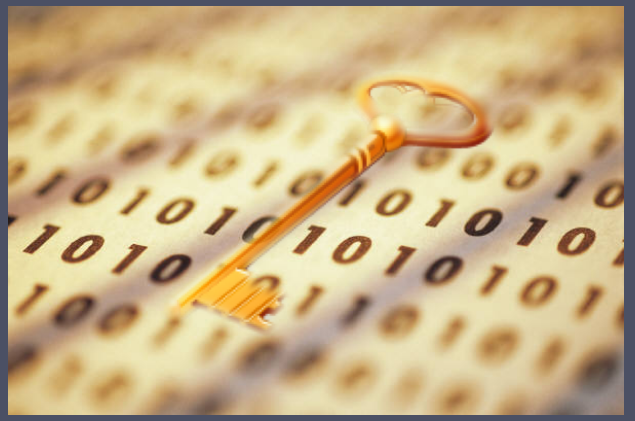
# Chapter 20

## Symmetric Encryption and Message Confidentiality

# Symmetric Encryption

- Also referred to as:
  - Conventional encryption
  - Secret-key or single-key encryption
- Only alternative before public-key encryption in 1970's
  - Still most widely used alternative
- Has five ingredients:
  - Plaintext
  - Encryption algorithm
  - Secret key
  - Ciphertext
  - Decryption algorithm



# Cryptography

## Classified along three independent dimensions:

### The type of operations used for transforming plaintext to ciphertext

- Substitution – each element in the plaintext is mapped into another element
- Transposition – elements in plaintext are rearranged

### The number of keys used

- Sender and receiver use same key – symmetric
- Sender and receiver each use a different key - asymmetric

### The way in which the plaintext is processed

- Block cipher – processes input one block of elements at a time
- Stream cipher – processes the input elements continuously

## Table 20.1 Types of Attacks on Encrypted Messages

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

# Computationally Secure Encryption Schemes

- Encryption is computationally secure if:
  - Cost of breaking cipher exceeds value of information
  - Time required to break cipher exceeds the useful lifetime of the information
- Usually very difficult to estimate the amount of effort required to break
- Can estimate time/cost of a brute-force attack

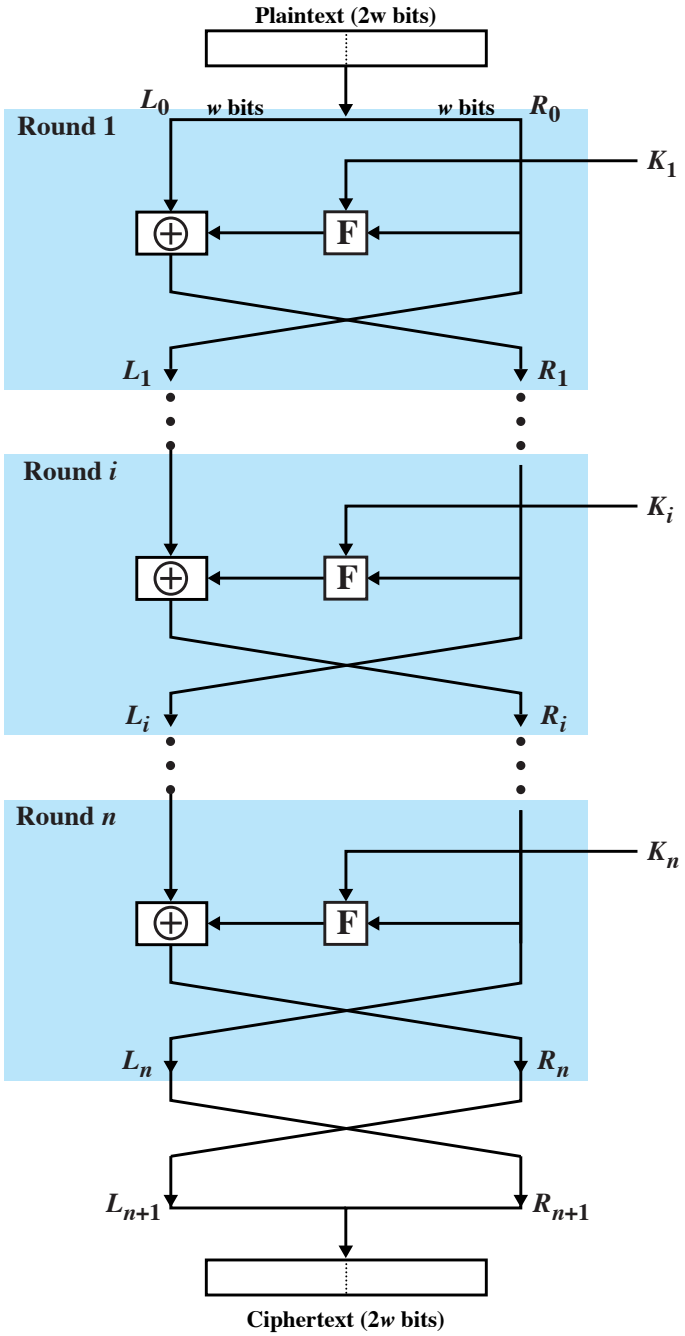
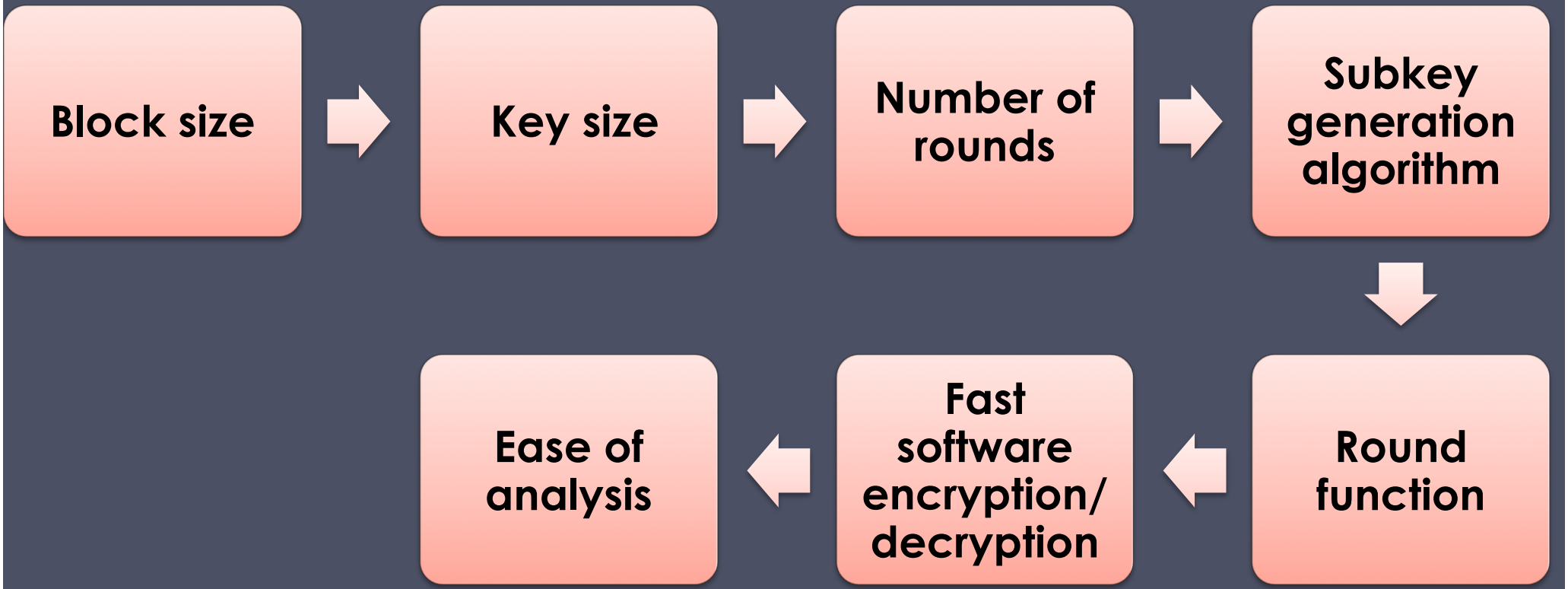



