4 1 2 3 2 3 4 1
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IP (initial permutation)

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```

XOR truth table

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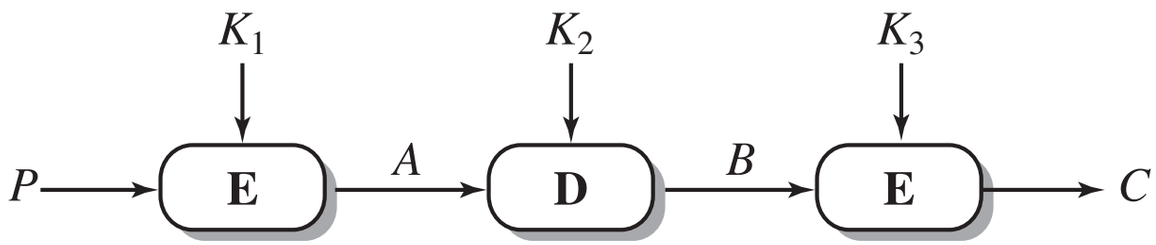
Symmetric Encryption: Triple DES

- 3 DES uses three keys and three executions of the DES algorithm. The function follows an encrypt-decrypt-encrypt (EDE) sequence

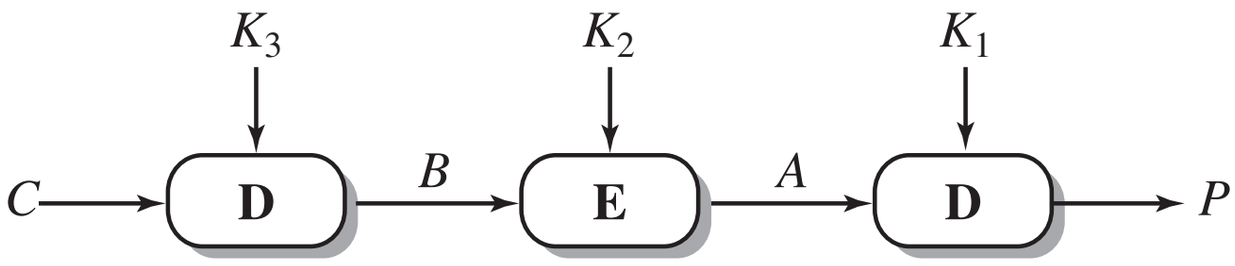


(a) Encryption

$$C = \mathrm{E}(K_3, \mathrm{D}(K_2, \mathrm{E}(K_1, p)))$$

C = ciphertext
P = plaintext
$\mathrm{E}[K, X]$ = encryption of X using key K
$\mathrm{D}[K, Y]$ = decryption of Y using key K

- Decryption is simply the same operation with the key reversed

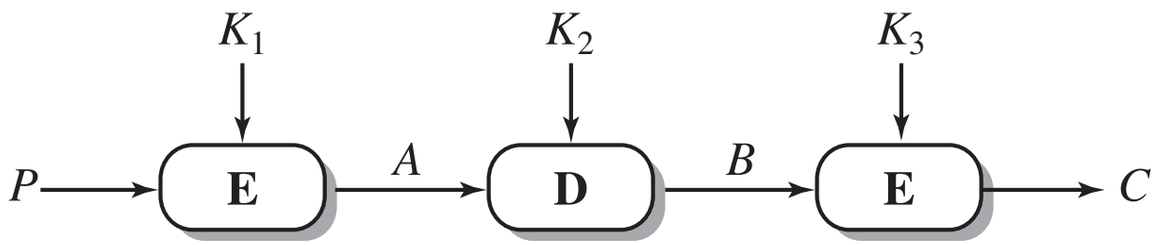


(b) Decryption

$$P = \mathrm{D}(K_1, \mathrm{E}(K_2, \mathrm{D}(K_3, \mathrm{C})))$$

Symmetric Encryption: Triple DES

- 3 DES uses three keys and three executions of the DES algorithm. The function follows an encrypt-decrypt-encrypt (EDE) sequence



(a) Encryption

$$C = \mathrm{E}(K_3, \mathrm{D}(K_2, \mathrm{E}(K_1, p)))$$

C = ciphertext
P = plaintext
$\mathrm{E}[K, X]$ = encryption of X using key K
$\mathrm{D}[K, Y]$ = decryption of Y using key K

- Can triple DES reduce to single DES?

