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Symmetric Crypto Systems

EECE 412

Module Outline

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

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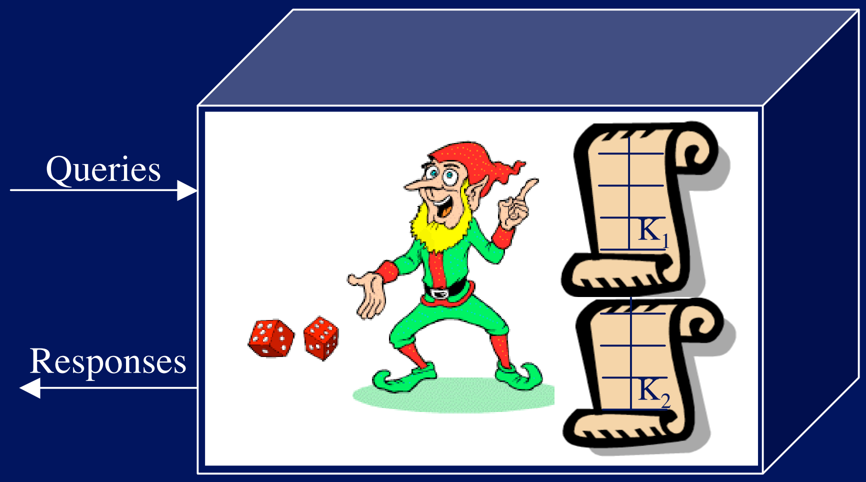
Block Ciphers “Under the Hood”

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

Advanced Encryption Standard

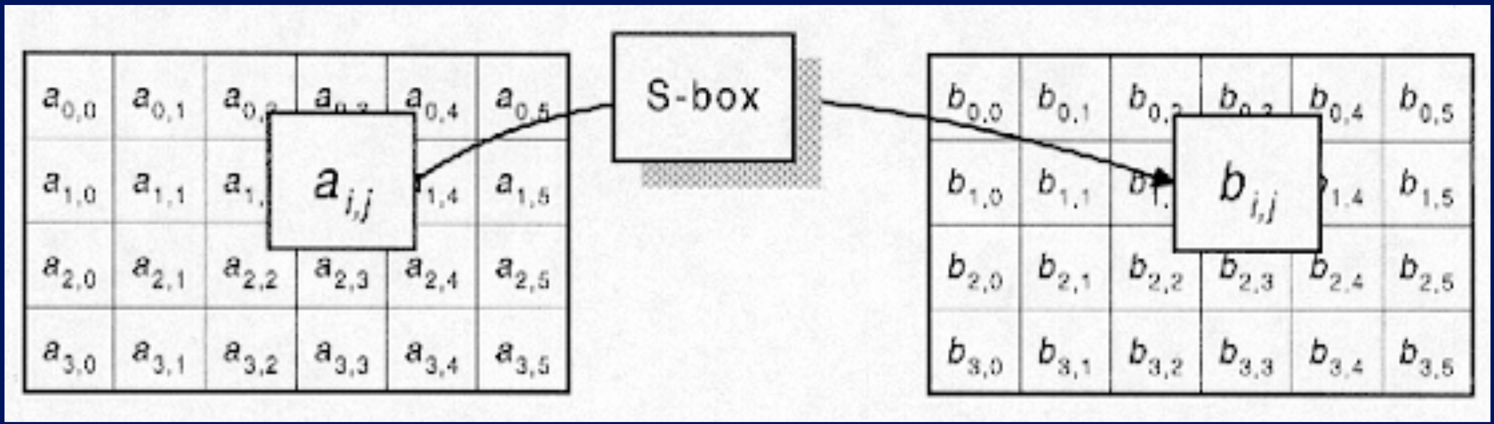
- Replacement for DES
- AES competition (late 90's)
  - NSA openly involved
  - Transparent process
  - Many strong algorithms proposed
  - Rijndael Algorithm ultimately selected
    - Pronounced like "Rain Doll" or "Rhine Doll"
- Iterated block cipher (like DES)

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 ByteSub

- Assume 192 bit block, 4x6 bytes



- ByteSub is AES's "S-box"
- Can be viewed as nonlinear (but invertible) composition of two math operations

AES "S-box"

