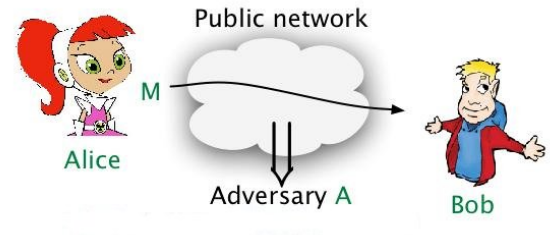
AUTHENTICATED ENCRYPTION

So Far ...



We have looked at methods to provide privacy and authenticity separately:

Goal	Primitive	Security notion
Data privacy	symmetric encryption	IND-CPA
Data authenticity	MAC	UF-CMA

Authenticated Encryption

In practice we often want both privacy and authenticity.

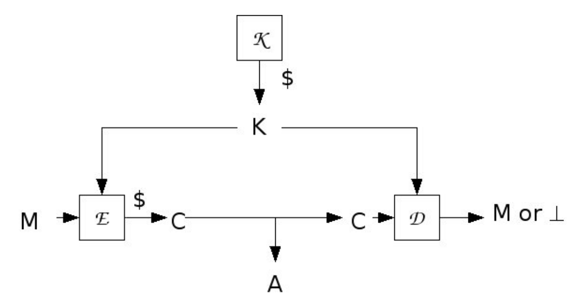
Example: A doctor wishes to send medical information M about Alice to the medical database. Then

- We want data privacy to ensure Alice's medical records remain confidential.
- We want authenticity to ensure the person sending the information is really the doctor and the information was not modified in transit.

We refer to this as authenticated encryption.

Authenticated Encryption Schemes

Syntactically, an authenticated encryption scheme is just a symmetric encryption scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ where



Privacy of Authenticated Encryption Schemes

The notion of privacy for symmetric encryption carries over, namely we want IND-CPA.

Integrity of Authenticated Encryption Schemes

Adversary's goal is to get the receiver to accept a "non-authentic" ciphertext C.

Integrity of ciphertexts: C is "non-authentic" if it was never transmitted by the sender.

INT-CTXT

Let $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be a symmetric encryption scheme and A an adversary.

Game $\text{INTCTXT}_{\mathcal{AE}}$

procedure Initialize
$K \xleftarrow{\$} \mathcal{K}$; $S \leftarrow \emptyset$

procedure Enc(M)
$C \xleftarrow{\$} \mathcal{E}_K(M)$
$S \leftarrow S \cup \{C\}$
Return C

procedure Finalize(C)
$M \leftarrow \mathcal{D}_K(C)$
if $(C \notin S \wedge M \neq \bot)$ then
  return true
Else return false

The int-ctxt advantage of A is

$$\mathbf{Adv}^{\text{int-ctxt}}_{\mathcal{AE}}(A) = \Pr[\text{INTCTXT}^A_{\mathcal{AE}} \Rightarrow \text{true}]$$

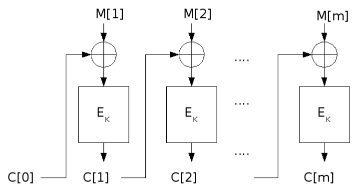
Integrity with privacy

The goal of authenticated encryption is to provide both integrity and privacy. We will be interested in IND-CPA + INT-CTXT.

Plain Encryption Does Not Provide Integrity

Alg $\mathcal{E}_K(M)$
$C[0] \xleftarrow{\$} \{0,1\}^n$
For $i = 1, \ldots, m$ do
  $C[i] \leftarrow \mathsf{E}_K(C[i-1] \oplus M[i])$
Return C

Alg $\mathcal{D}_K(C)$
For $i = 1, \ldots, m$ do
  $M[i] \leftarrow \mathsf{E}_K^{-1}(C[i]) \oplus C[i-1]$
Return M



Question: Is CBC\$ encryption INT-CTXT secure?

Answer: No, because any string $C[0]C[1]\ldots C[m]$ has a valid decryption.

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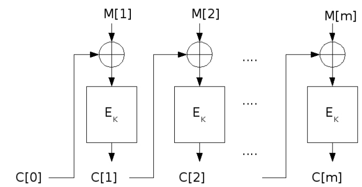

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Return M

adversary A
$C[0]C[1]C[2] \xleftarrow{\$} \{0,1\}^{3n}$
Return $C[0]C[1]C[2]$

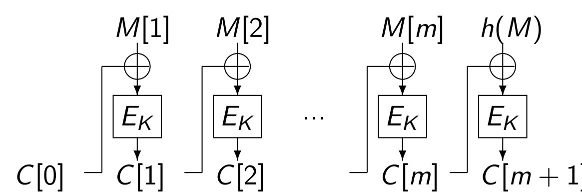
Then

$$\mathbf{Adv}^{\mathrm{int\text{-}ctxt}}_{\mathcal{SE}}(A) = 1$$

This violates INT-CTXT.

