Modern Symmetric Cryptography

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Terminology

- Cryptography
  - Art or science of hidden writing (confidential writing)
    - From Gr. kryptós, hidden + graph, r. de graphein, to write
  - Initially used to enforce the confidentiality of information
  - Steganography: art of concealing data
    - From Gr. steganós, hidden + graph, r. de graphein, to write

- Cryptanalysis
  - Art or science of breaking cryptographic systems or encrypted information

- Cryptology
  - Cryptography + cryptanalysis

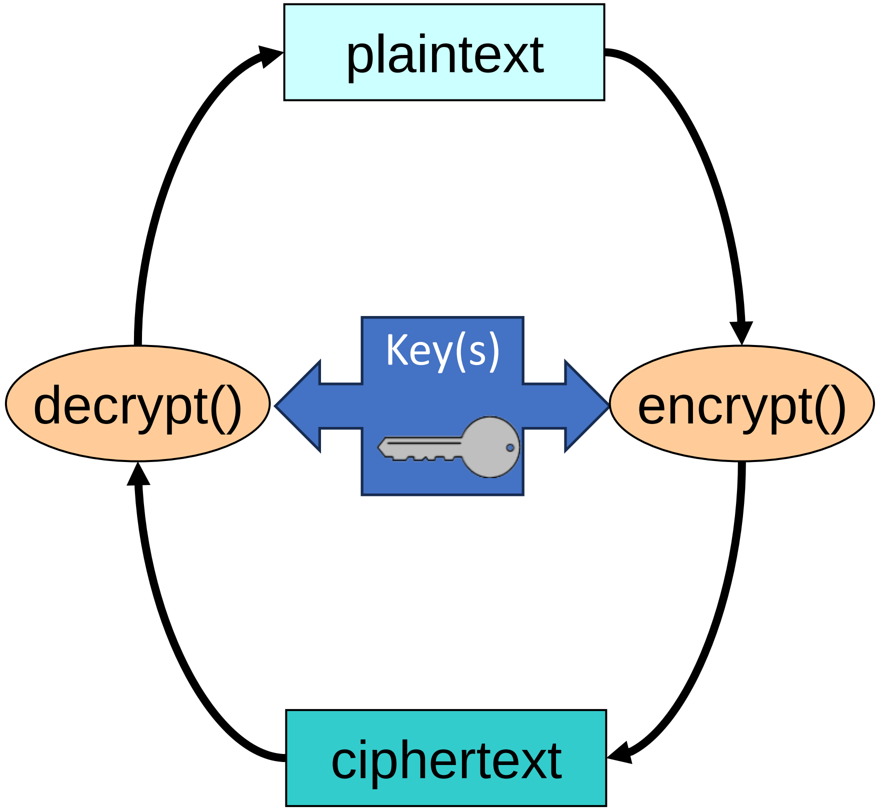
Cryptography: how does it work?

- Select a cipher (or cipher algorithm)
  - Specific cryptographic technique

- Apply the cipher with a key
  - **Encryption**: original information → cryptogram
  - **Decryption**: cryptogram → original information
  - **Key**: algorithm parameter
    - Influences algorithm execution

  - Original information aka plaintext or cleartext
  - Cryptogram aka ciphertext

Usually, information that follows some well-know format



Looks like a random sequence of symbols

Use cases for (symmetric) ciphers

- Self protection with secret key K
  - Alice encrypts plaintext **P** with key **K** → `Alice: C = {P}`$_k$
  - Alice decrypts ciphertext **C** with key **K** → `Alice: P'= {C}`$_k$
  - **P'** should be equal to **P** (requires checking)
  - Only Alice needs to know **K**

- Secure communication with secret key K
  - Alice encrypts plaintext **P** with key **K** → `Alice: C = {P}`$_k$
  - Bob decrypts cyphertext **C** with key **K** → `Bob: P'= {C}`$_k$
  - **P'** should be equal to **P** (requires checking)
  - **K** needs to be known by Alice & Bob

Goals of cryptanalysis

- Reveal the plaintext hidden in a ciphertext
  - Usually requires discovering the key the produced the cyphertext

- Sometimes requires discovering the cipher algorithm
  - Usually algorithms are not secret, but there are exceptions
  - Sometimes using reverse engineering

  - Lorenz, A5 (GSM), RC4 (WEP) , Crypto-1 (Mifare)
  - Algorithms for DRM (Digital Rights Management)

Cryptanalysis attacks

- Brute force
  - Exhaustive search of the key space until finding a match
    - GPUs are great for this!
  - Usually unfeasible for large key spaces
    - Key space: set of all possible keys with the same size
    - e.g., 128-bit keys allow a key space of 2^{128} values
  - Key randomness is fundamental!
    - Means that any key as the same probability of being the right one

- Clever attacks
  - Reduce the search space to a smaller set of potential candidates
    - Words, numbers, restricted size or alphabet
  - Identify patterns in different operations, etc.

Computer ciphers

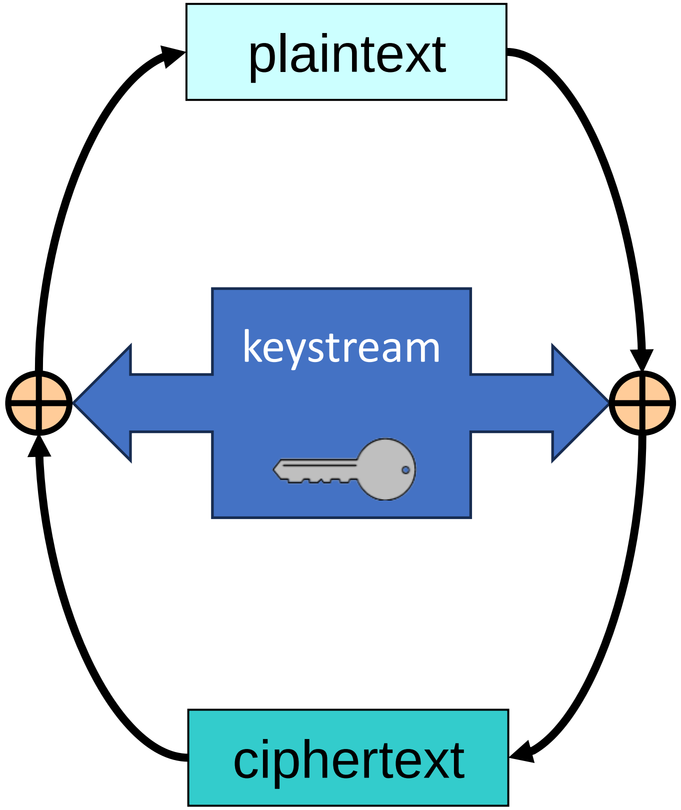
- Operate by making substitutions
  - Original information is a sequence of **symbols**
  - Each symbol is replaced by a **substitution symbol**
    - Usually with the same size
    - **Polyphonic substitution**: several, larger substitution symbols for each original symbol
  - Substitution symbols are picked from a **substitution alphabet**

- Usual symbols
  - Bit
  - Block of bits

- Strategies
  - **Monoalphabetic** substitution: key → one substitution alphabet
  - **Polyalphabetic** substitution: key → several substitution alphabets (one for each symbol)

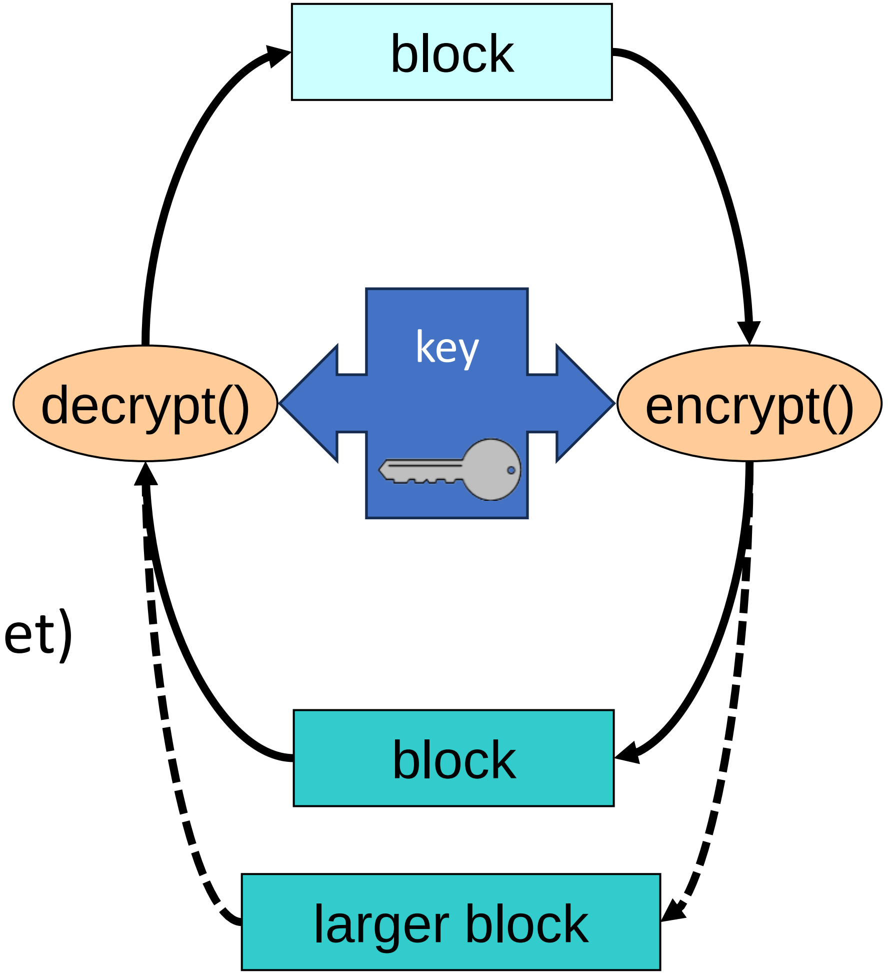
Computer ciphers: stream ciphers

- Encrypt/decrypt by mixing streams
  - They consider the data to cipher or decipher as a bit stream
  - Each plaintext/ciphertext bit is XORed (⊕) with each keystream bit
  - Usually explored in low-level communication protocols
- Polyalphabetic ciphers
  - Each bit (0 or 1) is not always encrypted the same way
- Keystream
  - Randomly produced, as long as the processed data
    - Vernam cipher (or **one-time pad**)
    - The only perfect cipher (but rarely used, very unpractical)
  - Pseudo-randomly produced from a limited key
    - Ordinary stream ciphers



Computer ciphers: block ciphers

- Encrypt/decrypt sequences of blocks
  - Symbols are fixed-length blocks of bits
  - Usually use byte blocks as symbols
- Are monoalphabetic ciphers
  - Transform each symbol into another symbol
  - The key defines the transformation (substitution alphabet)
- Some may be polyphonic ciphers
  - Ciphertext blocks longer than plaintext blocks
  - Used in **randomized ciphers**

