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# CSCI 667: Concepts of Computer Security

Lecture 4

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Derived from slides by William Enck, Micah Sherr, Patrick McDaniel, and Peng Ning

# Announcements

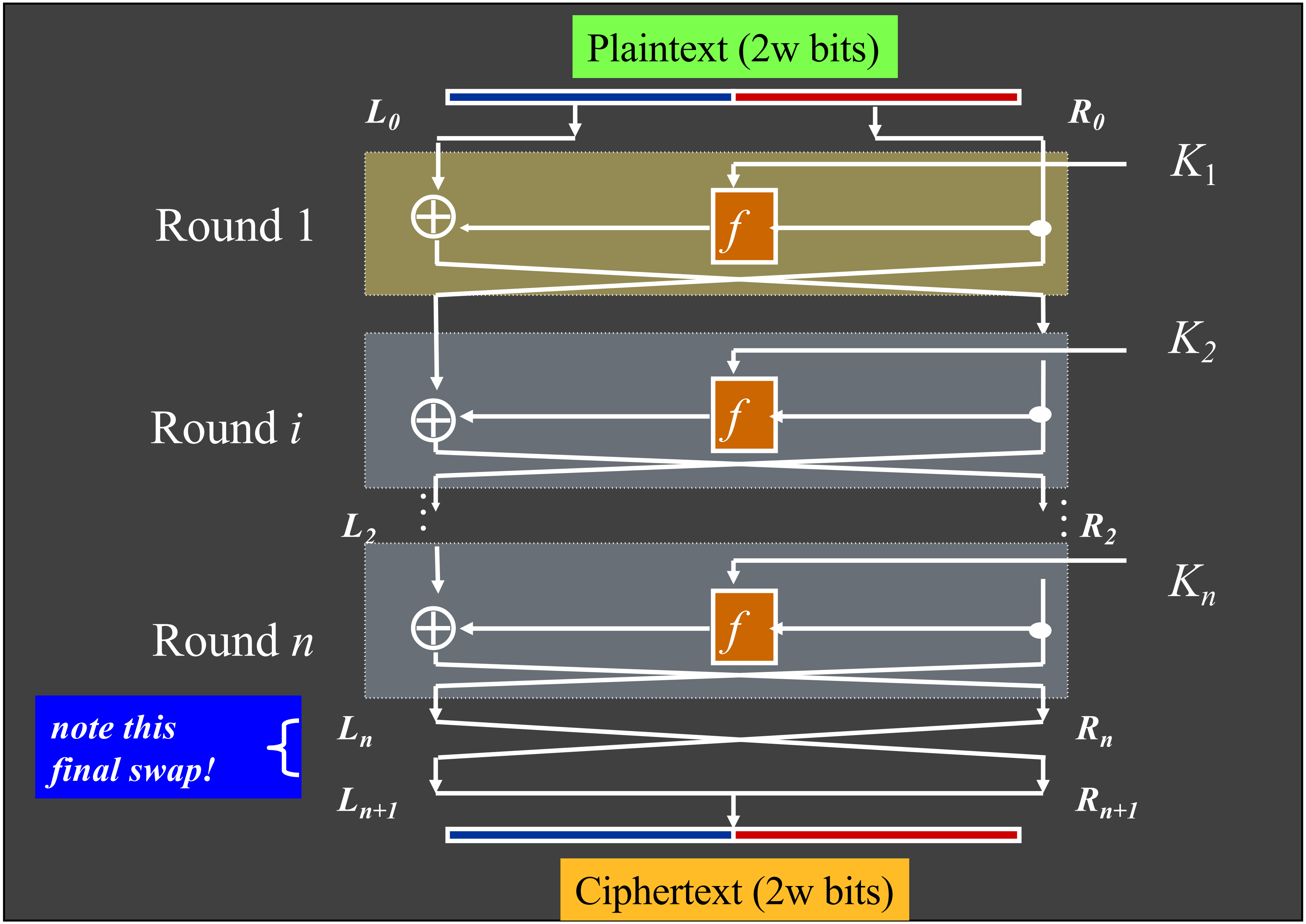
1. Homework 2  will be assigned on Thursday.
    - Due February 23rd at 11:59pm

# Announcements

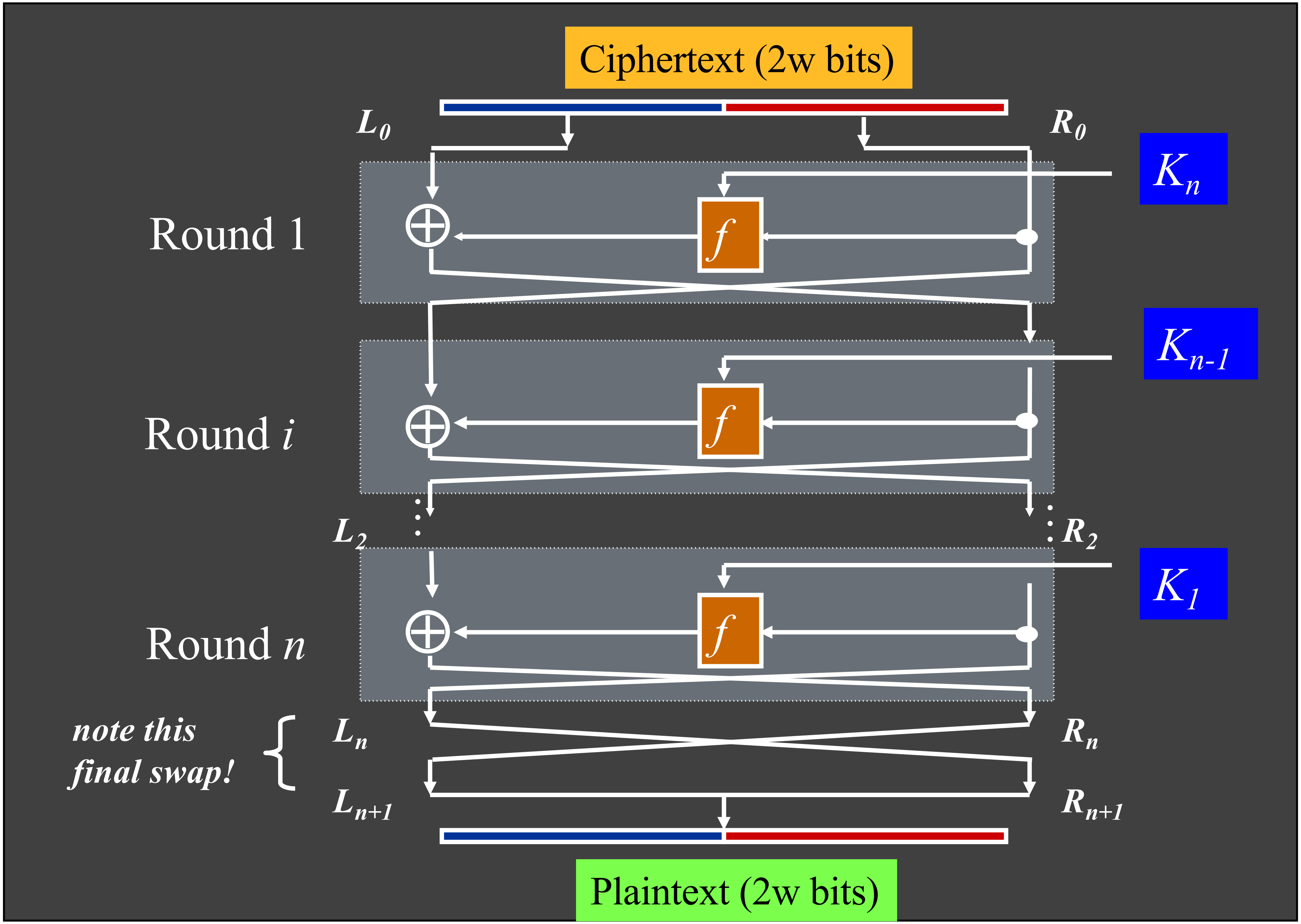
2. Project “Speed Dating” next Tuesday *(updated on the course schedule)*

- Make sure you prepare
  - Look at top conferences and papers
  - Get some general ideas of what you are interested in
  - Brainstorm some project ideas
  - **Project Proposal due Feb 23rd**

