CSE 410/565 Computer Security
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Lecture 3: Symmetric Encryption II

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Symmetric Encryption

- So far we've covered:
  - what secure symmetric encryption is
  - high-level design of block ciphers
  - DES
- Next, we'll talk about:
  - AES
  - block cipher encryption modes

Advanced Encryption Standard (AES)

- In 1997 NIST made a formal call for an unclassified publicly disclosed encryption algorithm available worldwide and royalty-free
  - the goal was to replace DES with a new standard called AES
  - the algorithm must be a symmetric block cipher
  - the algorithm must support (at a minimum) 128-bit blocks and key sizes of 128, 192, and 256 bits
- The evaluation criteria were:
  - security
  - speed and memory requirements
  - algorithm and implementation characteristics

AES

- In 1998 15 candidate AES algorithms were announced
- They were narrowed to 5 in 1999: MARS, RC6, Rijndael, Serpent, and Twofish
  - all five were thought to be secure
- In 2001 Rijndael was adopted as the AES standard
  - invented by Belgian researchers Deamen and Rijmen
  - designed to be simple and efficient in both hardware and software on a wide range of platforms
  - supports different block sizes (128, 192, and 256 bits)
  - supports keys of different length (128, 192, and 256 bits)
  - uses a variable number of rounds (10, 12, or 14)

AES

- During encryption:
  - the block is copied into the state matrix
  - the state is modified at each round of encryption and decryption
  - the final state is copied to the ciphertext

$$\begin{array}{|c|c|c|c|}\hline in_0 & in_4 & in_8 & in_{12} \\ \hline in_1 & in_5 & in_9 & in_{13} \\ \hline in_2 & in_6 & in_{10} & in_{14} \\ \hline in_3 & in_7 & in_{11} & in_{15} \\ \hline \end{array} \longrightarrow \begin{array}{|c|c|c|c|}\hline s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ \hline s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ \hline s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ \hline s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \\ \hline \end{array} \dashrightarrow \begin{array}{|c|c|c|c|}\hline s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ \hline s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ \hline s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ \hline s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \\ \hline \end{array} \longrightarrow \begin{array}{|c|c|c|c|}\hline out_0 & out_4 & out_8 & out_{12} \\ \hline out_1 & out_5 & out_9 & out_{13} \\ \hline out_2 & out_6 & out_{10} & out_{14} \\ \hline out_3 & out_7 & out_{11} & out_{15} \\ \hline \end{array}$$

AES

- The key schedule in AES
  - the key is treated as a 4×4 matrix as well
  - the key is then expanded into an array of words
  - each word is 4 bytes and there are 44 words (for 128-bit key)
  - four distinct words serve as a round key for each round

$$\begin{array}{|c|c|c|c|} \hline k_0 & k_4 & k_8 & k_{12} \\ \hline k_1 & k_5 & k_9 & k_{13} \\ \hline k_2 & k_6 & k_{10} & k_{14} \\ \hline k_3 & k_7 & k_{11} & k_{15} \\ \hline \end{array} \longrightarrow \begin{array}{|c|c|c|c|c|} \hline w_0 & w_1 & \cdots & w_{42} & w_{43} \\ \hline \end{array}$$

AES

- Rijndael doesn't have a Feistel structure
  - 2 out of 5 AES candidates (including Rijndael) don't use Feistel structure
  - they process the entire block in parallel during each round
- The operations are (3 substitution and 1 permutation operations):
  - SubBytes: byte-by-byte substitution using an S-box
  - ShiftRows: a simple permutation
  - MixColumns: a substitution using mod 2^8 arithmetics
  - AddRoundKey: a simple XOR of the current state with a portion of the expanded key

AES

- At a high-level, encryption proceeds as follows:
  - set initial state $s_0 = m$
  - perform operation AddRoundKey (XORs k_i and s_i)
  - for each of the first $Nr - 1$ rounds:
    - perform a substitution operation SubBytes on s_i and an S-box
    - perform a permutation ShiftRows on s_i
    - perform an operation MixColumns on s_i
    - perform AddRoundKey
  - the last round is the same except no MixColumns is used
  - set the ciphertext $c = s_{Nr}$

