CSCI 454/554 Computer and Network Security

Topic 3.2 Secret Key Cryptography – Modes of Operation

Processing with Block Ciphers

- 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

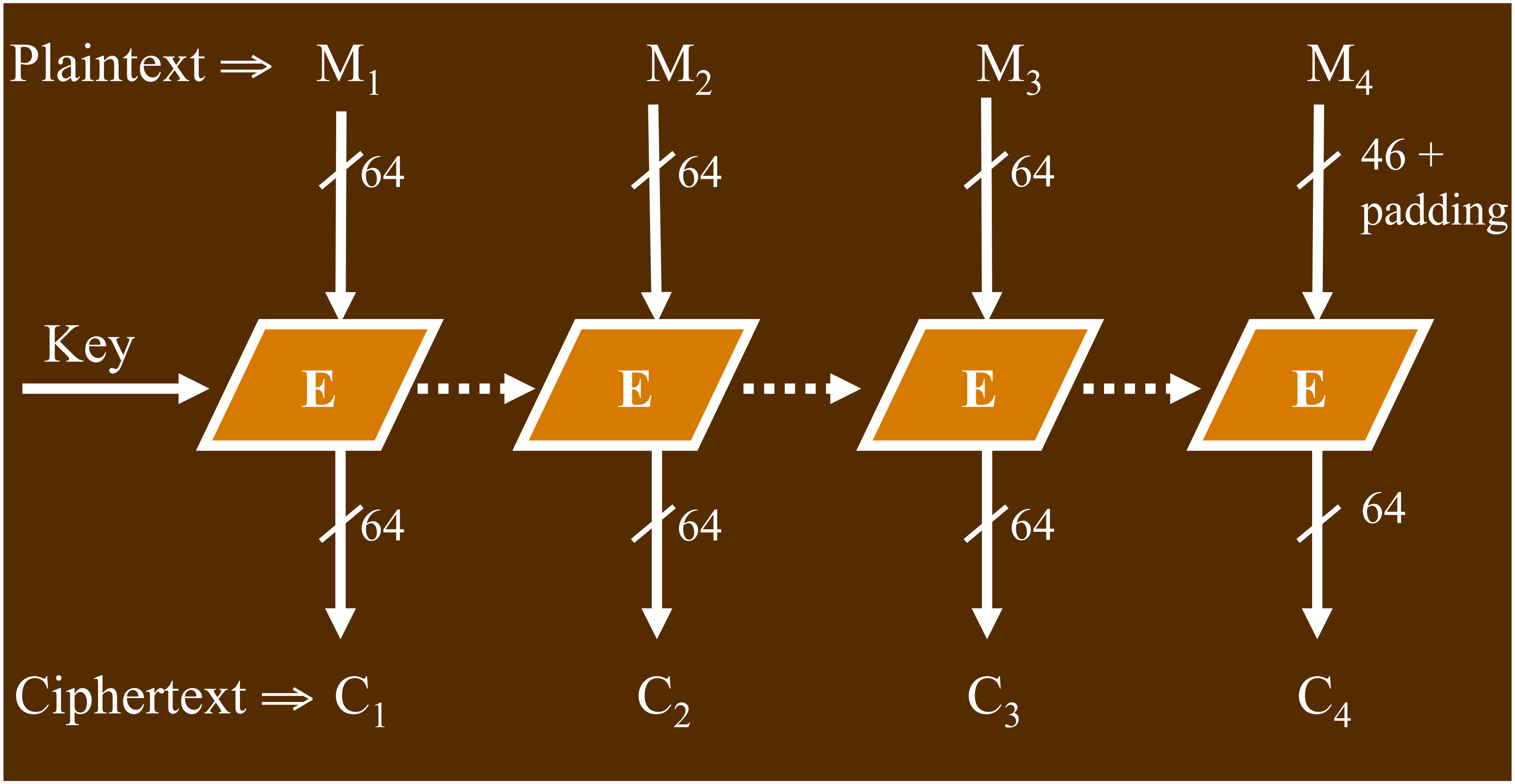
- Information leakage
  - Does it reveal info about the plaintext blocks?
- Ciphertext manipulation
  - Can an attacker modify ciphertext block(s) in a way that will produce a predictable/desired change in the decrypted plaintext block(s)?

  - Note: assume the structure of the plaintext is known, e.g., first block is employee #1 salary, second block is employee #2 salary, etc.

Issues… (Cont'd)

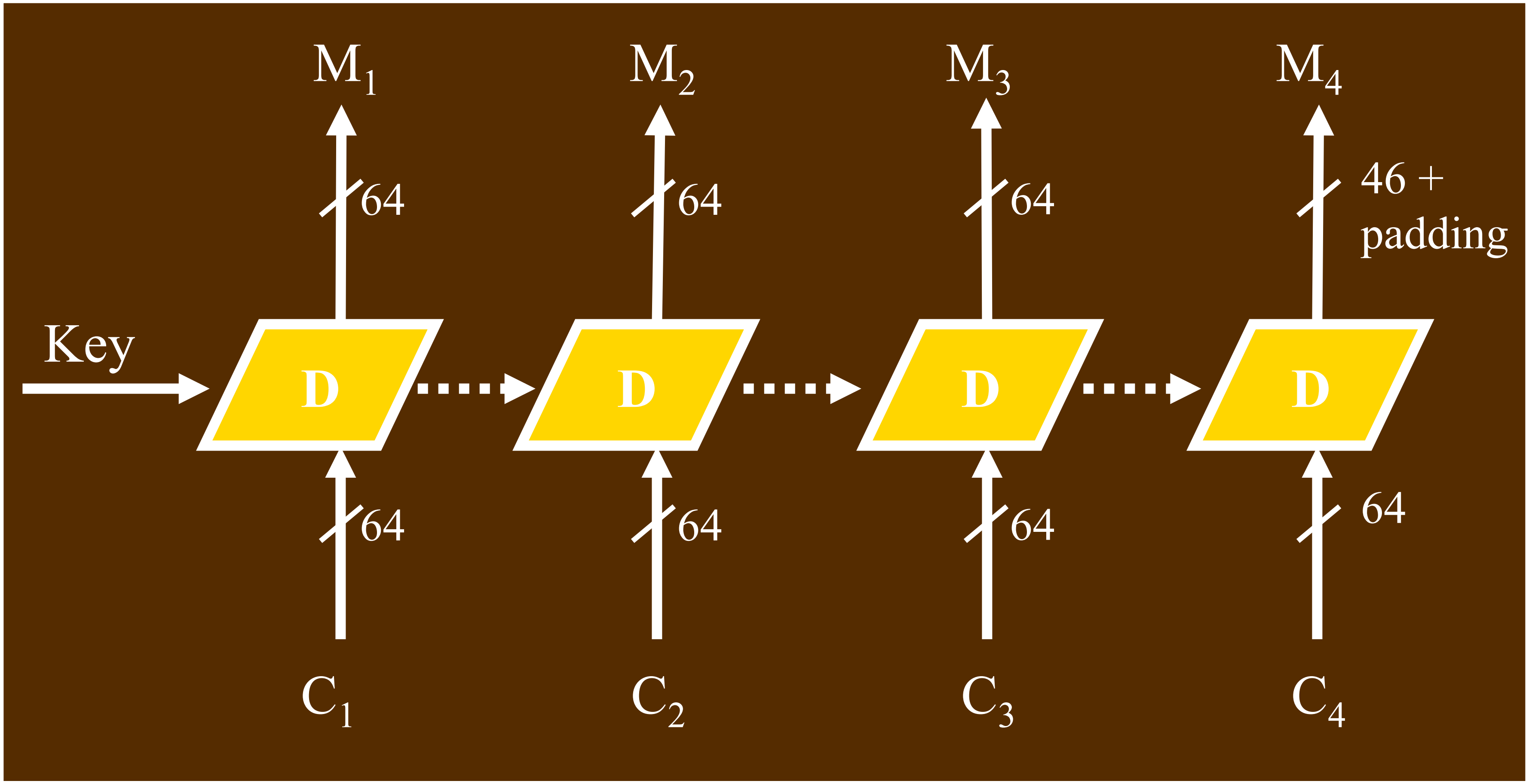
- Parallel/Sequential
  - Can blocks of plaintext (ciphertext) be encrypted (decrypted) in parallel?
- Error propagation
  - If there is an error in a plaintext (ciphertext) block, will there be an encryption (decryption) error in more than one ciphertext (plaintext) block?

Electronic Code Book (ECB)