# Complete Feistel Cipher: Encryption

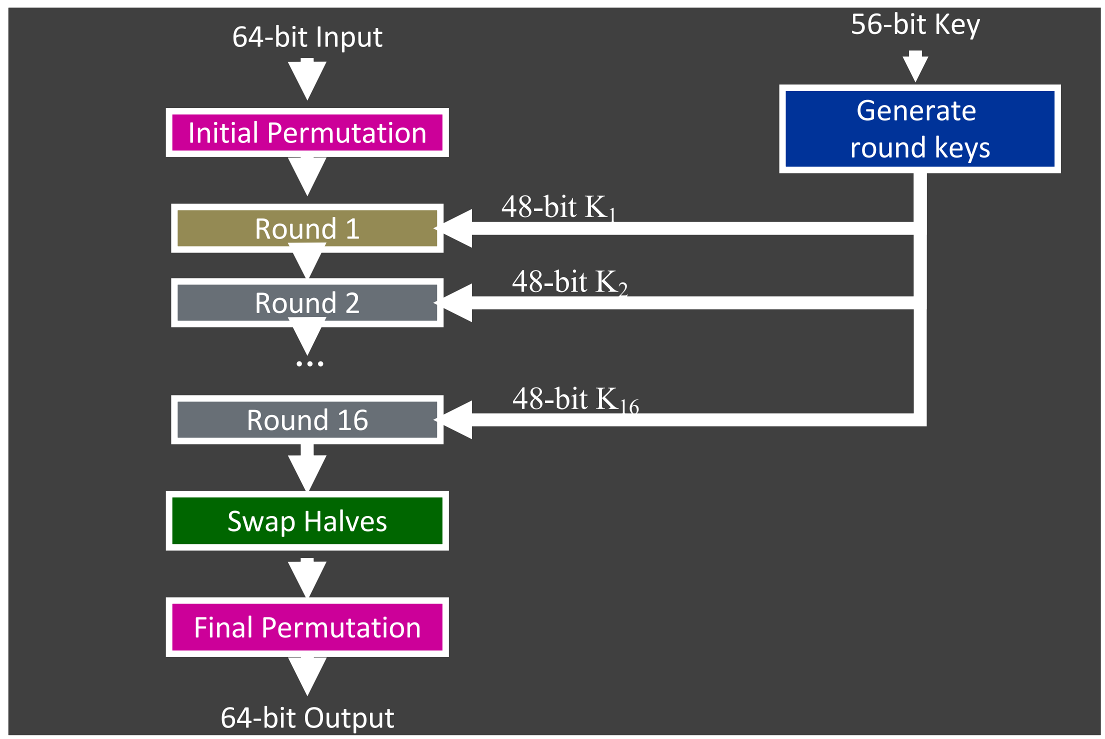


# Feistel Cipher: Decryption

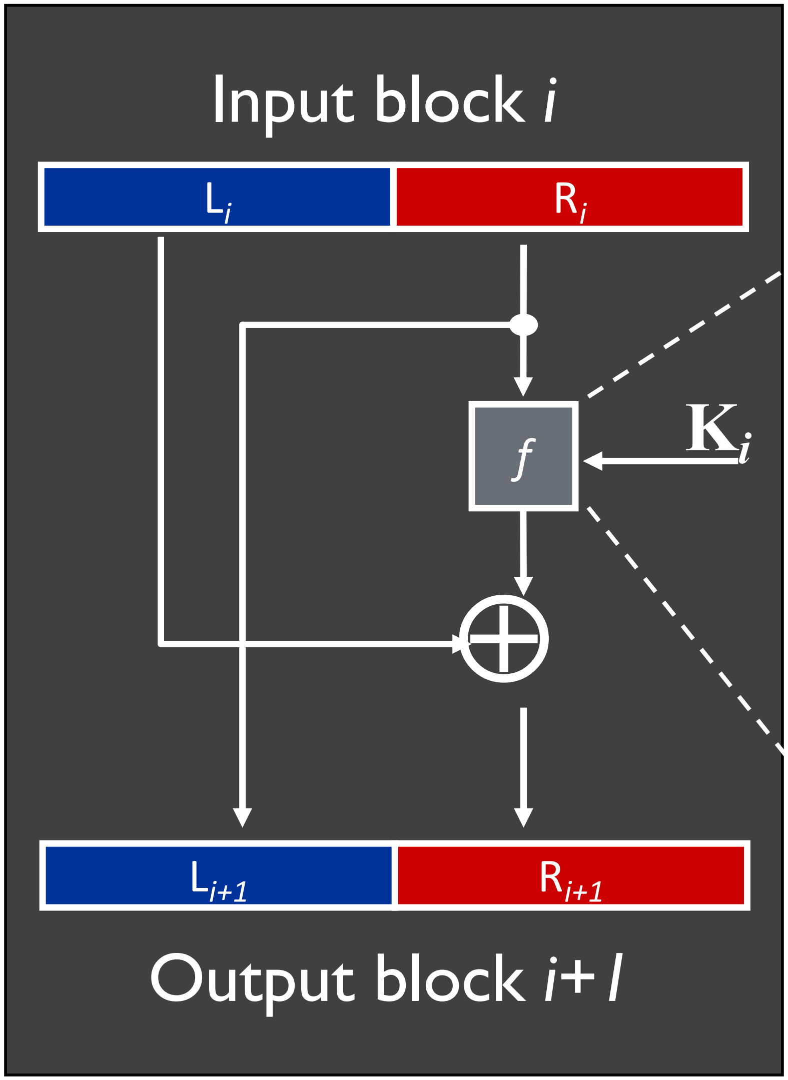


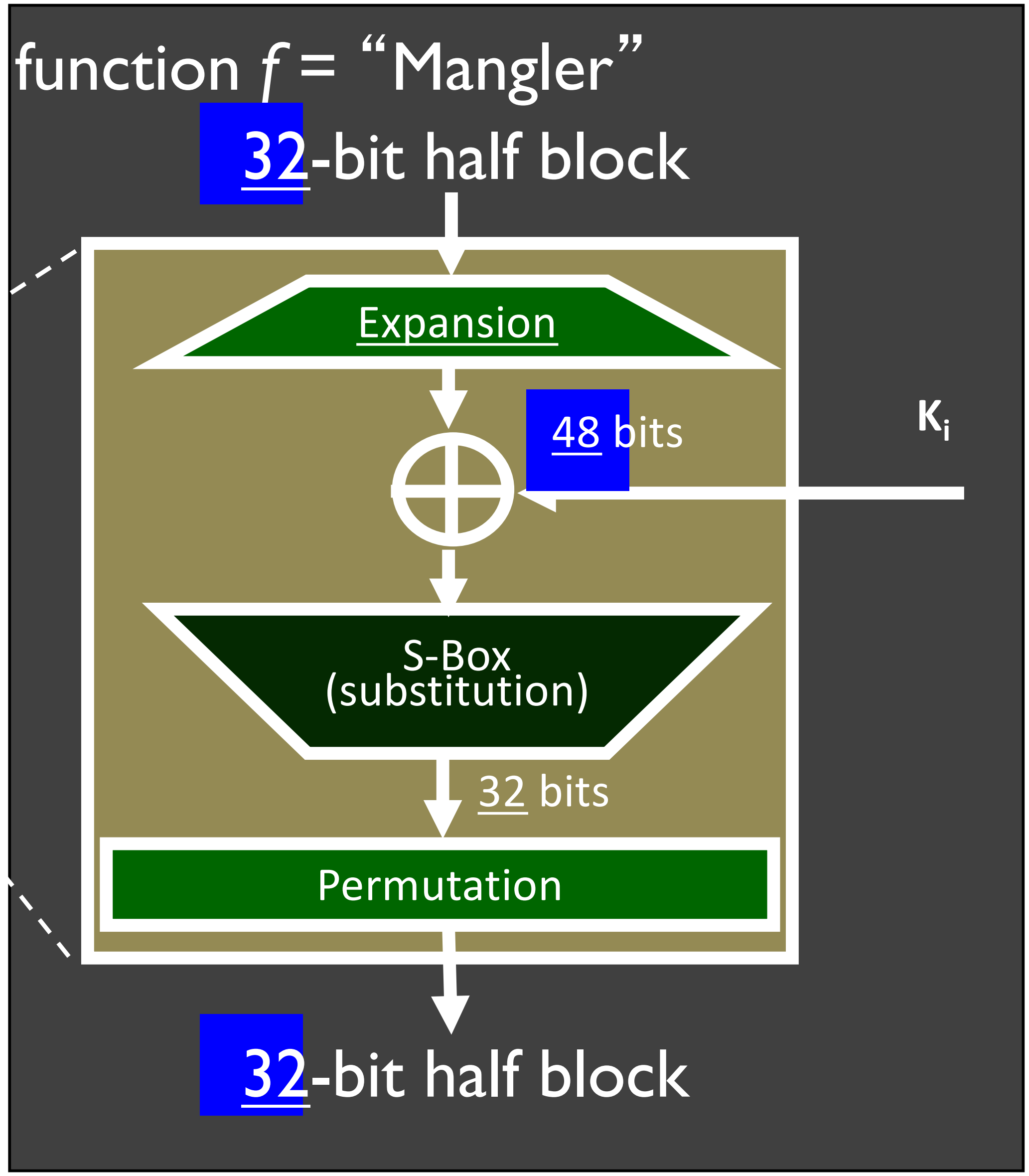
# Data Encryption Standard (DES)

- Introduced by the US NBS (now NIST) in 1972
- Signaled the beginning of the modern area of cryptography
- Basics
  - Feistel Cipher
  - 8-byte (64 bit) input
  - 8-byte (64 bit) output
  - 8-byte key
    (56 bits + 8 parity bits)
  - 16 rounds



# DES Round: *f* (Mangler) Function



# Substitution Box (S-Box)

- A substitution box (or S-box) is used to obscure the relationship between the plaintext and the ciphertext
  - Shannon's property of *confusion*: the relationship between key and ciphertext is complex as possible
  - In DES, S-boxes are carefully chosen to resist cryptanalysis
  - Thus, that is where the security comes from

| $S_5$ | | Middle 4 bits of input | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **0000** | **0001** | **0010** | **0011** | **0100** | **0101** | **0110** | **0111** | **1000** | **1001** | **1010** | **1011** | **1100** | **1101** | **1110** | **1111** |
| **Outer bits** | **00** | 0010 | 1100 | 0100 | 0001 | 0111 | 1010 | 1011 | 0110 | 1000 | 0101 | 0011 | 1111 | 1101 | 0000 | 1110 | 1001 |
| | **01** | 1110 | 1011 | 0010 | 1100 | 0100 | 0111 | 1101 | 0001 | 0101 | 0000 | 1111 | 1010 | 0011 | 1001 | 1000 | 0110 |
| | **10** | 0100 | 0010 | 0001 | 1011 | 1010 | 1101 | 0111 | 1000 | 1111 | 1001 | 1100 | 0101 | 0110 | 0011 | 0000 | 1110 |
| | **11** | 1011 | 1000 | 1100 | 0111 | 0001 | 1110 | 0010 | 1101 | 0110 | 1111 | 0000 | 1001 | 1010 | 0100 | 0101 | 0011 |

*Example*: Given a 6-bit input, the 4-bit output is found by selecting the row using the outer two bits, and the column using the inner four bits. For example, an input "011011" has outer bits "01" and inner bits "1101"; the corresponding output would be "1001".

# Avalanche Effect in DES: Change in Plaintext

| Round | | δ |
|---|---|---|
| | 02468aceeca86420<br>12468aceeca86420 | 1 |
| 1 | 3cf03c0fbad22845<br>3cf03c0fbad32845 | 1 |
| 2 | bad2284599e9b723<br>bad3284539a9b7a3 | 5 |
| 3 | 99e9b7230bae3b9e<br>39a9b7a3171cb8b3 | 18 |
| 4 | 0bae3b9e42415649<br>171cb8b3ccaca55e | 34 |
| 5 | 4241564918b3fa41<br>ccaca55ed16c3653 | 37 |
| 6 | 18b3fa419616fe23<br>d16c3653cf402c68 | 33 |
| 7 | 9616fe2367117cf2<br>cf402c682b2cefbc | 32 |
| 8 | 67117cf2c11bfc09<br>2b2cefbc99f91153 | 33 |

| Round | | δ |
|---|---|---|
| 9 | c11bfc09887fbc6c<br>99f911532eed7d94 | 32 |
| 10 | 887fbc6c600f7e8b<br>2eed7d94d0f23094 | 34 |
| 11 | 600f7e8bf596506e<br>d0f23094455da9c4 | 37 |
| 12 | f596506e738538b8<br>455da9c47f6e3cf3 | 31 |
| 13 | 738538b8c6a62c4e<br>7f6e3cf34bc1a8d9 | 29 |
| 14 | c6a62c4e56b0bd75<br>4bc1a8d91e07d409 | 33 |
| 15 | 56b0bd7575e8fd8f<br>1e07d4091ce2e6dc | 31 |
| 16 | 75e8fd8f25896490<br>1ce2e6dc365e5f59 | 32 |
| $IP^{-1}$ | da02ce3a89ecac3b<br>057cde97d7683f2a | 32 |

(from Stallings, Crypto and Net Security)

