TOPIC: 6.857

DATE: 3/4/15

FILE UNDER:

PAGE: L09.1

Admin:

Post project ideas to Piazza. Form teams!

Today:

- "Ideal" block cipher
- Modes of operation:
  - Common: ECB, CTR, CBC, CFB, ...
  - ideal (IND-CCA defn.)
  - Desai's "UFE" mode
- Start stream ciphers if time

Project idea:

"Program obfuscation"

(recent work often called "indistinguishability obfuscation")

Readings:

- Wikipedia "Block cipher modes of operation"
- Katz/Lindell Chapter 3 (esp. 3.6.2 & 3.7)
- Paar/Pelzl Chapter 5 (esp. 5.1)
- Ferguson et al. Chapter 4
- Wikipedia "ciphertext stealing"

For practical purposes, can treat AES as <u>ideal block cipher</u>:

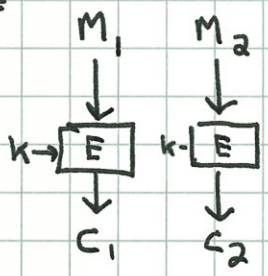
> For each key, mapping $Enc(K, \cdot)$ is a random independent permutation of $\{0,1\}^{128}$ to itself.

Modes of Operation:

<u>How to encrypt variable-length messages?</u> (using AES)

"ECB" = "Electronic code book"
"CTR" = "Counter mode"
"CBC" = "Cipher-block chaining" (& CBC-MAC)
"CFB" = "Cipher feedback"
... (others...)

ECB:



← divide data into b-bit blocks, where b = input block size

To handle data that is not a multiple of b bits in length:

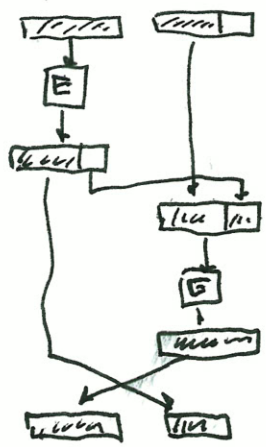
- Append a "1" bit (<u>always</u>)
- Append enough "0" bits to make length a multiple of b bits.

This gives <u>invertible</u> (1-1) "padding" operation.
Pad before encryption; unpad after decryption.

ECB preserves many patterns: repeated message blocks
⇒ repeated ciphertext blocks

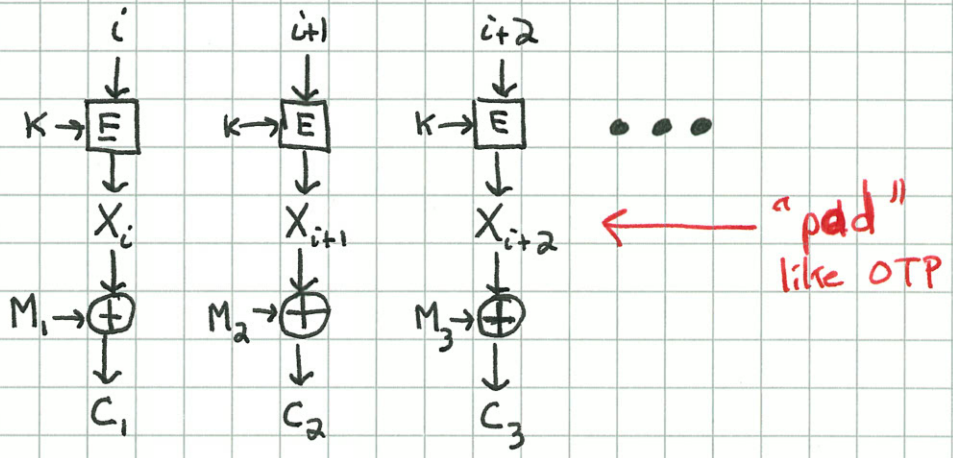
ECB really only good for encrypting <u>random</u> data (e.g. keys)

Ciphertext stealing



CTR (Counter mode):

Generate a PR (pseudorandom) sequence by encrypting $i, i+1, \ldots$
XOR with message to obtain ciphertext.



