Capture The Flags

A (somewhat) gentle introduction

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ON CAPTURE THE FLAGS (CTFS)

Capture The Flags are offline/online events that focus on computer security related topics.

The idea is to have a series of **challenges**, and the goal of each challenge is to capture a **flag**.

$$\mathrm{Flag}\{\mathrm{Crypt0IsH4rd}\}$$

The flag is protected by various mechanism, and to get it one has to **find**, **research** and **exploit** one or more **vulnerabilities**.

Each challenge belongs within a specific category.

- binary
- reverse
- **web**
- **crypto**
- mobile
- OSINT

Learning through CTFs can be **fun** and **instructive**.

$$\textbf{University} \Leftrightarrow \textbf{CTFs} \Leftrightarrow \textbf{Real-World}$$

THE BLACK-BOX TECHNIQUE

Computer Science is complex.

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Applied cryptography is very complex.

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Applied cryptography is very complex.

Q: How do you deal with such overwhelming complexity?

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Helpful idea:

being able to think in terms of

black boxes

Q: What is a **black box**?

Q: What is a **black box**?

A: It is anything that takes an **input** and produces an **output**.

Thinking in terms of black boxes allows us to

ignore implementation details!

When using **black boxes** we're only interested in the mapping

$$\text{Input} \longrightarrow \text{Output}$$

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$$\text{Input} \longrightarrow \text{Output}$$

This can remove a lot of complexity.

(but be careful cause you're gonna miss some details)

EXAMPLE OF BLACK BOXING

Example of Black Boxing (1/4)

Consider the following code

```python
def fun(arr, n):
    gap = n // 2
    while gap > 0:
        for i in range(gap, n):
            temp = arr[i]
            j = i
            while (j >= gap and arr[j - gap] > temp):
                arr[j] = arr[j - gap]
                j -= gap
            arr[j] = temp
        gap //= 2
```

(code/black-box.py)

Example of Black Boxing (2/4)

We can analyze the previous code in various ways.

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- If we "**black box it**" we're only interested in the mapping between input and output.

Example of Black Boxing (2/4)

We can analyze the previous code in various ways.

- If we "**black box it**" we're only interested in the mapping between input and output.
- If we "**white box it**" we're also interested about its implementation details.

Example of Black Boxing (2/4)

We can test the code as follows

```
def main():
    arr = [3, 5, 2, 1, 0, 2, 3, 1]
    n = len(arr)
    print(arr)
    fun(arr, n)
    print(arr)
```

Example of Black Boxing (3/4)

Executing it, we get

```
$ python3 black-box.py
Before function call
[3, 5, 2, 1, 0, 2, 3, 1]
After function call
[0, 1, 1, 2, 2, 3, 3, 5]
```

Example of Black Boxing (3/4)

Executing it, we get

```
$ python3 black-box.py
Before function call
[3, 5, 2, 1, 0, 2, 3, 1]
After function call
[0, 1, 1, 2, 2, 3, 3, 5]
```

What does the code do?

Example of Black Boxing (3/4)

Executing it, we get

```
$ python3 black-box.py
Before function call
[3, 5, 2, 1, 0, 2, 3, 1]
After function call
[0, 1, 1, 2, 2, 3, 3, 5]
```

What does the code do?

It sorts an array of integers (shell-sort)!

INTERFACES AND IMPLEMENTATIONS

When analyzing **real software implementations**, it is impossible to understand all the details.

When analyzing **real software implementations**, it is impossible to understand all the details.

Thinking in terms of **black boxes** therefore becomes a necessity.

Of course, a **black box** is simply an abstraction.

A model to help us not go crazy.

A **black box** is simply an abstraction.

Thus, it is always important to be **extremely aware** of what exactly is that we are "black boxing" at any given moment.

I suggest to always keep a mental boundary between

- **Interface Knowledge** (black box)
- **Implementation Knowledge** (white box)

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I also suggest to try to **implement** things yourself, so as to develop more **implementation knowledge**.

