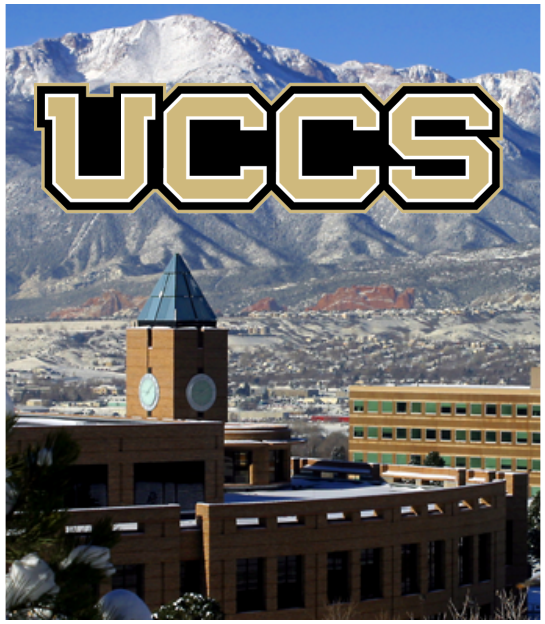


Symmetric Cryptography

Block Cipher Operation Modes

Sang-Yoon Chang, Ph.D.

Modern Cipher (vs. Classical Cipher)

Digital computer communications
based on bits

Product cipher

More sophisticated techniques

Module Objectives:

Block Cipher Operation Modes

Electronic Codebook (ECB)

Cipher Block Chaining (CBC)

Cipher Feedback (CFB)

Output Feedback (OFB)

Counter (CTR)

Block Cipher Operation Modes

Handle plaintext that can be longer than a block in a secure manner

Alice and Bob agrees on a key and a cipher (an enc./dec. function)

Variables

b: the block length

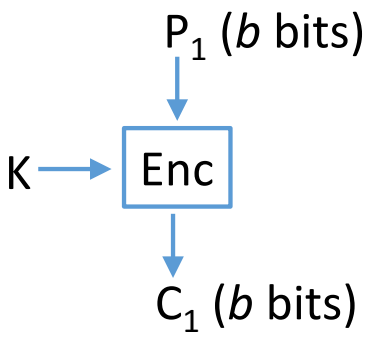
P_i: i-th plaintext block (b bits)

C_i: i-th ciphertext block (b bits)

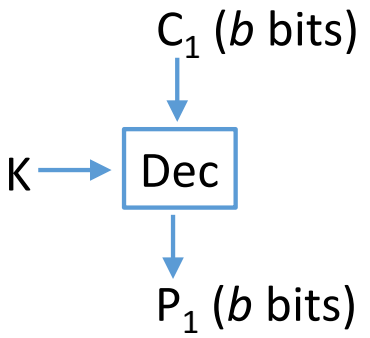
K: key

Electronic Code Book (ECB)

ECB Encryption (top) and Decryption (bottom)

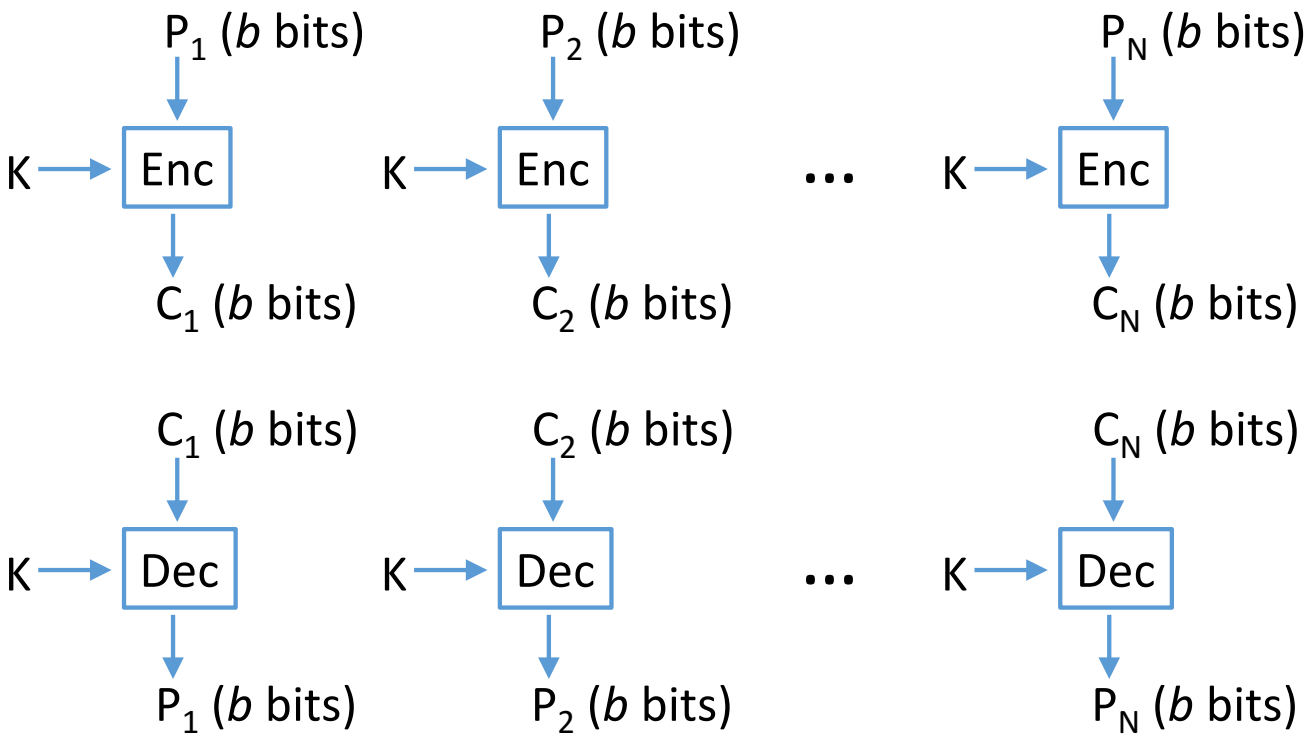


Alice



Bob

ECB Encryption (top) and Decryption (bottom)



Electronic Code Book (ECB)

A simple block cipher mode

Use the same raw key over multiple blocks

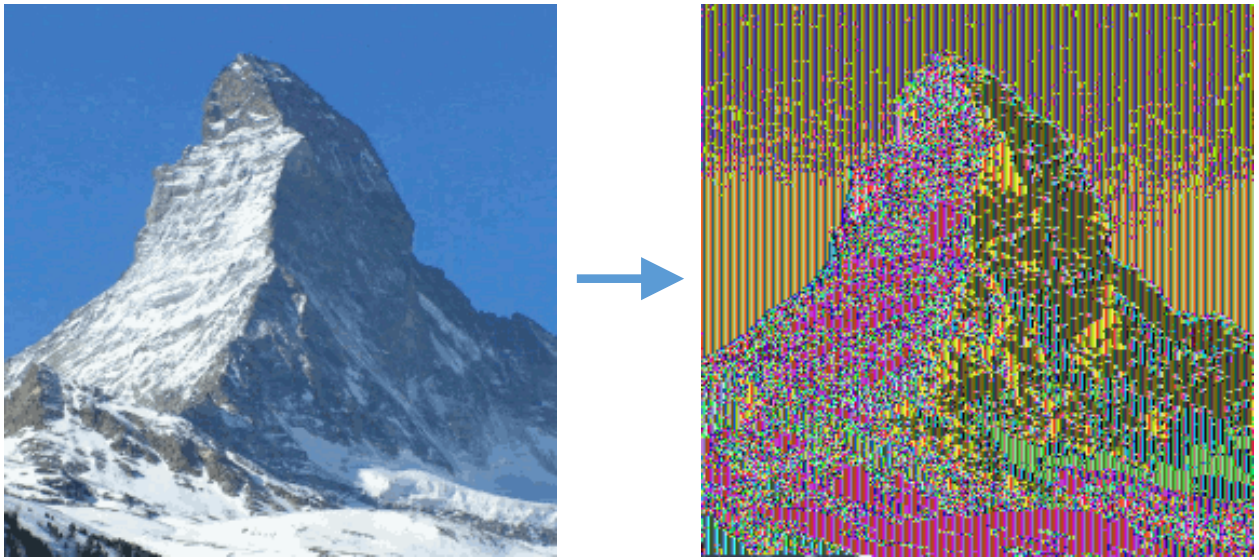
For block *i*, $C_i = Enc(K,P_i)$, $P_i = Dec(K,C_i)$

Electronic Code Book Security

Use the same raw key over multiple blocks

Redundancy/patterns in long plaintext
carries over to the ciphertext

Electronic Code Book Security



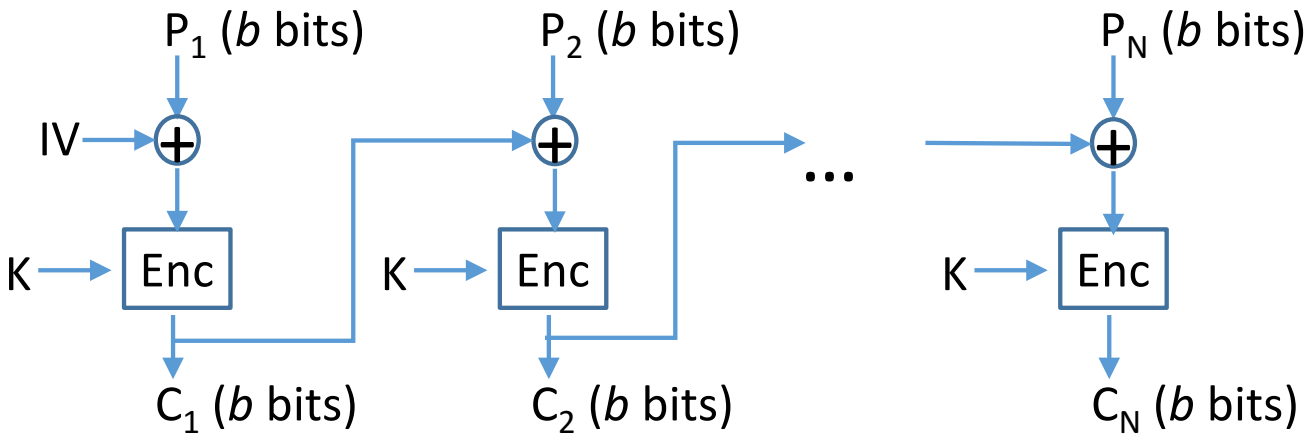
(Source: Dake from Wikimedia Commons)

Cipher Block Chaining (CBC) Mode

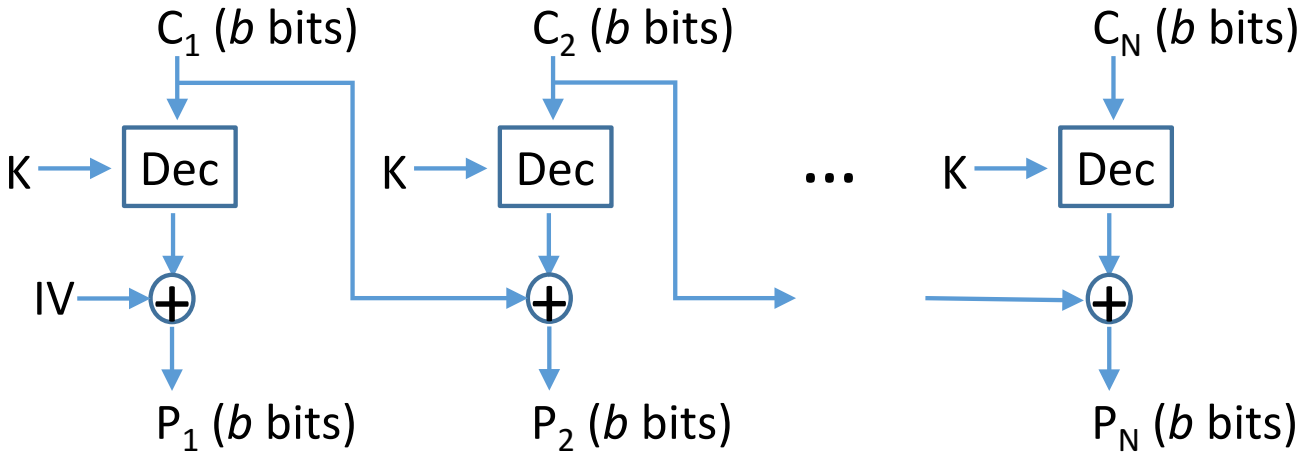
Each previous ciphertext block is chained
with the current plaintext block

Applicable when all data is already available

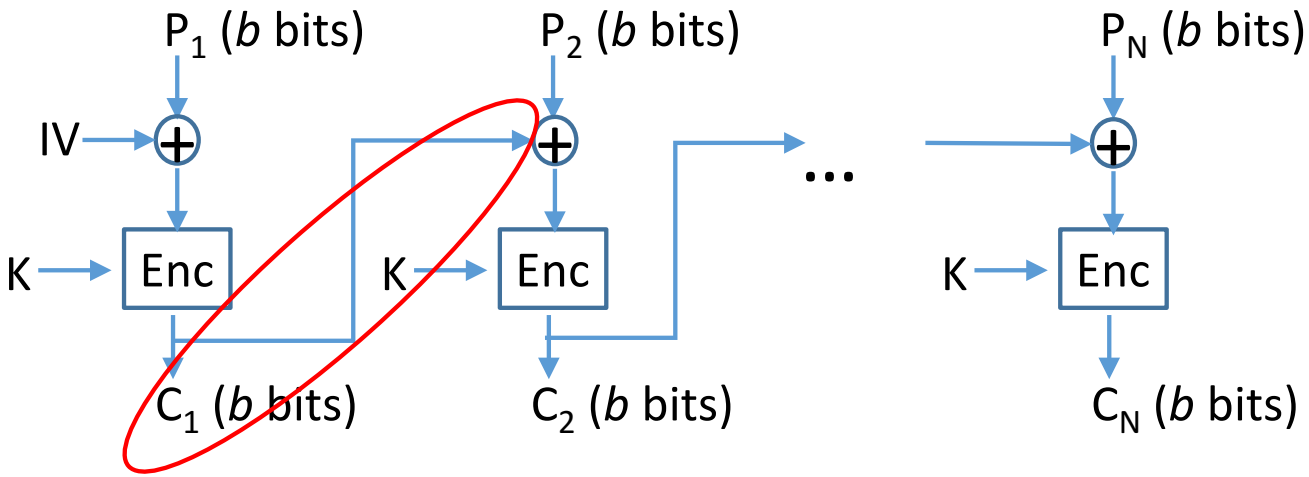
For block *i*,
Encryption: $C_i = Enc(K, [C_{i-1} \oplus P_i])$
Decryption: $P_i = Dec(K, C_i) \oplus C_{i-1}$



