1 CSCG 2025 - KDF_dream

Category: Crypto

Difficulty: Medium

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Flag: `dach2025{But_n1st_said_it_was_fine?!???_15f7a069}`

Description:

> We've managed to insert ourselves into a secure channel between two covert agents, however we overplayed our hand and they have become suspicious that their channel is compromised.
> Realising that there is no way to restablish trust over the compromised network, Alice called for them to carry out a NIST Certified KDF protocol to generate a symmetric OTP, and then for them to use this to encrypt a physical message at a dead drop location.
> We want to control the message she leaves, can you influence their conversation to control what Bob reads at the dead drop?

2 Introduction

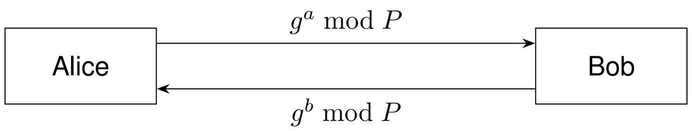
We are given some *Python* files simulating a series of communication exchanges between *Alice* and *Bob*. Luckily enough, we are already an established *Man-in-the-Middle*, so we can intercept, modify and drop any communication between these two parties. The goal of the challenge is to modify the exchanged messages so that *Bob* will receive the message with content like `allgoodprintflag` from *Alice*. The twist of this challenge lies in the used crypto algorithms like the used key derivation function (KDF) *SP800 108 Counter Mode* and its underlying primitives.

3 Reconnaissance

The communication starts with the popular *Diffie-Hellman Key Exchange* using a secure group. After both parties calculated the shared key *Alice* and *Bob* agree on one of the three *NIST* certified pseudo random functions (PRF) HMAC, CMAC and KMAC, for the KDF. Both parties randomly select a nonce and exchange these to have a common KDF context. After that, the shared key, the chosen PRF, the common context and some hardcoded string are used to derive a common key out of the KDF algorithm *SP800 108 Counter Mode*. *Alice* then sends *Bob* a message `wearecompromised` because she is already suspicious about the connection, as the description tells us. The only way to receive the flag is by somehow making sure *Bob* receives `allgoodprintflag` as a message.

4 We are the man in the middle

At first, we want to make sure we get to know the shared secret being calculated via the *Diffie-Hellman Key Exchange*. Both parties calculate the same shared secret $K = g^{ab} \bmod P$ through modular exponentiation with a prime `P`, which can then be used for symmetric encryption:



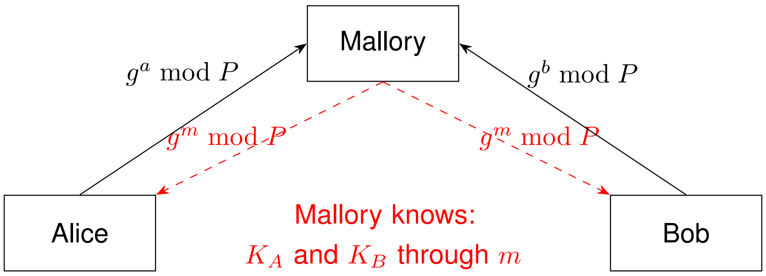
Computes:

$$K = (g^b)^a = g^{ab} \bmod P$$

Computes:

$$K = (g^a)^b = g^{ab} \bmod P$$

But this key exchange is highly vulnerable to a *Man-in-the-Middle* attack. We intercept the communication, inject our public key and thus get for each party another shared secret we can also calculate:



Computes:

$$K_A = (g^m)^a = g^{ma} \bmod P$$

Computes:

$$K_B = (g^m)^b = g^{mb} \bmod P$$

As in most CTF challenges, there is not only one way to solve a problem. The *Man-in-the-Middle* can also force a trivial shared secret `K=1` by simply sending `P-1` to each party. The reason for this is the following equation holding for any prime P:

$$(P-1) \equiv -1 \bmod P$$

This also means *Alice* and *Bob* are actually calculating

$$(-1)^k \bmod P$$

with k being their private secret. This results in the shared secret K

$$K = \begin{cases} 1 \bmod P & \text{if } a \text{ and } b \text{ are both even} \\ P-1 \bmod P & \text{if } a \text{ and } b \text{ are both odd} \\ \perp & \text{otherwise.} \end{cases}$$

The probability of both parties choosing even exponents is:

$$P_{\text{success}} = \left(\frac{1}{2}\right)^2 = 25\%$$

5 Deriving some flags

Now that we know the shared secret, we can decrypt every message *Alice* and *Bob* send each other via the KDF-derived OTPs, as we can calculate these ourselves. But this is not enough for the challenge, we need to influence the output and thus the derived OTPs.