A scheme whose decryption algorithm never outputs $\perp$ cannot provide integrity!

Encryption with Redundancy

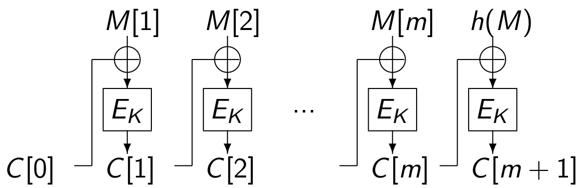


Here $E\colon \{0,1\}^k \times \{0,1\}^n \to \{0,1\}^n$ is our block cipher and $h\colon \{0,1\}^* \to \{0,1\}^n$ is a "redundancy" function, for example

- $h(M[1]\ldots M[m]) = 0^n$
- $h(M[1]\ldots M[m]) = M[1] \oplus \cdots \oplus M[m]$
- A CRC
- $h(M[1]\ldots M[m])$ is the first n bits of SHA1$(M[1]\ldots M[m])$.

The redundancy is verified upon decryption.

Encryption with Redundancy

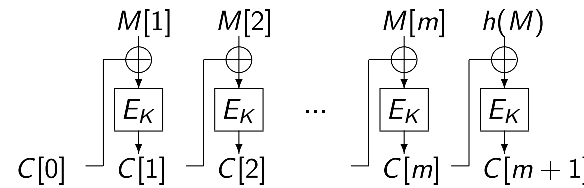


Let $E\colon \{0,1\}^k \times \{0,1\}^n \to \{0,1\}^n$ be our block cipher and $h\colon \{0,1\}^* \to \{0,1\}^n$ a redundancy function. Let $\mathcal{SE} = (\mathcal{K}, \mathcal{E}', \mathcal{D}')$ be CBC$ encryption and define the encryption with redundancy scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ via

Alg $\mathcal{E}_K(M)$
$M[1]\ldots M[m] \leftarrow M$
$M[m+1] \leftarrow h(M)$
$C \stackrel{\$}{\leftarrow} \mathcal{E}'_K(M[1]\ldots M[m]M[m+1])$
return C

Alg $\mathcal{D}_K(C)$
$M[1]\ldots M[m]M[m+1] \leftarrow \mathcal{D}'_K(C)$
if $(M[m+1] = h(M))$ then
return $M[1]\ldots M[m]$
else return $\perp$

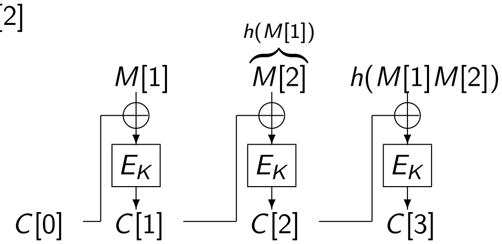
Arguments in Favor of Encryption with Redundancy



The adversary will have a hard time producing the last enciphered block of a new message.

Encryption with Redundancy Fails

adversary A
$M[1] \stackrel{\$}{\leftarrow} \{0,1\}^n$; $M[2] \leftarrow h(M[1])$
$C[0]C[1]C[2]C[3] \stackrel{\$}{\leftarrow} \mathbf{Enc}(M[1]M[2])$
Return $C[0]C[1]C[2]$



This attack succeeds for any (not secret-key dependent) redundancy function h.

WEP Attack

A "real-life" rendition of this attack broke the 802.11 WEP protocol, which instantiated h as CRC and used a stream cipher for encryption [BGW].

What makes the attack easy to see is having a clear, strong and formal security model.

Generic Composition

Build an authenticated encryption scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ by combining

- a given IND-CPA symmetric encryption scheme $\mathcal{SE} = (\mathcal{K}', \mathcal{E}', \mathcal{D}')$
- a given PRF $F : \{0,1\}^k \times \{0,1\}^* \to \{0,1\}^n$

	CBC\$-AES	CTR\$-AES	...
HMAC-SHA1			
CMAC			
ECBC			
⋮			

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A key $K = K_e||K_m$ for $\mathcal{AE}$ always consists of a key K_e for $\mathcal{SE}$ and a key K_m for F:

Alg $\mathcal{K}$

$K_e \xleftarrow{\$} \mathcal{K}'$; $K_m \xleftarrow{\$} \{0,1\}^k$
Return $K_e||K_m$

Generic Composition Methods

The order in which the primitives are applied is important. Can consider

Method	Usage
Encrypt-and-MAC (E&M)	SSH
MAC-then-encrypt (MtE)	SSL/TLS
Encrypt-then-MAC (EtM)	IPSec

We study these following [BN].