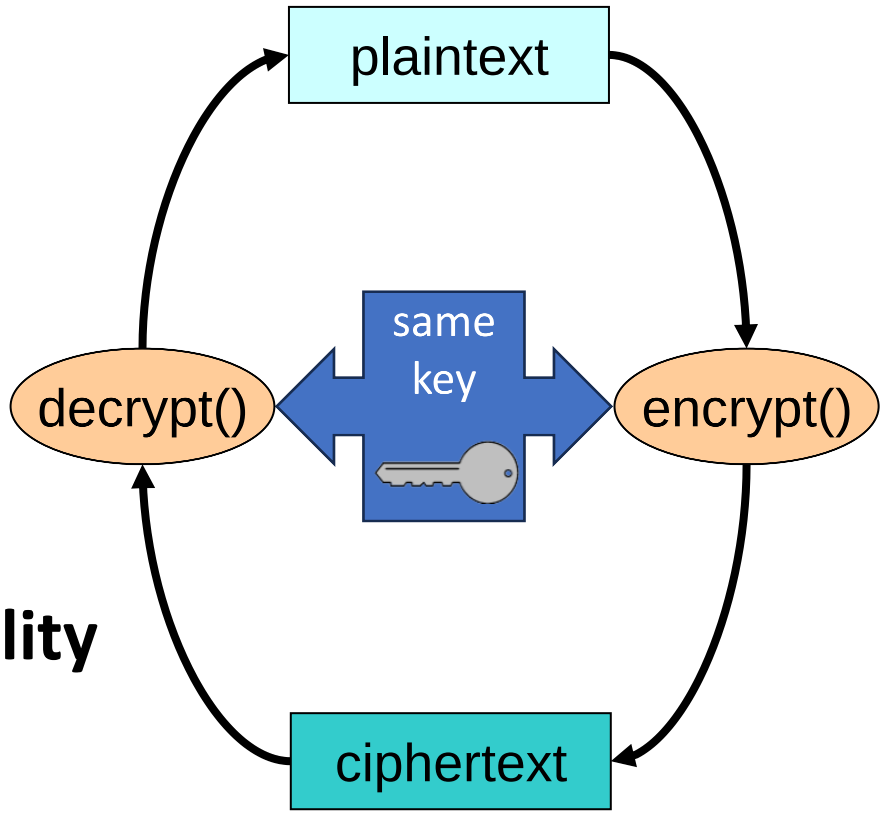


Computer ciphers: symmetric

- Encrypt/decrypt with the same key
  - The oldest strategy

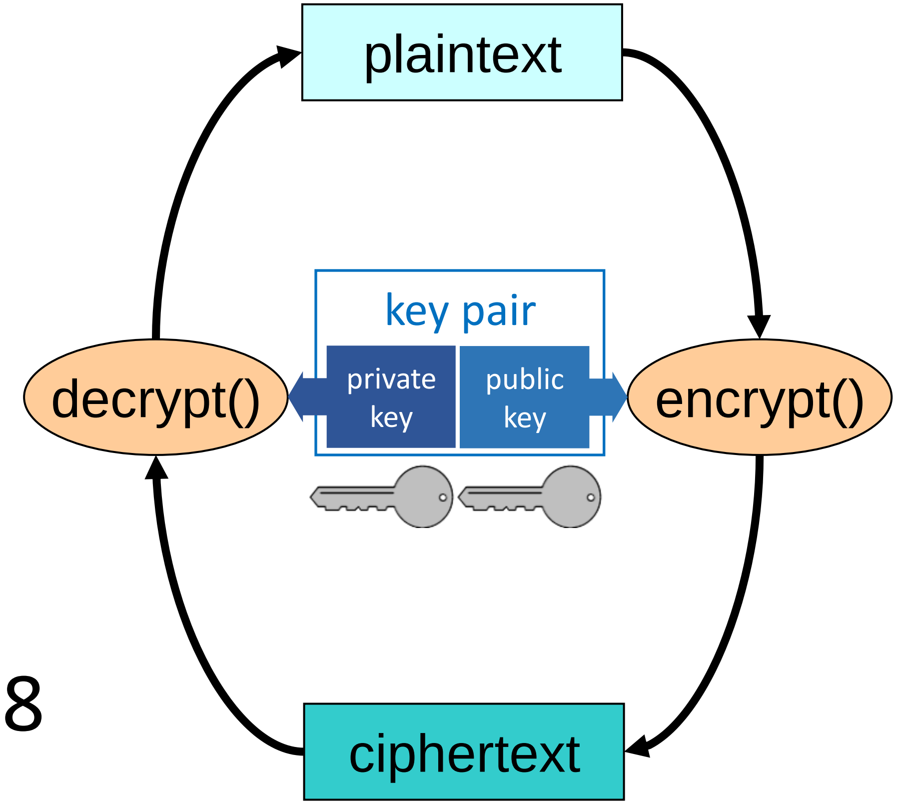
- Also called **secret key ciphers**

- Most common mechanism to provide **confidentiality**
  - Relatively simple to be implemented in software and hardware
  - Very good performance
  - Widely available across systems and platforms



Computer ciphers: asymmetric

- Encrypt/decrypt with two different keys
  – Key pair
- Key Pair
  – Private component, public component
  – Public computed from private (or from secret data)
- An approach that was first proposed in 1978
- Different algorithms work in different ways



Computer ciphers: combinations

- (Symmetric) stream ciphers
  - Polyalphabetic ciphers
  - Keystream defined by the key
  - Keystream and XOR implement a polyalphabetic transformation

- Symmetric block ciphers
  - Monoalphabetic ciphers
  - Substitution alphabet is defined by the algorithm & key

- Asymmetric (block) ciphers
  - Polyphonic ciphers
    - Not by nature, but for security reasons
  - The functionalities of these ciphers are not homogeneous

Techniques used by ciphers

- Confusion
  - Complex relationship between the key, plaintext and the ciphertext
  - Output bits (ciphertext) should depend on the input bits (plaintext + key) in a very complex way

- Diffusion
  - Plaintext statistics are dissipated in the ciphertext
    - If one plaintext bit toggles, then the ciphertext changes substantially, in an unpredictable or pseudorandom manner
  - Avalanche effect

(Symmetric) stream ciphers: examples

- A5/1, A5/2
  - Cellular communications
  - Initially secret, reverse engineered
  - Explored in a weak fashion (64-bit keys w/ 10 bits stuck at zero)

- E0
  - Bluetooth communications
  - Keys up to 128 bits

- RC4
  - Wi-Fi communications (WEP, deprecated)
  - Initially secret, reverse engineered, never officially published
  - Keys with 40 to 2048 bits

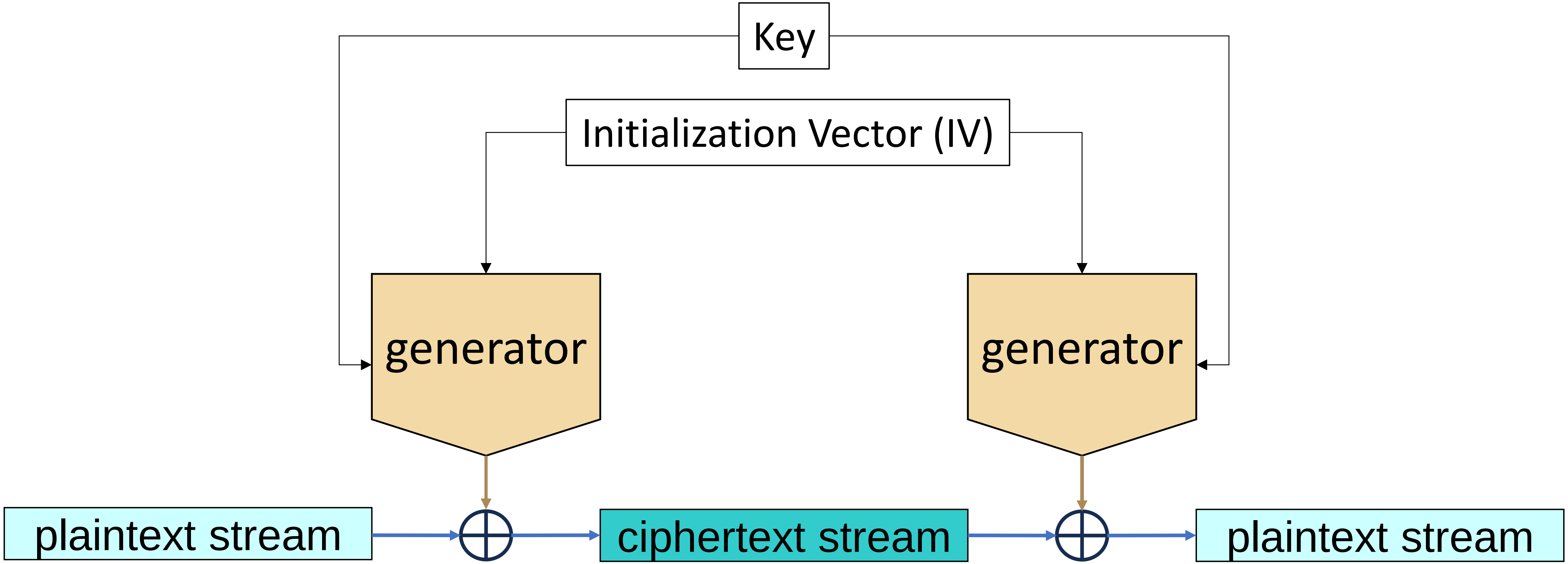
- Other
  - Salsa20, Chacha20, etc.

(Symmetric) stream ciphers: approach

- Use a cryptographically secure, pseudo-random bit **generator**
  - This generator produces the keystream
  - The generator implements a state machine
  - The generator is usually controlled by two values:
    - **Initialization Vector** (defines the initial state of the state machine)
    - **Key** (defines how one state moves to the next to produce the keystream)

- Cryptographically secure, pseudo-random means:
  - Statistically, the keystream looks like a totally random sequence of zeros and ones
  - If an attacker learns a part of the keystream, it cannot infer:
    - Past keystream values
    - Future keystream values

(Symmetric) stream ciphers: approach



Stream ciphers: exploitation considerations

- No two messages (P1,P2) should be encrypted with the same key and IV
  - Because they will be encrypted with the same keystream (KS)
  - The knowledge about one message reveals the other

$C1 = P1 \oplus KS$

$C2 = P2 \oplus KS$ → $P2 = C2 \oplus KS = C2 \oplus C1 \oplus P1$

  - Knowledge about P1 => immediate knowledge about P2
  - Known/chosen-plaintext attacks become very effective!