**Figure 20.1 Classical Feistel Network**

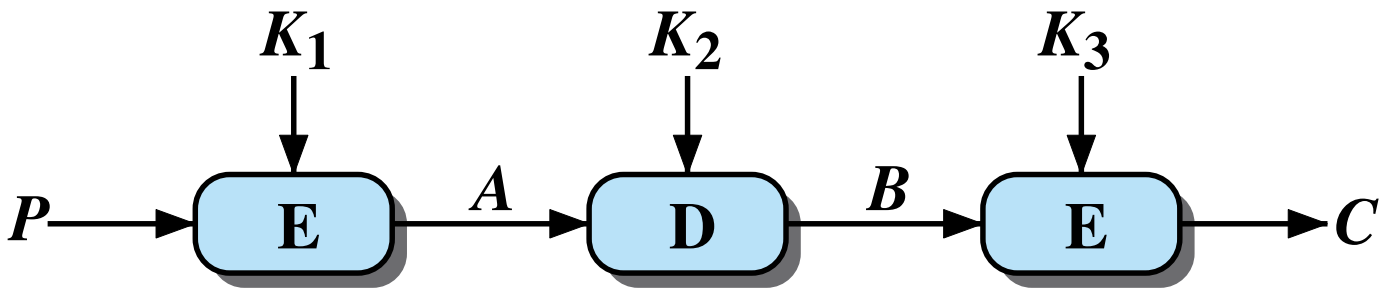
# Block Cipher Structure

- Symmetric block cipher consists of:
  - A sequence of rounds
  - With substitutions and permutations controlled by key
- Parameters and design features:

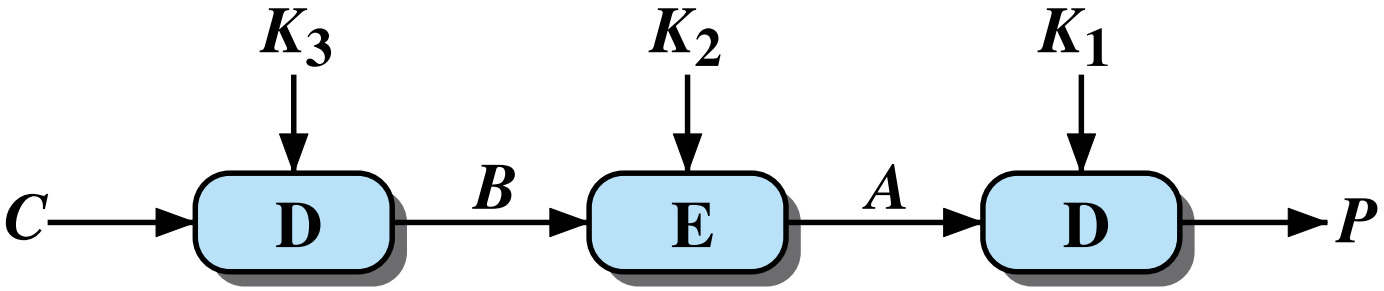


- Most widely used encryption scheme
- Adopted in 1977 by National Bureau of Standards (Now NIST)
- FIPS PUB 46
- Algorithm is referred to as the Data Encryption Algorithm (DEA)
- Minor variation of the Feistel network