# Avalanche Effect in DES: Change in Key

| Round | | δ | Round | | δ |
|---|---|---|---|---|---|
| | 02468aceeca86420<br>02468aceeca86420 | 0 | 9 | c11bfc09887fbc6c<br>548f1de471f64dfd | 34 |
| 1 | 3cf03c0fbad22845<br>3cf03c0f9ad628c5 | 3 | 10 | 887fbc6c600f7e8b<br>71f64dfd4279876c | 36 |
| 2 | bad2284599e9b723<br>9ad628c59939136b | 11 | 11 | 600f7e8bf596506e<br>4279876c399fdc0d | 32 |
| 3 | 99e9b7230bae3b9e<br>9939136b768067b7 | 25 | 12 | f596506e738538b8<br>399fdc0d6d208dbb | 28 |
| 4 | 0bae3b9e42415649<br>768067b75a8807c5 | 29 | 13 | 738538b8c6a62c4e<br>6d208dbbb9bdeeaa | 33 |
| 5 | 4241564918b3fa41<br>5a8807c5488dbe94 | 26 | 14 | c6a62c4e56b0bd75<br>b9bdeeaad2c3a56f | 30 |
| 6 | 18b3fa419616fe23<br>488dbe94aba7fe53 | 26 | 15 | 56b0bd7575e8fd8f<br>d2c3a56f2765c1fb | 33 |
| 7 | 9616fe2367117cf2<br>aba7fe53177d21e4 | 27 | 16 | 75e8fd8f25896490<br>2765c1fb01263dc4 | 30 |
| 8 | 67117cf2c11bfc09<br>177d21e4548f1de4 | 32 | IP–1 | da02ce3a89ecac3b<br>ee92b50606b62b0b | 30 |

(from Stallings, Crypto and Net Security)

# Cryptanalysis of DES

- DES has an effective 56-bit key length
- Wiener: $1,000,000 - 3.5 hours (never built)
- July 17, 1998, the EFF DES Cracker, which was built for less than $250,000 < 3 days
- January 19, 1999, Distributed.Net (w/EFF), 22 hours and 15 minutes (over many machines)
- We all assume that NSA and agencies like it around the world can crack (recover key) DES in milliseconds

- *What now? Give up on DES?*

# Variants of DES

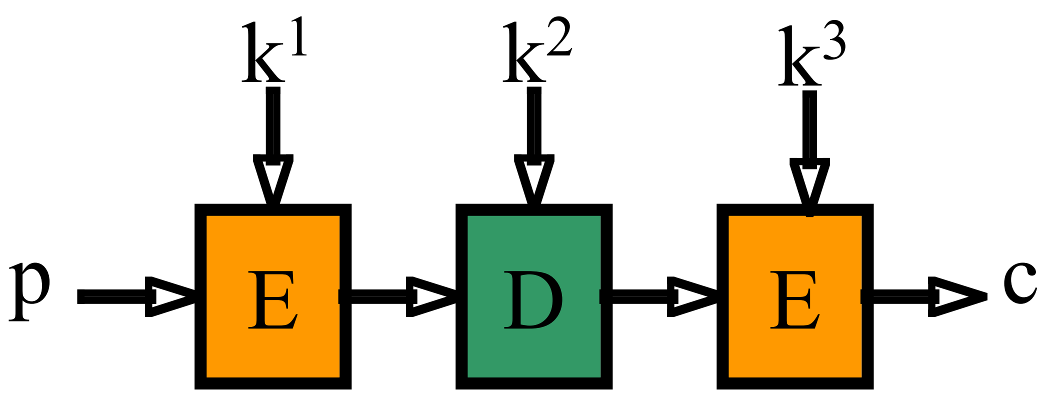
- DESX (XOR with separate keys ~= 60-bits)

$$DESX(m) = K_2 \oplus DES_K(m \oplus K_1)$$

  - Linear cryptanalysis
- Triple DES (three keys ~= 112 bits)
  - Keys $k_1$, $k_2$, $k_3$, but in practice $k_1 = k_3$

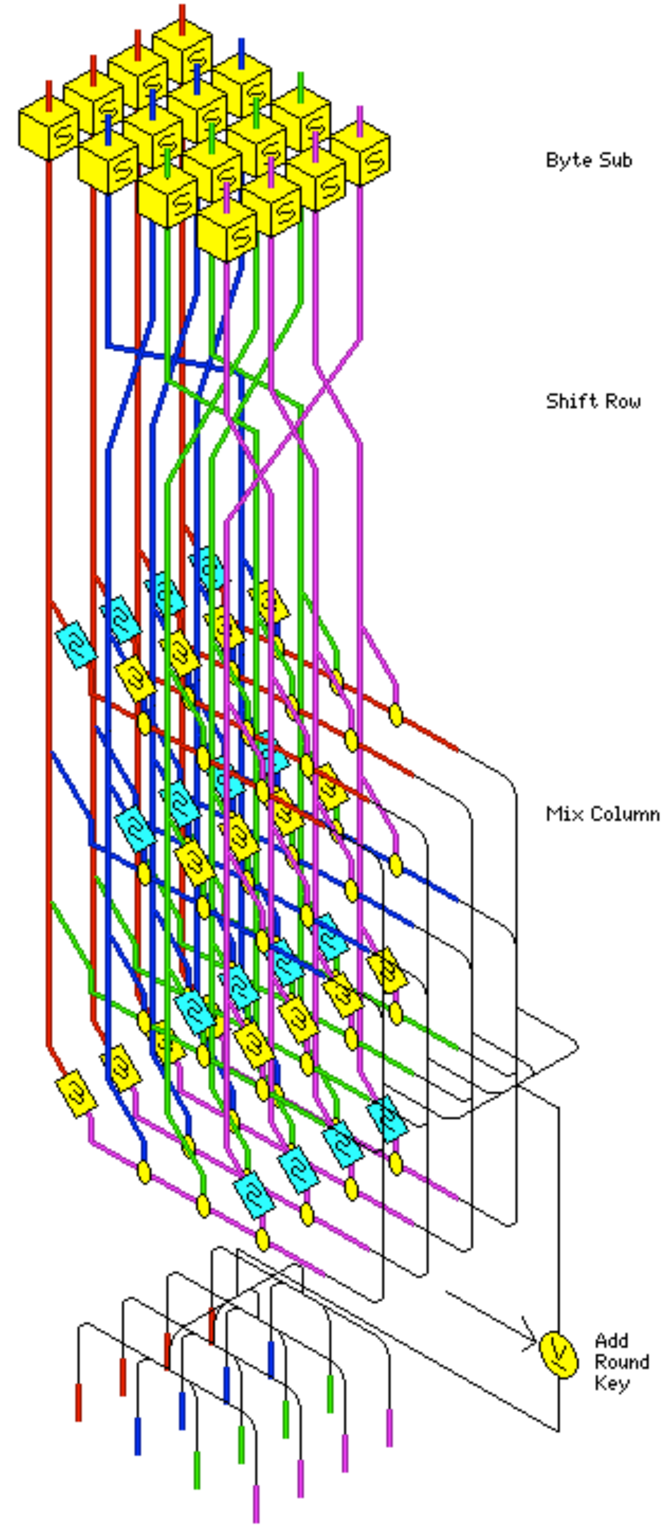
$$C = E(D(E(p, k1), k2), k3)$$

  - Compatible with normal DES if $k_1 = k_2 = k_3$

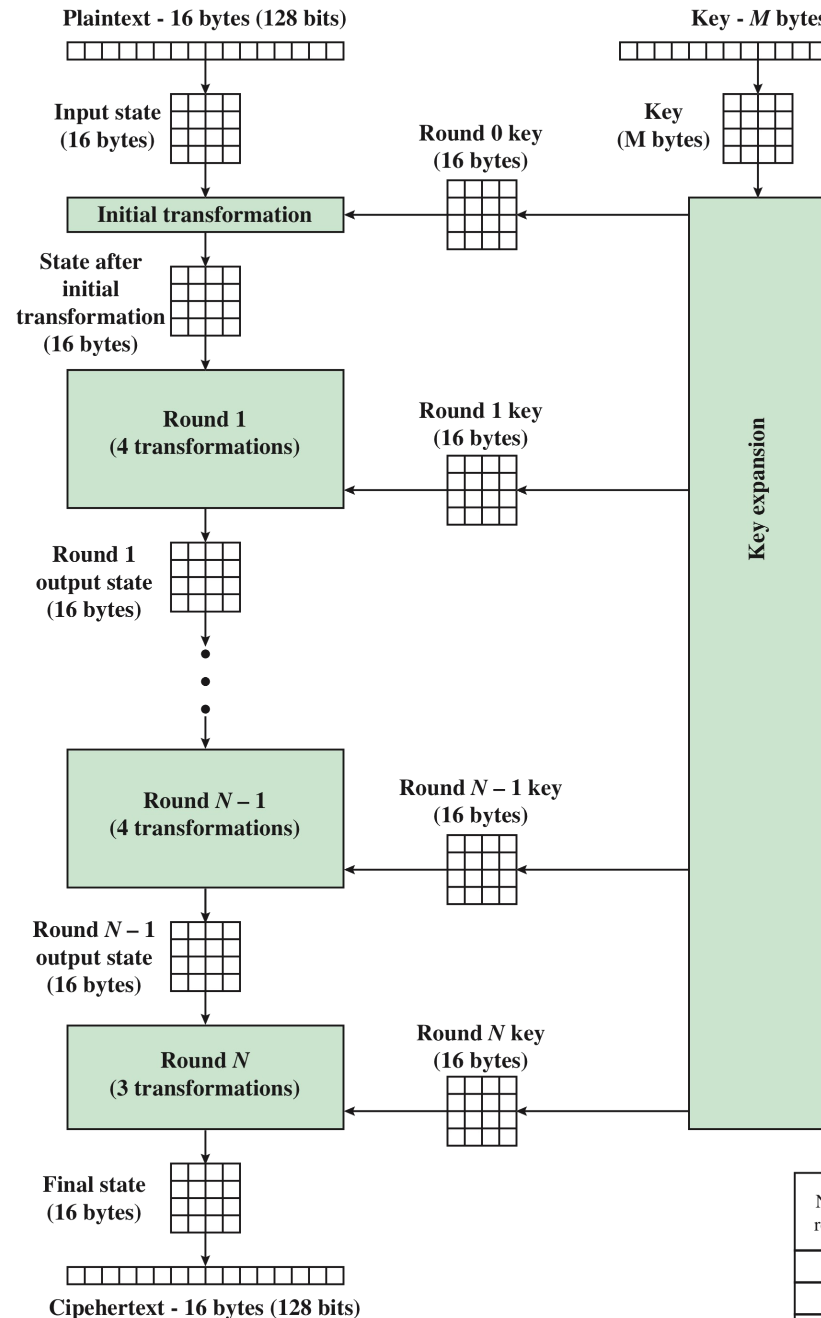


# Advanced Encryption Standard (AES)

- International NIST bakeoff between cryptographers
  - Rijndael (pronounced "Rhine-dall")
- Replaced DES as the "accepted" symmetric key cipher
  - Substitution-permutation network, not a Feistel network
  - Variable key lengths (128, 192, or 256 bits)
  - Block size: 128 bits
  - Fast implementation in both hardware and software
  - Small code and memory footprint