- Keystreams may be periodic (have a cycle)
  - Depends on the type and quality of the generator
  - Same problem as the one above (KS is reused)
  - Plaintext should be shorter than the period length

Stream ciphers: exploitation considerations

- Ciphertexts can be deterministically manipulated
  - Stream ciphers are simple and have no capability to detect manipulation
  - Each cipher bit depends only on one plaintext bit

$$C' = C \oplus \Delta \quad \Rightarrow \quad P' = P \oplus \Delta$$

- It is fundamental to have integrity control elements
  - In the ciphertext; or
  - In the plaintext
  - Objective is to detect accidental or malicious changes to P

Symmetric Block ciphers: examples

- DES (Data Encryption Standard)
  - Proposed in 1974, standard in 1977, nowadays deprecated
  - Input/output: 64-bit blocks
  - Key: 56 bits

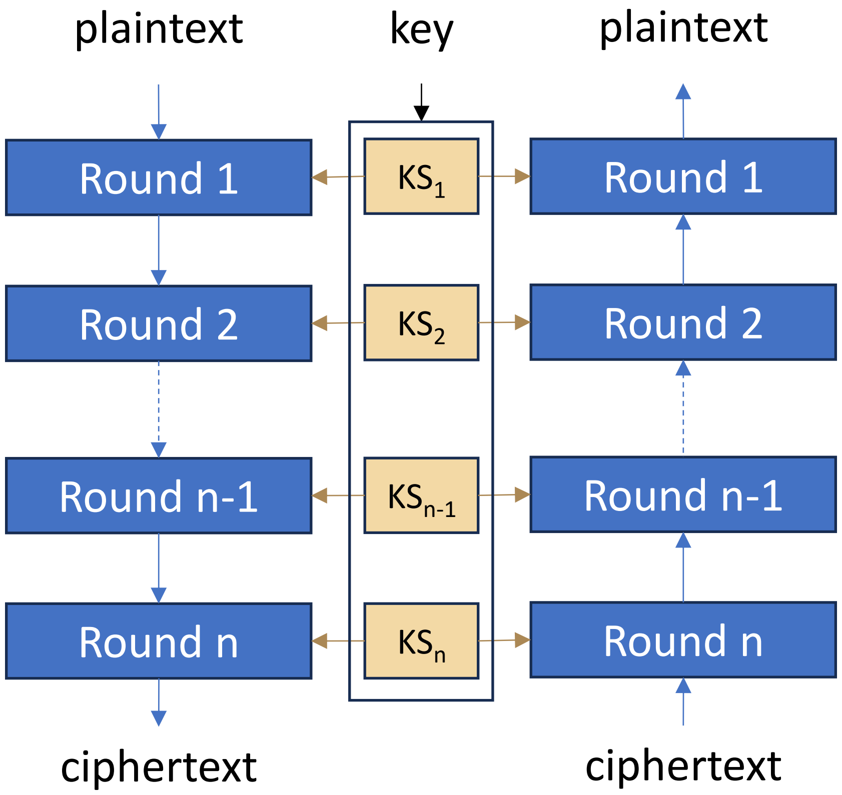
- AES (Advanced Encryption Standard)
  - Proposed in 1998 (Rijndael), standard since 2001
  - Input/output: 128-bit blocks
  - Key: 128, 192 or 256 bits
  - Mosty commonly used symmetric cipher in applications

- Other
  - IDEA, CAST, Twofish, Blowfish, RC5, RC6, Kasumi, etc.

Symmetric block ciphers: approach

- Use a pipeline of transformation **rounds**
  - Each round adds confusion and diffusion
  - Each round is usually controlled by a **subkey**
    - Aka **key schedule**
    - A value derived from the encryption/decryption key

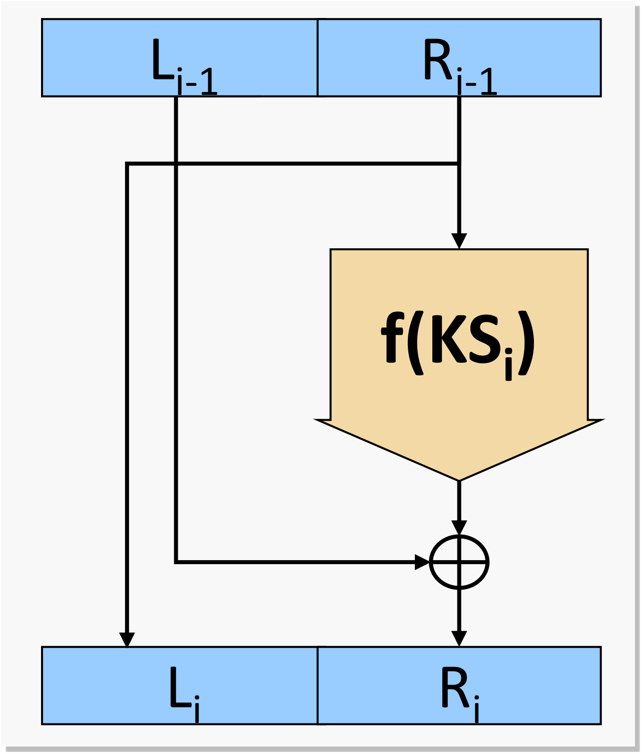
- Rounds need to be reversible
  - To allow decrypting what was encrypted
  - Make use of well-known structures:
    - Feistel networks
    - Substitution-permutation networks



Feistel network

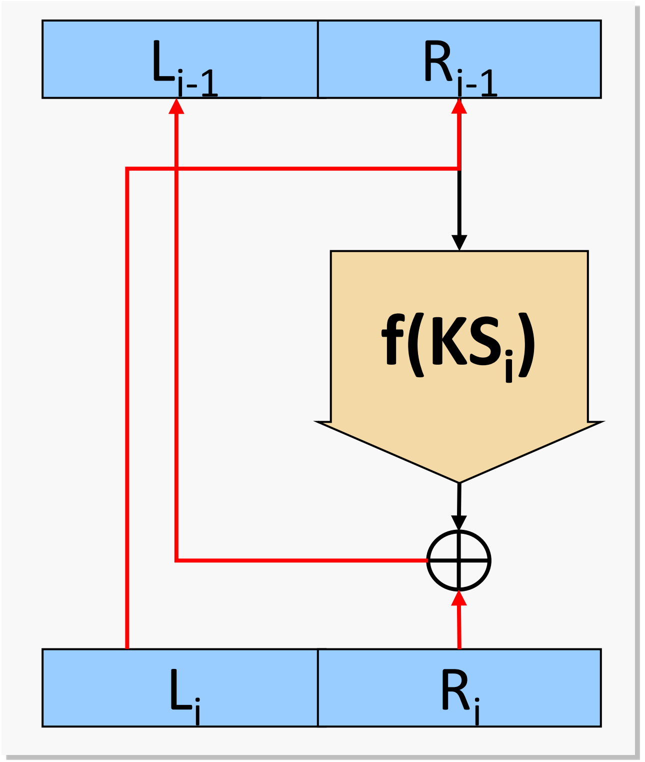
$L_i = R_{i-1}$

$R_i = L_{i-1} \oplus f(R_{i-1}, K_i)$



$R_{i-1} = L_i$

$L_{i-1} = R_i \oplus f(L_i, K_i)$



The function **f(KS$_i$)** doesn't need to be reversible!

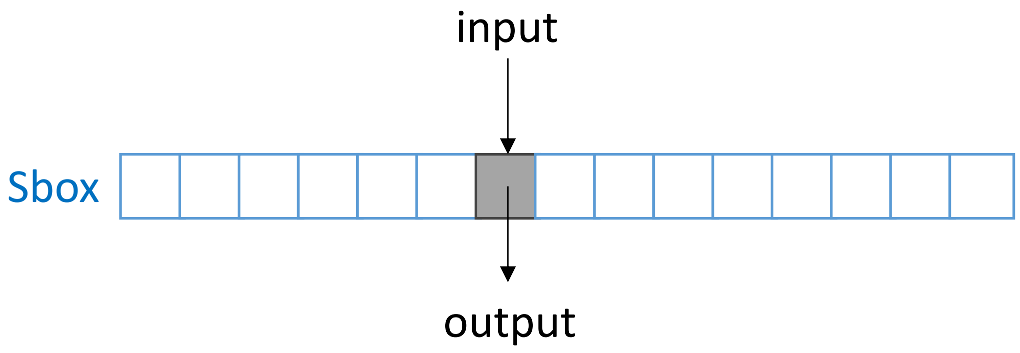
Substitution-Permutation network

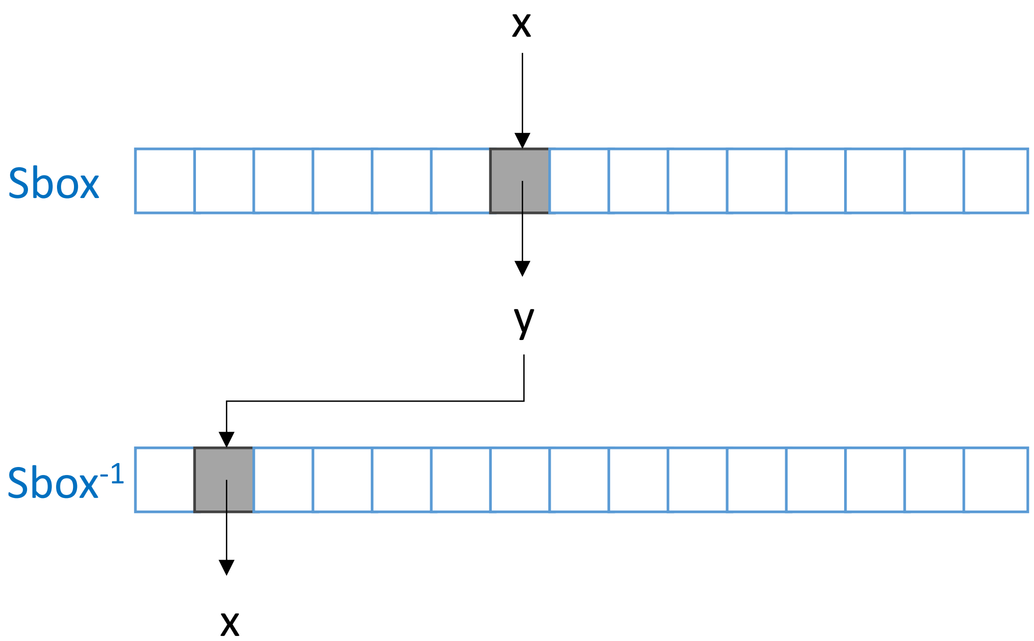
- SBox – Substitution Box
  - Table with an output for an input (index)

    output = SBox[input]

  - SBoxes may be constant or key-dependent
    - DES and AES use constant Sboxes
    - Blowfish and Twofish use variable, key-dependent SBoxes
  - In SP networks, SBoxes must be reversible
    - Bijective transformations

