CIS 5371, Fall 2023

Authenticated Encryption

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1. AE and Its Security Definitions

2. Failed Ways to Build AE

3. Generic Compositions

4. Padding-Oracle Attack on SSL/TLS
So Far

Transfer $5 to account 12345

Privacy

Encryption scheme

Authenticated Encryption
Achieve both of these aims

Authenticity

MAC
Authenticated Encryption (AE)

Emerged ~ 2000

Begin with two realizations

1. Authenticity is routinely needed/assumed
2. “Standard” privacy mechanisms don’t provide it

Provide an easier-to-correctly-use abstraction boundary
AE Syntax

**Key Gen**

![Key Gen diagram](image1)

**Encrypt**

![Encrypt diagram](image2)

**Decrypt**

![Decrypt diagram](image3)

Decryption may reject invalid ciphertexts
Defining Security for AE

- Use Left-or-Right security for privacy

Auth $\mathcal{E}$

procedure Initialize()

\[ K \leftarrow \mathcal{K} \]

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

procedure Enc($M$)

procedure Finalize($C'$)

Return $(\mathcal{D}_K(C') \neq \bot)$

\[ \text{Adv}^\text{auth}_{\mathcal{T}}(A) = \Pr[\text{Auth}_A \Rightarrow 1] \]

Authenticity

Must never receive from Enc

$C$ \rightarrow Enc \rightarrow M \rightarrow A \rightarrow C'$
Agenda

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Plain Encryption Doesn’t Provide Authenticity

**Question:** Does CBC provide authenticity?

**Answer:** No, because any ciphertext has valid decryption
A Bad Fix: CBC with Redundancy

On decryption, verify the decrypted last block is zero.

**Question:** Break the authenticity of this scheme with a single Enc query
An Attack
Complex Redundancy Doesn’t Help

Some (unkeyed) “redundancy” function, such as checksum

The redundancy is verified upon decryption

**Question:** Break the authenticity of this scheme with a single Enc query
An Attack
A Case Study: WEP

Used in IEEE WiFi standard

24-bit IV is a part of the ciphertext

IV, K → RC4 → CRC(M) → C
Attack 1: Exploiting Short IV

Assume all messages are of the same length, and fairly long

**Goal:** recover at least one message
Attack 1: Exploiting Short IV

Aim for an IV collision

For 24-bit IV’s, how many ctx to wait for collision prob ≈ 0.5?
Attack 1: Exploiting Short IV

\[ M \rightarrow \text{CRC}(M) \rightarrow C \]

- IV || \( C_1 \)
- IV || \( C_2 \)

Same IV, can recover \( M_1 \oplus M_2 \)
Attack 2: Chop-Chop Attack

Goal: recover the underlying message by exploiting Dec queries
Attack 2: Chop-Chop Attack

Illustrated Via A Simpler Variant of WEP

Example: \( \text{Parity}(10011) = 1 \oplus 0 \oplus 0 \oplus 1 \oplus 1 = 1 \)
Attack 2: Chop-Chop Attack
Illustrated For 4-bit Message
Decryption In CloseUp

Compare with $\text{Parity}(M_1 M_2 M_3)$
Exploit Decryption Response

If valid, $M_1 \oplus M_2 \oplus M_3 \oplus M_4 = 0$
Exploit Decryption Response

If invalid, \[ M_1 \oplus M_2 \oplus M_3 \oplus M_4 = 1 \]
Exploit Decryption Response

Learn $M_1 \oplus M_2 \oplus M_3 \oplus M_4$
Exploit Decryption Even Further

Learn $M_1 \oplus M_2 \oplus M_3$
Solve A System of Linear Equations

\[
\begin{align*}
M_1 \oplus M_2 \oplus M_3 \oplus M_4 &= \square \\
M_1 \oplus M_2 \oplus M_3 &= \square \\
M_1 \oplus M_2 &= \square \\
M_1 &= \square
\end{align*}
\]
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Constructing AE: Generic Composition

A good PRF, such as Encrypted CBC-MAC

Privacy-only encryption (such as CTR/CBC)

Compose them to build AE

<table>
<thead>
<tr>
<th>Method</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encrypt-and-MAC</td>
<td>SSH</td>
</tr>
<tr>
<td>MAC-then-Encrypt</td>
<td>SSL/TLS</td>
</tr>
<tr>
<td>Encrypt-then-MAC</td>
<td>IPSec</td>
</tr>
</tbody>
</table>
Encrypt-and-MAC: Simple Composition

No privacy: encrypting the same message results in the same tag
No authenticity if one can modify $C$ such that decryption is unchanged.

Privacy | Authenticity
---|---
No | No

for some bad encryption scheme
Encrypt-and-MAC in SSH

\[ M \]

Encode

\[ M \| \text{pad} \]

\[ \text{len}(M)\|\text{len}(\text{pad}) \]

CBC

\[ C \]

Privacy | Authenticity
--- | ---
Yes | Yes

\[ F_{K_m} \]

\[ T \]
MAC-then-Encrypt

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No authenticity if one can modify $C$ such that decryption is unchanged.

for some bad encryption scheme
MAC-then-Encrypt in TLS

\[ M \xrightarrow{F_{Km}} T \xrightarrow{CBC} C \]

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Encrypt-then-MAC

\[ M \xrightarrow{\mathcal{E}_{K_e}} C \xrightarrow{F_{K_m}} T \]

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Reusing Key May Lead to Attacks

EtM with CBC encryption and CBCMAC, same key

Good MAC if fixed input length

Break auth with one query
A Common Pitfall in Implementing EtM

Happened in ISO 1972 standard, and in RNCryptor of iOS

Forget to feed IV into MAC

Break auth with one query
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The Padding-Oracle Attack

“Lucky Thirteen” attack snarfs cookies protected by SSL encryption
Exploit is the latest to subvert crypto used to secure Web transactions.

