CS 5173/4173 Computer Security

Topic 3.2 Modes of Operation

Processing with Block Ciphers

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

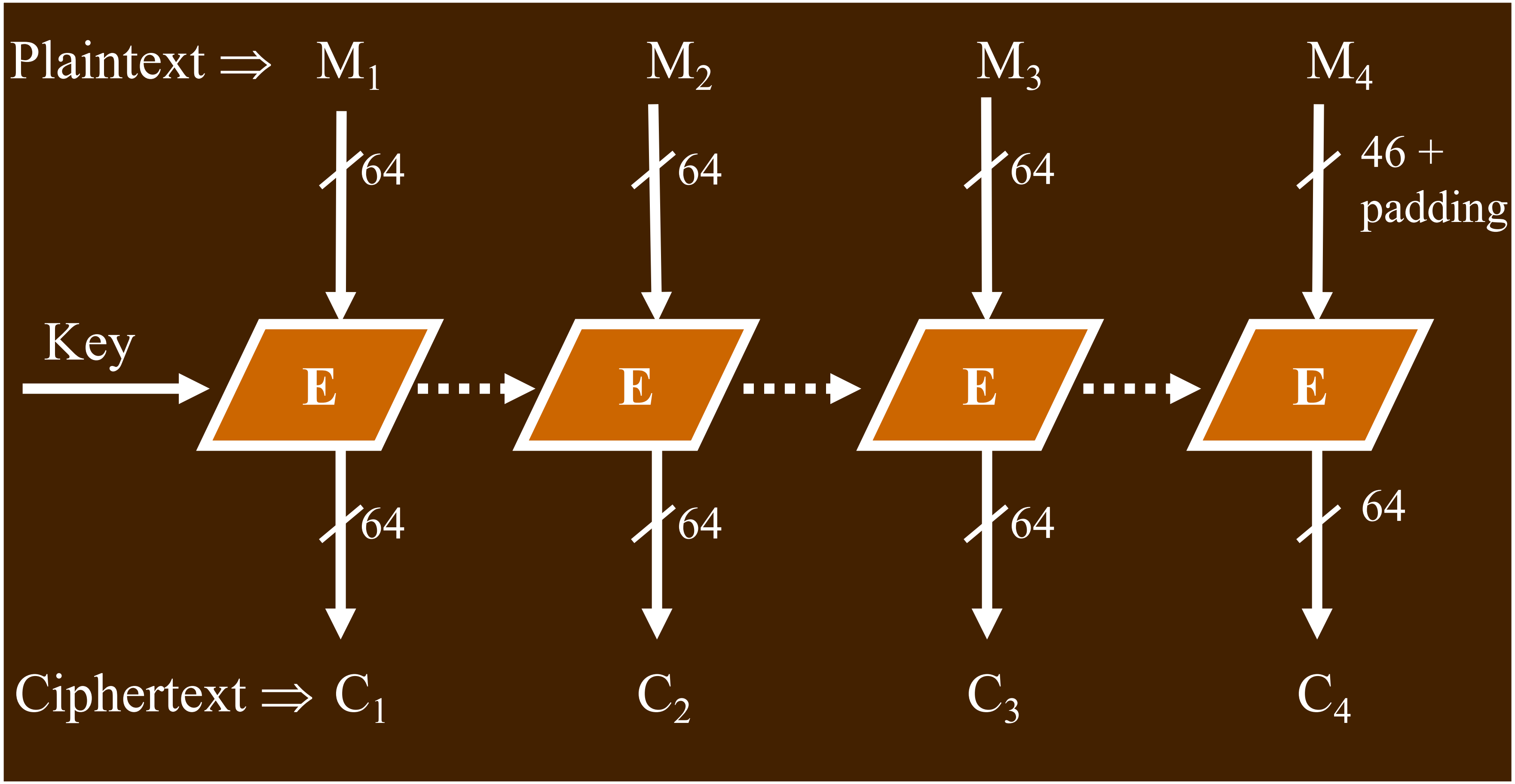
Issues for Block Chaining Mode

- 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.
- Information leakage
  - Does it reveal info about the plaintext blocks?

Issues… (Cont'd)

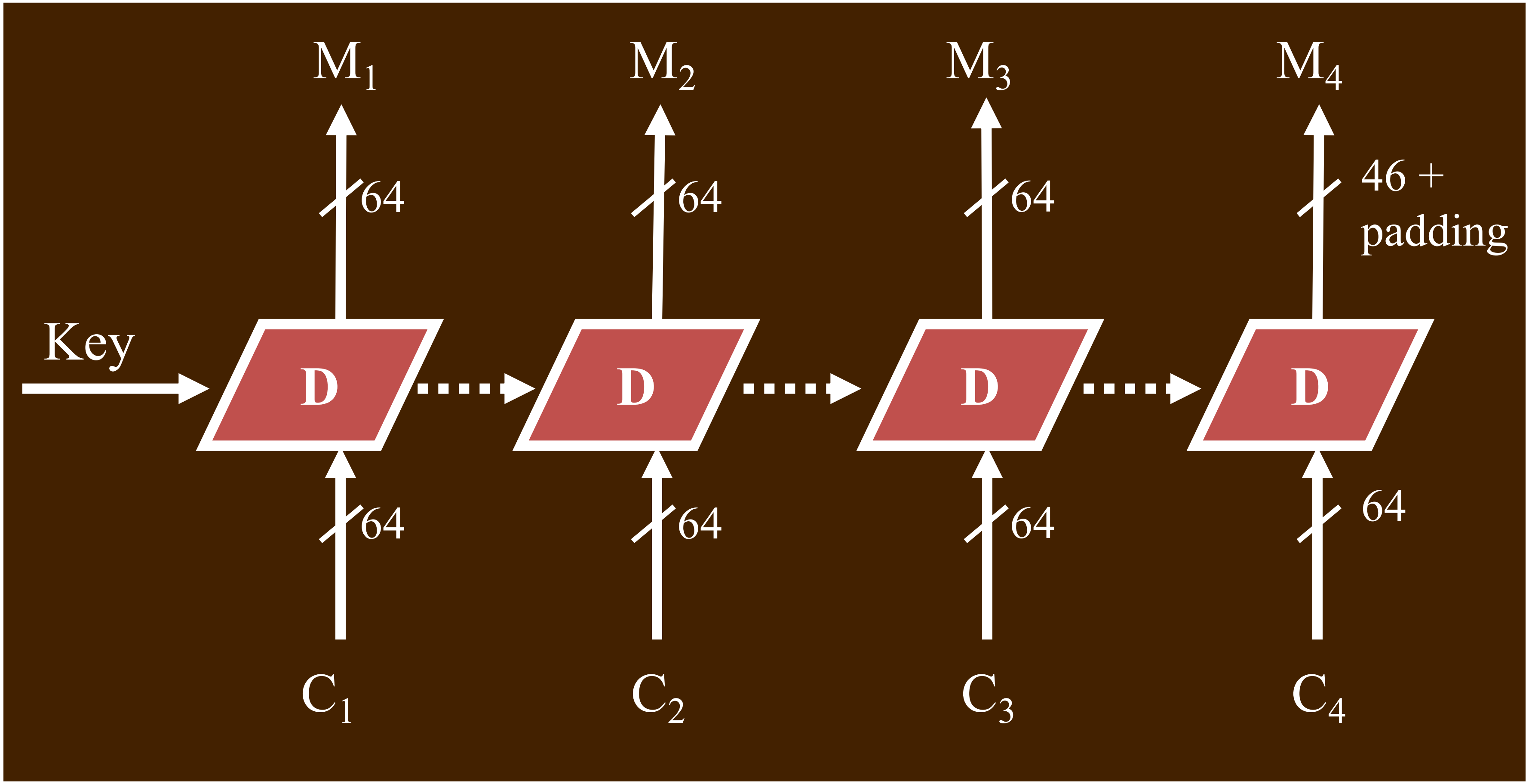
- Parallel/Sequential
  - Can blocks of plaintext (ciphertext) be encrypted (decrypted) in parallel?
- Error propagation
  - If there is an error in a plaintext (ciphertext) block, will there be an encryption (decryption) error in more than one ciphertext (plaintext) block?

Electronic Code Book (ECB)



