Project 1: Cryptography

This project counts for 8% of your course grade. This project is due on **Thursday, February 11** at **6 p.m.** Late submissions will be penalized by 10% of the maximum attainable score, plus an additional 10% every 4 hours until received. Late work will not be accepted after 20 hours following the day of the deadline.

This is a group project; you will work in (up to) teams of two and submit one project per team. If you have trouble forming a team, post to Slack's project partner finder channel.
The code and other answers you submit must be entirely your own group's work, and you are bound by the Honor Code. You may discuss the conceptualization of the project and the meaning of the questions, but you may not look at any part of another group's solution. You may consult published references, provided that you appropriately cite them (e.g., with program comments). Visit the course website for the full collaboration policy.

Your code for this project must be written in **Python 3**. Python 3 is not compatible with earlier releases. Be sure you use the correct version, or your solution will not run on the autograder. You may only use standard libraries that ship with Python 3 and the custom modules we provide.

You'll find the online components of this project at **https://project1.ecen4133.org**.

Introduction

In this project, you will investigate vulnerable applications of cryptography, inspired by security problems found in many real-world implementations. In Part 1.1, we'll guide you through attacking the authentication capability of an imaginary server API, by exploiting the length-extension vulnerability of hash functions in the MD5 and SHA family. In Part 1.2, you'll use a cutting-edge tool to generate MD5 hash collisions, and you'll investigate how hash collisions can be exploited to conceal malicious behavior in software. In Part 2.1, you'll practice a simple form of cryptanalysis by using frequency analysis to break a Vigenère Cipher. In Part 2.2 (for graduate students, or optionally otherwise), you'll perform a chosen ciphertext attack that exploits a padding oracle to decrypt a message without knowing the key.

Objectives:

- Understand common pitfalls when applying cryptographic primitives.
- Investigate how cryptographic failures can compromise the security of applications.
- Appreciate why you should use HMAC-SHA256 as a substitute for common hash functions.
- Understand why padding schemes are integral to cryptographic security.

1 Part 1

1.1 Length Extension

In most applications, you should use MACs such as HMAC-SHA256 instead of plain cryptographic hash functions (e.g. MD5, SHA-1, or SHA-256), because hashes, also known as digests, fail to match our intuitive security expectations. What we really want is something that behaves like a pseudorandom function, which HMACs approximate and hash functions do not.

One difference between hash functions and pseudorandom functions is that many hashes are subject to *length extension*. All the hash functions we've discussed use a design called the Merkle-Damgård construction. Each is built around a *compression function* f and maintains an internal state s, which is initialized to a fixed constant. Messages are processed in fixed-sized blocks by applying the compression function to the current state and current block to compute an updated internal state, i.e., $s_{i+1} = f(s_i, b_i)$. The result of the final application of the compression function becomes the output of the hash function.

A consequence of this design is that if we know the hash of an n-block message, we can find the hash of longer messages by applying the compression function for each block $b_{n+1}, b_{n+2}, \ldots$ that we want to add. This process is called length extension, and it can be exploited to attack many applications of hash functions.

Experiment with Length Extension in Python

To experiment with this idea, we'll use a Python implementation of the MD5 hash function, though SHA-1 and SHA-256 are vulnerable to length extension too. Download the `pymd5` from here: `https://ecen4133.org/static/project1/pymd5.py`, and learn how to use it by running `$ pydoc3 pymd5`. To follow along with these examples, run Python in interactive mode: `$ python3 -i`.

Consider the string "Use HMAC, not hashes". We can compute its MD5 hash by running:

```
from pymd5 import md5, padding
m = "Use HMAC, not hashes"
h = md5()
h.update(m)
print(h.hexdigest())
```

or, more compactly, `print(md5(m).hexdigest())`. The output should be:

```
3ecc68efa1871751ea9b0b1a5b25004d
```

MD5 processes messages in 512-bit blocks, so, internally, the hash function pads m to a multiple of that length. The padding consists of the bit 1, followed by as many 0 bits as necessary, followed by a 64-bit count of the number of bits in the unpadded message. (If the 1 and count won't fit in the current block, an additional block is added.) You can use the function `padding(`*`count`*`)` from the `pymd5` module to compute the padding that will be added to a *`count`*-bit message.