Implementation (white box)	Interface (black box)

```python
def fun(arr, n):
    gap = n // 2
    while gap > 0:
        for i in range(gap, n):
            temp = arr[i]
            j = i
            while (j >= gap and arr[j - gap] > temp):
                arr[j] = arr[j - gap]
                j -= gap
            arr[j] = temp
        gap //= 2
```

$$\mathrm{arr} = \{x_0, x_1, x_2, \ldots, x_n\}$$

$$\downarrow$$

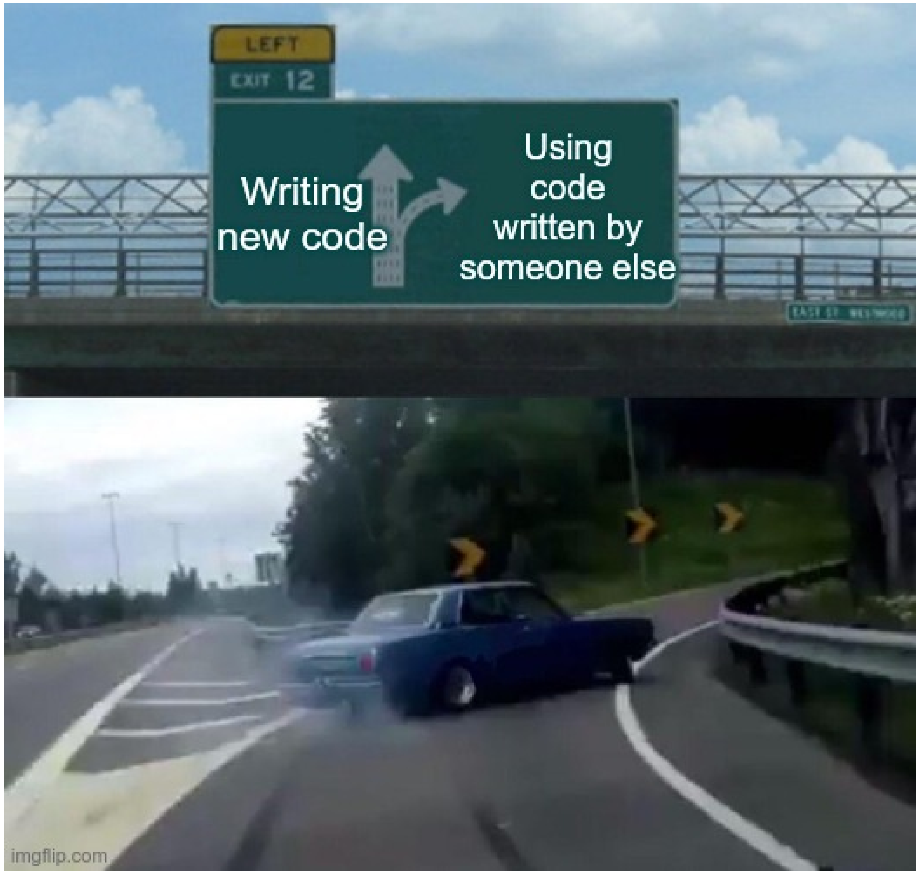
$$\mathrm{fun}(\mathrm{arr}, n)$$

$$\downarrow$$

$$\mathrm{arr} = \{x_{i_0}, x_{i_1}, x_{i_2}, \ldots, x_{i_n}\}$$

$$i_j \leq i_k \implies x_{i_j} \leq x_{i_k}$$

Confuse **interfaces** with **implementations** and sooner or later you will be in much trouble (imho)