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

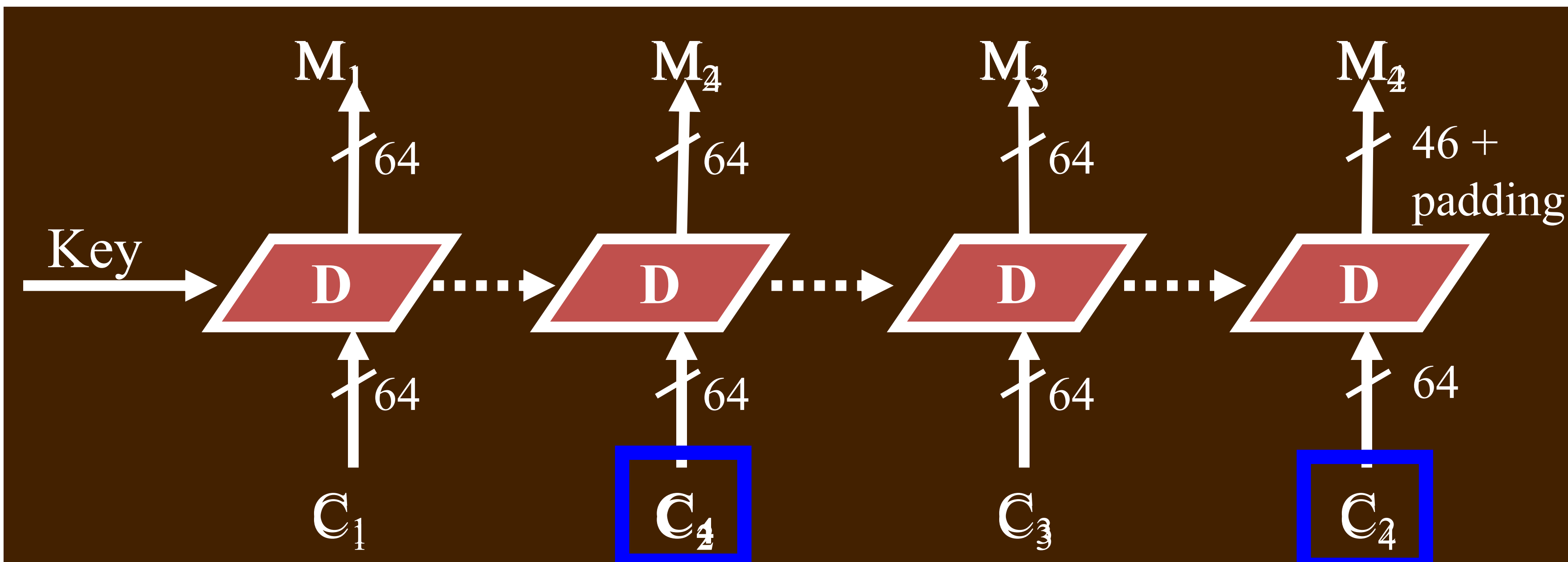
ECB Decryption



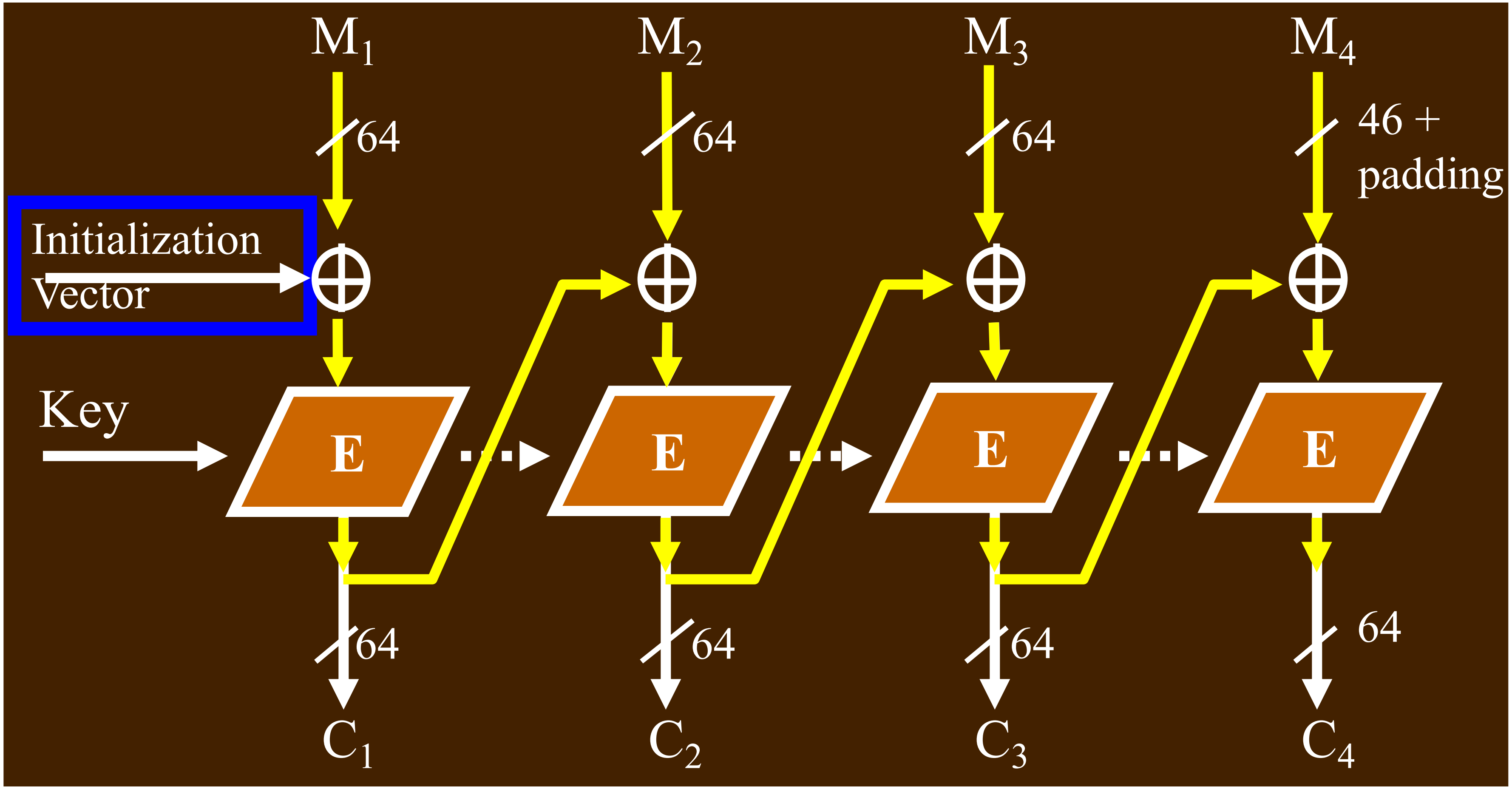
- Each block is independently decrypted

ECB Properties

- Does information leak?
- Can ciphertext be manipulated?
- Parallel processing possible?
- Do ciphertext errors propagate?



Cipher Block Chaining (CBC)

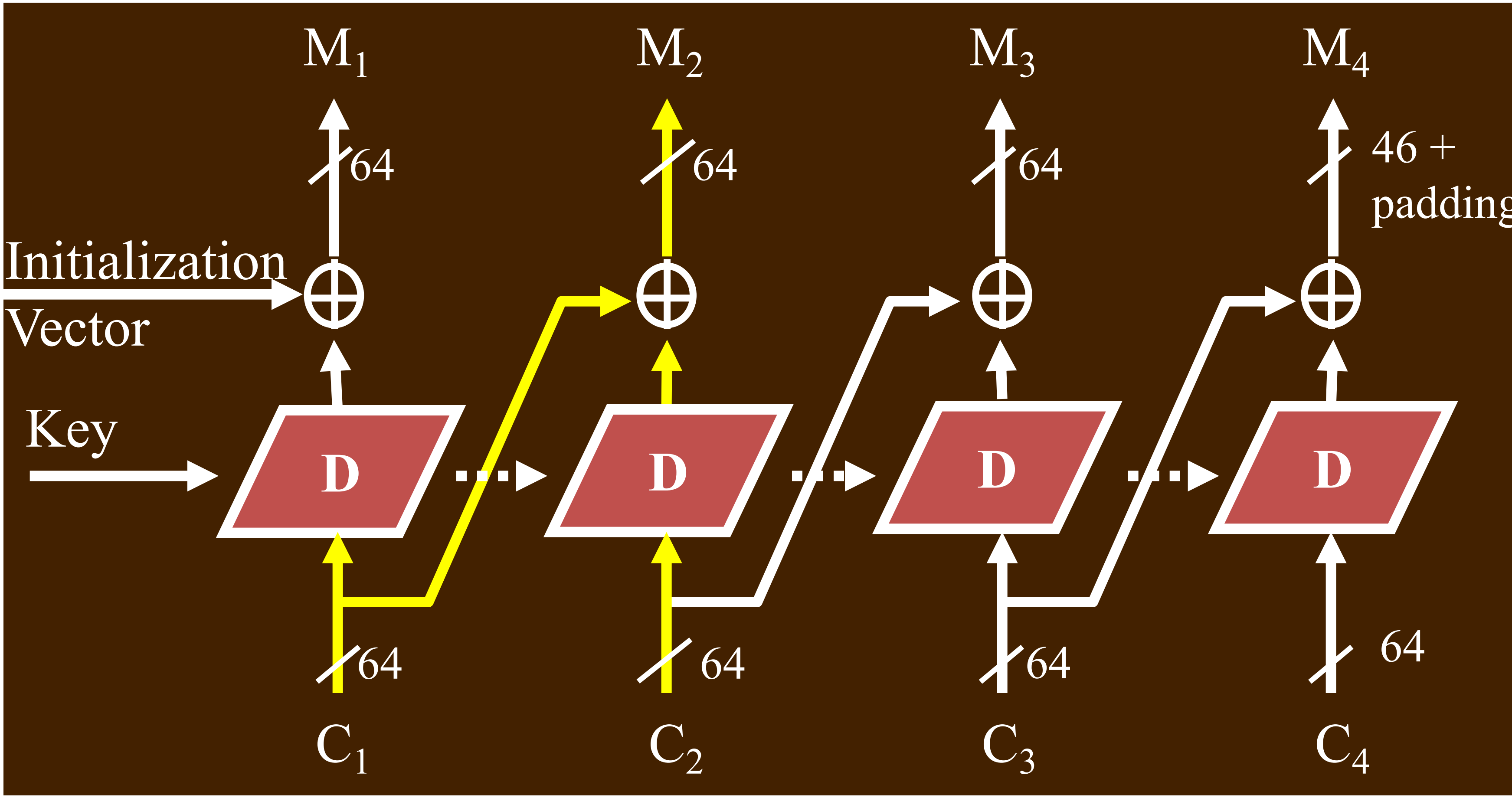


- Chaining dependency: each ciphertext block depends on all preceding plaintext blocks

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

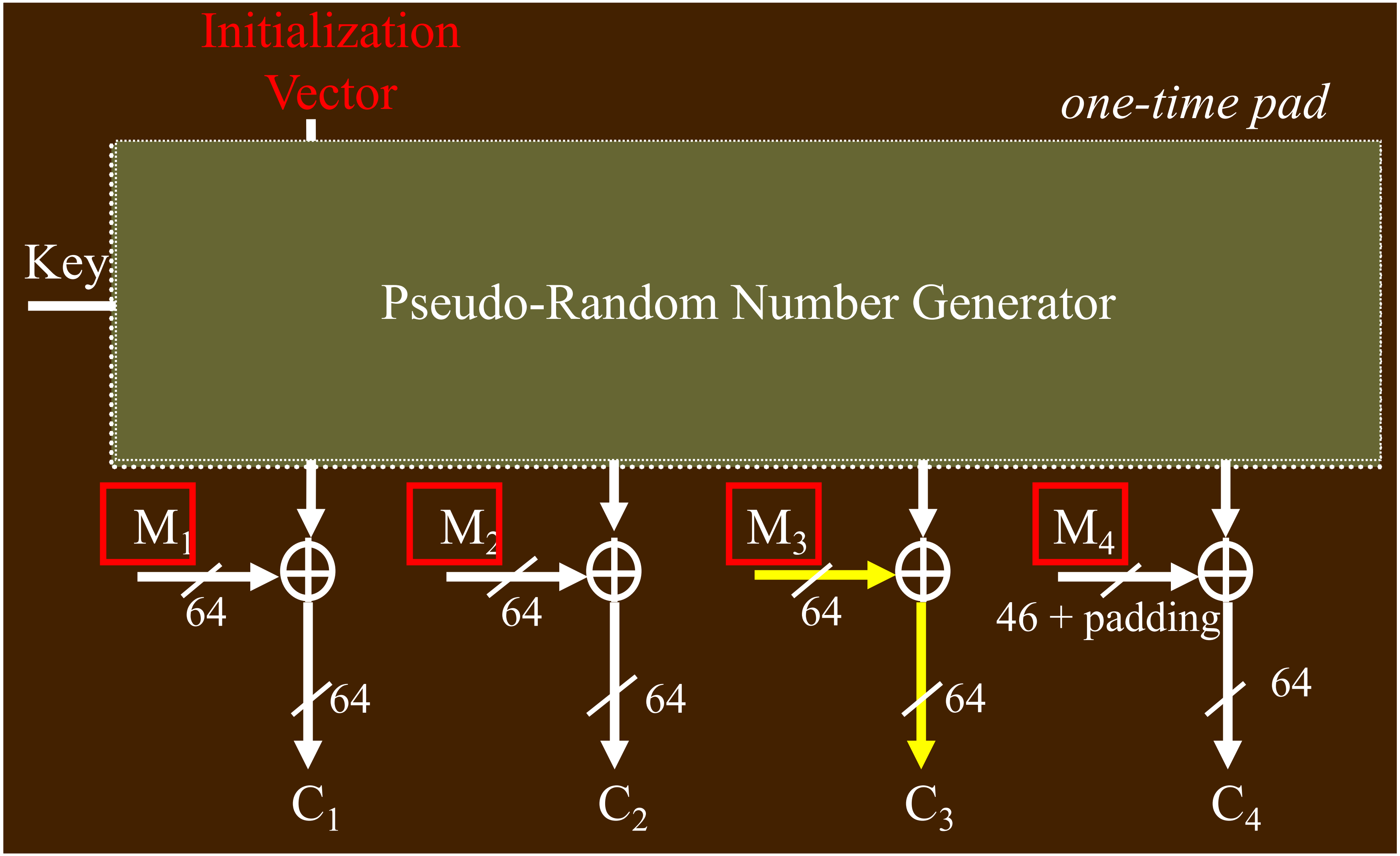


- How many ciphertext blocks does each plaintext block depend on?