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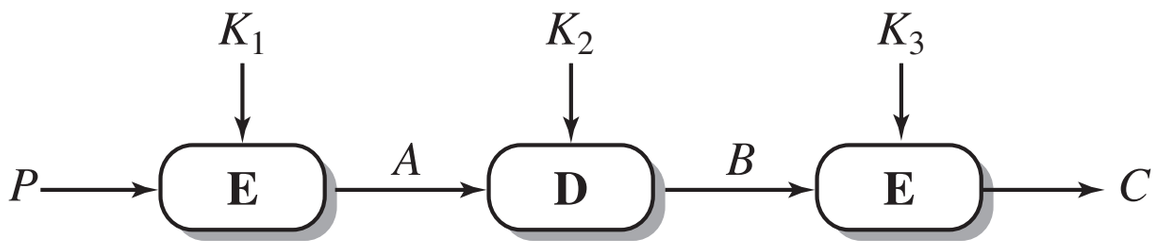

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P = plaintext
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$\mathrm{D}[K, Y]$ = decryption of Y using key K

- Can triple DES reduce to single DES?
  - K1=K2=K3

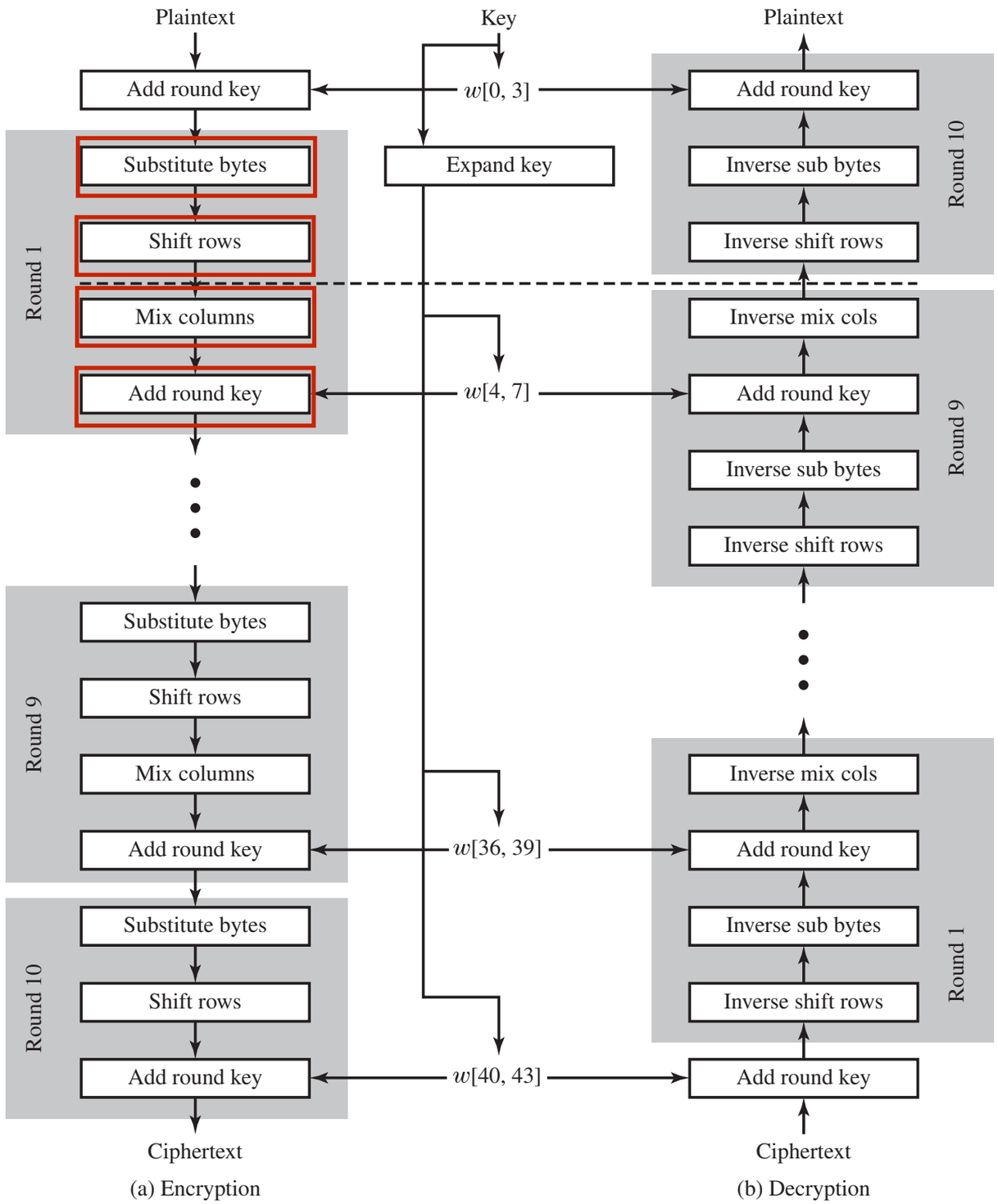
$$C = \mathrm{E}(K_1, \mathrm{D}(K_1, \mathrm{E}(K_1, P))) = \mathrm{E}[K, P]$$

There is no cryptographic significance to the use of decryption for the second stage of 3DES encryption. Its only advantage is that it allows users of 3DES to decrypt data encrypted by users of the older single DES.