# Data Encryption Standard (DES)




(a) Encryption




(b) Decryption

**Figure 20.2 Triple DES**

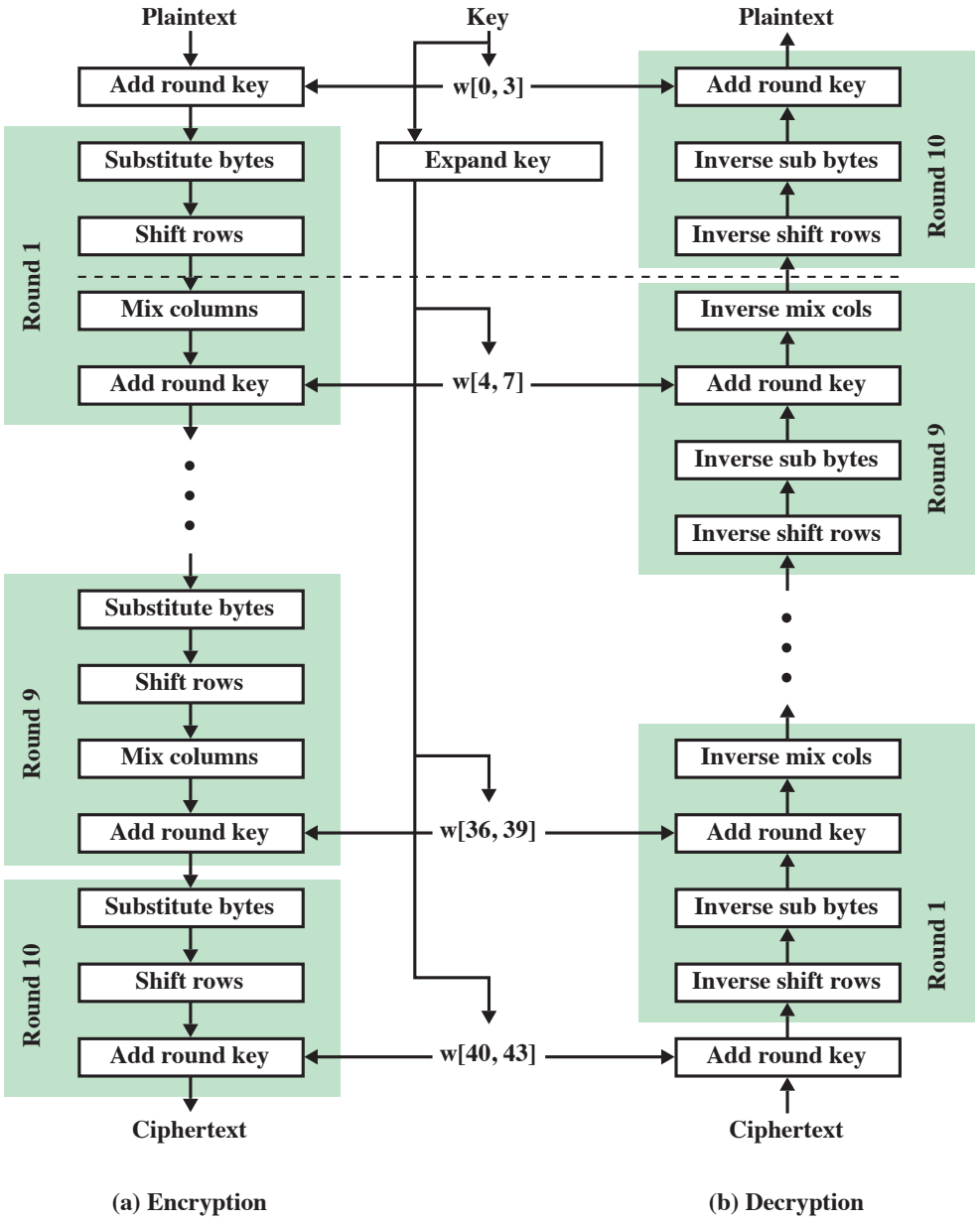



**Figure 20.3 AES Encryption and Decryption**

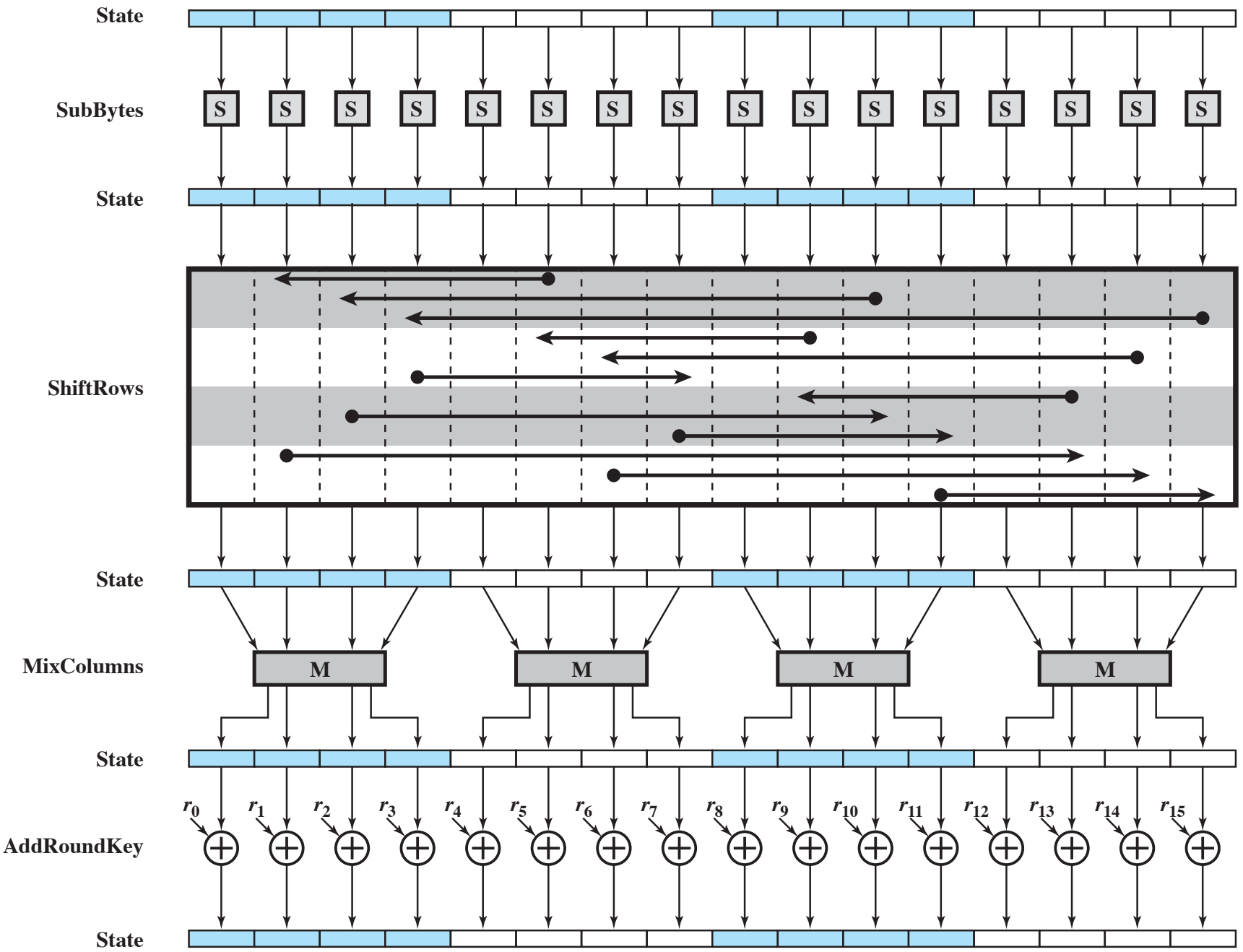



**Figure 20.4 AES Encryption Round**

# Table 20.2 AES S-Boxes

**(a) S-box**

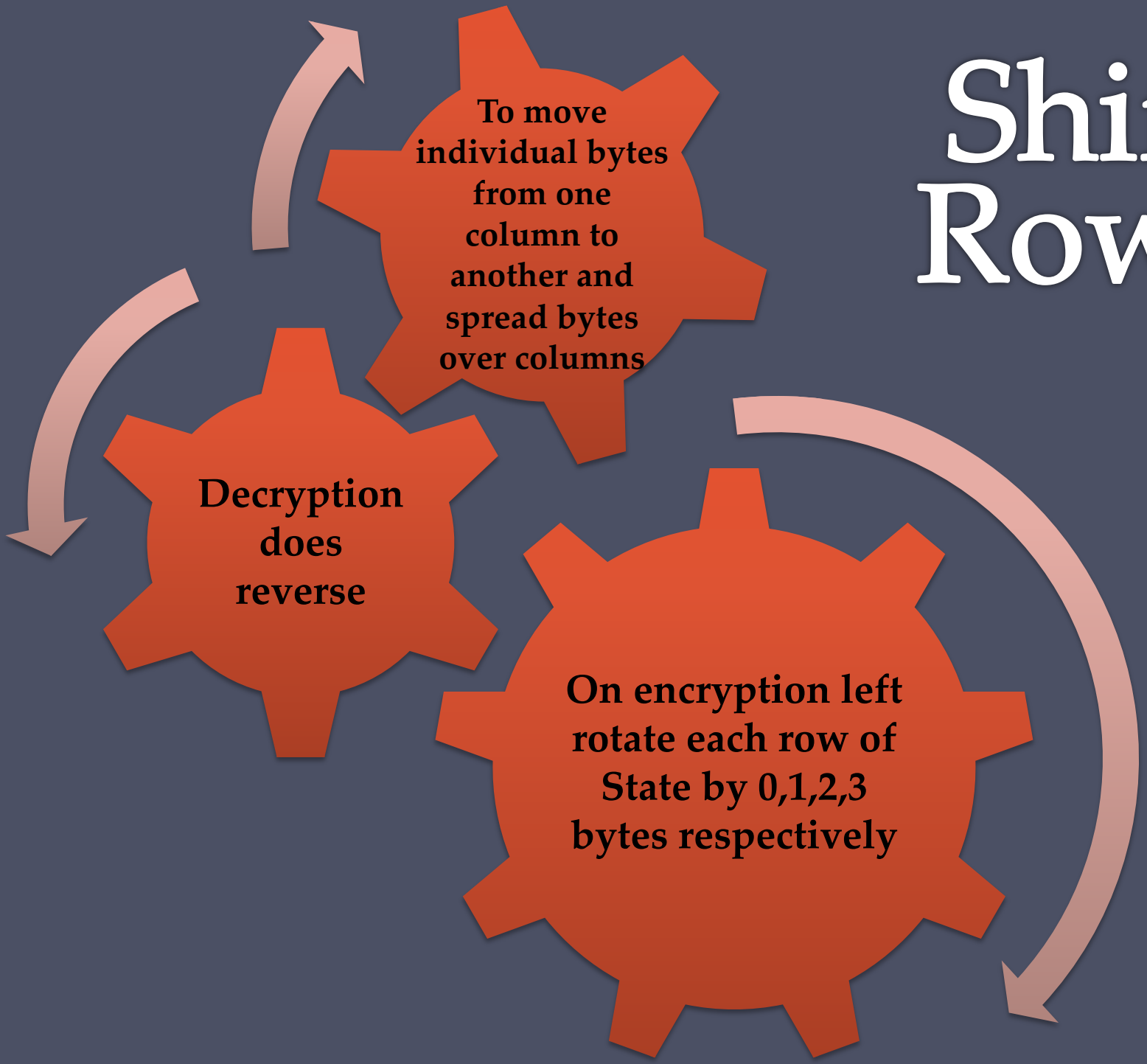
| | | *y* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | A | B | C | D | E | F |
| *x* | 0 | 63 | 7C | 77 | 7B | F2 | 6B | 6F | C5 | 30 | 01 | 67 | 2B | FE | D7 | AB | 76 |
| | 1 | CA | 82 | C9 | 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 | B1 | 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 |

# Table 20.2 AES S-Boxes

**(b) Inverse S-box**

| | | *y* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | A | B | C | D | E | F |