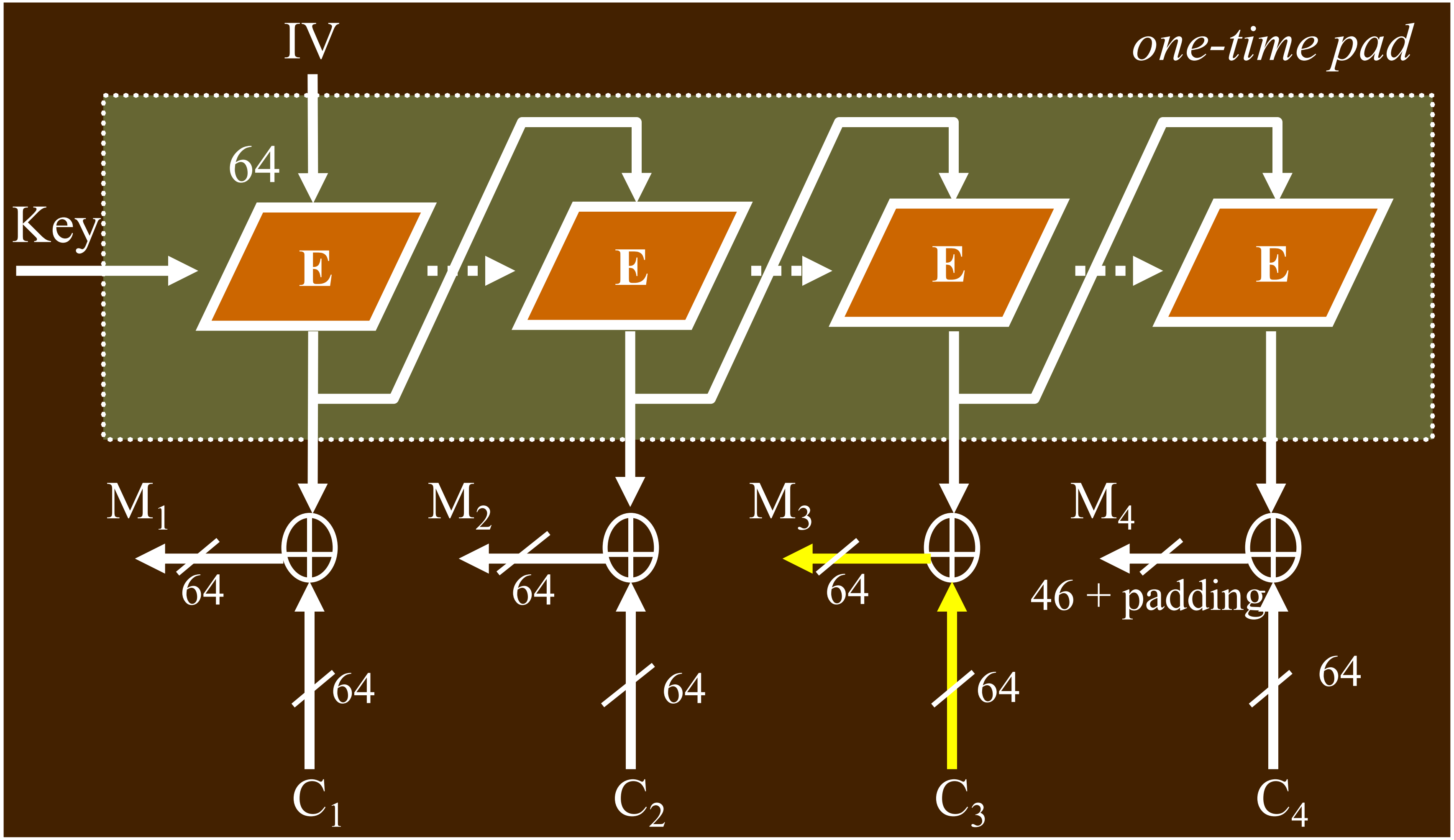
CBC Properties

- Does information leak?
  - Identical plaintext blocks will produce different ciphertext blocks
- Can ciphertext be manipulated predictably?
  - ???
- 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!

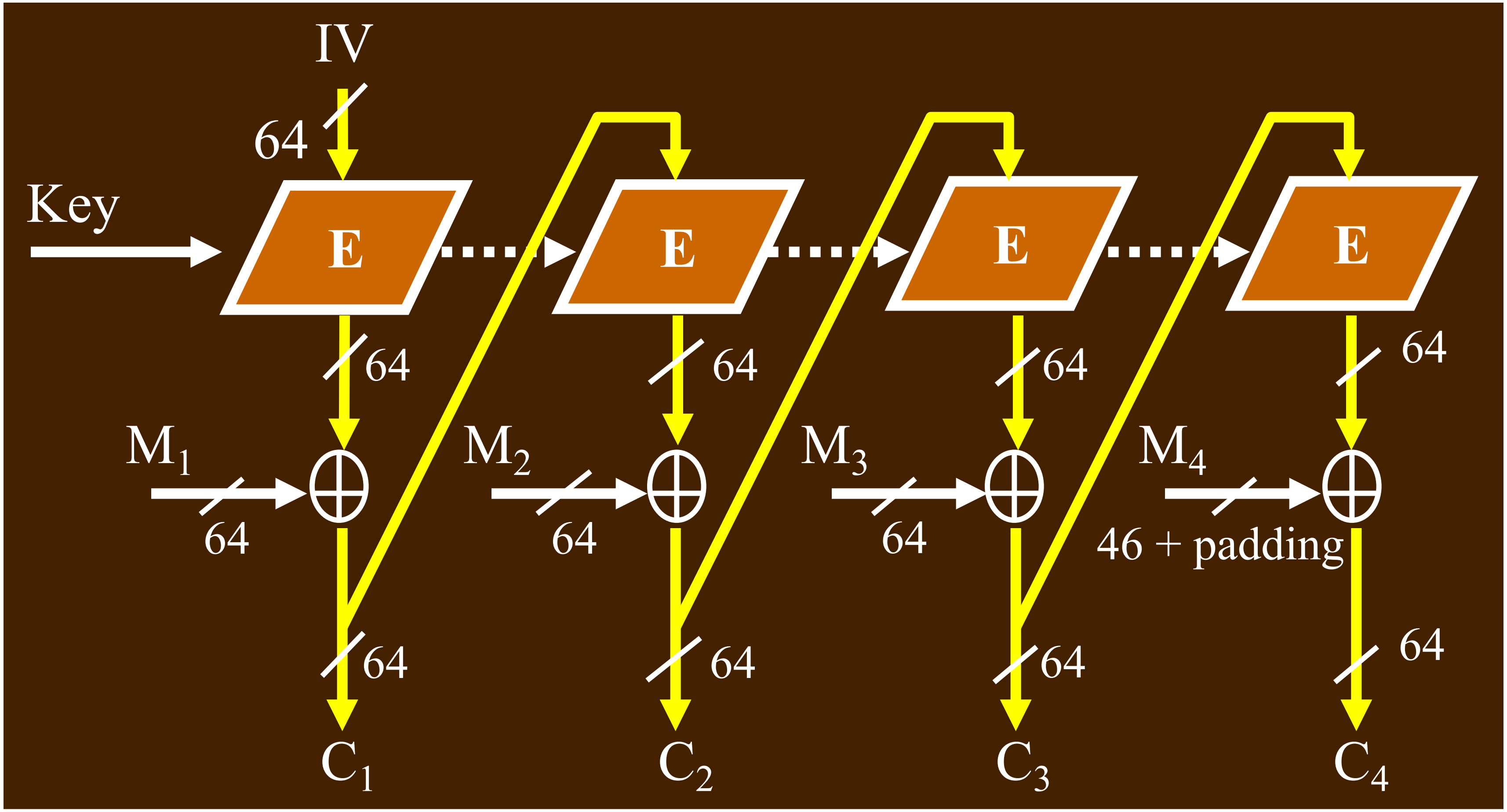
OFB Properties

- Does information leak?
  - identical plaintext blocks produce different ciphertext blocks
- Can ciphertext be manipulated predictably?
  - ???
- Parallel processing possible?
  - yes (generating pad), yes (XORing with blocks)
- Do ciphertext errors propagate?
  - ???

OFB … (Cont'd)

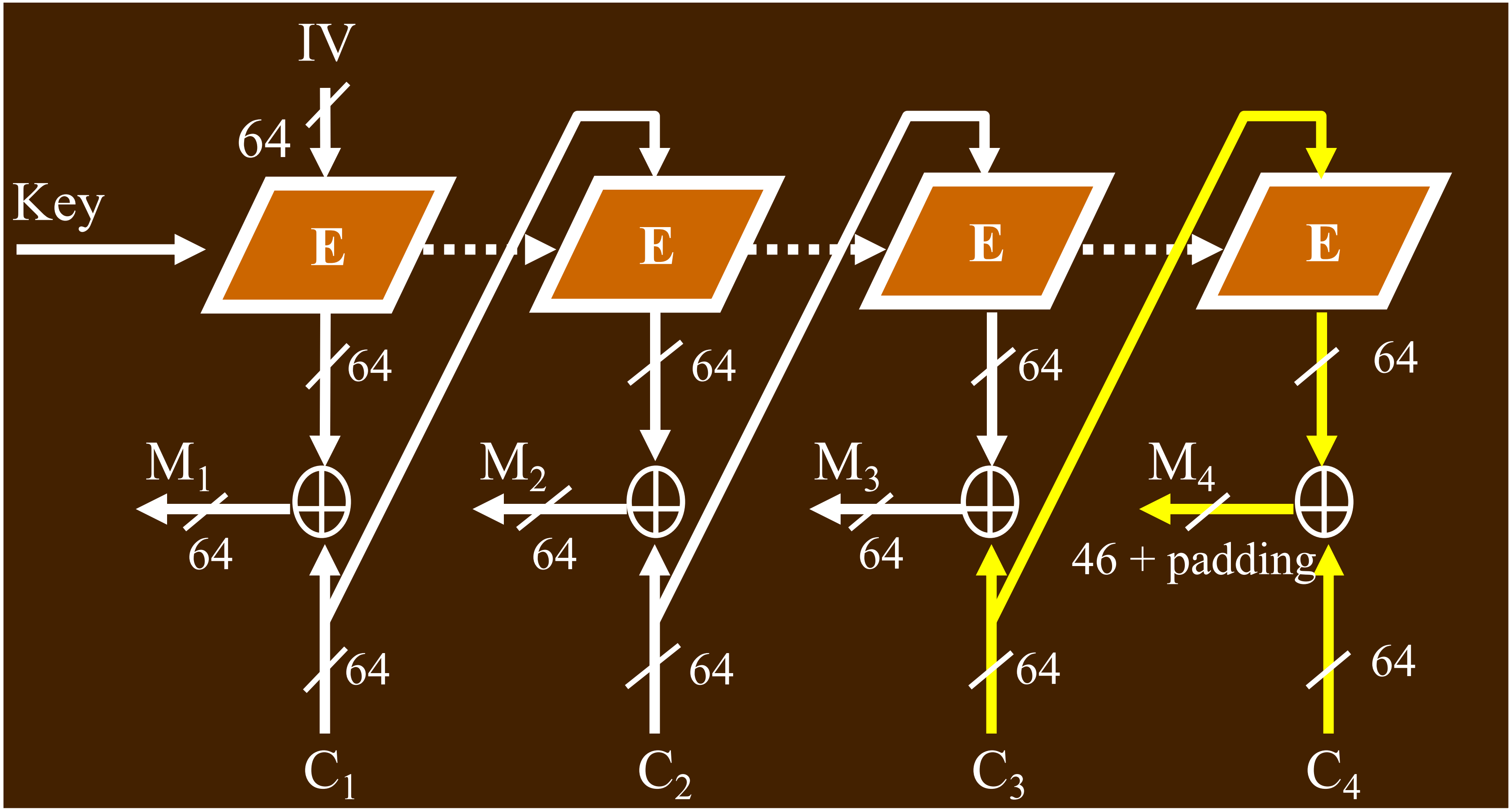
- If you know one plaintext/ciphertext pair, can easily derive the one-time pad that was used
  - i.e., should not reuse a one-time pad!
- Conclusion: IV must be different every time