AES

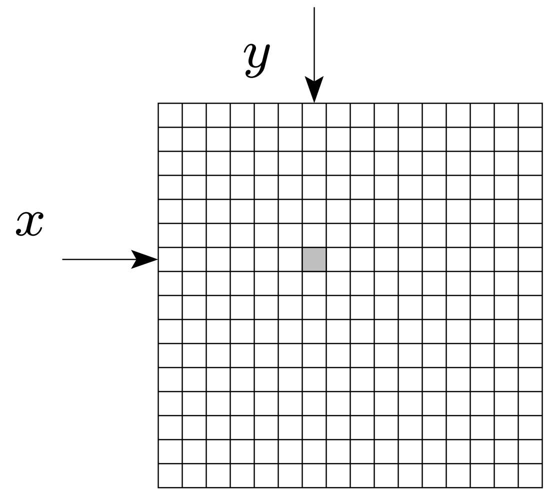
- More about Rijndael design…
  - ADDROUNDKEY is the only operation that uses key
    - that's why it is applied at the beginning and at the end
  - all operations are reversible
  - the decryption algorithm uses the expanded key in the reverse order
  - the decryption algorithm, however, is not identical to the encryption algorithm

AES

- The SUBBYTES operation
  - maps a state byte $s_{i,j}$ to a new byte $s'_{i,j}$ using S-box
  - the S-box is a 16×16 matrix with a byte in each position
    - the S-box contains a permutation of all possible 256 8-bit values
    - the values are computed using a formula
    - it was designed to resist known cryptanalytic attacks (i.e., to have low correlation between input bits and output bits)

AES

- The SUBBYTES operation
  - to compute the new $s'_{i,j}$:
    - set x to the 4 leftmost bits of $s_{i,j}$ and y to its 4 rightmost bits
    - use x as the row and y as the column to locate a cell in the S-box
    - use that cell value as $s'_{i,j}$



  - the same procedure is performed on each byte of the state

AES

- The ShiftRows operation
  - performs circular left shift on state rows
    - 2nd row is shifted by 1 byte
    - 3rd row is shifted by 2 bytes
    - 4th row is shifted by 3 bytes

$$
\begin{array}{|c|c|c|c|}
\hline
s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\
\hline
s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\
\hline
s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\
\hline
s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \\
\hline
\end{array}
\longrightarrow
\begin{array}{|c|c|c|c|}
\hline
s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\
\hline
s_{1,1} & s_{1,2} & s_{1,3} & s_{1,0} \\
\hline
s_{2,2} & s_{2,3} & s_{2,0} & s_{2,1} \\
\hline
s_{3,3} & s_{3,0} & s_{3,1} & s_{3,2} \\
\hline
\end{array}
$$

  - important because other operations operate on a single cell

AES

- The MIXCOLUMNS operation
  - multiplies the state by a fixed matrix

$$\begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} = \begin{bmatrix} s'_{0,0} & s'_{0,1} & s'_{0,2} & s'_{0,3} \\ s'_{1,0} & s'_{1,1} & s'_{1,2} & s'_{1,3} \\ s'_{2,0} & s'_{2,1} & s'_{2,2} & s'_{2,3} \\ s'_{3,0} & s'_{3,1} & s'_{3,2} & s'_{3,3} \end{bmatrix}$$

  - was designed to ensure good mixing among the bytes of each column
  - the coefficients 01, 02, and 03 are for implementation purposes (multiplication involves at most a shift and an XOR)

AES

- Decryption:
  - inverse S-box is used in SUBBYTES
  - inverse shifts are performed in SHIFTROWS
  - inverse multiplication matrix is used in MIXCOLUMNS
- Key expansion:
  - was designed to resist known attacks and be efficient
  - knowledge of a part of the key or round key doesn't enable calculation of other key bits
  - round-dependent values are used in key expansion

AES

- Summary of Rijndael design
  - simple design but resistant to known attacks
  - very efficient on a variety of platforms including 8-bit and 64-bit platforms
  - highly parallelizable
  - had the highest throughput in hardware among all AES candidates
  - well suited for restricted-space environments (very low RAM and ROM requirements)
  - optimized for encryption (decryption is slower)

AES Hardware Implementation

- It's been long known that hardware implementations of AES are extremely fast
  - the speed of encryption is compared with the speed of disk read
- Harware implementations however remained unaccessible to the average user
- Recently Intel introduced new AES instruction set (AES-NI) in its commodity processors
  - other processor manufacturers support it now as well
  - hardware acceleration can be easily used on many platforms

