Authenticated Encryption

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Based on http://cseweb.ucsd.edu/~mihir/cse107/

Motivation

In practice we often want both privacy and authenticity.

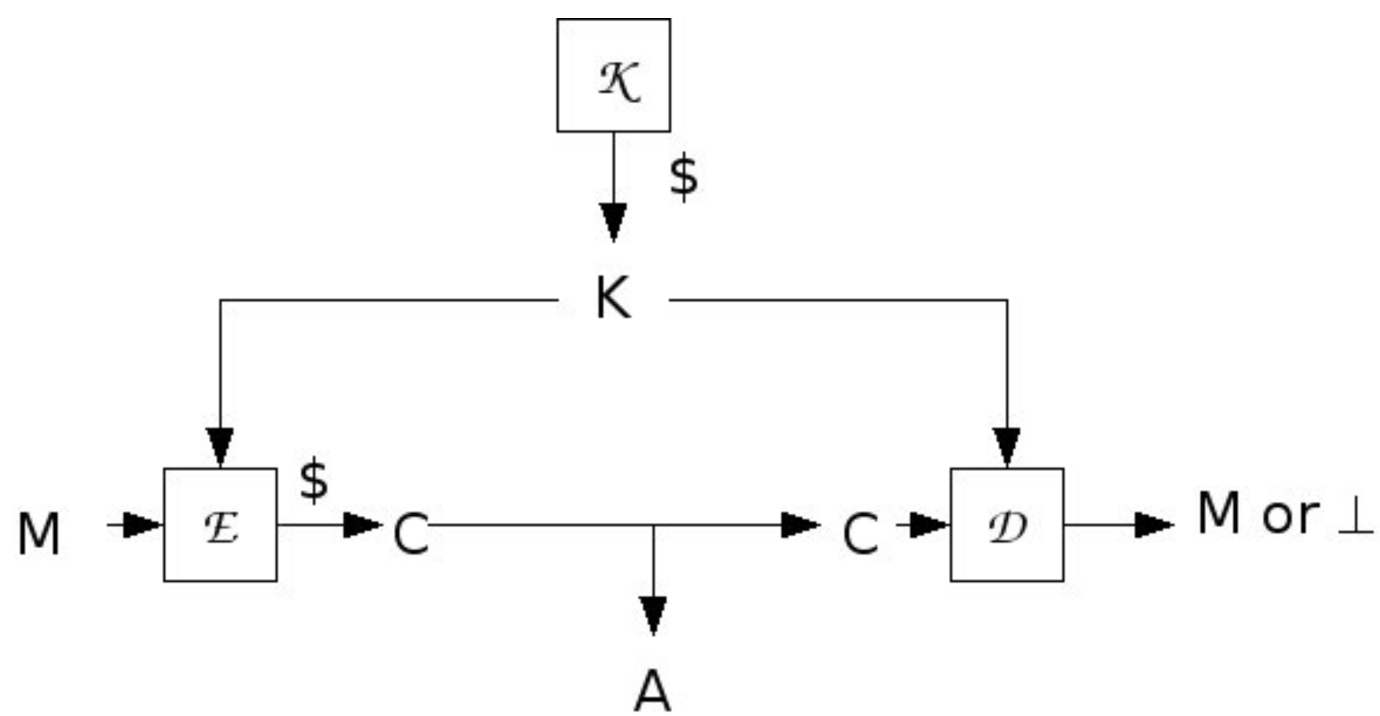
Example: A doctor wishes to send medical information M about Alice to the medical database. Then

- 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.

Syntax

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



Security

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- For authenticity, the adversary's goal is to get the receiver to accept a "non-authentic" ciphertext (i.e., not actually 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 $\mathsf{INTCTXT}_{\mathcal{AE}}$

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 $(C \notin S \wedge M \neq \perp)$ then
    return true
Else return false

The int-ctxt advantage of A is

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

Integrity + Privacy

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

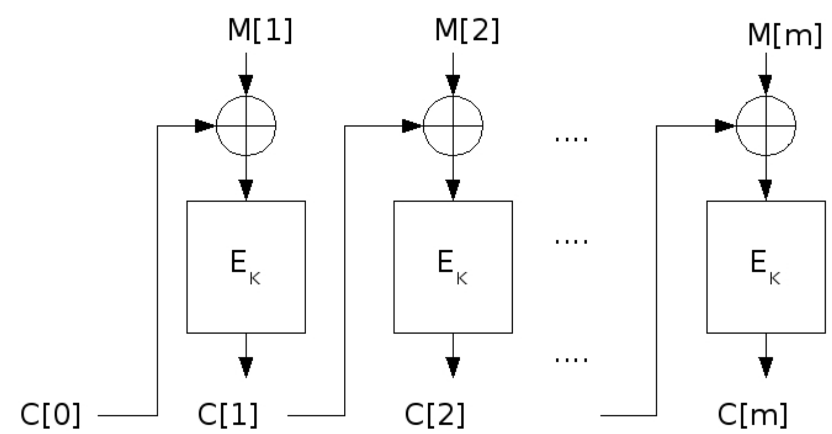
Plain Encryption: CBC\$

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?

