10 Message Authentication Codes

The challenge of CCA-secure encryption is dealing with ciphertexts that were generated by an adversary. Imagine there was a way to “certify” that a ciphertext was not adversarially generated — i.e., it was generated by someone who knows the secret key. We could include such a certification in the ciphertext, and the Dec algorithm could raise an error if it asked to decrypt something with invalid certification.

What we are asking for is not to hide the ciphertext but to authenticate it: to ensure that it was generated by someone who knows the secret key. The tool for the job is called a message authentication code. One of the most important applications of a message authentication code is to transform a CPA-secure encryption scheme into a CCA-secure one.

As you read this chapter, keep in mind that privacy and authentication are indeed different properties. It is possible to have one or the other or indeed both simultaneously. But one does not imply the other, and it is crucial to think about them separately.

10.1 Definition

A MAC is like a signature that can be added to a piece of data, which certifies that someone who knows the secret key attests to this particular data. In cryptography, the term “signature” means something specific, and slightly different than a MAC. Instead of calling the output of a MAC algorithm a signature, we call it a “tag” (or, confusingly, just “a MAC”).

Our security requirement for a MAC scheme is that only someone with the secret key can generate a valid tag. To check whether a tag is valid, you just recompute the tag for a given message and see whether it matches the claimed tag. This implies that both generating and verifying a MAC tag requires the secret key.

Definition 10.1 (MAC scheme)

A message authentication code (MAC) scheme for message space $M$ consists of the following algorithms:

- **KeyGen**: samples a key.
- **MAC**: takes a key $k$ and message $m \in M$ as input, and outputs a tag $t$. The MAC algorithm is deterministic.

How to Think About Authenticity Properties

Every security definition we’ve seen so far is about hiding information, so how do we make a formal definition about authenticity?

Before we see the security definition for MACs, let’s start with a much simpler (potentially obvious?) statement: “an adversary should not be able to guess a uniformly chosen $\lambda$-bit value.” We can formalize this idea with the following two libraries:
The left library allows the calling program to attempt to guess a uniformly chosen “target” string. The right library doesn’t even bother to verify the calling program’s guess — in fact it doesn’t even bother to sample a random target string!

The guess subroutines of these libraries give the same output on nearly all inputs. There is only one input r on which they disagree. If a calling program can manage to find the value r, then it can easily distinguish the libraries. Therefore, by saying that these libraries are indistinguishable, we are really saying that it’s hard for an adversary to find/generate this special value! That’s the kind of property we want to express.

Indeed, in this case, an adversary who makes q queries to the guess subroutine achieves an advantage of at most $q/2^\lambda$. For polynomial-time adversaries, this is a negligible advantage (since $q$ is a polynomial function of $\lambda$).

More generally, suppose we have two libraries, and a subroutine in one library checks some condition (and could return either true or false), while in the other library this subroutine always returns false. If the two libraries are indistinguishable, the calling program can’t tell whether the library is actually checking the condition or always saying false. This means it must be very hard to find an input for which the “correct” answer is true.

The MAC Security Definition

We want to say that only someone who knows the secret key can come up with valid MAC tags. In other words, the adversary cannot come up with valid MAC tags.

Actually, that property is not quite enough to be useful. A more useful property is: even if the adversary knows valid MAC tags corresponding to various messages, she cannot produce a valid MAC tag for a different message. We call it a forgery if the adversary can produce a “new” valid MAC tag.

To translate this security property to a formal definition, we define two libraries that allow the adversary to request MAC tags on chosen messages. The libraries also provide a mechanism to let the adversary check whether it has successfully found a forgery (since there is no way of checking this property without the secret key). One library will actually perform the check, and the other library will simply assume that forgeries are impossible. The two libraries are different only in how they behave when the adversary calls this verification subroutine on a forgery. By demanding that the two libraries be indistinguishable, we are actually demanding that it is difficult for the calling program to generate a forgery.

**Definition 10.2** (MAC security)

Let $\Sigma$ be a MAC scheme. We say that $\Sigma$ is a **secure MAC** if $L^\Sigma_{\text{mac-real}} \approx L^\Sigma_{\text{mac-fake}}$, where:
CHAPTER 10. MESSAGE AUTHENTICATION CODES

Discussion:

- The adversary can see valid tags of chosen messages, from the GETTAG subroutine. However, these tags shouldn’t count as a successful forgery. The way this is enforced is in the CHECKTAG subroutine of $L_{\text{mac-fake}}$ — instead of always responding false, it gives the correct answer (true) for any tags generated by GETTAG.