Initial counter value can be transmitted first:

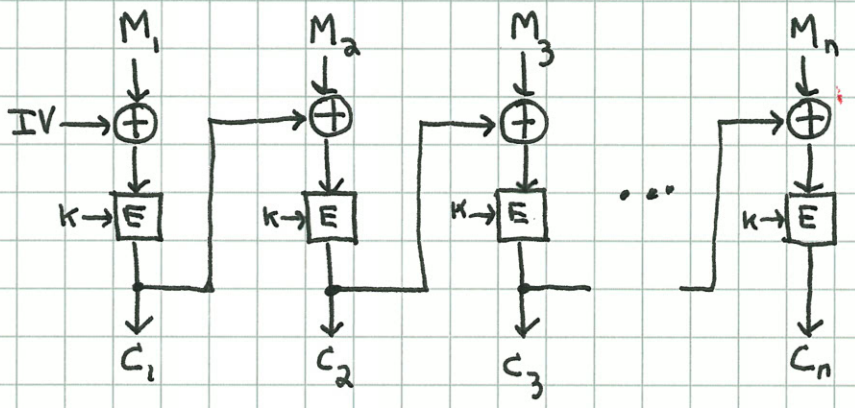
$i, C_1, C_2, \ldots$

Of course, no counter value should be re-used!

CBC (Cipher-block chaining):

Choose IV ("initialization value") randomly, then use each C_i is "IV" for M_{i+1}. Transmit IV with ciphertext:

$$IV, C_1, C_2, \ldots, C_n$$



Decryption easy, and parallelizable (∴ little error propagation)

Lookup "ciphertext stealing" for cute way of handling messages that are not a multiple of b bits in length. This method give ciphertext length = message length.

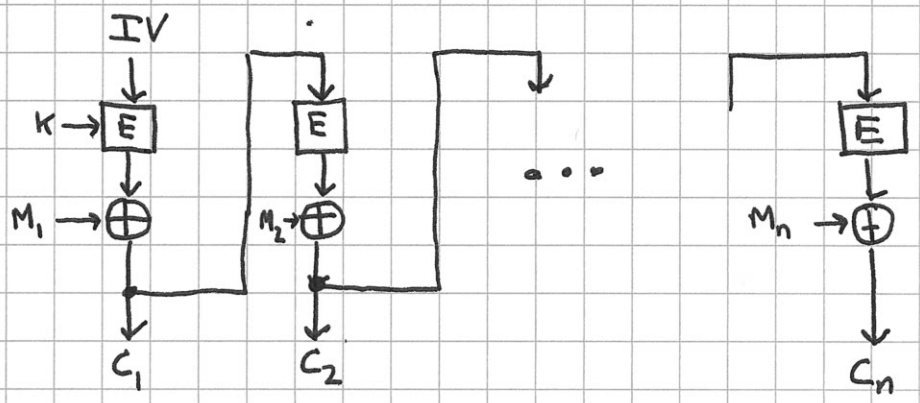
Last block C_n is the "CBC-MAC" (CBC Message Authentication code) for message M. [A fixed IV is used here.] The MAC is a "cryptographic checksum" (more later...) (If messages have variable length then key for last block should be different.)

MAC should use a different key than that used for encryption: requires 2 passes to do CBC-Enc, then CBC-MAC over ciphertext.

IV might be Enc(k, msg #) or Enc(k, nonce)
saves space if msg # does not need to be transmitted, or is short.

CFB (Cipher feedback mode)

Similar to CBC mode. Uses random IV transmitted with ciphertext.



If M is not a multiple of b bits in length, can just transmit shortened ciphertext. (No need for ciphertext stealing.)

Are these modes good ones? What do we want?

Goal → If block cipher is indistinguishable from ideal block cipher then mode provides indistinguishability based on chosen ciphertext attack (IND-CCA):

- Define as game with adversary.
- Mode is IND-CCA secure if adversary can win with probability at most $\frac{1}{2} + \varepsilon$ for "negligible" ε.

Let K be randomly chosen key.
Let E_K denote encryption (using mode) with key K.
Let D_K denote decryption

Phase I ("Find"):

- Adversary given black-box access to E_K, D_K (can encrypt/decrypt whatever it likes)
- Adversary outputs two messages m_0, m_1, of same length, plus state information s.

Phase II ("Guess"):

- Examiner secretly picks $d \xleftarrow{R} \{0,1\}$
  Examiner computes $y = E_K(m_d)$
- Adversary given y, s, access to E_K, and access to D_K (except on y)
- Adversary computes for a while, then must produce bit $\hat{d}$ as its guess for d.
- Adversary's advantage is $\left| P(\hat{d}=d) - \frac{1}{2} \right|$.