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

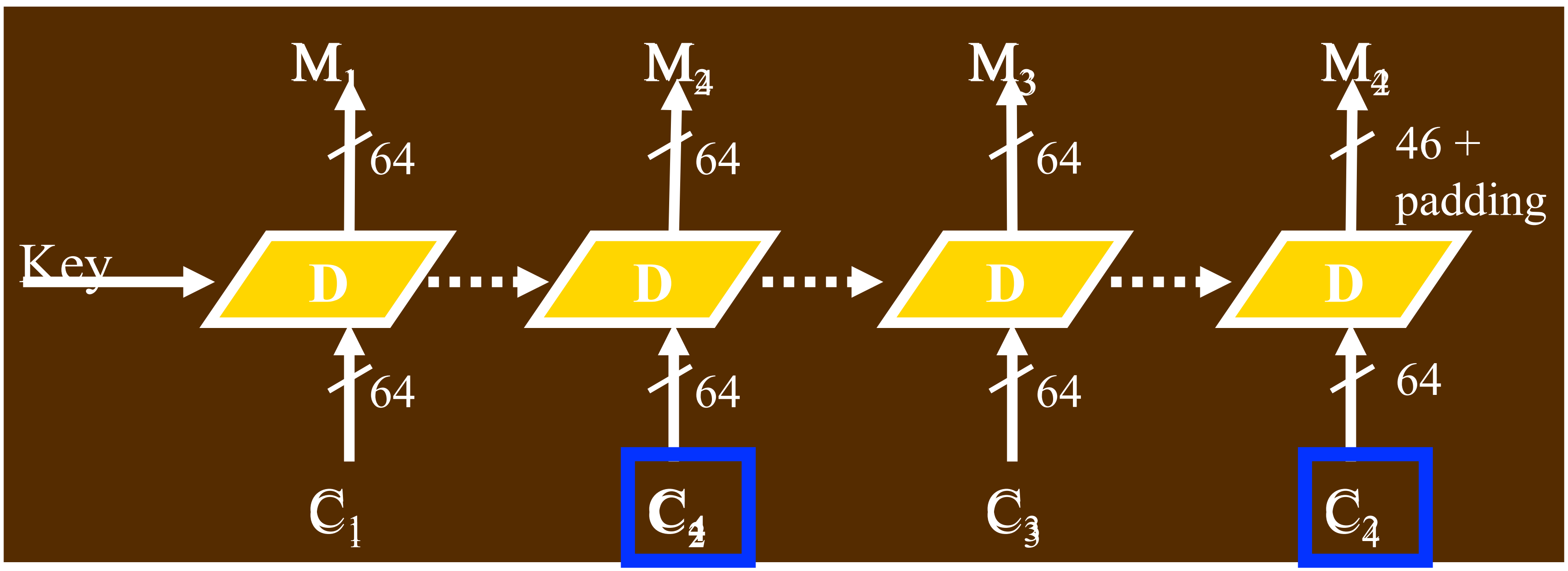
ECB Decryption



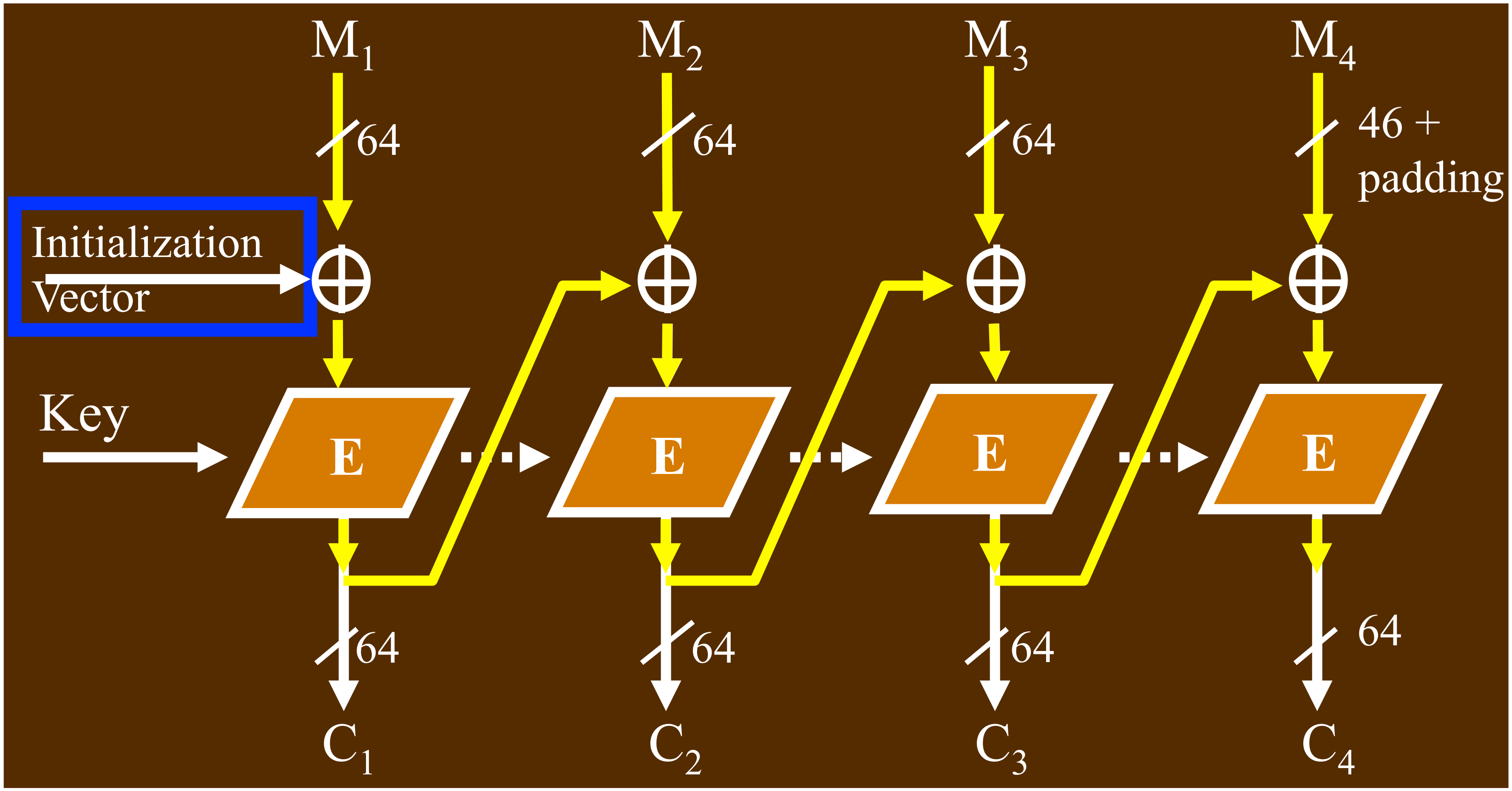
- Each block is independently decrypted

ECB Properties

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



Cipher Block Chaining (CBC)



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

Initialization Vectors

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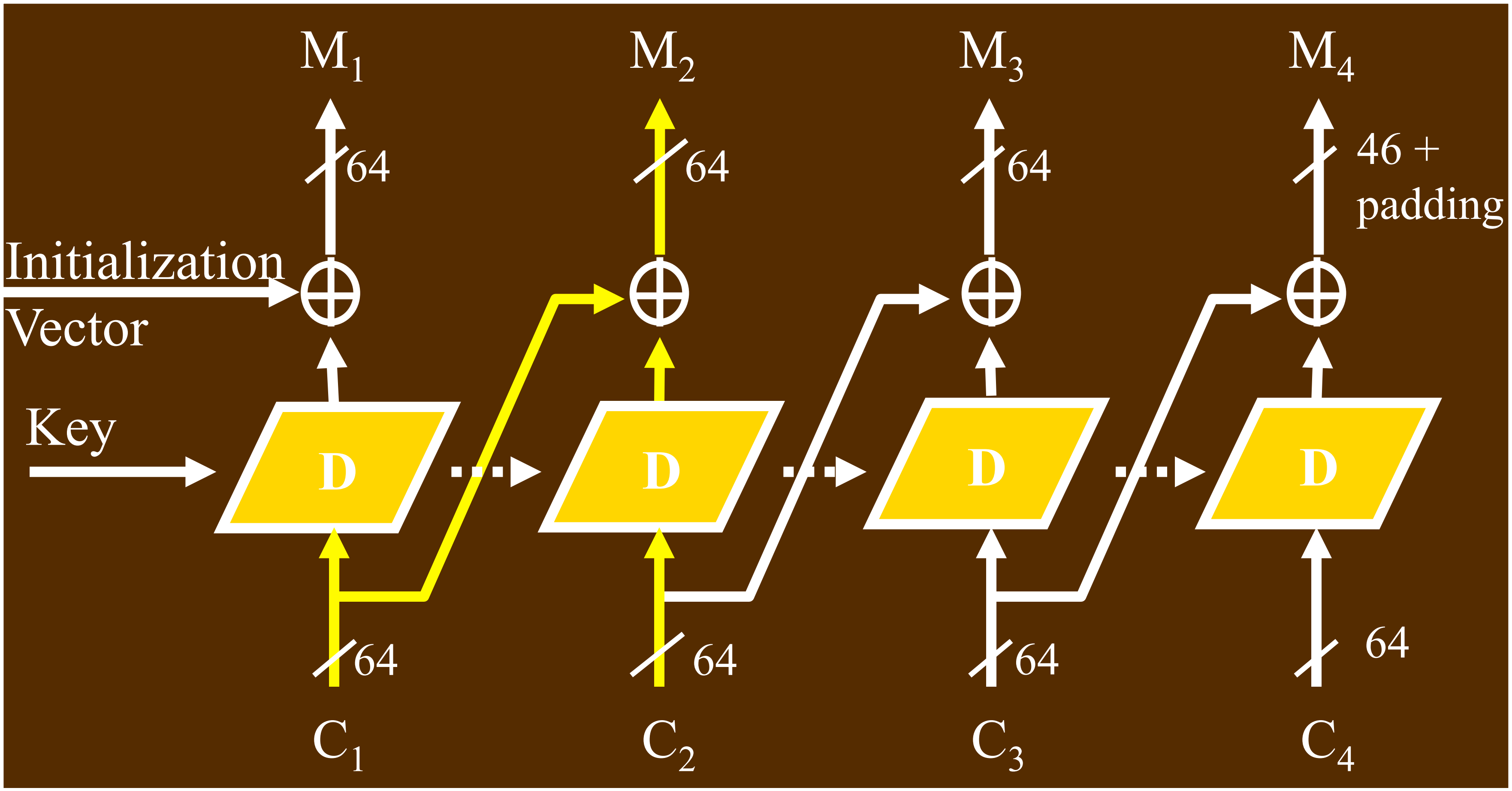
- Initialization Vector (IV)
  - Used along with the key; not secret
  - For a given plaintext, changing either the key, or the IV, will produce a different ciphertext
  - Why is that useful?
- IV generation and sharing
  - Random; may transmit with the ciphertext
  - Incremental; predictable by receivers