Even if we didn't know `m`, we could compute the hash of longer messages of the general form `m + padding(len(m)*8) +` *`suffix`* by setting the initial internal state of our MD5 function to

`MD5(m)`, instead of the default initialization value, and setting the function's message length counter to the size of *m* plus the padding (a multiple of the block size). To find the padded message length, guess the length of *m* and run `bits = (length_of_m + len(padding(length_of_m*8)))*8`.

The `pymd5` module lets you specify these parameters as additional arguments to the `md5` object:

```
h = md5(state=bytes.fromhex("3ecc68efa1871751ea9b0b1a5b25004d"), count=bits)
```

Now you can use length extension to find the hash of a longer string that appends the suffix "Good advice." Simply run:

```
x = "Good advice"
h.update(x)
print(h.hexdigest())
```

to execute the compression function over `x` and output the resulting hash. Verify that it equals the MD5 hash of `m.encode() + padding(len(m)*8) + x.encode()`. Notice that, due to the length-extension property of MD5, we didn't need to know the value of `m` to compute the hash of the longer string—all we needed to know was `m`'s length and its MD5 hash.

[This component is intended to introduce length extension and familiarize you with the `pymd5` module; you do not need to submit anything for it.]

Conduct a Length Extension Attack

Length extension attacks can cause serious vulnerabilities when people mistakenly try to construct something like an HMAC by using $hash(secret \parallel message)$[1].

The Bank of ECEN 4133 (which has poor security) hosts a server for controlling its Internet-of-Things (IoT) devices. The server is located at https://project1.ecen4133.org/*identikey*/lengthextension/.

The server has an API that allows users to perform pre-authorized actions by loading URLs of this form: `https://project1.ecen4133.org/`*`identikey`*`/lengthextension/api?token=`*`token`*`&command=`*`command1`*`&command=`*`command2`*`&...` Bank administrators authorize actions in advance by computing a valid *`token`* using a secret 8-byte password. The server checks that *`token`* is equal to MD5(*secret 8-byte password* $\parallel$ *the portion of the URL starting from the first* `command=`).

Using what you learned in the previous section and without guessing the password, apply length extension to create a URL ending with `&command=UnlockSafes` that is treated as valid by the server API. You have permission to use the server to check whether your command is accepted.

Hint: You might want to use the `quote()` function from Python's `urllib` module to encode non-ASCII characters in the URL.

Historical fact: In 2009, security researchers found that the API used by the photo-sharing site Flickr suffered from a length-extension vulnerability almost exactly like the one in this exercise.

[1] $\parallel$ is the symbol for concatenation, i.e.: "hello" $\parallel$ "world" = "helloworld".

What to submit A Python script named `len_ext_attack.py` that:

1. Accepts an authorized API URL as a command line argument (`sys.argv[1]`).
2. Modifies the URL so that it will execute the `UnlockSafes` command.
3. Prints **only** the modified URL.

You should make the following assumptions:

- The input URL will have a similar form as the examples on the website, but we may change the scheme, port, hostname, and API path, as well as the `commands`, and the number of commands (although there will be at least one). These values may be of substantially different lengths than in the examples. We recommend using Python's `urllib` to parse the URL.
- The secret password may be different than in the examples, but it will always be 8 bytes long.

1.2 Hash Collisions

MD5 and SHA-1 were once the most widely used cryptographic hash functions, but today they are considered dangerously insecure. This is because cryptographers have discovered efficient algorithms for finding *collisions*—pairs of messages with the same values for these functions.