Encryption secure against CCA attack if advantage is negligible.

Fact: To be IND-CCA secure, method must be randomized. !

(else Adv can encrypt m_0, m_1 & compare to y)

& randomization should not be evident to Adv (i.e. not usable for decryption)

Previous modes are not IND-CCA secure!

ECB: not randomized

CTR: starting counter value might be random, but it is transmitted in clear.
In any case, it is legal for Adv to ask for decryption of prefix of y (giving prefix of m_d)

CBC: similar to CTR: IV might be random, but it is xmitted in clear.
Decryption of prefix of y also works.

CFB: Same. IV in clear; prefix argument works.

Can one design a IND-CCA scheme?

Theorem: Modes ECB, CTR, CBC, CFB are not IND-CCA secure.

Proof: Adversary picks $m_0 = 0^x$, $m_1 = 1^x$ for large x.

Then $y = E_k(m_d)$

Let z = 1st half of y.

Since $z \neq y$, Adversary allowed in phase II to ask for $D_k(z)$.

This gives first half of m_d, revealing d.

Adversary always wins. ▨

Can one design a IND-CCA scheme?

Given a ciphertext y for a message m,

Adversary should not be able to construct a ciphertext z for a related (e.g. truncated) message.

(nonmalleability)

CRYPTO 2006

Here is a sketch of one IND-CCA secure method.
(due to Desai. UFE = "Unbalanced Feistel encryption")

M = long message, sequence $M_1, M_2, \ldots, M_n$ of b-bit blocks.

$K = (K_1, K_2, K_3)$ Three indep. keys for block ciphers

$r \xleftarrow{R} \{0,1\}^b$ starting counter value

pad $P = P_1, P_2, \ldots, P_n$ where $P_i = E_{K_1}(r+i)$ ← (CTR mode)

ciphertext $C = C_1, C_2, \ldots, C_n$ where $C_i = M_i \oplus P_i$

CBC-MAC: $X_0 = 0^b$

$X_i = E_{K_2}(X_{i-1} \oplus C_i) \quad 1 \le i < n$

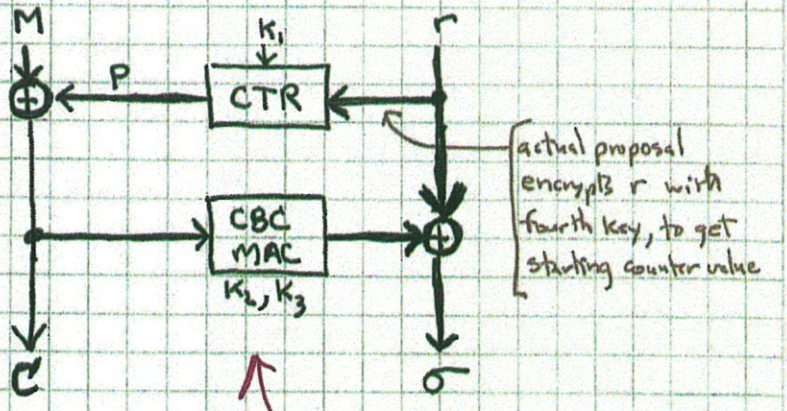
$X_n = E_{K_3}(X_{n-1} \oplus C_n)$ (MAC) ← last block uses K_3

$\sigma = r \oplus X_n$ use MAC to mask r (no message authentication)

Output: $C_1, C_2, \ldots, C_n, \sigma$

VO-PRF

VI-PRF



CBC-MAC uses K_2 mostly, but K_3 on last block

- Encryption with UFE can be done in single pass ("online" property) over data, but decryption requires two passes:
  - first to compute mask X_n, then to get r
  - second to decrypt C to get M
- Only designed for <u>confidentiality</u> (there is no way provided for receiver to tell if ciphertext has been tampered with.) (Need to use MAC on top of all of this, or some "combined mode" providing <u>both</u> confidentiality & integrity.)
- Note "unbalanced Feistel structure".
- Length of ciphertext $(C, \sigma) = |M| + |r|$;
  expansion only as needed for randomization.
  No need for "ciphertext stealing" since we use CTR mode.