CBC Decryption

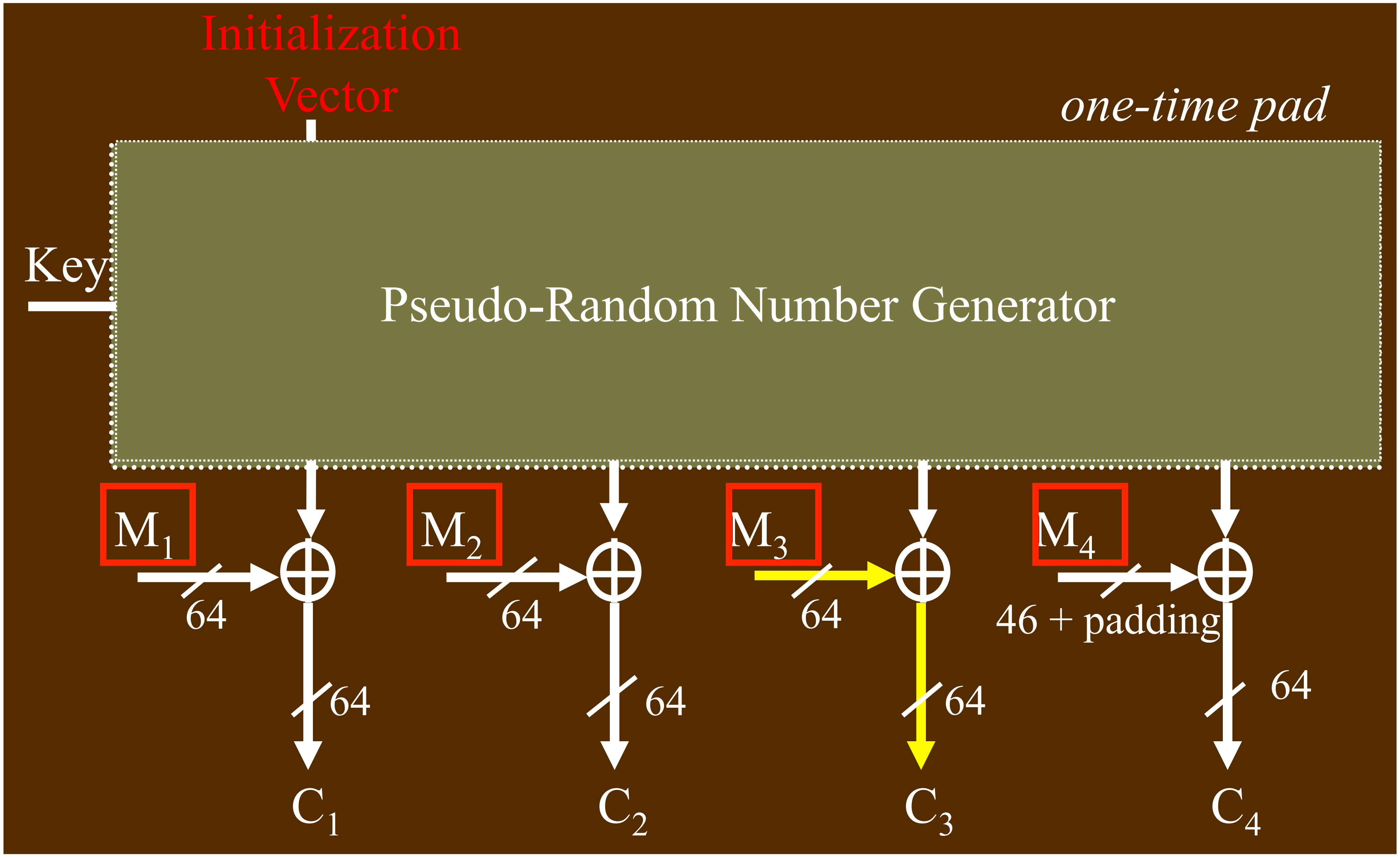


- How many ciphertext blocks does each plaintext block depend on?

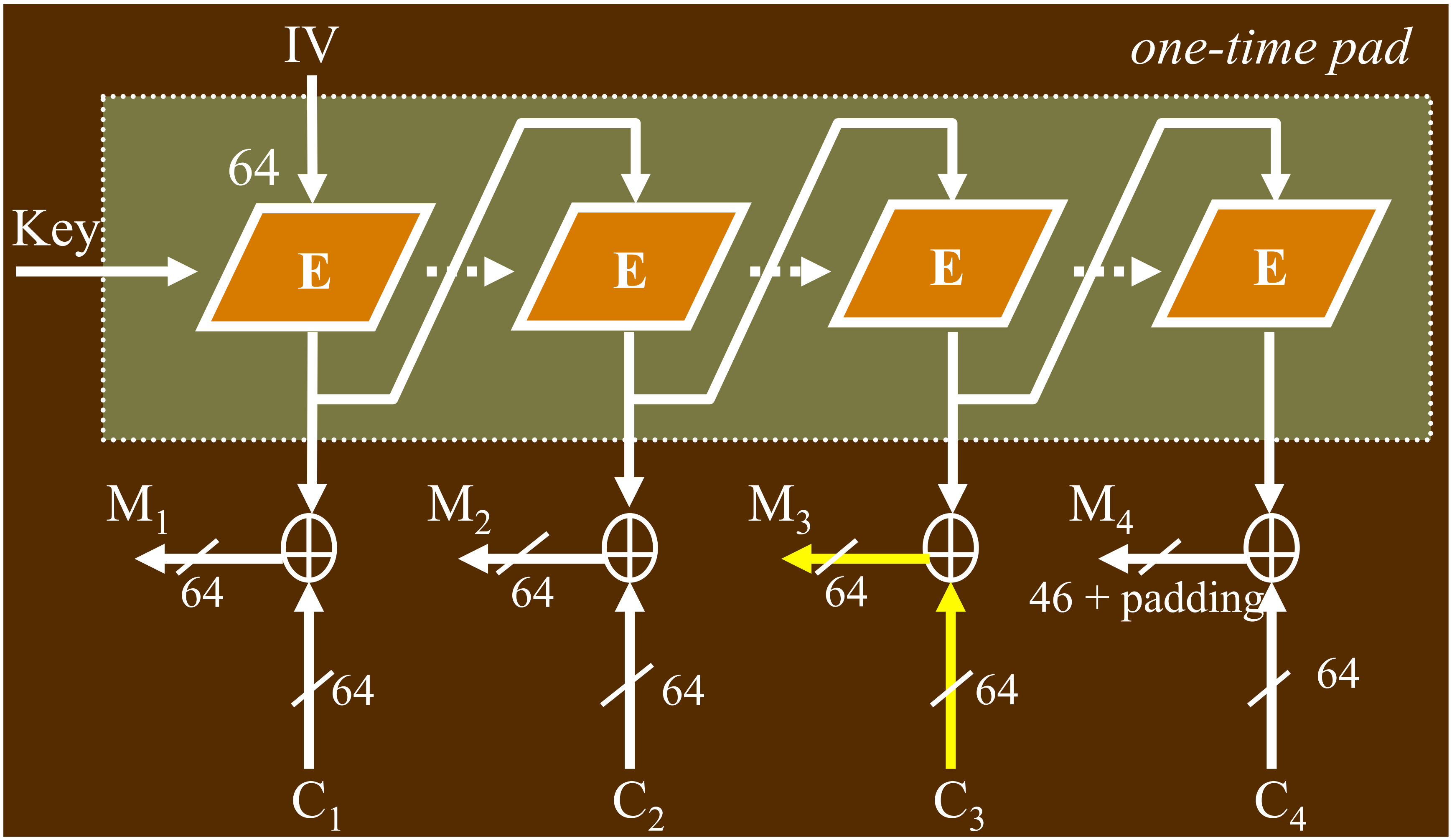
CBC Properties

- 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!

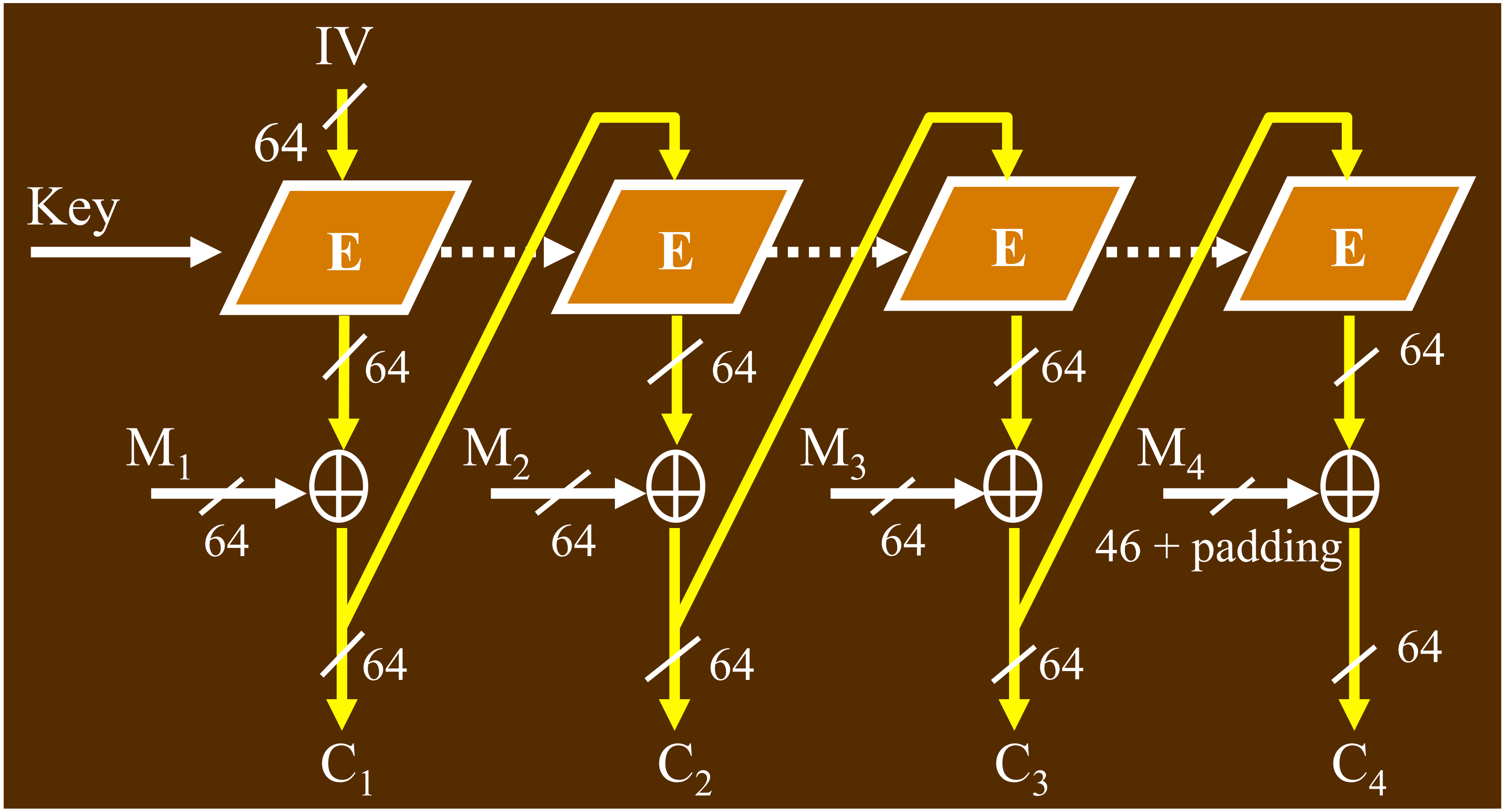
OFB Properties

- 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)