The first known MD5 collisions were announced on August 17, 2004, by Xiaoyun Wang, Dengguo Feng, Xuejia Lai, and Hongbo Yu. Here's one pair of colliding messages they published:

Message 1:

```
d131dd02c5e6eec4693d9a0698aff95c 2fcab58712467eab4004583eb8fb7f89
55ad340609f4b30283e488832571415a 085125e8f7cdc99fd91dbdf280373c5b
d8823e3156348f5bae6dacd436c919c6 dd53e2b487da03fd02396306d248cda0
e99f33420f577ee8ce54b67080a80d1e c69821bcb6a8839396f9652b6ff72a70
```

Message 2:

```
d131dd02c5e6eec4693d9a0698aff95c 2fcab50712467eab4004583eb8fb7f89
55ad340609f4b30283e4888325f1415a 085125e8f7cdc99fd91dbd7280373c5b
d8823e3156348f5bae6dacd436c919c6 dd53e23487da03fd02396306d248cda0
e99f33420f577ee8ce54b67080280d1e c69821bcb6a8839396f965ab6ff72a70
```

Convert each group of hex strings into a binary file.
(On Linux, run `$ xxd -r -p file.hex > file.bin`.)

1. What are the MD5 hashes of the two binary files? Verify that they're the same.
   (`$ openssl dgst -md5 file1.bin file2.bin`)
2. What are their SHA-256 hashes? Verify that they're different.
   (`$ openssl dgst -sha256 file1.bin file2.bin`)

[This component is intended to introduce you to MD5 collisions. You don't need to submit anything.]

Generating Collisions Yourself

In 2004, Wang's method took 5 hours to find an MD5 collision on a desktop PC. Since then, researchers have introduced vastly more efficient collision finding algorithms. You can compute your own MD5 collisions using a tool written by Marc Stevens that uses a more advanced technique.

You can download the `fastcoll` tool here:
`https://www.win.tue.nl/hashclash/fastcoll_v1.0.0.5.exe.zip` (Windows executable)
`https://www.win.tue.nl/hashclash/fastcoll_v1.0.0.5-1_source.zip` (source code)

If you are building `fastcoll` from source, you can compile using this makefile: `https://ecen4133.org/static/project1/Makefile`. You will also need the Boost libraries. On Ubuntu, you can install these using `apt-get install libboost-all-dev`. On OS X, you can install Boost via the Homebrew package manager using `brew install boost`.

1. Generate your own collision with this tool. How long did it take?
   (`$ time fastcoll -o file1 file2`)
2. What are your files? To get a hex dump, run `$ xxd -p file`.
3. What are their MD5 hashes? Verify that they're the same.
4. What are their SHA-256 hashes? Verify that they're different.

[This component is intended to introduce you to `fastcoll`. You don't need to submit anything.]

SHA-1 has similar vulnerabilities to MD5, but SHA-1 collisions are more expensive to compute. The first SHA-1 collision was published in 2017 (`http://shattered.io/`) and took 110 GPU-years to compute. Another attack, published on Jan. 7, 2020, computed a SHA-1 collision with arbitrary prefixes on a GPU cluster at a cost of about $75,000. These costs are likely to fall dramatically as the collision algorithms improve.

A Hash Collision Attack

The collision attack lets us generate two messages with the same MD5 hash and an arbitrary but identical prefix. (More expensive attacks allow generating collisions with *different* chosen prefixes.) Due to MD5's length-extension behavior, we can append any suffix to both messages and know that the longer messages will also collide. This lets us construct files that differ only in a binary "blob" in the middle and have the same MD5 hash, i.e. $\mathit{prefix} \,\|\, \mathit{blob}_A \,\|\, \mathit{suffix}$ and $\mathit{prefix} \,\|\, \mathit{blob}_B \,\|\, \mathit{suffix}$.

We can leverage this to create two programs that have identical MD5 hashes but arbitrarily different behaviors. We'll use Python 3, but almost any language would do. Put the following three lines into a file called `prefix`:

```
#!/usr/bin/python3
# coding: latin-1
blob = """
```

and put these three lines into a file called `suffix`:

```
"""
from hashlib import sha256
print(sha256(blob.encode("latin-1")).hexdigest())
```

Now use `fastcoll` to generate two files with the same MD5 hash that both begin with `prefix`. (`$ fastcoll -p prefix -o col1 col2`). Then append the suffix to both (`$ cat col1 suffix > file1.py; cat col2 suffix > file2.py`). Verify that `file1.py` and `file2.py` have the same MD5 hash but generate different output.

