THE UNIVERSITY OF BRITISH COLUMBIA

Symmetric Crypto Systems

EECE 412

 09/16/08

Module Outline

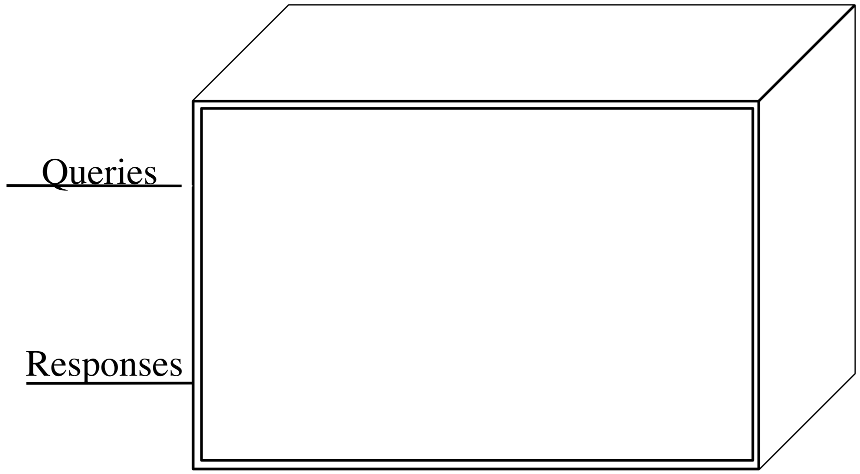
- Stream ciphers “under the hood”
- Block ciphers “under the hood”
- Modes of operation for block ciphers

Stream Ciphers

3

Random Generator (Stream Cipher)
as Random Oracle

- In:
  - short string (key)
  - length of the output



- Out: long random stream of bits (keystream)
- Applications:
  - Communications encryption
  - Storage encryption

Properties

- Should not reuse
  - Use seed

4

Stream Ciphers

- Not as popular today as block ciphers
- A5/1
  - Designed for hardware implementations
  - Based on shift registers
  - Used in GSM mobile phone system
- RC4
  - Designed for software implementations
  - Based on a changing lookup table
  - Used many places