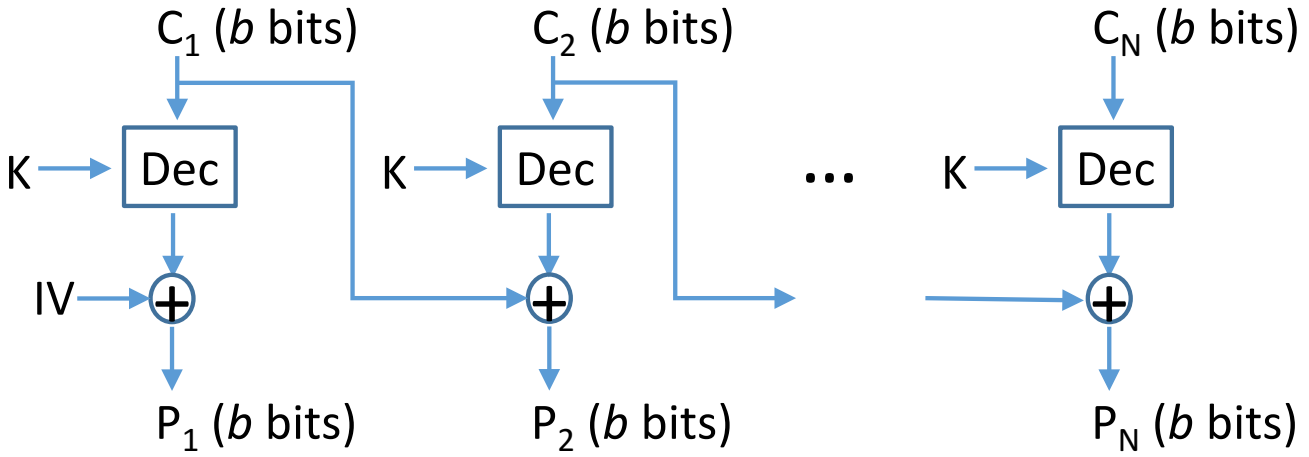
CBC Encryption



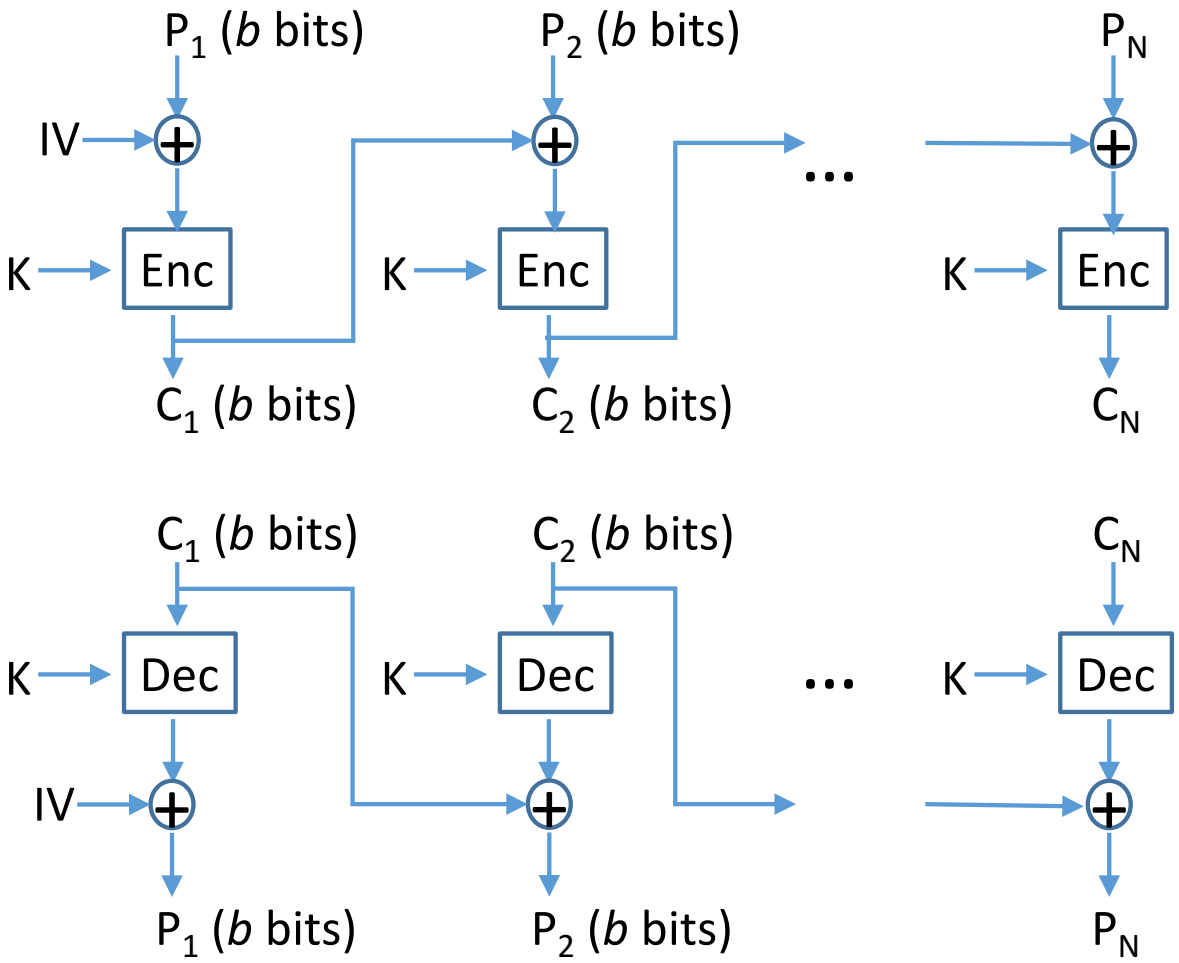
CBC Decryption



CBC Encryption



CBC Decryption



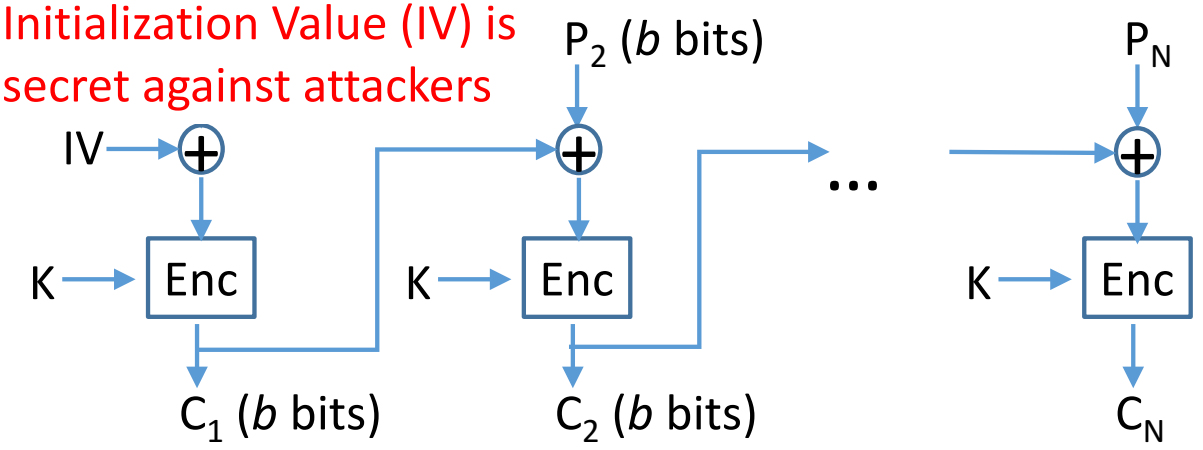
CBC Encryption

$C_i = Enc(K, [C_{i-1} \oplus P_i])$

CBC Decryption

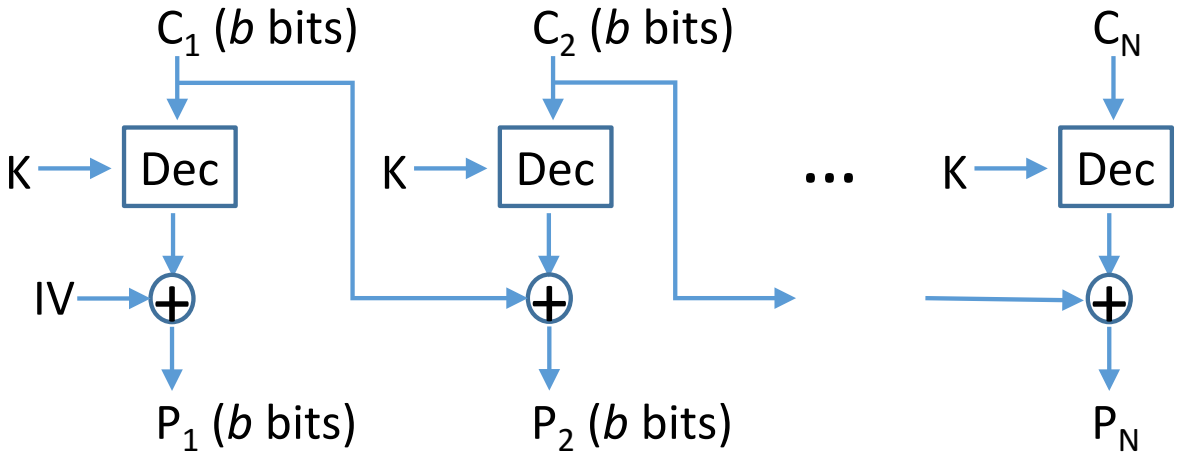
$P_i = Dec(K, C_i) \oplus C_{i-1}$

Initialization Value (IV) is secret against attackers



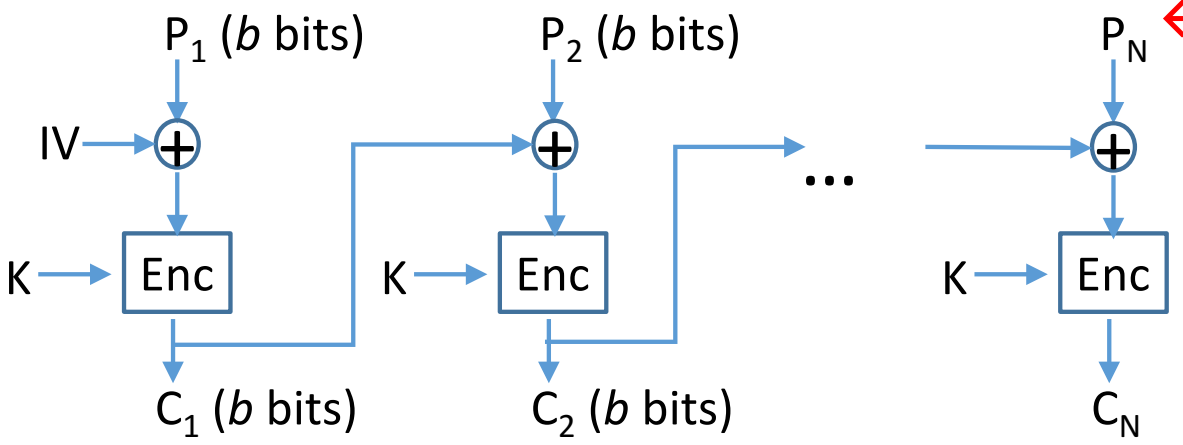
CBC Encryption

$C_i = Enc(K, [C_{i-1} \oplus P_i])$



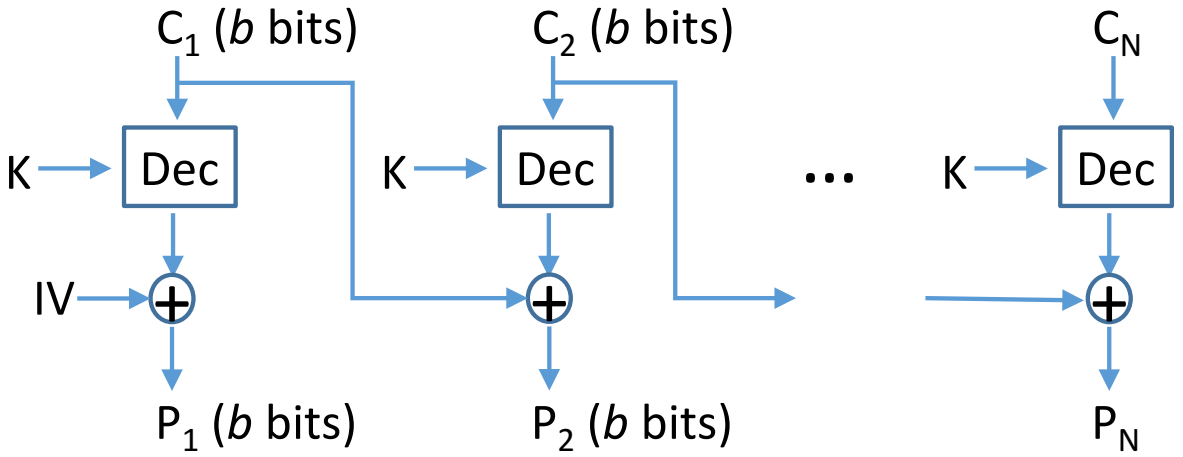
CBC Decryption

$P_i = Dec(K, C_i) \oplus C_{i-1}$



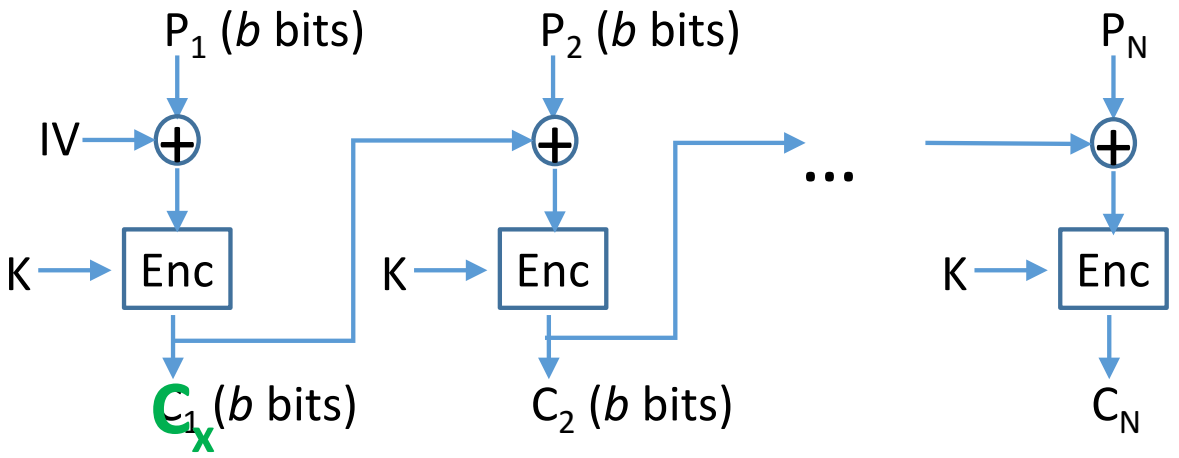
CBC Encryption

$C_i = Enc(K, [C_{i-1} \oplus P_i])$



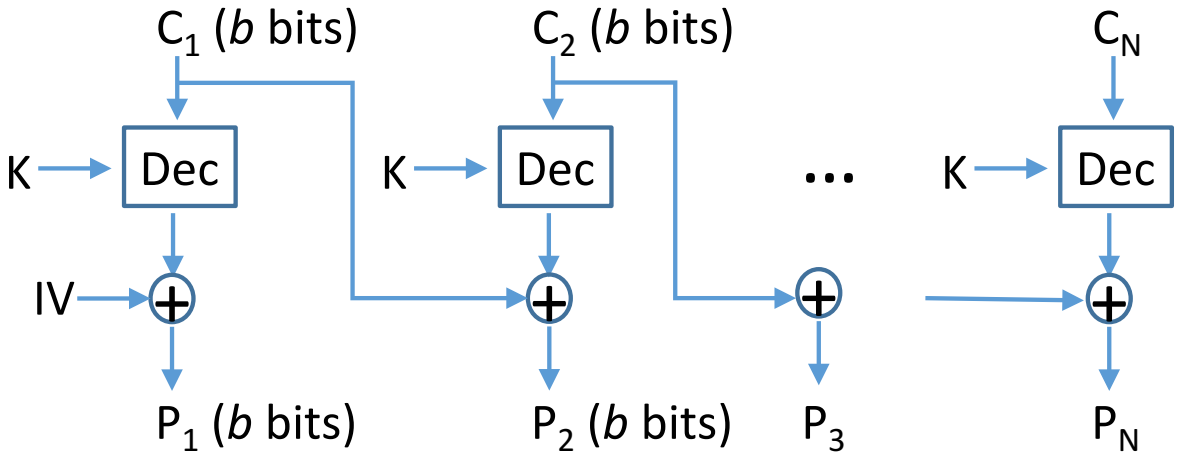
CBC Decryption

$P_i = Dec(K, C_i) \oplus C_{i-1}$



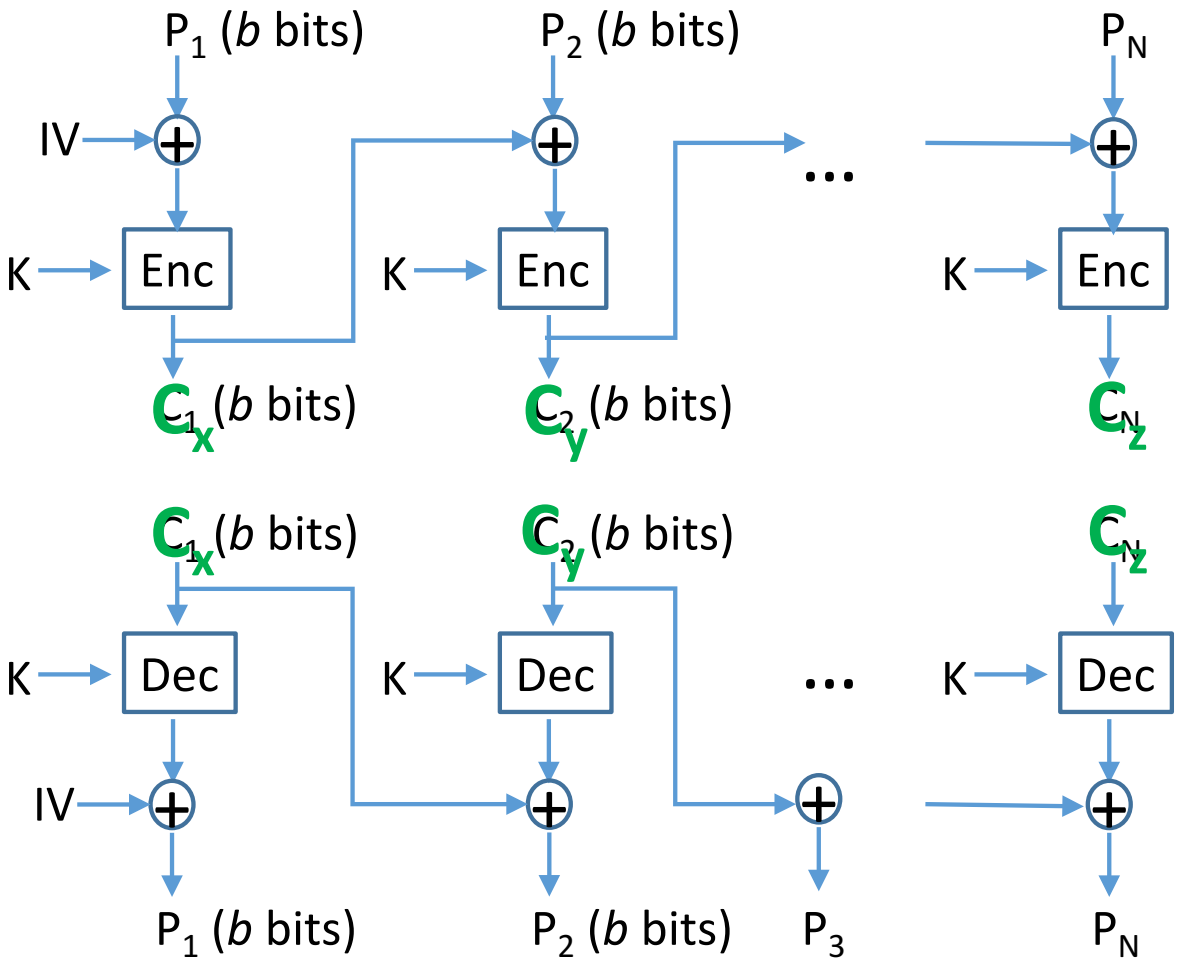
CBC Encryption

$C_i = Enc(K, [C_{i-1} \oplus P_i])$



CBC Decryption

$P_i = Dec(K, C_i) \oplus C_{i-1}$