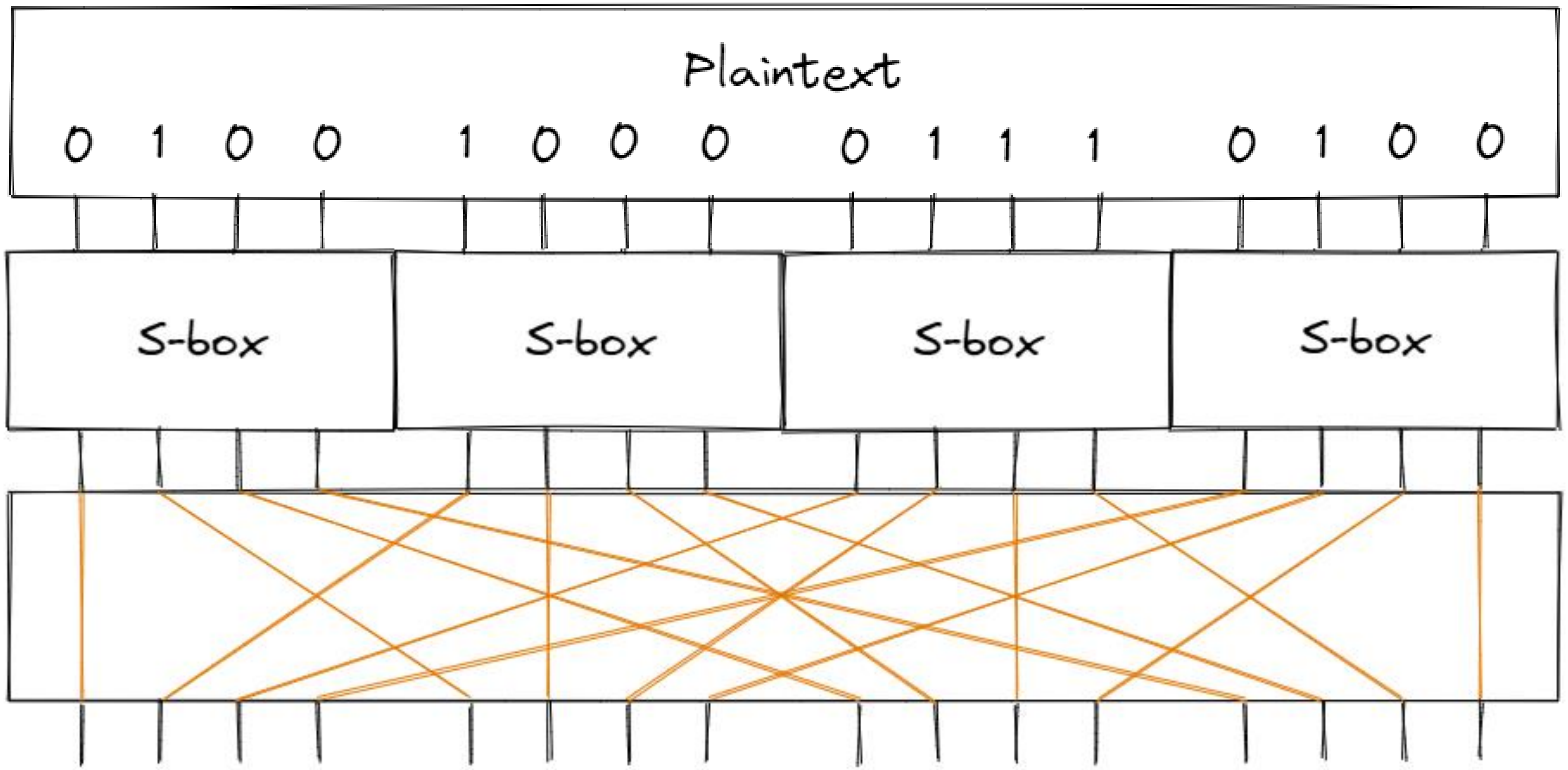
    y = SBox[x] $x = SBox^{-1}[y]$



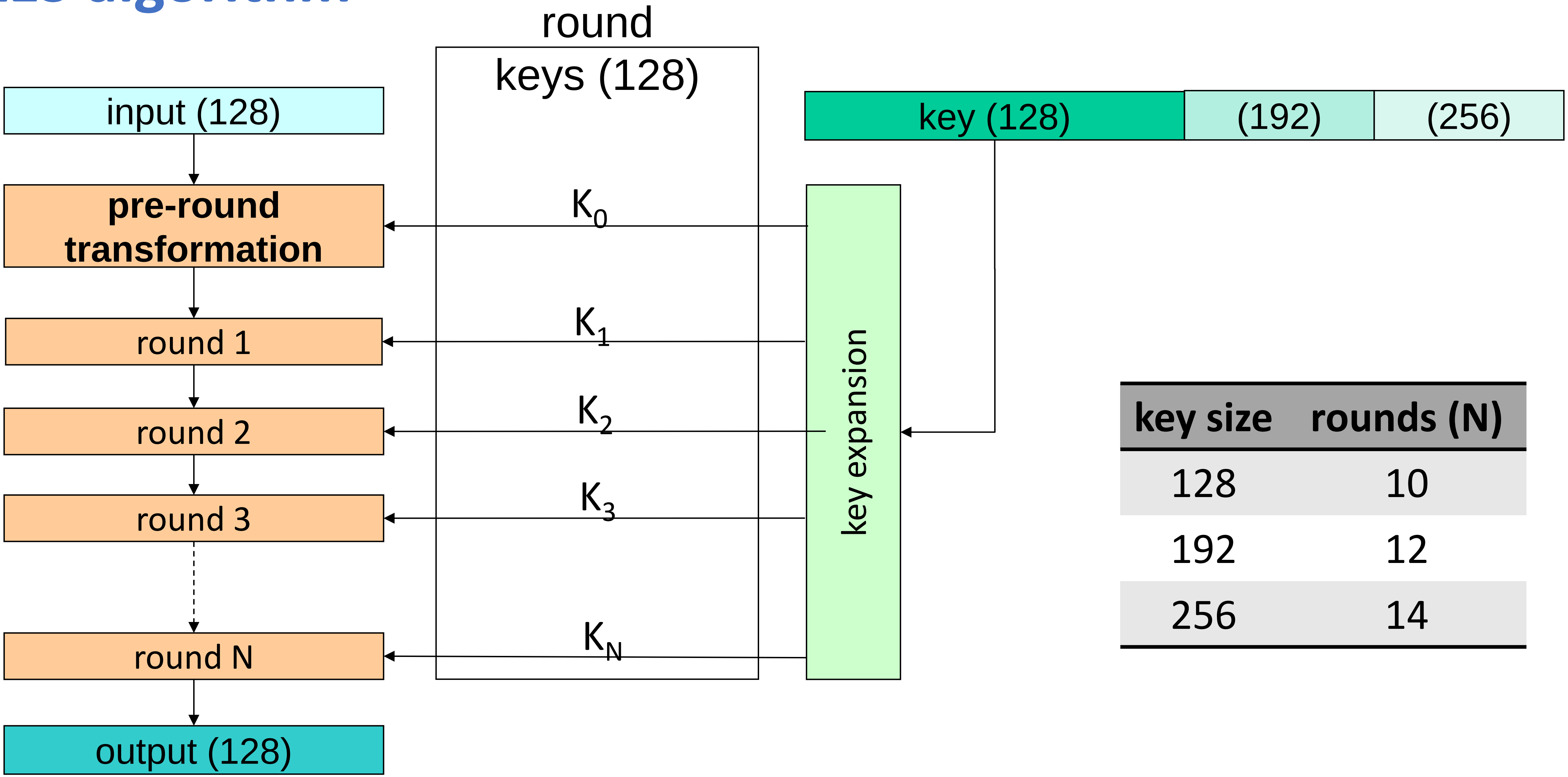


- PBox – Permutation Box
  - Changes the positions of the input bits
    - Bits are not modified, only the position is modified

Substitution-Permutation network

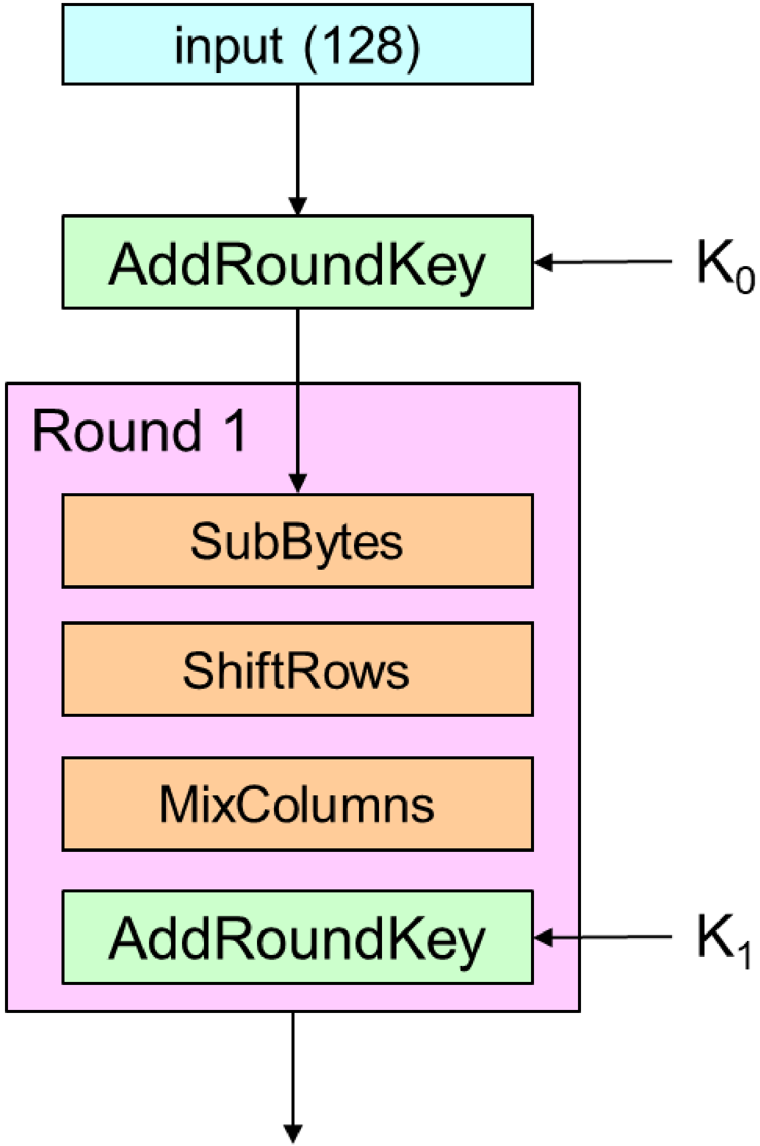


AES algorithm

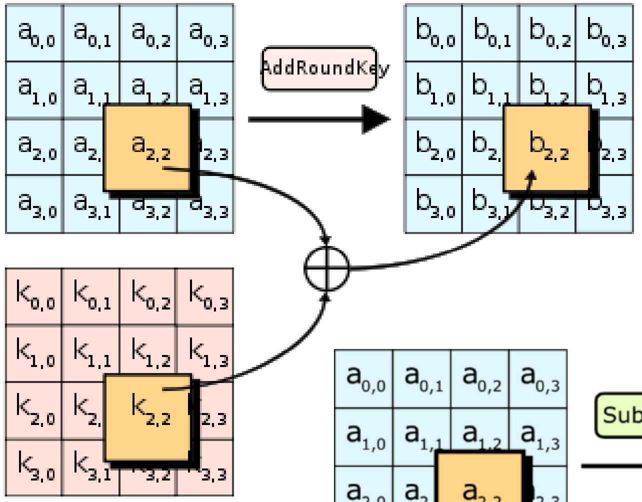


key size	rounds (N)
128	10
192	12
256	14

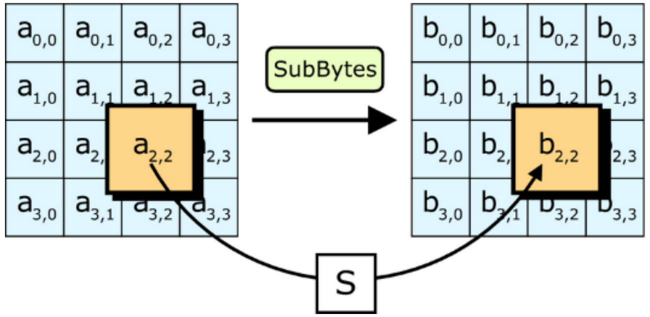
AES (enccryption) round



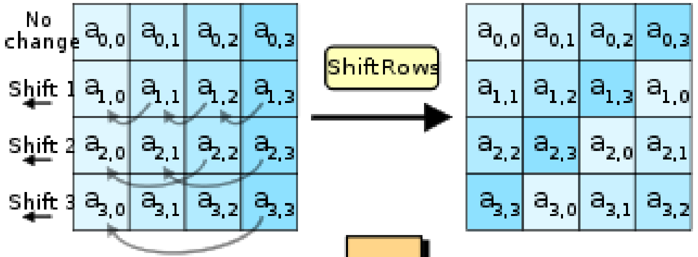
- AddRoundKey
  - 128-bit XOR
  - Output is a 4x4 byte matrix