Encrypt-and-MAC

$\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ is defined by

Alg $\mathcal{E}_{K_e||K_m}(M)$

$C' \xleftarrow{\$} \mathcal{E}'_{K_e}(M)$
$T \leftarrow F_{K_m}(M)$
Return $C'||T$

Alg $\mathcal{D}_{K_e||K_m}(C'||T)$

$M \leftarrow \mathcal{D}'_{K_e}(C')$
If $(T = F_{K_m}(M))$ then return M
Else return $\perp$

Security	Achieved?
IND-CPA	
INT-CTXT	

Encrypt-and-MAC

$\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ is defined by

Alg $\mathcal{E}_{K_e \| K_m}(M)$	**Alg** $\mathcal{D}_{K_e \| K_m}(C' \| T)$
$C' \xleftarrow{\$} \mathcal{E}'_{K_e}(M)$	$M \leftarrow \mathcal{D}'_{K_e}(C')$
$T \leftarrow F_{K_m}(M)$	If $(T = F_{K_m}(M))$ then return M
Return $C' \| T$	Else return $\perp$

Security	Achieved?
IND-CPA	NO
INT-CTXT	

Why? $T = F_{K_m}(M)$ is a deterministic function of M and allows detection of repeats.

Encrypt-and-MAC

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Why? May be able to modify C' in such a way that its decryption is unchanged.

MAC-then-Encrypt

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$T \leftarrow F_{K_m}(M)$	$M \| T \leftarrow \mathcal{D}'_{K_e}(C)$
$C \xleftarrow{\$} \mathcal{E}'_{K_e}(M \| T)$	If $(T = F_{K_m}(M))$ then return M
Return C	Else return $\perp$

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Why? $\mathcal{SE}' = (\mathcal{K}', \mathcal{E}', \mathcal{D}')$ is IND-CPA secure.

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Why? If $C\|\|T$ is new then T will be wrong.

Two keys or one?

We have used separate keys K_e, K_m for the encryption and message authentication. However, these can be derived from a single key K via $K_e = F_K(0)$ and $K_m = F_K(1)$, where F is a PRF such as a block cipher, the CBC-MAC or HMAC.

Trying to directly use the same key for the encryption and message authentication is error-prone, but works if done correctly.

Exercise

Let $E = AES$. Let $\mathcal{K}$ return a random 128-bit AES key K. Let $\mathcal{SE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ where $\mathcal{E}$, $\mathcal{D}$ are below. Here, $X[i]$ denotes the i-th 128-bit block of a string whose length is a multiple of 128.

Alg $\mathcal{E}_K(M)$
if $|M| \neq 512$ then return $\perp$
$M[1] \ldots M[4] \leftarrow M$
$C_e[0] \xleftarrow{\$} \{0,1\}^{128}$ $C_m[0] \leftarrow 0^{128}$
for $i = 1, \ldots, 4$ do
  $C_e[i] \leftarrow E_K(C_e[i-1] \oplus M[i])$
  $C_m[i] \leftarrow E_K(C_m[i-1] \oplus M[i])$
$C_e \leftarrow C_e[0]C_e[1]C_e[2]C_e[3]C_e[4]$
$T \leftarrow C_m[4]$; return (C_e, T)

Alg $\mathcal{D}_K((C_e, T))$
if $|C_e| \neq 640$ then return $\perp$
$C_m[0] \leftarrow 0^{128}$
for $i = 1, \ldots, 4$ do
  $M[i] \leftarrow E_K^{-1}(C_e[i]) \oplus C_e[i-1]$
  $C_m[i] \leftarrow E_K(C_m[i-1] \oplus M[i])$
if $C_m[4] \neq T$ then return $\perp$
return M

Exercise

1. Is $\mathcal{SE}$ IND-CPA-secure? Why or why not?
2. Is $\mathcal{SE}$ INT-CTXT-secure? Why or why not?
3. Is $\mathcal{SE}$ an Encrypt-and-MAC construction? Justify your answer.

Generic Composition in Practice

AE in	is based on	which in general is	and in this case is
SSH	E&M	insecure	secure
SSL	MtE	insecure	insecure
SSL + RFC 4344	MtE	insecure	secure
IPSec	EtM	secure	secure
WinZip	EtM	secure	insecure

Why?

- Encodings
- Specific “E” and “M” schemes
- For WinZip, disparity between usage and security model

Authenticated encryption today

- Dedicated schemes: OCB, OCBx (x=1,2,3), GCM, CCM, EAX
- TLS uses GCM
- CAESAR competition to standardize new schemes: `http://competitions.cr.yp.to/caesar.html`