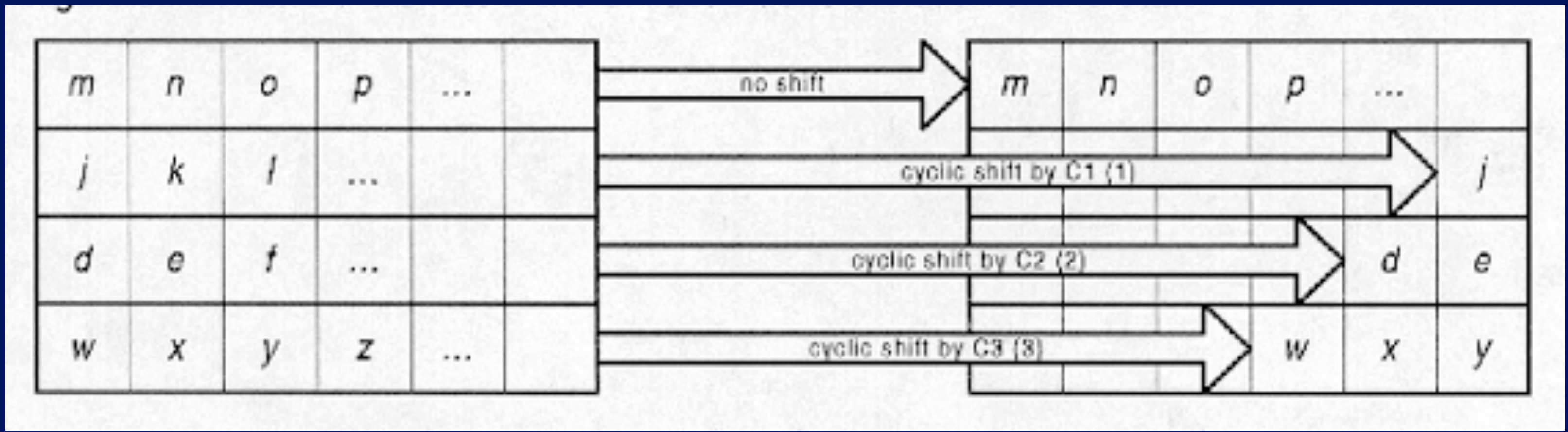
Last 4 bits of input

First
bits o
input

	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	63	7c	77	7b	f2	6b	6f	c5	30	01	67	2b	fe	d7	ab	76
1	ca	82	c9	7d	fa	59	47	f0	ad	d4	a2	af	9c	a4	72	c0
2	b7	fd	93	26	36	3f	f7	cc	34	a5	e5	f1	71	d8	31	15
3	04	c7	23	c3	18	96	05	9a	07	12	80	e2	eb	27	b2	75
4	09	83	2c	1a	1b	6e	5a	a0	52	3b	d6	b3	29	e3	2f	84
5	53	d1	00	ed	20	fc	b1	5b	6a	cb	be	39	4a	4c	58	cf
6	d0	ef	aa	fb	43	4d	33	85	45	f9	02	7f	50	3c	9f	a8
7	51	a3	40	8f	92	9d	38	f5	bc	b6	da	21	10	ff	f3	d2
8	cd	0c	13	ec	5f	97	44	17	c4	a7	7e	3d	64	5d	19	73
9	60	81	4f	dc	22	2a	90	88	46	ee	b8	14	de	5e	0b	db
a	e0	32	3a	0a	49	06	24	5c	c2	d3	ac	62	91	95	e4	79
b	e7	c8	37	6d	8d	d5	4e	a9	6c	56	f4	ea	65	7a	ae	08
c	ba	78	25	2e	1c	a6	b4	c6	e8	dd	74	1f	4b	bd	8b	8a
d	70	3e	b5	66	48	03	f6	0e	61	35	57	b9	86	c1	1d	9e
e	e1	f8	98	11	69	d9	8e	94	9b	1e	87	e9	ce	55	28	df
f	8c	a1	89	0d	bf	e6	42	68	41	99	2d	0f	b0	54	bb	16