Symmetric Encryption: AES

- Advanced encryption standard (AES) [more secure and efficient]
  - Block length 128 bits
  - Key length can be 128, 192, or 256 bits
  - Not a Feistel structure, processes the entire data block in parallel during each round using substitutions and permutation. [Feistel structure: half of the data block is used to modify the other half, and then the halves are swapped.]
  - Key operations: substitute bytes, shift rows, mix columns, and add round key.
  - All operations are reversible: for substitute bytes, shift rows, mix columns, an inverse function is used in the decryption; for add round key, the inverse is achieved by XOR the same round key to the block — $\mathbf{A} \oplus \mathbf{A} \oplus \mathbf{B} = \mathbf{B}$.
  - It is easy to verify that decryption does recover the plaintext by reversible operations.

Symmetric Encryption: AES



Symmetric Encryption: AES

- Substitute Bytes Transformation
  - AES defines a 16·16 matrix of byte values, called an S-box

x \ y	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	63	7C	77	7B	F2	6B	6F	C5	30	01	67	2B	FE	D7	AB	76
1	CA	82	C9	7D	FA	59	47	F0	AD	D4	A2	AF	9C	A4	72	C0
2	B7	FD	93	26	36	3F	F7	CC	34	A5	E5	F1	71	D8	31	15
3	04	C7	23	C3	18	96	05	9A	07	12	80	E2	EB	27	B2	75
4	09	83	2C	1A	1B	6E	5A	A0	52	3B	D6	B3	29	E3	2F	84
5	53	D1	00	ED	20	FC	BI	5B	6A	CB	BE	39	4A	4C	58	CF
6	D0	EF	AA	FB	43	4D	33	85	45	F9	02	7F	50	3C	9F	A8
7	51	A3	40	8F	92	9D	38	F5	BC	B6	DA	21	10	FF	F3	D2
8	CD	0C	13	EC	5F	97	44	17	C4	A7	7E	3D	64	5D	19	73
9	60	81	4F	DC	22	2A	90	88	46	EE	B8	14	DE	5E	0B	DB
A	E0	32	3A	0A	49	06	24	5C	C2	D3	AC	62	91	95	E4	79
B	E7	C8	37	6D	8D	D5	4E	A9	6C	56	F4	EA	65	7A	AE	08
C	BA	78	25	2E	1C	A6	B4	C6	E8	DD	74	1F	4B	BD	8B	8A
D	70	3E	B5	66	48	03	F6	0E	61	35	57	B9	86	C1	1D	9E
E	E1	F8	98	11	69	D9	8E	94	9B	1E	87	E9	CE	55	28	DF
F	8C	A1	89	0D	BF	E6	42	68	41	99	2D	0F	B0	54	BB	16

  - Leftmost 4 bits — row index, rightmost 4 bits — column index, check S-box for 8-bit output value

Example:

EA	04	65	85
83	45	5D	96
5C	33	98	B0
F0	2D	AD	C5

→

87	F2	4D	97
EC	6E	4C	90
4A	C3	46	E7
8C	D8	95	A6

Symmetric Encryption: AES

- Inverse Substitute Bytes Transformation
  - Inverse S-box

x \ y	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	52	09	6A	D5	30	36	A5	38	BF	40	A3	9E	81	F3	D7	FB
1	7C	E3	39	82	9B	2F	FF	87	34	8E	43	44	C4	DE	E9	CB
2	54	7B	94	32	A6	C2	23	3D	EE	4C	95	0B	42	FA	C3	4E
3	08	2E	A1	66	28	D9	24	B2	76	5B	A2	49	6D	8B	D1	25
4	72	F8	F6	64	86	68	98	16	D4	A4	5C	CC	5D	65	B6	92
5	6C	70	48	50	FD	ED	B9	DA	5E	15	46	57	A7	8D	9D	84
6	90	D8	AB	00	8C	BC	D3	0A	F7	E4	58	05	B8	B3	45	06
7	D0	2C	1E	8F	CA	3F	0F	02	C1	AF	BD	03	01	13	8A	6B
8	3A	91	11	41	4F	67	DC	EA	97	F2	CF	CE	F0	B4	E6	73
9	96	AC	74	22	E7	AD	35	85	E2	F9	37	E8	1C	75	DF	6E
A	47	F1	1A	71	1D	29	C5	89	6F	B7	62	0E	AA	18	BE	1B
B	FC	56	3E	4B	C6	D2	79	20	9A	DB	C0	FE	78	CD	5A	FA
C	1F	DD	A8	33	88	07	C7	31	B1	12	10	59	27	80	EC	5F
D	60	51	7F	A9	19	B5	4A	0D	2D	E5	7A	9F	93	C9	9C	EF
E	A0	E0	3B	4D	AE	2A	F5	B0	C8	EB	BB	3C	83	53	99	61
F	17	2B	04	7E	BA	77	D6	26	E1	69	14	63	55	21	0C	7D

-A low correlation between input bits and output bits

-The output cannot be described as a simple mathematical function of the input.