Secure Encryption

- For symmetric encryption to be secure, the key must be chosen completely at random
  - cryptography failures are often due to incorrect implementations
- Using a strong block cipher is not enough for secure encryption!
  - if you need to send more than 1 block (i.e., 16 bytes) over the key lifetime, applying plain block cipher to the message as

    $$\mathsf{Enc}_k(b_1), \mathsf{Enc}_k(b_2), \ldots$$

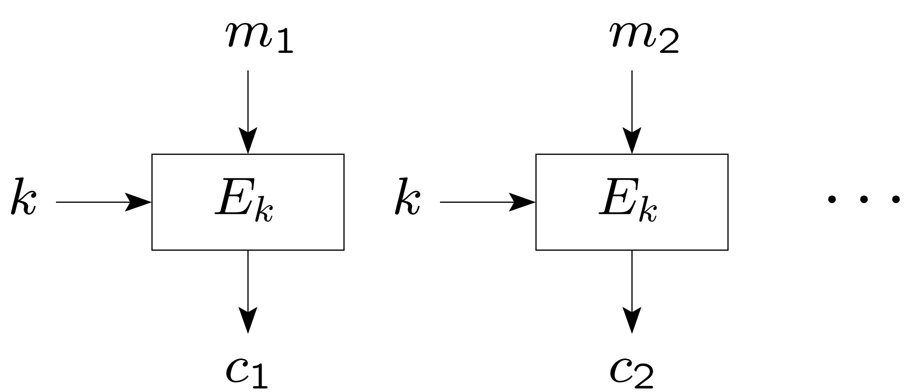
    will fail even weak definitions of secure encryption
  - no deterministic encryption can be secure if multiple blocks are sent

Encryption Modes

- Encryption modes indicate how messages longer than one block are encrypted and decrypted
- 4 modes of operation were standardized in 1980 for Digital Encryption Standard (DES)
  - can be used with any block cipher
  - electronic codebook mode (ECB), cipher feedback mode (CFB), cipher block chaining mode (CBC), and output feedback mode (OFB)
- 5 modes were specified with the current standard Advanced Encryption Standard (AES) in 2001
  - the 4 above and counter mode

Encryption Modes

- Electronic Codebook (ECB) mode
  - divide the message m into blocks $m_1 m_2 \ldots m_\ell$ of size n each
  - encipher each block separately: for $i = 1, \ldots, \ell$, $c_i = E_k(m_i)$, where E denotes block cipher encryption
  - the resulting ciphertext is $c = c_1 c_2 \ldots c_\ell$

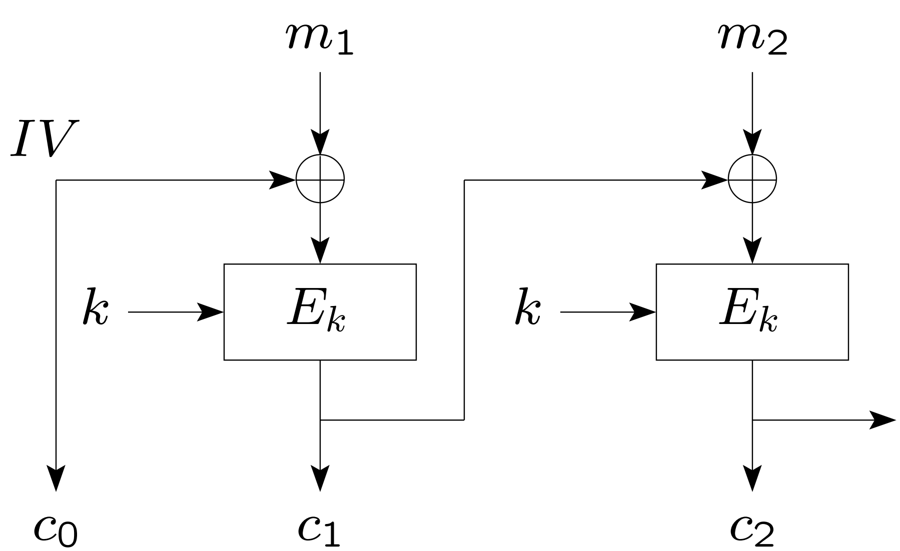


Encryption Modes

- Properties of ECB mode:
  - identical plaintext blocks result in identical ciphertexts (under the same key)
  - each block can be encrypted and decrypted independently
  - this mode doesn't result in secure encryption
- ECB mode is a plain invocation of the block cipher
  - it allows the block cipher to be used in other, more complex cryptographic constructions

