Symmetric Crypto Systems

EECE 412

Module Outline

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

learning objectives

explain main properties of block and stream ciphers,

match a cipher type and mode of operation to the system at hand,

explain how ECB, CBC, OFB, and CTR modes of operation work and draw diagrams showing that,

given a mode of operation, identify its advantages and shortcomings.

Stream Ciphers

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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*

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

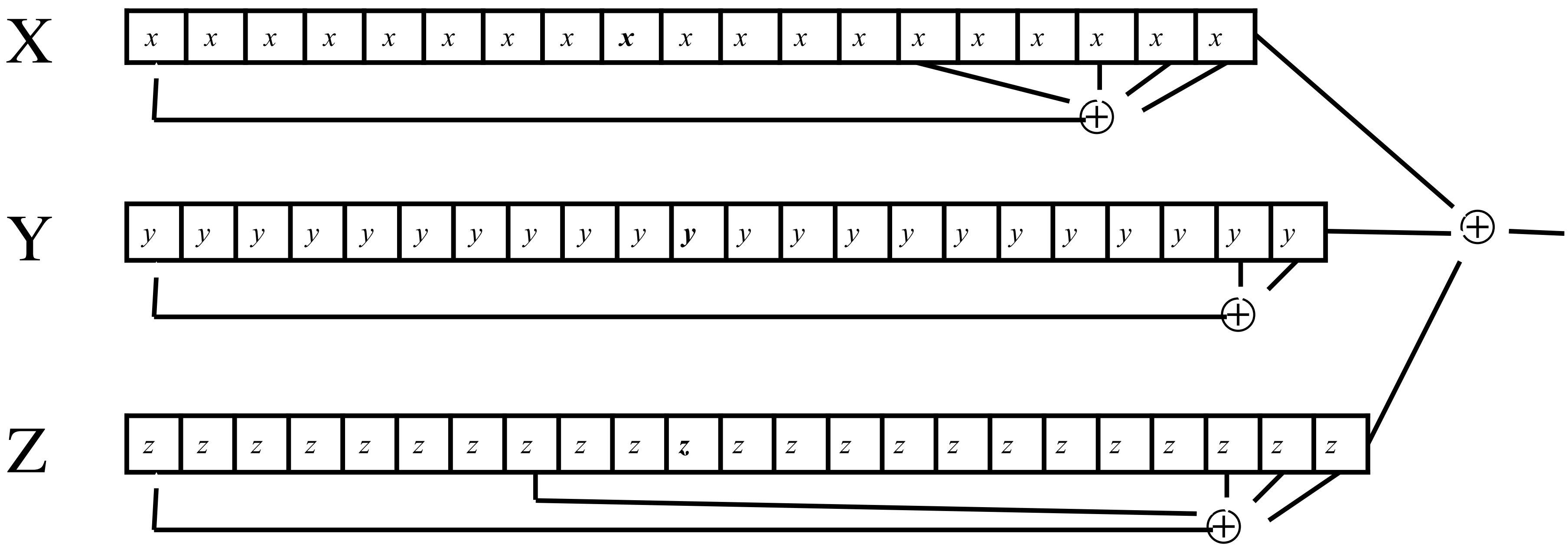
A5/1

- 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: $m = \text{maj}(x_8, y_{10}, z_{10})$
  - Examples: $\text{maj}(0,1,0) = 0$ and $\text{maj}(1,1,0) = 1$
- 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

