Information Security Systems (CS-501)

Encipherment Using Modern Symmetric-Key Ciphers

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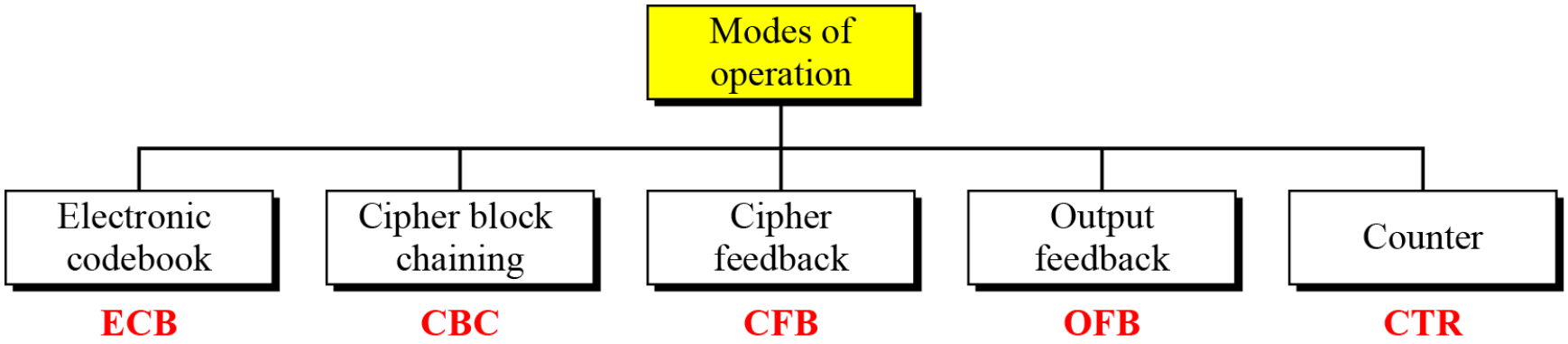
8-1 USE OF MODERN BLOCK CIPHERS

Symmetric-key encipherment can be done using modern block ciphers. Modes of operation have been devised to encipher text of any size employing either DES or AES.

Topics discussed in this section:

8-1 Continued

Figure 8.1 *Modes of operation*



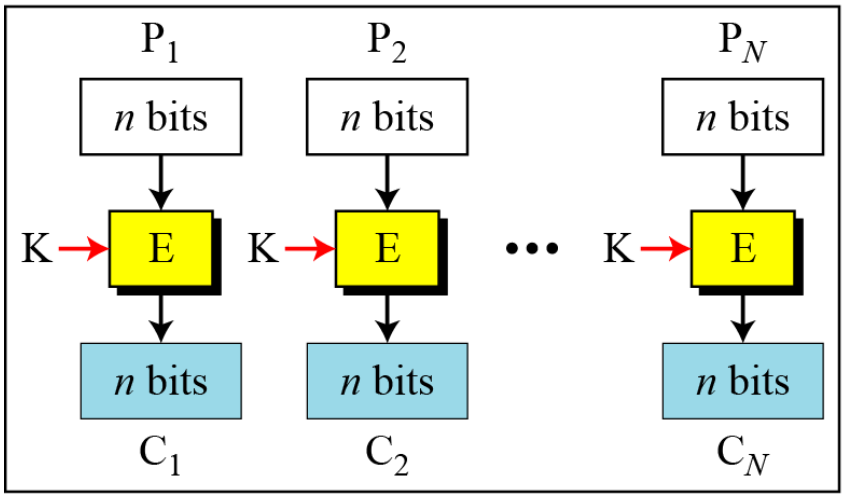
8.1.1 Electronic Codebook (ECB) Mode

The simplest mode of operation is called the electronic codebook (ECB) mode.

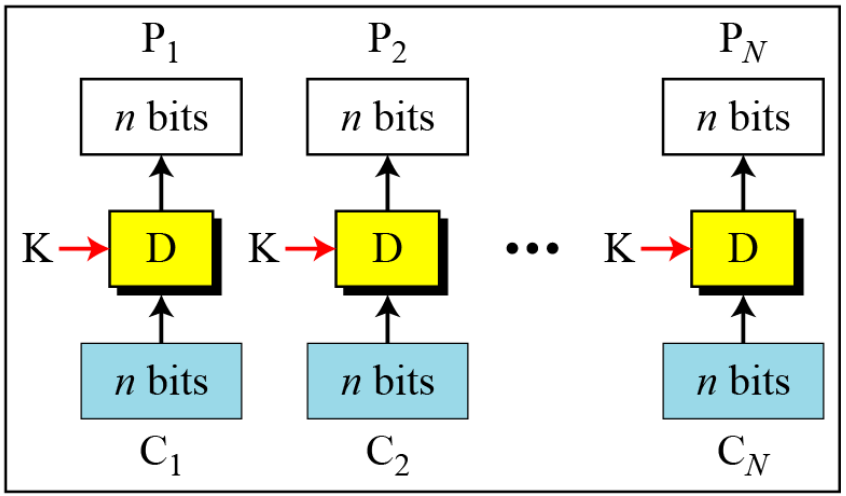
Encryption: $C_i = E_K(P_i)$ Decryption: $P_i = D_K(C_i)$

Figure 8.2 *Electronic codebook (ECB) mode*

E: Encryption D: Decryption
P_i: Plaintext block i C_i: Ciphertext block i
K: Secret key



Encryption



Decryption

8.1.1 Continued

Example 8.1

It can be proved that each plaintext block at Alice's site is exactly recovered at Bob's site. Because encryption and decryption are inverses of each other,

Encryption: $C_i = E_K(P_i)$ Decryption: $P_i = D_K(C_i)$

8.1.1 Continued

Example 8.3: Security issue

Assume that Eve works in a company a few hours per month (her monthly payment is very low).
She knows that the company uses several blocks of information for each employee in which the seventh block is the amount of money to be deposited in the employee's account.
Eve can intercept the ciphertext sent to the bank at the end of the month, replace the block with the information about her payment with a copy of the block with the information about the payment of a full-time colleague.
Each month Eve can receive more money than she deserves.