# AES Encryption Process




| No. of rounds | Key Length (bytes) |
|---|---|
| 10 | 16 |
| 12 | 24 |
| 14 | 32 |

**Figure 5.1 AES Encryption Process**

(from Stallings, Crypto and Net Security)

# AES Data Structures

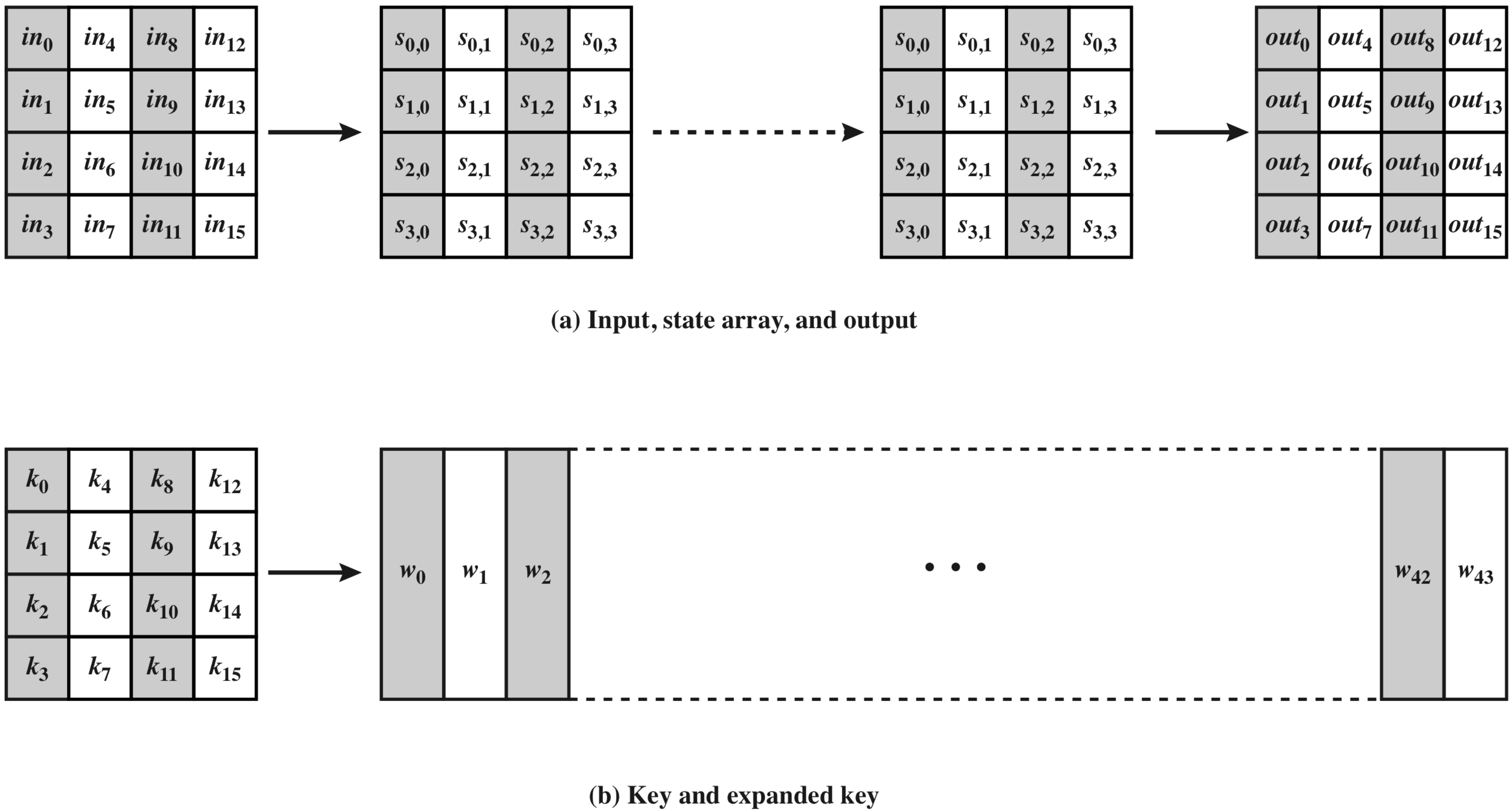



**Figure 5.2 AES Data Structures**

(from Stallings, Crypto and Net Security)

# AES Encryption and Decryption

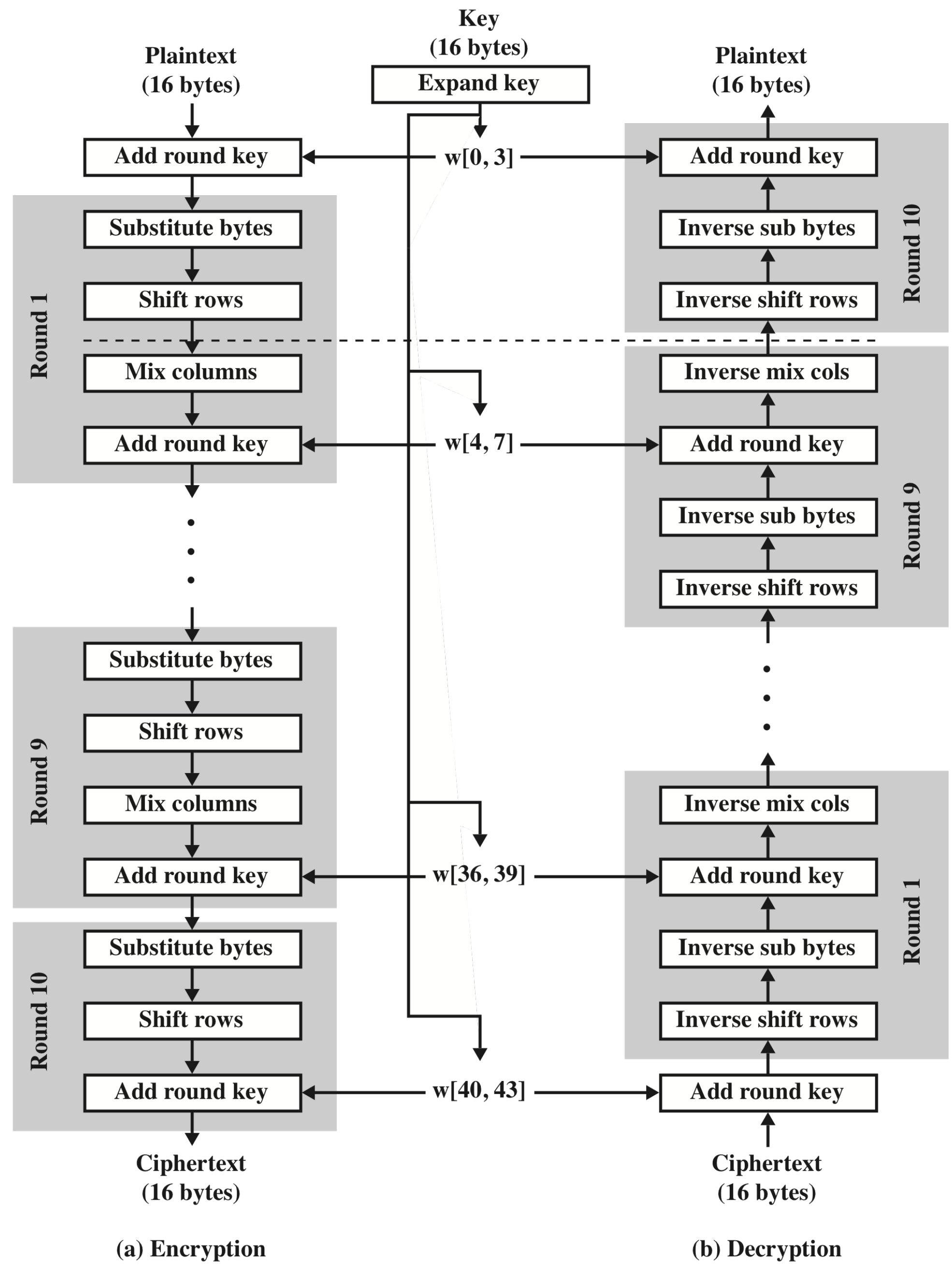



**Figure 5.3 AES Encryption and Decryption**

(from Stallings, Crypto and Net Security)

