

Padding Oracle Attack Lab

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1 Overview

The learning objective of this lab is for students to get a hands-on experience on an interesting attack on crypto systems. Some systems, when decrypting a given ciphertext, verify whether the padding is valid or not, and throw an error if the padding is invalid. This seemingly-harmless behavior enables a type of attack called *padding oracle attack*. The attack was originally published in 2002 by Serge Vaudenay, and many well-known systems were found vulnerable to this attack, including Ruby on Rails, ASP.NET, and OpenSSL.

In this lab, students are given two oracle servers running inside a container. Each oracle has a secret message hidden inside, and it lets you know the ciphertext and the IV, but not the plaintext or the encryption key. You can send a ciphertext (and the IV) to the oracle; it will decrypt the ciphertext using the encryption key, and tell you whether the padding is valid or not. Your job is to use the response from the oracle to figure out the content of the secret message. This lab covers the following topics:

- Secret-key encryption
- Encryption modes and paddings
- Padding oracle attack

Readings. Detailed coverage of the secret-key encryption can be found in the following, but the padding oracle attack is not covered in the current edition (future editions will include this attack). Students can find tutorials on this attack from online resources, such as Wikipedia.

- Chapter 21 of the SEED Book, *Computer & Internet Security: A Hands-on Approach*, 2nd Edition, by Wenliang Du. See details at <https://www.handsonsecurity.net>.

Lab environment. This lab has been tested on the SEED Ubuntu 20.04 VM. You can download a pre-built image from the SEED website, and run the SEED VM on your own computer. However, most of the SEED labs can be conducted on the cloud, and you can follow our instruction to create a SEED VM on the cloud.

2 Lab Environment

In this lab, we use a container to run the padding oracle.

Container Setup and Commands. Please download the `Labsetup.zip` file to your VM from the lab's website, unzip it, enter the `Labsetup` folder, and use the `docker-compose.yml` file to set up the lab environment. Detailed explanation of the content in this file and all the involved `Dockerfile` can be found from the user manual, which is linked to the website of this lab. If this is the first time you set up a SEED lab environment using containers, it is very important that you read the user manual.

In the following, we list some of the commonly used commands related to Docker and Compose. Since we are going to use these commands very frequently, we have created aliases for them in the `.bashrc` file (in our provided SEEDUbuntu 20.04 VM).

```
$ docker-compose build # Build the container images
$ docker-compose up    # Start the containers
$ docker-compose down  # Shut down the containers

// Aliases for the Compose commands above
$ dcbuild              # Alias for: docker-compose build
$ dcup                 # Alias for: docker-compose up
$ dcdown               # Alias for: docker-compose down
```

All the containers will be running in the background. To run commands on a container, we often need to get a shell on that container. We first need to use the "docker ps" command to find out the ID of the container, and then use "docker exec" to start a shell on that container. We have created aliases for them in the `.bashrc` file.

```
$ dockps              // Alias for: docker ps --format "{{.ID}}  {{.Names}}"
$ docksh <id>        // Alias for: docker exec -it <id> /bin/bash

// The following example shows how to get a shell inside hostC
$ dockps
b1004832e275  hostA-10.9.0.5
0af4ea7a3e2e  hostB-10.9.0.6
9652715c8e0a  hostC-10.9.0.7

$ docksh 96
root@9652715c8e0a:/#

// Note: If a docker command requires a container ID, you do not need to
//       type the entire ID string. Typing the first few characters will
//       be sufficient, as long as they are unique among all the containers.
```

If you encounter problems when setting up the lab environment, please read the “Common Problems” section of the manual for potential solutions.

3 Task 1: Getting Familiar with Padding

For some block ciphers, when the size of a plaintext is not a multiple of the block size, padding may be required. The PKCS#5 padding scheme is widely used by many block ciphers (see Chapter 21.4 of the SEED book for details). However, PKCS#5 is only defined for block sizes of 8 bytes. This proves problematic for block ciphers which have block sizes longer than 8 bytes, like AES. To fix this issue, the PKCS#7 padding scheme was invented. We will conduct the following experiments to understand how this type of padding works.