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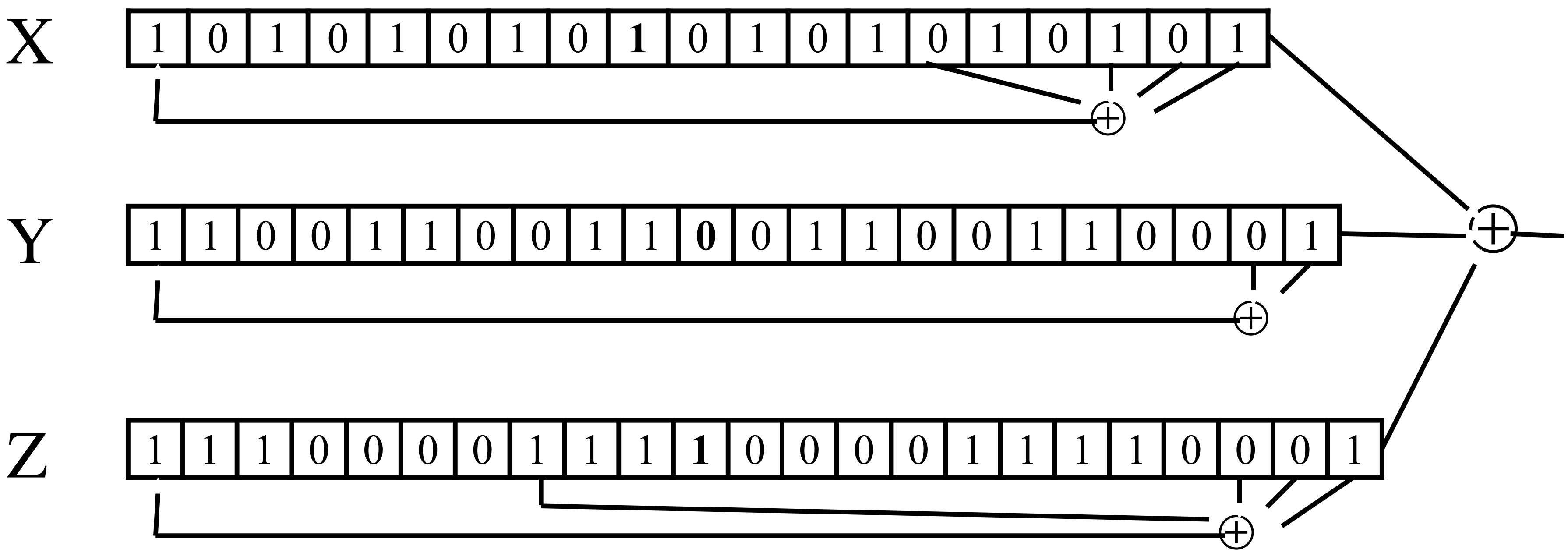
A5/1: example



- 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 $0 \oplus 1 \oplus 0 = 1$

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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)

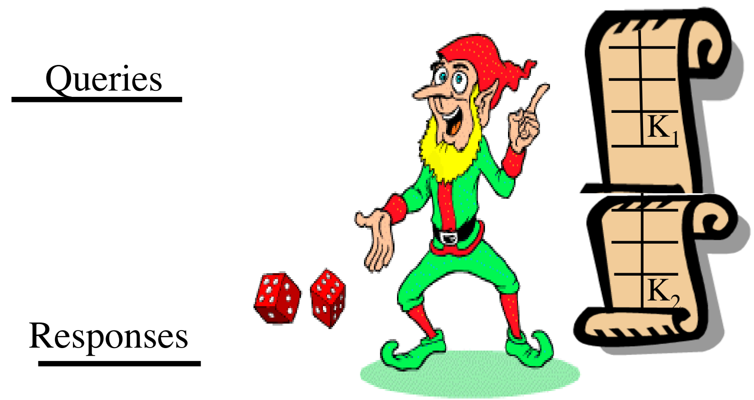
as Random Oracle

In

fixed size short string (plaintext) M,

DES -- 64 bits

Key K



Out

same fixed size short string (ciphertext) C

Notation

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

Properties

- Invertible

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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

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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,…,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.

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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 bits (Rijndael had also 192 or 256)
- **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

review questions

in A5/1, how is the keystream bit is used after its been obtained (after all it's only a single bit)?

how would you define "confusion" and "diffusion" in the context of ciphers?