Encryption Modes

- Cipher Block Chaining (CBC) mode
  - set $c_0 = IV \xleftarrow{R} \{0,1\}^n$ (initialization vector)
  - encryption: for $i = 1, \ldots, \ell$, $c_i = E_k(m_i \oplus c_{i-1})$
  - decryption: for $i = 1, \ldots, \ell$, $m_i = c_{i-1} \oplus D_k(c_i)$, where D is block cipher decryption



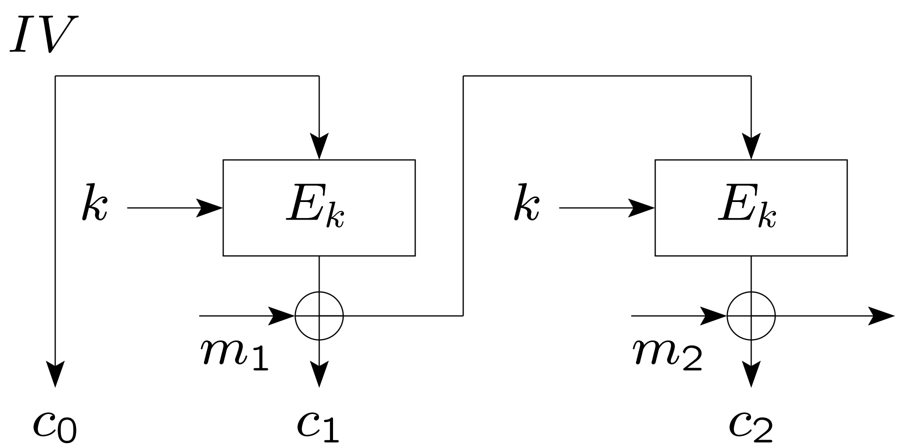
Encryption Modes

- Properties of CBC mode:
  - this mode is CPA-secure (has a formal proof) if the block cipher can be assumed to produce pseudorandom output
  - a ciphertext block depends on all preceding plaintext blocks
  - sequential encryption, cannot use parallel hardware
  - IV must be random and communicated intact
    - if the IV is not random, security quickly degrades
    - if someone can fool the receiver into using a different IV, security issues arise

Encryption Modes

- Cipher Feedback (CFB) mode
  - the message is XORed with the encryption of the feedback from the previous block
  - generate random IV and set initial input $I_1 = IV$
  - encryption: $c_i = E_k(I_i) \oplus m_i$; $I_{i+1} = c_i$
  - decryption: $m_i = c_i \oplus E_k(I_i)$