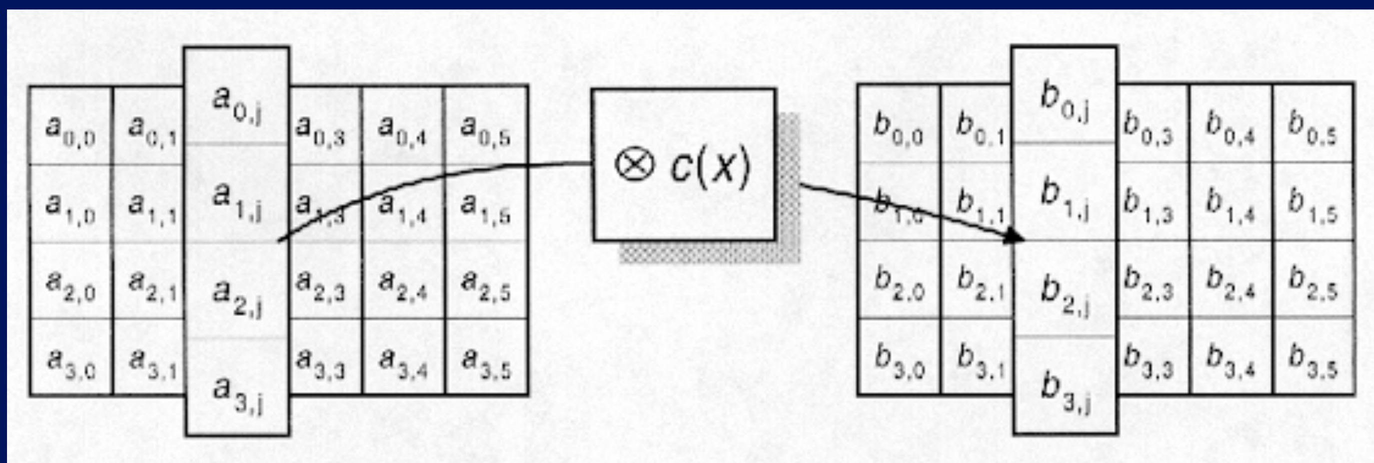
AES ShiftRow

- Cyclic shift rows



AES MixColumn

- Nonlinear, invertible operation applied to each column



- Implemented as a (big) lookup table

AES AddRoundKey

- XOR subkey with block

$$\begin{bmatrix} a_{00} & a_{01} & a_{02} & a_{03} & a_{04} & a_{05} \\ a_{10} & a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{20} & a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{30} & a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \end{bmatrix} \oplus \begin{bmatrix} k_{00} & k_{01} & k_{02} & k_{03} & k_{04} & k_{05} \\ k_{10} & k_{11} & k_{12} & k_{13} & k_{14} & k_{15} \\ k_{20} & k_{21} & k_{22} & k_{23} & k_{24} & k_{25} \\ k_{30} & k_{31} & k_{32} & k_{33} & k_{34} & k_{35} \end{bmatrix} = \begin{bmatrix} b_{00} & b_{01} & b_{02} & b_{03} & b_{04} & b_{05} \\ b_{10} & b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{20} & b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ b_{30} & b_{31} & b_{32} & b_{33} & b_{34} & b_{35} \end{bmatrix}$$

Block Subkey

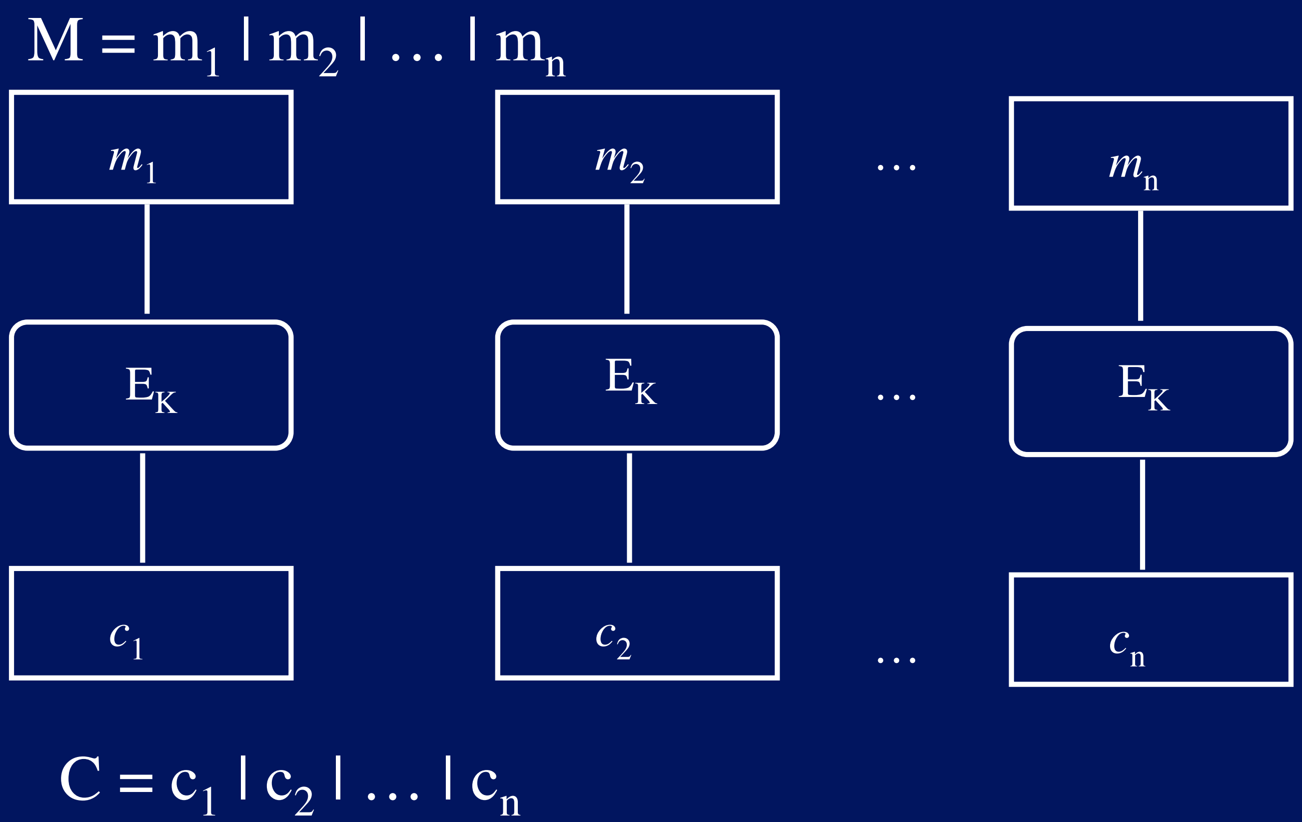
- RoundKey (subkey) determined by **key schedule** algorithm