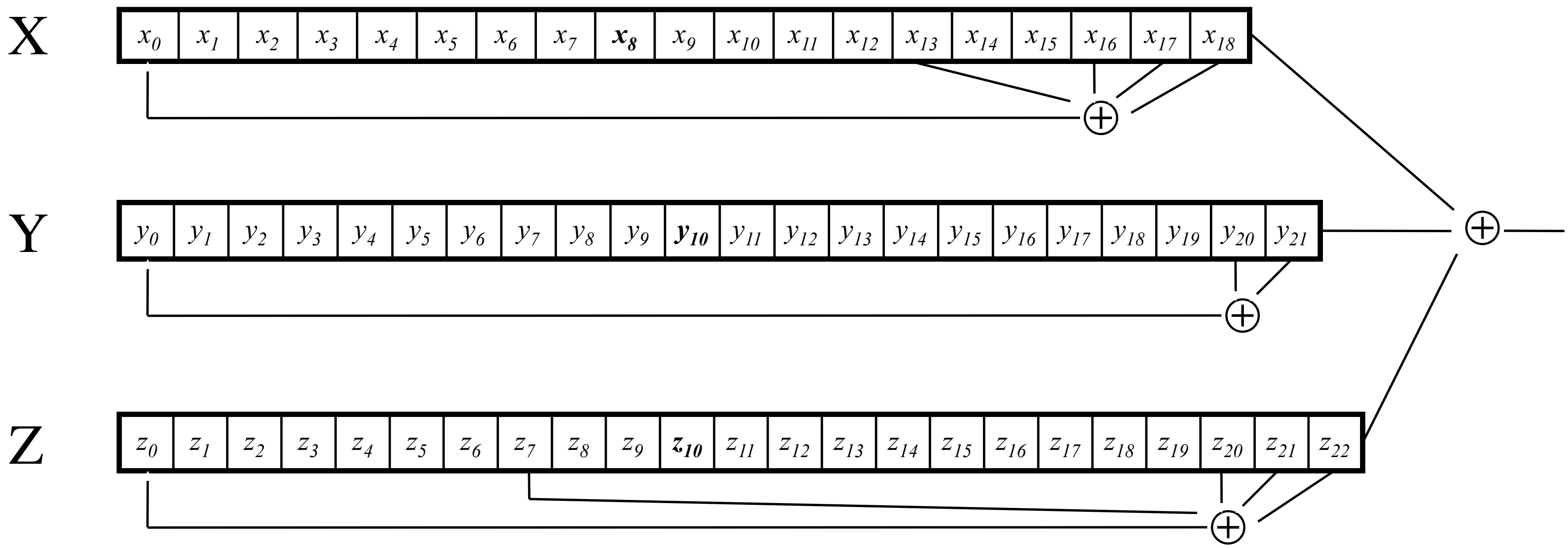
A5/1

- A5/1 consists of 3 shift registers
  - X: 19 bits $(x_0, x_1, x_2, \ldots, x_{18})$
  - Y: 22 bits $(y_0, y_1, y_2, \ldots, y_{21})$
  - Z: 23 bits $(z_0, z_1, z_2, \ldots, z_{22})$

A5/1

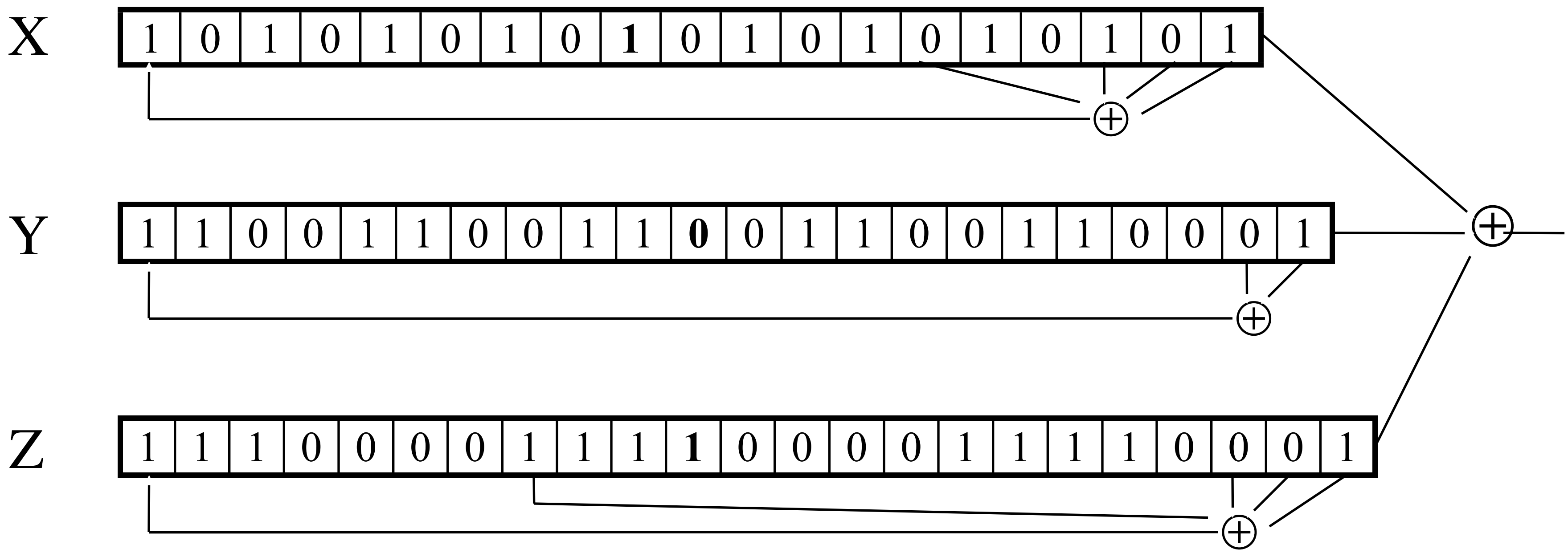
- At each step: $m = \mathrm{maj}(x_8, y_{10}, z_{10})$
  - Examples: $\mathrm{maj}(0,1,0) = 0$ and $\mathrm{maj}(1,1,0) = 1$
- If $x_8 = m$ then X steps
  - $t = x_{13} \oplus x_{16} \oplus x_{17} \oplus x_{18}$
  - $x_i = x_{i-1}$ for $i = 18,17,\ldots,1$ and $x_0 = t$
- If $y_{10} = m$ then Y steps
  - $t = y_{20} \oplus y_{21}$
  - $y_i = y_{i-1}$ for $i = 21,20,\ldots,1$ and $y_0 = t$
- If $z_{10} = m$ then Z steps
  - $t = z_7 \oplus z_{20} \oplus z_{21} \oplus z_{22}$
  - $z_i = z_{i-1}$ for $i = 22,21,\ldots,1$ and $z_0 = t$
- Keystream bit is $x_{18} \oplus y_{21} \oplus z_{22}$