The dualism

Interface Knowledge

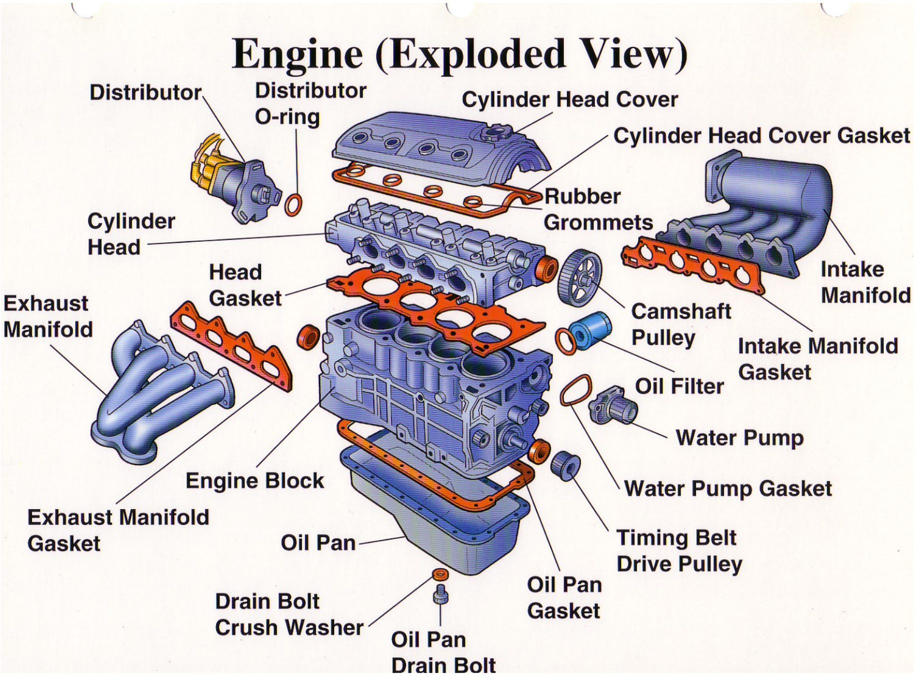
$$\updownarrow$$

Implementation Knowledge

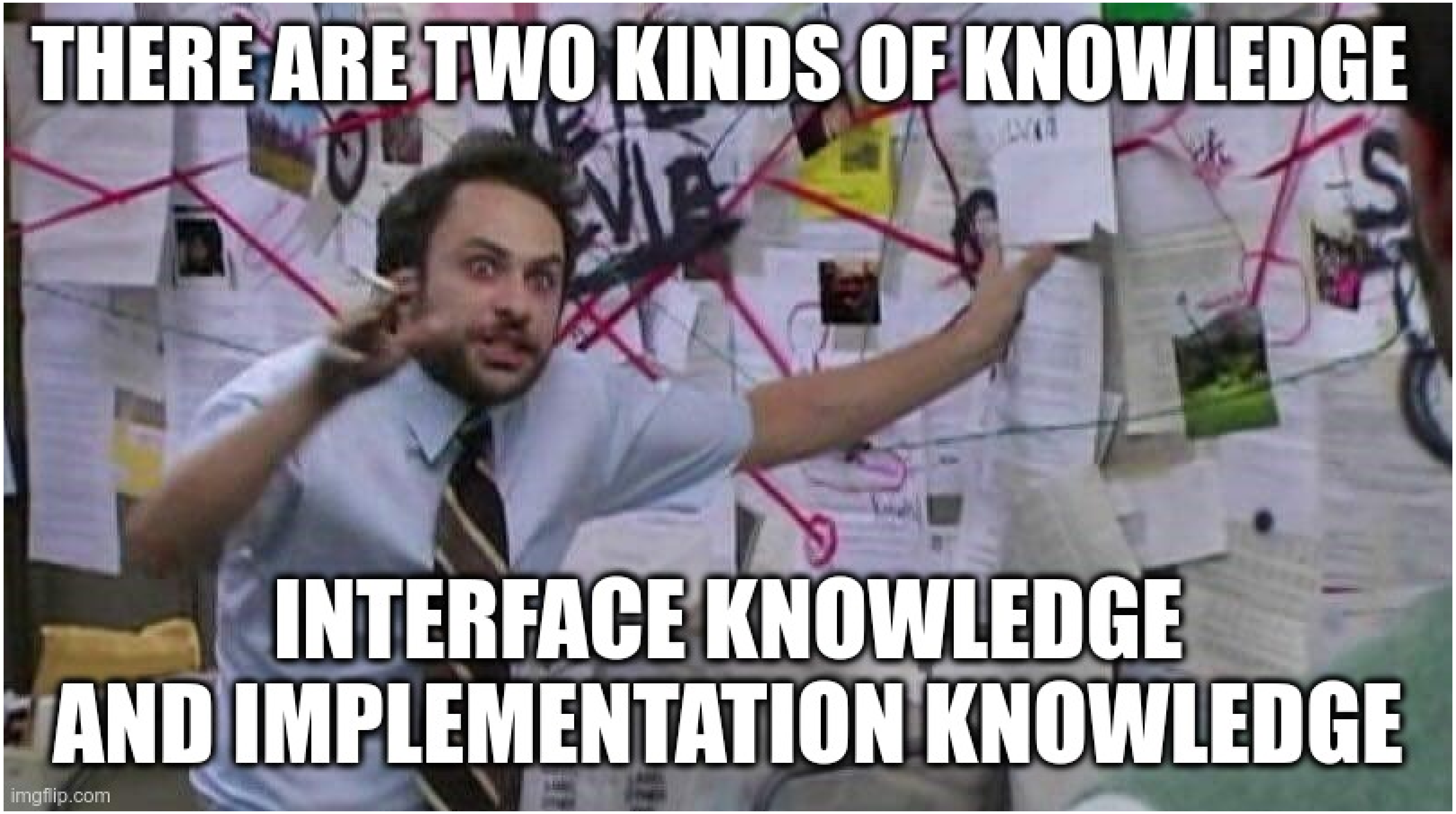
applies to all sorts of technologies.