Cipher Feedback Mode (CFB)



- Ciphertext block C_j depends on all preceding plaintext blocks

CFB Decryption

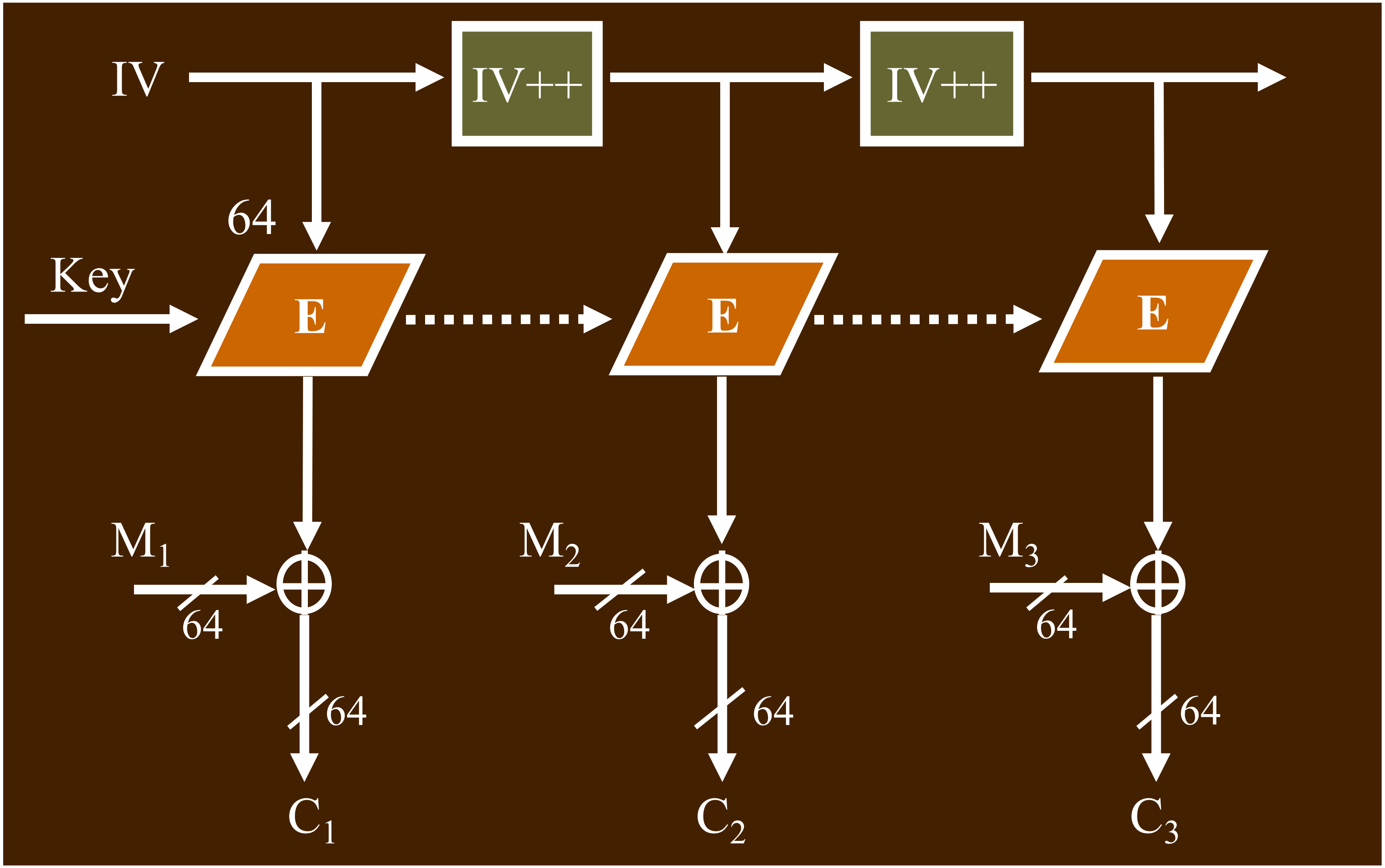


- No block decryption required!

CFB Properties

- Does information leak?
  - Identical plaintext blocks produce different ciphertext blocks
- Can ciphertext be manipulated predictably?
  - ???
- 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 predictably
  - ???
- Parallel processing possible
  - Yes (both generating pad and XORing)
- Do ciphertext errors propagate?
  - ???

CS 5173/4173 Computer Security

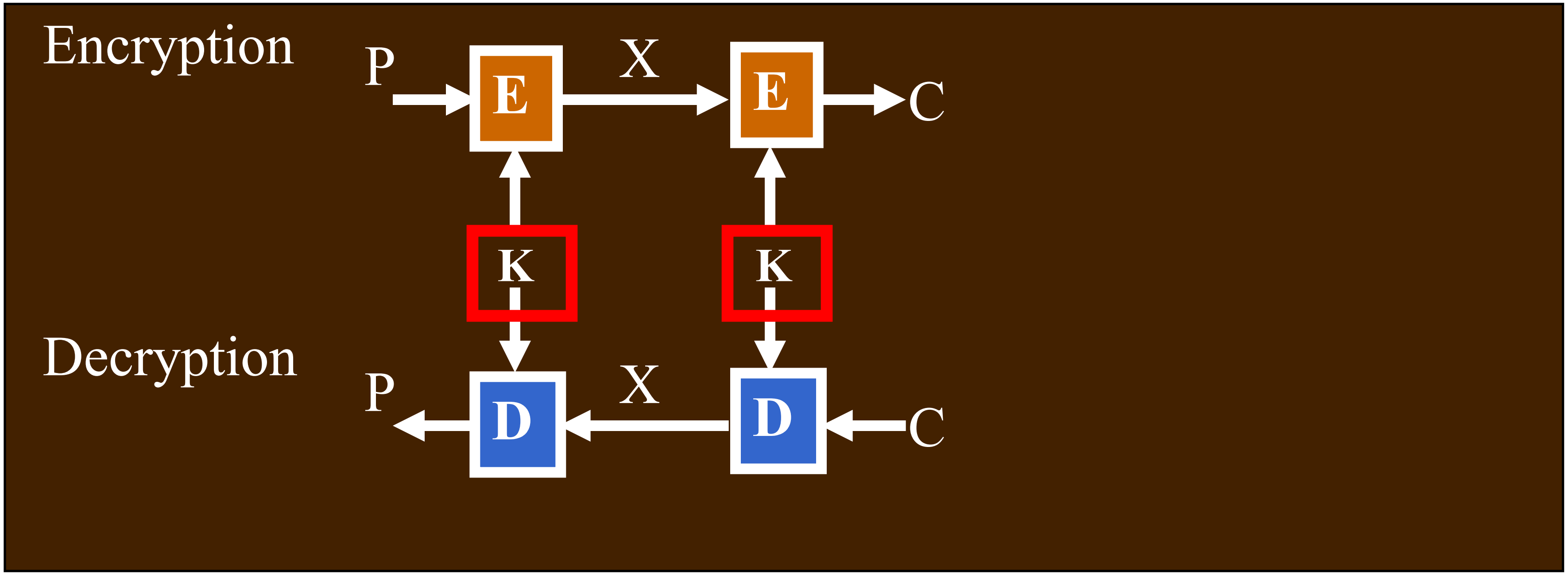
Topic 3.3 Secret Key Cryptography – Triple DES

Stronger DES

- Major limitation of DES
  - Key length is too short
- Can we apply DES multiple times to increase the strength of encryption?

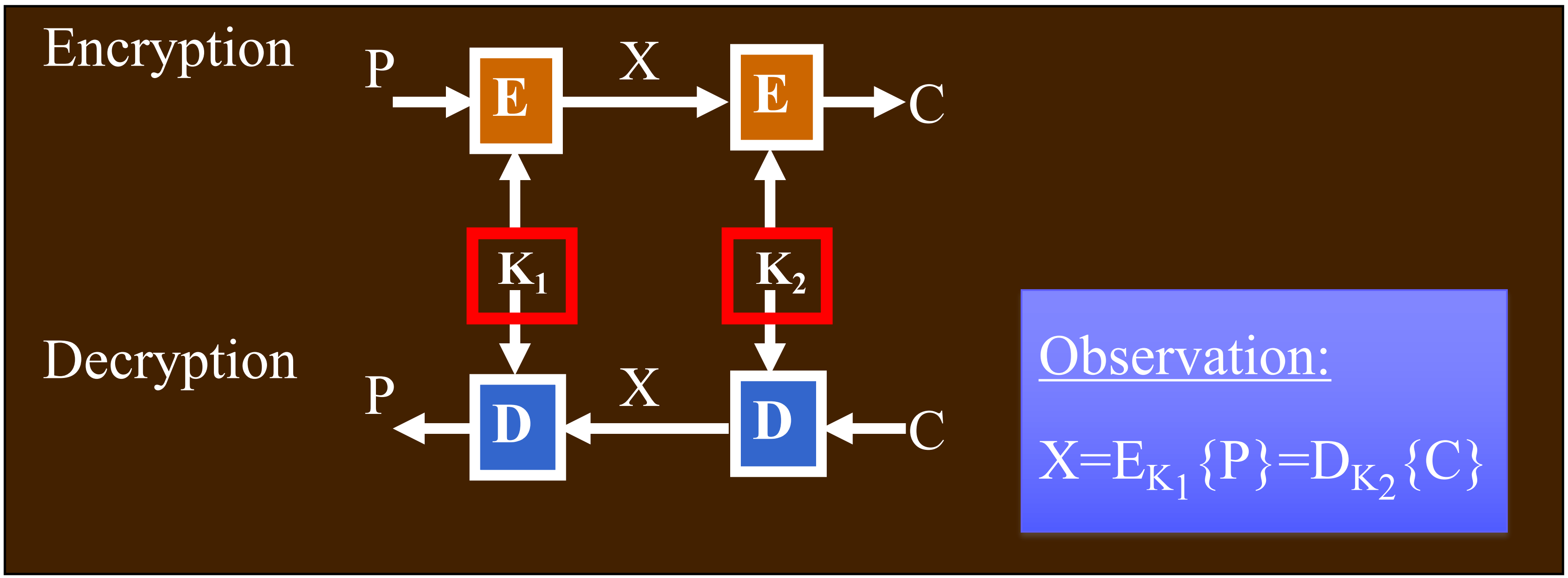
Double Encryption with DES

- Does encrypting using the same key make things more secure?



Double Encryption with DES

- Encrypt the plaintext twice, using two different DES keys
- Total key material increases to 112 bits
  - is that the same as key strength of 112 bits?