8.1.1 Continued

Error Propagation

A single bit error in transmission can create errors in several bits in the corresponding block.
However, the error does not have any effect on the other blocks.

8.1.2 Cipher Block Chaining (CBC) Mode

In CBC mode, each plaintext block is exclusive-ored with the previous ciphertext block before being encrypted.

Figure 8.3 *Cipher block chaining (CBC) mode*

E: Encryption
P_i: Plaintext block i
K: Secret key

D : Decryption
C_i : Ciphertext block i
IV: Initial vector (C_0)

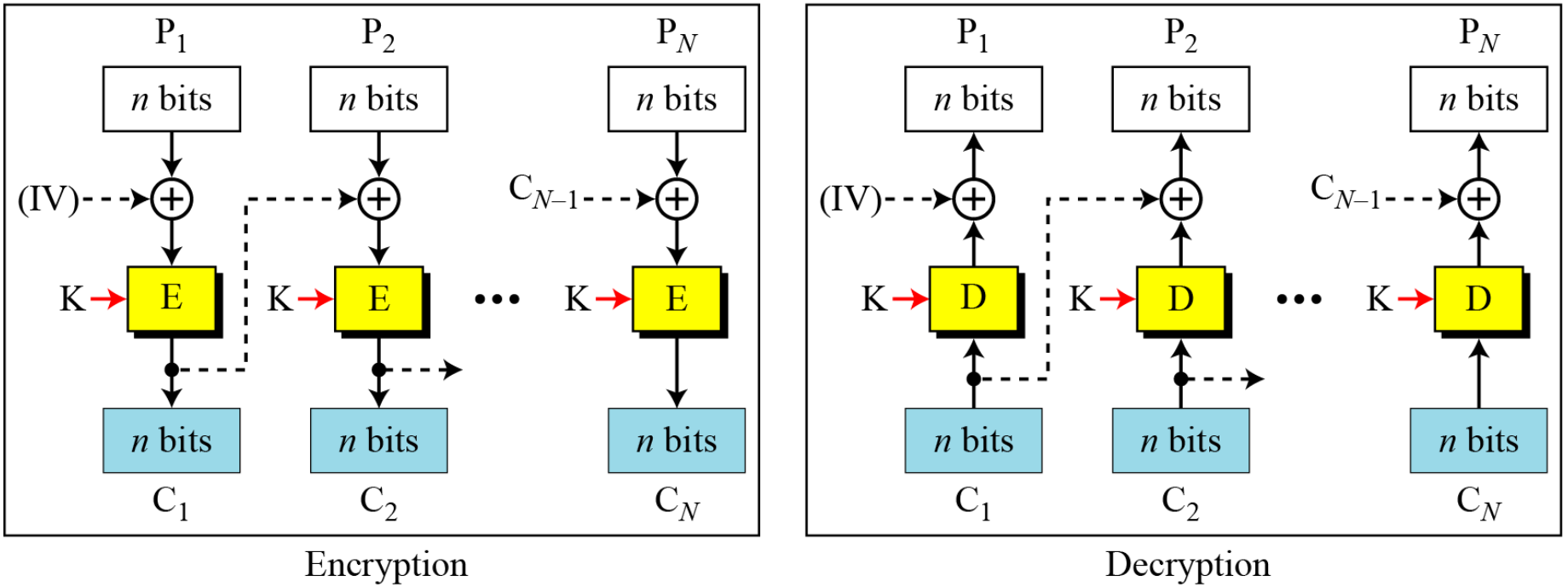
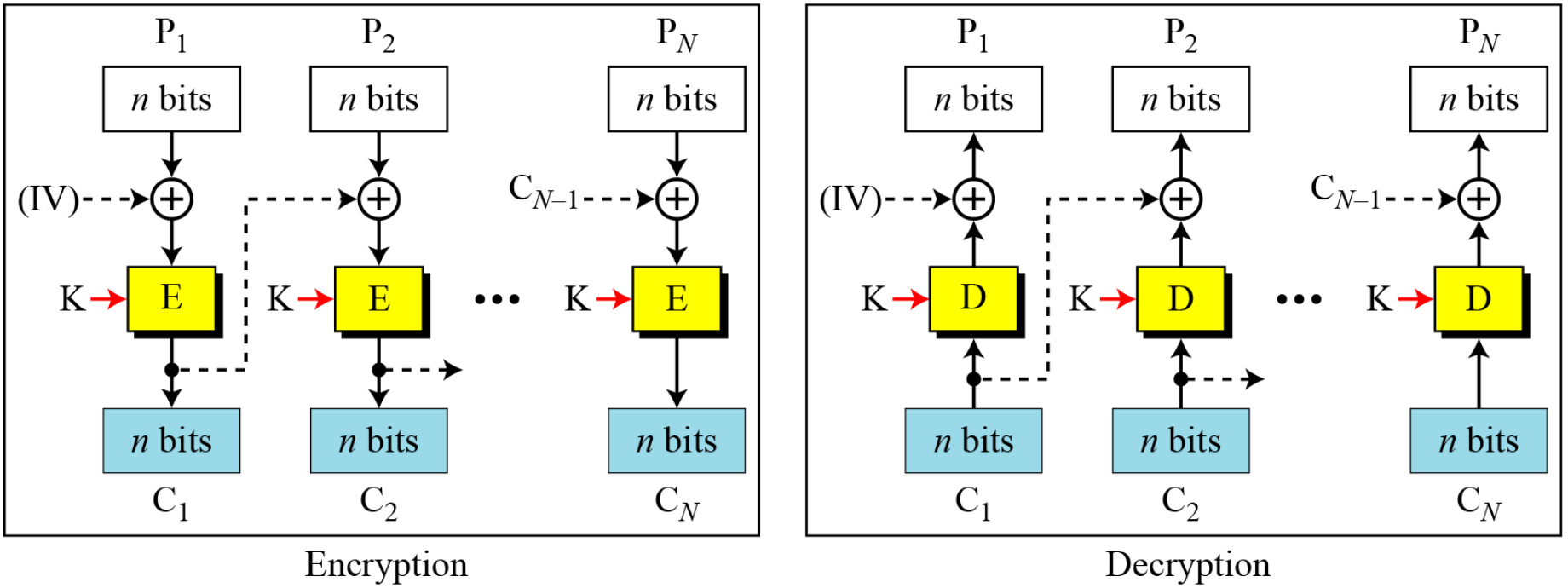