A5/1



- Each value is a single bit
- Key is used as **initial fill** of registers
- Each register steps or not, based on (x_8, y_{10}, z_{10})
- Keystream bit is XOR of right bits of registers

A5/1: example



- In this example, $m = \text{maj}(x_8, y_{10}, z_{10}) = \text{maj}(\mathbf{1},\mathbf{0},\mathbf{1}) = \mathbf{1}$
- Register X steps, Y does not step, and Z steps
- Keystream bit is XOR of right bits of registers
- Here, keystream bit will be $0 \oplus 1 \oplus 0 = 1$

Shift Register Crypto

- Shift register-based crypto is efficient in hardware
- Harder to implement in software
- In the past, very popular
- Today, more is done in software due to faster processors
- Shift register crypto still used some

Use of Stream Ciphers

- Stream ciphers were big in the past
  - Efficient in hardware
  - Speed needed to keep up with voice, etc.
  - Today, processors are fast, so software-based crypto is fast enough

Block Ciphers “Under the Hood”

Random Permutation (Block Cipher) as Random Oracle

- In
  - fixed size short string (plaintext) M,
    - DES -- 64 bits
  - Key K

- Out
  - same fixed size short string (ciphertext) C

Notation

- $C = \{ M \}_K$
- $M = \{ C \}_K$

Related Notes

- Main properties of block ciphers
  - invertible
  - confusing
  - diffusing
- Main block ciphers
  - Data Encryption Standard (DES)
  - Advanced Encryption Standard (AES) a.k.a., Rijndael

(Iterated) Block Cipher

- Plaintext and ciphertext consists of fixed sized blocks
- Ciphertext obtained from plaintext by iterating a **round function**
- Input to round function consists of key and the output of previous round
- Usually implemented in software

Feistel Cipher

- type of block cipher design, not a specific cipher
- Split plaintext block into left and right halves:
  Plaintext = (L_0,R_0)
- For each round $i=1,2,\ldots,n$, compute

  $L_i = R_{i-1}$

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

  where F is **round function** and K_i is **subkey**
- Ciphertext = (L_n,R_n)

Feistel Cipher

- Decryption: Ciphertext = (L_n,R_n)
- For each round $i=n,n-1,\ldots,1$, compute

  $R_{i-1} = L_i$

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

  where F is round function and K_i is subkey
- Plaintext = (L_0,R_0)
- Formula "works" for any function F
- But only secure for certain functions F
  - silly round function example: F(x, y) == 0 for any x and y.

Advanced Encryption Standard

- Replacement for DES
- AES competition (late 90's)
  - NSA openly involved
  - Transparent process
  - Many strong algorithms proposed
  - Rijndael Algorithm ultimately selected
    - Pronounced like "Rain Doll" or "Rhine Doll"
    - invented by Joan Daemen and Vincent Rijmen
- Iterated block cipher (like DES)