Even **cars**…

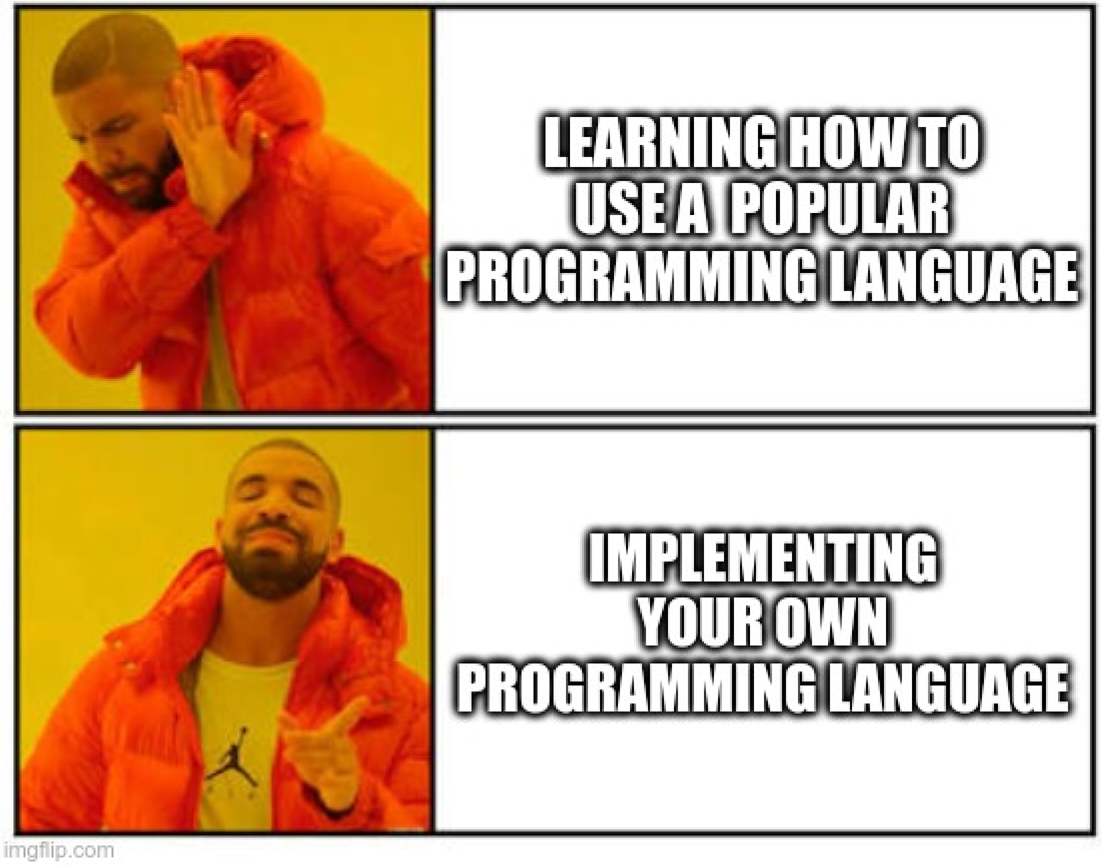
Implementation	Interface
(white box)	(black box)



I suspect it is an **intrinsic property of technology.**



Of the two, I believe **implementation knowledge** is much rarer, and, therefore, potentially more valuable.