Figure 8.3 *Cipher block chaining (CBC) mode*

E: Encryption
P_i: Plaintext block i
K: Secret key

D : Decryption
C_i : Ciphertext block i
IV: Initial vector (C_0)



Encryption:
$C_0 = IV$
$C_i = E_K (P_i \oplus C_{i-1})$

Decryption:
$C_0 = IV$
$P_i = D_K (C_i) \oplus C_{i-1}$

8.1.2 Continued

Example 8.4

It can be proved that each plaintext block at Alice's site is recovered exactly at Bob's site. Because encryption and decryption are inverses of each other,

$$P_i = D_K(C_i) \oplus C_{i-1} = D_K(E_K(P_i \oplus C_{i-1})) \oplus C_{i-1} = P_i \oplus C_{i-1} \oplus C_{i-1} = P_i$$

Initialization Vector (IV)

The initialization vector (IV) should be known by the sender and the receiver.

8.1.2 Continued

Error Propagation

In CBC mode, a single bit error in ciphertext block C_j during transmission may create error in most bits in plaintext block P_j during decryption.

8.1.3 Cipher Feedback (CFB) Mode

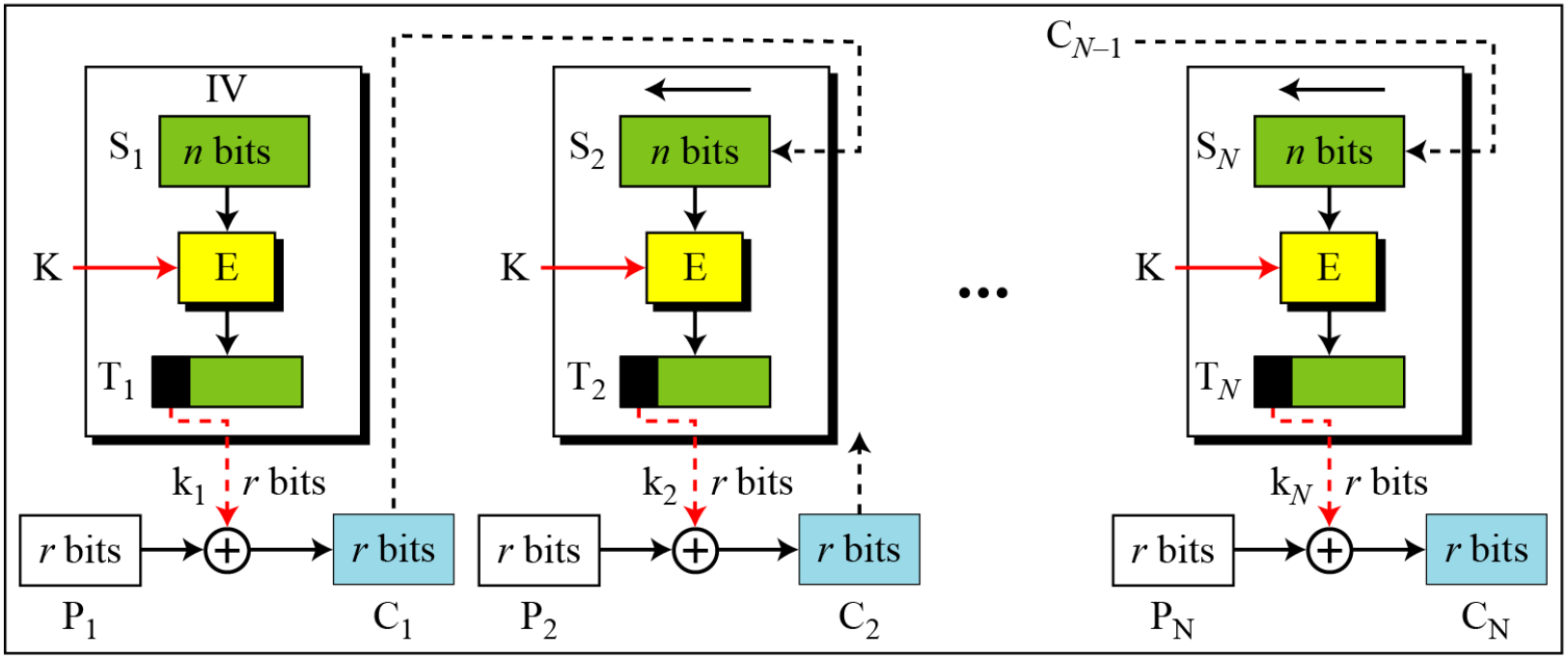
In some situations, we need to use DES or AES as secure ciphers, but the plaintext or ciphertext block sizes are to be smaller.