- Leftmost 4 bits — row index, rightmost 4 bits — column index, check S-box for 8-bit output value

Example:

EA	04	65	85
83	45	5D	96
5C	33	98	B0
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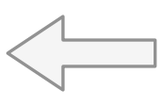


87	F2	4D	97
EC	6E	4C	90
4A	C3	46	E7
8C	D8	95	A6

Symmetric Encryption: AES

- Shift Row Transformation
  - First row of state is not altered
  - Second row: 1-byte circular left shift
  - Third row: 2-byte circular left shift
  - ….
- Inverse Shift Row Transformation
  - Circular shifts in the opposite direction

Example:

87	F2	4D	97
EC	6E	4C	90
4A	C3	46	E7
8C	D8	95	A6

→

87	F2	4D	97
6E	4C	90	EC
46	E7	4A	C3
A6	8C	D8	95

Symmetric Encryption: AES

- Mix Column Transformation

02	03	01	01
01	02	03	01
01	01	02	03
03	01	01	02

Predefine Matrix

$*$

$S_{0,0}$	$S_{0,1}$	$S_{0,2}$	$S_{0,3}$
$S_{1,0}$	$S_{1,1}$	$S_{1,2}$	$S_{1,3}$
$S_{2,0}$	$S_{2,1}$	$S_{2,2}$	$S_{2,3}$
$S_{3,0}$	$S_{3,1}$	$S_{3,2}$	$S_{3,3}$

State Array

$=$

$S'_{0,0}$	$S'_{0,1}$	$S'_{0,2}$	$S'_{0,3}$
$S'_{1,0}$	$S'_{1,1}$	$S'_{1,2}$	$S'_{1,3}$
$S'_{2,0}$	$S'_{2,1}$	$S'_{2,2}$	$S'_{2,3}$
$S'_{3,0}$	$S'_{3,1}$	$S'_{3,2}$	$S'_{3,3}$

New State Array

$$S'_{0,j} = (2 * S_{0,j}) \oplus (3 * S_{1,j}) \oplus S_{2,j} \oplus S_{3,j}$$

$$S'_{1,j} = S_{0,j} \oplus (2 * S_{1,j}) \oplus (3 * S_{2,j}) \oplus S_{3,j}$$

$$S'_{2,j} = S_{0,j} \oplus S_{1,j} \oplus (2 * S_{2,j}) \oplus (3 * S_{3,j})$$

$$S'_{3,j} = (3 * S_{0,j}) \oplus S_{1,j} \oplus S_{2,j} \oplus (2 * S_{3,j})$$

Example:

02	03	01	01
01	02	03	01
01	01	02	03
03	01	01	02

Predefine Matrix

$*$

87	F2	4D	97
6E	4C	90	EC
46	E7	4A	C3
A6	8C	D8	95

Symmetric Encryption: AES

- Mix Column Transformation

Example:

02	03	01	01
01	02	03	01
01	01	02	03
03	01	01	02

Predefine Matrix

*

87	F2	4D	97
6E	4C	90	EC
46	E7	4A	C3
A6	8C	D8	95

→

47	40	A3	4C
37	D4	70	9F
94	E4	3A	42
ED	A5	A6	BC

$01 * x = x$

$02 * x$ x left most digit is 0 —> binary multiplication

x left most digit is 1 —> shift left by 1, then XOR with 1B (0001 1011)

$03 * x = (02 \oplus 01) * x = (02 * x) \oplus x$

87=1000 0111 02*87: 1) shift left by 1: 0000 1110 2) XOR with 1B: 0001 0101

6E=0110 1110 02*6E=1101 1100 03*6E=(02*6E) XOR 6E= 1011 0010

46=0100 0110 01*46=0100 0110

A6=1010 0110 01*A6=1010 0110

XOR

0100 0111 —> 47

Symmetric Encryption: AES

- Add Round Key Transformation
  - State XOR Round Key (element-wise)

- Inverse Add Round Key Transformation
  - Identical to the forward, i.e., State XOR Round Key. XOR operation is its own inverse.

Example:

0100 0000 ⊕ 0001 1001 = 0101 1001

47	40	A3	4C
37	D4	70	9F
94	E4	3A	42
ED	A5	A6	BC

State

⊕

AC	19	28	57
77	FA	D1	5C
66	DC	29	00
ED	A5	A6	BC

Key

=

EB	59	8B	1B
40	2E	A1	C3
F2	38	13	42
1E	84	E7	D2

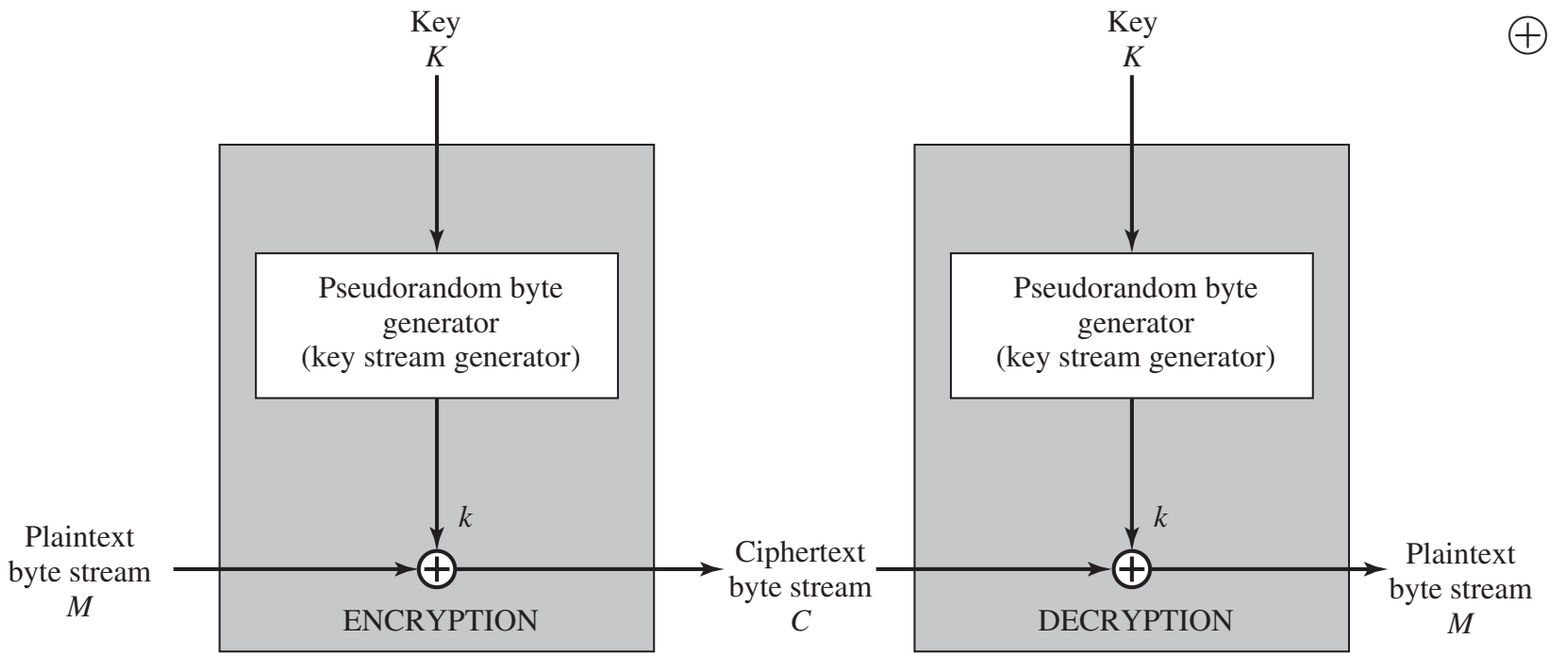
Symmetric Encryption: Stream Cipher

- Stream cipher processes the input elements continuously, producing output one element at a time, as it goes along.
- A key is input to a pseudorandom bit generator that produces a stream of numbers — key stream
- A key stream XOR plaintext stream (bitwise)

```
  11001100    plaintext
⊕ 01101100    key stream
  10100000    ciphertext
```

- Decryption requires the use of the same pseudorandom sequence

```
  10100000    ciphertext
⊕ 01101100    key stream
  11001100    plaintext
```



Symmetric Encryption: Stream Cipher

- As secure as block cipher of comparable key length
- Faster and use far less code
- Reuse key incurs security issue (block cipher can reuse keys)
  - Example: Two plaintexts are encrypted with the same key using a stream cipher, then XOR of two ciphertexts is the XOR of the original plaintexts

Symmetric Encryption: RC4

- Stream cipher
- A variable length key 1-256 bytes
- Use key to initialize state vector S (permutation)
- Once S vector is initialized, the input key is no longer used
- Key stream is generated by S (cycling, swapping…) and take XOR with plaintext for encryption

Cipher Block Modes of Operation

- DES/3DES the block length is 64 bits
- How to tackle a longer plaintext?

Cipher Block Modes of Operation

- DES/3DES the block length is 64 bits
- How to tackle a longer plaintext?
  - Break the plaintext into 64-bit blocks (padding the last block if necessary)