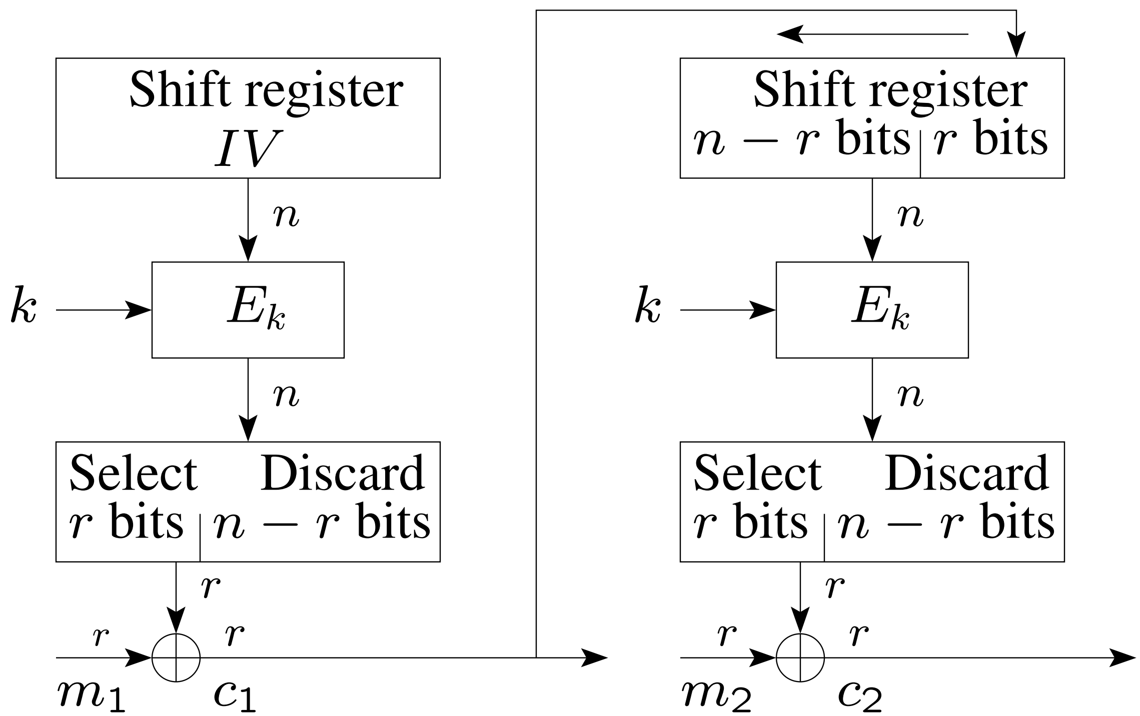
Encryption Modes



- This mode allows the block cipher to be used as a stream cipher
  - if our application requires that plaintext units shorter than the block are transmitted without delay, we can use this mode
  - the message is transmitted in r-bit units (r is often 8 or 1)

Encryption Modes

- Cipher Feedback (CFB) mode
  - input: key k, r-bit plaintext blocks $m_1, \ldots$
  - output: n-bit IV, r-bit ciphertext blocks $c_1, \ldots$

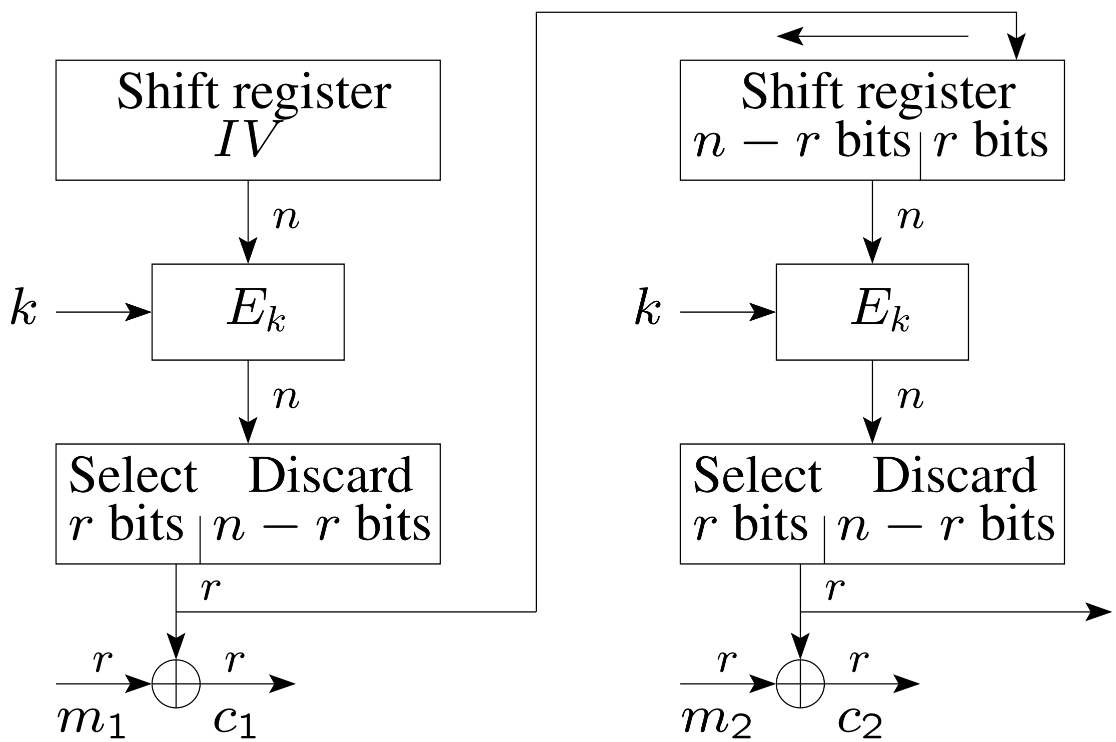


Encryption Modes

- Properties of CFB mode:
  - the mode is CPA-secure (under the same assumption that the block cipher is strong)
  - similar to CBC, a ciphertext block depends on all previous plaintext blocks
  - throughput is decreased when the mode is used on small units
    - one encryption operation is applied per r bits, not per n bits