AES Overview

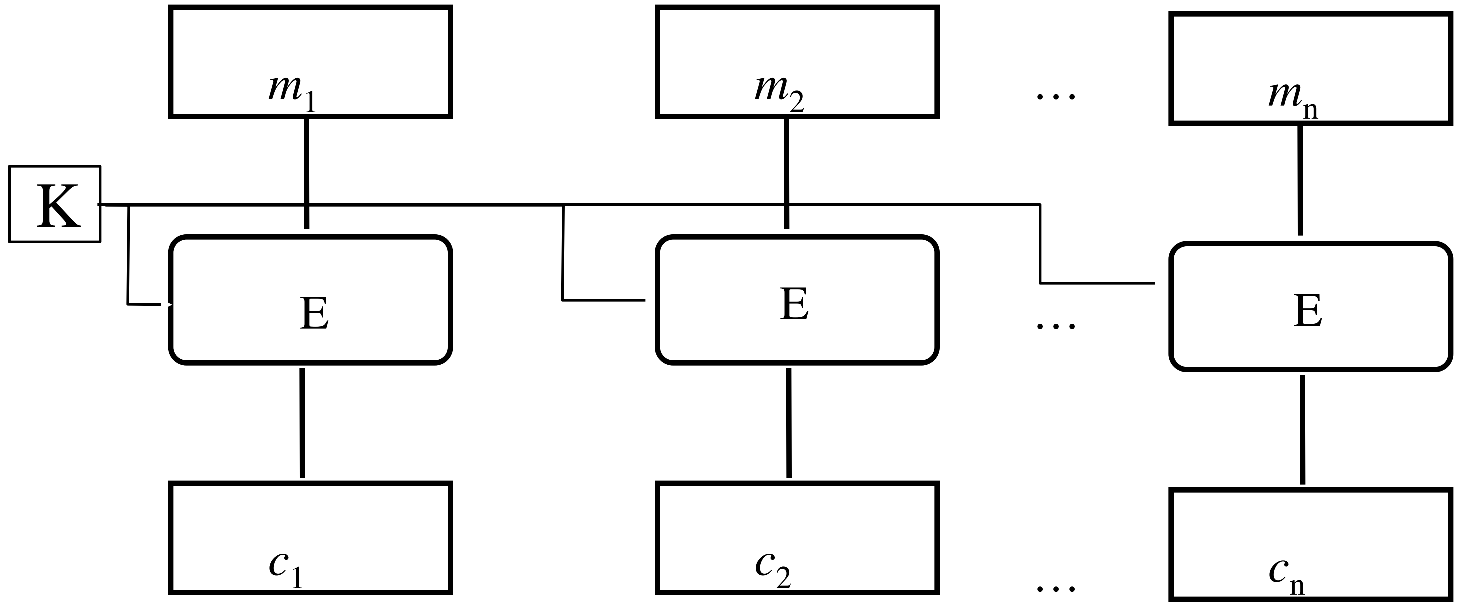
- **Block size:** 128, 192 or 256 bits
- **Key length:** 128, 192 or 256 bits (independent of block size)
- 10 to 14 rounds (depends on key length)
- Each round uses 4 functions (in 3 “layers”)
  - ByteSub (nonlinear layer)
  - ShiftRow (linear mixing layer)
  - MixColumn (nonlinear layer)
  - AddRoundKey (key addition layer)

AES demonstration

Modes of Operation

Electronic Code Book (ECB)