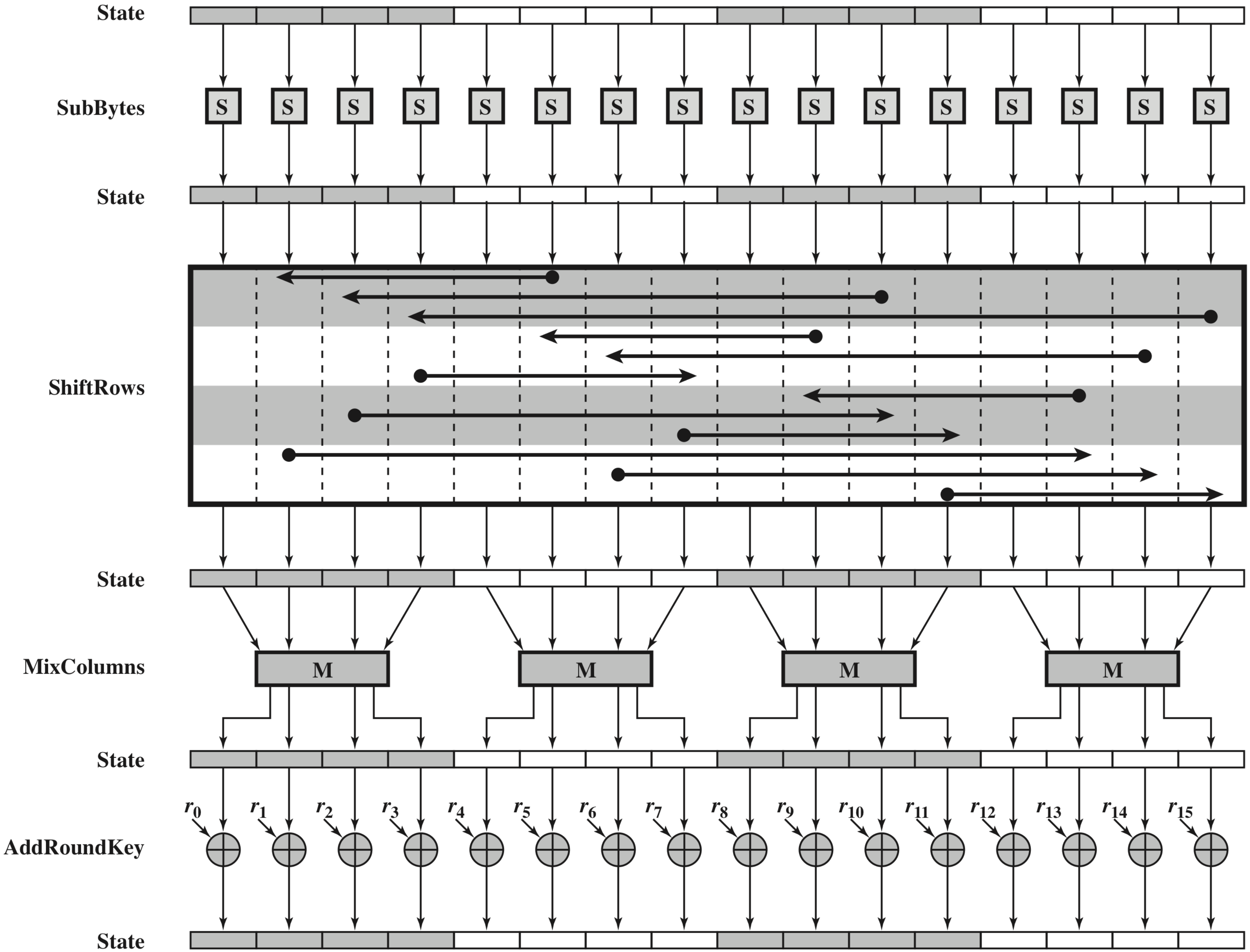



**Figure 5.4 AES Encryption Round**

(from Stallings, Crypto and Net Security)

# S-box and Inverse S-box

## S-box

| | y | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| x | 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 | 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 |

## Inverse S-box

| | y | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| x | 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 | 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 |

(from Stallings, Crypto and Net Security)

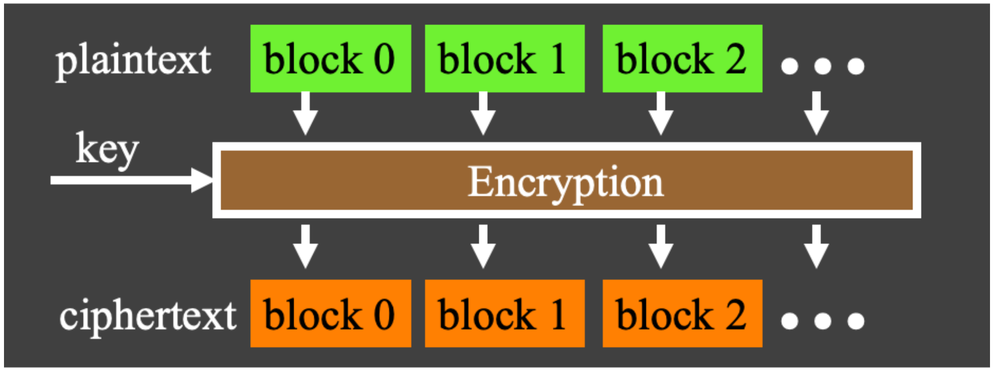
# Implementation Aspects

- AES can be implemented very efficiently on an 8-bit processor
- SubBytes operates at the byte level and only requires a table of 256 bytes
- ShiftRows is a simple byte-shifting operation
- AddRoundKey is a bytewise XOR operation
- MixColumns requires matrix multiplication in the field $GF(2^8)$, which means all operations are carried out on bytes
- Designers believe this very efficient implementation was a key factor in its selection as the AES cipher

(from Stallings, Crypto and Net Security)

# Modes of Operation

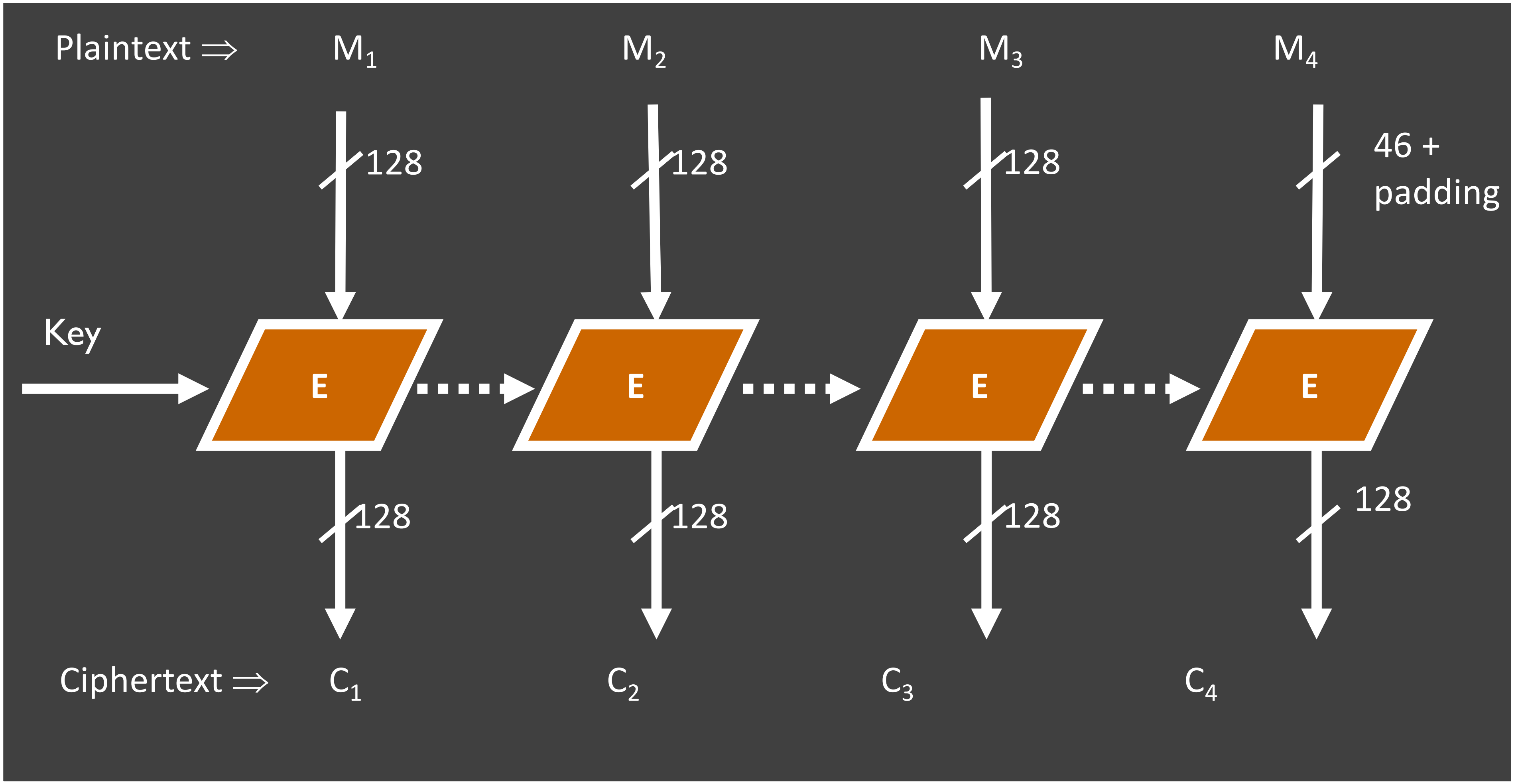
- Most ciphers work on blocks of fixed (small) size
- How to encrypt long messages?
- Modes of operation
  - ECB (Electronic Code Book)
  - CBC (Cipher Block Chaining)
  - OFB (Output Feedback)
  - CFB (Cipher Feedback)
  - CTR (Counter)



# Issues for Block Chaining Modes

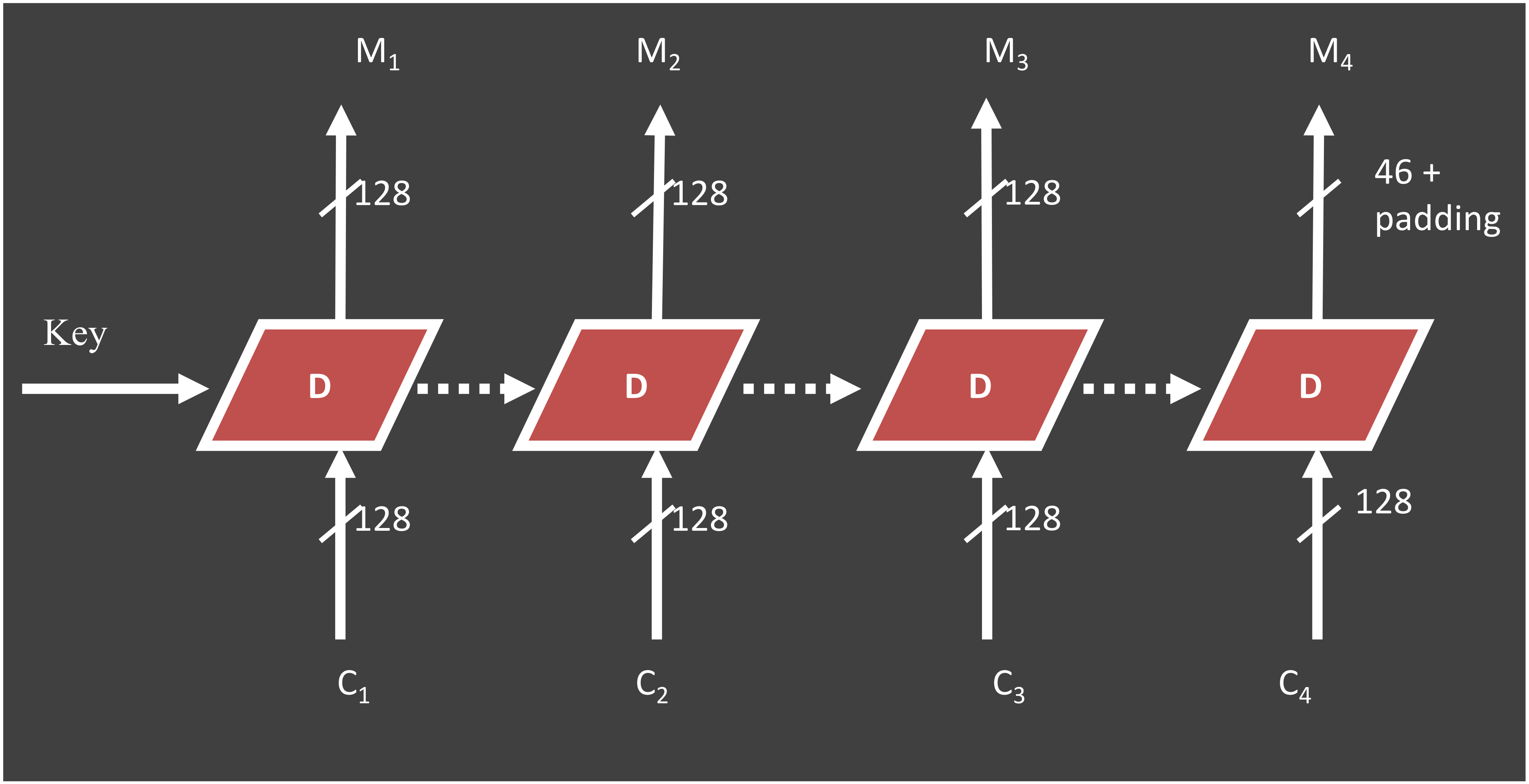
- *Information leakage*: Does it reveal info about the plaintext blocks?
- *Ciphertext manipulation*: Can an attacker modify ciphertext block(s) in a way that will produce a predictable/desired change in the decrypted plaintext block(s)?
  - Note: assume the structure of the plaintext is known, e.g., first block is employee #1 salary, second block is employee #2 salary, etc.
- *Parallel/Sequential*: Can blocks of plaintext (ciphertext) be encrypted (decrypted) in parallel?
- *Error Propagation*: If there is an error in a plaintext (ciphertext) block, will there be an encryption (decryption) error in more than one ciphertext (plaintext) block?