Meaner POODLE bug that bypasses TLS crypto bites 10 percent of websites
Some of the world’s leading sites are vulnerable to an easier, more simplified attack.

Researchers poke hole in custom crypto built for Amazon Web Services
Even when engineers do everything by the book, secure crypto is still hard.

New TLS encryption-busting attack also impacts the newer TLS 1.3
Researchers discover yet another Bleichenbacher attack variation (yawn!).
Attack Model: Chosen Prefix Secret Suffix

Goal: Recover $M$
This Model Is Realistic: Attacking SSL

- Visit attacker.com
- Cookie with bank.com

Encrypted communication via SSL

Bank of America

bank.com
This Model Is Realistic: Attacking SSL

Encrypted communication via SSL

Request resource
/AA at bank.com

cookie with bank.com

attacker.com
This Model Is Realistic: Attacking SSL

$M$

encrypted

GET /AA cookie: $M$

attacker.com

bank.com
This Model Is Realistic: Attacking SSL

Enc oracle

encrypted

GET /AA cookie: \( M \)

Dec oracle

bank.com
Encryption In SSL: MAC-then-Encrypt

\[ M \rightarrow \text{MAC} \rightarrow M^T \rightarrow \text{padding} \rightarrow \text{CBC} \rightarrow C \]
Padding In SSL Encryption

block length is 16 bytes

Consider byte strings only

- 31 bytes, 1 byte
- 24 bytes, 7 bytes, 1 byte
- 16 bytes, 15 bytes, 1 byte
The Attack in Action

Illustration For Two-block Message

Enc

Dec

$M_1$  $M_2$

$M$

Aim: Recover the message byte by byte
Recover Last Byte of First Block

\[ \mathcal{E}_K(M_1M_2) \]

Diagram with nodes labeled \( C_0 \), \( C_1 \), \( C_2 \), \( C_3 \), \( C_4 \) and an empty string.
Recover Last Byte of First Block

Enc

Dec

\[
C_0 \quad C_1 \quad C_2 \quad C_3 \quad C_4
\]
CBC Decryption

To pass MAC check, want the last byte of $V$ to be 15

Pass with prob $\sim 1/256$
If valid, last byte of $V = M_1 \oplus C_0 \oplus C_3$ is 15.

Learn last byte of $M_1$.
Exploit Decryption Output

If invalid, restart

After $t$ attempts, succeed with prob $\sim 1 - (1 - 1/256)^t$ times
Exercise: Recover Last Byte of Second Block

$\mathcal{E}_K(M_1M_2)$

$C_0$ $C_1$ $C_2$ $C_3$ $C_4$

Enc

Empty string

A

How to query Dec?
Recover **Second Last Byte of First Block**

\[
\mathcal{E}_K(0^8 M_1 M_2)
\]

Second last byte of \( M_1 \) is now the **last byte** of the first block of \( 0^8 M_1 M_2 \)
Querying Dec: A Wrong Approach

This is the tag position, but the last byte is overwritten
How To Query Dec

\[ \mathcal{E}_K(M_1 M_2) = C_0 C_1 C_2 C_3 C_4 \]

\[ \mathcal{E}_K(0^8 M_1 M_2) = B_0 B_1 B_2 B_3 B_4 \]
CBC Decryption

\[ V = M'_1 \oplus B_0 \oplus C_3 \]

Learn last byte of \( M'_1 \)

0^8 then 15 bytes of \( M_1 \)
Patching Via Different Padding

Secure if implement properly
Careless Implementation Leads To Attack

\[ C \xrightarrow{\text{CBC Dec}} M \]

- **Secure** if return a single error signal
- **Broken** if tell what kind of error it is.

\[ M \xrightarrow{T} \text{MAC} \]

Correct padding?

\[ T' \]
Scanning For Vulnerable Implementations

"Given final block not properly padded"

About 16,000 results (0.32 seconds)

Stack Overflow
https://stackoverflow.com › questions › given-final-bl...

Given final block not properly padded - java
Nov 8, 2011 — BadPaddingException: Given final block not properly padded. Such issues can arise if a bad key is used during decryption.
7 answers · Top answer: If you try to decrypt PKCS5-padded data with the wrong key, and then ...

Given final block not properly padded exception - Stack Overflow   Apr 11, 2018
Given final block not properly padded. AES Decryption - Stack ...   Nov 13, 2022
Given final block not properly padded. Such issues can arise if ...   Jul 10, 2020
"Get Key Failed: Given final block not properly padded" when I ...   Sep 22, 2021

More results from stackoverflow.com
Implementation Is Hard: **Timing Leakage**
How To Attack
Illustration For Two-block Message

\[ \mathcal{E}_K(M_1M_2) \]
Recover Last Byte of Second Block

\[ C_0 \quad C_1 \quad C_2 \quad C_3 \quad C_4 \]

\[ C_0 \quad R \quad C_2 \]

random
CBC Decryption

If $V$ ends with a zero byte

$V = M_2 \oplus C_1 \oplus R$

Bad tag signal