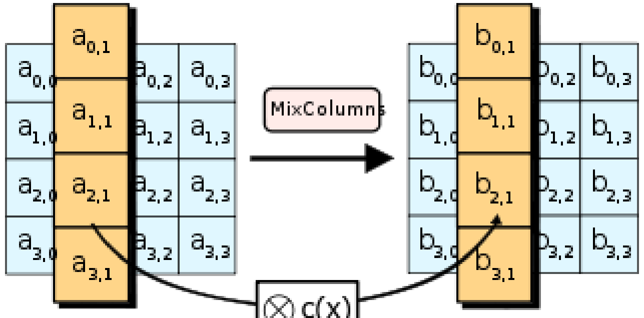
- SubBytes
  - 256-element S-box
  - Each matrix byte is substituted



- ShiftRows
  - Rows are rotated left
  - Byte shifts vary (0, 1, 2 & 3)



- MixColumns
  - Each column is transformed
  - Not performed in the last round



https://aescryptography.blogspot.com

AES in CPU instruction sets

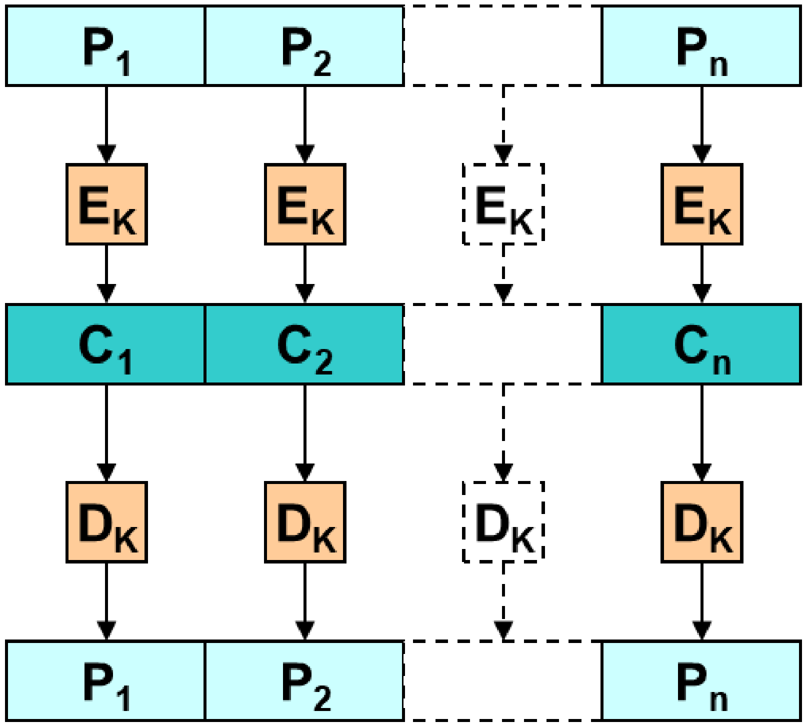
- Intel AES New Instructions (AES-NI)

AESENC	Perform one round of an AES encryption flow
AESENCLAST	Perform the last round of an AES encryption flow
AESDEC	Perform one round of an AES decryption flow
AESDECLAST	Perform the last round of an AES decryption flow
AESKEYGENASSIST	Assist in AES round key generation
AESIMC	Assist in AES Inverse Mix Columns

- ARMv8 Cryptographic Extension
  - … and other

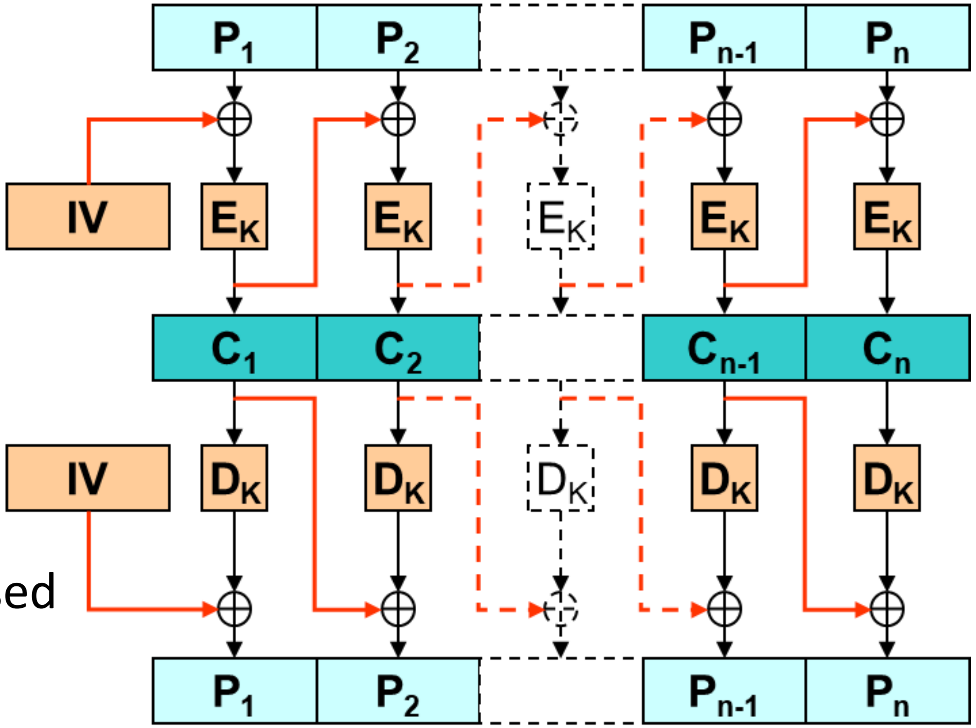
Cipher Modes: Electronic Code Book (ECB)

- Direct encryption of each block: $C_i = E_K(P_i)$
- Direct decryption of each block: $P_i = D_K(C_i)$
- Blocks are processed independently
  - Parallelism is possible
  - Uniform random access exists
- Problem:
  - Exposes patterns existing in the clear text
  - If $P_i = P_j$ then $C_i = C_j$

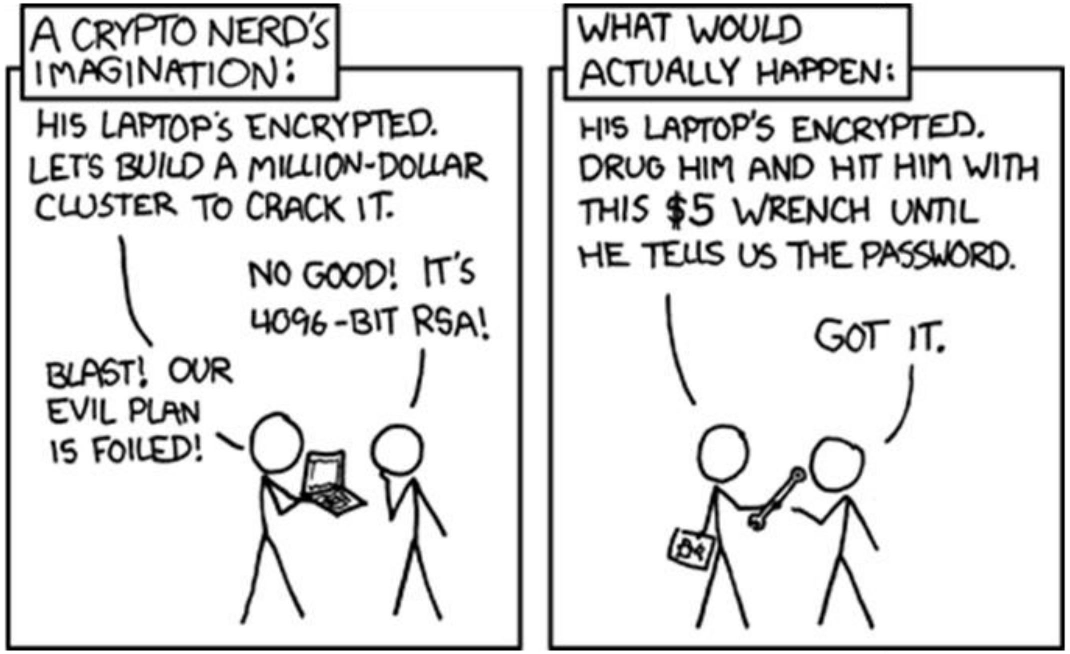


Cipher Modes: Cipher Block Chaining (CBC)

- Encrypt each block T_i combined with C_{i-1}: $C_i = E_K(P_i \oplus C_{i-1})$
- Decrypt each block C_i combined C_{i-1}: $P_i = D_K(C_i) \oplus C_{i-1}$
  - Parallelism and uniform random access is possible
- First block uses an IV (Initialization Vector)
  - Better not reuse for the same key
  - Random value, sequence value, etc.
  - May be sent openly
- Polyalphabetic transformation
  - The feedback prevents equal blocks from being equally processed
  - Seems like we have a different key per block