Cipher Block Modes of Operation

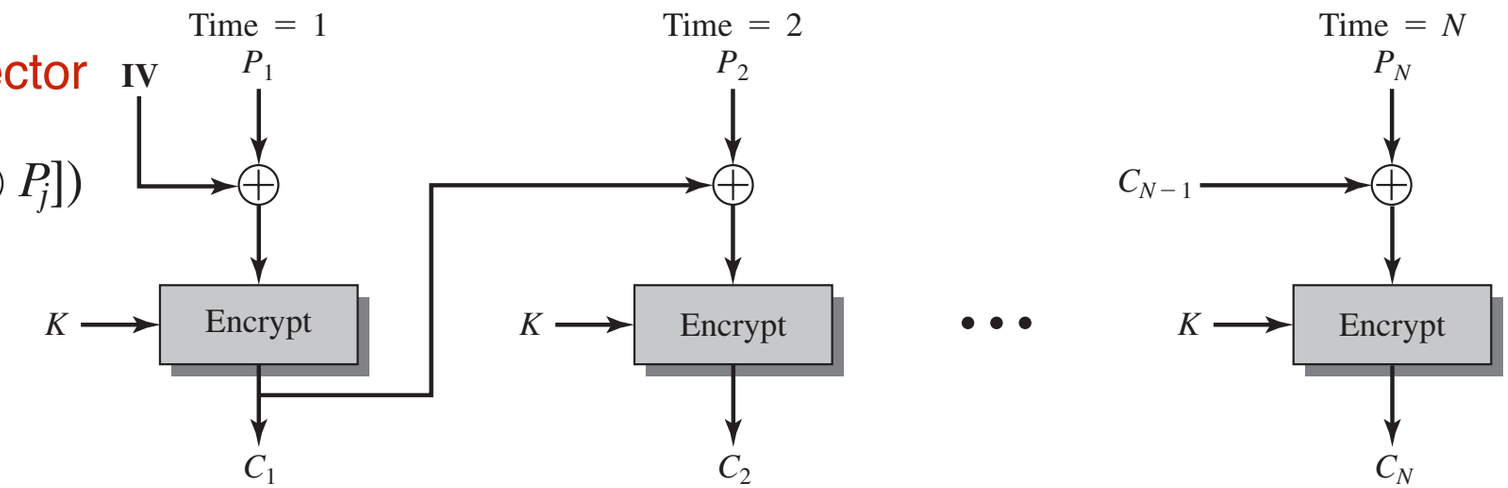
- Electronic Code book
  - Description: Each block of 64 plaintext bits is encoded independently using the same key.
  - Typical Application: Secure transmission of single values (e.g., an encryption key)

Cipher Block Modes of Operation

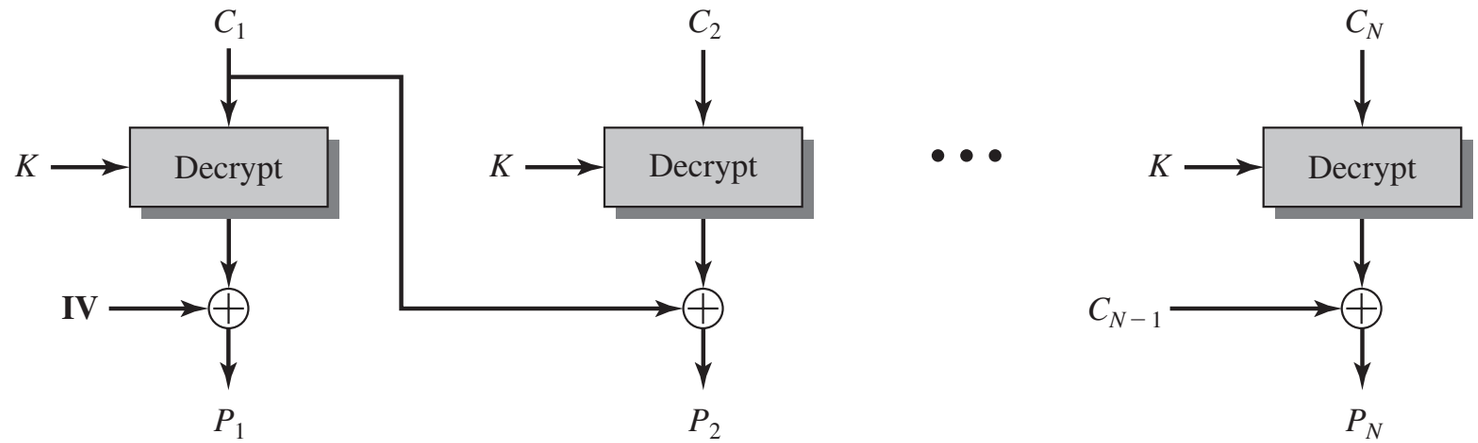
- Cipher Block Chaining (CBC)