CBC Encryption

$C_i = Enc(K, [C_{i-1} \oplus P_i])$

CBC Decryption

$P_i = Dec(K, C_i) \oplus C_{i-1}$

Stream Modes of Operation for Block Cipher

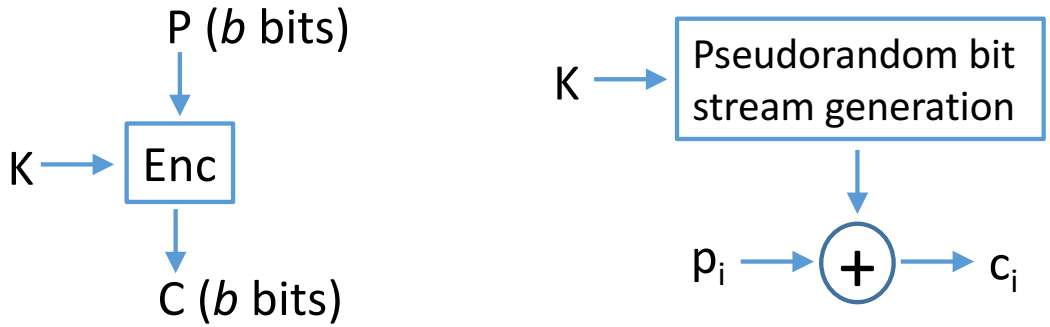
Cipher feedback (CFB) mode

Output feedback (OFB) mode

Counter (CTR) mode

Block Cipher vs. Stream Cipher

Block cipher (left) processes in blocks (multiple bits) while stream cipher (right) processes them a bit/byte at a time



Stream Modes of Operation for Block Cipher

Block cipher for pseudo-random generator

XOR the data (enables smaller unit)

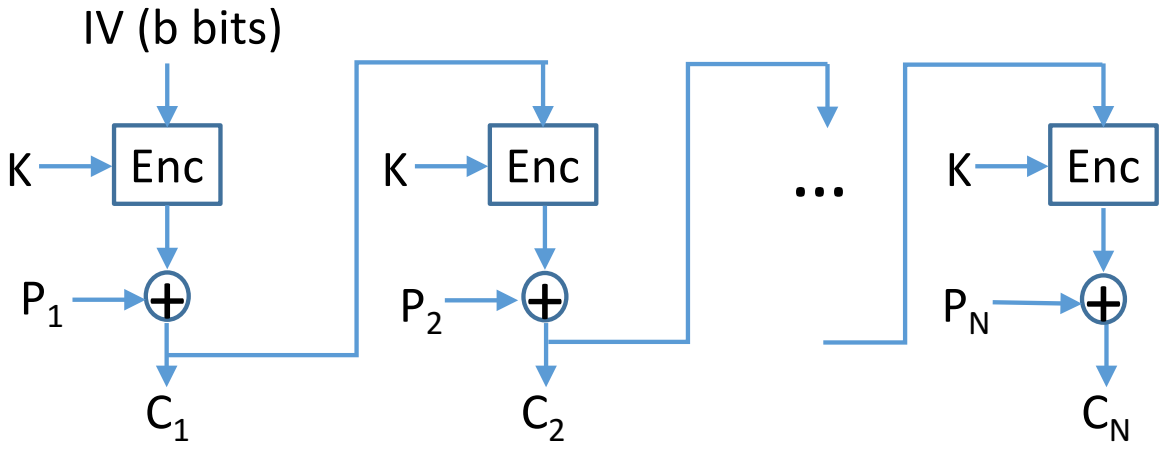
CFB mode, OFB mode, and CTR mode

Cipher Feedback (CFB) Mode

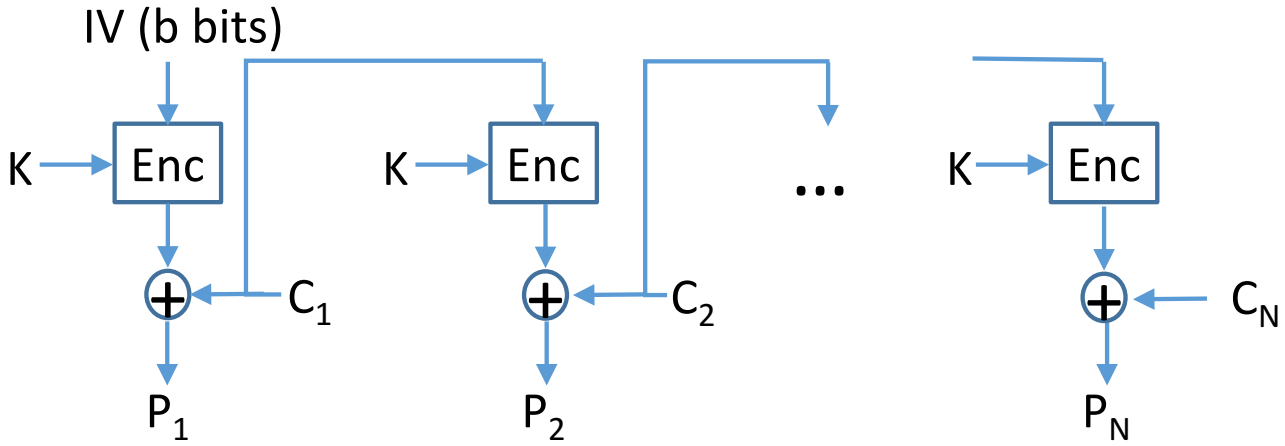
Use key to generate pseudo-random bits

Ciphertext is fed to the pseudo-random generator

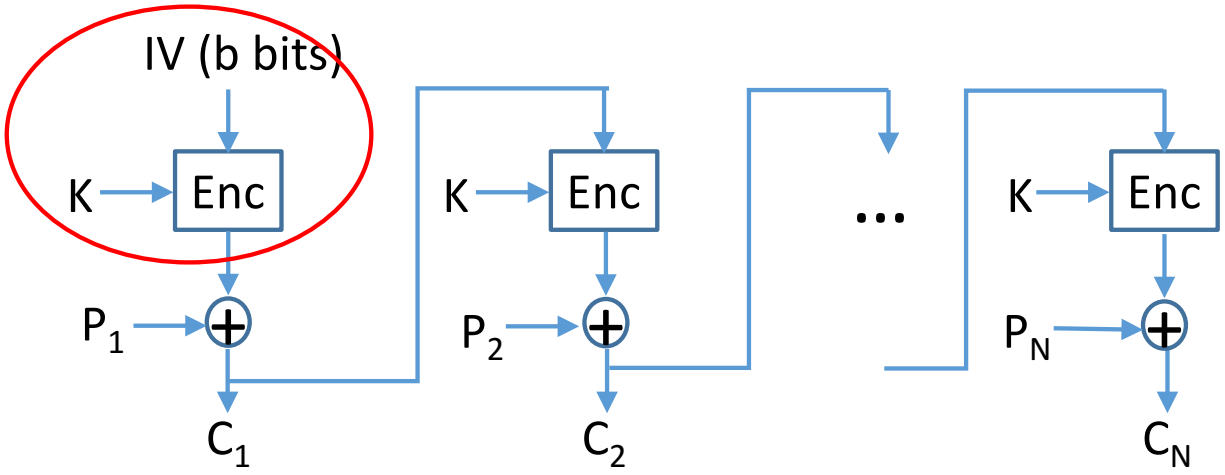
Encryption: $C_i = P_i \oplus Enc(K, C_{i-1}))$
Decryption: $P_i = C_i \oplus Enc(K, C_{i-1}))$