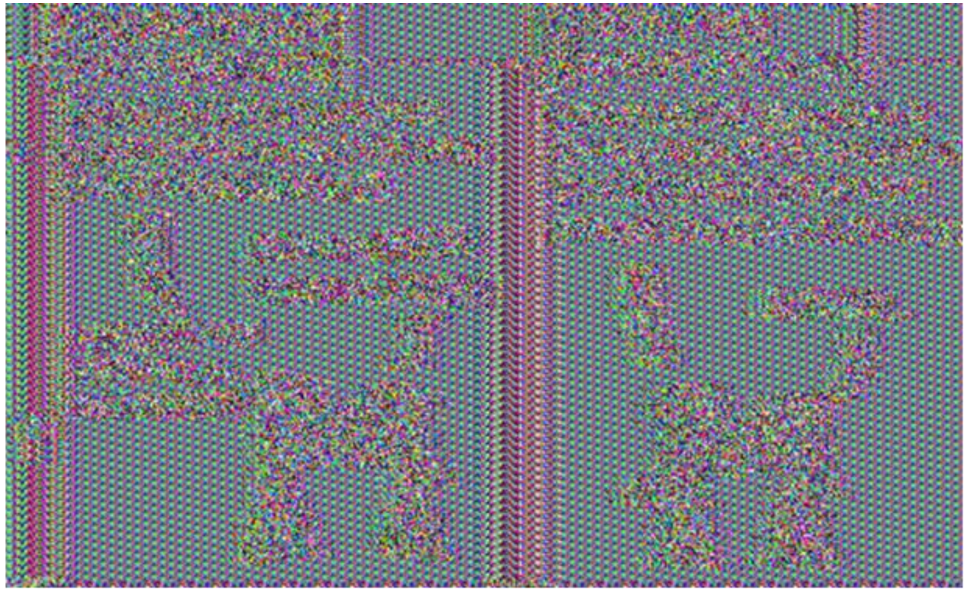


ECB vs CBC: pattern exposure



https://xkcd.com/538/

ECB



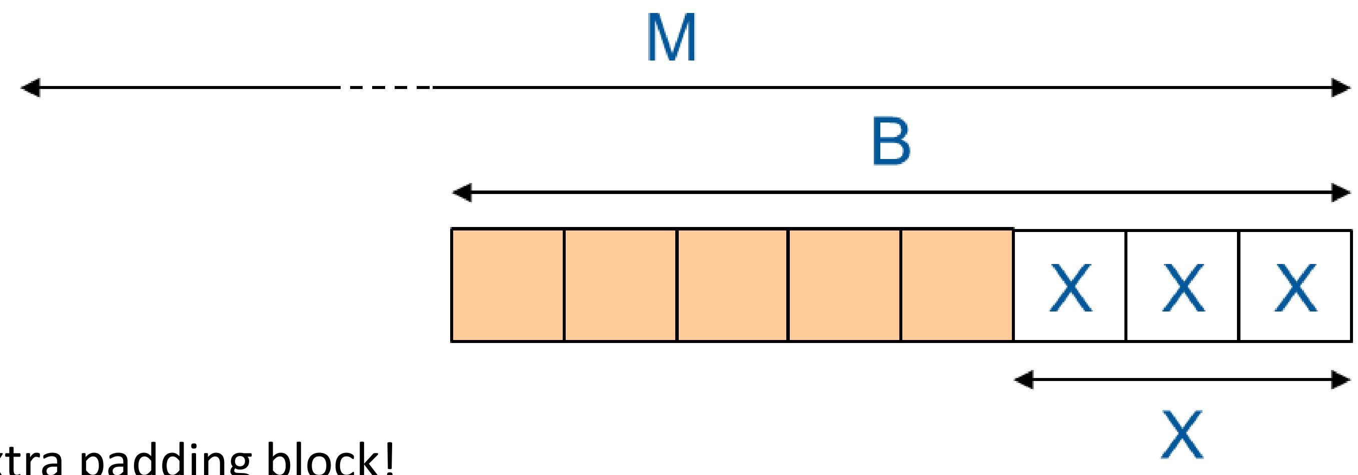
CBC

ECB/CBC cipher modes: contents not block-aligned

- ECB and CBC require block-aligned inputs
  - Final sub-blocks need special treatment

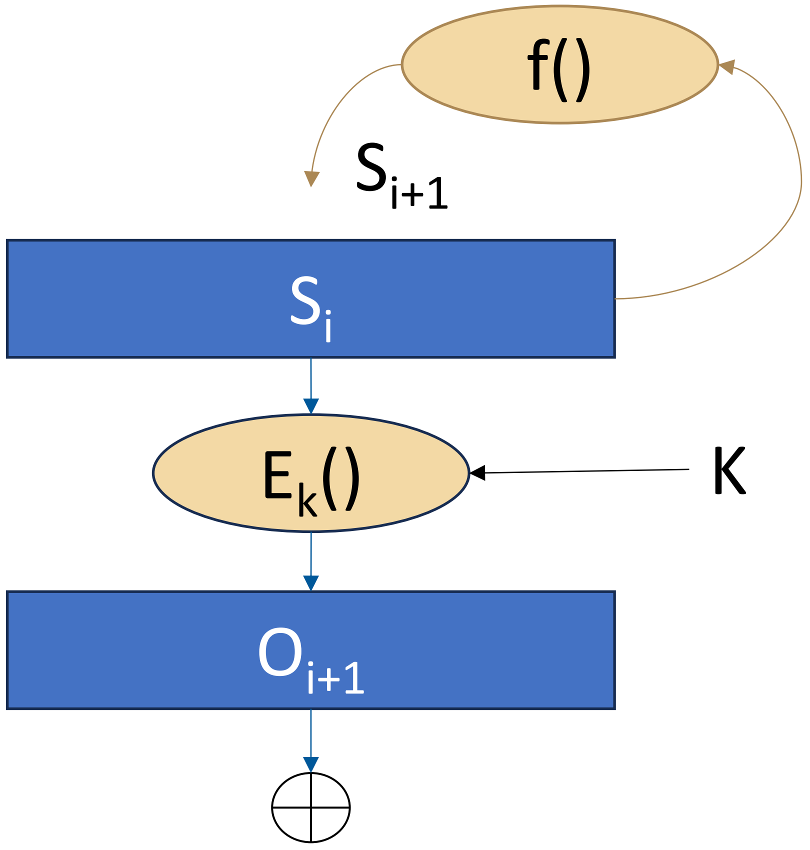
- Alternatives
  - Padding
    - Of last block, identifiable
  - Different processing for the sub-block
    - Adds complexity, rarely used

- PKCS #7 padding
  - **X = B – (M mod B)**
  - **X** extra bytes, with the value **X**
  - PKCS #5: Equal to PKCS #7 with **B = 8**
  - Drawback: perfectly aligned inputs get an extra padding block!



Stream cipher modes

- Stream ciphers use a pseudorandom generator
  - There are multiple techniques to implement them
  - Some techniques are specially suited for hardware implementations
    - Typically used in mobile, battery-powered devices
  - Other techniques are more suitable for CPU-based implementations
- Stream cipher modes
  - They use a block cipher to implement a stream cipher generator
  - The fundamental idea is:
    - The generator is a state machine with state S_i on iteration i
    - The output of the generator for state S_i is $O_{i+1} = E_K(S_i)$
    - The state S_i is updated to S_{i+1} using some transformation function f
    - S_0 is defined by an IV
  - The generator only uses block cipher encryptions (or decryptions)



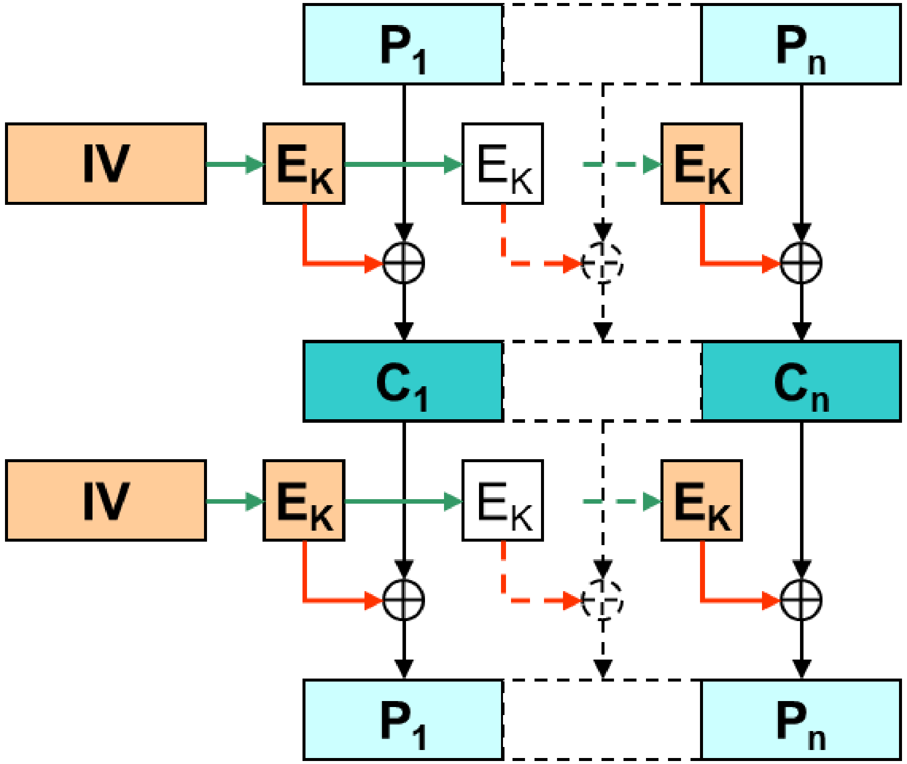
Stream cipher modes: n-bit OFB (Output Feedback)