Extend this technique to produce a pair of programs, `good.py` and `evil.py`, that have identical MD5 hashes. `good.py` should execute a benign payload: `print("Use SHA-256 instead!")`. `evil.py` should execute a pretend malicious payload: `print("MD5 is perfectly secure!")`. Ensure that your programs output **only** these messages, and that they **exactly** match what is specified.

What to submit Two Python scripts named `good.py` and `evil.py` that:

1. Have identical MD5 hashes.
2. Have different SHA-256 hashes.
3. Print different messages, as specified above.

Note that we may rename these programs before grading them.

2 Part 2

2.1 Classical Cryptanalysis

Here is a Python dictionary of the relative frequency of letters in English text:

```
{ "A": .08167, "B": .01492, "C": .02782, "D": .04253, "E": .12702, "F": .02228,
  "G": .02015, "H": .06094, "I": .06996, "J": .00153, "K": .00772, "L": .04025,
  "M": .02406, "N": .06749, "O": .07507, "P": .01929, "Q": .00095, "R": .05987,
  "S": .06327, "T": .09056, "U": .02758, "V": .00978, "W": .02360, "X": .00150,
  "Y": .01974, "Z": .00074 }
```

Here is some plaintext:

```
ethicslawanduniversitypolicieswarningtodefendasystemyouneedtobeabletot
hinklikeanattackerandthatincludesunderstandingtechniquesthatcanbeusedt
ocompromisesecurityhoweverusingthosetechniquesintherealworldmayviolate
thelawortheuniversitysrulesanditmaybeunethicalundersomecircumstancesev
enprobingforweaknessesmayresultinseverepenaltiesuptoandincludingexpuls
ioncivilfinesandjailtimeourpolicyineecsisthatyoumustrespecttheprivacya
ndpropertyrightsofothersatalltimesorelseyouwillfailthecourseactinglawf
ullyandethicallyisyourresponsibilitycarefullyreadthecomputerfraudandab
useactcfaaafederalstatutethatbroadlycriminalizescomputerintrusionthisi
soneofseverallawsthatgovernhackingunderstandwhatthelawprohibitsifindou
btwecanreferyoutoanattorneypleasereviewitsspoliciesonresponsibleuseoft
echnologyresourcesandcaenspolicydocumentsforguidelinesconcerningproper
```

The *population variance* of a finite population X of size N and mean μ is given by

$$\mathrm{Var}(\mathrm{X}) = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{x_i} - \mu)^2.$$

1. What is the population variance of the relative letter frequencies in English text?
2. What is the population variance of the relative letter frequencies in the given plaintext?
3. For each of the following keys — `yz`, `xyz`, `wxyz`, `vwxyz`, `uvwxyz` — encrypt the plaintext with a Vigenère cipher and the given key, then calculate the population variance of the relative letter frequencies in the resulting ciphertext.
4. Viewing a Vigenère key of length k as a collection of k independent Caesar ciphers, calculate the mean of the frequency variances of the ciphertext for each one. (E.g., for key `yz`, calculate the frequency variance of the even numbered ciphertext characters and the frequency variance of the odd numbered ciphertext characters. Then take their mean.)
5. Consider the ciphertext that was produced with key `uvwxyz`. Let's assume you are trying to figure out the length of the key used to encrypt that ciphertext. Calculate the mean of the frequency variances that arise if you assume that the key had length 2, 3, 4, and 5 (using the same technique you did in part (4)). How can this help you determine the length of the key?

[This component is intended to lead you to techniques that will help with Vigenère cryptanalysis. You don't need to submit anything.]

Solving Vigenère Ciphers

Visit `https://project1.ecen4133.org/`*`identikey`*`/vigenere/` to generate a unique Vigenère ciphertext based on your identikey. If you have a partner, enter your two identikeys (e.g. erwu1234rori1723). The ciphertext is encrypted with an English word. Use the techniques in the previous part to create a program that can decrypt Vigenère ciphers, including your example from the website, without being provided the key.