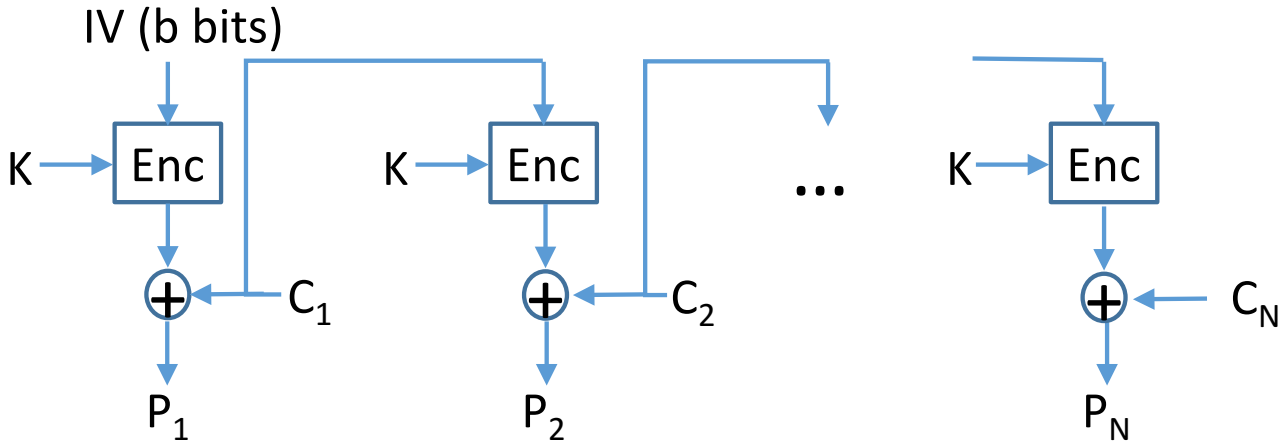
CFB Encryption



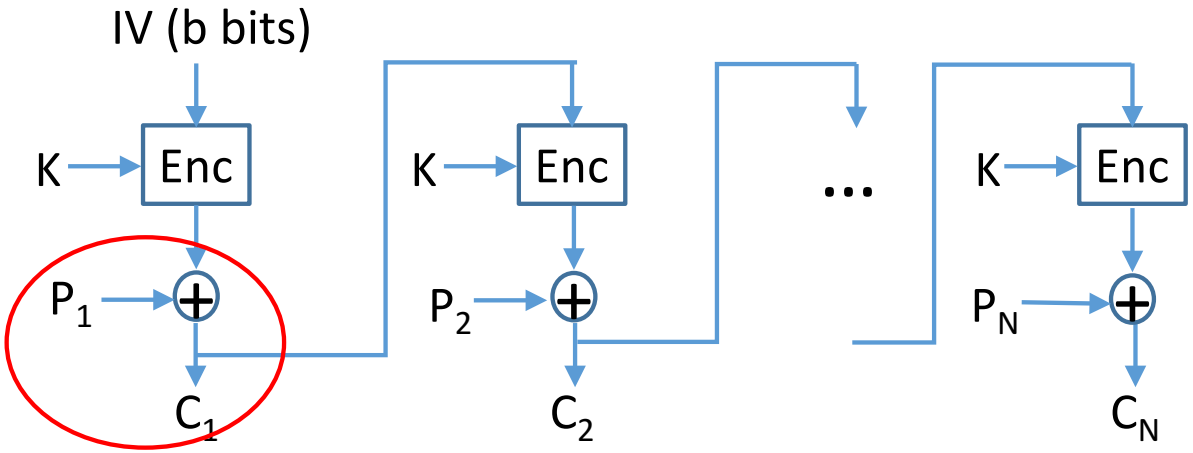
CFB Decryption



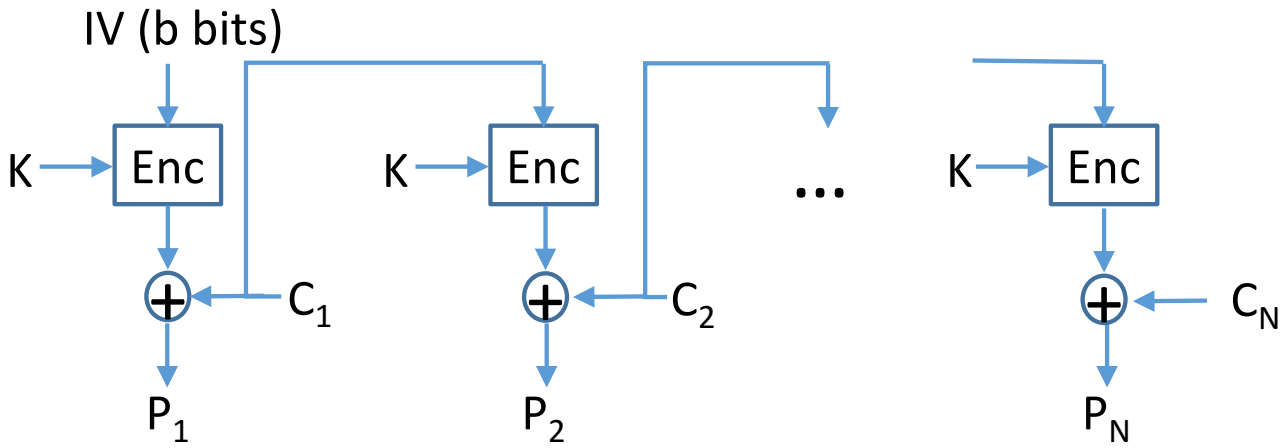
CFB Encryption



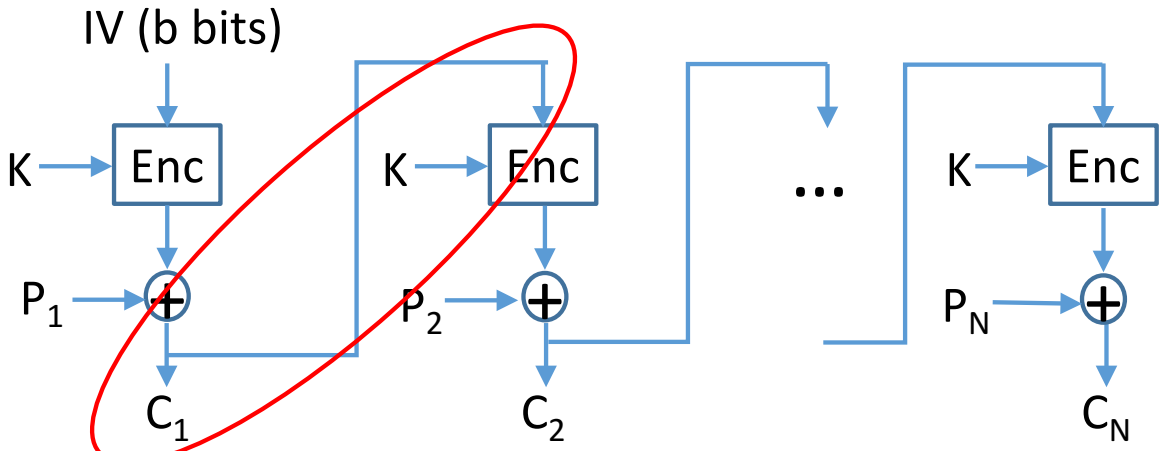
CFB Decryption



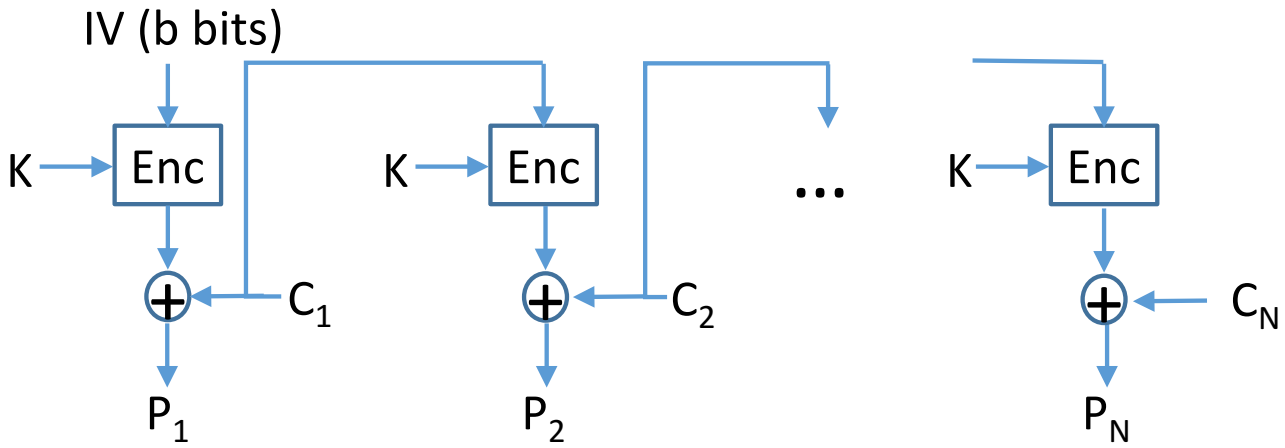
CFB Encryption



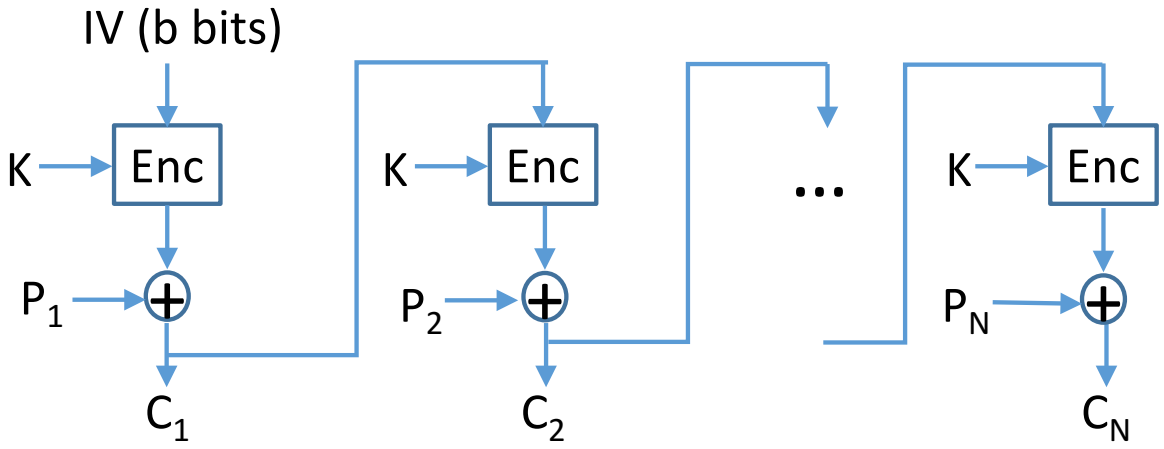
CFB Decryption



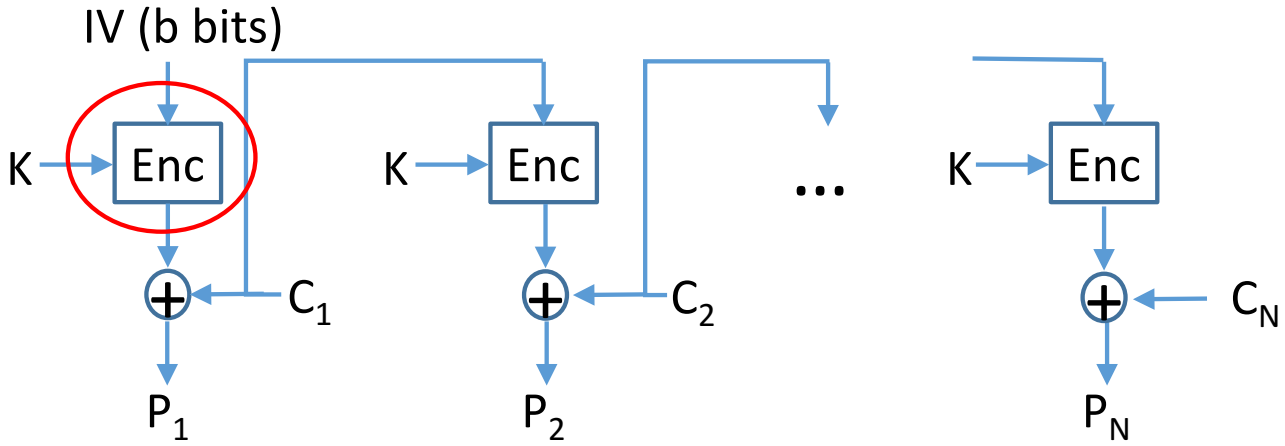
CFB Encryption



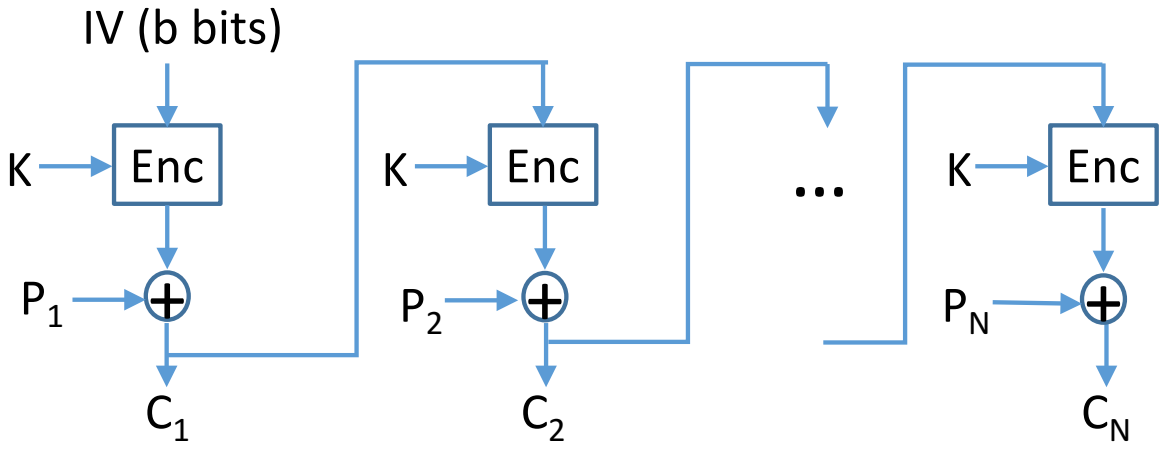
CFB Decryption



CFB Encryption

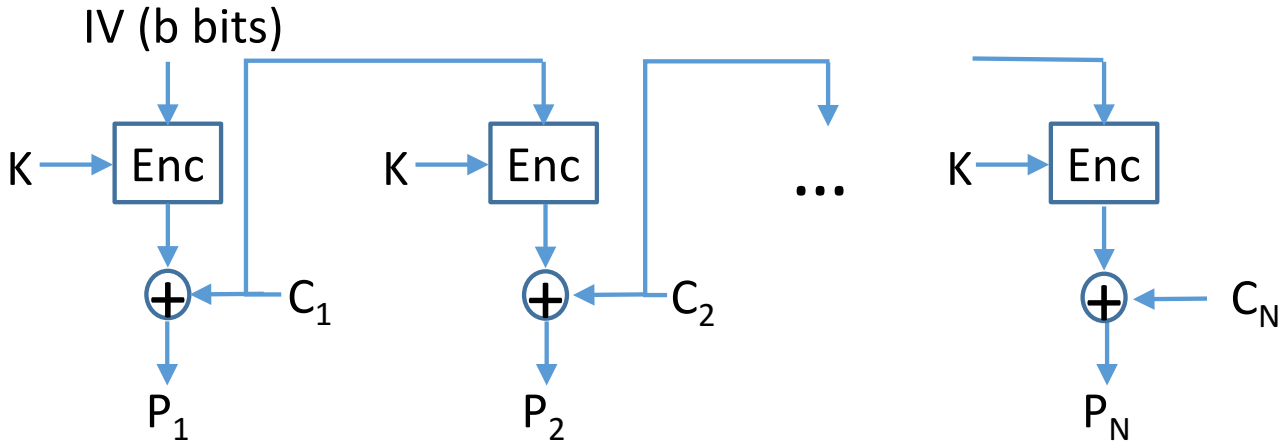


CFB Decryption



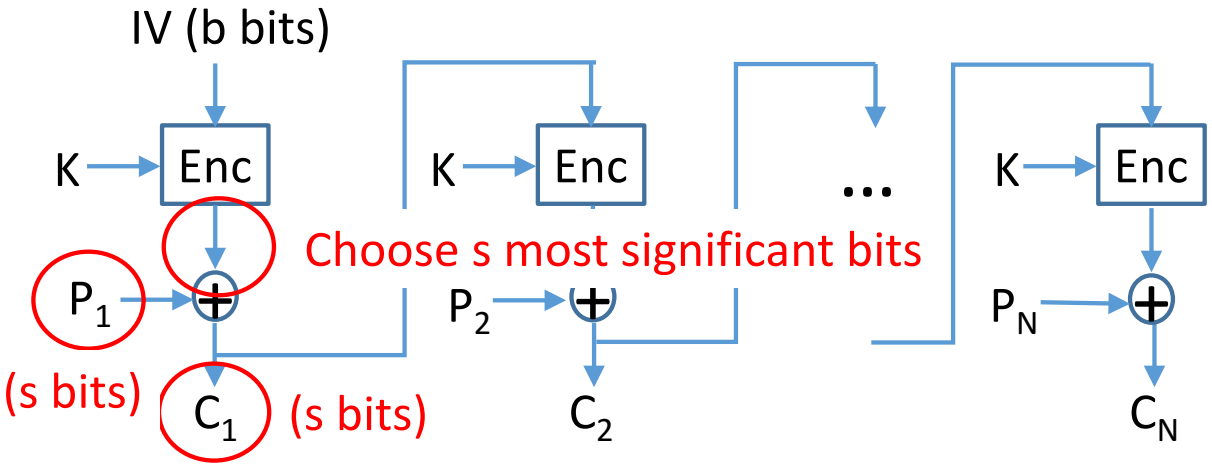
CFB Encryption

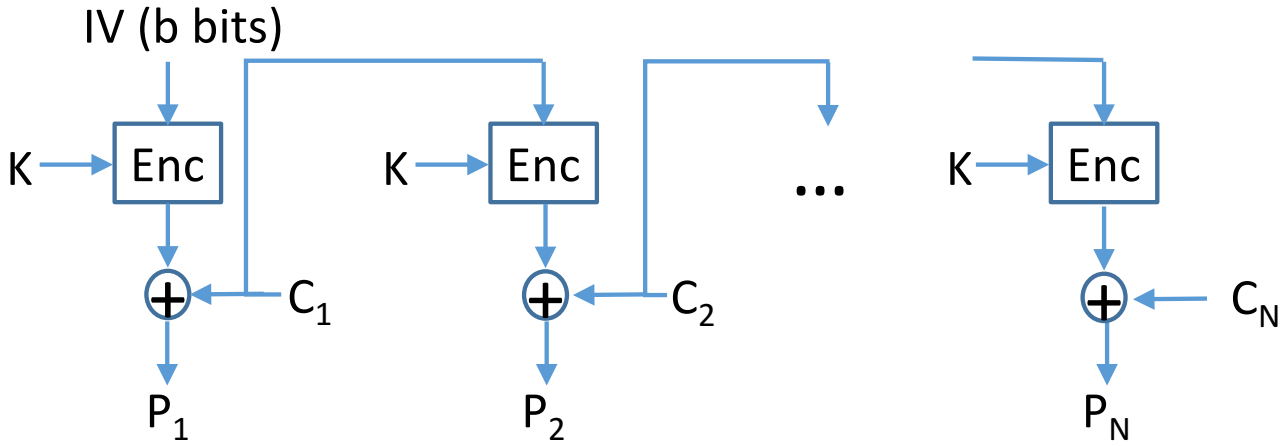
$C_i = P_i \oplus Enc(K, C_{i-1}))$



CFb Decryption

$P_i = C_i \oplus Enc(K, C_{i-1}))$





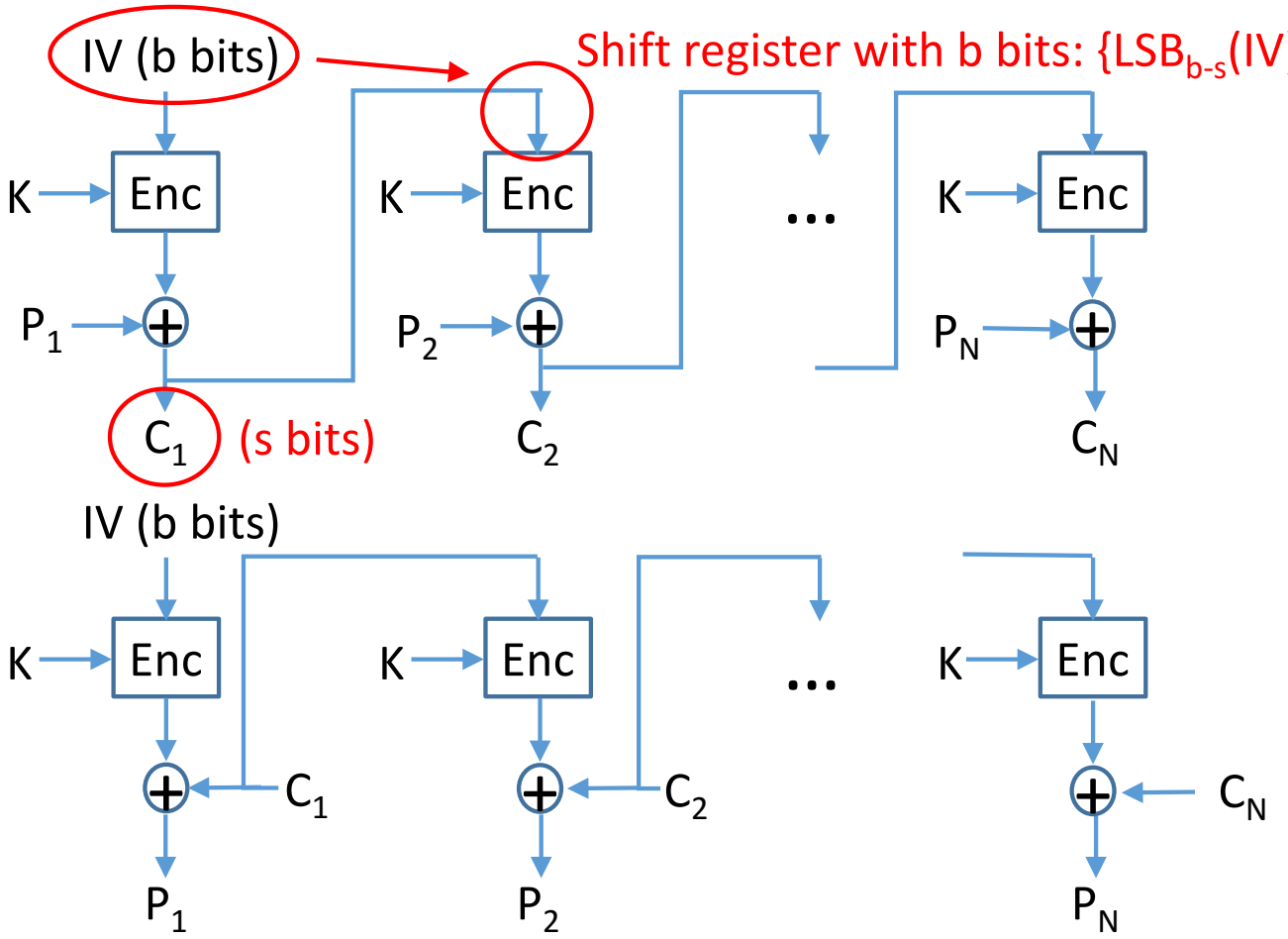
s-bit CFB mode

CFB Encryption

$C_i = P_i \oplus Enc(K, C_{i-1}))$

CFB Decryption

$P_i = C_i \oplus Enc(K, C_{i-1}))$



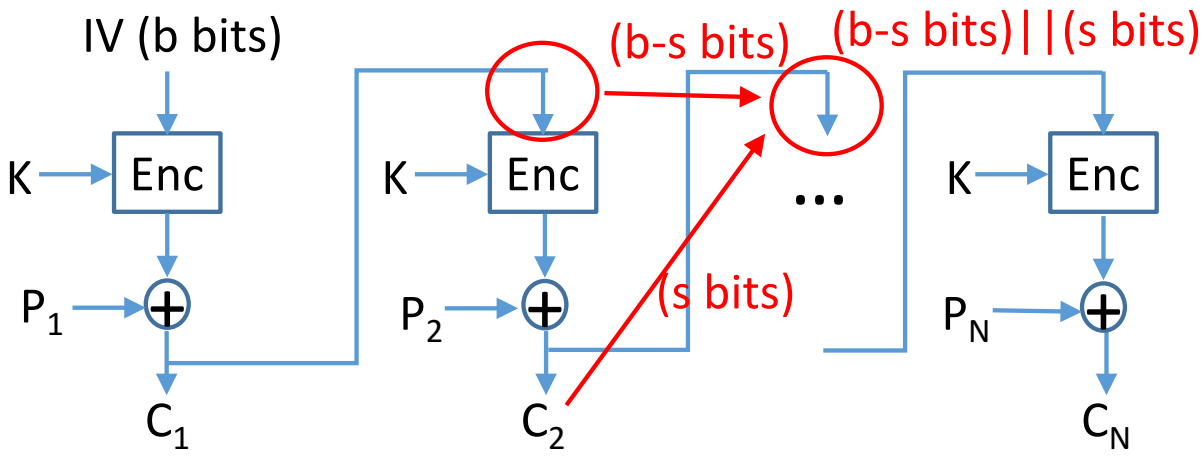
s-bit CFB mode

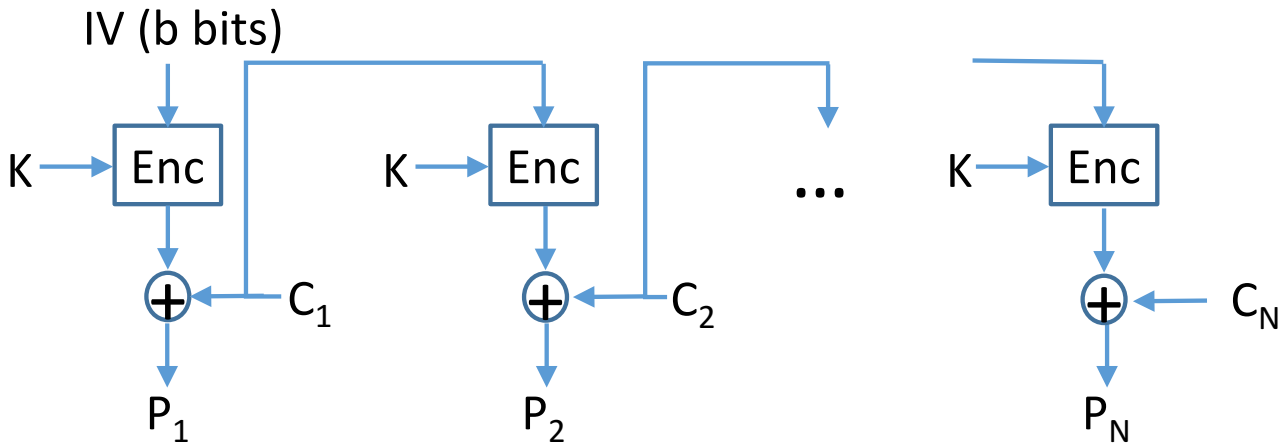
CFB Encryption

$C_i = P_i \oplus Enc(K, C_{i-1}))$

CFB Decryption

$P_i = C_i \oplus Enc(K, C_{i-1}))$