PYTHON REVIEW

CTFs involve a diverse and heterogeneous set of **technologies**.

We will restrict your focus on **python**.

Q: What is **Python**?

Q: What is **Python**?

Python is an **interpreted** programming language that can be used in many different contexts

- Data science
- Cybersecurity
- Web development
- DevOps

Q: **Interpreted**?

There exists a program, the **interpreter**, which takes in input python code and which executes each line of the code to produce an **effect**.

$$\text{Python code} \longrightarrow \text{Python Interpreter} \longrightarrow \text{Effect}$$

010101010111010101110101010101

We write code to change bits

101010101000101010001010101010

There are various online tutorials on how to install python in your environment.

https://www.python.org/downloads/

Basic structure of a python program

```python
#!/usr/bin/env python

def main():
    print("Hello World!")

if __name__ == "__main__":
    main()
```

(code/python-review/hello.py)

Basic structure of a python program

```
#!/usr/bin/env python

def main():
    print("Hello World!")

if __name__ == "__main__":
    main()
```

(**code/python-review/hello.py**)

NOTE: The code is executed from top to bottom.

```
$ python3 hello.py
Hello World!
```

I suggest you to (briefly) review the following basic programming construct:

- **variables**
- **functions**
- **conditionals**
- **iteration**
- **basic data structures**
- **classes**

I suggest you to (briefly) review the following basic programming construct:

- **variables**
- **functions**
- **conditionals**
- **iteration**
- **basic data structures**
- **classes**

NOTE: No need to be an expert

Variables in Python

```python
#!/usr/bin/env python

if __name__ == "__main__":
    boolean = True
    integer = 10
    floating = 10.5
    string = "Hello"
```

(code/python-review/variables.py)

Functions in Python

```
#!/usr/bin/env python

def my_sum(a, b):
    return a + b

if __name__ == "__main__":
    result = my_sum(3, 5)
    print(result)
```

(code/python-review/functions.py)

Conditionals in Python

```python
#!/usr/bin/env python

def absolute_value(a):
    if a > 0:
        return a
    else:
        return -a

if __name__ == "__main__":
    print(absolute_value(-10))
    print(absolute_value(10))
```

(code/python-review/conditionals.py)

Iterations in Python

```python
#!/usr/bin/env python

def check_prime(n):
    for i in range(0, n):
        if n % i == 0:
            return False
    return True

if __name__ == "__main__":
    print(check_prime(7))
    print(check_prime(10))
```

(code/python-review/iterations.py)

Basic data structures in Python

```
#!/usr/bin/env python

if __name__ == "__main__":
    my_list = [10, 13, 3, 0, 6]
    first_element = my_list[0]
    last_element = my_list[4]
    length = len(my_list)

    my_dictionary = {"a": 0, "b": 0, "c": 0}
    value = my_dictionary["a"]
    my_dictionary["d"] = 0

    my_tuple = (10, 20)
    elem = my_tuple[0]
```

(code/python-review/data-structures.py)

Classes in Python

```python
#!/usr/bin/env python

class Person:
    def __init__(self, name, age):
        self.name = name
        self.age = age

    def set_age(self, age):
        self.age = age

    def get_age(self):
        return self.age

if __name__ == "__main__":
    p1 = Person("Leonardo", 27)
    p2 = Person("Giuseppe", 22)
    print(p1.get_age())
```

(code/python-review/classes.py)

OUT FIRST CHALLENGES

Let's start by analyzing some challenges together.

CAESAR CIPHER

The idea of a **Caesar Cipher** is to hide the meaning of a message by **shifting** each letter of the alphabet by a specific constant $c = 3$.

Shift when $c = 3$

For a single letter

$$\mathrm{A} \longrightarrow \mathrm{A} + 3 = \mathrm{D}$$

Shift when $c = 3$

For the entire alphabet

$$\begin{gathered}\mathrm{ABCDEFGHIJKLMNOPQRSTUVWXYZ}\\ \downarrow \\ \mathrm{DEFGHIJKLMNOPQRSTUVWXYZABC}\end{gathered}$$

Applying Caesar Cipher

HELLO WORLD

$\downarrow$

KHOOR ZRUOG

The Challenge (1/2)

We are given a file `chal.txt` with the following content

```
BHWC{ODEBPEJC_EO_JKP_AJKQCD!}
```

and we need to recover the flag

```
FLAG{...}
```

The Challenge (2/2)

We're also given the code that wasa used to generate `chal.txt`

```
def main():
    shift_value = random.randint(0, 25)
    c = Caesar(shift=shift_value)
    with open("chal.txt", "w") as f:
        encrypted_flag = c.encrypt(FLAG)
        f.write(encrypted_flag)
```

How would you solve it?