Figure 8.4 *Encryption in cipher feedback (CFB) mode*

E : Encryption
P_i: Plaintext block i
K: Secret key

D : Decryption
C_i: Ciphertext block i
IV: Initial vector (S_1)

S_i: Shift register
T_i: Temporary register



8.1.3 Continued

Note

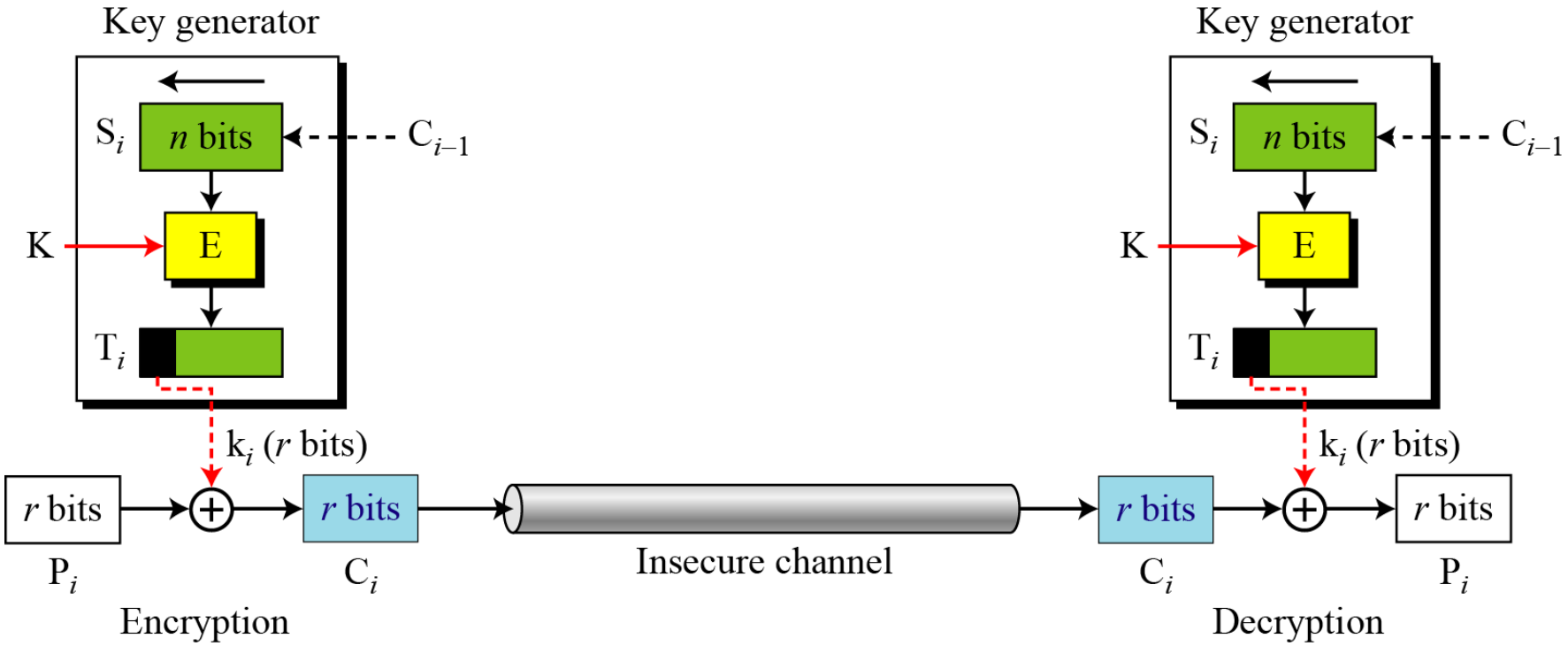
In CFB mode, encipherment and decipherment use the encryption function of the underlying block cipher.

The relation between plaintext and ciphertext blocks is shown below:

$$\textbf{Encryption: } C_i = P_i \oplus \text{SelectLeft}_r \{E_K [\text{ShiftLeft}_r (S_{i-1}) \mid C_{i-1})]\}$$
$$\textbf{Decryption: } P_i = C_i \oplus \text{SelectLeft}_r \{E_K [\text{ShiftLeft}_r (S_{i-1}) \mid C_{i-1})]\}$$