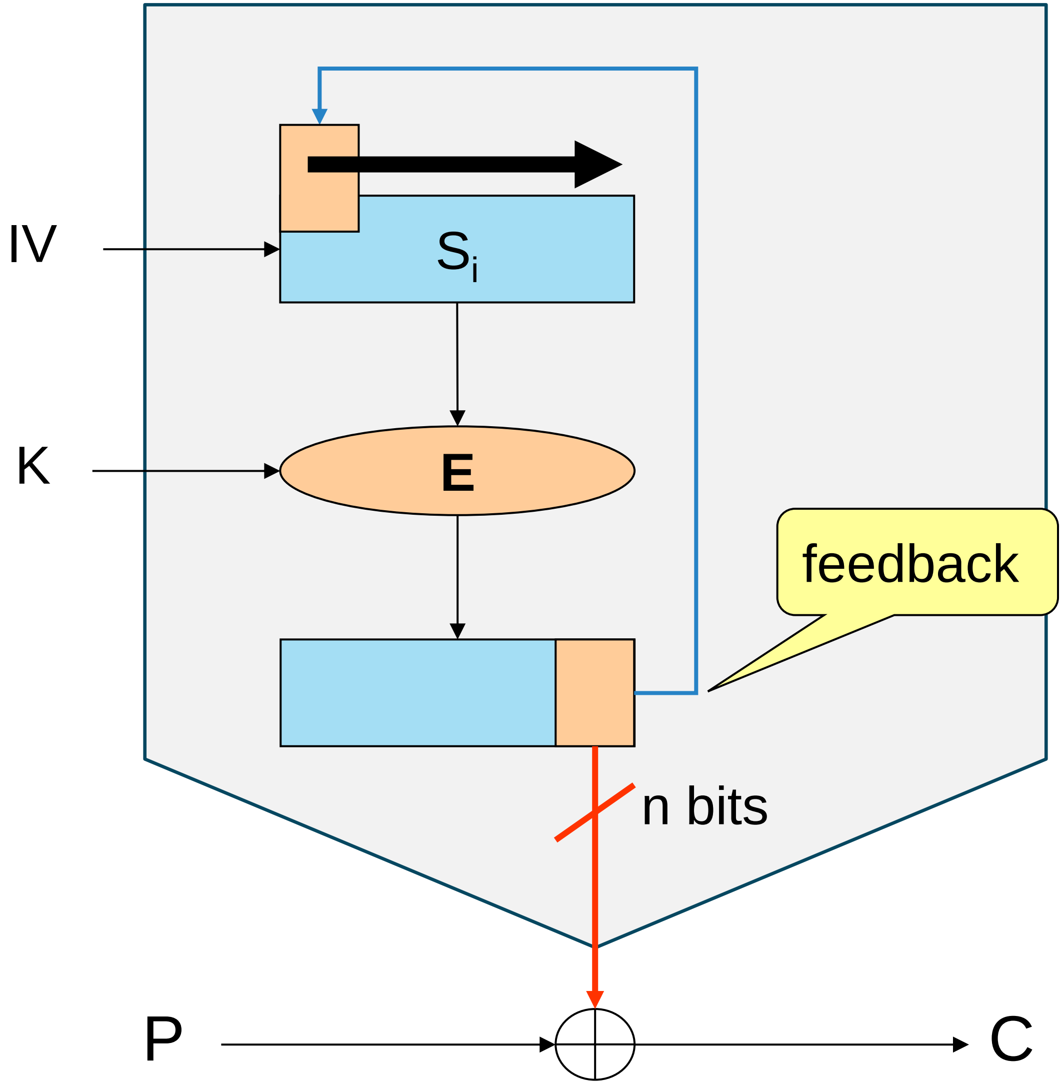
$C_i = T_i \oplus E_K(S_{i-1})$

$T_i = C_i \oplus E_K(S_{i-1})$

$S_{i+1} = f(S_i, E_K(S_i))$

$S_0 = IV$





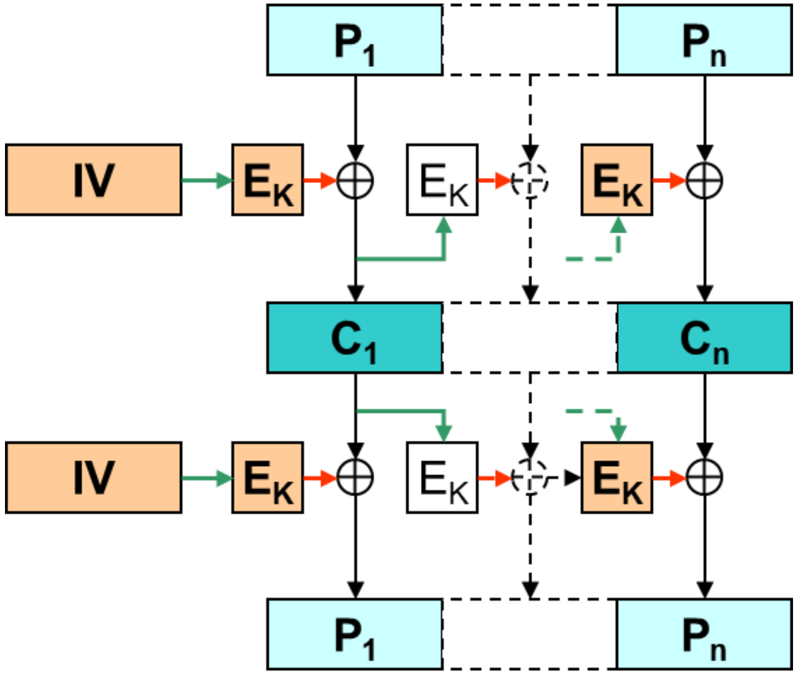
Stream cipher modes: n-bit CFB (Ciphertext Feedback)

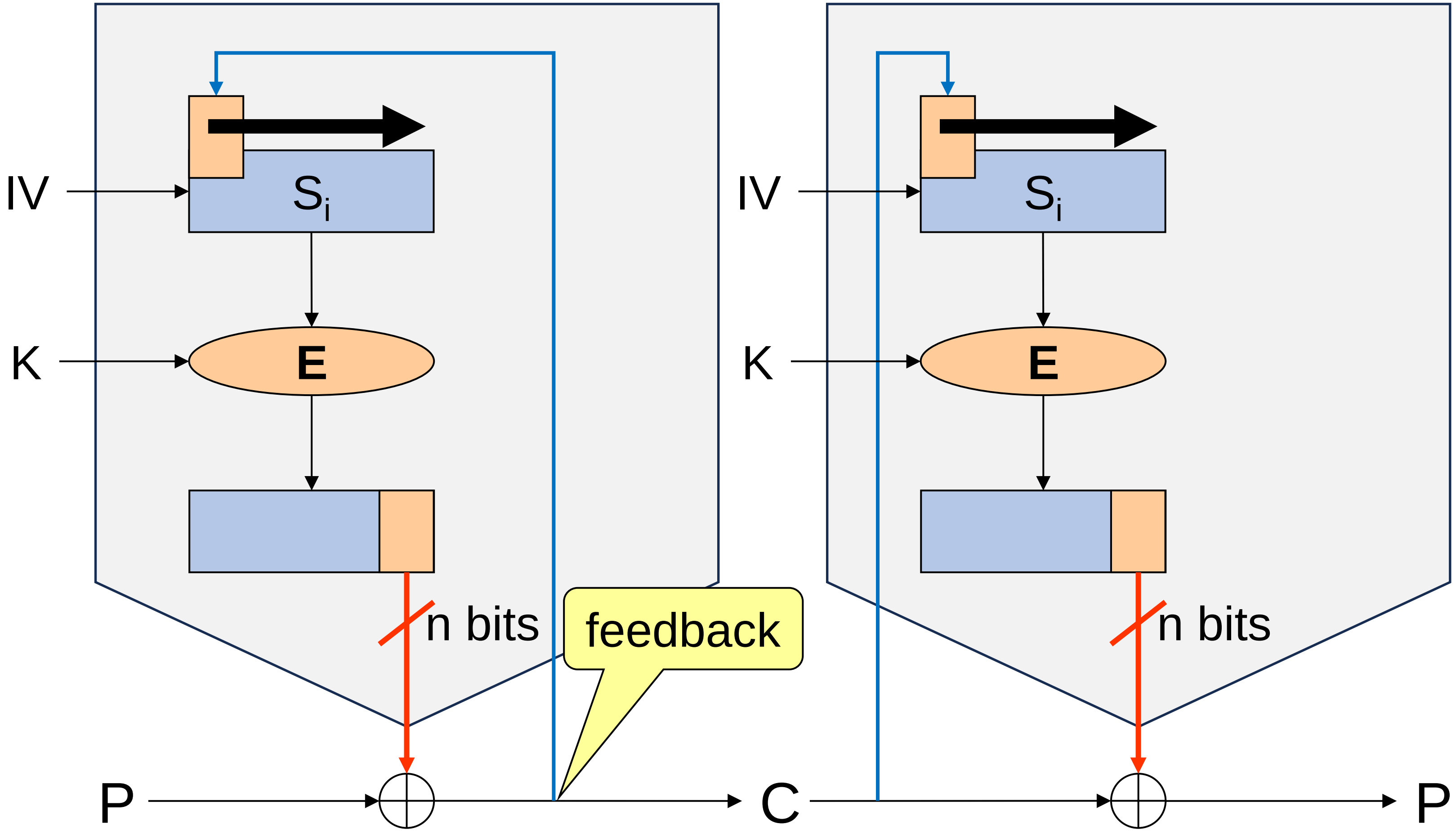
$C_i = T_i \oplus E_K(S_{i-1})$

$T_i = C_i \oplus E_K(S_{i-1})$

$S_{i+1} = f(S_i, C_i)$

$S_0 = IV$





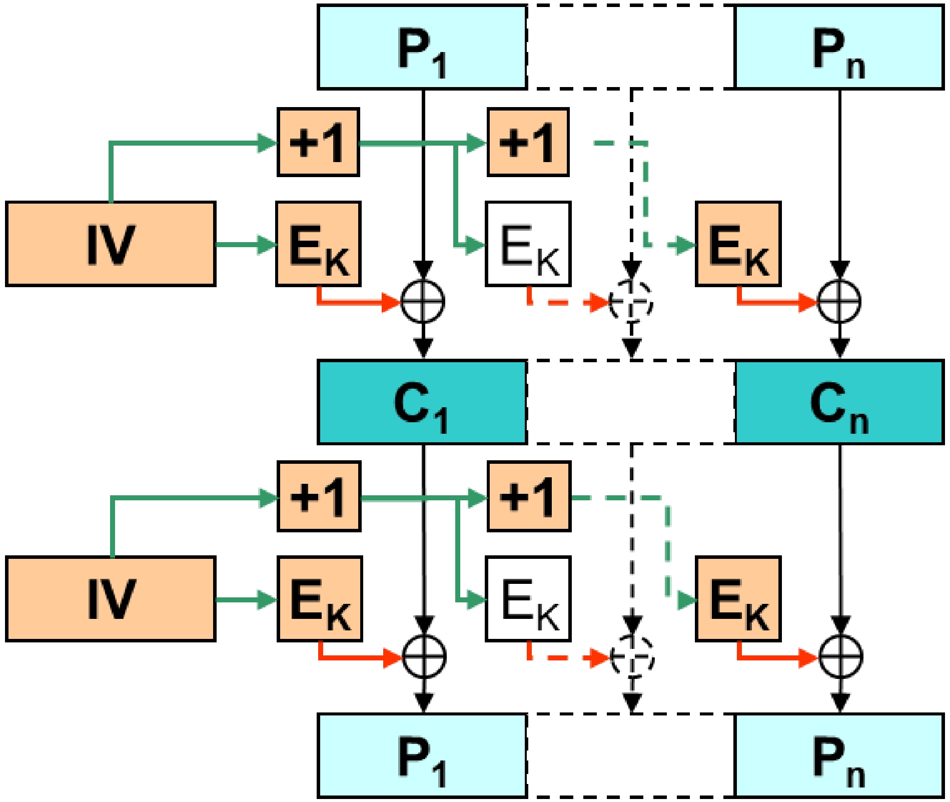
Cipher modes: n-bit CTR (Counter)