AES Decryption

- To decrypt, process must be invertible
- Inverse of MixAddRoundKey is easy, since $\oplus$ is its own inverse
- MixColumn is invertible (inverse is also implemented as a lookup table)
- Inverse of ShiftRow is easy (cyclic shift the other direction)
- ByteSub is invertible (inverse is also implemented as a lookup table)

Modes of Operation

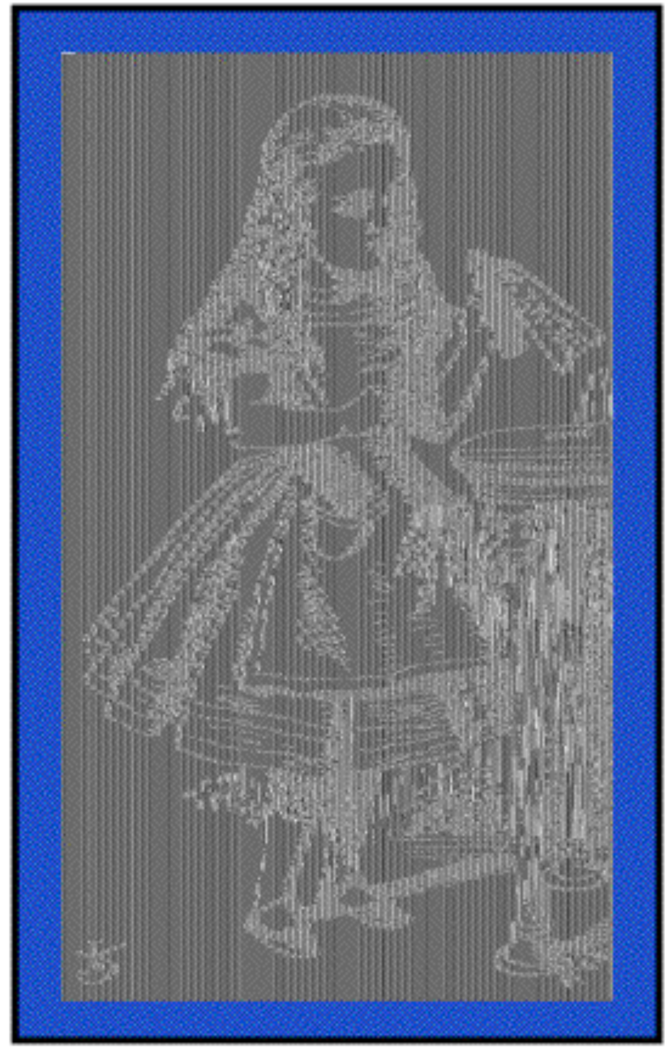
Electronic Code Book (ECB)