We can use the "echo -n" command to create a file. The following example creates a file P with length 5 (without the -n option, the length will be 6, because a newline character will be added by echo):

```
$ echo -n "12345" > P
```

We use "openssl enc -aes-128-cbc -e" to encrypt this file using 128-bit AES with CBC mode. To see what is added to the padding during the encryption, we will decrypt the ciphertext using "openssl enc -aes-128-cbc -d". Unfortunately, decryption by default will automatically remove the padding, making it impossible for us to see the padding. However, the command does have an option called "-nopad", which disables the padding, i.e., during the decryption, the command will not remove

the padded data. Therefore, by looking at the decrypted data, we can see what data are used in the padding.

```
$ openssl enc -aes-128-cbc -e -in P -out C
$ openssl enc -aes-128-cbc -d -nopad -in C -out P_new
```

It should be noted that padding data may not be printable, so you need to use a hex tool to display the content. The following example shows how to display a file in the hex format:

```
$ xxd P_new
00000000: 3132 3334 350b 0b0b 0b0b 0b0b 0b0b 0b0b 12345.....
```

Your job is to create three files, which contain 5 bytes, 10 bytes, and 16 bytes, respectively. Using the method above, please figure out what paddings are added to the three files.

When decrypting the 16 byte file, why do we see a full block of padding? Why is this necessary?

4 Task 2: Padding Oracle Attack (Level 1)

Some systems, when decrypting a given ciphertext, verify whether the padding is valid or not, and throw an error if the padding is invalid. This seemingly-harmless behavior enables a type of attack called *padding oracle attack*. The attack was originally published in 2002 by Serge Vaudenay, and many well-known systems were found vulnerable to this type of attacks, including Ruby on Rails, ASP.NET, and OpenSSL.

4.1 The Oracle Setup

In this task, we provide a padding oracle hosted on port 5000. The oracle has a secret message inside, and it prints out the ciphertext of this secret message. The encryption algorithm and mode used is AES-CBC, and the encryption key is K , which is unknown to others. You can interact with the oracle using "nc 10.9.0.80 5000". You will see the following hexadecimal data provided by the oracle. The first 16 bytes is the IV, and the rest is the ciphertext. From the length, you can see that the ciphertext has 32 bytes, i.e., 2 blocks, but the actual length of the plaintext is unknown due to the padding.

```
$ nc 10.9.0.80 5000
01020304050607080102030405060708a9b2554b094411...
```

The oracle accepts input from you. The format of the input is the same as the message above: 16-bytes of the IV, concatenated by the ciphertext. The oracle will decrypt the ciphertext using its own secret key K and the IV provided by you. It will not tell you the plaintext, but it does tell you whether the padding is valid or not. Your task is to use the information provided by the oracle to figure out the actual content of the secret message. For the sake of simplicity, you only need to find out one block of the secret message. For the debugging purpose, we provide the secret message in the following (it is in the source code of the oracle).

```
static std::array<unsigned char, 29> PLAIN_TEXT = {
    0x11, 0x22, 0x33, 0x44, 0x55, 0x66, 0x77, 0x88,
    0x11, 0x22, 0x33, 0x44, 0x55, 0x66, 0x77, 0x88,
    0x11, 0x22, 0x33, 0x44, 0x55, 0x66, 0x77, 0x88,
    0xaa, 0xbb, 0xcc, 0xdd, 0xee
};
```

The secret message is provided only for debugging purposes, and you cannot assume that you know this message. You need to use the padding oracle attack to derive this message; you need to show your steps.

4.2 Deriving the Plaintext Manually

The objective of this task is to figure out the plaintext of the secret message. It has two blocks P1 and P2. We only need to get P2 (getting P1 is similar). We have provided a skeleton code called `manual_attack.py`. You can use this as a basis to construct your attack. We will explain each piece of this code.

First, let's get the ciphertext from the oracle. The ciphertext in this task consists of two blocks, and we use two 16-byte bytearray's C1 and C2 to hold the content of these two blocks.

```
oracle = PaddingOracle('10.9.0.80', 5000)

# Get the IV + Ciphertext from the oracle
iv_and_ctext = bytearray(oracle.ciphertext)
IV = iv_and_ctext[00:16]
C1 = iv_and_ctext[16:32] # 1st block of ciphertext
C2 = iv_and_ctext[32:48] # 2nd block of ciphertext

print("C1: " + C1.hex())
print("C2: " + C2.hex())
```