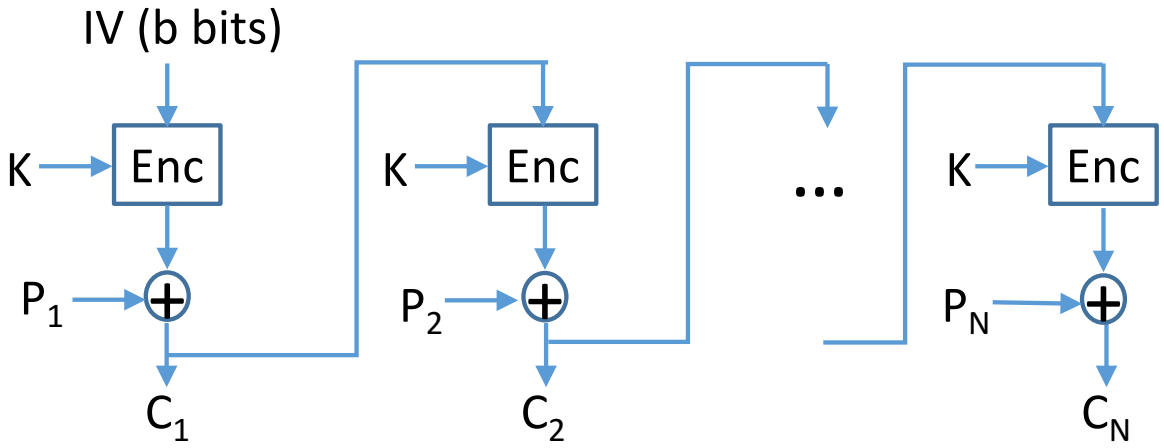
s-bit CFB mode

CFB Encryption

$C_i = P_i \oplus Enc(K, C_{i-1}))$

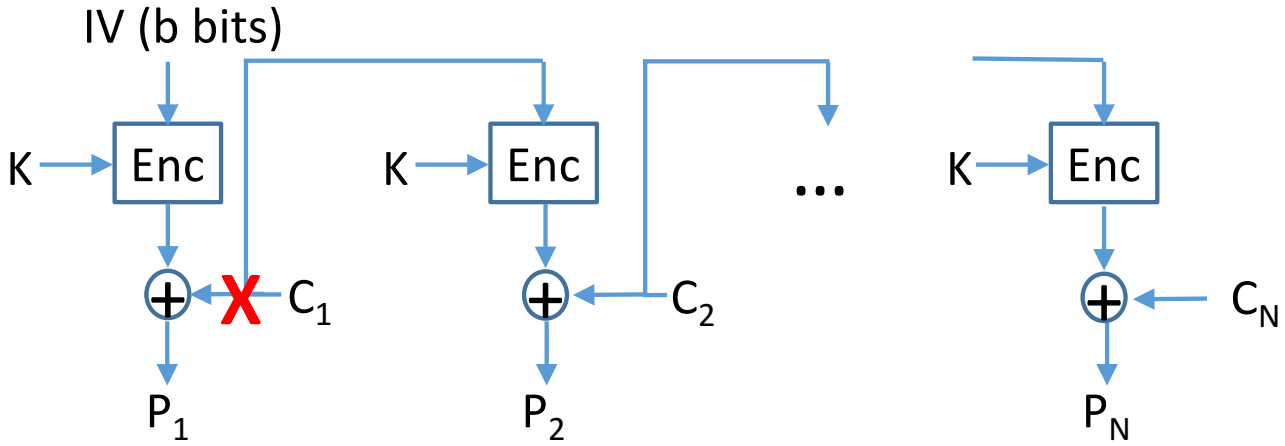
CFB Decryption

$P_i = C_i \oplus Enc(K, C_{i-1}))$



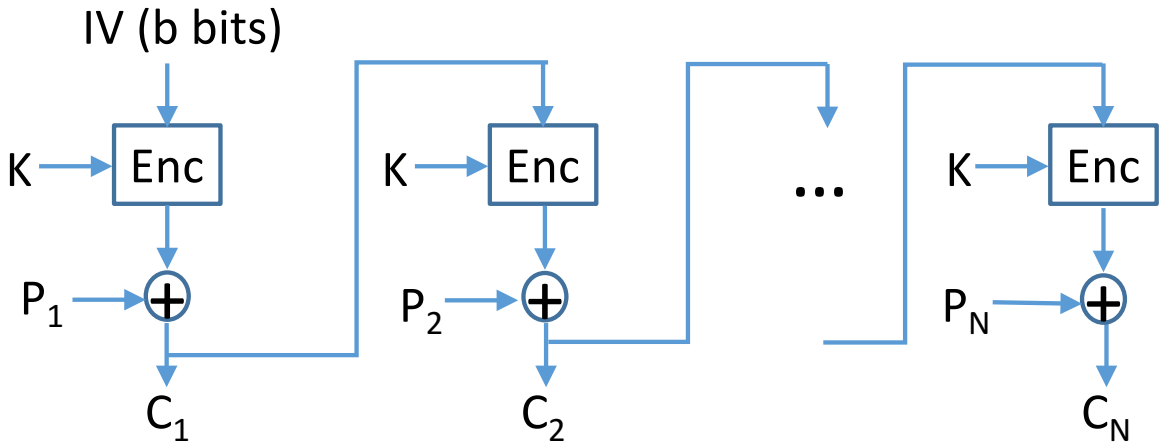
CFB Encryption

$C_i = P_i \oplus Enc(K, C_{i-1}))$



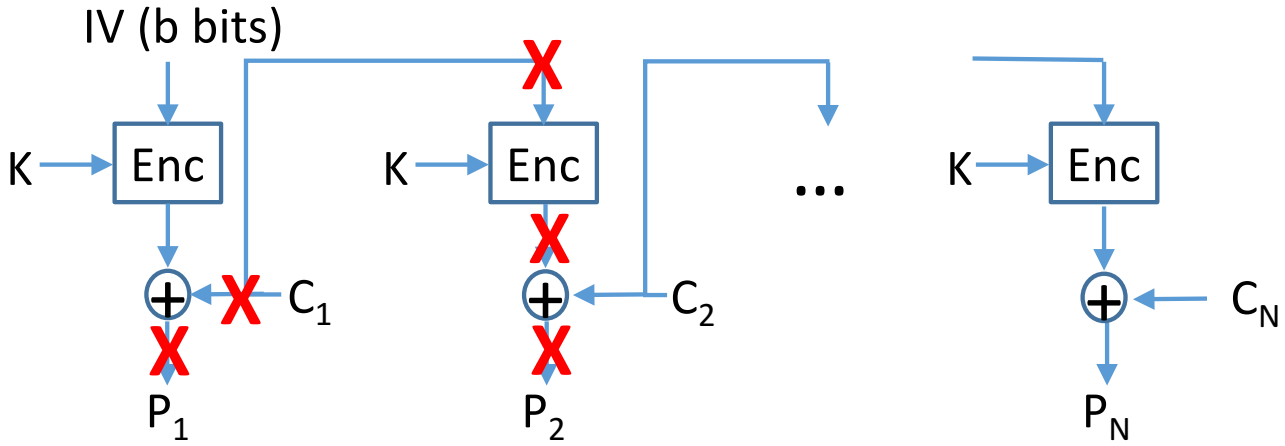
CFB Decryption

$P_i = C_i \oplus Enc(K, C_{i-1}))$



CFB Encryption

$C_i = P_i \oplus Enc(K, C_{i-1}))$



CFB Decryption

$P_i = C_i \oplus Enc(K, C_{i-1}))$

Output Feedback (OFB) Mode

Cipher function output is the feedback

Feedback is independent to P_i and C_i

Encryption: $C_i = P_i \oplus \text{Enc}(K, [C_{i-1} \oplus P_{i-1}])$

Decryption: $P_i = C_i \oplus \text{Enc}(K, [C_{i-1} \oplus P_{i-1}])$

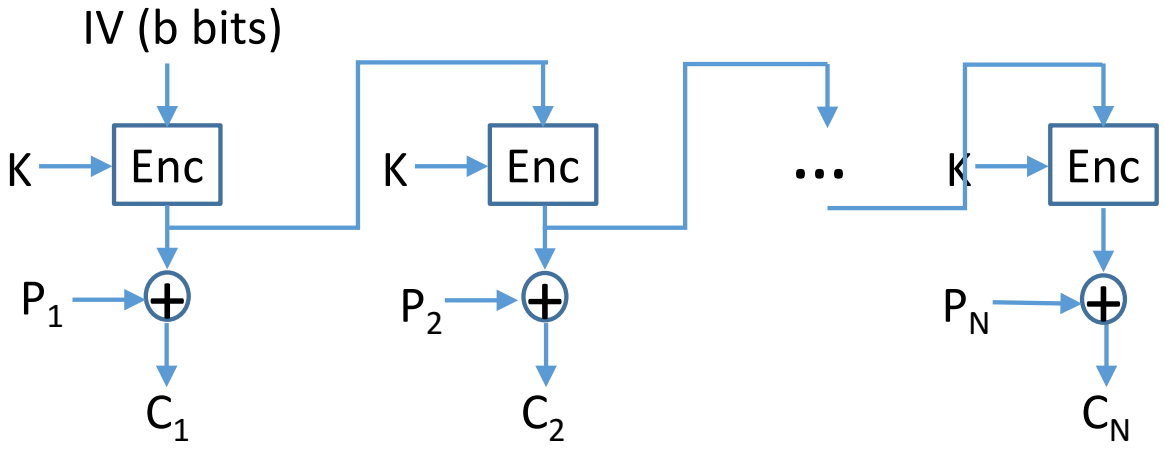
Output Feedback (OFB) Mode

Cipher function output is the feedback

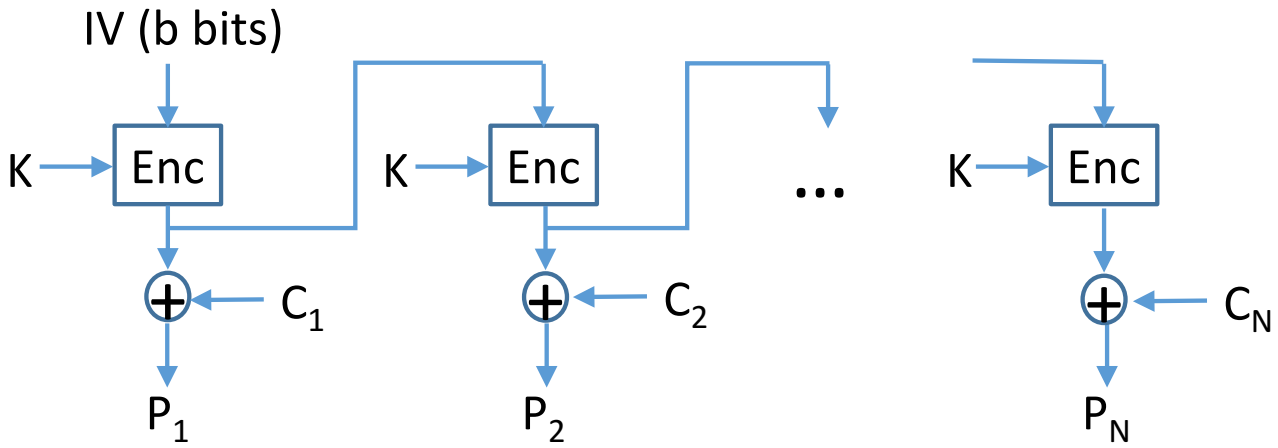
Feedback is independent to P_i and C_i

Encryption: $C_i = P_i \oplus Enc(K, [C_{i-1} \oplus P_{i-1}])$

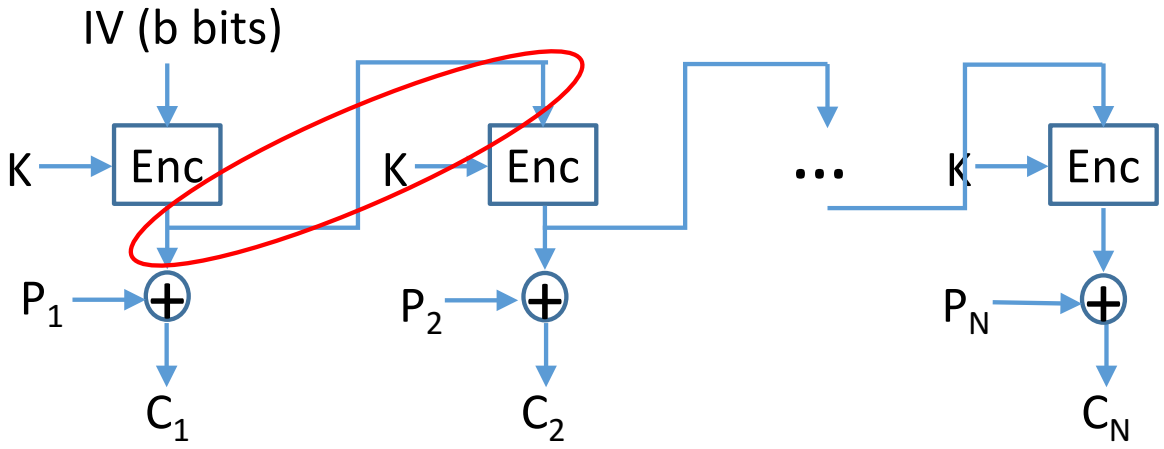
Decryption: $P_i = C_i \oplus Enc(K, [C_{i-1} \oplus P_{i-1}])$