How would you solve it?

Hint: KNOWN-PLAINTEXT ATTACK

KNOWN-PLAINTEXT ATTACK

The plaintext flag starts with F. We can use this fact to compute the shift used.

$$\text{shift} = \mathrm{ASCII}(c_1) - \mathrm{ASCII}(F) \mod 26$$

Where c_1 is the first letter of the ciphertext

In our case

$$\begin{aligned}
\text{shift} &= \text{ASCII}(c_1) - \text{ASCII}(F) \mod 26 \\
&= \text{ASCII}(B) - \text{ASCII}(F) \mod 26 \\
&= 66 - 70 \mod 26 \\
&= -4 \mod 26 \\
&= 22
\end{aligned}$$

Implemented in code

```python
#!/usr/bin/env python3

from caesar import Caesar

def solve():
    flag = open("./chal.txt", "r").read()

    # extract shift_value with a KNOWN PLAINTEXT ATTACK
    shift_value = (ord(flag[0]) - ord('F')) % 26

    # decipher the rest
    c = Caesar(shift=shift_value)
    decrypted_flag = c.decrypt(flag)
    print(decrypted_flag)

if __name__ == "__main__":
    solve()
```

```
$ python3 solution.py
FLAG{SHIFTING_IS_NOT_ENOUGH!}
```

ONE-TIME PAD

This challenge starts with the following text

Who needs AES when you have XOR?

The challenge is made up of two files

- A **challenge.py** python script
- An **output.txt** file with the following content

```
Flag: 134af6e1297bc4a96f6a87fe046684e8047084ee046d84c5282dd7ef292dc9
```

(**code/one-time-pad**)

The python script contains the following code

```python
#!/usr/bin/python3
import os
flag = open('flag.txt', 'r').read().strip().encode()

class XOR:
    def __init__(self):
        self.key = os.urandom(4)
    def encrypt(self, data):
        xored = b''
        for i in range(len(data)):
            xored += bytes([data[i] ^ self.key[i % len(self.key)]])
        return xored
    def decrypt(self, data):
        return self.encrypt(data)

def main():
    global flag
    crypto = XOR()
    print ('Flag:', crypto.encrypt(flag).hex())

if __name__ == '__main__':
    main()
```

(code/one-time-pad/challenge.py)

We can infer that the `output.txt` file was encrypted using the `XOR` class defined in `challenge.py`.

In particular, the code implements a **one-time-pad**.

The idea behind the one-time-pad is to compute the encrypted text by using the XOR operation between the original message bytes and a **random key**.

$$\text{Plaintext} \oplus \text{Random key} \longrightarrow \text{Encrypted text}$$

To work properly, the scheme requires that:

1. The key must be generated using cryptographically secure pseudo-random bytes.
2. The key must be as long as the message.
3. For each message, a new key must be generated.

Is this the case?

```python
class XOR:
    def __init__(self):
        self.key = os.urandom(4)

    def encrypt(self, data):
        xored = b''
        for i in range(len(data)):
            xored += bytes([data[i] ^ self.key[i % len(self.key)]])
        return xored

    def decrypt(self, data):
        return self.encrypt(data)
```

(code/one-time-pad/challenge.py)

The initialization of the key is done using `os.urandom()`, which provides with cryptography safe random bytes.

```
def __init__(self):
    self.key = os.urandom(4)
```

(code/one-time-pad/challenge.py)

Decryption is the same as encryption

```python
def decrypt(self, data):
    return self.encrypt(data)
```

(code/one-time-pad/challenge.py)

Finally, encryption is done by xoring the byte of the message with the byte of the key

```python
def encrypt(self, data):
    xored = b''
    for i in range(len(data)):
        xored += bytes([data[i] ^ self.key[i % len(self.key)]])
    return xored
```

(code/one-time-pad/challenge.py)

What happens when

```
len(data) > len(self.key)
```

?

```
len(data) > len(self.key)
```

At some point the bytes of the keys are re-used again, even though this shouldn't be possible.