CFB as a Stream Cipher

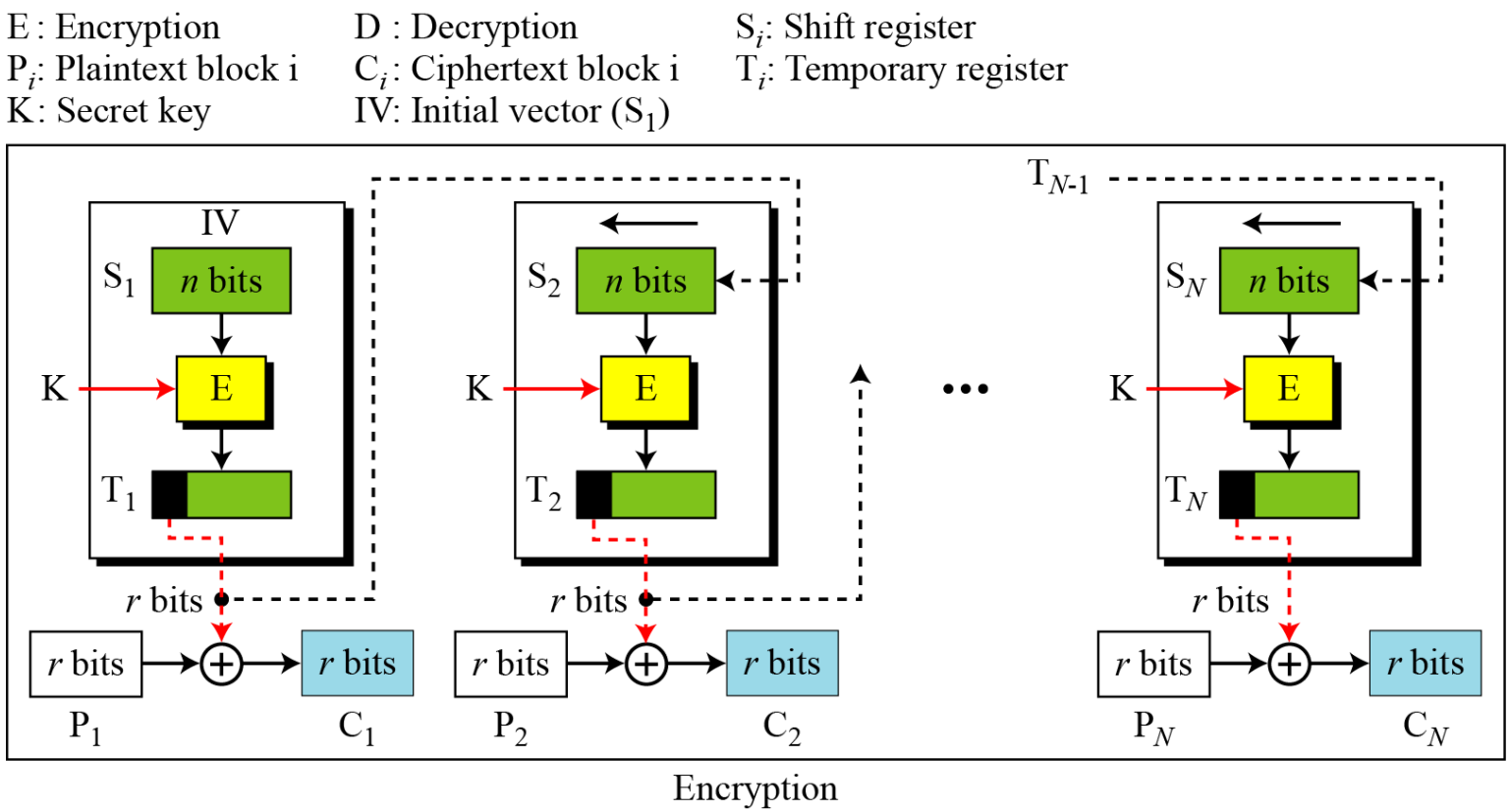
Figure 8.5 *Cipher feedback (CFB) mode as a stream cipher*



18.1.4 Output Feedback (OFB) Mode

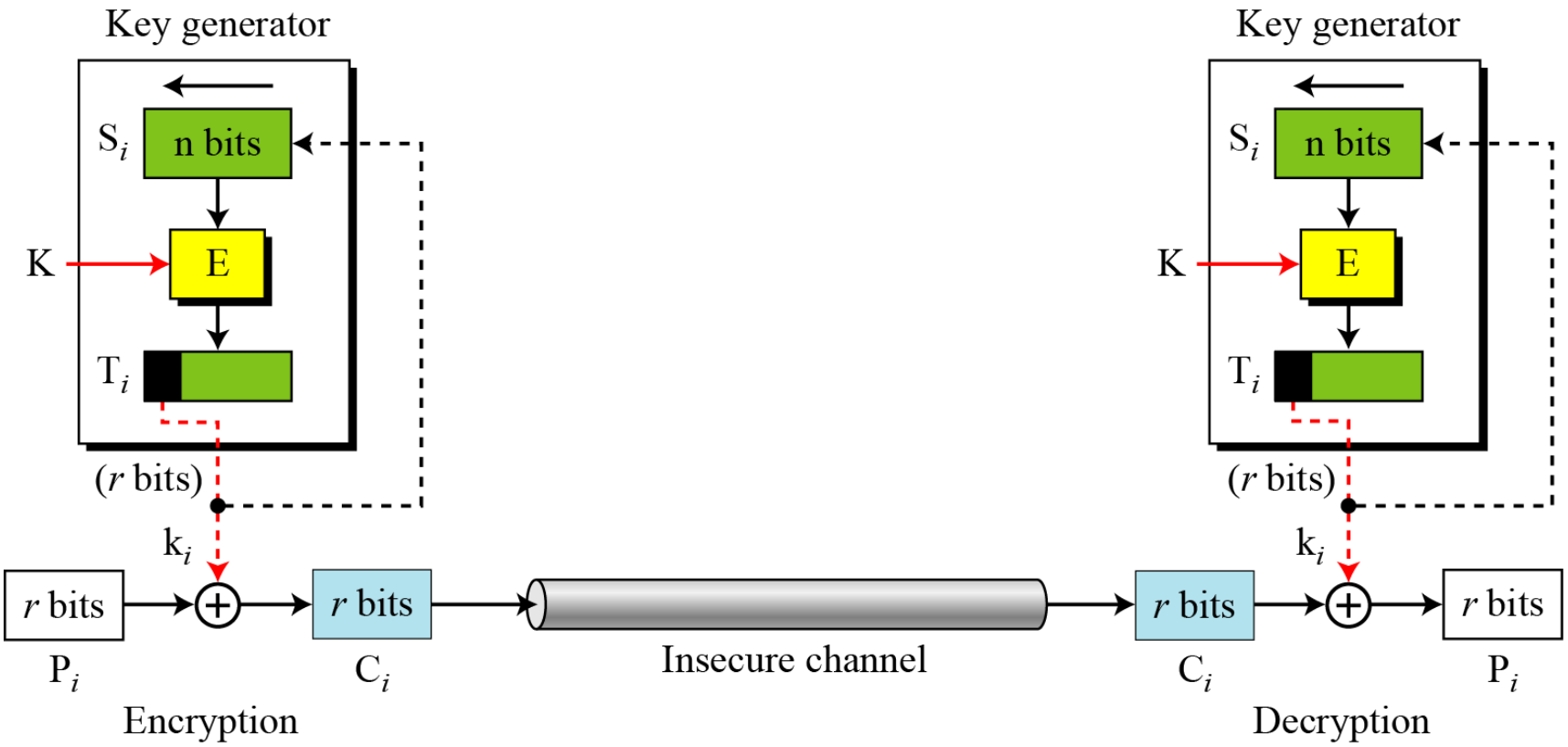
In this mode each bit in the ciphertext is independent of the previous bit or bits. This avoids error propagation.