| *x* | 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 | F4 |
| | 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 |

# Shift Rows


To move individual bytes from one column to another and spread bytes over columns
Decryption does reverse
On encryption left rotate each row of State by 0,1,2,3 bytes respectively

# Mix Columns and Add Key

- Mix columns
  - Operates on each column individually
  - Mapping each byte to a new value that is a function of all four bytes in the column
  - Use of equations over finite fields
  - To provide good mixing of bytes in column
- Add round key
  - Simply XOR State with bits of expanded key
  - Security from complexity of round key expansion and other stages of AES

# Stream Ciphers

Processes input elements continuously

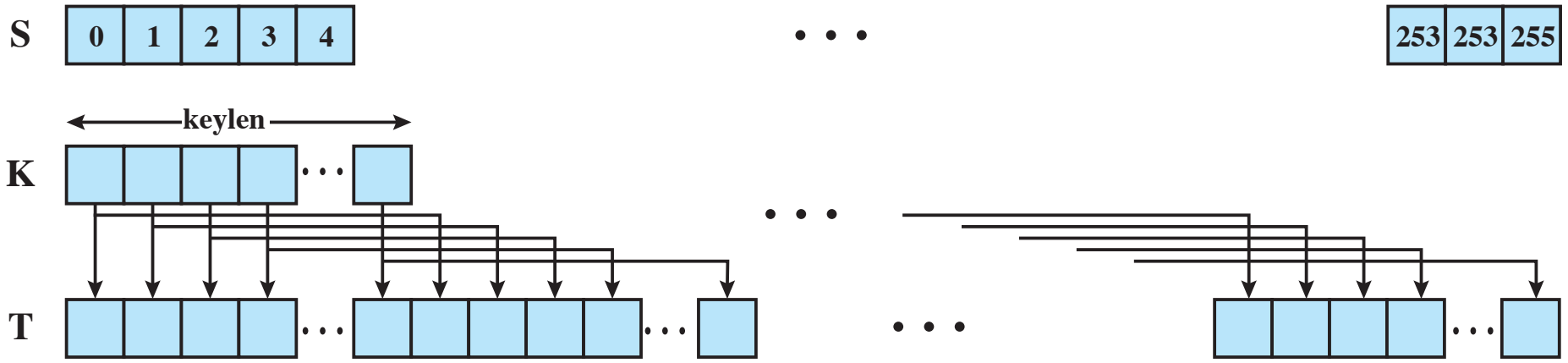
Key input to a pseudorandom bit generator