There is a NIST document describing the algorithm for *SP 800 108* in detail. It is basically a loop like the following:

```
for i = 1 to n, do
    K(i) = PRF(K, [i] || label || 0x00 || context || [L])
    result = result || K(i)
```

`[x]` just means the integer is padded to 4 bytes. The `label` is the hardcoded string `keygen_for_secure_bagdrop` and L is the length of the derived key.

Having a look at the used PRFs, one of them seems more suspicious than the others. *HMAC* and *KMAC* internally use hash functions, so they are not that interesting for us, as predicting the output of a hash function is nearly impossible. You would have to brute force the appropriate input for some desired output. But *CMAC* is different, being based on the symmetric crypto algorithm *AES* and the *Cipher Block Chaining Mode* (CBC).

There are some nice explanations out there on how the AES-CMAC works. As we know the shared secret from the *Diffie-Hellman Key Exchange*, we also know the key used for *AES*, so we can easily reverse the process of *CMAC*. For the KDF context of each party, we have control over exactly the second half (*for Alice*) and the first half (*for Bob*). So in both cases, we control 16 bytes for the OTP generation.

We will go for the first part of the context of *Bob* influencing his OTP. The reason for this is that at the time of intercepting the nonces and modifying the one dedicated to *Bob*, we already know the nonce for *Alice* and thus can calculate her OTP, which will be important later.

To proceed, we need some formulas. Each M_i got its own block, so overall there are 5 blocks in the *CMAC*. K_{IN} is the shared secret key from the *Diffie-Hellman Key Exchange* used as the encryption key for *AES*. $M_i[x:y]$ represents all of the bytes of M_i starting with index `x` until index `y`. `K'` is the *AES* subkey we can easily calculate via the shared key and `T` is the target OTP we want to forge. The green highlighted parts $M_2[14:16]$ and $M_3[0:14]$ are the first half of the context we can control:

$$
\begin{aligned}
c_1 &= \mathrm{AES}(K_{\mathrm{IN}},\, M_1)\\
c_2 &= \mathrm{AES}(K_{\mathrm{IN}},\, c_1 \oplus M_2) = \mathrm{AES}\Big(K_{\mathrm{IN}},\, c_1 \oplus (M_2[0:14] \| \mathbf{M_2[14:16]})\Big)\\
c_3 &= \mathrm{AES}(K_{\mathrm{IN}},\, c_2 \oplus M_3) = \mathrm{AES}(K_{\mathrm{IN}},\, c_2 \oplus (\mathbf{M_3[0:14]} \| M_3[14:16]))\\
c_4 &= \mathrm{AES}(K_{\mathrm{IN}},\, c_3 \oplus M_4) = \mathrm{AES}(K_{\mathrm{IN}},\, c_3 \oplus (M_4[0:14] \| 0x00 \| 0x00))\\
T = c_5 &= \mathrm{AES}(K_{\mathrm{IN}},\, c_4 \oplus M_5 \oplus K')
\end{aligned}
$$

Now we can just rearrange and substitute the formula as follows:

$$
\begin{aligned}
\mathrm{AES}^{-1}(K_{\mathrm{IN}}, T) &= c_4 \oplus M_5 \oplus K'\\
&= \mathrm{AES}(K_{\mathrm{IN}},\, c_3 \oplus (M_4[0{:}14] \| \mathrm{0x00} \| \mathrm{0x00}))\\
&\qquad \oplus M_5 \oplus K'\\
\mathrm{AES}^{-1}(K_{\mathrm{IN}},\, \mathrm{AES}^{-1}(K_{\mathrm{IN}}, T)&\\
\oplus M_5 \oplus K') &= c_3 \oplus (M_4[0{:}14] \| \mathrm{0x00} \| \mathrm{0x00})\\
&= \mathrm{AES}(K_{\mathrm{IN}},\, c_2 \oplus (\mathbf{M_3[0{:}14]} \| M_3[14{:}16]))\\
&\qquad \oplus (M_4[0{:}14] \| \mathrm{0x00} \| \mathrm{0x00})\\
\mathrm{AES}^{-1}\Big(K_{\mathrm{IN}},\, \mathrm{AES}^{-1}(K_{\mathrm{IN}},\, \mathrm{AES}^{-1}(K_{\mathrm{IN}}, T)&\\
\oplus M_5 \oplus K')&\\
\oplus (M_4[0{:}14] \| \mathrm{0x00} \| \mathrm{0x00})\Big) &= c_2 \oplus (\mathbf{M_3[0{:}14]} \| M_3[14{:}16])\\
&= \mathrm{AES}(K_{\mathrm{IN}},\, c_1 \oplus (M_2[0{:}14] \| \mathbf{M_2[14{:}16]}))\\
&\qquad \oplus (\mathbf{M_3[0{:}14]} \| M_3[14{:}16])\\
\mathrm{AES}^{-1}\Big(K_{\mathrm{IN}},\, \mathrm{AES}^{-1}(K_{\mathrm{IN}},\, \mathrm{AES}^{-1}(K_{\mathrm{IN}}, T)&\\
\oplus M_5 \oplus K')&\\
\oplus (M_4[0{:}14] \| \mathrm{0x00} \| \mathrm{0x00})\Big)&\\
\oplus \mathrm{AES}(K_{\mathrm{IN}},\, c_1 \oplus (M_2[0{:}14] \| \mathbf{M_2[14{:}16]})) &= (\mathbf{M_3[0{:}14]} \| M_3[14{:}16])
\end{aligned}
$$