What to submit A Python script named `vigenere.py` that:

1. Reads a Vigenère ciphertext from `stdin`.
2. Determines the key used to encrypt it.
3. Prints **only** the key.

You should make the following assumptions:

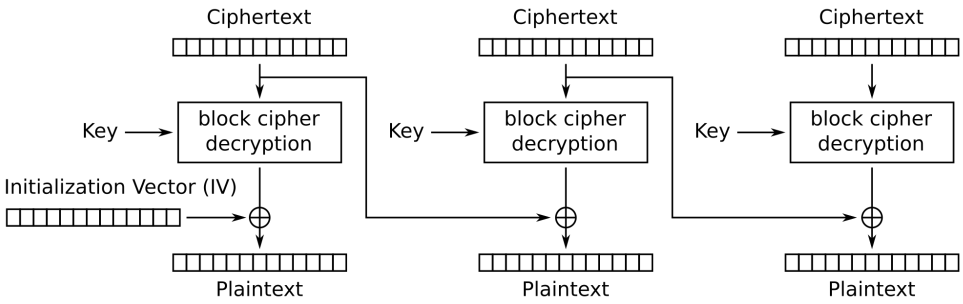
- One of the test cases we use will be the ciphertext you obtained from the website, but we will also test with other ciphertexts.
- The ciphertext consists of only English capital letters A–Z.
- The length of the ciphertext will be between 1000 and 10000 letters.
- The plaintext is written in English and has relatively normal letter frequencies.
- The length of the key is between 2 and 13 letters.
- Encrypting with the key letter `A` results in no change, `B` results in an increment by one place in the alphabet, `C` results in an increment by two places, etc. Decryption works in the opposite direction.

You can find starter code here: `https://ecen4133.org/static/project1/vigenere.py`

2.2 Padding Oracle Attack (grad students)

If your group has a graduate student in it (enrolled in the ECEN 5133 section), you must do this part. Otherwise, it is optional (but encouraged!)
Cipher-Block Chaining, or CBC, is a block cipher mode of encrypting variable length inputs. When encrypting with CBC mode, each plaintext block is XORed with the previous ciphertext block before being encrypted. This also means that when decrypting, each block of plaintext is generated by being XORed with the previous block of ciphertext, as seen in the figure above.

In order for the message to be a multiple of the block length, CBC mode uses a padding scheme. PKCS #7 defines a standard for padding the message to the necessary length, in which the final block is filled with B bytes, each with the value B. For example, if the block size is 16 bytes and your message only fills 12 bytes of the last block, the final 4 bytes will be padded with (0x04, 0x04, 0x04, 0x04). To avoid ambiguity, if the message length is an exact multiple of the block size, a full block of padding is appended (e.g., 16 bytes of 0x10).



Cipher Block Chaining (CBC) mode decryption

Padding Oracle Attacks

After decrypting the ciphertext, the receiver strips off the padding to return the original message. But what happens if it finds that the padding is malformed? For example, the last block might end in (0x03 0x02). In that case, the crypto library will likely return an error.

In a client-server scenario where the server is supposed to decrypt the message but keep the message content secret, a Padding Oracle vulnerability exists if the server indicates to the client that the padding was invalid. In this case, it is possible for an attacker to interactively query the server with manipulated copies of the ciphertext until the padding error does not occur, allowing them to determine, byte-by-byte, what the plaintext contains *without knowing the key!*

To prevent padding oracle attacks, implementations should check the integrity of the ciphertext using a MAC *before decrypting it*. Older implementations often decrypt first, then check a MAC, which easily leads to this vulnerability.

Exploit a CBC Padding Oracle

In our relentless pursuit of justice, we've discovered a website containing dead drop—a place where spies leave anonymous, encrypted messages for other spies to later retrieve. It is located at `https://project1.ecen4133.org/`*`identikey`*`/paddingoracle/`.