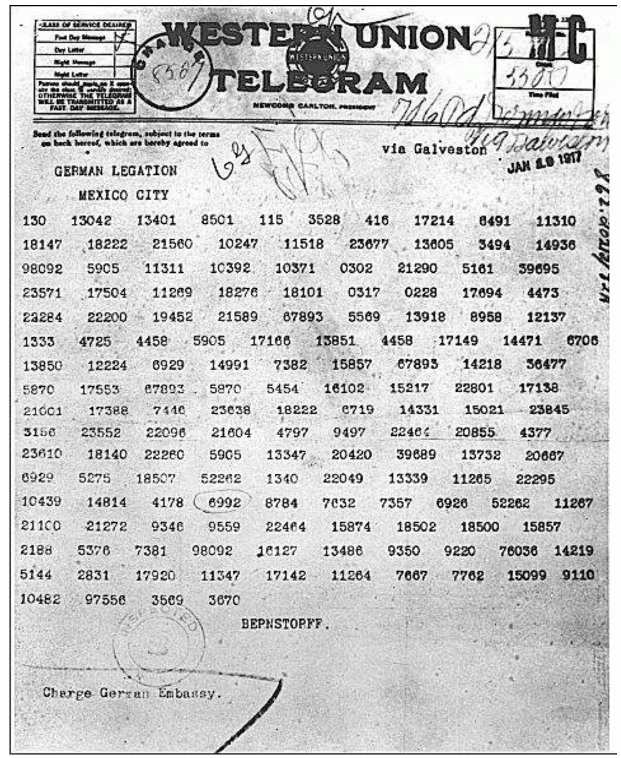
- confusion -- obscuring the relationship between the plaintext and ciphertext
- diffusion -- spreading the plaintext statistics through the ciphertext

Modes of Operation

Code book

Literally, a book filled with “codewords”

Februar	13605
fest	13732
finanzielle	13850
folgender	13918
Frieden	17142
Friedenschluss	17149
:	:


WESTERN UNION TELEGRAM

via Galveston

JAN 19 1917

GERMAN LEGATION

MEXICO CITY

130 13042 13401 8501 115 3528 416 17214 6491 11310
18147 18222 21560 10247 11518 23677 13605 3494 14936
98092 5905 11311 10392 10371 0302 21290 5161 39695
23571 17504 11269 18276 18101 0317 0228 17694 4473
22284 22200 19452 21589 67893 5569 13918 8958 12137
1333 4725 4458 5905 17166 13851 4458 17149 14471 6706
13850 12224 6929 14991 7382 15857 67893 14218 36477
5870 17553 67893 5870 5454 16102 15217 22801 17138
21001 17388 7446 23638 18222 6719 14331 15021 23845
3156 23552 22096 21604 4797 9497 22464 20855 4377
23610 18140 22260 5905 13347 20420 39689 13732 20667
6929 5275 18507 52262 1340 22049 13339 11265 22295
10439 14814 4178 6992 8784 7632 7357 6926 52262 11267
21100 21272 9346 9559 22464 15874 18502 18500 15857
2188 5376 7381 98092 16127 13486 9350 9220 76036 14219
5144 2831 17920 11347 17142 11264 7667 7762 15099 9110
10482 97556 3569 3670

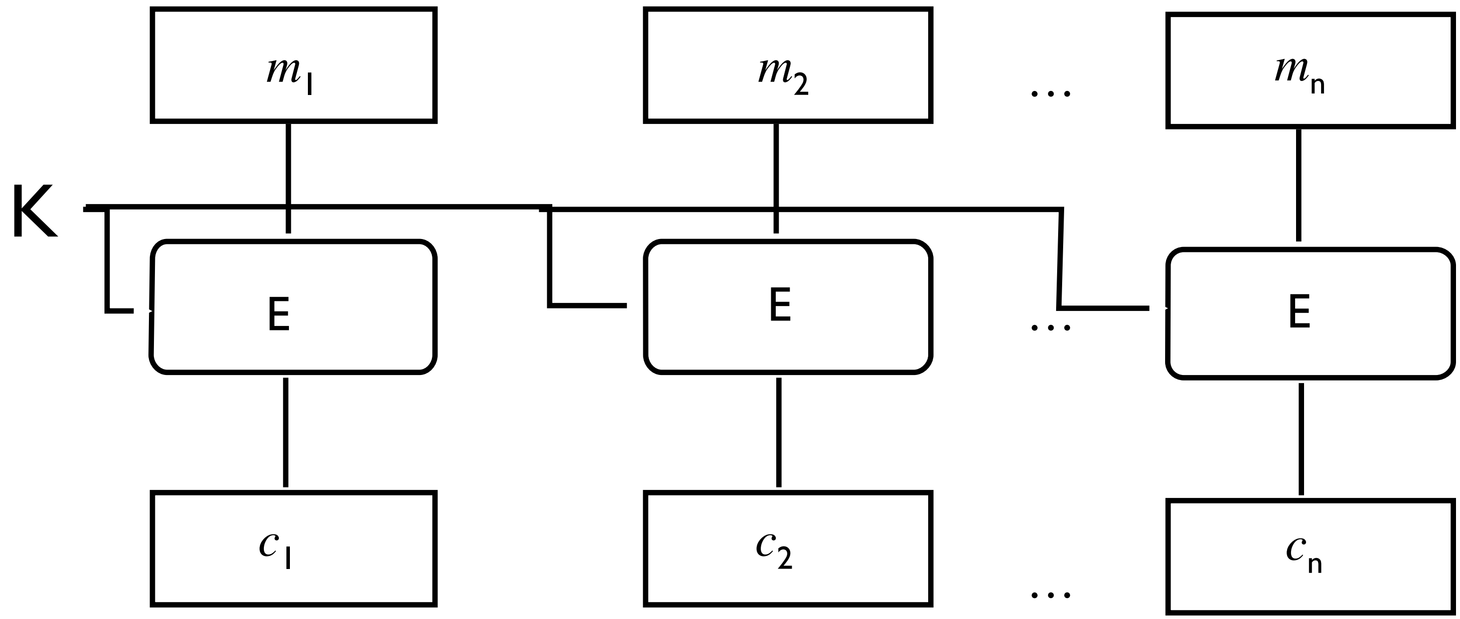
BERNSTORFF.