Drawbacks

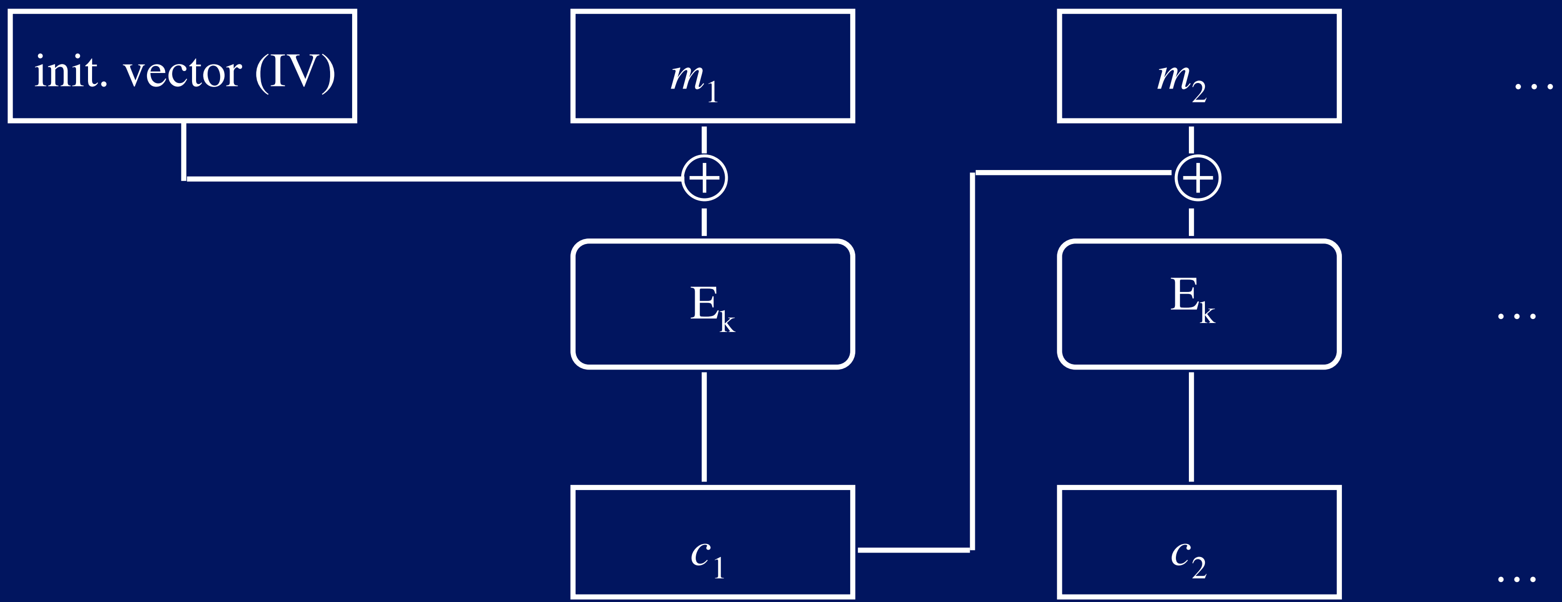
- Same message has same ciphertext
- Redundant/repetitive patterns will show through
- Subject to “cut-and-splice” attacks

Alice in ECB Mode



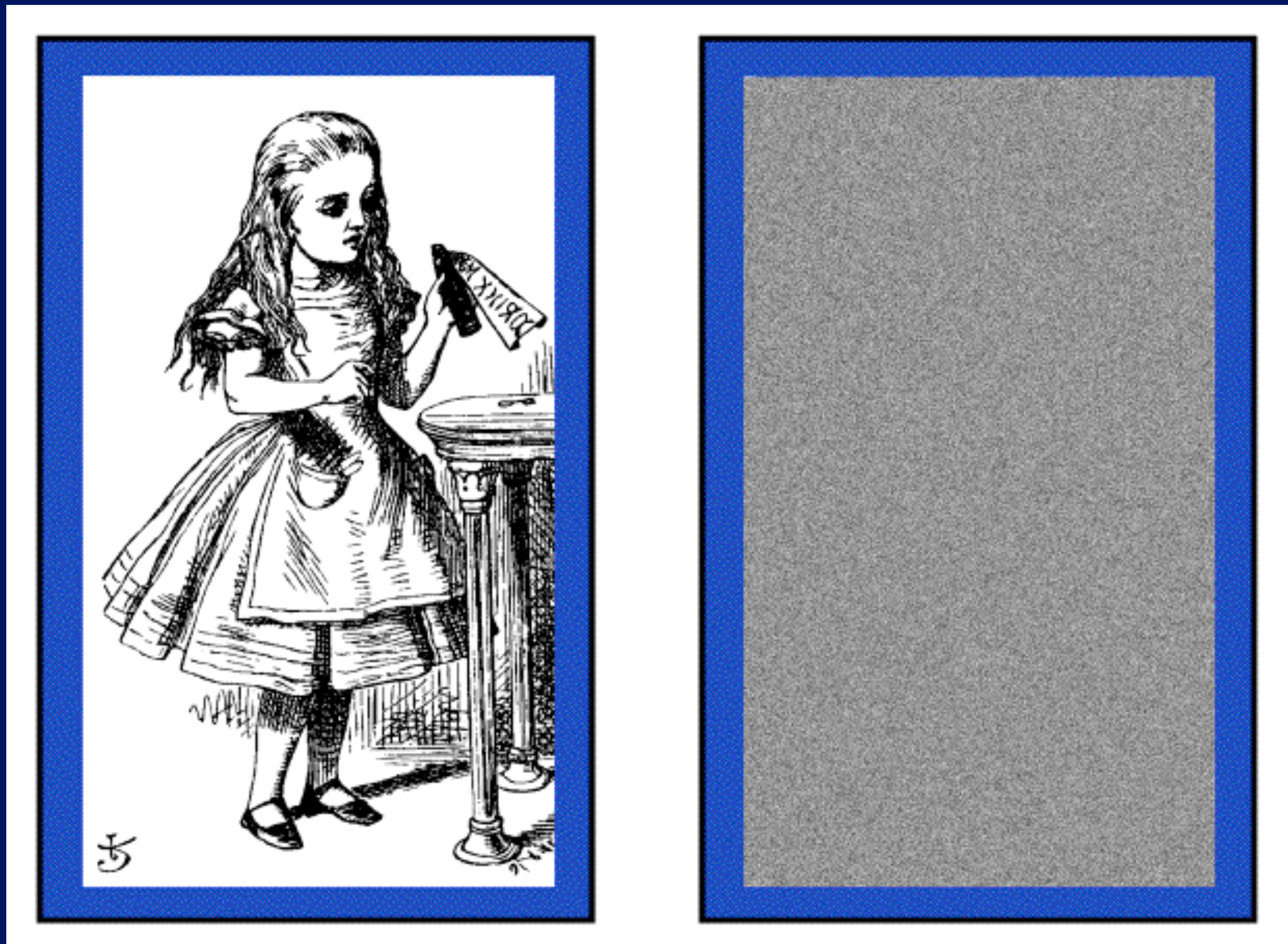
Cipher Block Chaining (CBC)