$M = m_1 \mid m_2 \mid \ldots \mid m_n$



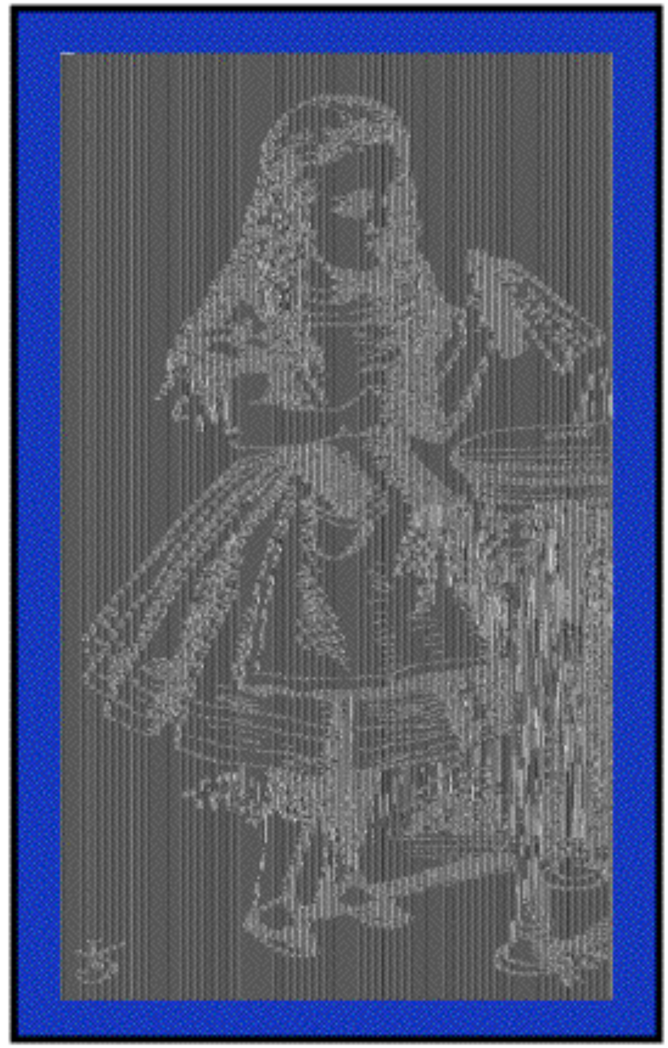
$C = c_1 \mid c_2 \mid \ldots \mid c_n$

$c_i = E_K(m_i)$

Drawbacks

- Same message has same ciphertext
- Redundant/repetitive patterns will show through
- Subject to "cut-and-splice" attacks

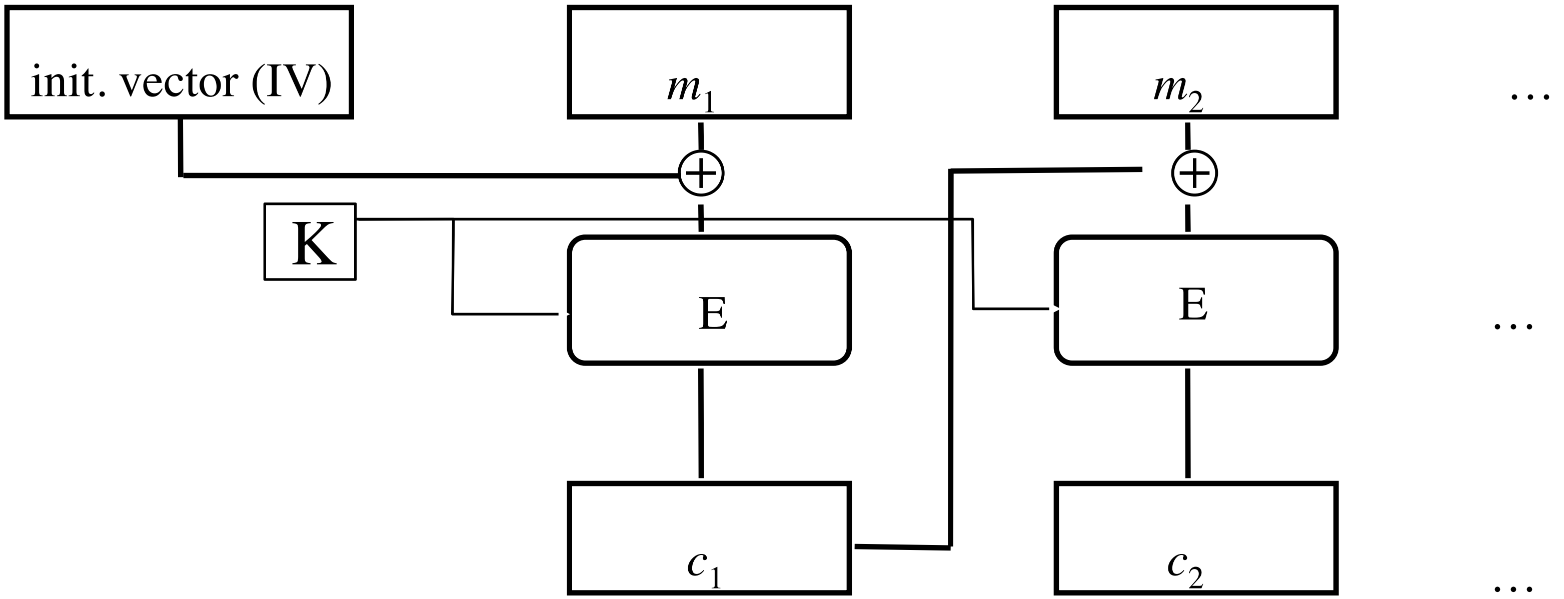
Alice in ECB Mode



Cipher Block Chaining (CBC)