Charge German Embassy.

Modern block ciphers are code books!

Electronic Code Book (ECB)

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



$c_i = E_K(m_i)$ $C = c_1 \mid c_2 \mid \ldots \mid c_n$

Drawbacks

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

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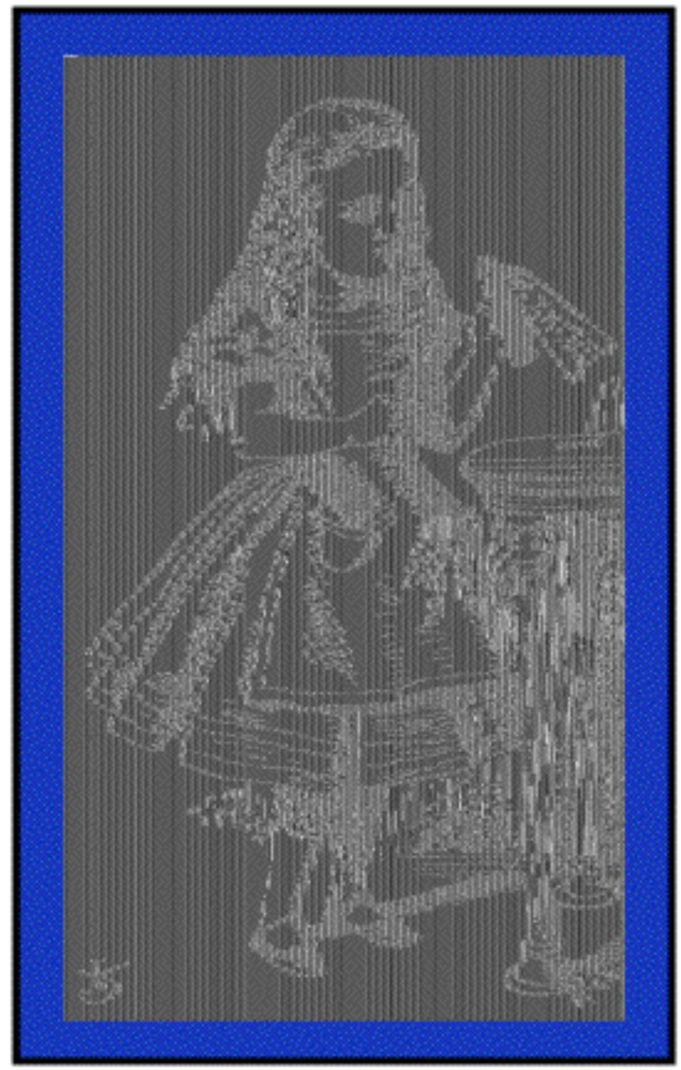
Alice in ECB Mode