The Meet-in-the-Middle Attack

1. Choose a plaintext P and generate ciphertext C, using double-DES with $\mathcal{K}1+\mathcal{K}2$
2. Then…
   a. encrypt P using single-DES for all possible 2^{56} values K_1 to generate all possible single-DES ciphertexts for P: $X_1, X_2, \ldots, X_{2^{56}}$;
   store these in a table indexed by ciphertex values
   b. decrypt C using single-DES for all possible 2^{56} values K_2 to generate all possible single-DES plaintexts for C: $Y_1, Y_2, \ldots, Y_{2^{56}}$;
   for each value, check the table

Steps … (Cont'd)

3. Meet-in-the-middle:
   – Each match ($X_i = Y_j$) reveals a *candidate key pair* K_i+K_j
   – There are 2^{112} pairs but there are only 2^{64} X's
4. On average, how many pairs have identical X and Y?
   — For any pair (X, Y), the probability that X = Y is $1/ 2^{64}$
   — There are 2^{112} pairs.
   — The expected number of pairs that result in identical X and Y is $2^{112} / 2^{64} = 2^{48}$

Steps … (Cont'd)

5. The attacker uses a second pair of plaintext and ciphertext to try the 2^{48} Key pairs

– There are 2^{48} key pairs and 2^{64} X's (Y's)

– The probability that a false key pair results in identical X and Y is $2^{48} / 2^{64} = 2^{-16}$

— The correct key pair always leads to identical X and Y

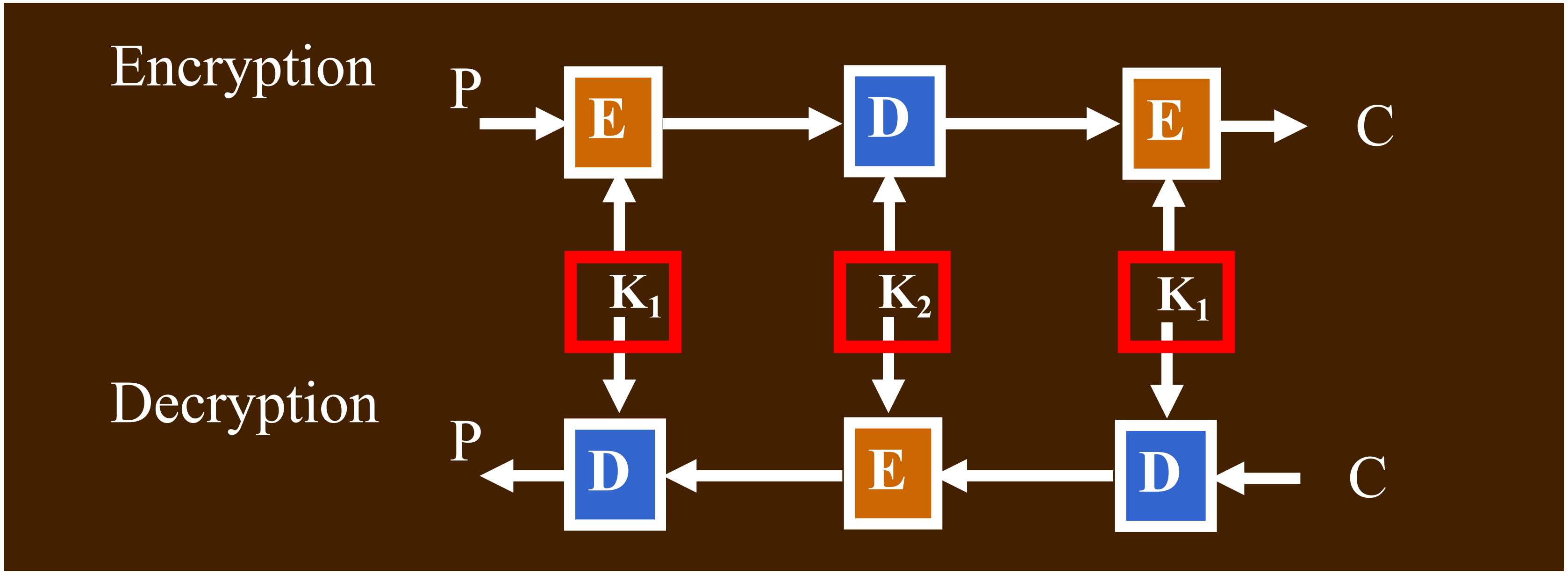
— A false key pair leads to identical X and Y at the probability of 2^{-16} (i.e., 1/65536)

— Hence, after examine two pairs of plaintext and ciphtertext, the attacker can normally identify the key

Attack Complexity

- How many DES encryptions and decryptions the attacker need to compute?
  - $2 \times 2^{56} + 2 \times 2^{48}$
- An expensive attack (computation + storage)
  - still, enough of a threat to discourage use of double-DES

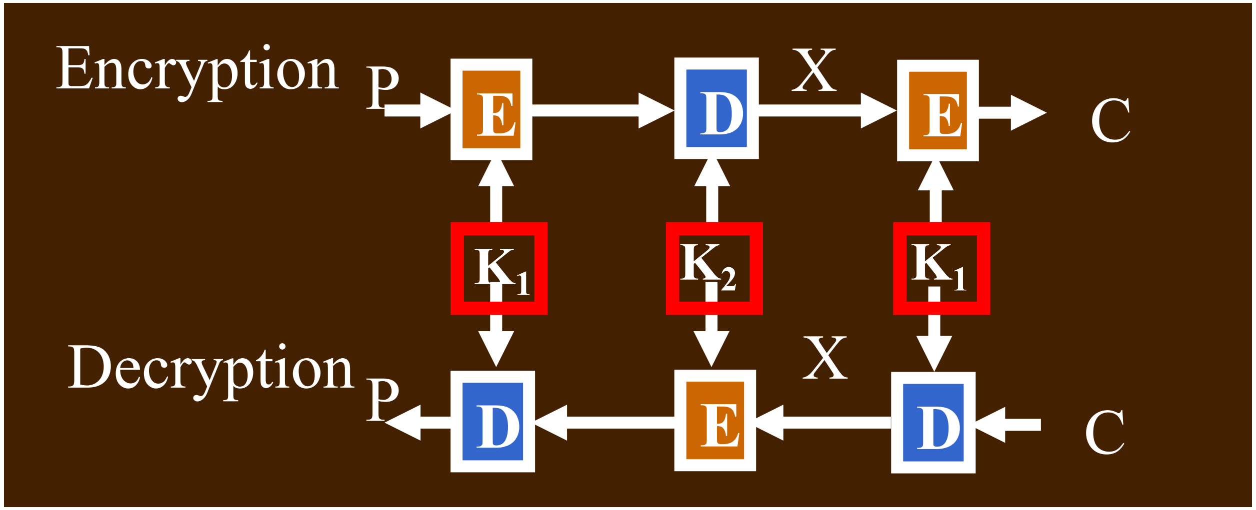
Triple Encryption (Triple DES-EDE)



- Apply DES encryption/decryption three times
  - why EDE?
  - One reason might be that by taking k1 = k2 = key, 3DES becomes single DES with key. 3DES can communicate with single DES.

Triple DES (Cont'd)

- Widely used
  - equivalent strength to using a 112 bit key
  - strength about 2^{112} against M-I-T-M attack



Observation:

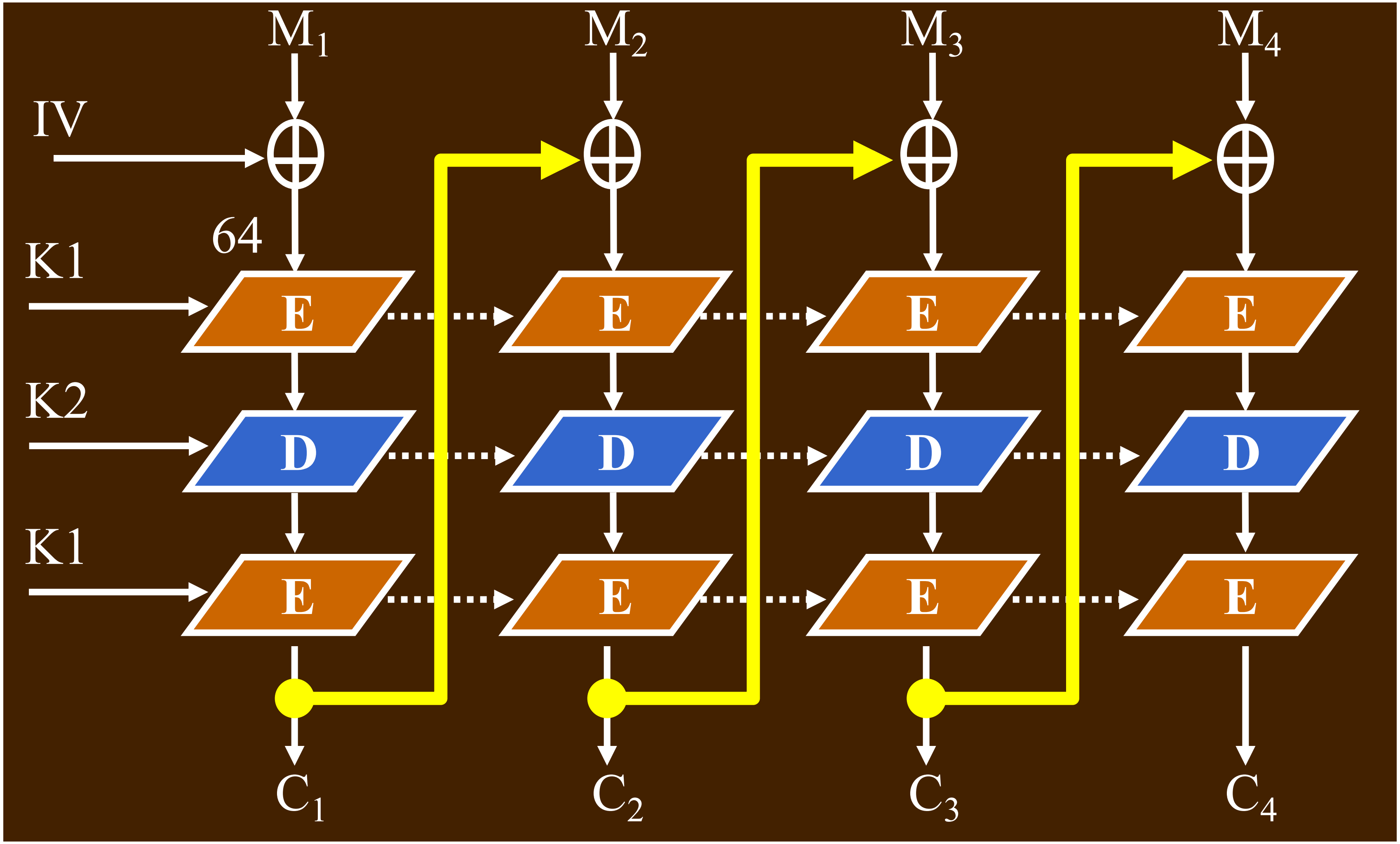
$X = D_{K_2}\{E_{K_1}\{P\}\} = D_{K_1}\{C\}$

Triple DES (Cont'd)

- However: inefficient / expensive to compute
  - one third as fast as DES on the same platform, and DES is already designed to be slow in software