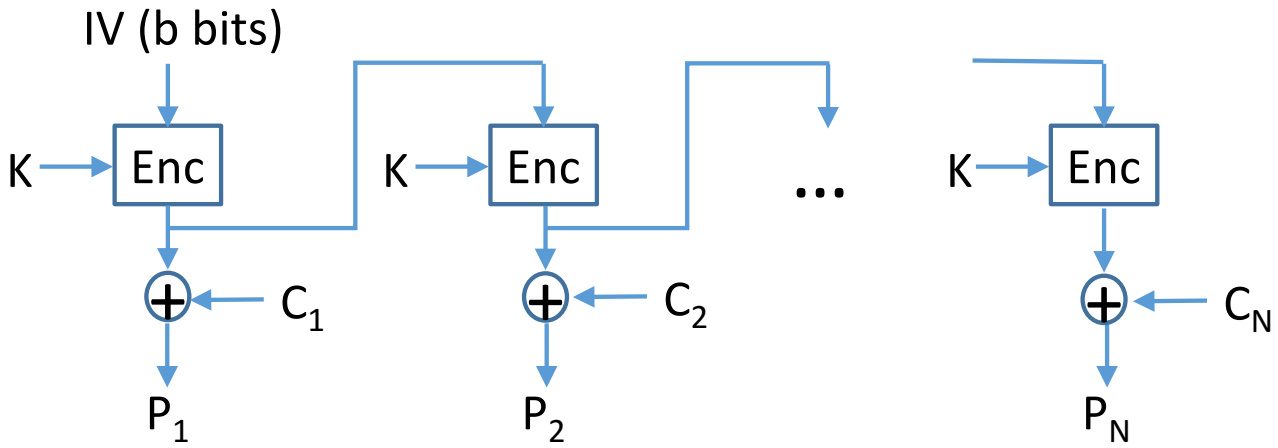
OFB Encryption



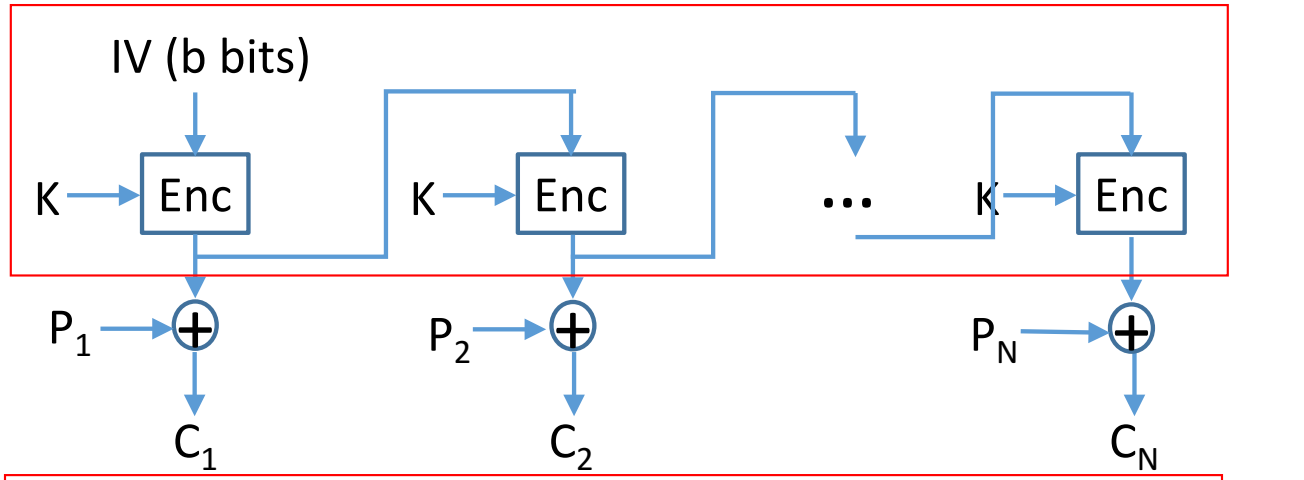
OFB Decryption



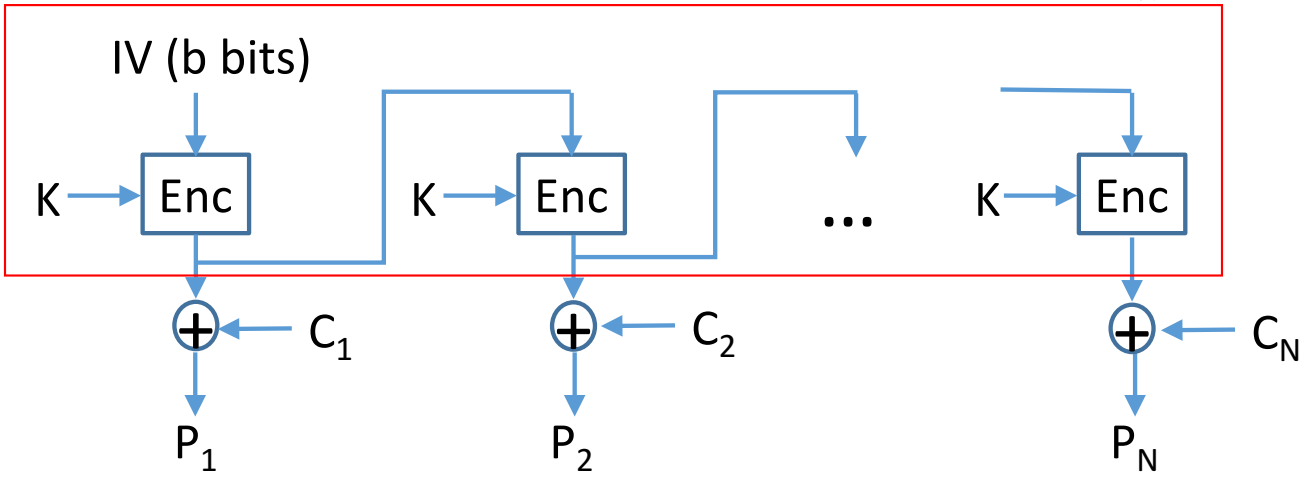
OFB Encryption



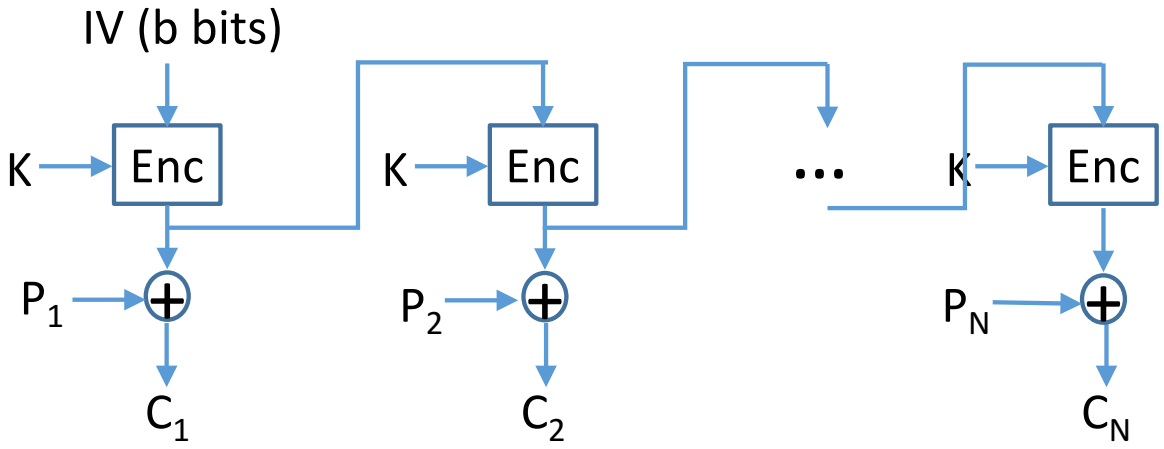
OFB Decryption



OFB Encryption

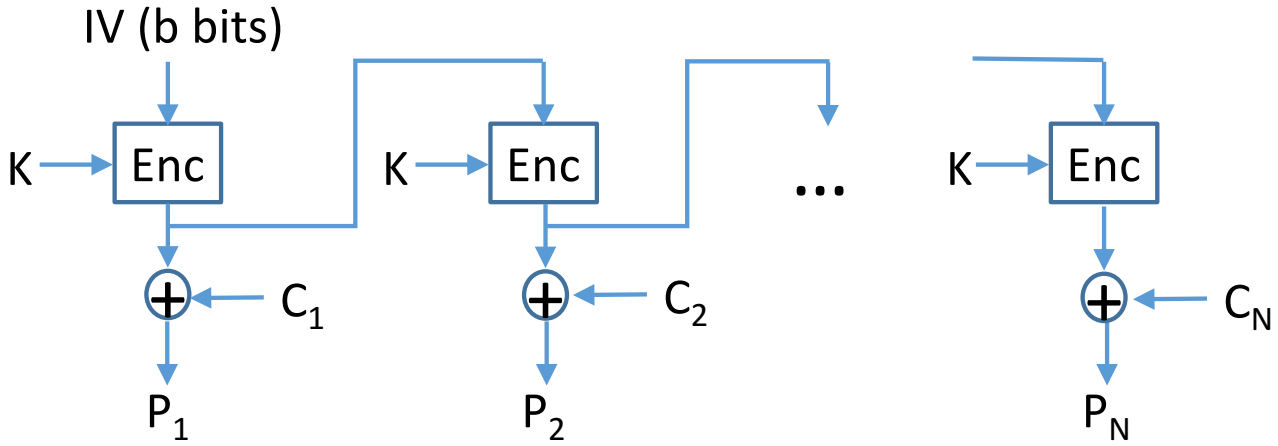


OFB Decryption



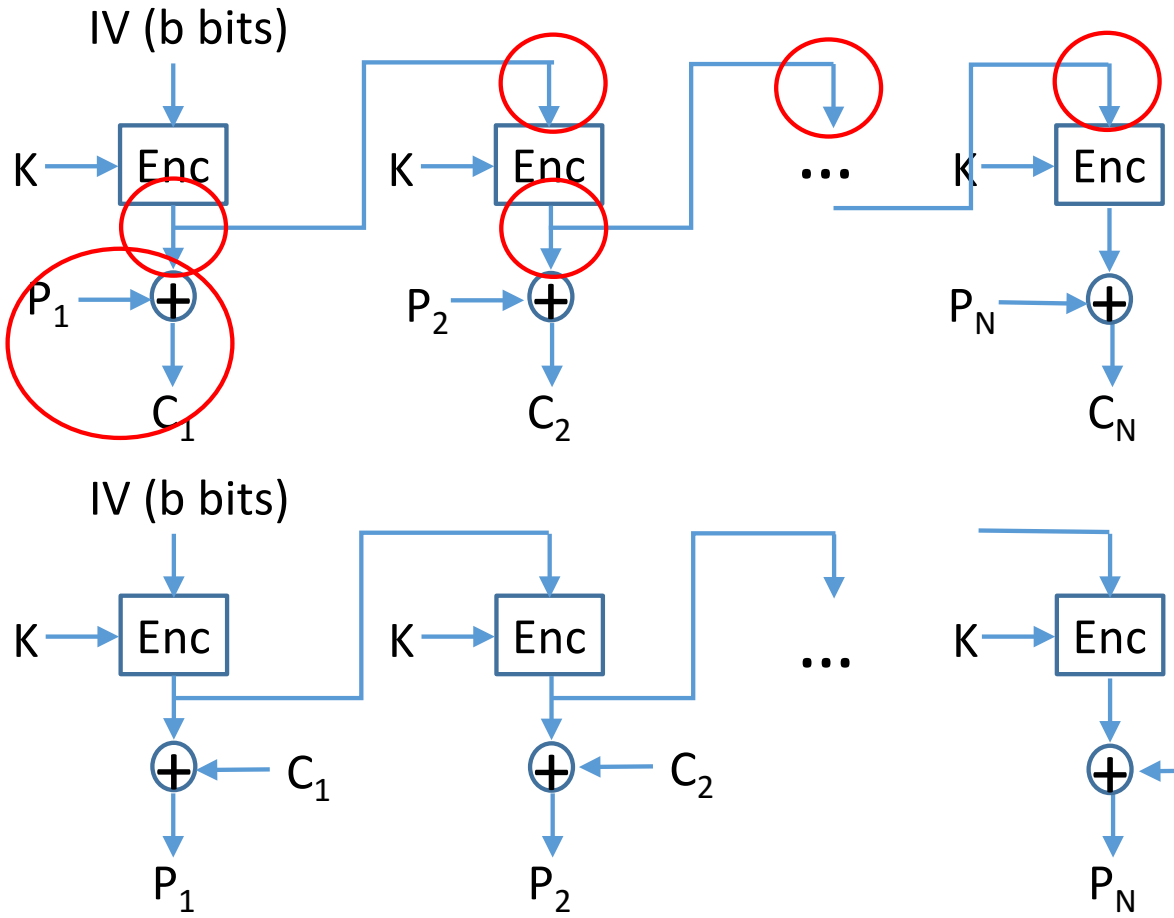
OFB Encryption

$C_i = P_i \oplus Enc(K, [C_{i-1} \oplus P_{i-1}])$



OFB Decryption

$P_i = C_i \oplus Enc(K, [C_{i-1} \oplus P_{i-1}])$



OFB Encryption

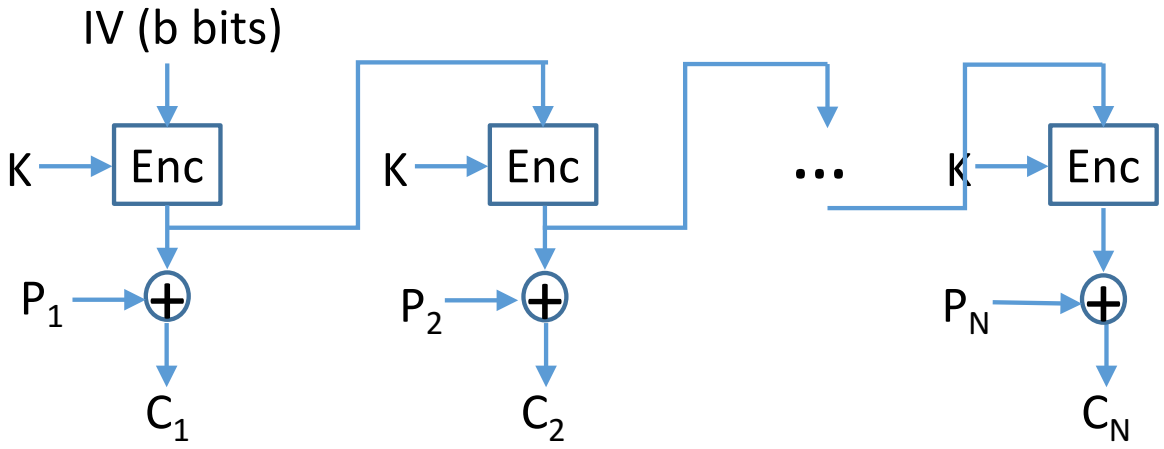
$C_i = P_i \oplus$
$\quad Enc(K, [C_{i-1} \oplus P_{i-1}])$

Because

$X \oplus Y = Z \rightarrow X = Y \oplus Z$

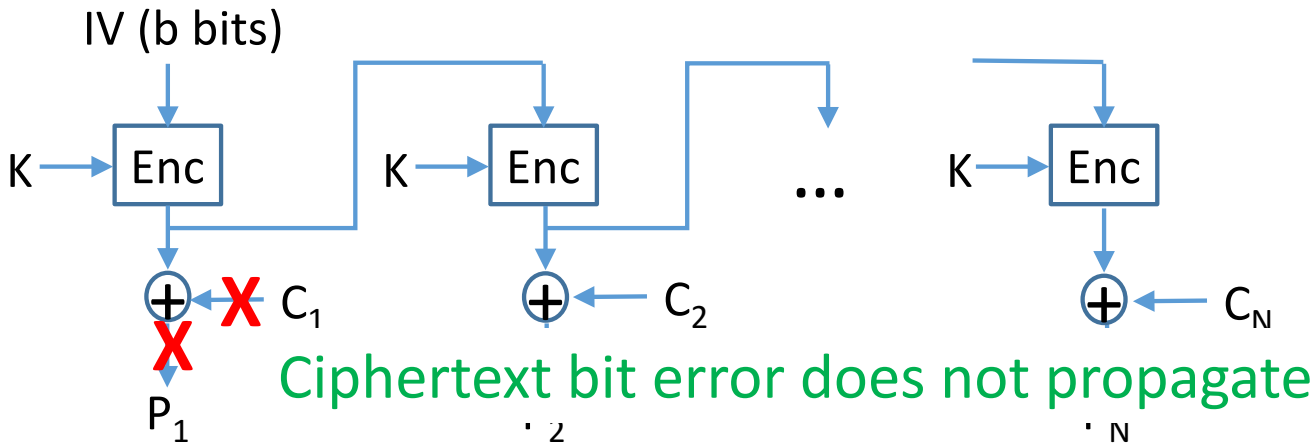
OFB Decryption

$P_i = C_i \oplus$
$\quad Enc(K, [C_{i-1} \oplus P_{i-1}])$



OFB Encryption