Now we have on both sides of the equation parts we can control. We just need to brute force $M_2[14:16]$ until the two bytes $M_3[14:16]$, which we are not able to control, are the correct ones. There might be the rare case in which we can't fulfill the equation, although we tried all of the $2^{16} = 65535$ variations. In this case, we need to repeat the whole exploit. Because of the equation holding, using the calculated context will result in our selected OTP target `T`. Before calculating the context for *Bob*, we need to determine our OTP target `T`. This can be done using the calculated OTP_A from *Alice*, the hardcoded `allgoodprintflag` string m_{flag} and the hardcoded `wearecompromised` string $m_{compromised}$:

$$T = OTP_A \oplus m_{flag} \oplus m_{compromised}$$

With this information and the derived equation, the implementation is straightforward:

```python
from Crypto.Cipher import AES
from Crypto.Util.number import long_to_bytes, bytes_to_long
from Crypto.Util.py3compat import bord

def xor(a, b):
    return bytes(x ^ y for x, y in zip(a, b))

def _shift_bytes(bs, xor_lsb=0):
    num = (bytes_to_long(bs) << 1) ^ xor_lsb
    return long_to_bytes(num, len(bs))[-len(bs):]

def get_aes_cmac_subkey(key):
    L = AES.new(key, AES.MODE_ECB).encrypt(b"\x00"*16)

    const_Rb = 0x87

    if bord(L[0]) & 0x80:
        _k1 = _shift_bytes(L, const_Rb)
    else:
        _k1 = _shift_bytes(L)
    if bord(_k1[0]) & 0x80:
        _k2 = _shift_bytes(_k1, const_Rb)
    else:
        _k2 = _shift_bytes(_k1)
    return _k2

def forge_nonce_for_target(key, T, ctx_second_half):
    c = AES.new(key, AES.MODE_ECB)
    aes_subkey = get_aes_cmac_subkey(key)

    ctx_first_half_2_16 = None
    testing_int = 0
    ctx_first_half_0_2 = b''

    while testing_int <= 0xFFFF:
        ctx_first_half_0_2 = testing_int.to_bytes(2, 'big')
        attempt = xor(
            c.decrypt(
                xor(
                    c.decrypt(
                        xor(
                            xor(
                                c.decrypt(T), b'\x00\x80\x80\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00'
                            ), aes_subkey
                        )
                    ), ctx_second_half[2:16] + b'\x00\x00'
                )
            ), c.encrypt(
                xor(c.encrypt(b'\x00\x00\x00\x01keygen_for_s'), b'ecure_bagdrop\x00' +
                ↪   ctx_first_half_0_2)
            )
        )

        if attempt[-2:] == ctx_second_half[0:2]:
            ctx_first_half_2_16 = attempt
            break
        testing_int += 1

    # ctx_first_half[0:2] || ctx_first_half[2:16]
    return ctx_first_half_0_2, ctx_first_half_2_16
```

The returned value from the `forge_nonce_for_target` function is the calculated first half of the context from *Bob*. After sending *Bob* the forged nonce, he will receive `allgoodprintflag` and we get the flag `dach2025{But_n1st_said_it_was_fine?!???_15f7a069}`. The *NIST* once proposed *CMAC* as one of the PRFs you could use together with the KDF *SP800 108 Counter Mode*. But when some employees from *Amazon* reported some security issues with this combination, *NIST* revoked it and added a precise description of the attack in the appendix of their publication.

6 Mitigation

The first problem is the usage of the *Diffie-Hellman Key Exchange* without any authentication. By using signatures or a public key infrastructure (PKI), the parties could have validated each other's identities, preventing the *Man-in-the-Middle* from sharing their keys or manipulating the key exchange. For the KDF part, obviously you shouldn't use *SP800 108 Counter Mode* with *CMAC* but with for example *HMAC*. Overall, you must be very careful when any crypto modules come into play. Although the *Python* library *cryptography* wasn't used in this challenge but instead *pycryptodome*, they got a great note in their documentation to KDFs:

> [...] this module is full of land mines, dragons, and dinosaurs with laser guns.