Initialization vector

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



(a) Encryption



(b) Decryption

$$\mathrm{D}(K, C_j) = \mathrm{D}(K, \mathrm{E}(K, [C_{j-i} \oplus P_j]))$$

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

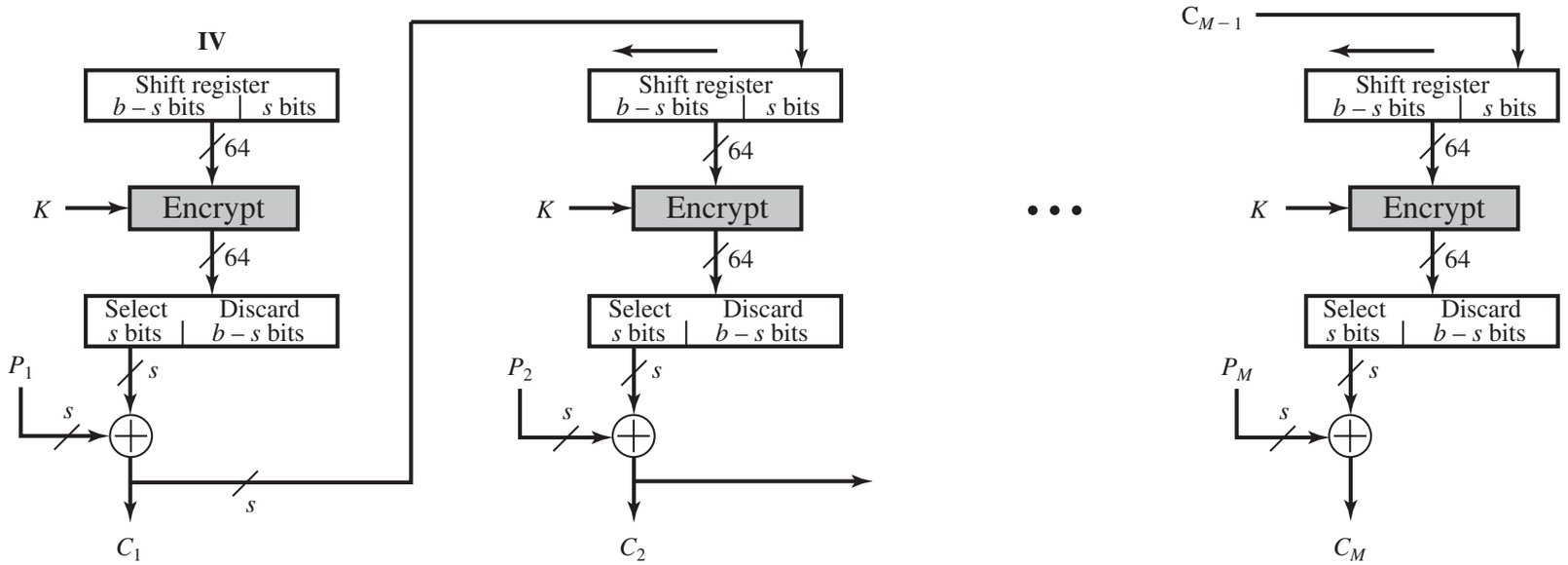
$$C_{j-1} \oplus \mathrm{D}(K, C_j) = C_{j-1} \oplus C_{j-1} \oplus P_j = P_j$$

Cipher Block Modes of Operation

- Cipher Block Chaining (CBC)
  - Initialization vector (IV) must be known to both the sender and receiver
  - IV should be protected as key, e.g., adversary change bits in IV, then the plaintext in block 1 can be changed.
  - Typical application: General-purpose block-oriented transmission; authentication