$c_i = E_K(m_i \oplus c_{i-1})$

$M = m_1 \mid m_2 \mid \ldots \mid m_n$



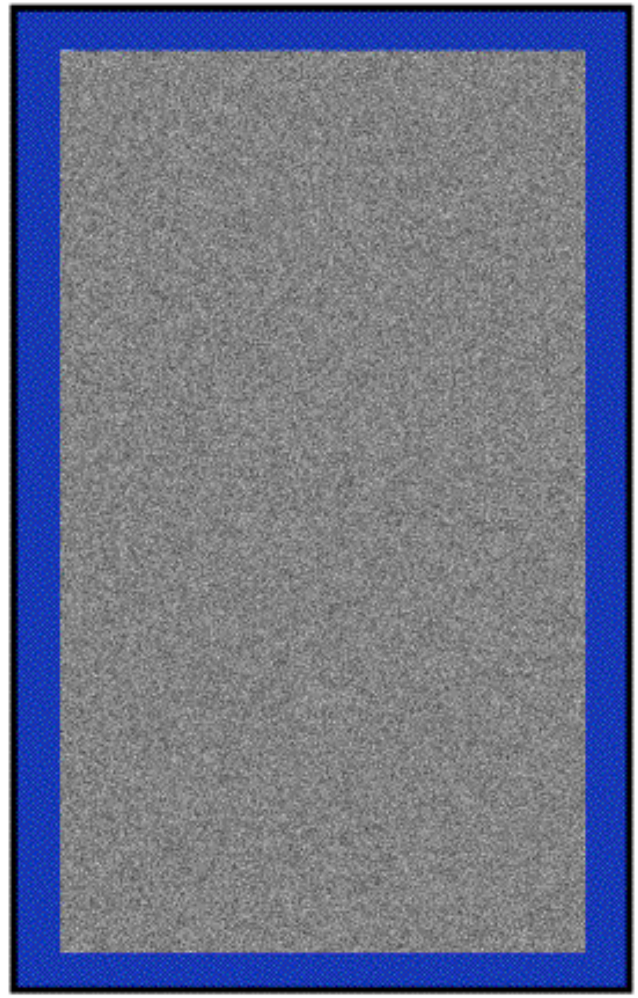
$C = IV \mid c_1 \mid c_2 \mid \ldots \mid c_n$

Decrypting with CBC

$c_i = D_K(m_i) \oplus c_{i-1}$

29

Alice in CBC Mode



Output Feedback (OFB)Mode

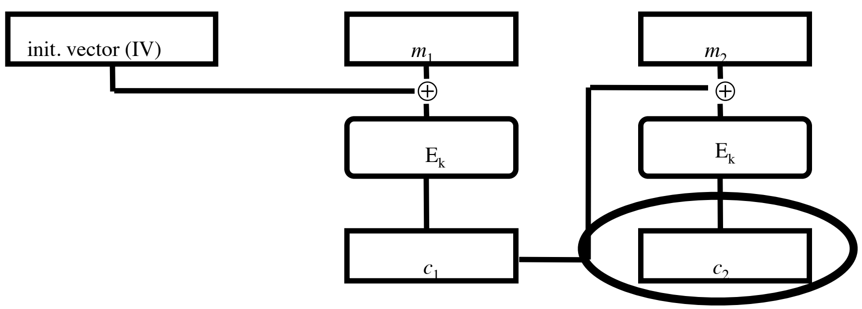
- $C_i = m_i \oplus E_K(K_{i-1})$, $K_0 = IV$
- $K_1 = E_K(IV)$, $K_2=E_K(K_1)$, … $K_i=E_K(K_{i-1})$ …
- Purpose
  - use block cipher as a stream cipher

Counter Encryption

- Drawbacks of feedback modes
  - Hard to parallelize
    - CBC -- cannot pre-compute
    - OFB -- memory requirements
- Counter Encryption is easier to parallelize
  - $c_i = m_i \oplus E_K(IV+i)$
  - $m_i = c_i \oplus E_K(IV+i)$

Message Authentication Code (MAC)

- Purpose
  - protect message integrity and authenticity
- How to do MAC with a block cipher?