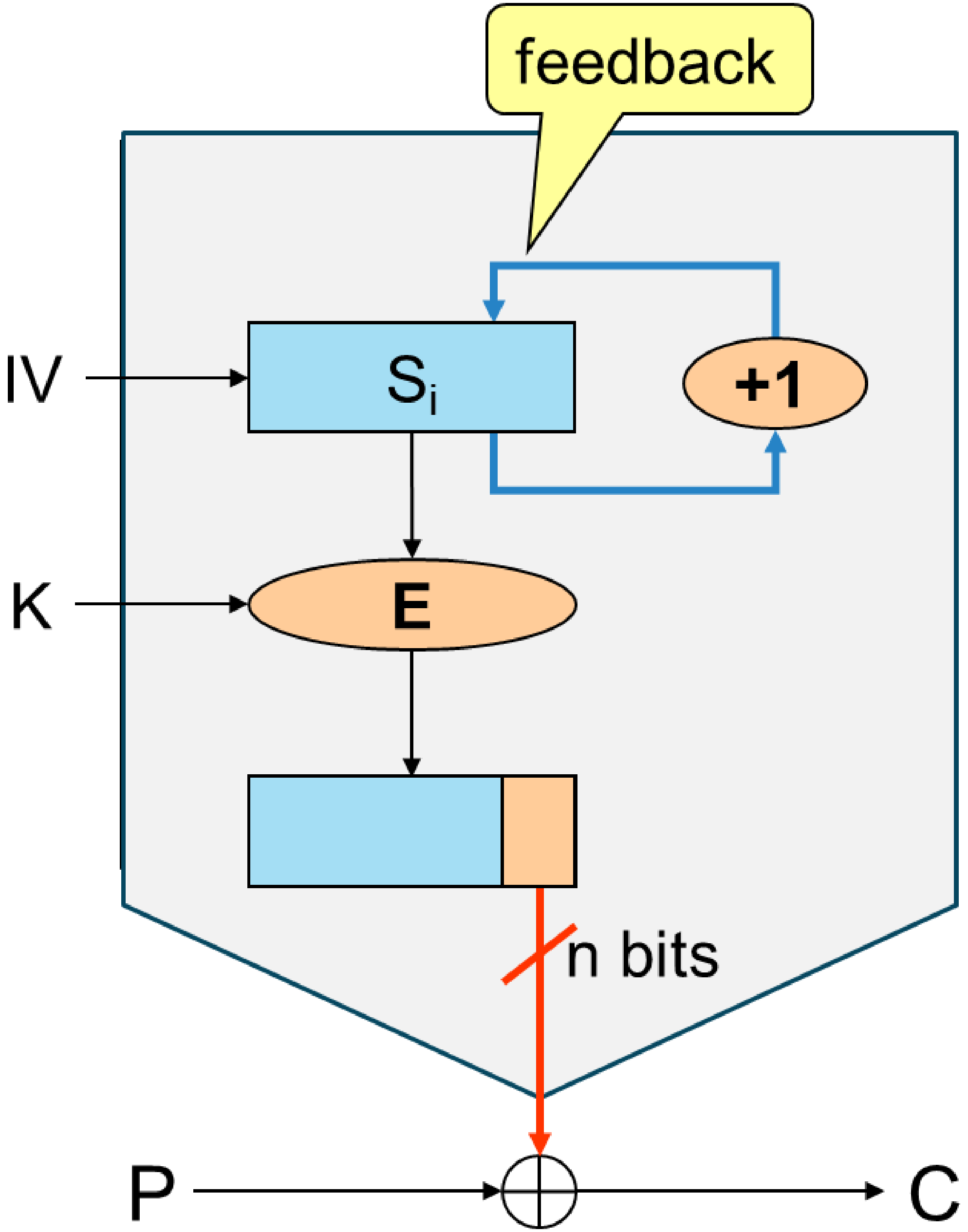
$C_i = T_i \oplus E_K(S_{i-1})$

$T_i = C_i \oplus E_K(S_{i-1})$

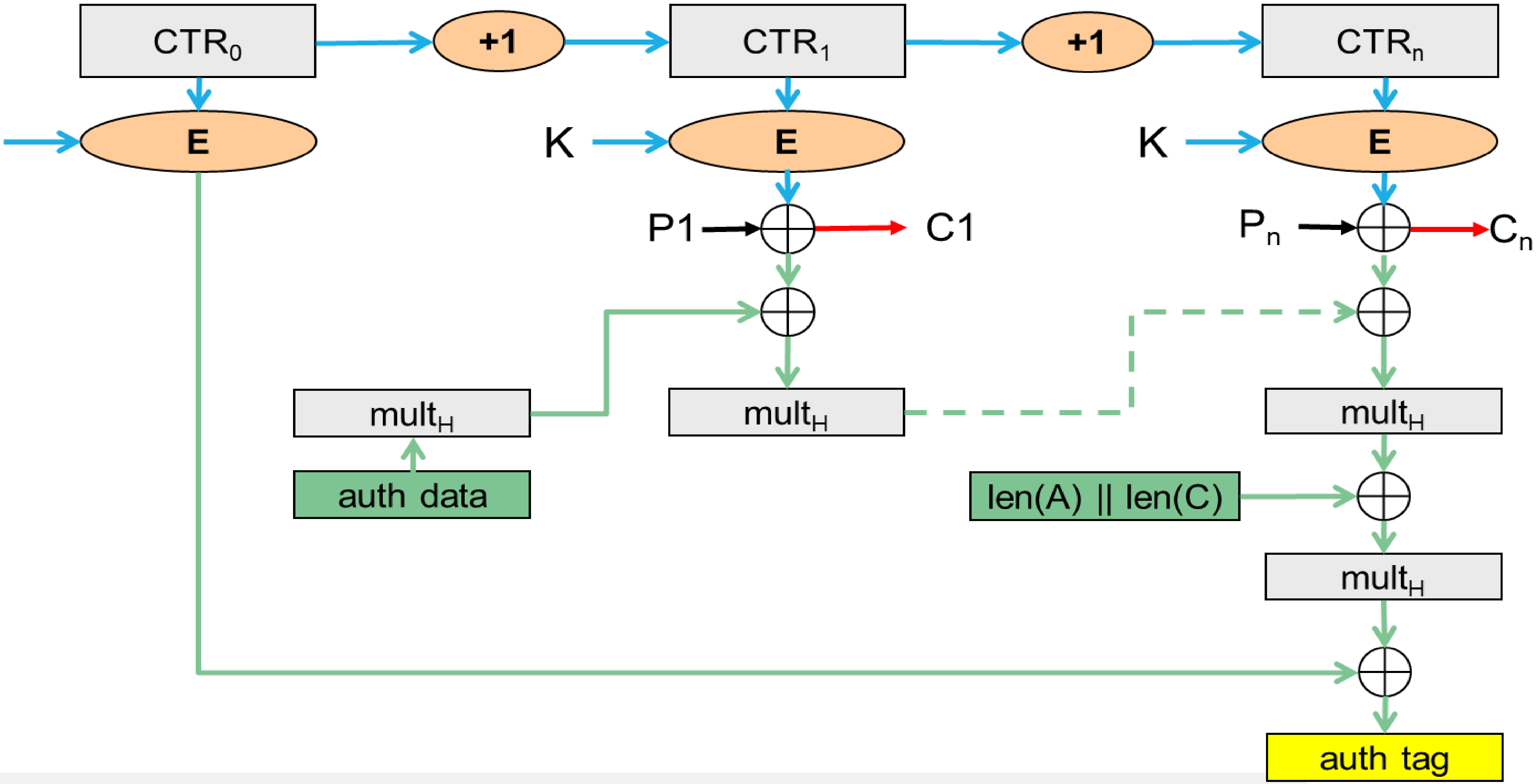
$S_{i+1} = S_i + 1$

$S_0 = IV$





Stream cipher modes: Galois with Counter Mode (GCM)



Cipher Modes: comparison

<table>
<tr><th rowspan="2"></th><th colspan="2">Block</th><th colspan="4">Stream</th></tr>
<tr><th>ECB</th><th>CBC</th><th>OFB</th><th>CFB</th><th>CTR</th><th>GCM</th></tr>
<tr><td>Input pattern hiding</td><td></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Same key for different messages</td><td>✓</td><td>✓</td><td colspan="4">other IV</td></tr>
<tr><td>Tampering difficulty</td><td>✓</td><td>✓ (...)</td><td></td><td>(...)</td><td></td><td>✓</td></tr>
<tr><td>Pre-processing</td><td></td><td></td><td>✓</td><td></td><td>✓</td><td>✓</td></tr>
<tr><td>Parallel processing</td><td rowspan="2">✓</td><td rowspan="2">decrypt</td><td rowspan="2">With pre-proc</td><td rowspan="2">decrypt</td><td rowspan="2">✓</td><td rowspan="2">✓</td></tr>
<tr><td>Uniform random access</td></tr>
<tr><td>Cryptogram single bit error propagation on decryption</td><td>same block</td><td>same & next block</td><td></td><td>a few next bits</td><td></td><td>detected</td></tr>
<tr><td>Capacity to recover from losses</td><td>some</td><td>some</td><td></td><td>some</td><td></td><td>detected</td></tr>
</table>

Cipher Modes: multiple encryption

- Invented for extending the lifetime of DES
  - DES was never cryptanalyzed
  - But its key was too short (56 bits only)
  - Its key could be discovered by brute force

- Triple encryption EDE, or 3DES-EDE

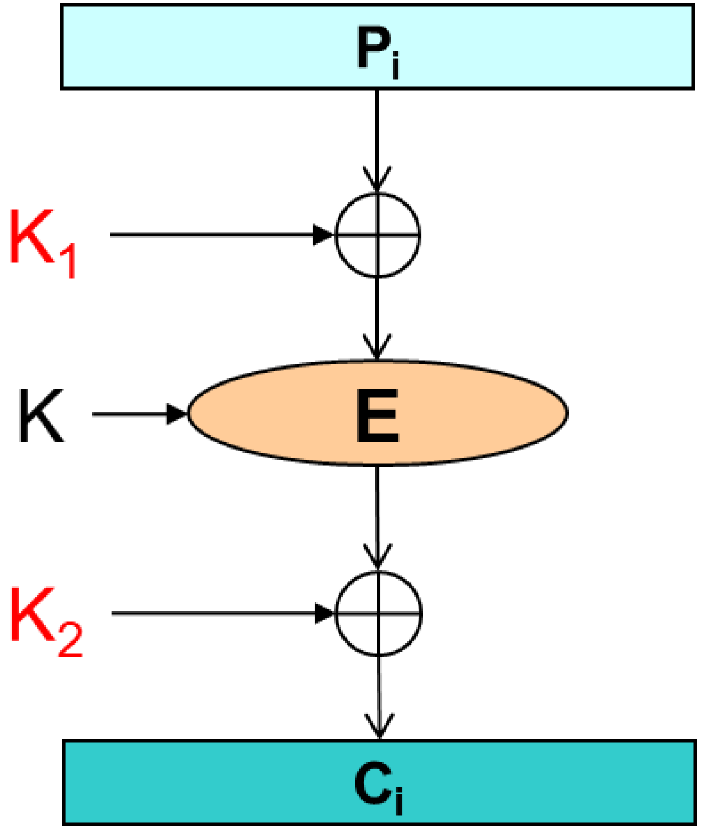
  $C_i = E_{K3}(D_{K2}(E_{K1}(P_i)))$ $P_i = D_{K1}(E_{K2}(D_{K3}(C_i)))$

  - With K1 ≠ K2 ≠ K3, it uses a 168-bit key
  - With K1 = K3 ≠ K2, it uses a 112-bit key
  - If K1 = K2 = K3 , then we get simple encryption
  - In all cases, **3 times slower than DES**

Cipher Modes: DESX

- Another solution for extending the lifetime of DES
  - Much faster than 3DES
  - Two extra keys are used to add confusion
    - Before the cipher input
    - After the cipher output

$C_i = E_K(K_1 \oplus P_i) \oplus K_2 \qquad P_i = K_1 \oplus D_K(K_2 \oplus C_i)$



- The equivalent key length is 184 bits
  - 64 + 64 + 56 bits
  - More than with 3DES