  In order for the two libraries to behave differently, the adversary must call CHECKTAG on input $(m, t)$ such that $m$ was never used as an argument to GETTAG (so that $L_{\text{mac-fake}}$ responds false) but where the tag is actually correct (so that $L_{\text{mac-real}}$ responds true).

- The adversary can successfully distinguish if it finds any forgery — a valid MAC tag of any “fresh” message. The definition doesn’t care whether it’s the tag of any particular meaningful message.

MAC Applications

Although MACs are less embedded in public awareness than encryption, they are extremely useful. A frequent application of MACs is to store some information in an untrusted place, where we don’t intend to hide the data, only ensure that the data is not changed.

- A browser cookie is a small piece of data that a webserver stores in a user’s web browser. The browser presents the cookie data to the server upon each request.

  Imagine a webserver that stores a cookie when a user logs in, containing that user’s account name. What stops an attacker from modifying their cookie to contain a different user’s account name? Adding a MAC tag of the cookie data (using a key known only to the server) ensures that such an attack will not succeed. The server can trust any cookie data whose MAC tag is correct.

- When Alice initiates a network connection to Bob, they must perform a TCP handshake:
1. Alice sends a special SYN packet containing her initial sequence number $A$. In TCP, all packets from Alice to Bob include a sequence number, which helps the parties detect when packets are missing or out of order. It is important that the initial sequence number be random, to prevent other parties from injecting false packets.

2. Bob sends a special SYN+ACK packet containing $A + 1$ (to acknowledge Alice’s $A$ value) and the initial sequence number $B$ for his packets.

3. Alice sends a special ACK packet containing $B + 1$, and then the connection is established.

When Bob is waiting for step 3, the connection is considered “half-open.” While waiting, Bob must remember $B$ so that he can compare to the $B + 1$ that Alice is supposed to send in her final ACK. Typically the operating system allocates only a very limited amount of resources for these half-open connections.

In the past, it was possible to perform a denial of service attack by starting a huge number of TCP connections with a server, but never sending the final ACK packet. The server’s queue for half-open connections fills up, which prevents other legitimate connections from starting.

A clever backwards-compatible solution to this problem is called SYN cookies. The idea is to let Bob choose his initial sequence number $B$ to be a MAC of the client’s IP address, port number, and some other values. Now there is nothing to store for half-open connections. When Alice sends the final ACK of the handshake, Bob can recompute the initial sequence number from his MAC key.

These are all cases where the person who generates the MAC is the same person who later verifies the MAC. You can think of this person as choosing not to store some information, but rather leaving the information with someone else as a “note to self.” There are other useful settings where one party generates a MAC while the other verifies.

- In two-factor authentication, a user logs into a service using something they know (e.g., a password) and something they have (e.g., a mobile phone). The most common two-factor authentication mechanism is called timed one-time passwords (TOTP). When you (as a user) enable two-factor authentication, you generate a secret key $k$ and store it both on your phone and with the service provider. When you wish to log in, you open a simple app on your phone which computes $p = \text{MAC}(k, T)$, where $T$ is the current date + time (usually rounded to the nearest 30 seconds). The value $p$ is the “timed one-time password.” You then log into the service using your usual (long-term) password and the one-time password $p$. The service provider has $k$ and also knows the current time, so can verify the MAC $p$.

From the service provider’s point of view, the only other place $k$ exists is in the phone of this particular user. Intuitively, the only way to generate a valid one-time password at time $T$ is to be in possession of this phone at time $T$. Even if an attacker sees both your long-term and one-time password over your shoulder, this does not help him gain access to your account in the future (well, not after 30 seconds in the future).
10.2 A PRF is a MAC

The definition of a PRF says (more or less) that even if you’ve seen the output of the PRF on several chosen inputs, all other outputs look independently & uniformly random. Furthermore, uniformly chosen values are hard to guess, as long as they are sufficiently long (e.g., $\lambda$ bits).

In other words, after seeing some outputs of a PRF, any other PRF output will be hard to guess. This is exactly the intuitive property we require from a MAC. And indeed, we will prove in this section that a PRF is a secure MAC. While the claim makes intuitive sense, proving it formally is a little tedious. This is due to the fact that in the MAC security game, the adversary can make many verification queries $\text{CHECKTAG}(m, t)$ before asking to see the correct MAC of $m$. Dealing with this event is the source of all the technical difficulty in the proof.

We start with a technical claim that captures the idea that “if you can blindly guess at uniformly chosen values and can also ask to see the values, then it is hard to guess a random value before you have seen it.”