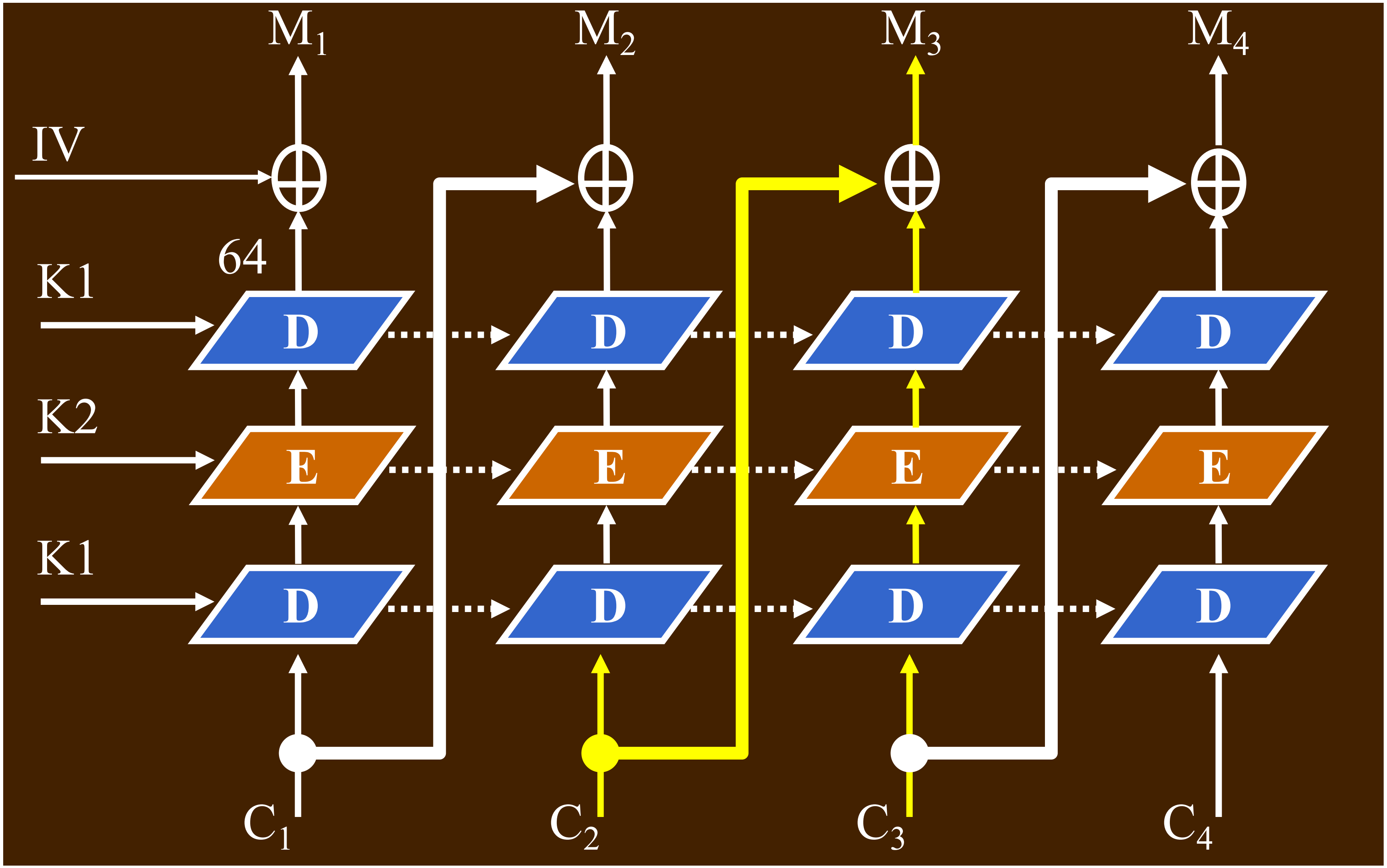
- Next question: how is block chaining used with triple-DES?

3DES-EDE: Outside Chaining Mode



- What basic chaining mode is this?

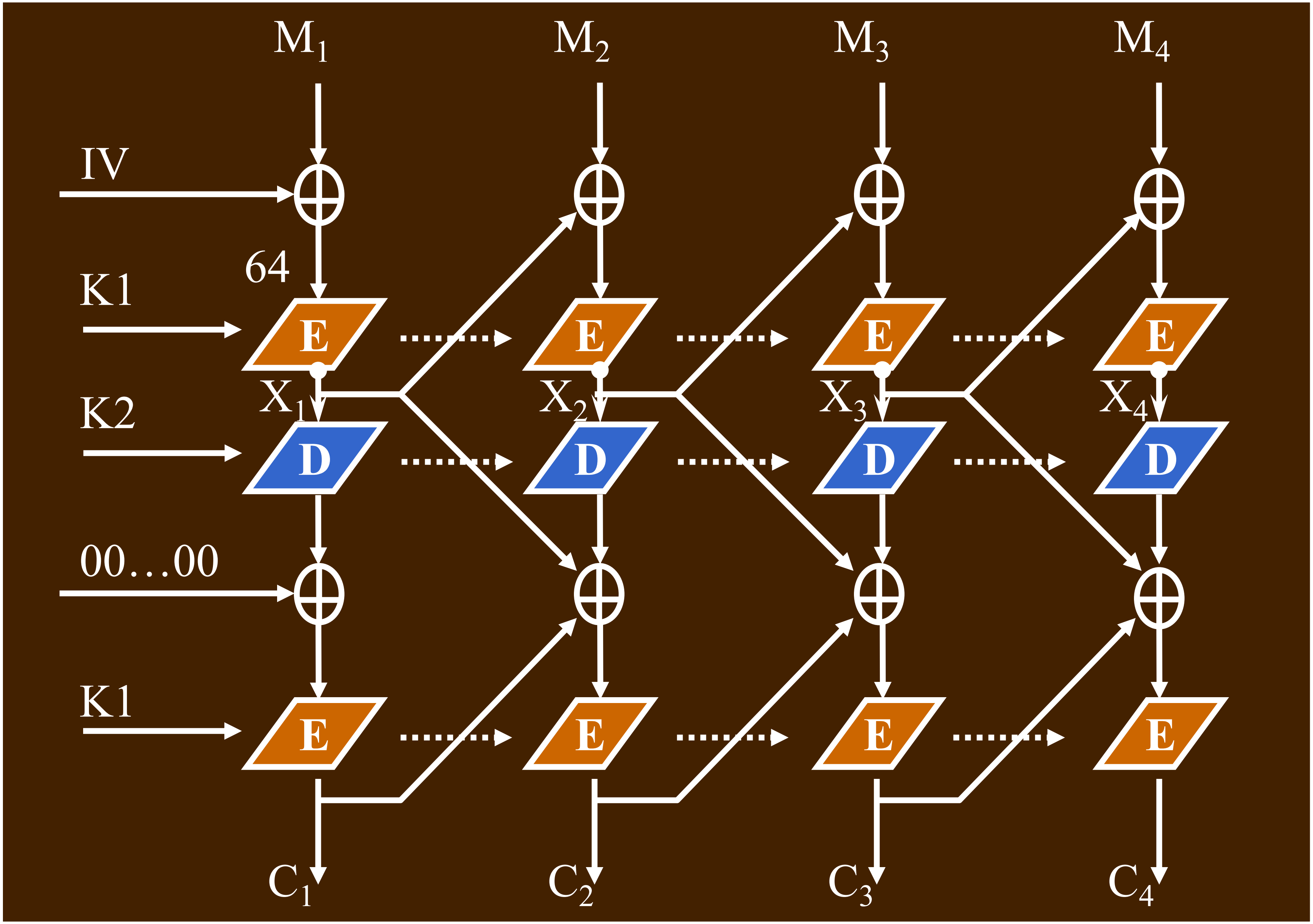
3DES-EDE: OCM Decryption



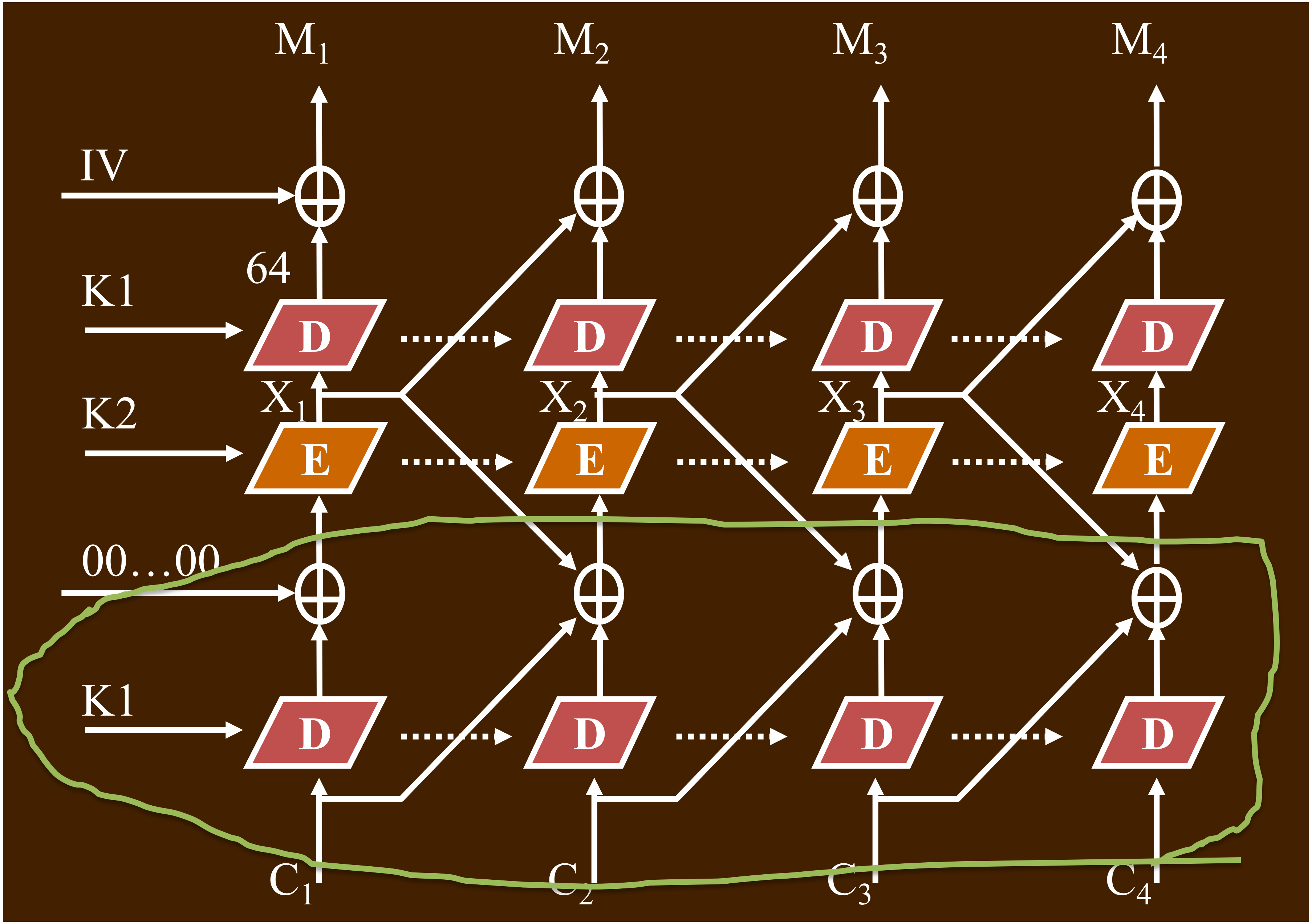
OCM Properties

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

3DES-EDE: Inside Chaining Mode



3DES-EDE: ICM Decryption



ICM Properties

- Does information leak?
  - identical plaintext blocks produce different ciphertext blocks
- Can ciphertext be manipulated predictably?
  - ???
- Parallel processing possible?
  - no (encryption), yes (partial of the decryption)
- Do ciphertext errors propagate?
  - ???