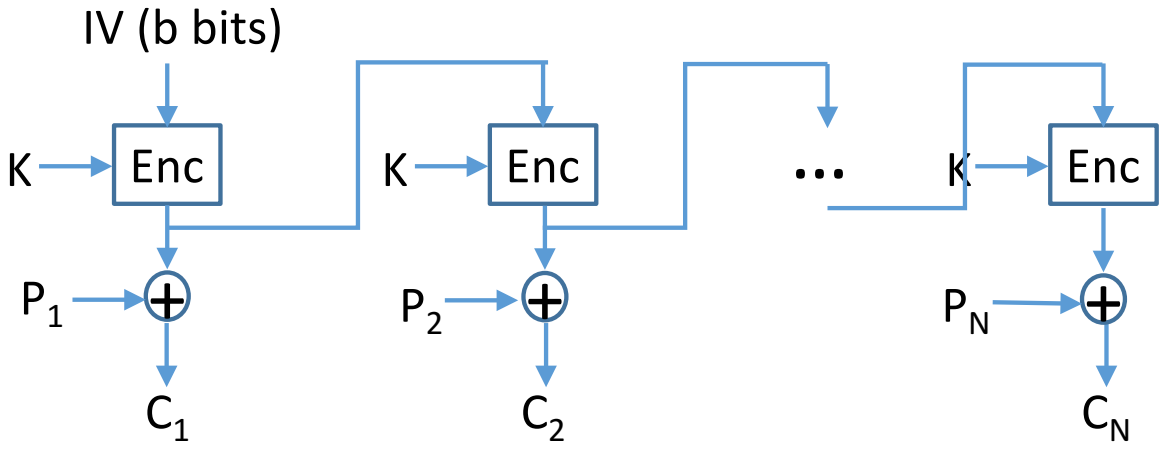
$C_i = P_i \oplus Enc(K, [C_{i-1} \oplus P_{i-1}])$



OFB Decryption

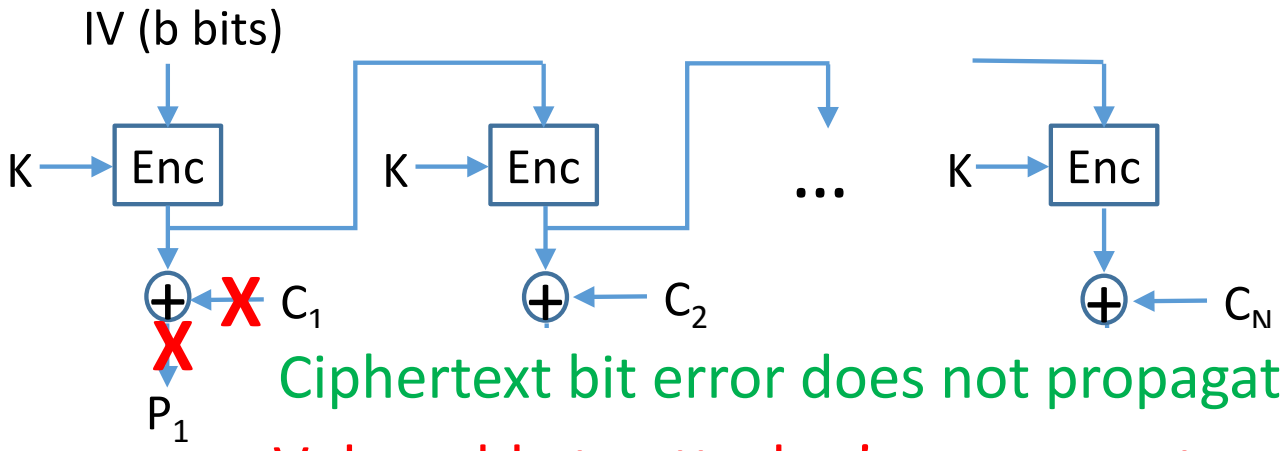
$P_i = C_i \oplus Enc(K, [C_{i-1} \oplus P_{i-1}])$

Ciphertext bit error does not propagate



OFB Encryption

$C_i = P_i \oplus Enc(K, [C_{i-1} \oplus P_{i-1}])$



OFB Decryption

$P_i = C_i \oplus Enc(K, [C_{i-1} \oplus P_{i-1}])$

Ciphertext bit error does not propagate

Vulnerable to attacker's message stream modification

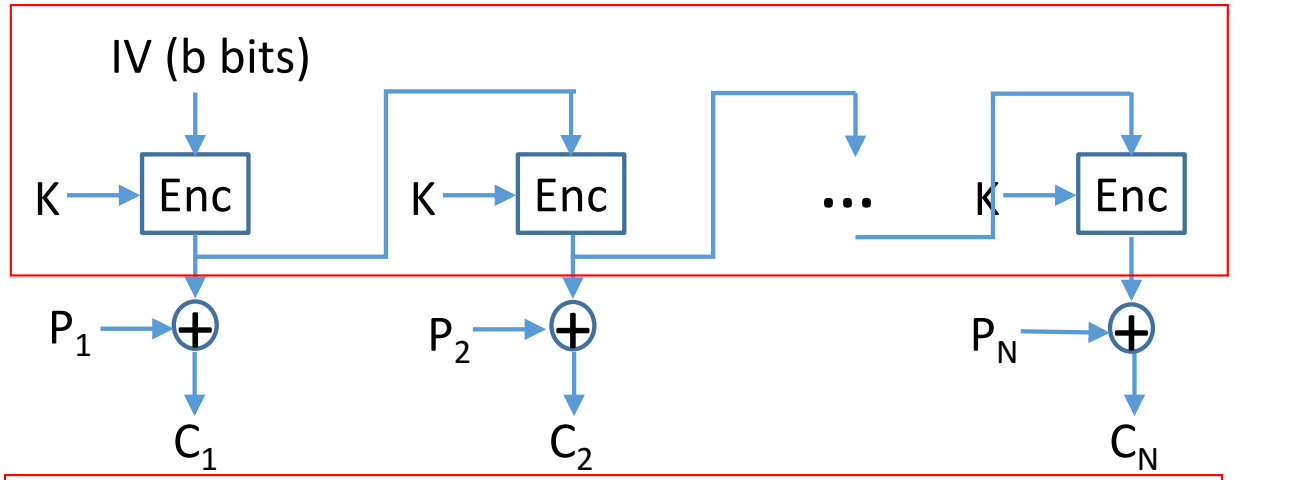
Counter (CTR) Mode

No explicit chaining/feedback

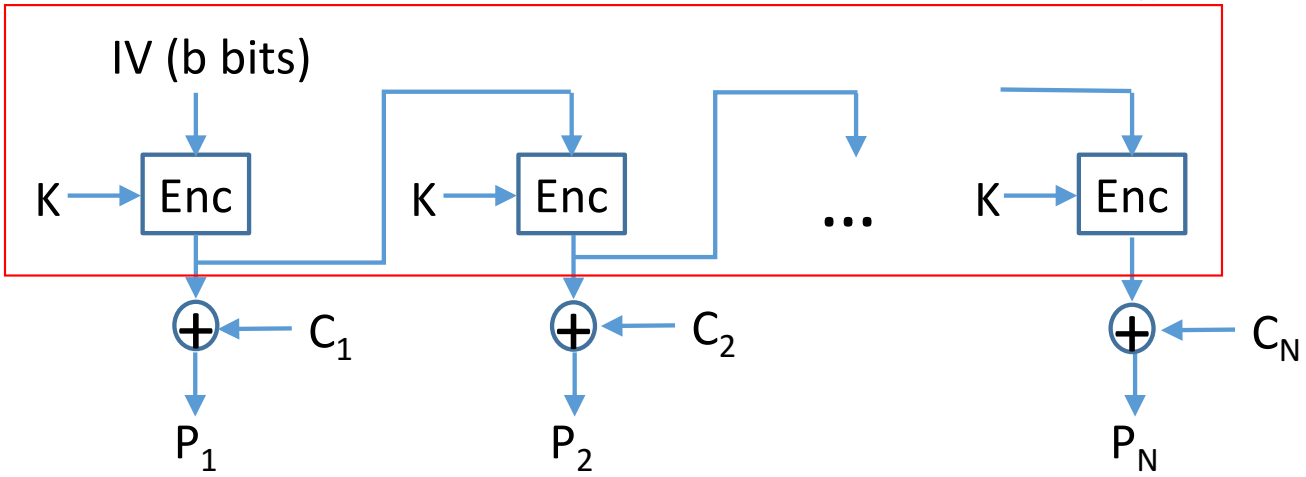
Counter for pseudo-random generation

The initial counter (T_1) must be nonce

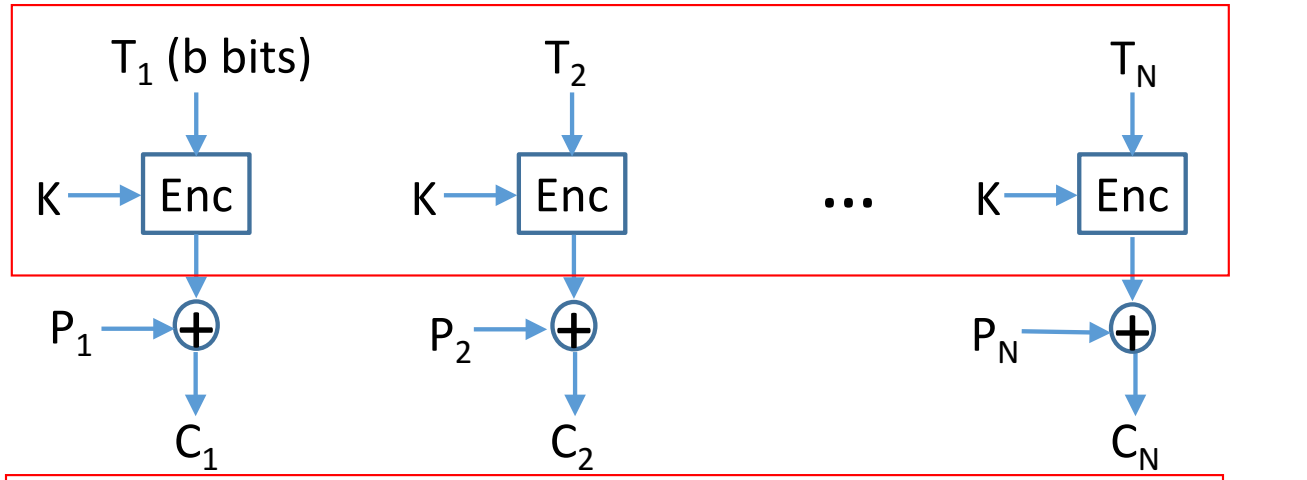
Encryption: $C_i = P_i \oplus Enc(K, T_i)$
Decryption: $P_i = C_i \oplus Enc(K, T_i)$