Plain Encryption Does Not Provide Integrity

Alg $\mathcal{E}_K(M)$

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

adversary A

$C[0]C[1]C[2] \stackrel{\$}{\leftarrow} \{0,1\}^{3n}$
Return $C[0]C[1]C[2]$

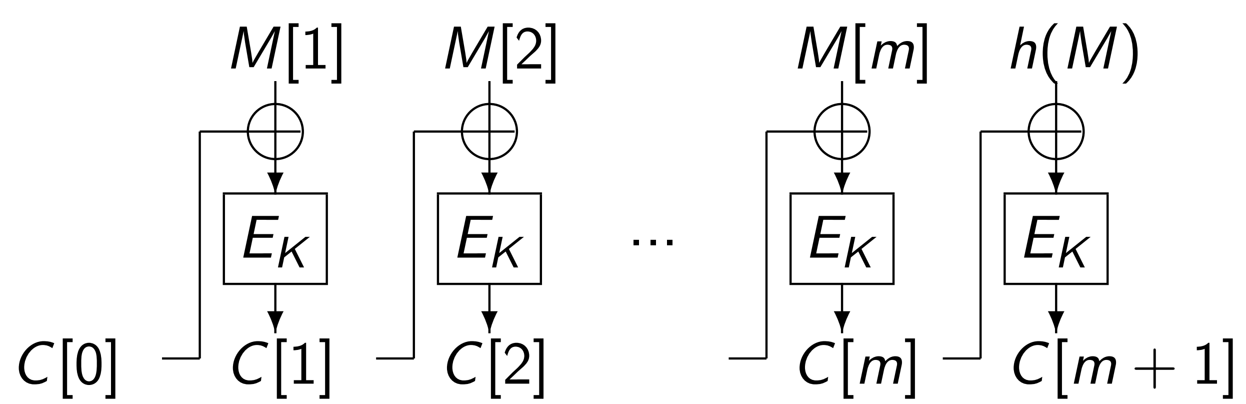
Then

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

This violates INT-CTXT.

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

Encryption with Redundancy

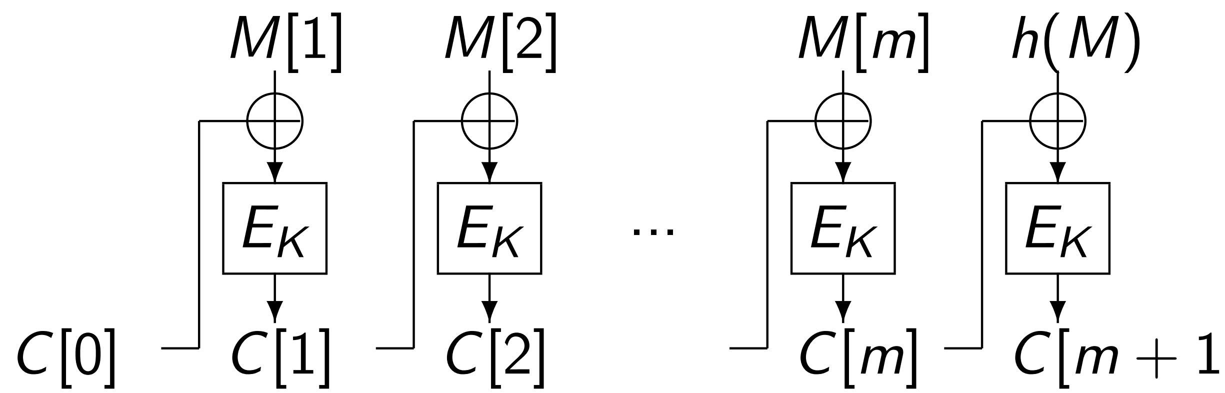


Here $E\colon \{0,1\}^k \times \{0,1\}^n \to \{0,1\}^n$ is our block cipher and $h\colon \{0,1\}^* \to \{0,1\}^n$ is a "redundancy" function, for example