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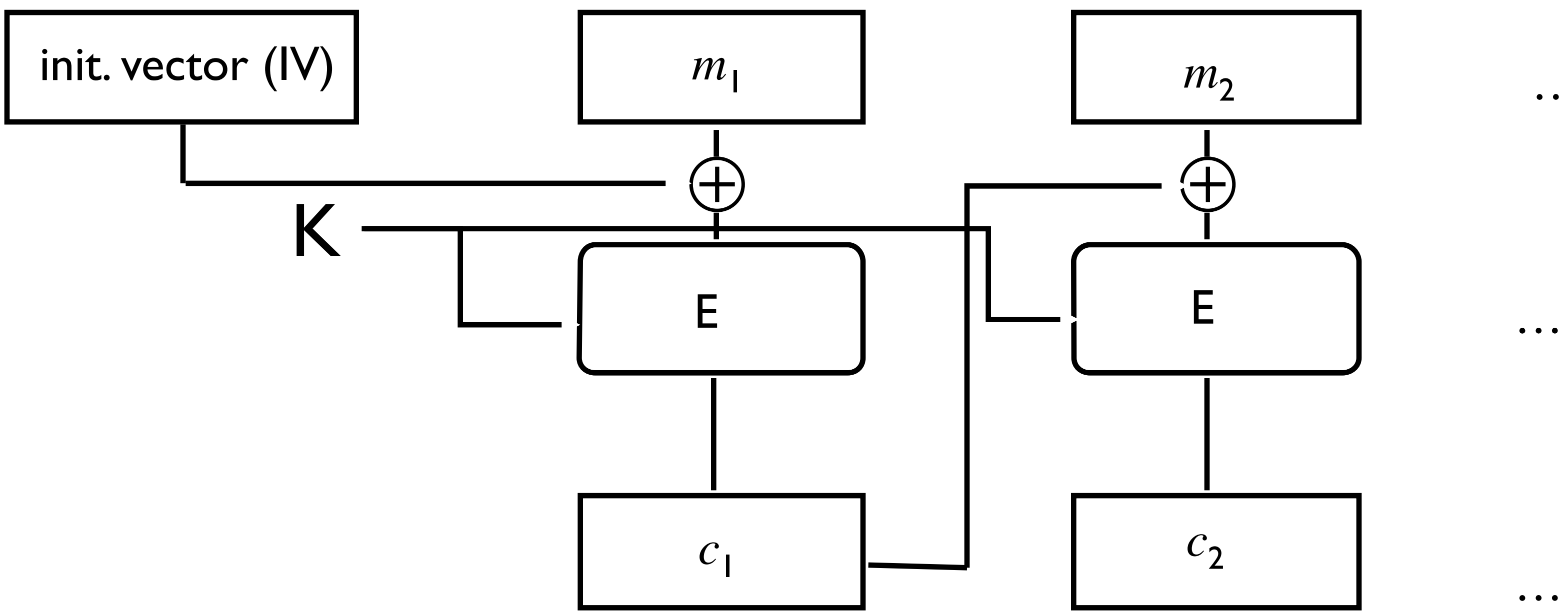
Cipher Block Chaining (CBC)