# Electronic Code Book (ECB)




- The easiest mode of operation; each block is independently encrypted

# ECB Decryption

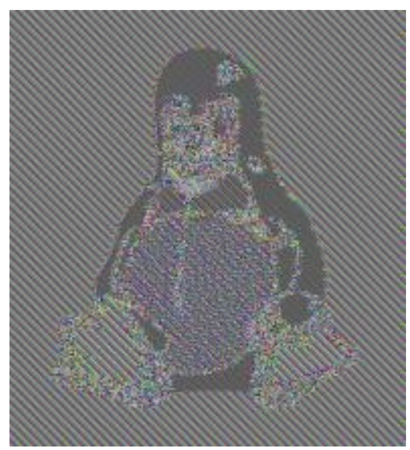



- Each block is independently decrypted

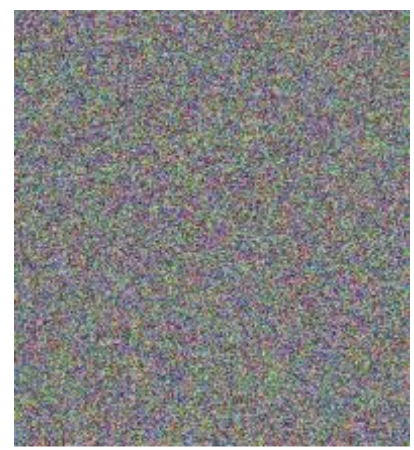
# ECB Issues

- *Information leaks*: two ciphertext blocks that are the same
- *Manipulation*: switch ciphertext with predictable results on plaintext (e.g., shuffle).
- *Parallel*: yes
- *Propagate*: no

Plaintext

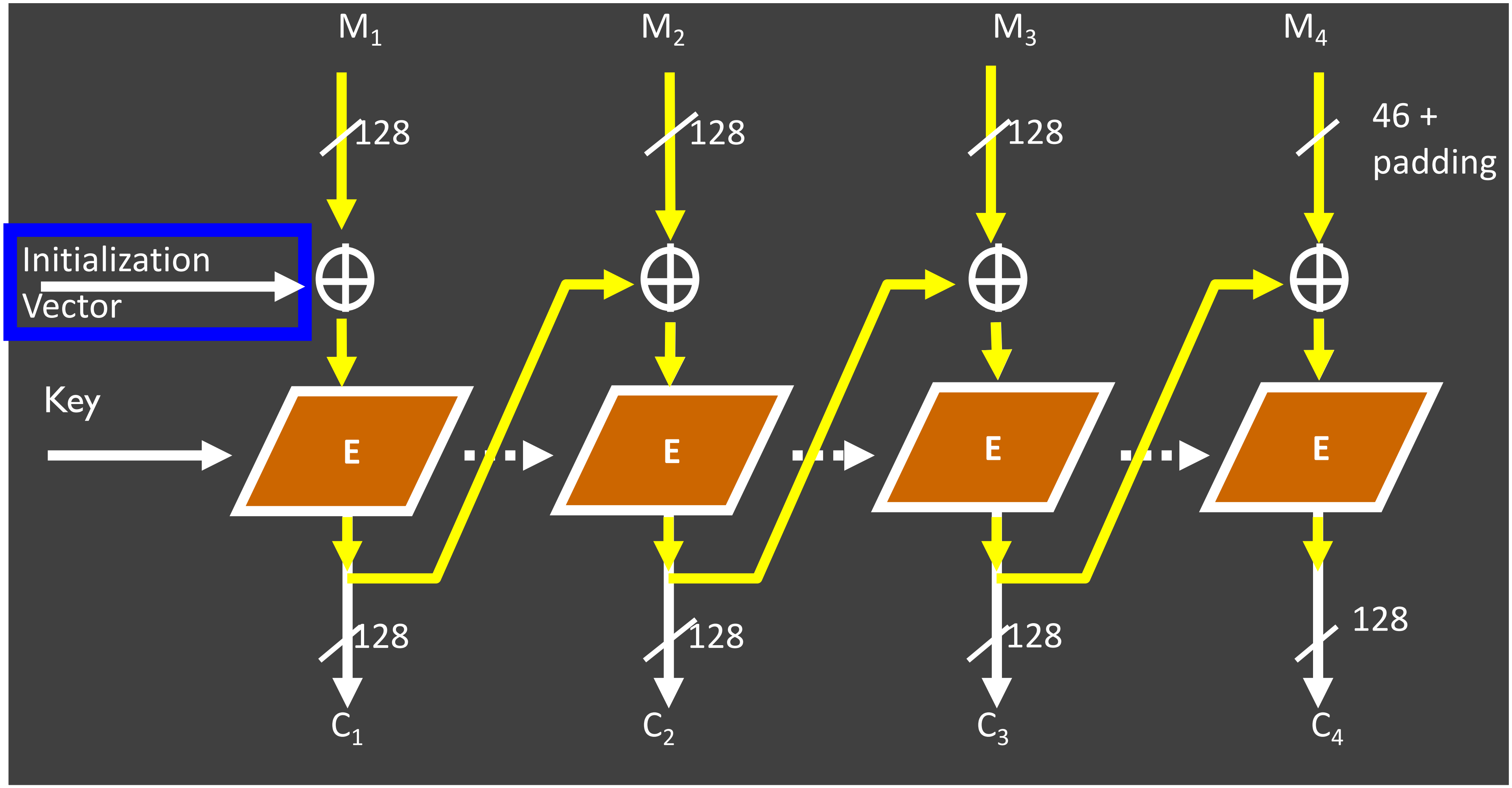


ECB



Other modes

# Cipher Block Chaining (CBC)

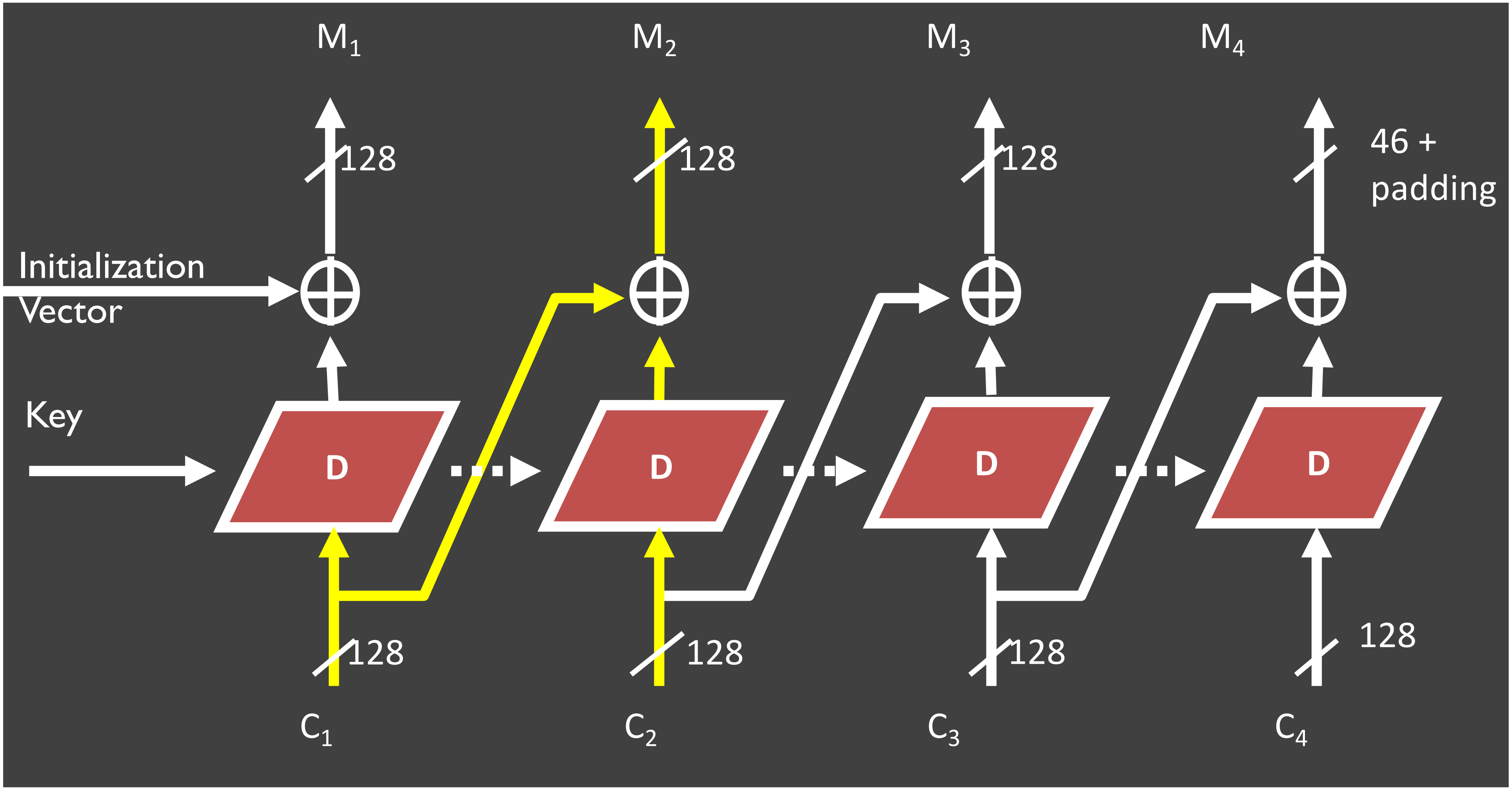



- Chaining dependency: each ciphertext block depends on all preceding plaintext blocks