- Produces stream of random like numbers
- Unpredictable without knowing input key
- XOR keystream output with plaintext bytes

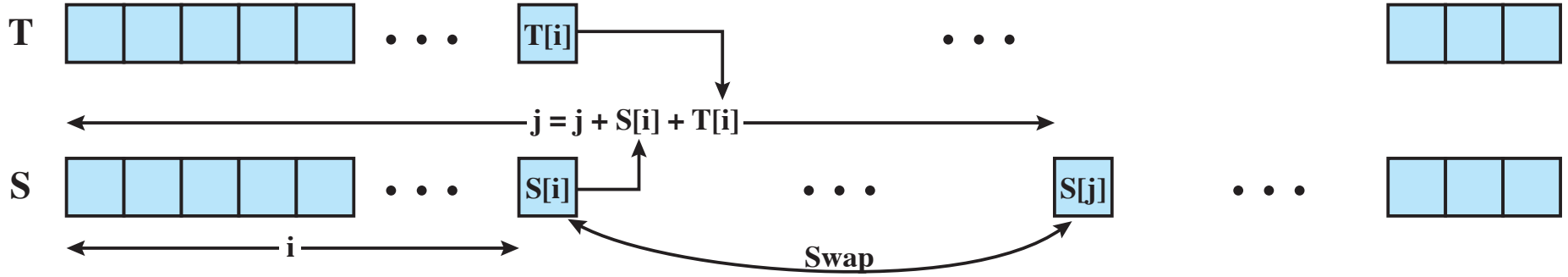
## Table 20.3 Speed Comparisons of Symmetric Ciphers on a Pentium 4

| Cipher | Key Length | Speed (Mbps) |
|---|---|---|
| DES | 56 | 21 |
| 3DES | 168 | 10 |
| AES | 128 | 61 |
| RC4 | Variable | 113 |

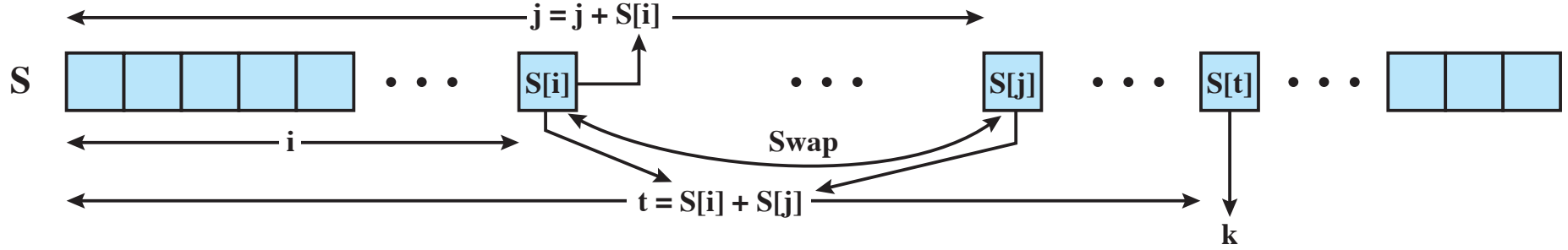
*Source*: http://www.cryptopp.com/benchmarks.html




(a) Initial state of S and T




(b) Initial permutation of S




(c) Stream Generation

**Figure 20.5 RC4**

# Table 20.4
# Block Cipher Modes of Operation

| Mode | Description | Typical Application |
|---|---|---|
| Electronic Codebook (ECB) | Each block of 64 plaintext bits is encoded independently using the same key. | •Secure transmission of single values (e.g., an encryption key) |
| Cipher Block Chaining (CBC) | The input to the encryption algorithm is the XOR of the next 64 bits of plaintext and the preceding 64 bits of ciphertext. | •General-purpose block-oriented transmission<br>•Authentication |
| Cipher Feedback (CFB) | Input is processed *s* bits at a time. Preceding ciphertext is used as input to the encryption algorithm to produce pseudorandom output, which is XORed with plaintext to produce next unit of ciphertext. | •General-purpose stream-oriented transmission<br>•Authentication |
| Output Feedback (OFB) | Similar to CFB, except that the input to the encryption algorithm is the preceding DES output. | •Stream-oriented transmission over noisy channel (e.g., satellite communication) |
| Counter (CTR) | Each block of plaintext is XORed with an encrypted counter. The counter is incremented for each subsequent block. | •General-purpose block-oriented transmission<br>•Useful for high-speed requirements |

# Electronic Codebook (ECB)

- Simplest mode
- Plaintext is handled *b* bits at a time and each block is encrypted using the same key
- "Codebook" because have unique ciphertext value for each plaintext block
  - Not secure for long messages since repeated plaintext is seen in repeated ciphertext
- To overcome security deficiencies you need a technique where the same plaintext block, if repeated, produces different ciphertext blocks