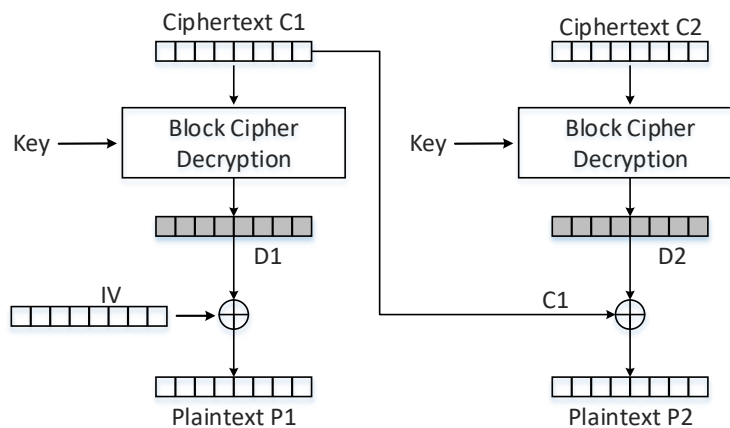


Figure 1: Decryption using CBC

As depicted in Figure 1, D1 and D2 are the output of the AES block cipher. If we can get their values, we can easily get the plaintext by xoring them with the ciphertext (or IV for the first block). In this task, we focus on the second block P2. Therefore, if we can figure out the values of D2, we can calculate P2 using $P2 = C1 \oplus D2$.

We will not explain the details of the padding oracle attack in this lab description. Students can find the details from online resources, such as Wikipedia (the current SEED book does not cover this attack). The general idea of the attack is to send to the oracle a ciphertext with modified C1 (let's call it CC1). Although the oracle will not tell us the result of $D2 \oplus CC1$, it does tell us whether the result has a valid padding or not. That opens the door for us to figure out the value of D2.

There are 16 bytes in D2, we can figure out its value one byte at a time. In the skeleton code, we have initialized two arrays D2 and CC1. Their initial values do not really matter. Your task is to use an iterative process to figure out the value for the D2 array. For each iteration, you need to construct the CC1 array properly.

```

# The initial value of D2 does not matter. Our job is to
# find its correct values.
D2 = bytearray(16)

D2[0] = C1[0]
D2[1] = C1[1]
...
D2[15] = C1[15]

# CC1 is used to replace the C1 block in the ciphertext
# Its values need to be set properly in each round
CC1 = bytearray(16)

CC1[0] = 0x00
CC1[1] = 0x00
...
CC1[15] = 0x00

```

In each iteration, we focus on one byte of CC1. We try all 256 possible values for that byte, and send the constructed ciphertext CC1 + C2 (plus the IV) to the oracle, and see which value makes the padding valid. As long as our construction is correct, there will be one valid value. This value helps us get one byte of D2. The code in the following focuses on K=1. It can help us find the value for D[15].

```

K = 1
for i in range(256):
    CC1[16 - K] = i
    status = oracle.decrypt(IV + CC1 + C2)
    if status == "Valid":
        print("Valid: i = 0x{:02x}".format(i))
        print("CC1: " + CC1.hex())

```

You can use the skeleton code as your basis, manually change the value of K, use the execution result in each round to set the D2 accordingly, and then re-run the program with a updated CC1 to get the next byte of D2, i.e., D2[14]. Repeating the step, you can get D2[13], D2[12], ..., D2[0]. Once you get the entire D2, you get the value of the plaintext P2.

```

# Once you get all the 16 bytes of D2, you can easily get P2
P2 = xor(C1, D2)
print("P2: " + P2.hex())

```

Note. Figuring out all the 16 bytes of D2 may be too tedious. Students can stop after getting 6 bytes of D2. That will unlock the last 6 bytes of the plaintext P2 (including the padding). It is sufficient. Although students can write code to automate the entire process, it is the intention of the lab to force students to do it manually. Therefore, the lab report needs to include how each byte (for at least 6 bytes) of D2 is obtained. In the next task, students will be required to automate this process.

5 Task 3: Padding Oracle Attack (Level 2)

We did manual attacks in the previous task. In this task, we will automate the attack process, and this time, we need to get all the blocks of the plaintext. When the container starts, two padding oracle servers will

be started, one for the Level-1 task, and the other is for the Level-2 task, i.e., this task. The Level-2 server listens to port 6000. Although the key and the secret message are in the binary code of the oracle program, we have tried to obfuscate them, so it will not be very easy to find them from the binary. Moreover, learning the secret message does not help the padding oracle attack at all. Students' grade depends on how they derive the secret message using the padding oracle attack, not on whether they know the secret message or not.

It should be noted that every time you make a new connection to the oracle, the oracle will generate a new key and IV to encrypt the secret message (the message is still the same). That is why you will see a different ciphertext. However, if you stay inside an existing connection, the key and IV will not change.

You can write a program to derive all the blocks of the secret message in one run, but you are allowed to write your program to get one block at a time. Eventually, you need to print out all the blocks. In your report, you need to include your code, along with the screenshots of the execution results.

6 Submission

You need to submit a detailed lab report, with screenshots, to describe what you have done and what you have observed. You also need to provide explanation to the observations that are interesting or surprising. Please also list the important code snippets followed by explanation. Simply attaching code without any explanation will not receive credits.

7 Acknowledgment

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