This vulnerability breaks the implementation.

Indeed, we can extract all key bytes by doing, once again, a **KNOWN-PLAINTEXT ATTACK**

$$K_0 = C_0 \oplus \text{ASCII}(F)$$
$$K_1 = C_1 \oplus \text{ASCII}(L)$$
$$K_2 = C_2 \oplus \text{ASCII}(A)$$
$$K_3 = C_3 \oplus \text{ASCII}(G)$$

NOTE: This is enough to break the entire ciphertext.

Solution

```
#!/usr/bin/env python3

def solve():
    with open("./output.txt", "r") as f:
        output = f.read()
        flag = output.split("Flag: ")[1]
        encrypted_bytes = bytes.fromhex(flag)

        # extract key bytes
        key = [0, 0, 0, 0]
        key[0] = encrypted_bytes[0] ^ ord('F')
        key[1] = encrypted_bytes[1] ^ ord('L')
        key[2] = encrypted_bytes[2] ^ ord('A')
        key[3] = encrypted_bytes[3] ^ ord('G')

        # decrypt flag
        plaintext = ["A"] * len(encrypted_bytes)
        for i in range(0, len(encrypted_bytes)):
            plaintext[i] = chr(encrypted_bytes[i] ^ key[i % 4])
        plaintext = "".join(plaintext)

        print(plaintext)
```

(code/one-time-pad/solution.py)

YOUR TURN

MANY-TIMES PAD

They told me to use it one time.

But really, what's the issue here if I use it more than once?

Many-Times pad

- **FILES**: https://teaching.leonardotamiano.xyz/university/2023
  2024/cns/02/many-times-pad.zip
- **IP**: `204.216.217.175`
- **PORT**: `4321`

We can explore the challenge with `nc`

```
$ nc 204.216.217.175 4321
Welcome to Many-times pad.

Make a choice:
 [1] Show flag
 [2] Encrypt
```

With option 1 we receive a base64 encoded falg

```
Flag: 75SMMJiMn3fLPCFP+ubDEAwL1cXgYF7s8XN4Stqg
```

If we decode it however we see unrecognizable bytes

```
$ echo "75SMMJiMn3fLPCFP+ubDEAwL1cXgYF7s8XN4Stqg" | base64 -d | hexdump

ef 94 8c 30 98 8c 9f 77  cb 3c 21 4f fa e6 c3 10  |...0...w.<!O....|
0c 0b d5 c5 e0 60 5e ec  f1 73 78 4a da a0        |.....`^..sxJ..  |
```

With option 1 we receive a base64 encoded falg

```
Flag: 75SMMJiMn3fLPCFP+ubDEAwL1cXgYF7s8XN4Stqg
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If we decode it however we see unrecognizable bytes

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$ echo "75SMMJiMn3fLPCFP+ubDEAwL1cXgYF7s8XN4Stqg" | base64 -d | hexdump

ef 94 8c 30 98 8c 9f 77  cb 3c 21 4f fa e6 c3 10  |...0...w.<!O....|
0c 0b d5 c5 e0 60 5e ec  f1 73 78 4a da a0        |.....`^..sxJ..  |
```

NOTE: This means the flag is encrypted!

With option 2 we can send an arbitrary input

```
Send data to encrypt:
HELLOWORLD
```

However that input has to be base64 encoded before, otherwise we get an error message

```
[ERROR]: Could not understand data: make sure to base64 your payload!
```

With proper base64 input instead we get a response back

```
Send data to encrypt:
SEVMTE9XT1JMRAo=
Encrypted: g9SGPimPgvOcRIk=
```

This seems to be the relative encrypted version of our payload.