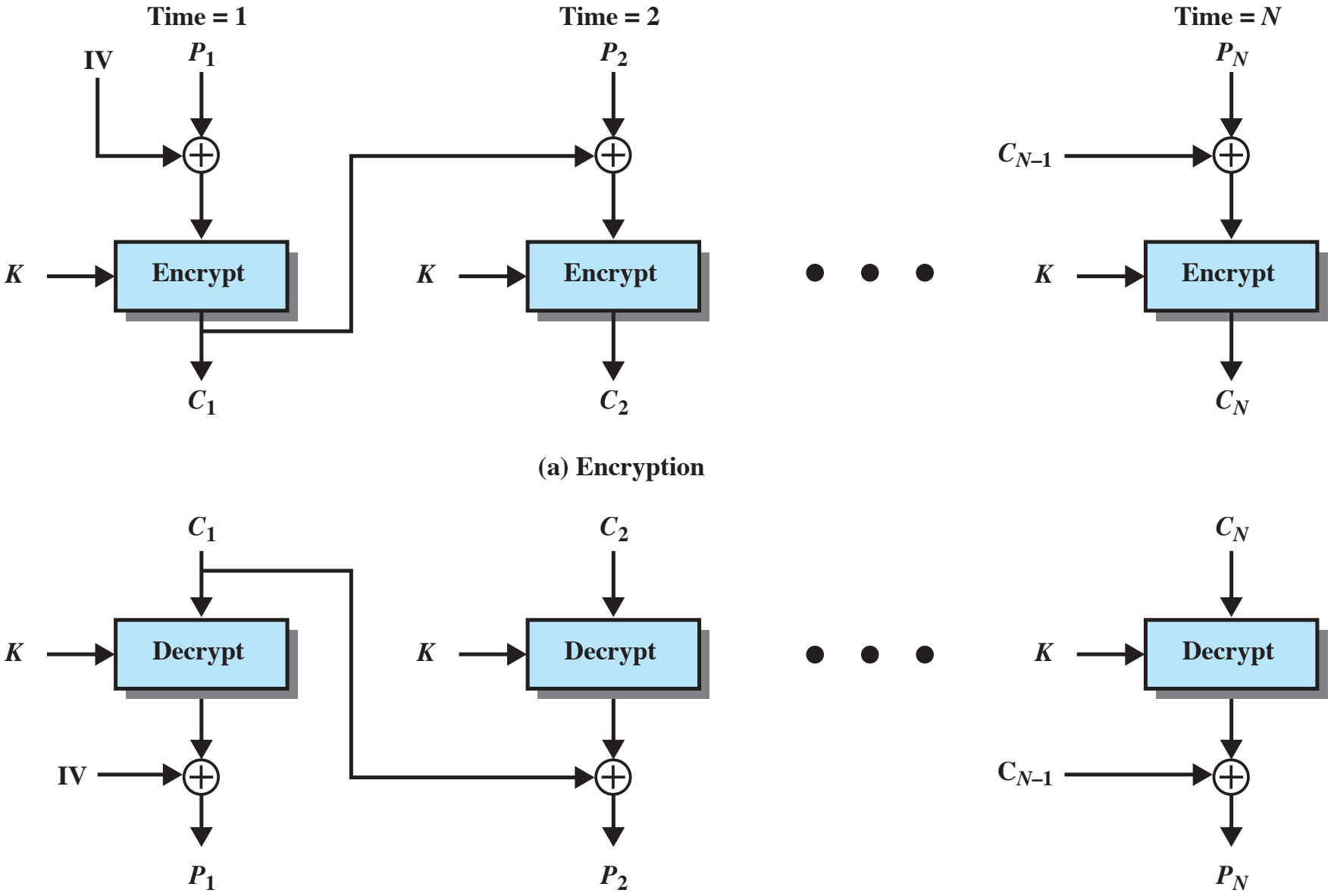



**Figure 20.6 Cipher Block Chaining (CBC) Mode**

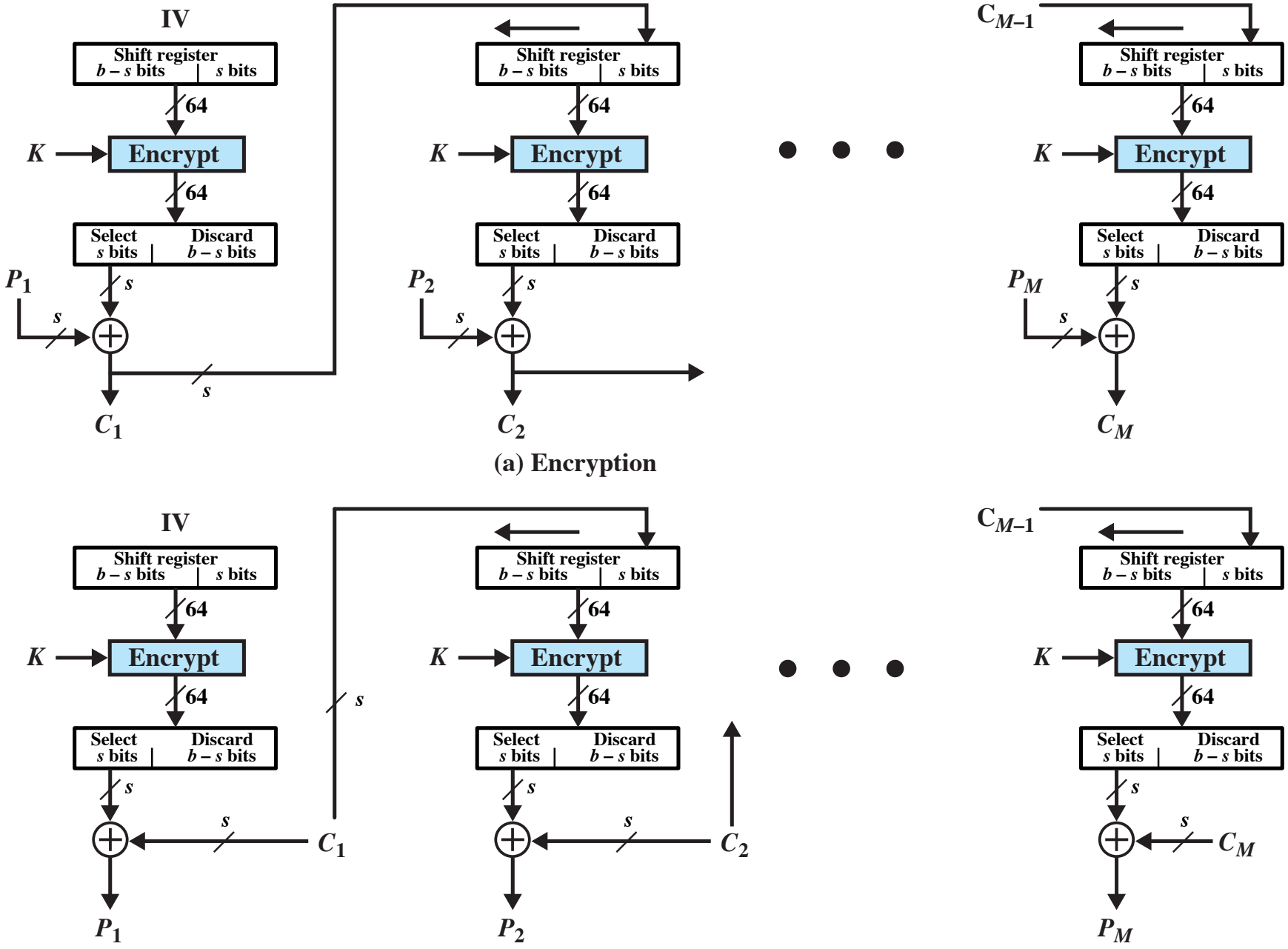



**Figure 20.7 *s*-bit Cipher Feedback (CFB) Mode**

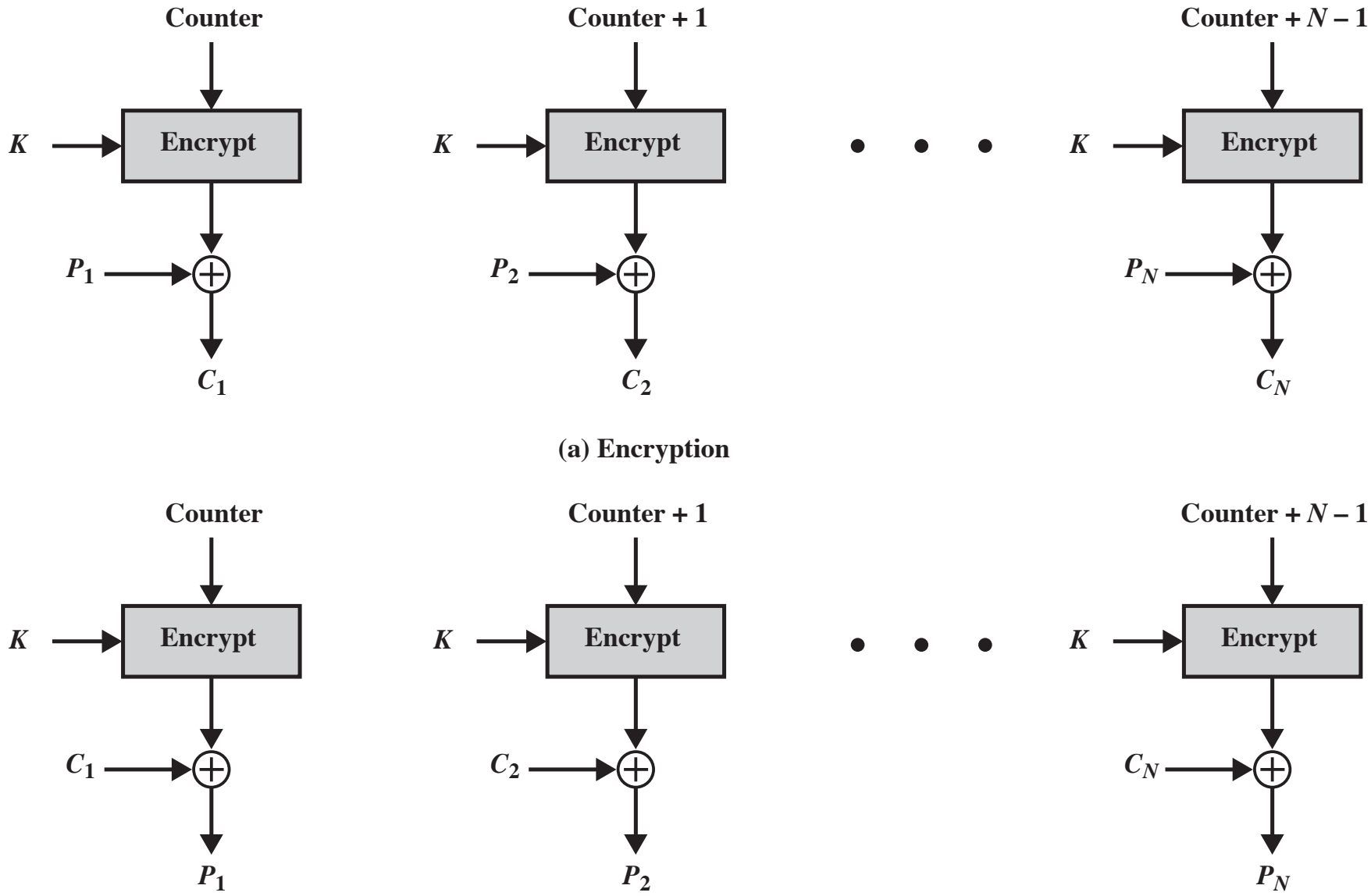



**Figure 20.8 Counter (CTR) Mode**

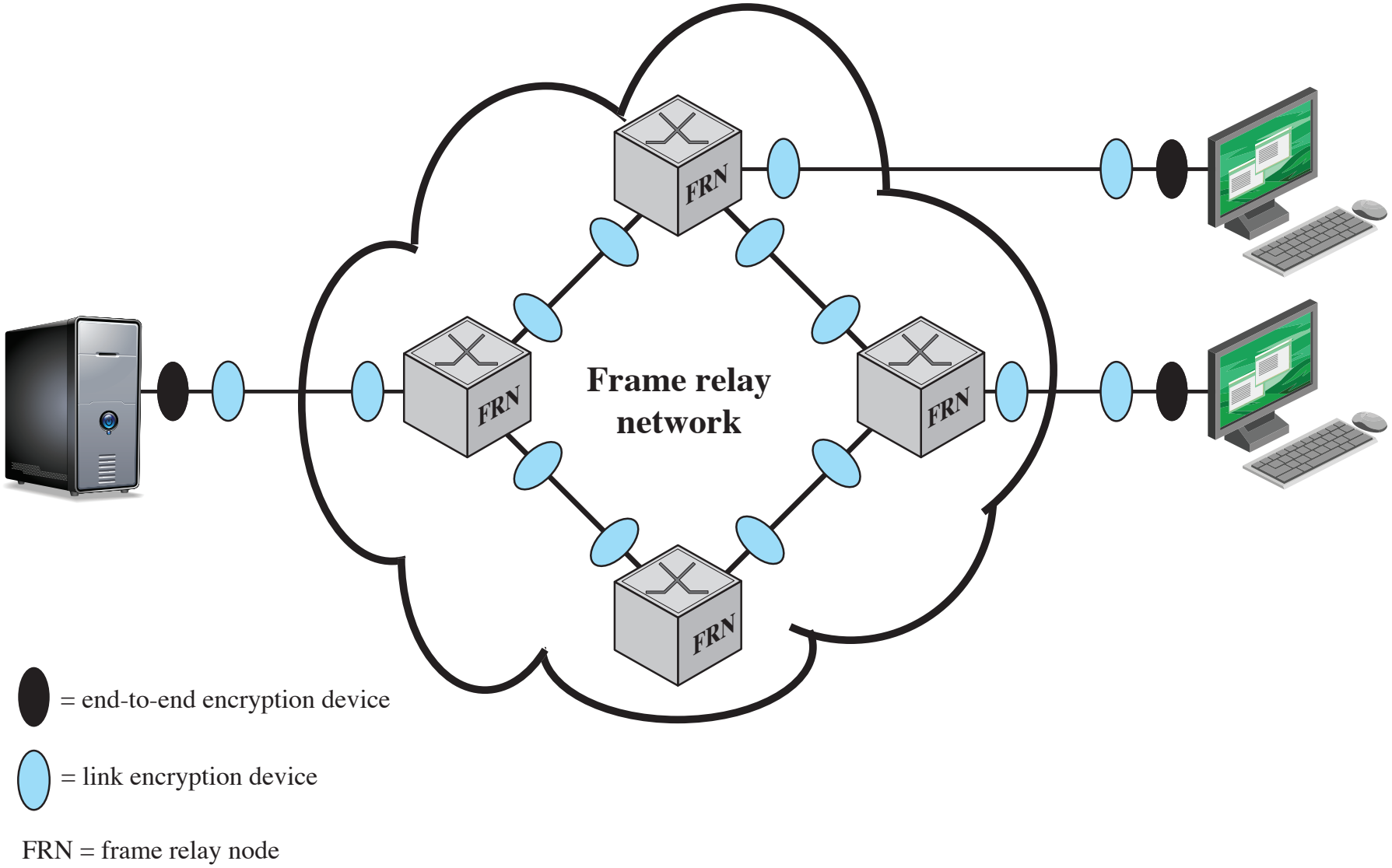



**Figure 20.9 Encryption Across a Frame Relay Network**

# Key Distribution

- The means of delivering a key to two parties that wish to exchange data without allowing others to see the key
- Two parties (A and B) can achieve this by:

1. A key could be selected by A and physically delivered to B
2. A third party could select the key and physically deliver it to A and B
3. If A and B have previously and recently used a key, one party could transmit the new key to the other, encrypted using the old key
4. If A and B each have an encrypted connection to a third party C, C could deliver a key on the encrypted links to A and B

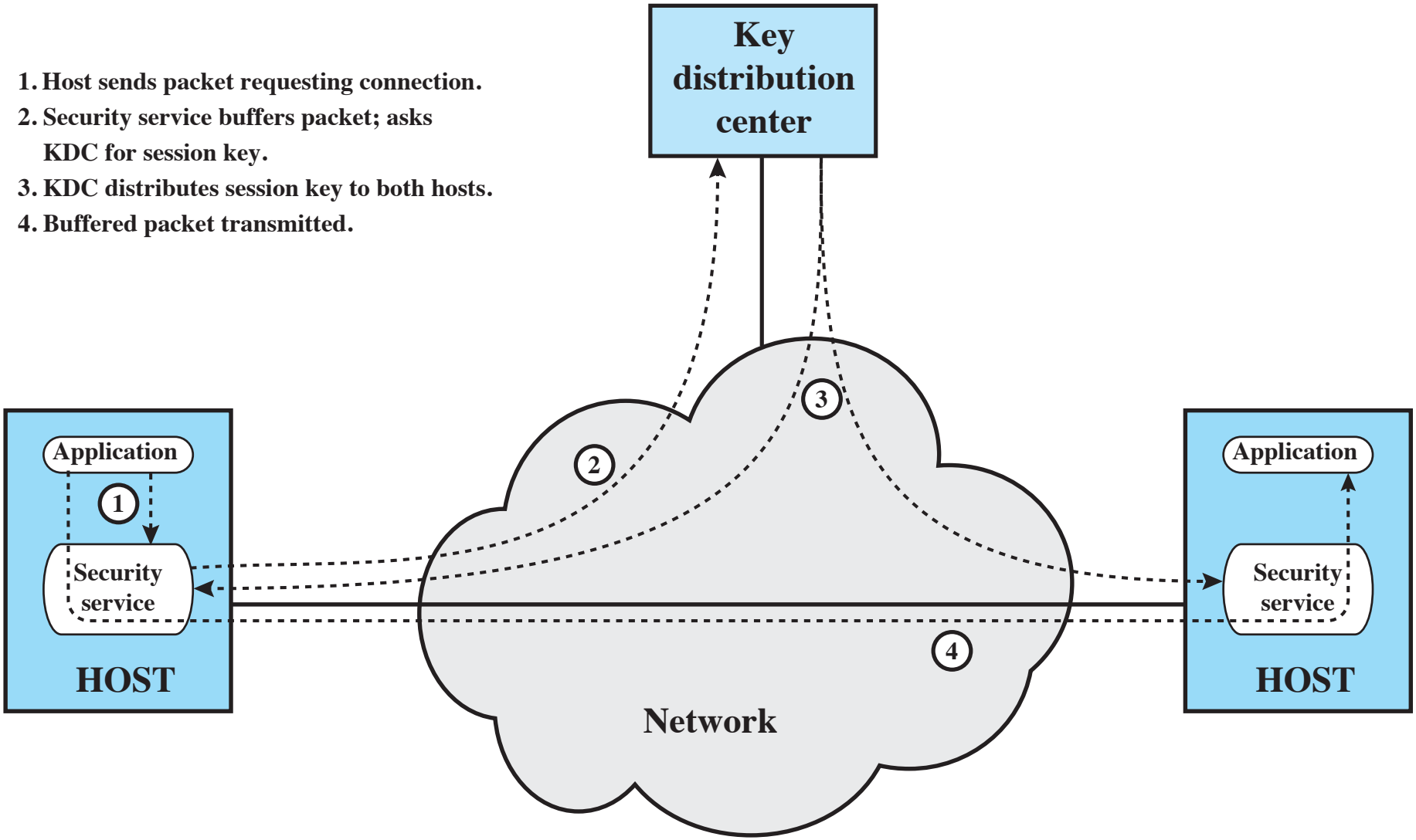



**Figure 20.10 Automatic Key Distribution for Connection-Oriented Protocol**

# Summary

- Symmetric encryption principles
  - Cryptography
  - Cryptanalysis
  - Feistel cipher structure
- Data encryption standard
  - Data encryption standard
  - Triple DES
- Advanced encryption standard
  - Overview of the algorithm
  - Algorithm details

- Stream ciphers and RC4
  - Stream cipher structure
  - The RC4 algorithm
- Cipher block modes of operation
  - Electronic codebook mode
  - Cipher block chaining mode
  - Cipher feedback mode
  - Counter mode
- Location of symmetric encryption devices
- Key distribution