CS 5173/4173 Computer Security

Topic 3.4 Secret Key Cryptography –
MAC with Secret Key Ciphers

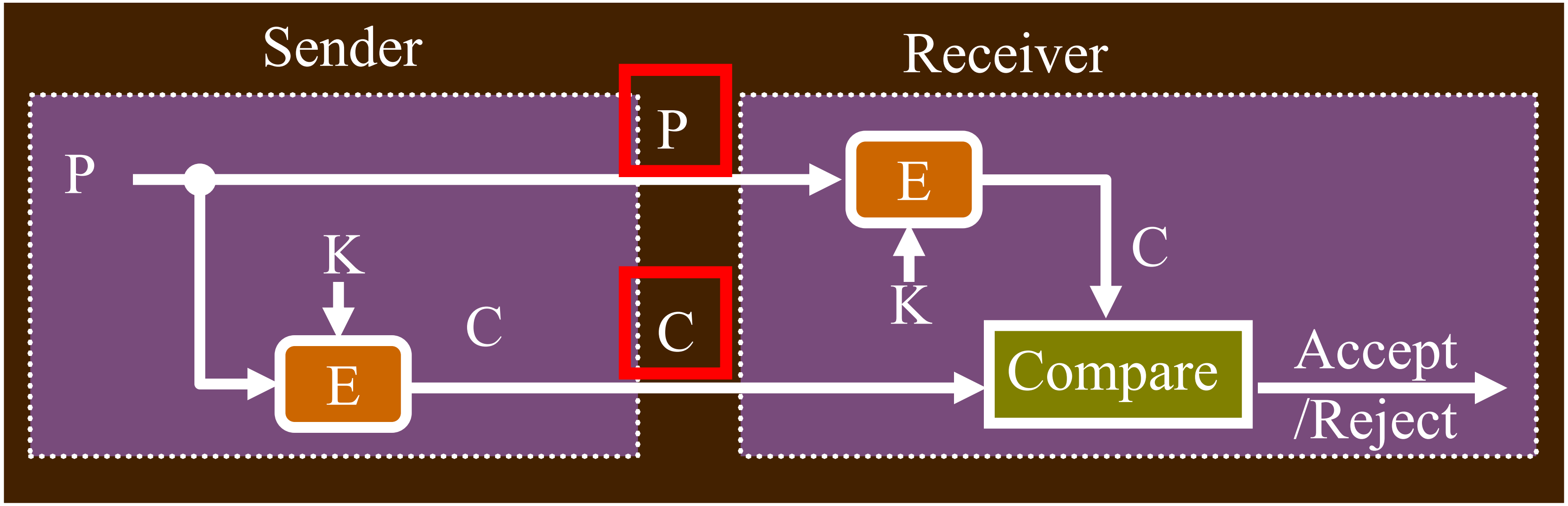
Message Authentication/Integrity

- Encryption easily provides confidentiality of messages
  - only the party sharing the key (the "key partner") can decrypt the ciphertext
- How to use encryption to authenticate messages and verify the integrity? That is,
  - prove the message was created by the key partner
  - prove the message wasn't modified by someone other than the key partner

Approach #1

- If the decrypted plaintext “looks plausible”, then conclude ciphertext was produced by the key partner
  - i.e., illegally modified ciphertext, or ciphertext encrypted with the wrong key, will probably decrypt to random-looking data
- But, is it easy to verify data is “plausible-looking”?

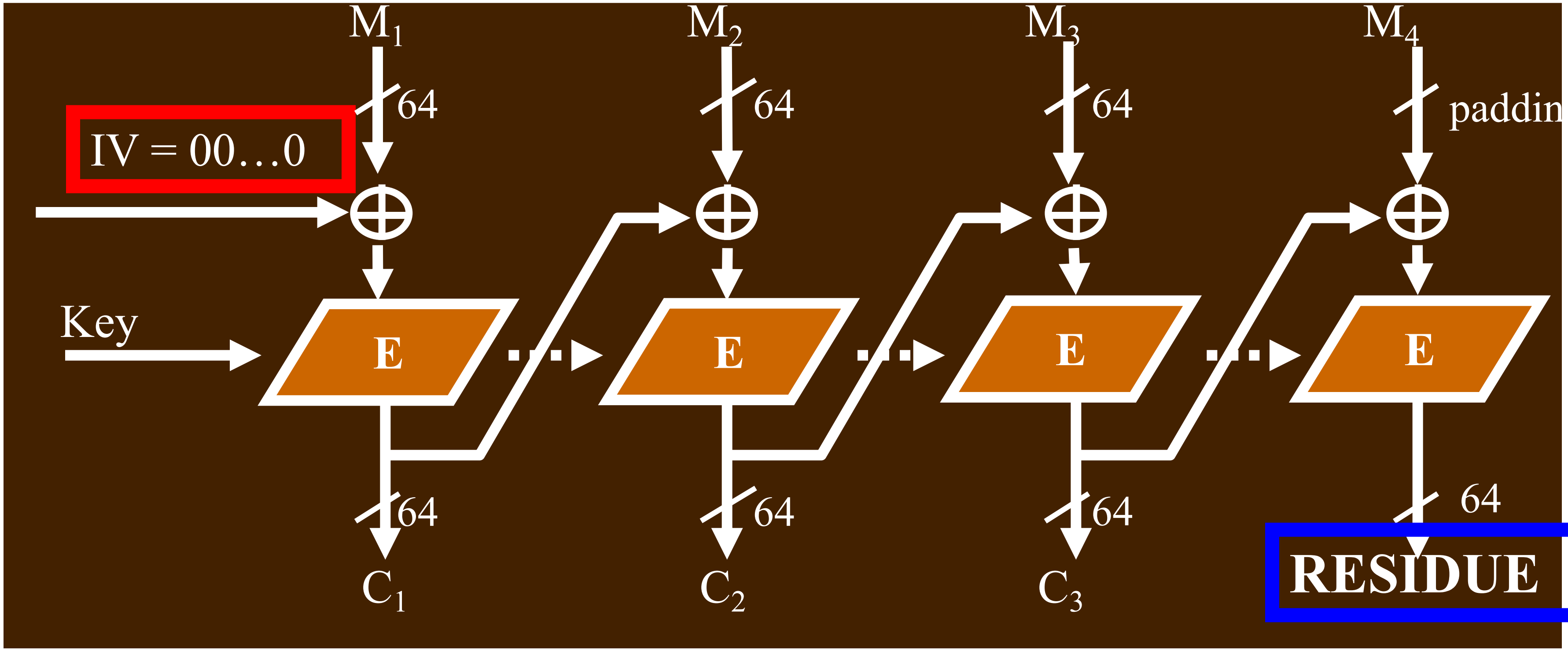
Approach #2: Plaintext+Ciphertext



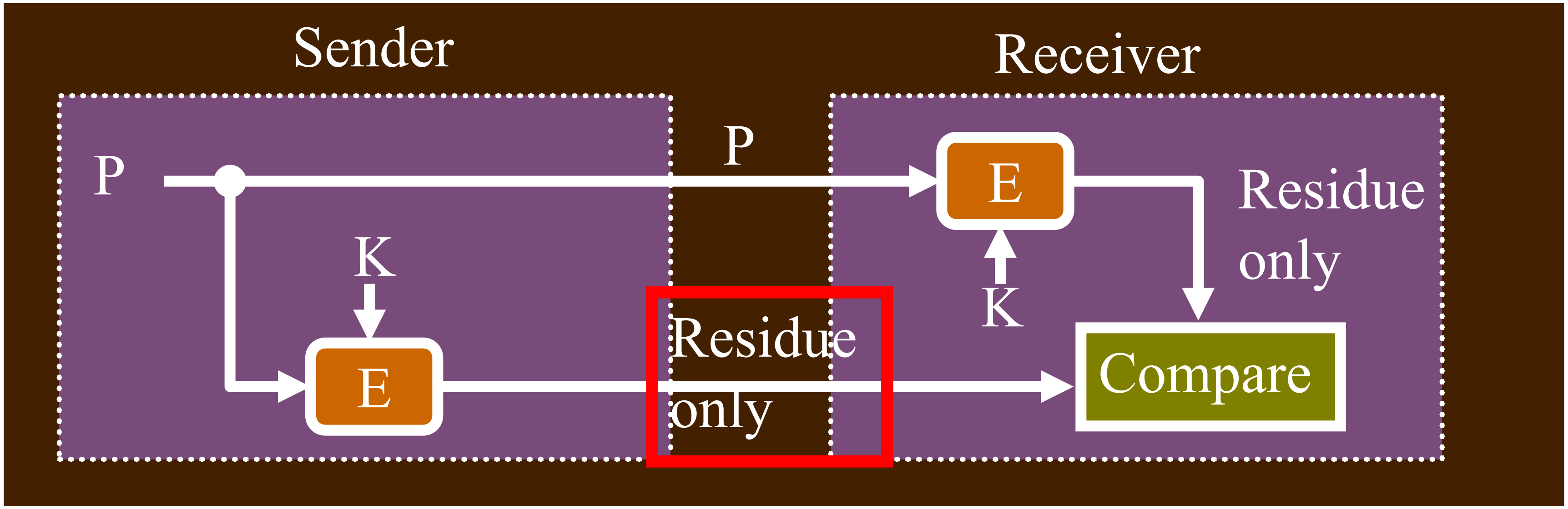
- Send plaintext and ciphertext
  - receiver encrypts plaintext, and compares result with received ciphertext
  - forgeries / modifications easily detected
  - any problems / drawbacks?

Approach #3: Use Residue

- Encrypt plaintext using DES CBC mode, with IV set to zero
  - the last (final) ciphertext output block is called the *residue*



Approach #3… (Cont'd)



- Transmit the plaintext and this residue
  - receiver computes same residue, compares to the received residue
  - forgeries / modifications highly likely to be detected

Message Authentication Codes

- *MAC*: a small fixed-size block (i.e., independent of message size) generated from a message using secret key cryptography
  - also known as *cryptographic checksum*

Requirements for MAC

1. Given M and MAC(M), it should be computationally infeasible (expensive) to construct (or find) another message M’ such that MAC(M’) = MAC(M)
2. MAC(M) should be uniformly distributed in terms of M
   – for randomly chosen messages M and M’, P(MAC(M)=MAC(M’)) = 2^{-k}, where k is the number of bits in the MAC

Requirements … (cont'd)

3. Knowing MAC(M), it should be computationally infeasible for an attacker to find M.

S.K. Crypto for Confidentiality AND Authenticity?

- So far we've got
  - confidentiality (encryption),

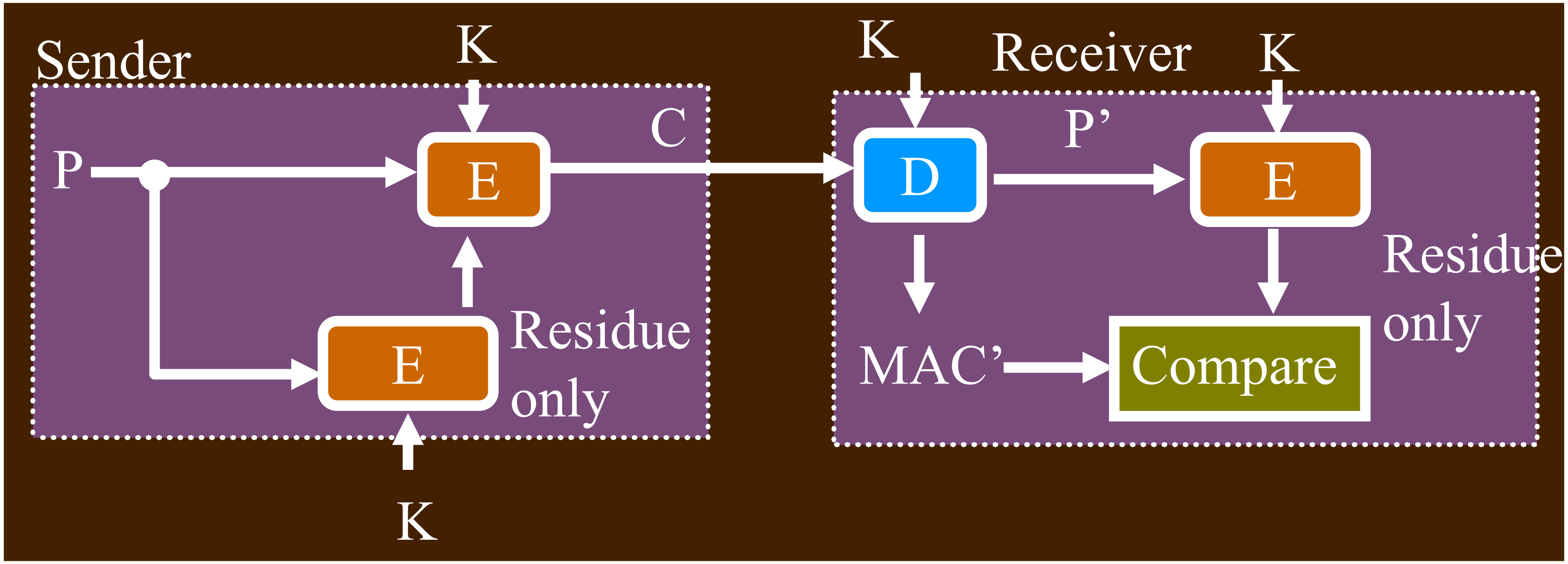
  or…

  - authenticity (MACs)
- Can we get both at the same time with one cryptographic operation?