Claim 10.3 The following two libraries are indistinguishable:

$$L_{\text{guess-L}}$$

$T := \text{empty assoc. array}$

$\text{GUESS}(m \in \{0, 1\}^m, g \in \{0, 1\}^\lambda)$:

if $T[m]$ undefined:

$T[m] \leftarrow \{0, 1\}^\lambda$

return $g \equiv T[m]$

$\text{REVEAL}(m \in \{0, 1\}^m)$:

if $T[m]$ undefined:

$T[m] \leftarrow \{0, 1\}^\lambda$

return $T[m]$

$$L_{\text{guess-R}}$$

$T := \text{empty assoc. array}$

$\text{GUESS}(m \in \{0, 1\}^m, g \in \{0, 1\}^\lambda)$:

// returns false if $T[m]$ undefined

return $g \equiv T[m]$

$\text{REVEAL}(m \in \{0, 1\}^m)$:

if $T[m]$ undefined:

$T[m] \leftarrow \{0, 1\}^\lambda$

return $T[m]$

Both libraries maintain an associative array $T$ whose values are sampled uniformly the first time they are needed. Calling programs can try to guess these values via the $\text{GUESS}$ subroutine, or simply learn them via $\text{REVEAL}$. Note that the calling program can call $\text{GUESS}(m, \cdot)$ both before and after calling $\text{REVEAL}(m)$.

Intuitively, since the values in $T$ are $\lambda$ bits long, it should be hard to guess $T[m]$ before calling $\text{REVEAL}(m)$. That is exactly what we formalize in $L_{\text{guess-R}}$. In fact, this library doesn’t bother to even choose $T[m]$ until $\text{REVEAL}(m)$ is called. All calls to $\text{GUESS}(m, \cdot)$ made before the first call to $\text{REVEAL}(m)$ will return $\text{false}$.

Proof Let $q$ be the number of queries that the calling program makes to $\text{GUESS}$. We will show that the libraries are indistinguishable with a hybrid sequence of the form:

$$L_{\text{guess-L}} \equiv L_{\text{hyb-0}} \equiv L_{\text{hyb-1}} \equiv \cdots \equiv L_{\text{hyb-q}} \equiv L_{\text{guess-R}}$$
The $h$th hybrid library in the sequence is defined as:

\[
\mathcal{L}_{\text{hyb-}h}
\]

\[
\begin{align*}
\text{count} & := 0 \\
T & := \text{empty assoc. array} \\
\text{GUESS}(m, g): & \quad \text{count} := \text{count} + 1 \\
& \quad \text{if } T[m] \text{ undefined and count} > h: \\
& \quad \quad T[m] \leftarrow \{0, 1\}^\lambda \\
& \quad \quad \text{return } g \equiv T[m] \\
& \quad \quad \text{// returns false if } T[m] \text{ undefined } \\
\text{REVEAL}(m): & \quad \text{if } T[m] \text{ undefined:} \\
& \quad \quad T[m] \leftarrow \{0, 1\}^\lambda \\
& \quad \quad \text{return } T[m]
\end{align*}
\]

This hybrid library behaves like $\mathcal{L}_{\text{guess-}R}$ for the first $h$ queries to $\text{GUESS}$, in the sense that it will always just return false when $T[m]$ is undefined. After $h$ queries, it will behave like $\mathcal{L}_{\text{guess-}L}$ by actually sampling $T[m]$ in these cases.

In $\mathcal{L}_{\text{hyb-0}}$, the clause “count $> 0$” is always true so this clause can be removed from the if-condition. This modification results in $\mathcal{L}_{\text{guess-L}}$, so we have $\mathcal{L}_{\text{guess-L}} \equiv \mathcal{L}_{\text{hyb-0}}$.

In $\mathcal{L}_{\text{hyb-}q}$, the clause “count $> q$” in the if-statement is always false since the calling program makes only $q$ queries. Removing the unreachable if-statement it results in $\mathcal{L}_{\text{guess-R}}$, so we have $\mathcal{L}_{\text{guess-R}} \equiv \mathcal{L}_{\text{hyb-}q}$.