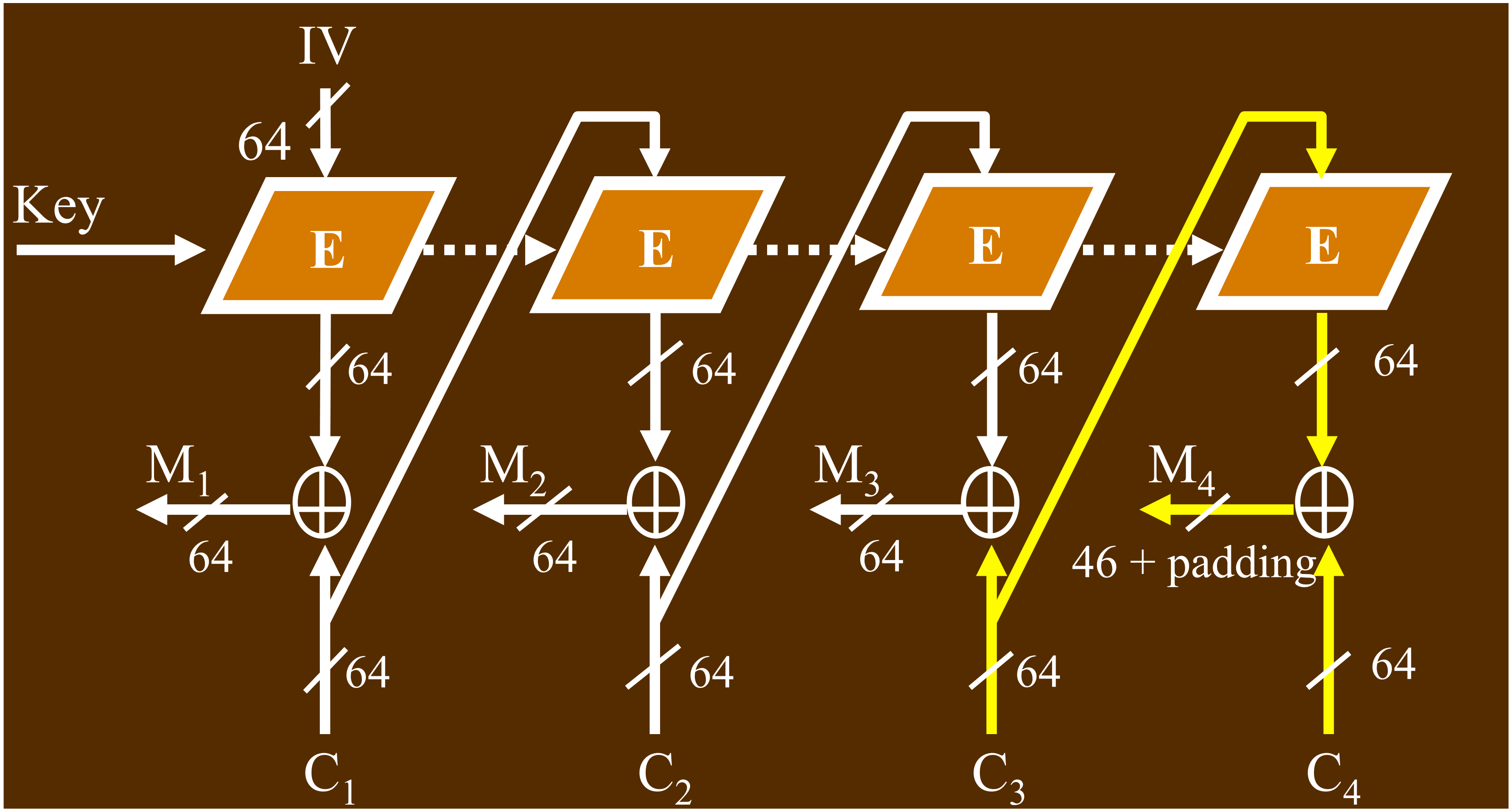
- If you know one plaintext/ciphertext pair, can easily derive the one-time pad that was used
  - i.e., should not reuse a one-time pad!
- Conclusion: IV must be different every time

Cipher Feedback Mode (CFB)



- Ciphertext block C_j depends on all preceding plaintext blocks

CFB Decryption

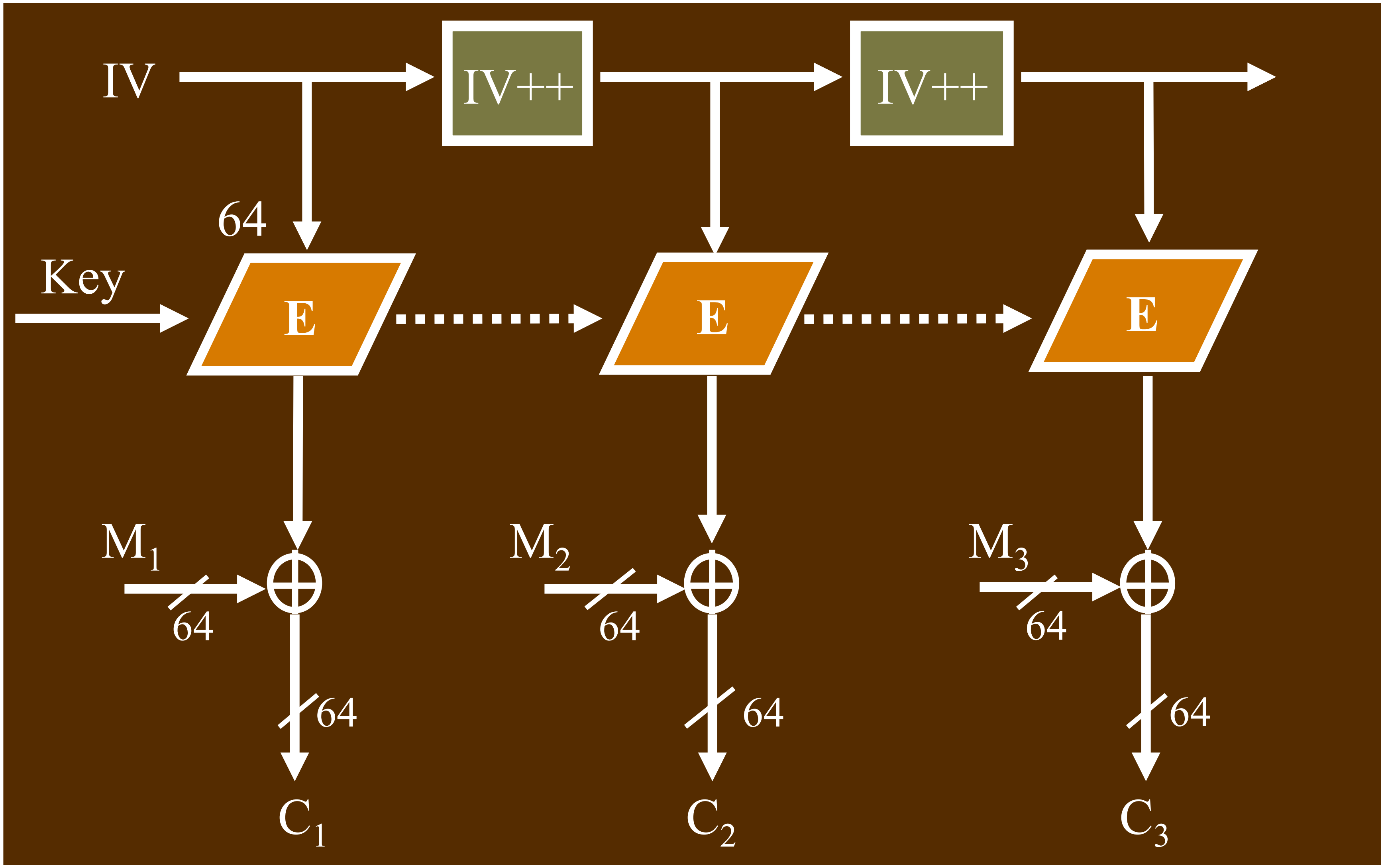


- No block decryption required!

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

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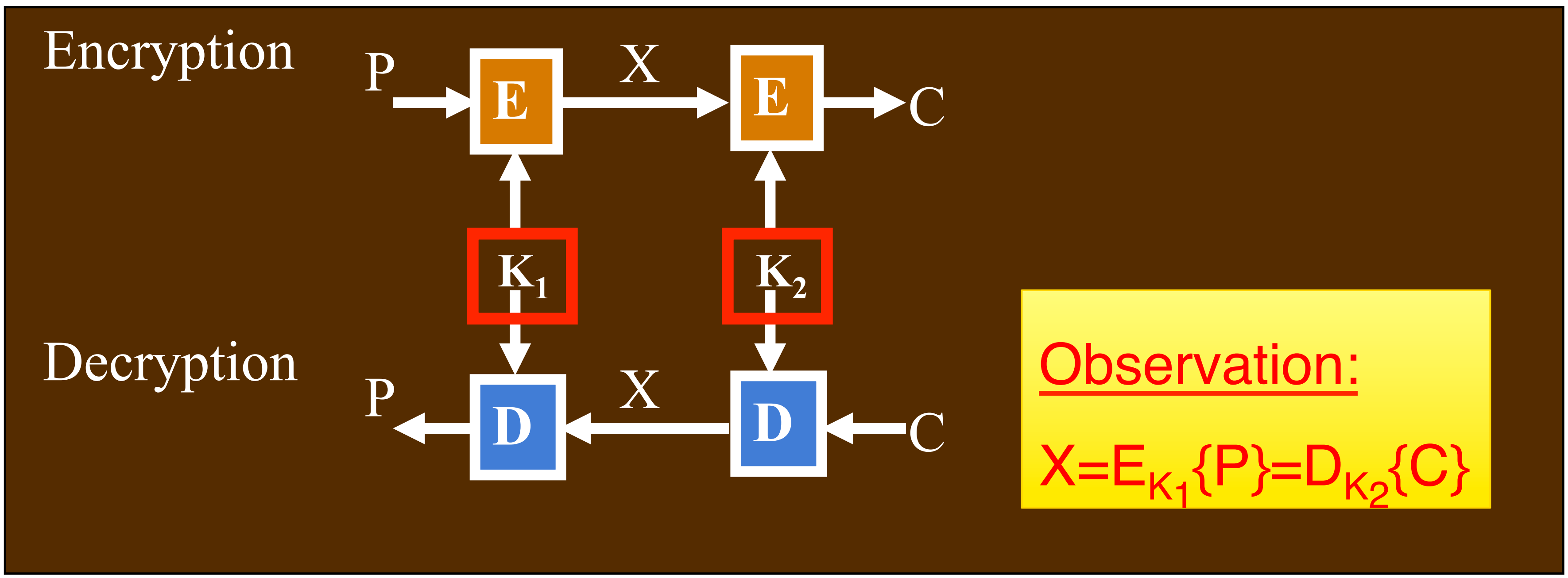
Topic 3.3 Secret Key Cryptography – Triple DES

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

- 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?



Concerns About Double DES

WILLIAM & MARY

- Wasn't clear at the time if DES was a group
  (it's not)
  - If it were, then $E_{k2}(E_{k1}(P)) \equiv E_{k3}(P)$, for all P
  - Not good?
- Possible attack (better than brute force): meet-in-the-middle
  - A known-plaintext attack

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 keypair* K_i+K_j
   - there should be approx. (2^{112} / 2^{64}) = 2^{48} such pairs for one value of (P,C)
     - 2^{112} possible keys, but there are only 2^{64} X's
4. Repeat the above, for a second plaintext/ ciphertext pair (P',C'), and find those 2^{48} candidate keypairs $K_i'+K_j'$

Why 2^{48} (another view)?