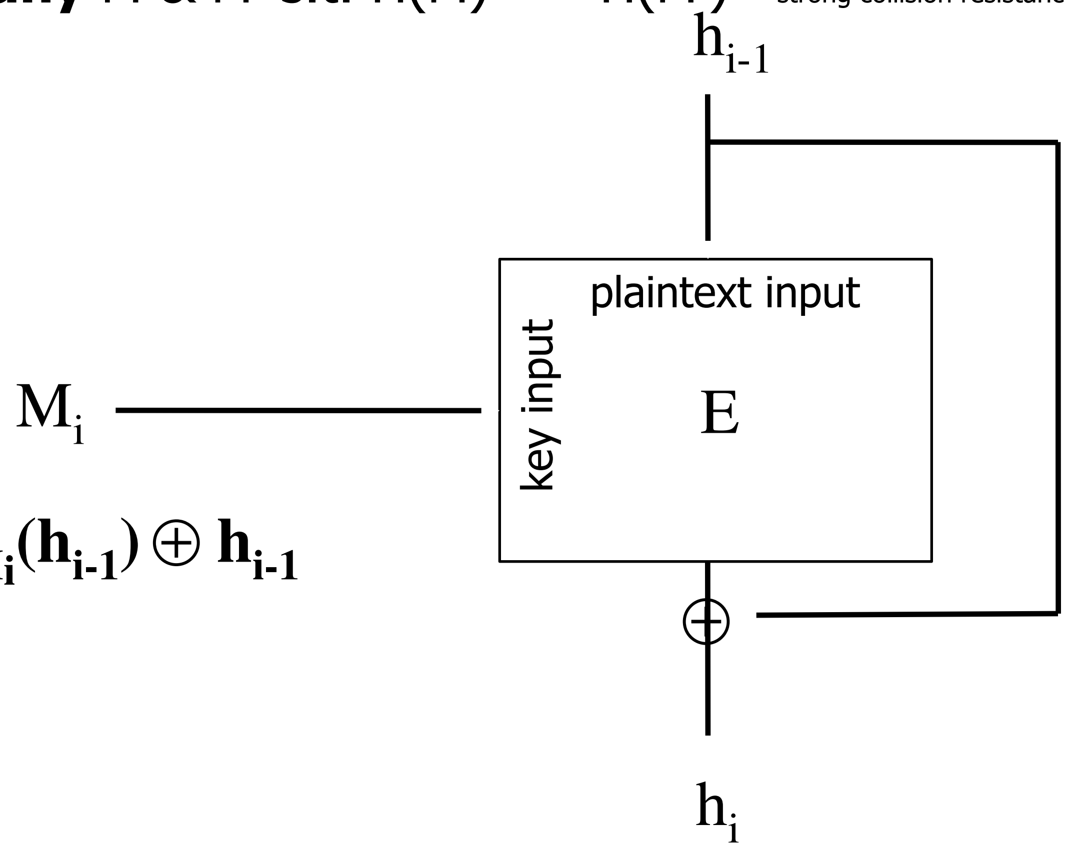
In CBC mode, the last block of cipher text serves as the MAC for the entire message

36

Hash Function from a Block Cipher

$h = H(M)$

1. Easy to compute h from M - efficient
2. Hard to compute M from h – one way
3. For **given** M, hard to find another M′ s.t. H(M) == H(M′) – weak collision resistance
4. For **any** M & M′ s.t. H(M) == H(M′) – strong collision resistance



$$\mathbf{h_i = E_{M_i}(h_{i-1}) \oplus h_{i-1}}$$

37

Common Hash Functions and Applications

- Common hash functions
  - (Message Digest) MD5 value 128b
  - (Secure Hash Algorithm) SHA-1 180b value, SHA-256, SHA-512
- Applications
  - MACs
    - $MAC_K(M) = H(K,M)$
    - $HMAC_K(M) = H(K \oplus A, H(K \oplus B, M))$, A & B = magic (pg. 94, Stamp)
  - Time stamping service
  - key updating
    - $K_i = H(K_{i-1})$
    - Backward security
  - Autokeying
    - $K_{i+1} = H(K_i, M_{i1}, M_{i2}, \ldots)$
    - Forward security

Key Points

- Ciphers are either substitution, transposition (a.k.a., permutation), or product
- Any block cipher should confuse and defuse
- Block ciphers are implemented in SP-networks
- Stream ciphers and hash functions are commonly implemented with block ciphers
- Hash functions used for
    - fingerprinting data, MAC, key updating, autokeying,

39