- $h(M[1] \ldots M[m]) = 0^n$
- $h(M[1] \ldots M[m]) = M[1] \oplus \cdots \oplus M[m]$
- 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: $\{0,1\}^k \times \{0,1\}^n \to \{0,1\}^n$ be our block cipher and h: $\{0,1\}^* \to \{0,1\}^n$ 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

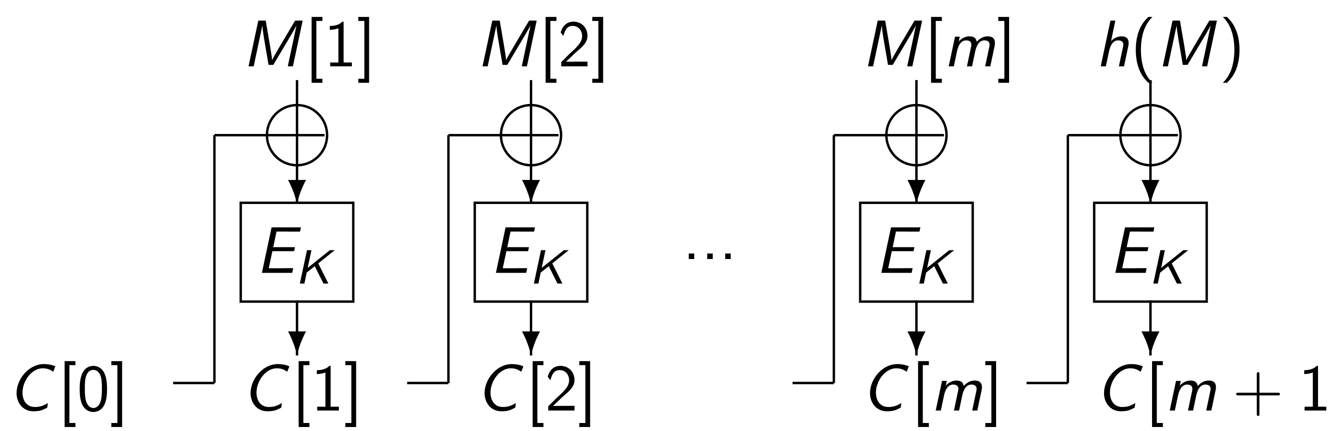
Alg $\mathcal{E}_K(M)$

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

Does it Work?

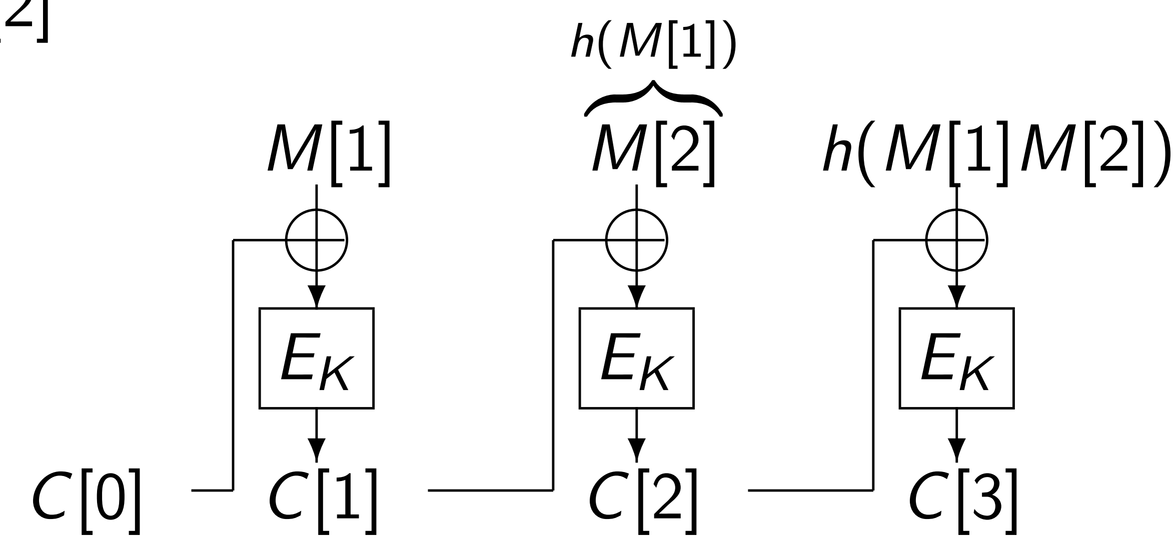


The adversary will have a hard time producing the last enciphered block of a new message.