# Initialization Vectors

- Initialization Vector (IV)
  - Used along with the key; not secret
  - For a given plaintext, changing either the key, or the IV, will produce a different ciphertext
  - Why is that useful?
- IV generation and sharing
  - Random; may transmit with the ciphertext
  - Incremental; predictable by receivers

# CBC Decryption

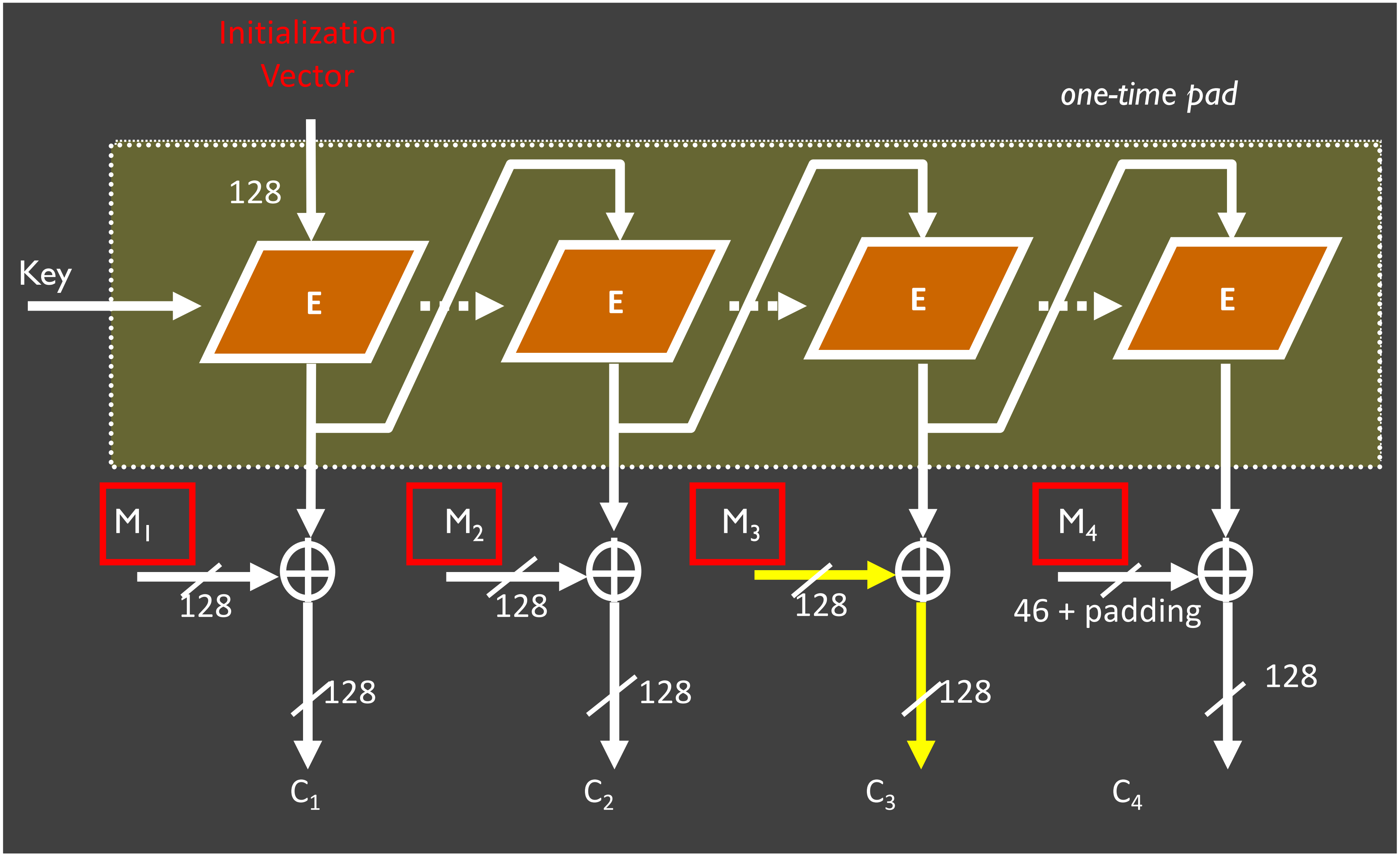



- How many ciphertext blocks does each plaintext block depend on?

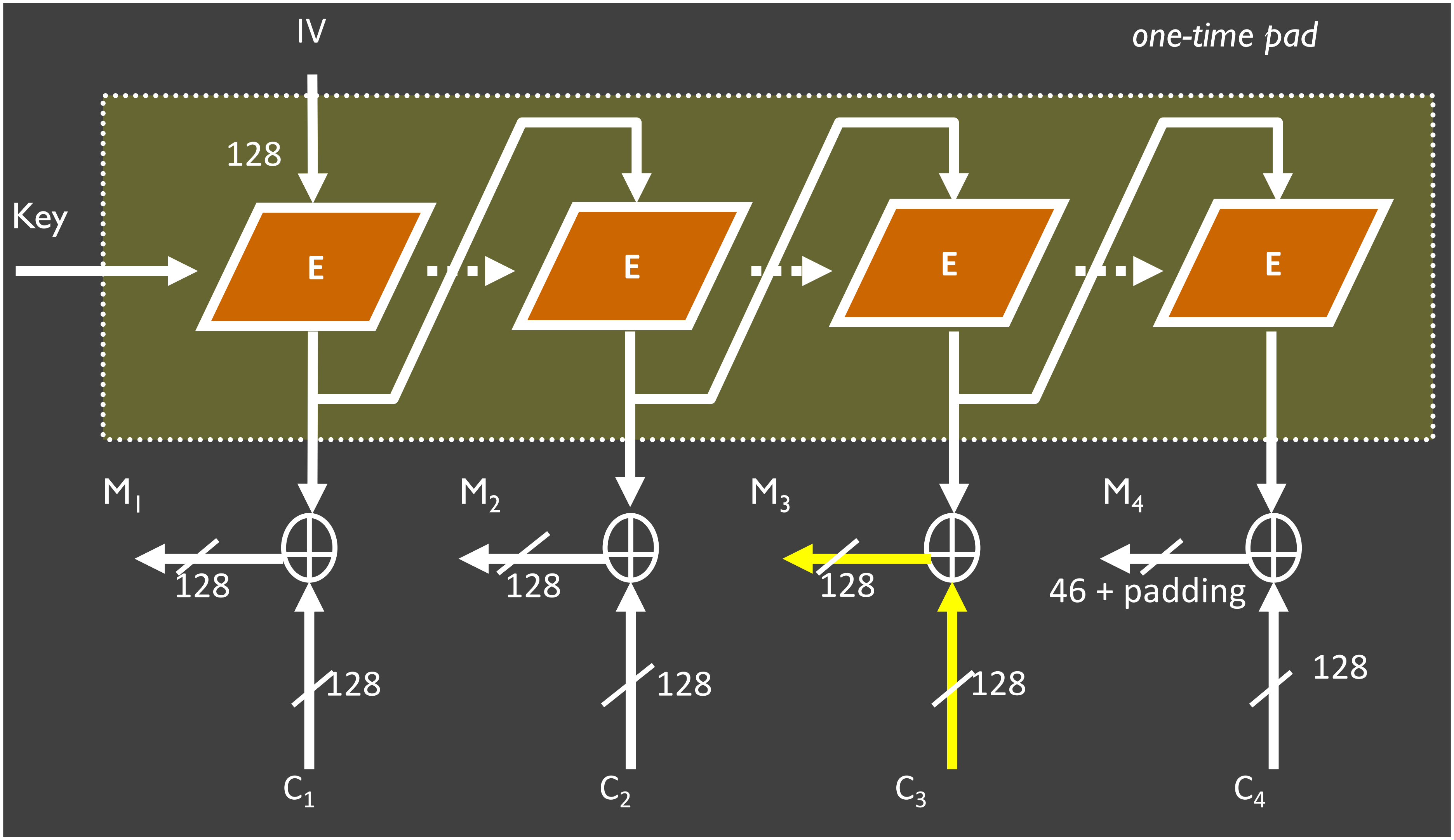
# CBC Properties

- Does information leak?
  - Identical plaintext blocks will produce different ciphertext blocks
- Can ciphertext be manipulated profitably?
  - ???
- Parallel processing possible?
  - no (encryption), yes (decryption)
- Do ciphertext errors propagate?
  - yes (encryption), a little (decryption)

# Output Feedback Mode (OFB)



# OFB Decryption




No block decryption required!