-The table contains only $2^{56}/2^{64} = 1/2^8$ of all possible 64-bit values

-there are 2^{56} entries X_i

-for each X_i, there is only $1/2^8$ chance there is a matching Y_i

Steps … (Cont'd)

5. Look for an identical candidate keypair that produces collisions for both (P,C) and (P',C')
   - the probability the same candidate keypair occurs for both plaintexts, but is not the keypair used in the double-DES encryption: $2^{48} / 2^{64} = 2^{-16}$

- An expensive attack (computation + storage)
  - still, enough of a threat to discourage use of double-DES

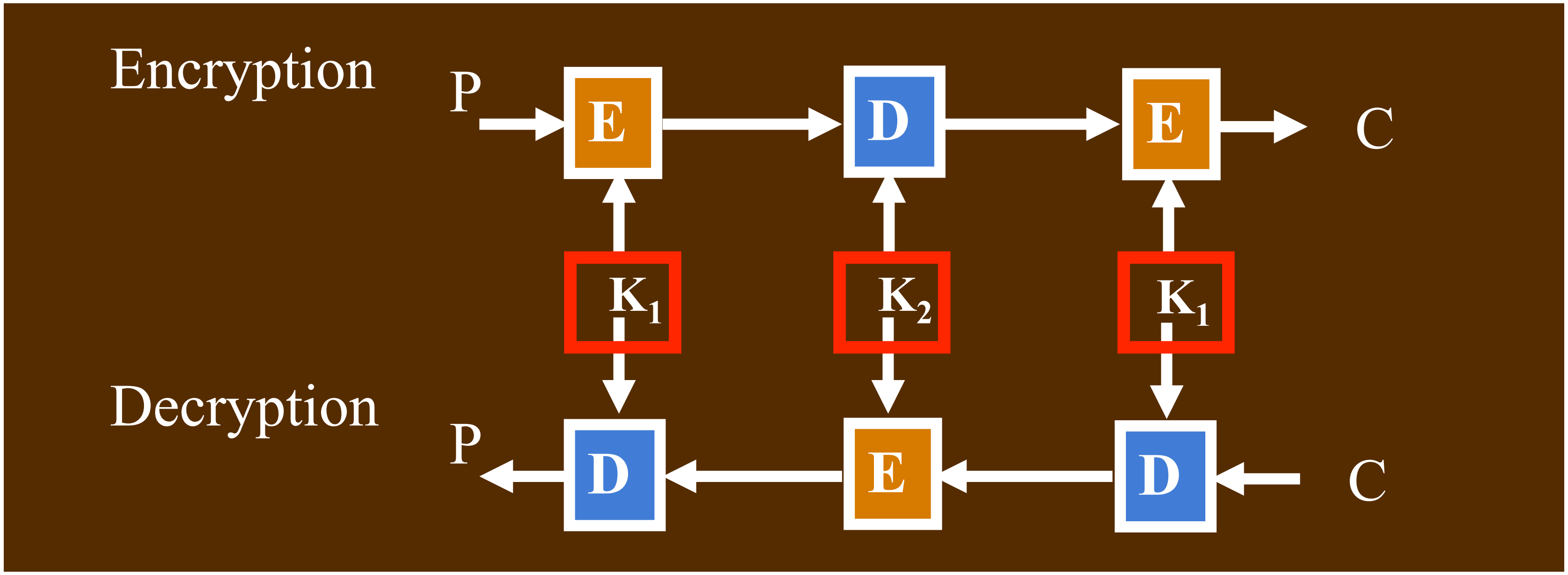
Why 2^{-16}?

-there are about 2^{48} candidate keypairs K_i+K_j

-at most one is $\mathcal{K}1+\mathcal{K}2$, the rest are imposters

-if K_i+K_j is an imposter, the probability using K_i+K_j that E(P') = D(C') is $1/2^{64}$

Triple Encryption (Triple DES-EDE)

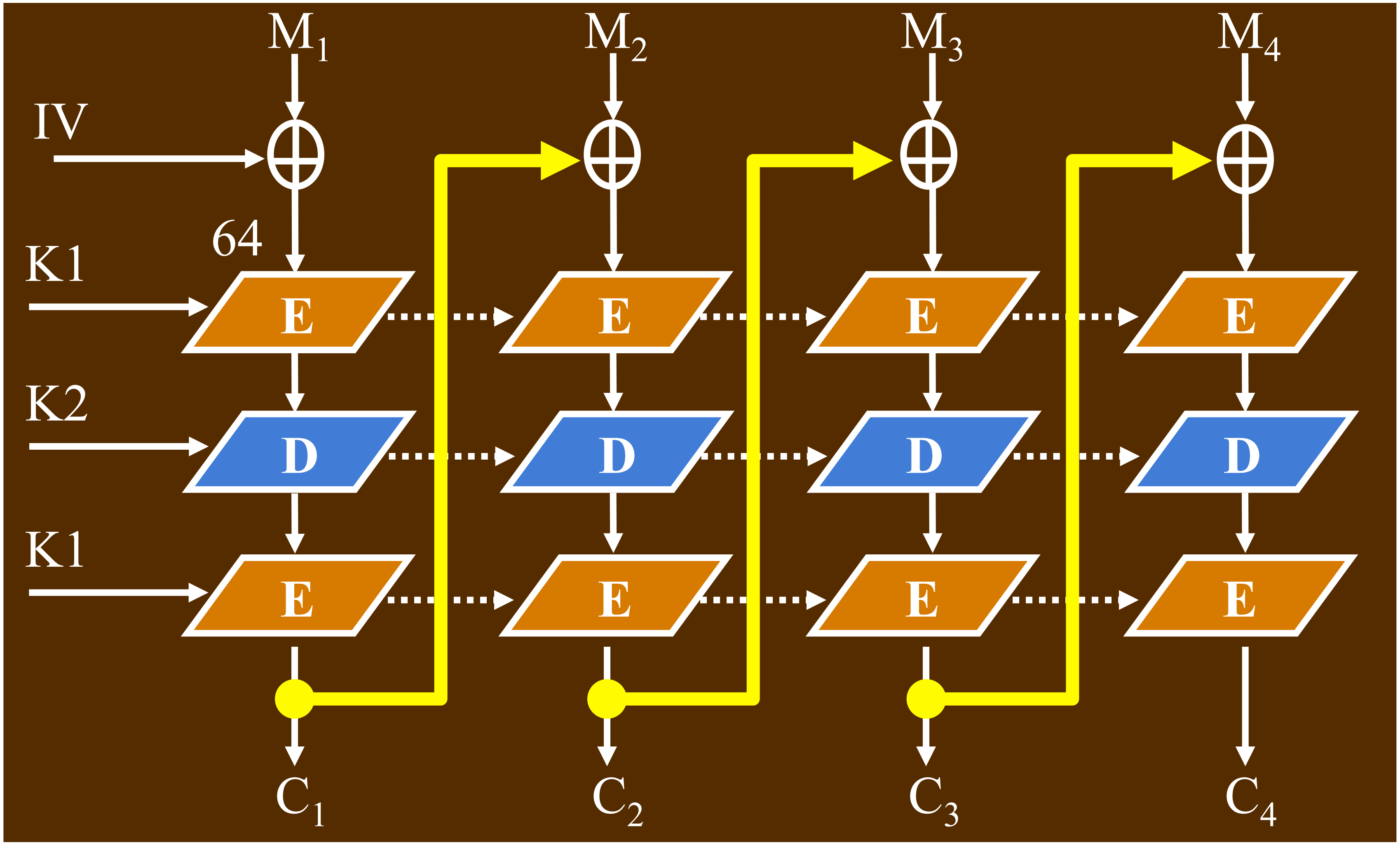


- Why not E-E-E?
  - again, wasn't clear if DES was a group
- Apply DES encryption/decryption three times
  - why not 3 different keys?
  - why not the same key 3 times?

Triple DES (Cont'd)

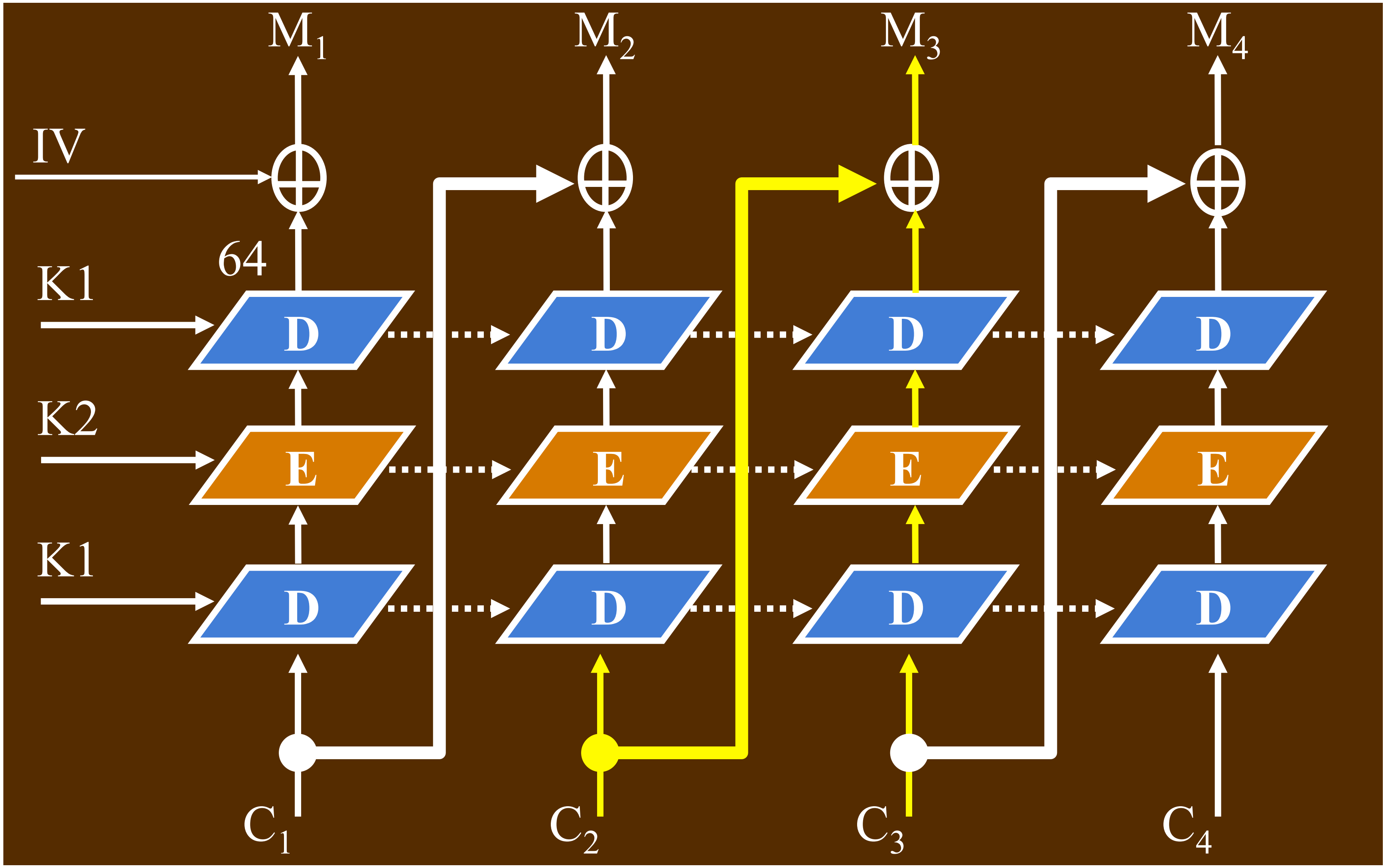
- Widely used
  - equivalent strength to using a 112 bit key
  - strength about 2^{110} against M-I-T-M attack
- However: inefficient / expensive to compute
  - one third as fast as DES on the same platform, and DES is already designed to be slow in software
- Next question: how is block chaining used with triple-DES?