We can now analyze the source code of the server,
`server.py`

Python Client (1/5)

Finally, we develop the following client application to interact with the server in the file `client.py`

```
#!/usr/bin/env python3

import socket
from base64 import b64decode
from base64 import b64encode

REMOTE_IP = "204.216.217.175"
REMOTE_PORT = 4321
```

(code/many-times-pad/client.py)

Python Client (2/5)

```python
def solve():
    with socket.socket(socket.AF_INET, socket.SOCK_STREAM) as sock:
        sock.connect((REMOTE_IP, REMOTE_PORT))

        # ignore initial response
        sock.recv(len(b'Welcome to Many-times pad.\n\n'))
```

(code/many-times-pad/client.py)

Python Client (3/5)

Get flag

```python
try:
    sock.recv(len(b'Make a choice:\n [1] Show flag\n [2] Encrypt\n\n'))
    sock.send(b'1')
    s = sock.recv(1024).decode("utf-8")
    b64_flag = s.split("Flag: ")[1]
    flag_bytes = b64decode(b64_flag)
    print(f"Flag_encrypted_bytes = {list(flag_bytes)}")

except Exception as e:
    print("Could not read flag")
    exit()
```

(code/many-times-pad/client.py)

Python Client (4/5)

Send text to encrypt

```python
plaintext = b"HELLO"
try:
    sock.recv(len(b'Make a choice:\n [1] Show flag\n [2] Encrypt\n\n'))
    sock.send(b'2')
    sock.recv(len(b'Send data to encrypt:\n'))

    print(f"Sending plaintext: {list(plaintext)}")

    sock.send(b64encode(plaintext))
    s = sock.recv(1024).decode("utf-8")
    encrypted_bytes_b64 = s.split("Encrypted: ")[1]
    encrypted_bytes = b64decode(encrypted_bytes_b64)
    print(f"Received Encrypted: {list(encrypted_bytes)}")

except Exception as e:
    print("Could not send plaintext")
    exit()
```

(code/many-times-pad/client.py)

Python Client (5/5)

```
if __name__ == "__main__":
    solve()
```

(code/many-times-pad/client.py)

When executing the client we get

```
$ python3 client.py
Flag_encrypted_bytes = [81, 113, 165, 138, 136, 158, ...]
Sending plaintext: [72, 69, 76, 76, 79]
Received Encrypted: [91, 7, 196, 133, 243]
```

Now its your turn.

Modify the client code, and get the flag!

LCG LOTTERY

Can you predict the unpredictable?

LCG Lottery

- **FILES**: https://teaching.leonardotamiano.xyz/university/2023
2024/cns/02/lcg-lottery.zip
- **IP**: `204.216.217.175`
- **PORT**: `4444`

We can explore the challenge with `nc`

```
$ nc 204.216.217.175 4444
Welcome to LCG-Lottery.

Make a choice:
 [1] Draw
 [2] Guess
```

With option 1 we receive a number encoded in base64


```
OTY5Nzk2MDMy
```


We can decode it as follows

```
$ echo -e "OTY5Nzk2MDMy" | base64 -d
969796032
```

With option 2 we can send a number to the server, but we must encode it in base64

```
NzYyNzY3NjA3
Wrong!
```

If we analyze the code of the challenge, we see that the server initializes a PRNG with secret parameters

```python
def challenge(req):
    global FLAG, A, B, C

    seed = int.from_bytes(os.urandom(32))
    prng = LCG(seed, A, B, C)
    guessed = 0
```

The numbers we receive are numbers obtained directly from the PRNG

```
if opt == "1":
    number = prng.next()
    data_out = wrap(str(number).encode("utf-8")) + b'\n'
    req.sendall(data_out)
```

To actually read the flag, we need to guess correctly 3 numbers in a row.

```python
elif opt == "2":
    data_in = req.recv(4096).decode().strip()
    try:
        guess = unwrap(data_in)
        if int(guess) == prng.next():
            guessed += 1
            if guessed > 3:
                data_out = b'Thats it: ' + FLAG + b'\n'
            else:
                data_out = b'Keep going!\n'
        else:
            data_out = b'Wrong!\n'
            guessed = 0
        req.sendall(data_out)
```

The **PRNG** used is the **Linear Congruential Generator** (LCG)

```python
class LCG(object):
    def __init__(self, seed, a, b, c):
        self.x = seed % c
        self.a = a
        self.b = b
        self.c = c

    def next(self):
        self.x = (self.x * self.a + self.b) % self.c
        return self.x
```

Now its your turn.

Write the code, and get the flag!