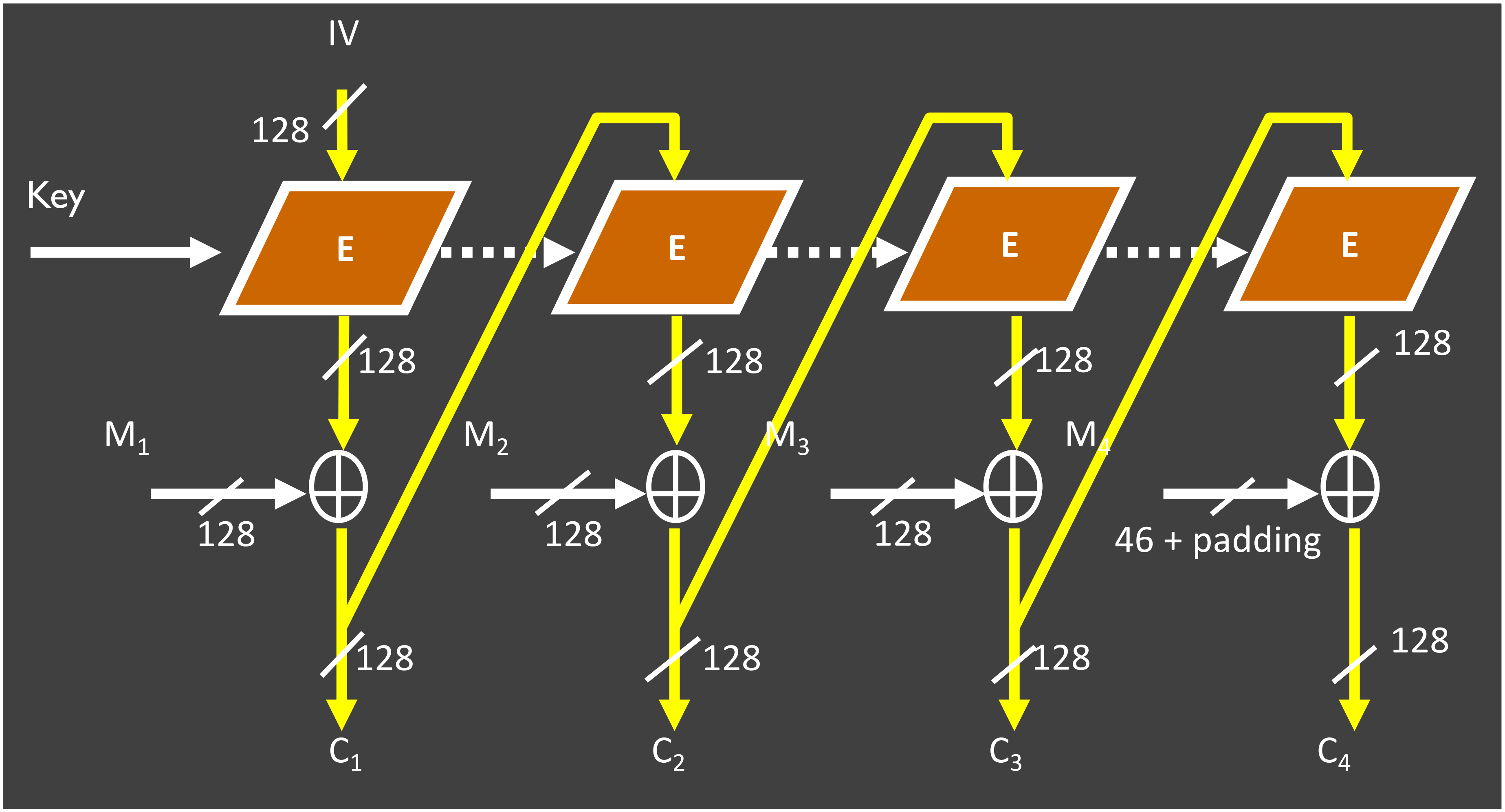
# OFB Properties

- Does information leak?
  - identical plaintext blocks produce different ciphertext blocks
- Can ciphertext be manipulated profitably?
  - ???
- Parallel processing possible?
  - no (generating pad), yes (XORing with blocks)
- Do ciphertext errors propagate?
  - ???

# OFB … (Cont' d)

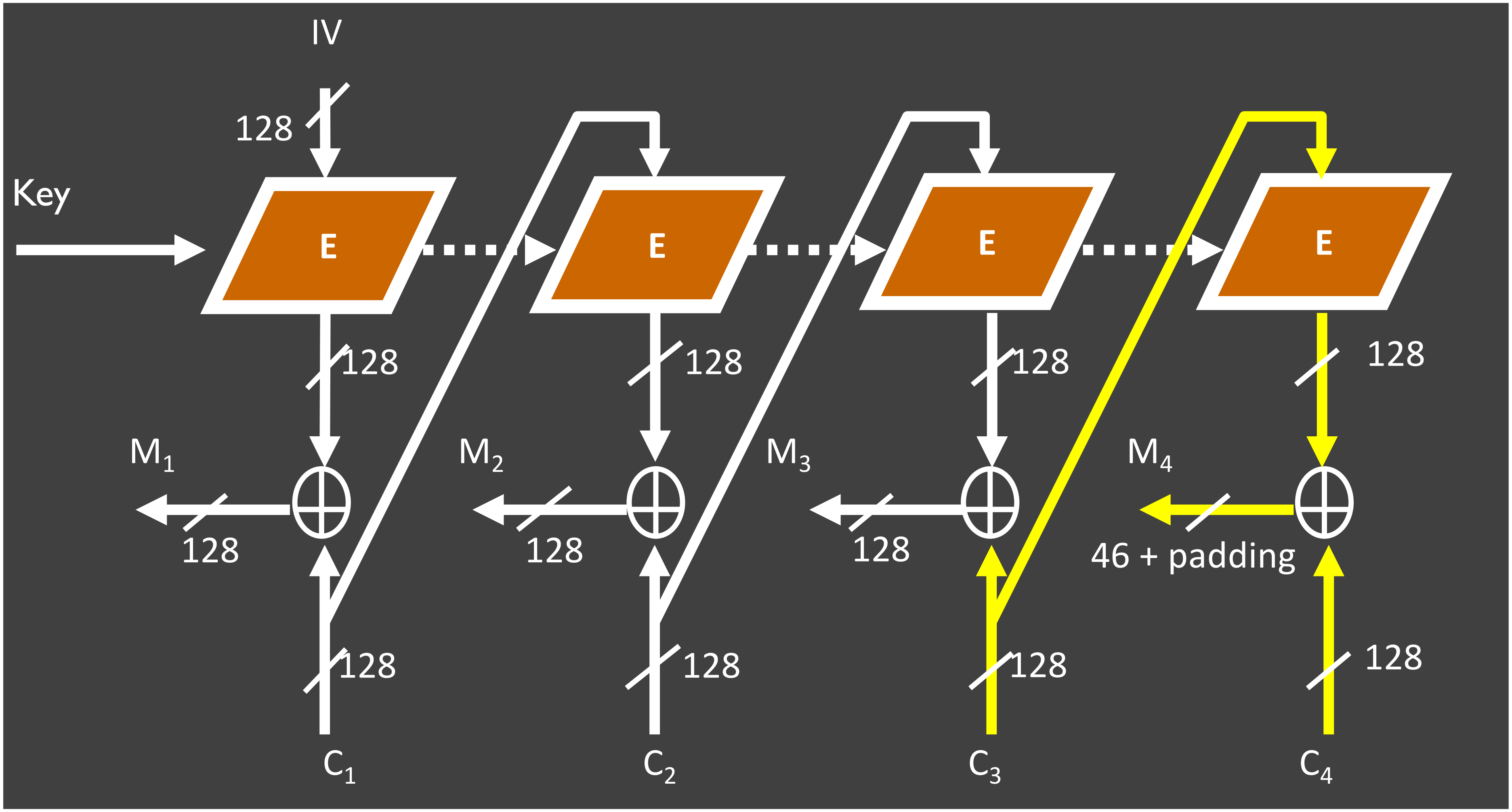
- If you know one plaintext/ciphertext pair, can easily derive the one-time pad that was used
  - i.e., should not reuse a one-time pad!
- Conclusion: IV must be different every time

# Cipher Feedback Mode (CFB)




- Ciphertext block $C_j$ depends on all preceding plaintext blocks

# CFB Decryption

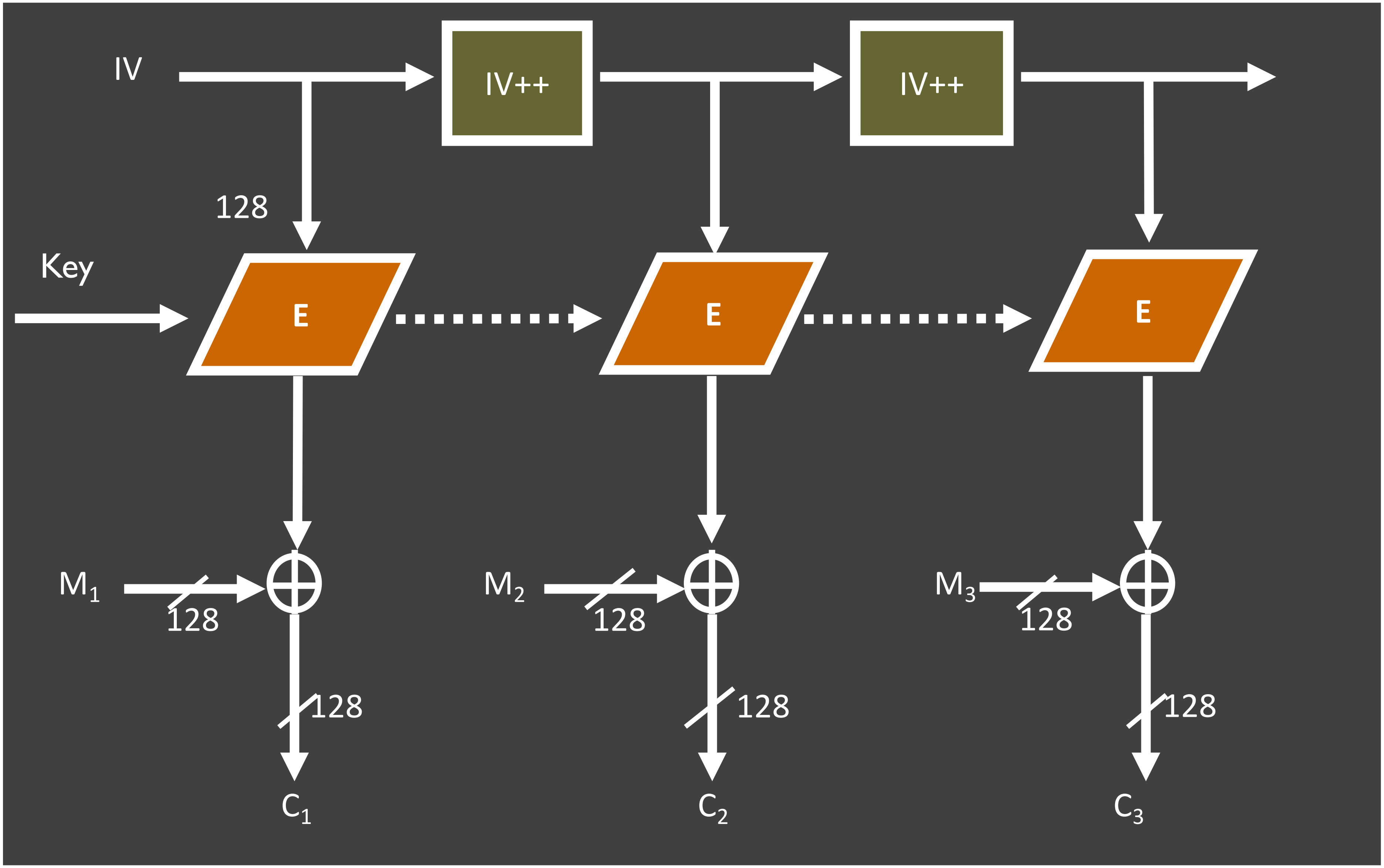



- No block decryption required!

# CFB Properties

- Does information leak?
  - Identical plaintext blocks produce different ciphertext blocks
- Can ciphertext be manipulated profitably?
  - ???
- Parallel processing possible?
  - no (encryption), yes (decryption)
- Do ciphertext errors propagate?
  - ???

# Counter Mode (CTR)



# CTR Mode Properties

- Does information leak?
  - Identical plaintext block produce different ciphertext blocks
- Can ciphertext be manipulated profitably
  - ???
- Parallel processing possible
  - Yes (both generating pad and XORing)
- Do ciphertext errors propagate?
  - ???
- Allow decryption the ciphertext at any location
  - Ideal for random access to ciphertext