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

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

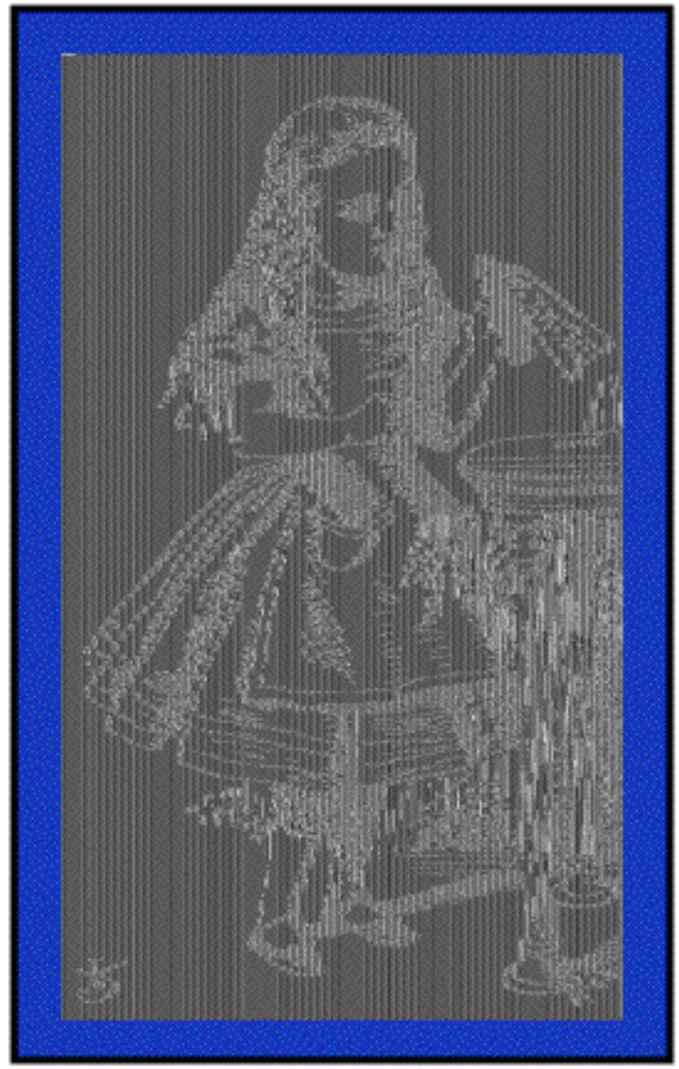


$C = IV \mid c_1 \mid c_2 \mid \ldots \mid c_n$

Decrypting with CBC: $m_i = D_K(c_i) \oplus c_{i-1}$

Drawback: cannot precompute c_i without c_{i-1}

Alice in ECB Mode



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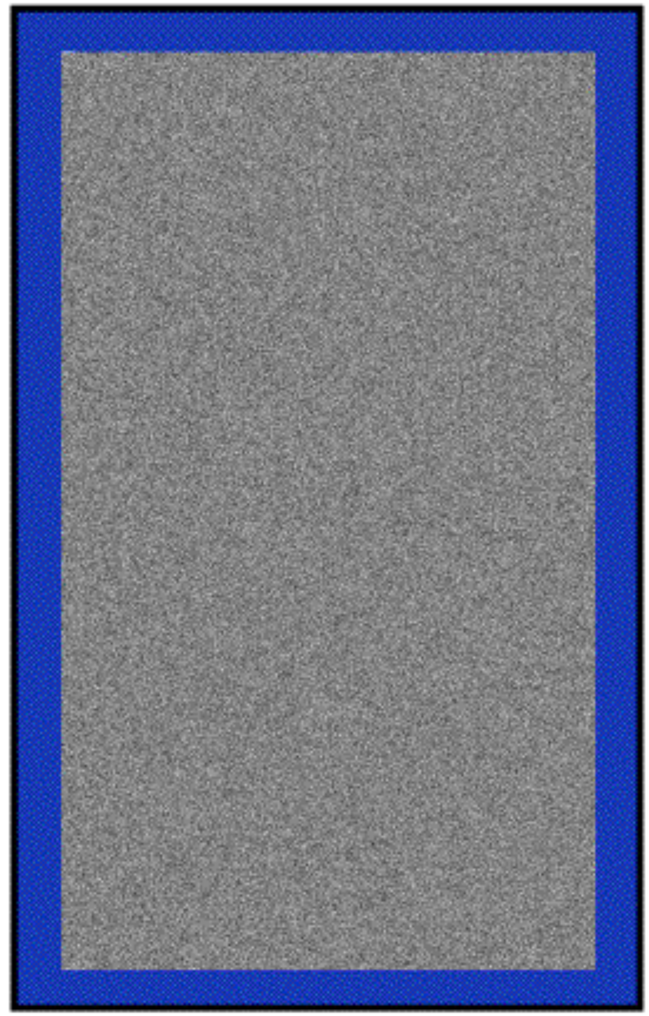
Alice in CBC Mode



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Output Feedback (OFB) Mode

K_0 = IV, $K_1 = E_K(IV)$, $K_2=E_K(K_1)$, … $K_i=E_K(K_{i-1})$ …

- $C_i = m_i \oplus K_i$

draw OFB diagram, similar to the one for CBC

Purpose

use block cipher as a stream cipher

Drawback

K_1, ... K_i must be kept in memory

TLS example

CipherSuite TLS_RSA_WITH_AES_256_CBC_SHA = { 0x00, 0x35 };

CipherSuite TLS_DH_RSA_WITH_AES_256_CBC_SHA = { 0x00, 0x37 };

Counter Mode (CTR)

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

draw CTR diagram for decryption

$m_i = c_i \oplus E_K(IV+i)$

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IPSec example

Case #3: Encrypting 48 bytes (3 blocks) using AES-CBC with 128-bit key

Key : 0x6c3ea0477630ce21a2ce334aa746c2cd

IV : 0xc782dc4c098c66cbd9cd27d825682c81

Plaintext : "This is a 48-byte message (exactly 3 AES blocks)"