Figure 8.6 *Encryption in output feedback (OFB) mode*



OFB as a Stream Cipher

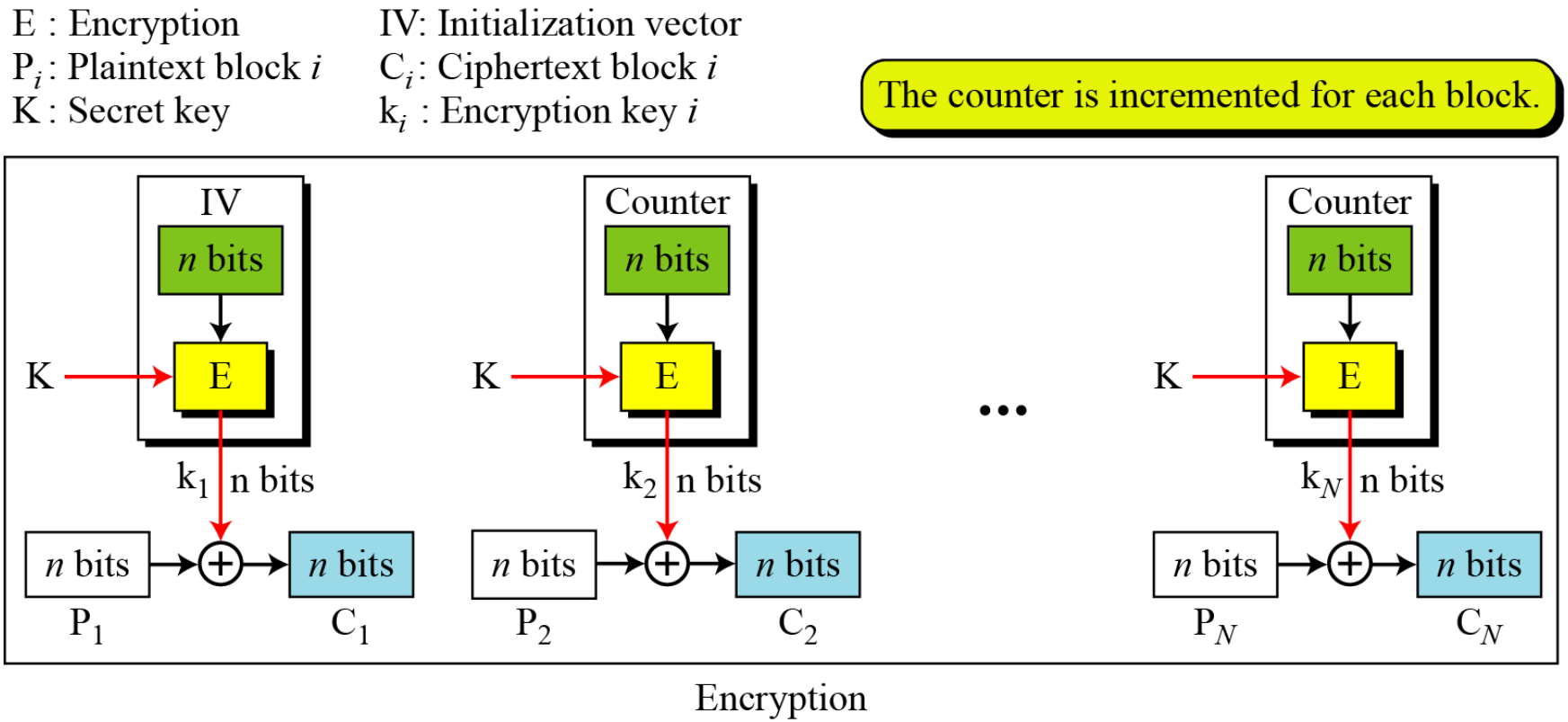
Figure 8.7 *Output feedback (OFB) mode as a stream cipher*