3DES-EDE: Outside Chaining Mode



- What basic chaining mode is this?

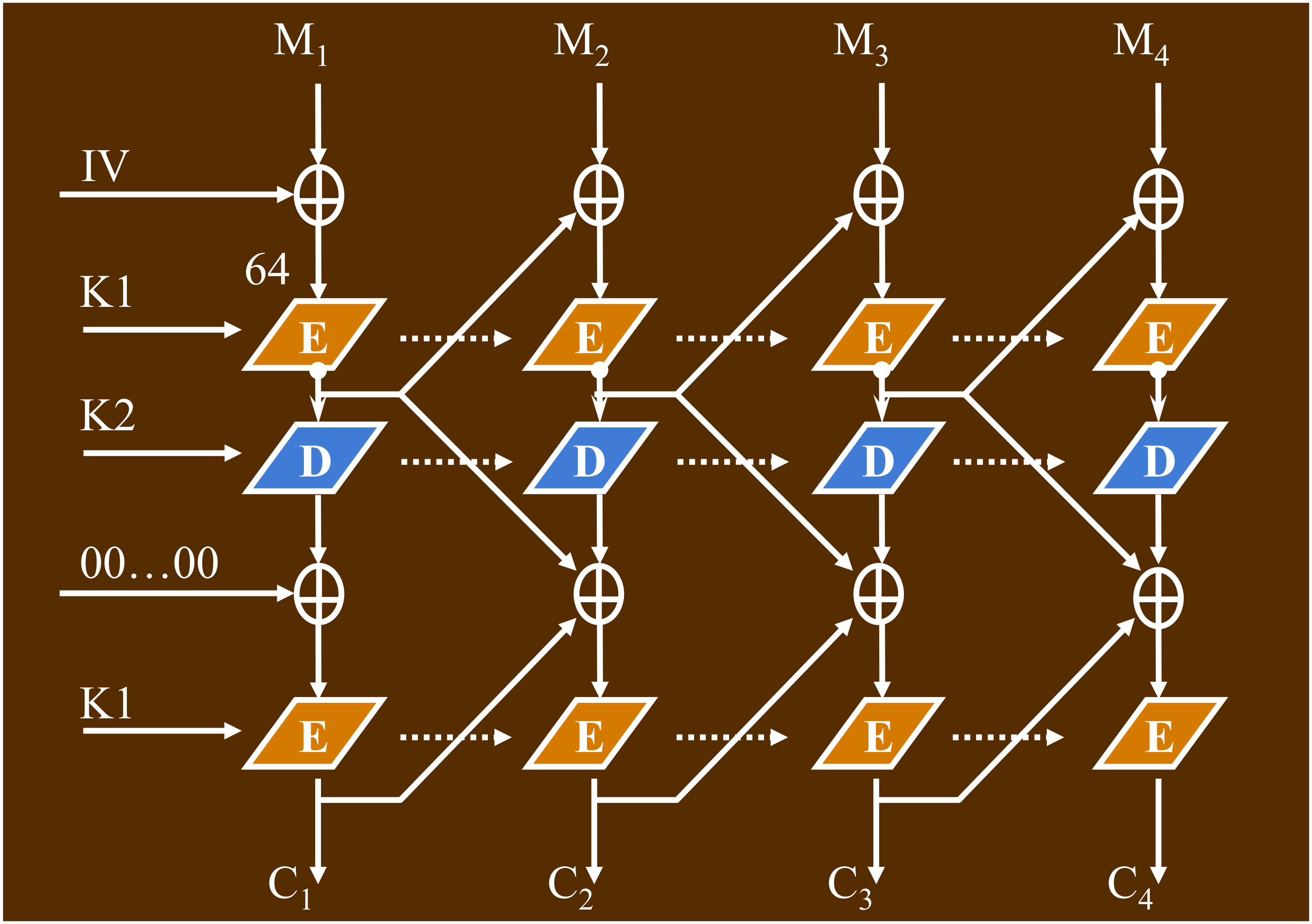
3DES-EDE: OCM Decryption



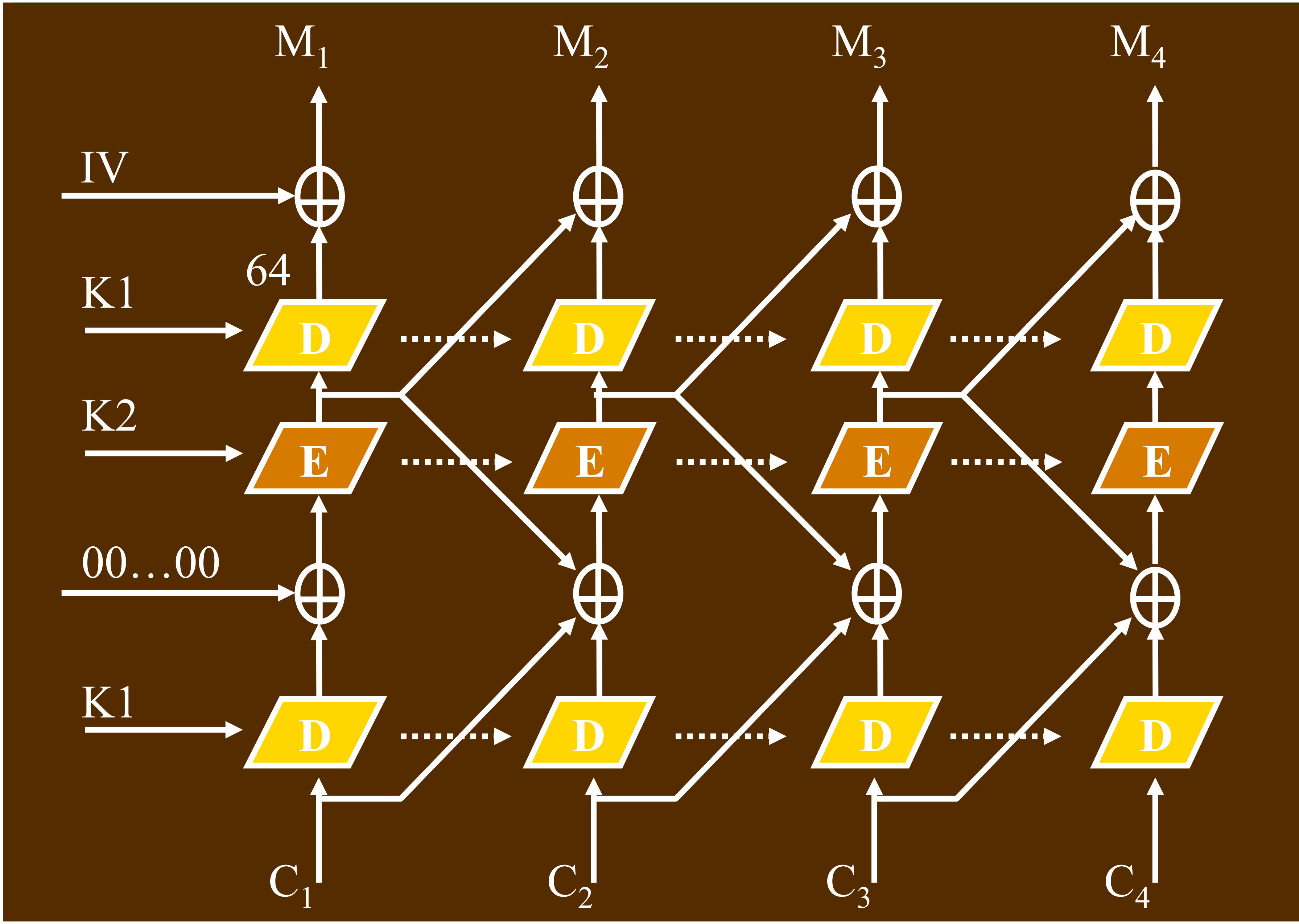
OCM Properties

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

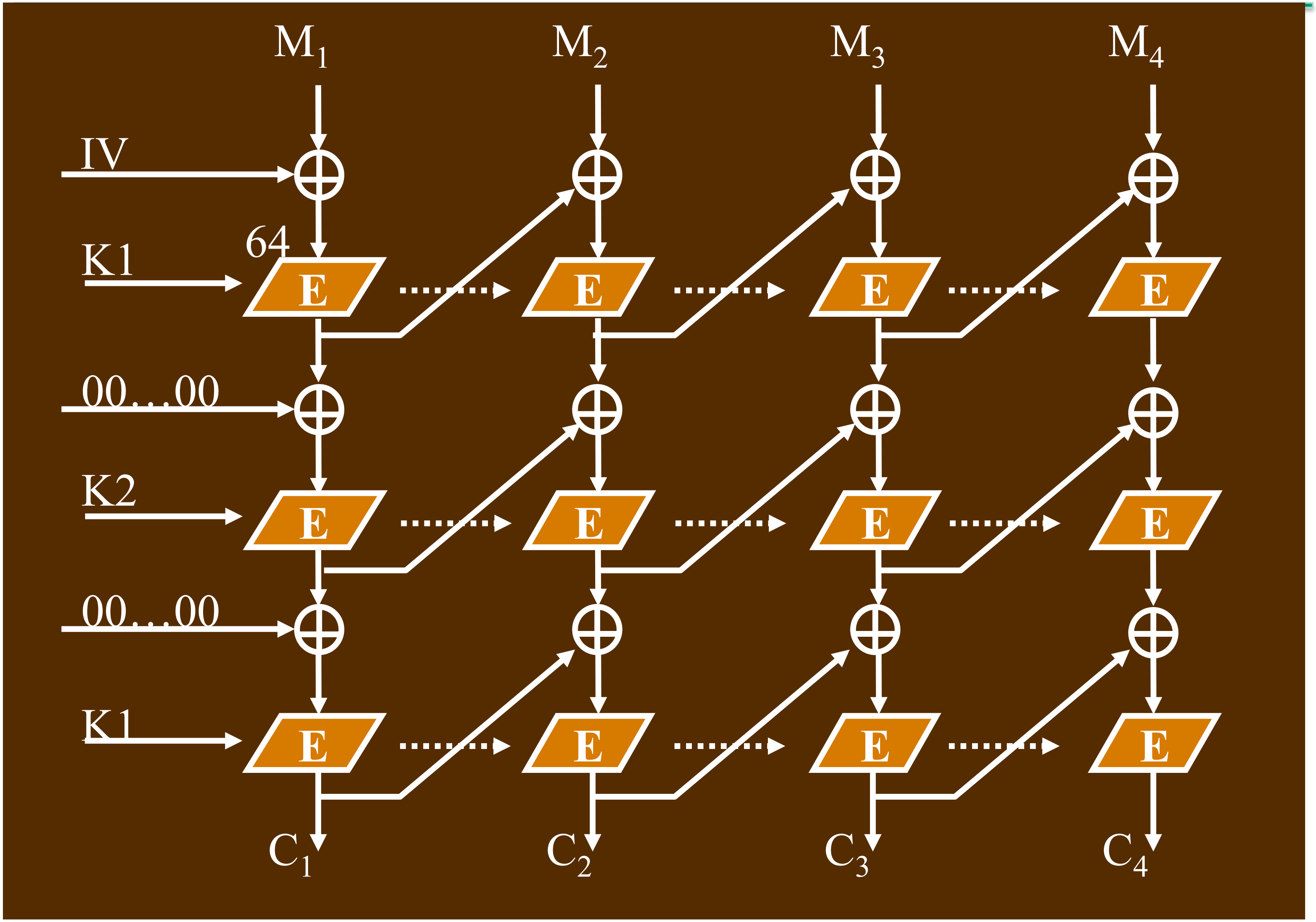
3DES-EDE: Inside Chaining Mode



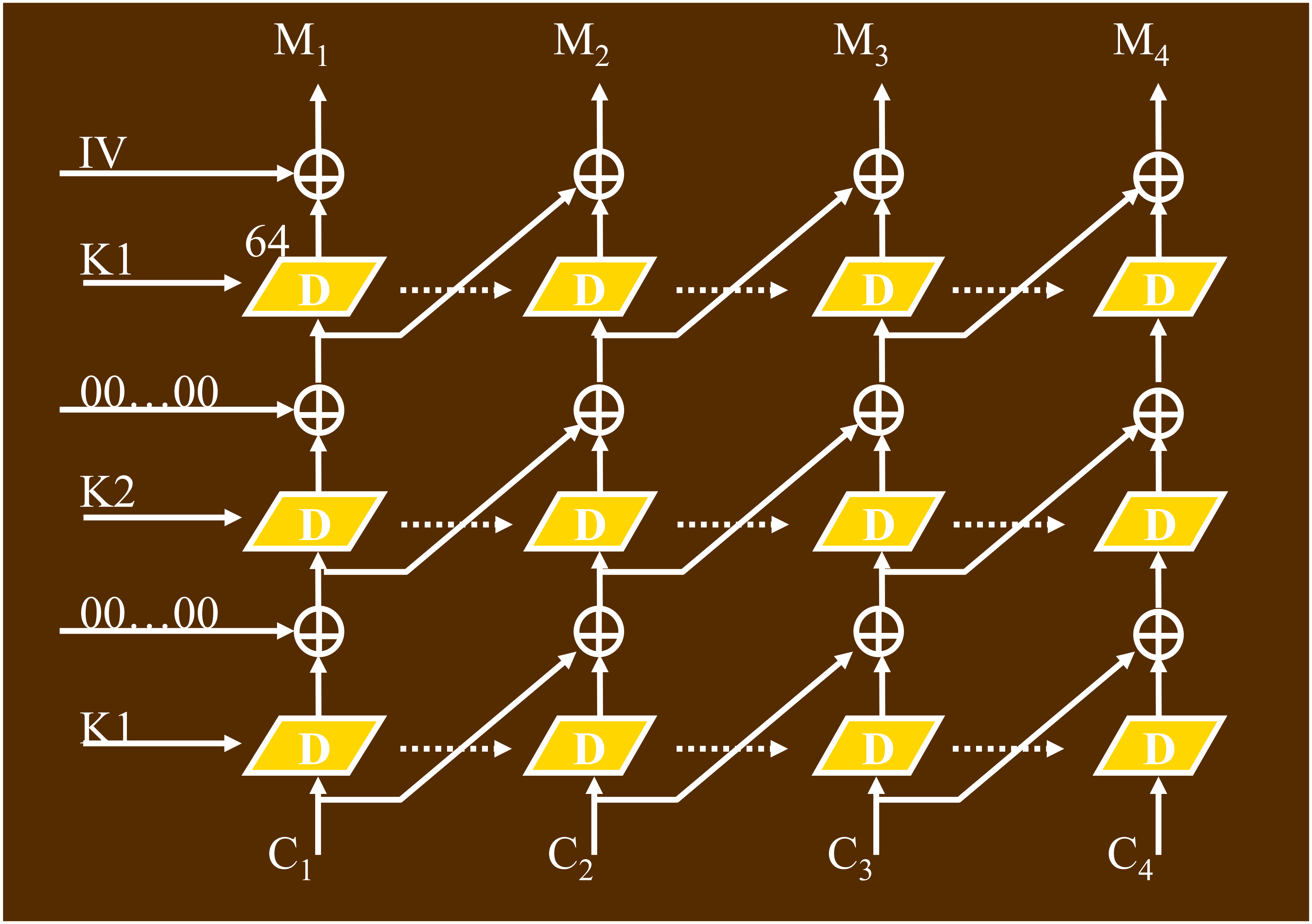
3DES-EDE: ICM Decryption



3DES-EEE: Inside Chaining Mode



3-DES EEE: ICM Decryption



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Topic 3.4 Secret Key Cryptography – MAC with Secret Key Ciphers