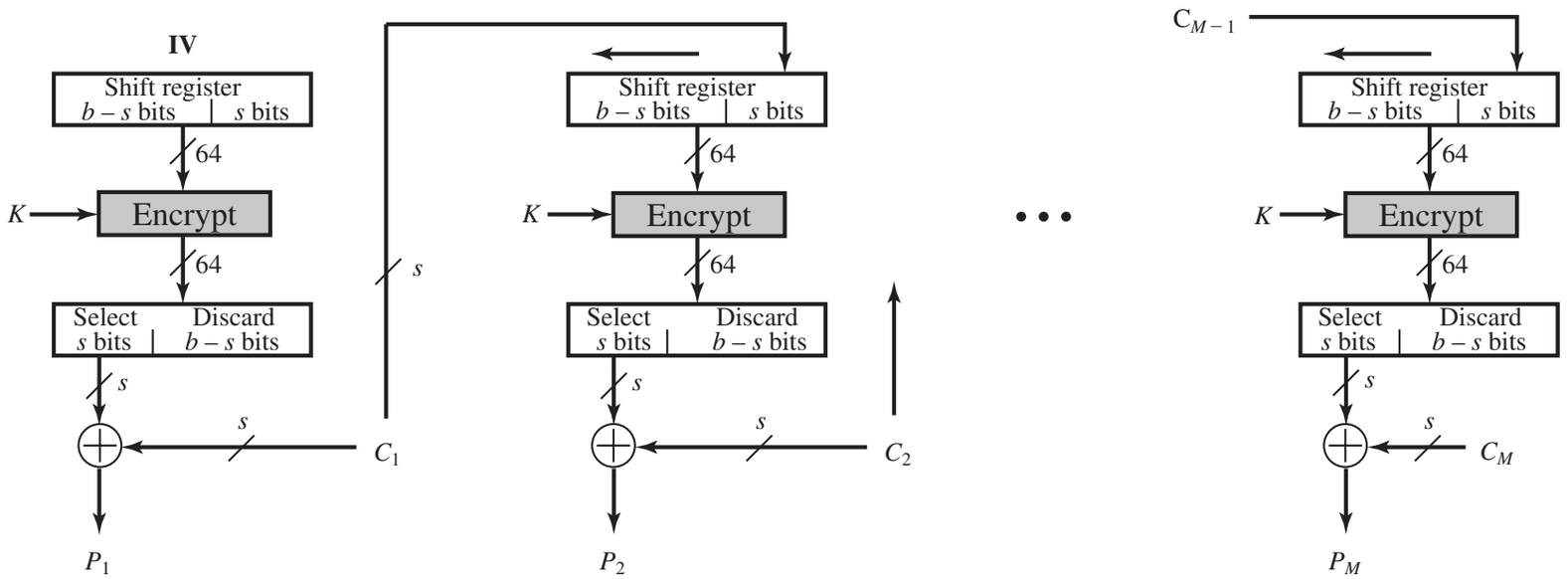
Cipher Block Modes of Operation

- Cipher Feedback (CFB)
  - convert block cipher into a stream cipher



$C_1 = P_1 \oplus \mathrm{S}_s[\mathrm{E}(K, \mathrm{IV})]$

(a) Encryption



$P_1 = C_1 \oplus \mathrm{S}_s[\mathrm{E}(K, \mathrm{IV})]$

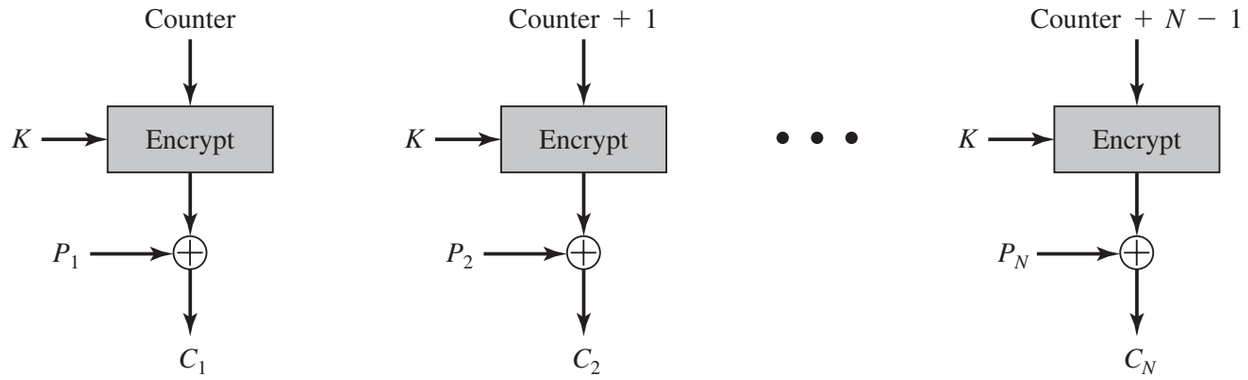
(b) Decryption

Cipher Block Modes of Operation

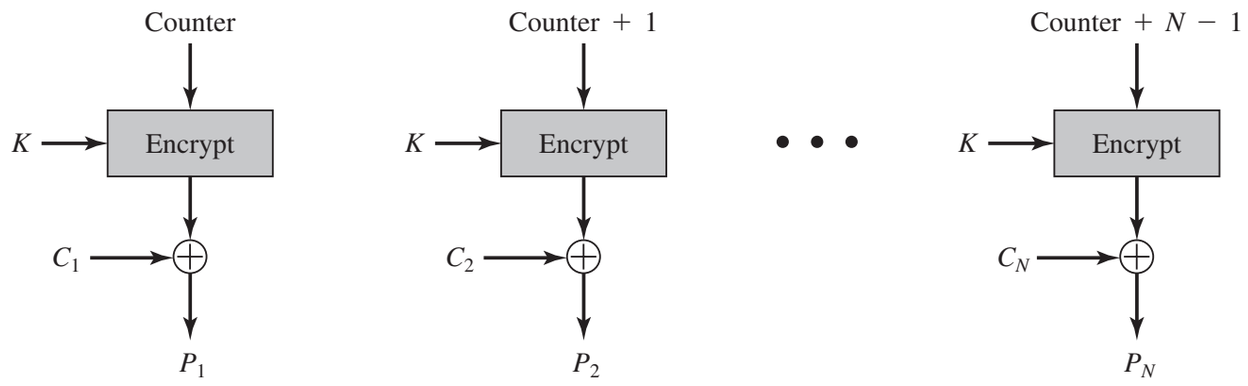
- Cipher Feedback (CFB)
  - Decryption also uses the encryption function, but not decryption function
  - Typical application: General-purpose stream-oriented transmission; authentication

Cipher Block Modes of Operation

- Counter (CTR)
  - Counter size = plaintext block size
  - Counter is initialized to some value and then incremented by 1 for each subsequent block



(a) Encryption



(b) Decryption

Cipher Block Modes of Operation

- Counter (CTR)
  - No chain, multiple blocks process in parallel
  - Counter at i block cannot be computed until i-1 prior blocks are computed
  - Only need encryption algorithm
  - Typical application: General-purpose block-oriented transmission; Useful for high-speed requirements

Summary

- Cryptography
  - Context, Ingredients, Classification, Attacks
- Symmetric Encryption: Block Cipher
  - DES/Triple DES (Feistel Cipher Structure)
  - AES
- Symmetric Encryption: Stream Cipher
  - RC4
- Cipher Block Modes of Operation
  - Electronic Code book (ECB)
  - Cipher Block Chaining (CBC)
  - Cipher Feedback (CFB)
  - Counter (CTR)

Thank You

Quiz Time

- 15 minutes