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

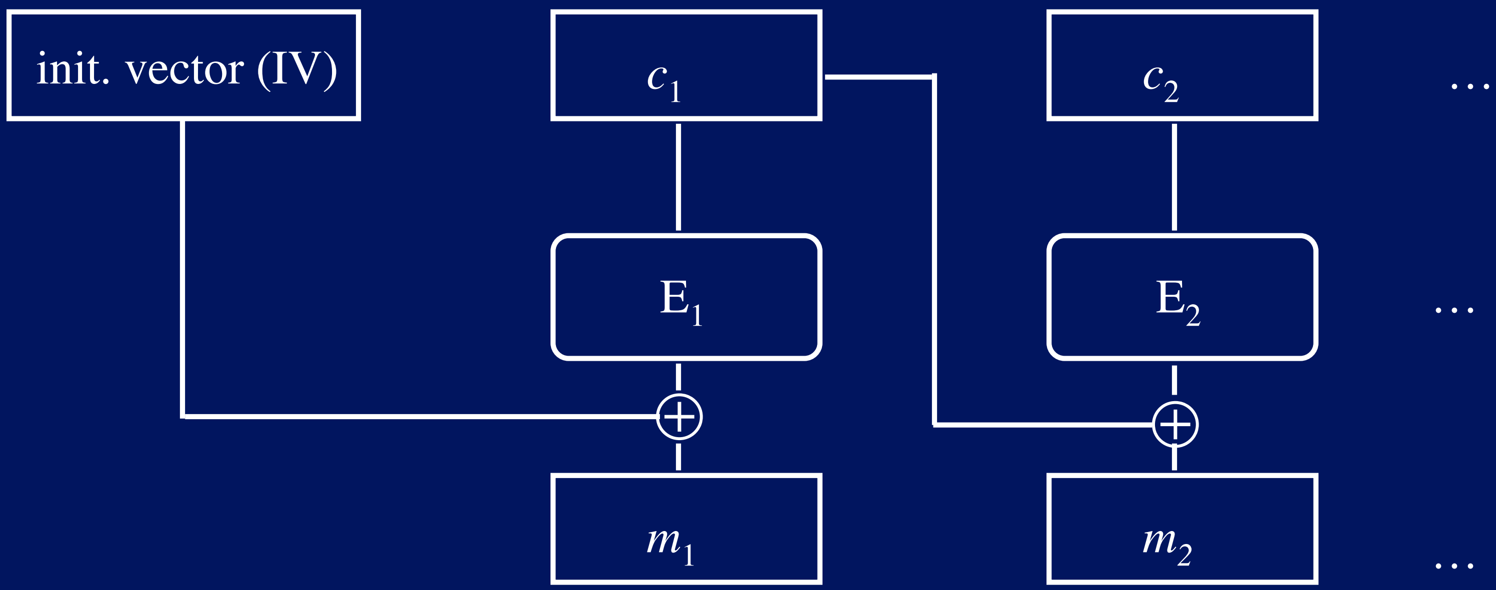


$C = IV \mid c_1 \mid c_2 \mid \ldots \mid c_n$

Alice in CBC Mode



Decryption with CBC

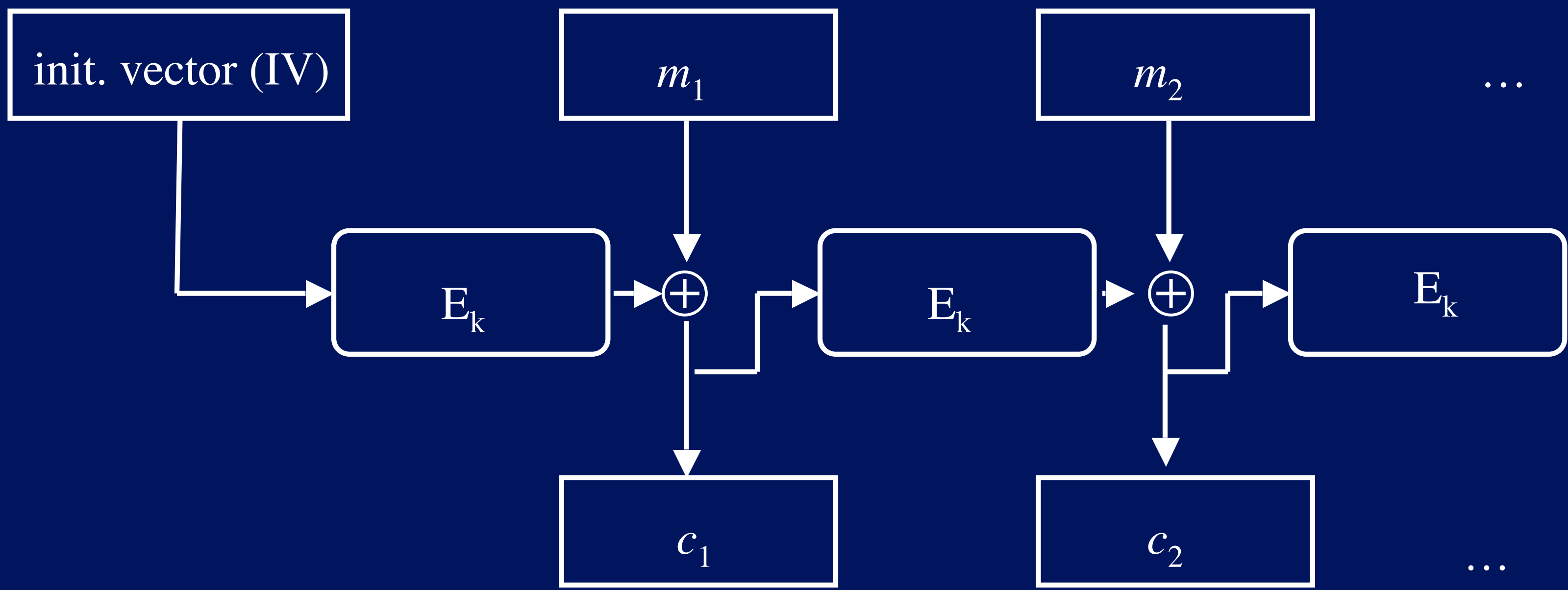


Output Feedback (OFB)

- $K_1 = \{IV\}_K$, $K_2=\{K_1\}_K$, … $K_i=\{K_{i-1}\}_K$ …
- Purpose: use block cipher as a stream cipher
- $C_i = \{m_i\}_{Ki}$, e.g., $c_i = m_i \oplus K_i$

Cipher Feedback (CFB) Mode

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



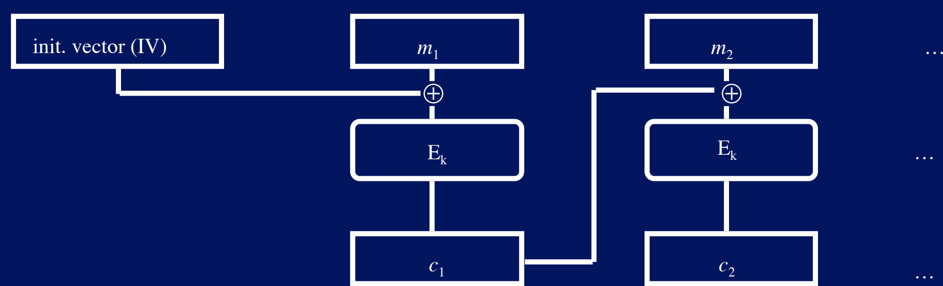
$C = IV \mid c_1 \mid c_2 \mid \ldots \mid c_n$