Attempt #1

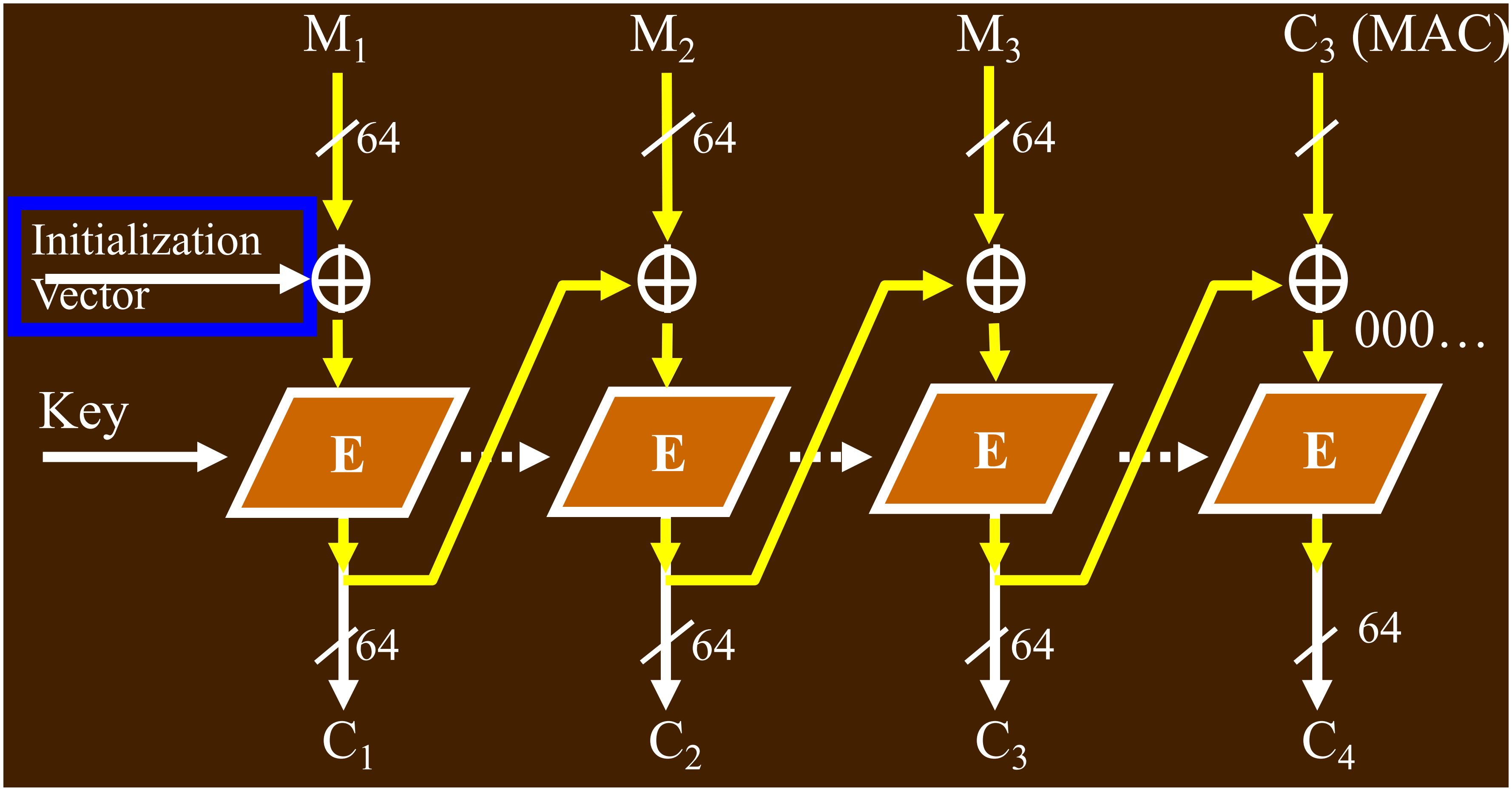
1. Compute residue (MAC) using key K
2. Attach MAC to the plaintext P
3. Encrypt the concatenated quantity P | MAC using the same key K to produce C
4. Transmit C to receiver
5. Receiver decrypts received C’ with K to get P’| MAC’
6. Receiver computes MAC(P’) using K, and compares to received MAC’

Attempt #1… (cont'd)



- This method does not work…
- The last block is always the encryption of zeros, which does not depend on the message and thus cannot offer integrity protection

Attempt #1… (cont'd)



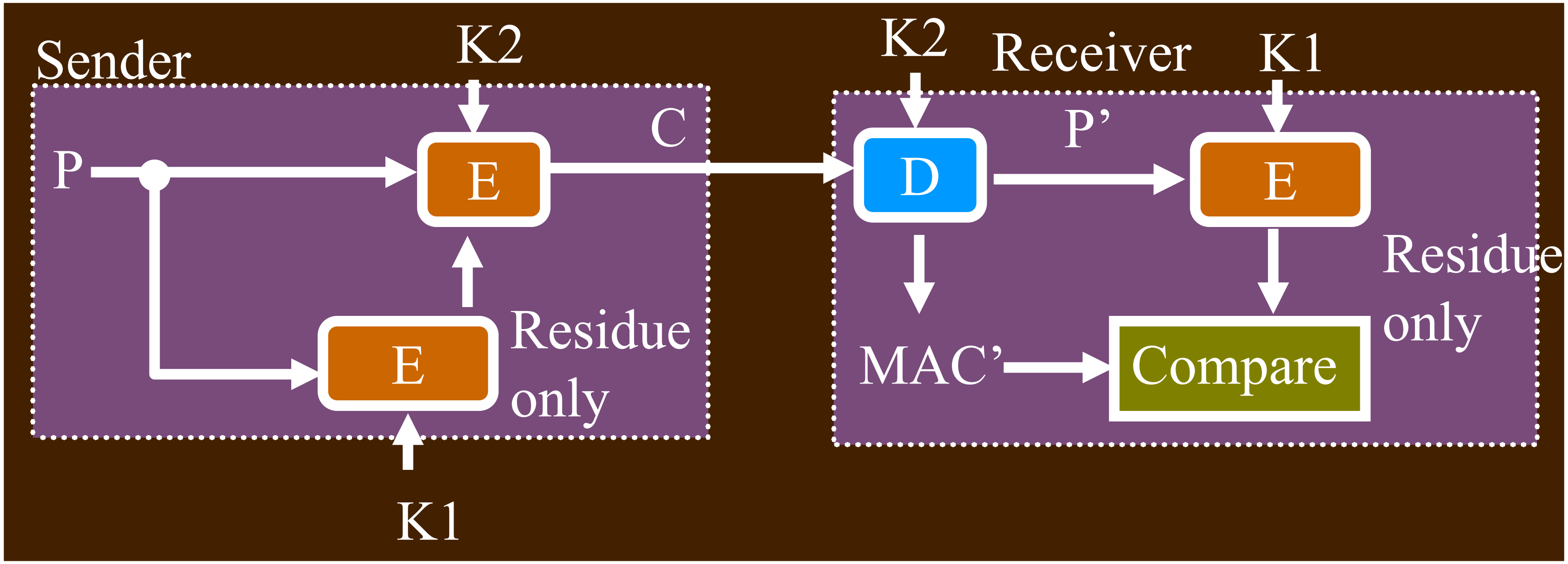
$P \mid MAC = M_1 \mid M_2 \mid M_3 \mid C_3(MAC)$

$E(P \mid MAC) = C_1 \mid C_2 \mid C_3 \mid C_4$

Attempt #2

1. Compute residue (MAC) using key K1
2. Attach MAC to the plaintext P
3. Encrypt the concatenated quantity P | MAC using a different key K2 to produce C
4. Transmit C to receiver
5. Receiver decrypts received C’ with K2 to get P’| MAC’
6. Receiver computes MAC(P’) using K1, and compares to received MAC’

Attempt #2… (cont’d)



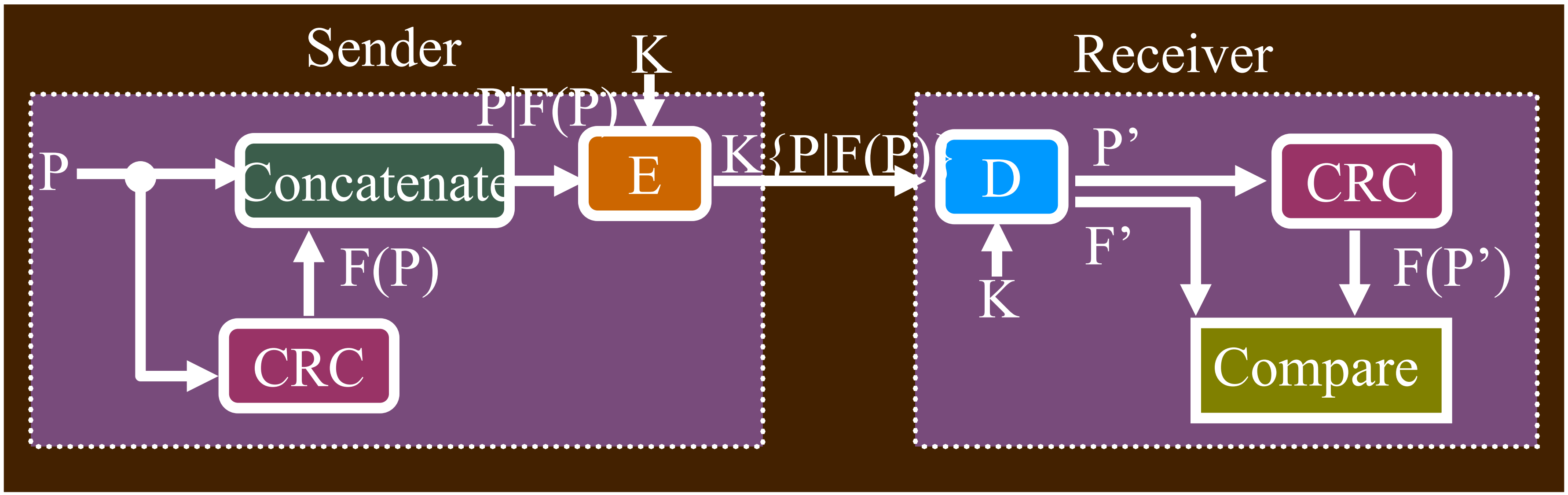
- Good (cryptographic) quality, but…
- Expensive! Two separate, full encryptions with different keys are required

Attempt #3

1. Sender computes an error-detection code F(P) of the plaintext P
2. Sender concatenates P and F(P) and encrypts
   - i.e., $C = E_K(P \mid F(P))$
3. Receiver decrypts received ciphertext C' using K, to get P'|F'
4. Receiver computes F(P') and compares to F' to authenticate received message P' = P

- How does this authenticate P?

Attempt #3... (Cont'd)



- Subtle attacks are known if the CRC is short
- Need to use long CRC codes.

Summary

1. ECB mode is not secure
   – CBC most commonly used mode of operation
2. Triple-DES (with 2 keys) is much stronger than DES
   – usually uses EDE in Outer Chaining Mode
3. MACs use crypto to authenticate messages at a small cost of additional storage / bandwidth
   – but at a high computational cost

Quiz 2(2) Cipher Feedback Mode (CFB)