Message Authentication

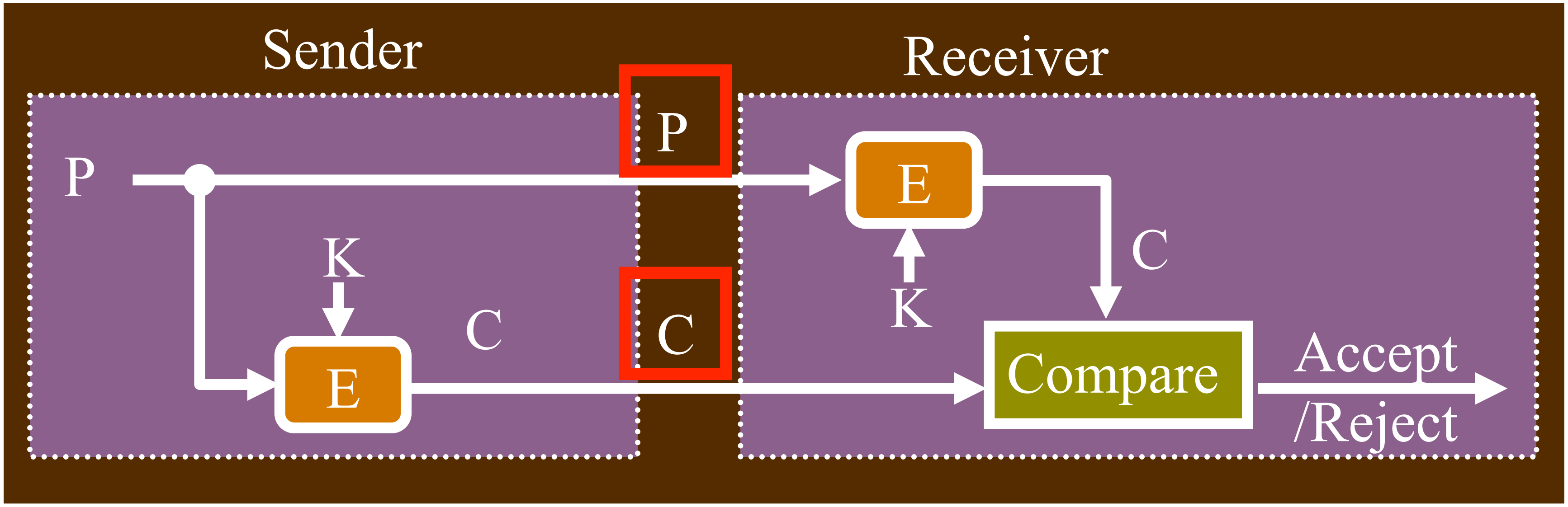
- Encryption easily provides confidentiality of messages
  - only the party sharing the key (the "key partner") can decrypt the ciphertext
- How to use encryption to authenticate messages? That is,
  - prove the message was created by the key partner
  - prove the message wasn't modified by someone other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

Approach #1

WILLIAM & MARY

- The quick and dirty approach
- 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"? What if all data is plausible?