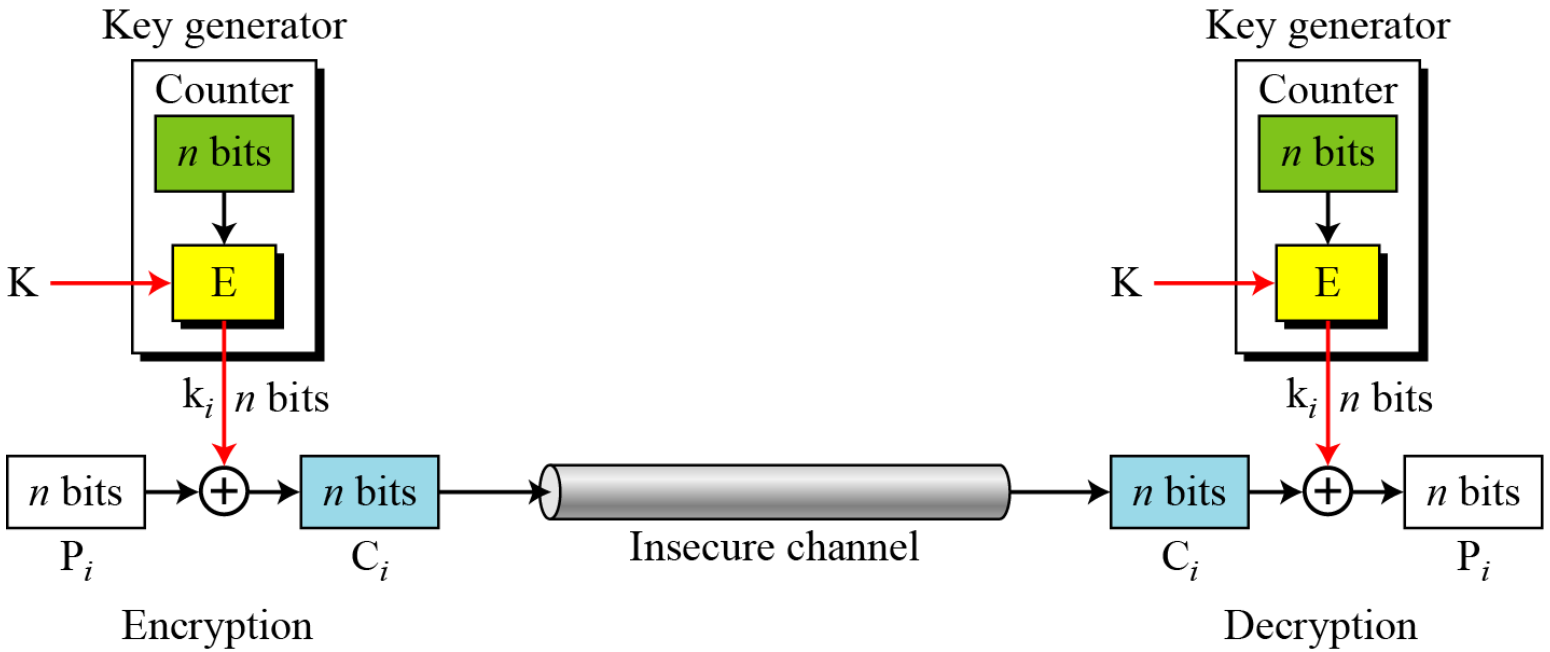
8.1.5 Counter (CTR) Mode

In the counter (CTR) mode, there is no feedback. The pseudorandomness in the key stream is achieved using a counter.

Figure 8.8 *Encryption in counter (CTR) mode*



8.1.5 Continued



8.1.5 Continued

Algorithm 8.5 *Encryption algorithm for CTR*

```
CTR_Encryption (IV, K, Plaintext blocks)
{
    Counter ← IV
    for (i = 1 to N)
    {
        Counter ← (Counter + i − 1) mod 2^N
        k_i ← E_K (Counter)
        C_i ← P_i ⊕ k_i
    }
    return Ciphertext blocks
}
```

Comparison of Different Modes

Table 8.1 *Summary of operation modes*

Operation Mode	*Description*	*Type of Result*	*Data Unit Size*
ECB	Each n-bit block is encrypted independently with the same cipher key.	Block cipher	n
CBC	Same as ECB, but each block is first exclusive-ored with the previous ciphertext.	Block cipher	n
CFB	Each r-bit block is exclusive-ored with an r-bit key, which is part of previous cipher text	Stream cipher	$r \leq n$
OFB	Same as CFB, but the shift register is updated by the previous r-bit key.	Stream cipher	$r \leq n$
CTR	Same as OFB, but a counter is used instead of a shift register.	Stream cipher	n

8-2 USE OF STREAM CIPHERS

Although the five modes of operations enable the use of block ciphers for encipherment of messages or files in large units and small units, sometimes pure stream are needed for enciphering small units of data such as characters or bits.

Topics discussed in this section:

8.2.1 RC4

8.2.1 RC4

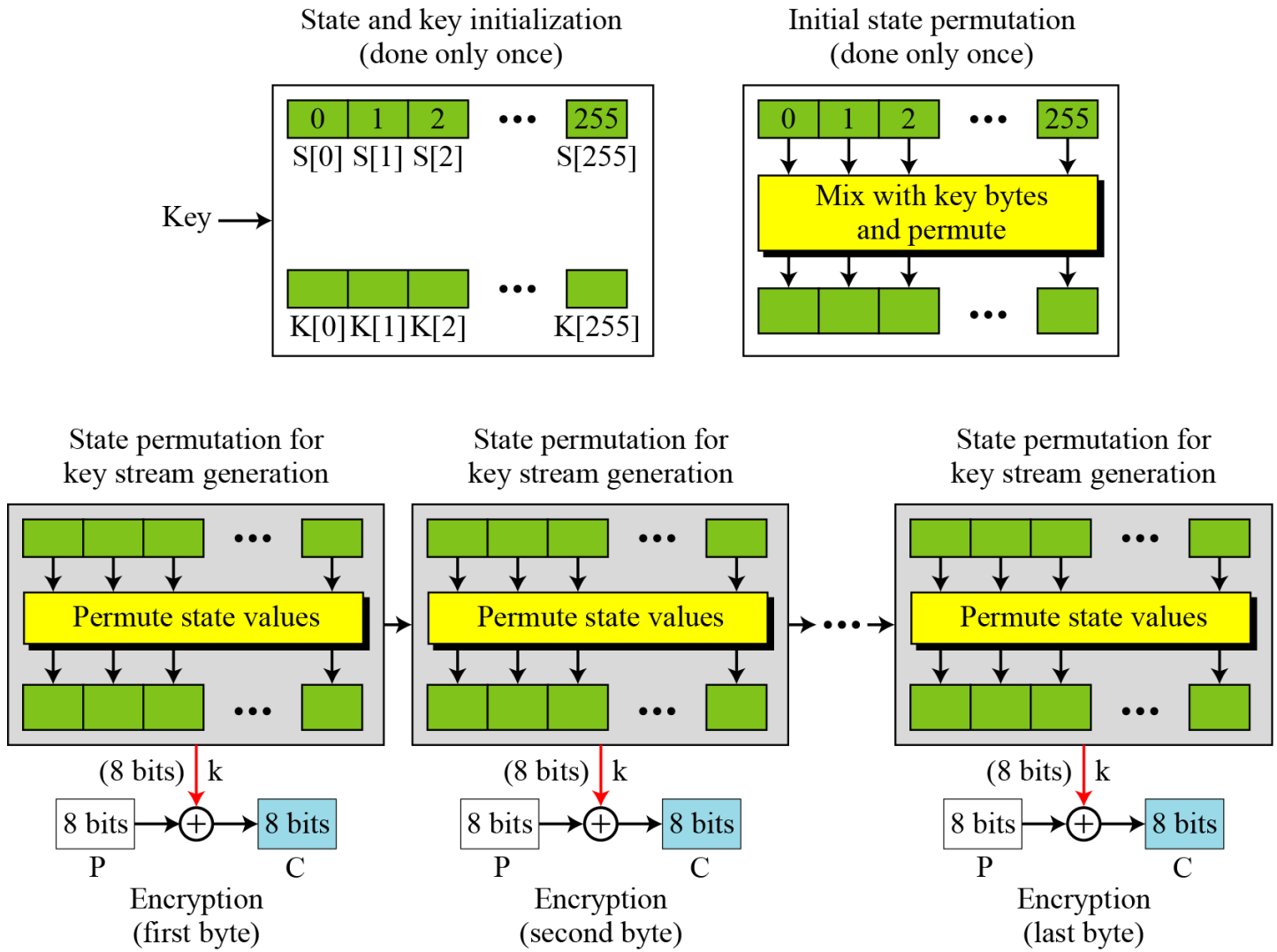
RC4 is a byte-oriented stream cipher in which a byte (8 bits) of a plaintext is exclusive-ored with a byte of key to produce a byte of a ciphertext.

State

RC4 is based on the concept of a state.

S[0]	S[1]	S[2]	···	S[255]

Figure 8.10 *The idea of RC4 stream cipher*



Initialization

Initialization is done in two steps:

```
for (i = 0 to 255)
{
    S[i]  ← i
    K[i]  ← Key [i mod KeyLength]
}
```

```
j ← 0
for (i = 0 to 255)
{
    j ← (j + S[i] + K[i]) mod 256
    swap (S[i] , S[j])
}
```

Key Stream Generation

The keys in the key stream are generated, one by one.

```
i  ← (i + 1) mod 256
j  ← (j + S[i]) mod 256
swap (S [i] , S[j])
k  ← S [(S[i] + S[j]) mod 256]
```

8.2.1 Continued

Algorithm

Algorithm 8.6 *Encryption algorithm for RC4*

```
RC4_Encryption (K)
{
    // Creation of initial state and key bytes
    for (i = 0 to 255)
    {
        S[i] ← i
        K[i] ← Key [i mod KeyLength]
    }
    // Permuting state bytes based on values of key bytes
    j ← 0
    for (i = 0 to 255)
    {
        j ← (j + S[i] + K[i]) mod 256
        swap (S[i] , S[j])
    }
```

Algorithm Continued

```
// Continuously permuting state bytes, generating keys, and encrypting
i ← 0
j ← 0
while (more byte to encrypt)
{
    i ← (i + 1) mod 256
    j ← (j + S[i]) mod 256
    swap (S [i] , S[j])
    k ← S [(S[i] + S[j]) mod 256]
    // Key is ready, encrypt
    input P
    C ← P ⊕ k
    output C
}
}
```

8.2.1 Continued

Example 8.5

To show the randomness of the stream key, we use a secret key with all bytes set to 0. The key stream for 20 values of *k* is (222, 24, 137, 65, 163, 55, 93, 58, 138, 6, 30, 103, 87, 110, 146, 109, 199, 26, 127, 163).

Example 8.6

Repeat Example 8.5, but let the secret key be five bytes of (15, 202, 33, 6, 8). The key stream is (248, 184, 102, 54, 212, 237, 186, 133, 51, 238, 108, 106, 103, 214, 39, 242, 30, 34, 144, 49). Again the randomness in the key stream is obvious.