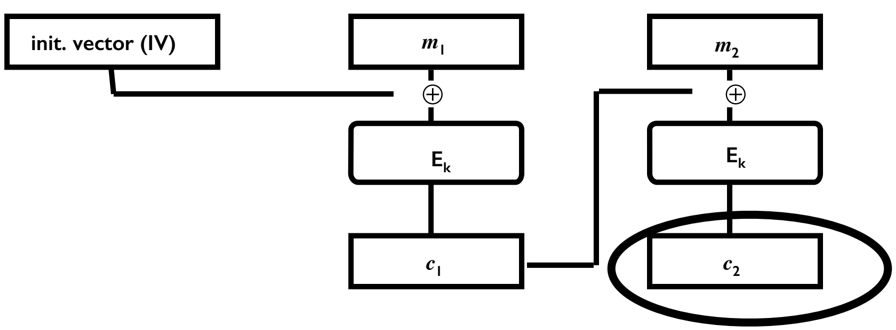
Ciphertext: 0xd0a02b3836451753d493665d33f0e886

2dea54cdb293abc7506939276772f8d5

021c19216bad525c8579695d83ba2684

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

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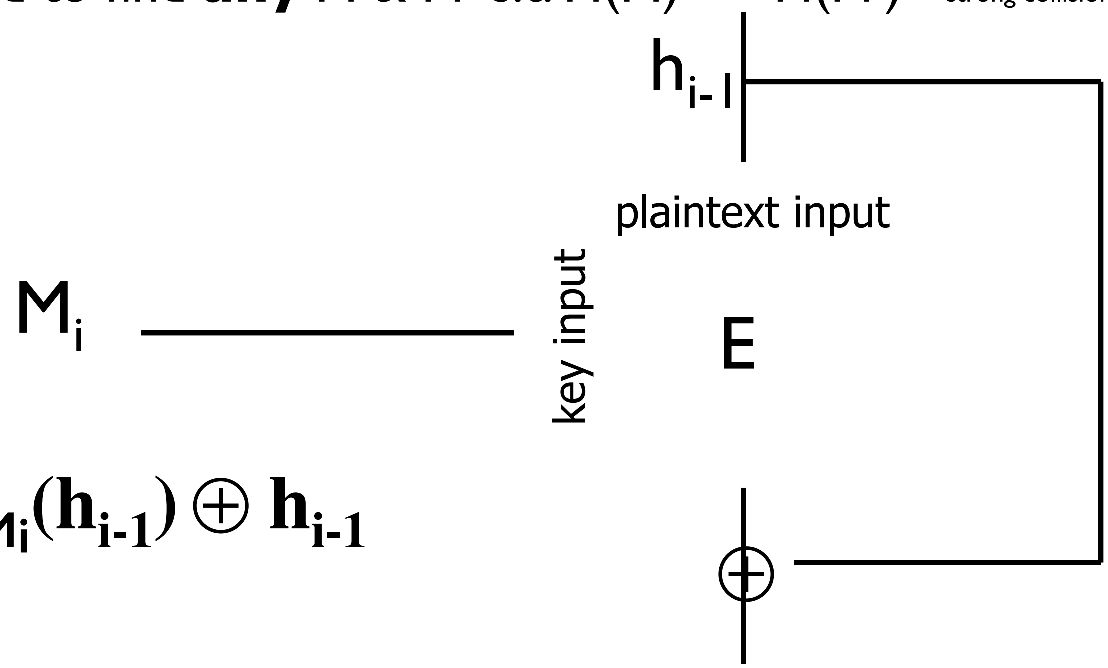
Hash Function from a Block Cipher

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. Hard to find **any** M & M’ s.t. H(M) == H(M’) – strong collision resistance



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

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 (Section 5.7, 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

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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

    Backward & forward security properties

learning objectives

explain main properties of block and stream ciphers,

match a cipher type and mode of operation to the system at hand,

explain how ECB, CBC, OFB, and CTR modes of operation work and draw diagrams showing that,

given a mode of operation, identify its advantages and shortcomings,

explain how MAC can be implemented and how it's different from just hash and from a cipher,

explain backward and forward security and how they can be achieved.