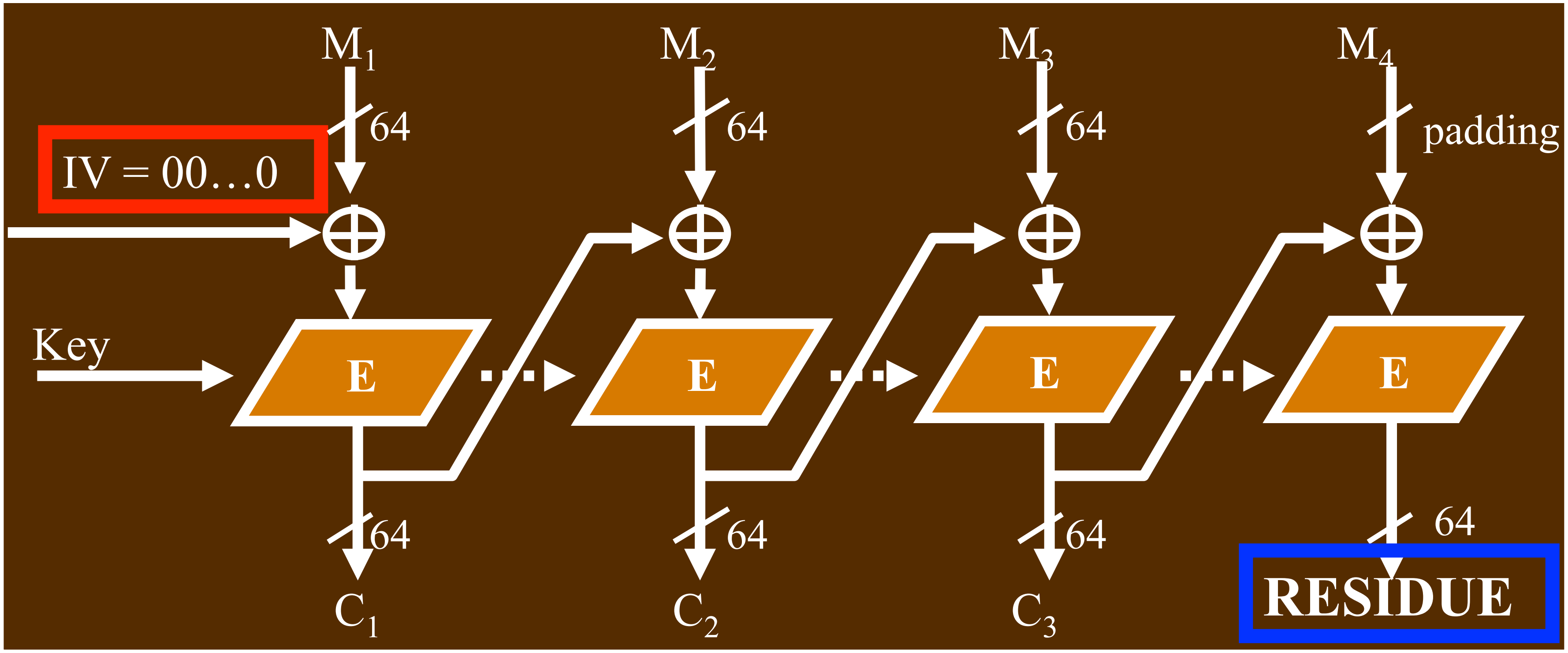
Approach #2: Plaintext+Ciphertext



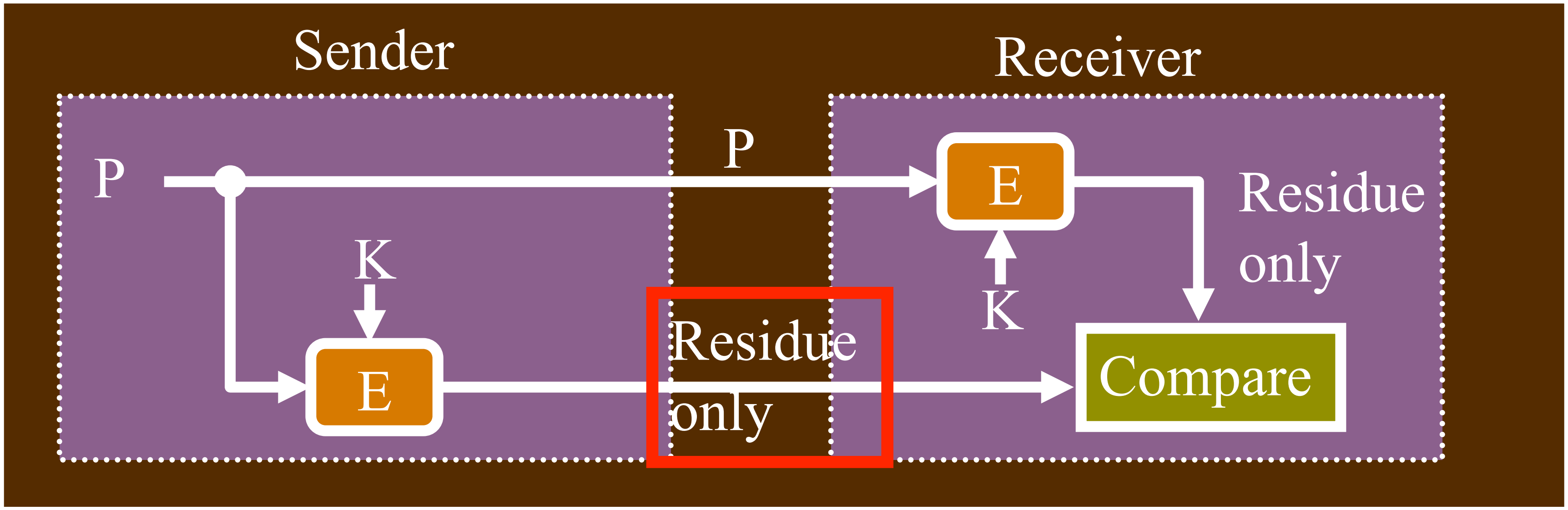
- Send plaintext and ciphertext
  - receiver encrypts plaintext, and compares result with received ciphertext
  - forgeries / modifications easily detected
  - any problems / drawbacks?

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(M1), MAC(M2), . . . of some (known or chosen) messages M1, M2, . . ., it should be computationally infeasible for an attacker to find the MAC of some other message M'

Crypto for Confidentiality AND Authenticity?

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

or…

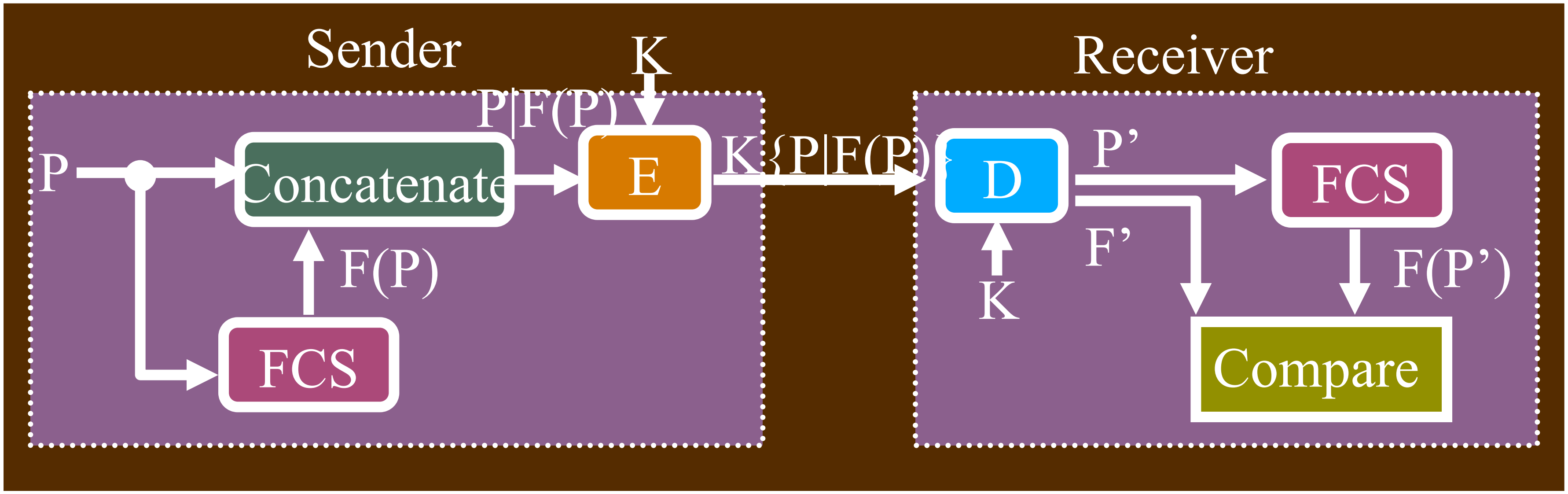
  - authenticity (MACs)
- Can we get both at the same time with one cryptographic operation?

Attempt #1

1. Sender computes an error-correcting code or Frame-Check Sequence (*FCS*) F(P) of the plaintext P
2. Sender concatenates P and F(P) and encrypts
   - i.e., C = E_K(P | 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 #1… (Cont'd)

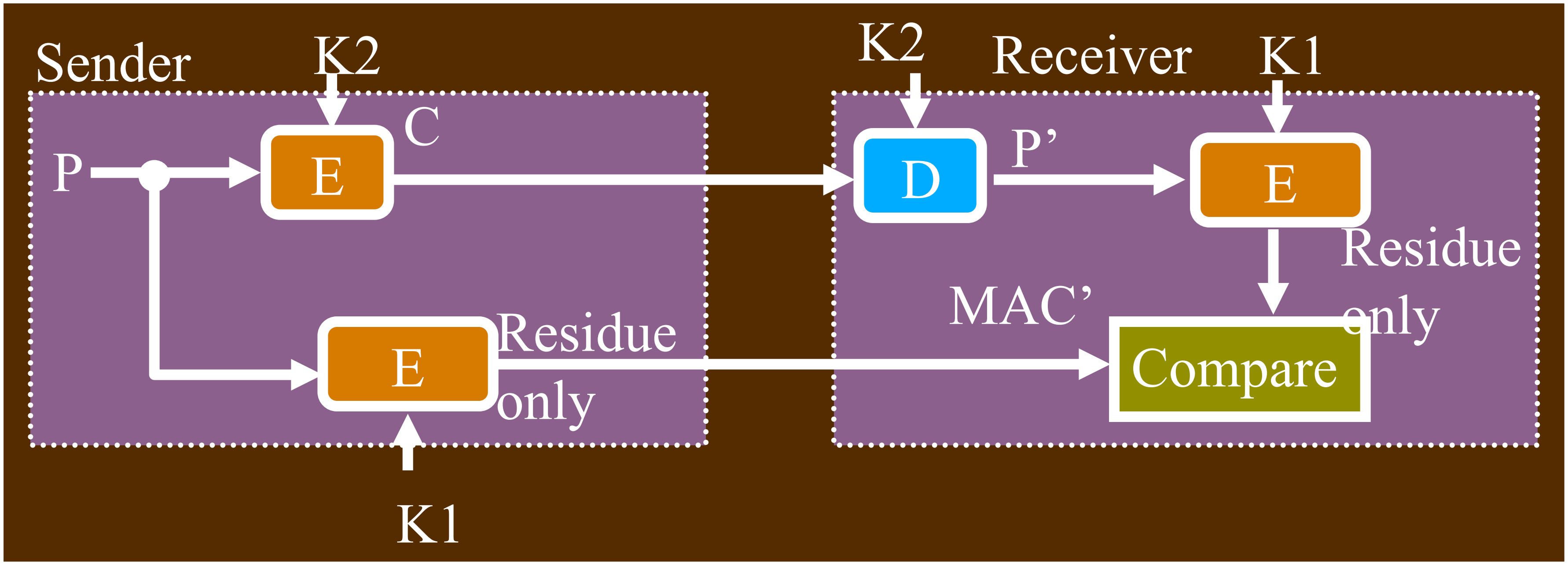


- The order (1) FCS, then (2) encryption is critical
  - why not (2), then (1)?
- "Subtle weaknesses" known in this approach, so not preferred

Attempt #2

1. Compute residue (MAC) using key K1
2. Encrypt plaintext message M using key K2 to produce C
3. Transmit MAC | C to receiver
4. Receiver decrypts received C′ with K2 to get P′
5. Receiver computes MAC(P′) using K1, compares to received MAC′

Attempt #2… (cont'd)



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

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