Attacks

adversary A

$M[1] \xleftarrow{\$} \{0,1\}^n\,;\; M[2] \leftarrow h(M[1])$
$C[0]C[1]C[2]C[3] \xleftarrow{\$} \textbf{Enc}(M[1]M[2])$
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 given PRF $F : \{0,1\}^k \times \{0,1\}^* \to \{0,1\}^n$

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 $\mathcal{K}$

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

Generic Composition

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

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	

MAC-then-Encrypt

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

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

Security	Achieved?
IND-CPA	
INT-CTXT	

Encrypt-then-MAC

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

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

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

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

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

Security	Achieved?
IND-CPA	
INT-CTXT	

Two keys?

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.

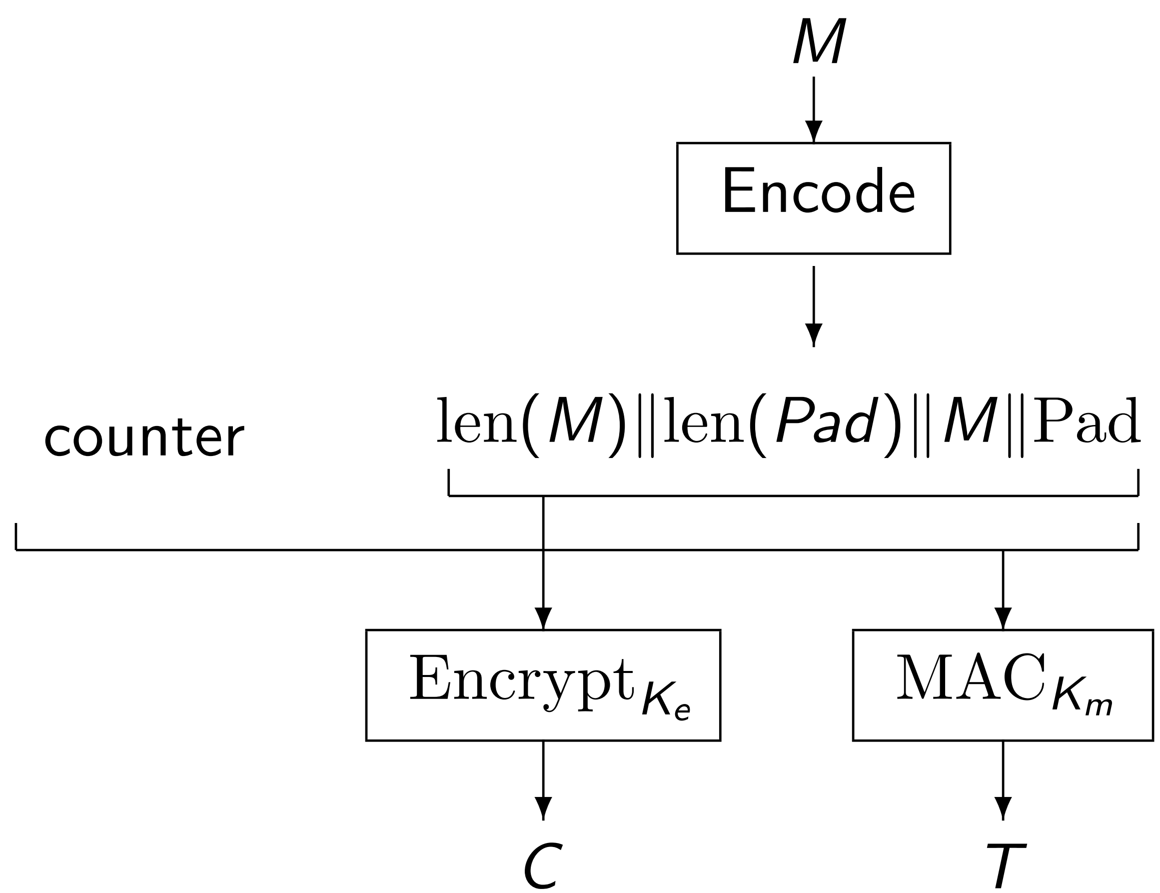
Generic Composition in Practice

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

AE in SSH



SSH2 encryption uses inter-packet chaining which is insecure [D, BKN]. RFC 4344 [BKN] proposed fixes that render SSH provably IND-CPA + INT-CTXT secure. Fixes recommended by Secure Shell Working Group and included in OpenSSH since 2003. Fixes included in PuTTY since 2008.