Counter Encryption

- Drawbacks of feedback modes
  - Hard to parallelize
    - CBC -- cannot precompute
    - OFB -- memory requirements
- $K_i = \{IV + i\}_K$

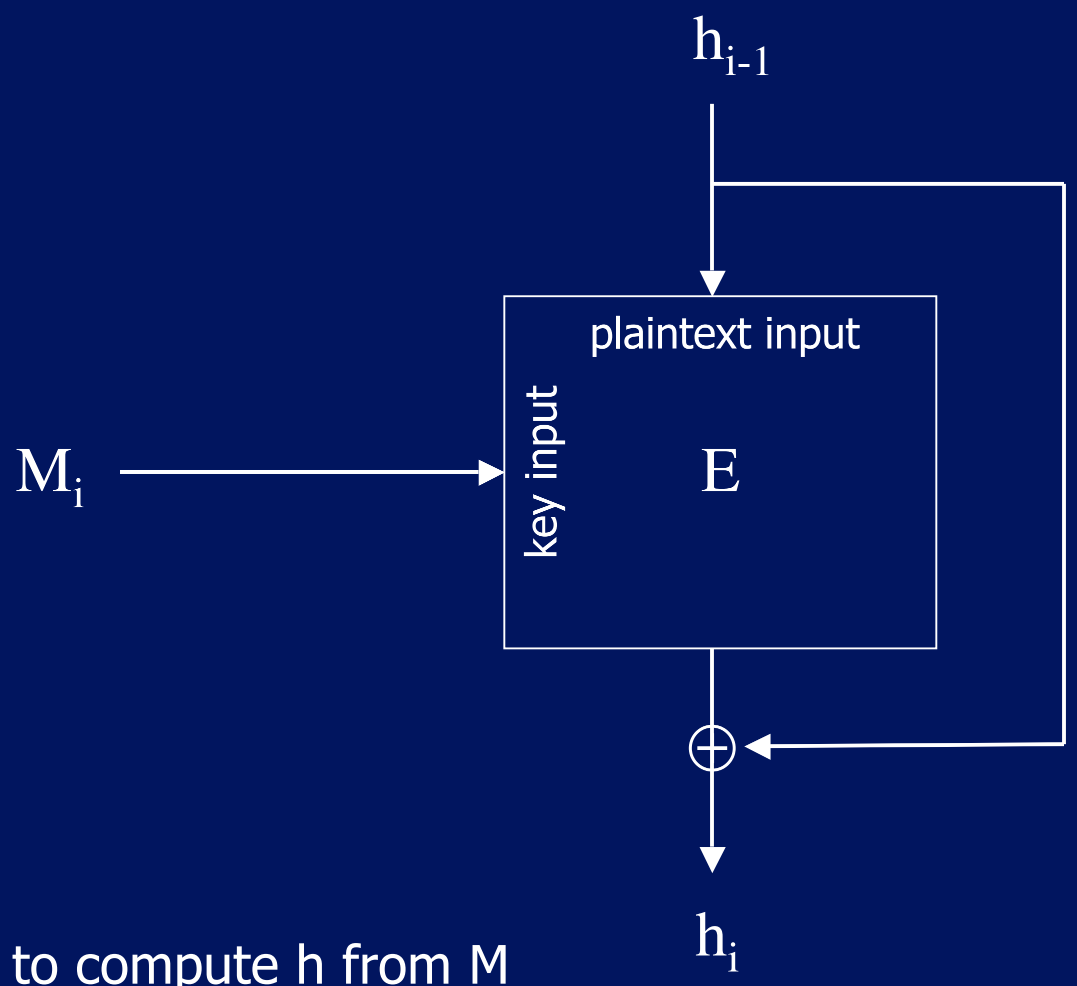
Message Authentication Code (MAC)

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



- How to do MAC and encryption of a message?

Hash Function from a Block Cipher



h = H(M)

1. Easy to compute h from M
2. Hard to compute M from h
3. For given M, hard to find another M′ s.t. H(M) == H(M′)
4. Hard to find some M & M′ s.t. H(M) == H(M′) -- collision-resistance

Common Hash Functions and Applications

- Common hash functions
  - (Message Digest) MD5 value 128b
  - (Secure Hash Algorithm) SHA-1 160b value, SHA-256, SHA-512
- Applications
  - MACs
    - $MAC_K(M) = H(K,M)$
    - $HMAC_K(M) = H(K \oplus A, H(K \oplus B, M))$
  - 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,