Encryption Modes

- Output Feedback (OFB) mode
  - similar to CFB, but the feedback is from encryption output and is independent of the message

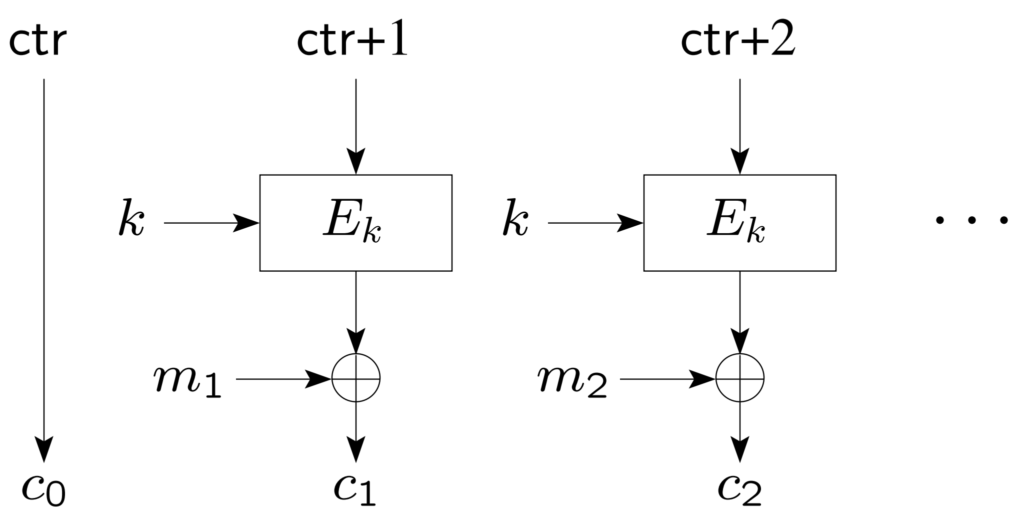


Encryption Modes

- Output Feedback (OFB) mode:
  - n-bit feedback is recommended
  - using fewer bits for the feedback reduces the size of the cycle
- Properties of OFB:
  - the mode is CPA-secure
  - the key stream is plaintext-independent
  - similar to CFB, throughput is decreased for $r < n$, but the key stream can be precomputed

Encryption Modes

- Counter (CRT) mode
  - a counter is encrypted and XORed with a plaintext block
  - no feedback into the encryption function
  - initially set ctr $= IV \stackrel{R}{\leftarrow} \{0,1\}^n$



Encryption Modes

- Counter (CRT) mode
  - encryption: for $i = 1, \ldots, \ell$, $c_i = E_k(\mathsf{ctr} + i) \oplus m_i$
  - decryption: for $i = 1, \ldots, \ell$, $m_i = E_k(\mathsf{ctr} + i) \oplus c_i$
- Properties:
  - there is no need to pad the last block to full block size
  - if the last plaintext block is incomplete, we just truncate the last cipherblock and transmit it

Encryption Modes

- Advantages of counter mode
  - Hardware and software efficiency: multiple blocks can be encrypted or decrypted in parallel
  - Preprocessing: encryption can be done in advance; the rest is only XOR
  - Random access: ith block of plaintext or ciphertext can be processed independently of others
  - Security: at least as secure as other modes (i.e., CPA-secure)
  - Simplicity: doesn't require decryption or decryption key scheduling
- But what happens if the counter is reused?

Summary

- AES is the current block cipher standard
  - it offers strong security and fast performance
- Five encryption modes are specified as part of the standard
  - ECB mode is not for secure encryption
  - any other encryption mode achieves sufficient security
    - use one of these modes for encryption even if the message is a single block
- Strong randomness is required for cryptographic purposes
  - key generation, IV generation, etc.