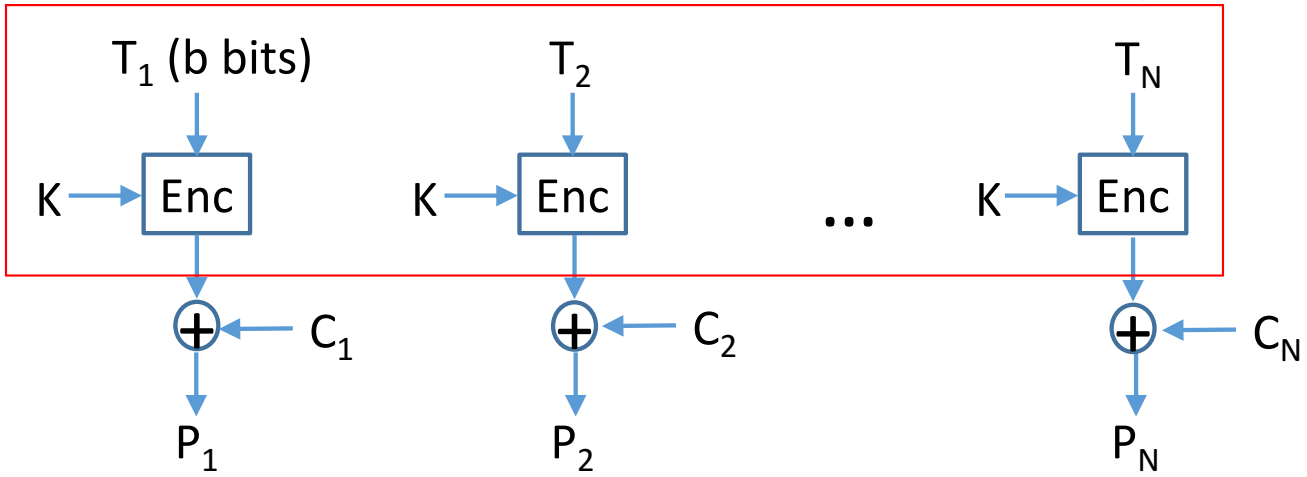
OFB Encryption



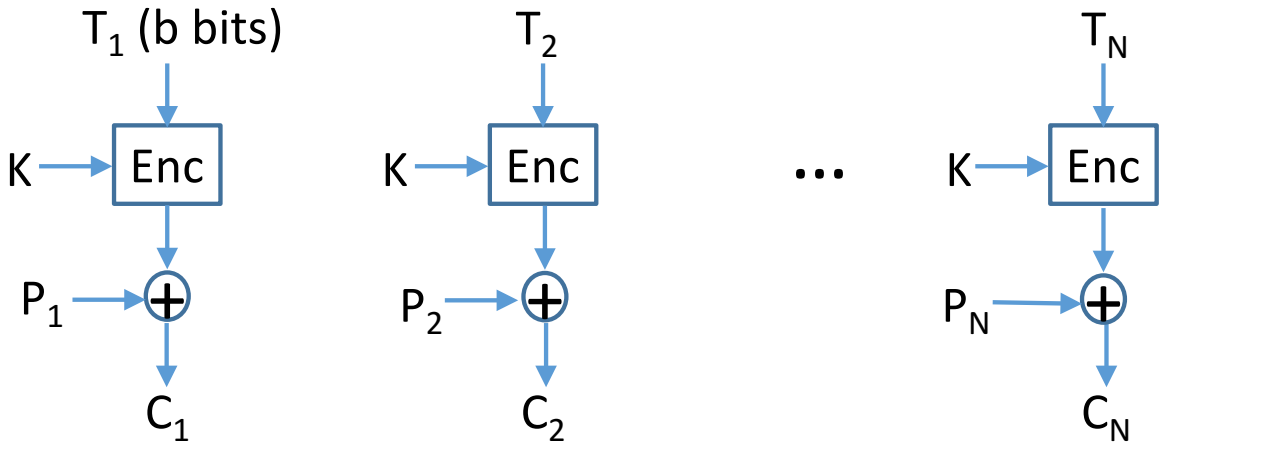
OFB Decryption



CTR Encryption

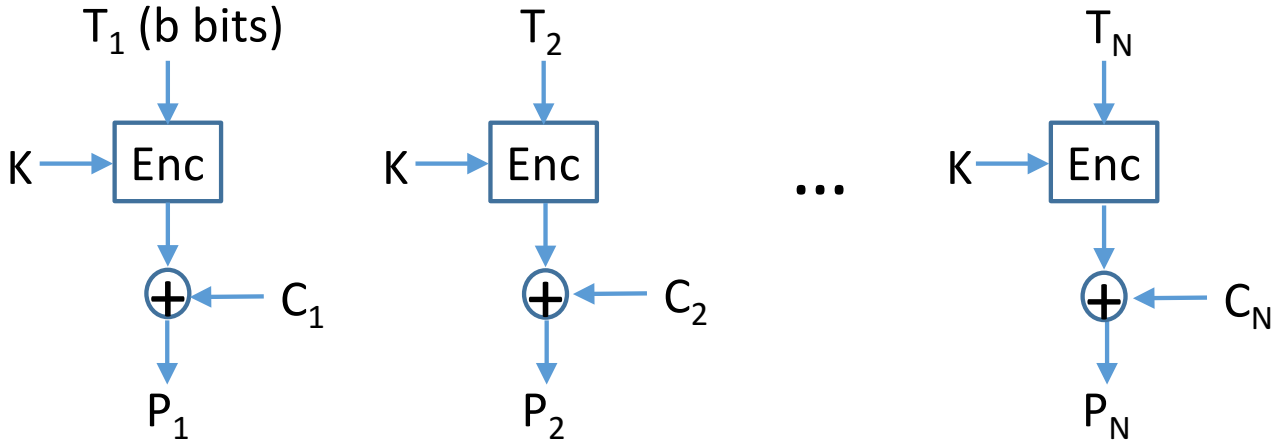


CTR Decryption



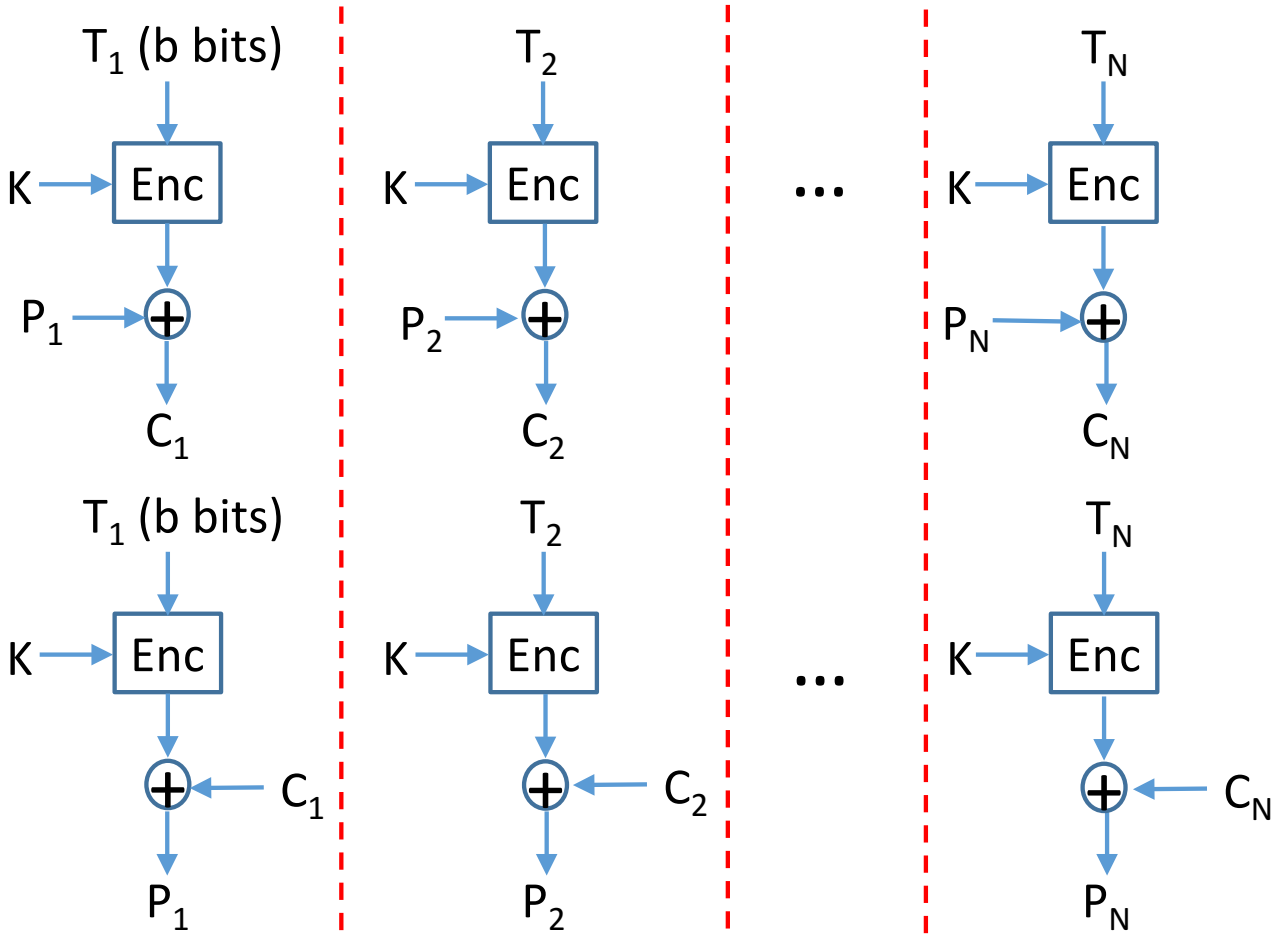
CTR Encryption

$C_i = P_i \oplus Enc(K, T_i)$



CTR Decryption

$P_i = C_i \oplus Enc(K, T_i)$

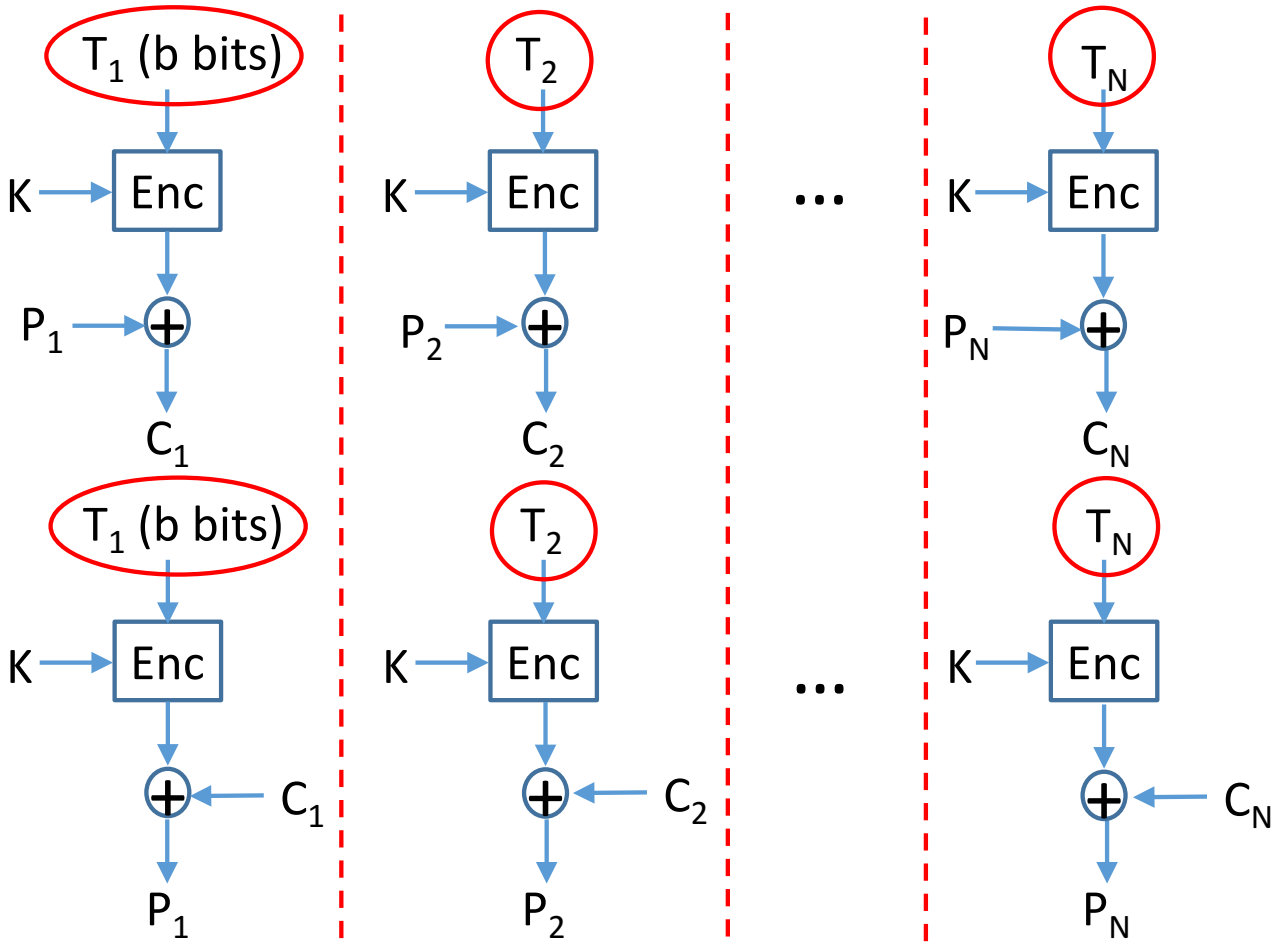


CTR Encryption

$C_i = P_i \oplus \mathrm{Enc}(K, T_i)$

CTR Decryption

$P_i = C_i \oplus \mathrm{Enc}(K, T_i)$



CTR Encryption

$C_i = P_i \oplus \mathrm{Enc}(K, T_i)$

CTR Decryption

$P_i = C_i \oplus \mathrm{Enc}(K, T_i)$

CTR Mode Use

Standard requires that the counter is initialized to different values every time it is used (every plaintext has Different T_1)

Used in Asynchronous Transfer Mode network security and IPSec (IP security)

Block Cipher Modes Feedback

ECB, CBC, CFB, OFB, CTR

Except for ECB, chaining and
dependence across blocks

For CTR, the CTR value is dependent
(implicit feedback within counter)