To encrypt a message m, the sending spy computes:
$c = \text{AES128-CBC-Encrypt}_{k_1}(m \parallel \text{HMAC-SHA256}_{k_2}(m))$

AES128-CBC-Encrypt() pads the input as described above.

The site has a form that allows the spies to test whether messages can be properly decrypted. The form uses JavaScript to make an HTTP GET request to this URL:
`https://project1.ecen4133.org/`*`identikey`*`/paddingoracle/verify?message=`*`message`*

Your task is to create a program that can use the site as a padding oracle to decipher the messages.

Agent Kerckhoffs has conducted some preliminary analysis that may be useful. He has written some Python representing what we suspect the server does when the `/verify` endpoint is accessed:

```
def pad(message):
    n = AES.block_size - len(message) % AES.block_size
```

```
    if n == 0:
        n = AES.block_size
    return message + bytes([n]*n)

def unpad(message):
    n = message[-1]
    if n < 1 or n > AES.block_size or message[-n:] != bytes([n]*n):
        raise Exception('invalid_padding')
    return message[:-n]

def encrypt(message, key):
    iv = get_random_bytes(AES.block_size)
    cipher = AES.new(key, AES.MODE_CBC, iv)
    return iv + cipher.encrypt(pad(message))

def decrypt(ciphertext, key):
    if len(ciphertext) % AES.block_size:
        raise Exception('invalid_length')
    if len(ciphertext) < 2 * AES.block_size:
        raise Exception('invalid_iv')
    iv =  ciphertext[:AES.block_size]
    cipher = AES.new(key, AES.MODE_CBC, iv)
    return unpad(cipher.decrypt(ciphertext[AES.block_size:]))

def hmac(message, mac_key):
    h = HMAC.new(mac_key, digestmod=SHA256)
    h.update(message)
    return h.digest()

def verify(message, mac, mac_key):
    if mac != hmac(message, mac_key):
        raise Exception('invalid_mac')

def macThenEncrypt(message, key, mac_key):
    return encrypt(message + hmac(message, mac_key), key)

def decryptThenVerify(ciphertext, key, mac_key):
    plaintext = decrypt(ciphertext, key)
    message, mac = plaintext[:-SHA256.digest_size], plaintext[-SHA256.digest_size:]
    verify(message, mac, mac_key)
    return message

@app.route('/verify', methods=['GET'])
def dec_oracle_route():
    ciphertext = bytes.fromhex(request.args['message'])
    try:
        decryptThenVerify(ciphertext, KEY, MAC_KEY)
```

```
except(e):
    return {'status': e}
return {'status': 'valid'}
```

What to submit A Python script called `padding_oracle.py` that:

1. Accepts two command-line arguments: the oracle URL (`sys.argv[1]`) and the hex-encoded encrypted message (`sys.argv[2]`).
2. Uses the provided URL as a padding oracle to decrypt the message.
3. Prints **only** the decrypted message, as human-readable text (not hex). Don't print the MAC or the padding.

You can find starter code here: `https://ecen4133.org/static/project1/padding_oracle.py`

You have permission to use the following oracle URL to decipher the messages:

`https://project1.ecen4133.org/`*`identikey`*`/paddingoracle/verify`

However, **do not hard-code the URL**, as we will use a different endpoint for grading.

Start Early! The padding oracle server may become congested near the project deadline. If the server slows down, this will not be a reason for an extension.

Submission Details

Submit your solutions via **Moodle**

Submission checklist:

`len_ext_attack.py`
`good.py`
`evil.py`
`vigenere.py`
`padding_oracle.py` (grad only)
Combine these files into a **tarball** named project1.*identikeys*.tgz and upload it to Moodle. If you have a partner, list both identikeys in the filename (e.g. `project1.erwu1234whdi9987.tgz`); only one of you has to submit to Moodle.
To create a tarball, put all the files in the same directory and run: `tar czf project1.erwu1234.tgz len_ext_attack.py good.py evil.py vigenere.py padding_oracle.py`
You can verify by extracting it in a different directory (`tar xf project1.erwu1234.tgz`) and seeing that all the expected files are there.