It remains to show that $\mathcal{L}_{\text{hyb-}h} \approx \mathcal{L}_{\text{hyb-}(h+1)}$ for all $h$. We can do so by rewriting these two libraries as follows:

\[
\begin{align*}
\mathcal{L}_{\text{hyb-}h} & \quad \text{count} := 0 \\
& \quad T := \text{empty assoc. array} \\
\text{GUESS}(m, g): & \quad \text{count} := \text{count} + 1 \\
& \quad \text{if } T[m] \text{ undefined and count} > h: \\
& \quad \quad T[m] \leftarrow \{0, 1\}^\lambda \\
& \quad \quad \text{if } g = T[m] \text{ and count} = h + 1: \\
& \quad \quad \quad \text{bad} := 1 \\
& \quad \quad \text{return } g \equiv T[m] \\
& \quad \text{// returns false if } T[m] \text{ undefined } \\
\text{REVEAL}(m): & \quad \text{if } T[m] \text{ undefined:} \\
& \quad \quad T[m] \leftarrow \{0, 1\}^\lambda \\
& \quad \quad \text{return } T[m]
\end{align*}
\]

\[
\begin{align*}
\mathcal{L}_{\text{hyb-(}h+1)} & \quad \text{count} := 0 \\
& \quad T := \text{empty assoc. array} \\
\text{GUESS}(m, g): & \quad \text{count} := \text{count} + 1 \\
& \quad \text{if } T[m] \text{ undefined and count} > h: \\
& \quad \quad T[m] \leftarrow \{0, 1\}^\lambda \\
& \quad \quad \text{if } g = T[m] \text{ and count} = h + 1: \\
& \quad \quad \quad \text{bad} := 1; \text{return false} \\
& \quad \quad \text{return } g \equiv T[m] \\
& \quad \text{// returns false if } T[m] \text{ undefined } \\
\text{REVEAL}(m): & \quad \text{if } T[m] \text{ undefined:} \\
& \quad \quad T[m] \leftarrow \{0, 1\}^\lambda \\
& \quad \quad \text{return } T[m]
\end{align*}
\]
The library on the left is equivalent to $L_{hyb-h}$ since the only change is the highlighted lines, which don’t actually affect anything. In the library on the right, if $T[m]$ is undefined during the first $h + 1$ calls to GUESS, the subroutine will return false (either by avoiding the if-statement altogether or by triggering the highlighted lines). This matches the behavior of $L_{hyb-(h+1)}$, except that the library shown above samples the value $T[m]$ which in $L_{hyb-(h+1)}$ would not be sampled until the next call of the form GUESS$(m, \cdot)$ or REVEAL$(m)$. But the method of sampling is the same, only the timing is different. This difference has no effect on the calling program.

So the two libraries above are indeed equivalent to $L_{hyb-h}$ and $L_{hyb-(h+1)}$. They differ only in code that is reachable when bad = 1. From Lemma 4.8, we know that these two libraries are indistinguishable if $\Pr[bad = 1]$ is negligible. In these libraries there is only one chance to set bad = 1, and that is by guessing/predicting uniform $T[m]$ on the $(h+1)$th call to GUESS. This happens with probability $1/2^\lambda$, which is indeed negligible.

This shows that $L_{hyb-h} \cong L_{hyb-(h+1)}$, and completes the proof.

We now return to the problem of proving that a PRF is a MAC.

Claim 10.4 Let $F$ be a secure PRF with input length $in$ and output length $out = \lambda$. Then the scheme $MAC(k, m) = F(k, m)$ is a secure MAC for message space $\{0, 1\}^\lambda$.

Proof We show that $L_{mac\text{-}real}^F \cong L_{mac\text{-}fake}^F$, using a standard sequence of hybrids.

The starting point is the $L_{mac\text{-}real}$ library, with the details of this MAC scheme filled in.

We have factored out the PRF operations in terms of the library $L_{prf\text{-}real}$ from the PRF security definition.

We have applied the PRF-security of $F$ and replaced $L_{prf\text{-}real}$ with $L_{prf\text{-}rand}$.
Consider the hybrid experiment above, and suppose the calling program makes a call to \texttt{checktag}(m, t). There are two cases:

- **Case 1:** there was a previous call to \texttt{gettag}(m). In this case, the value \(T[m]\) is defined in \(\mathcal{L}_{\text{guess-R}}\) and \((m, T[m])\) already exists in \(\mathcal{T}\). In this case, the result of \texttt{guess}(m, t) (and hence, of \texttt{checktag}(m, t)) will be \(t = T[m]\).

- **Case 2:** there was no previous call to \texttt{gettag}(m). Then there is no value of the form \((m, \star)\) in \(\mathcal{T}\). Furthermore, \(T[m]\) is undefined in \(\mathcal{L}_{\text{guess-R}}\). The call to \texttt{guess}(m, t) will
In both cases, the result of \(\text{CHECKTAG}(m, t)\) is true if and only if \((m, t) \in \mathcal{T}\).

In the previous hybrid, the \(\text{GUESS-RAND}\) subroutine is never called. Removing that unused subroutine and renaming \(\text{REVEAL}\) to \(\text{LOOKUP}\) results in the \(\mathcal{L}_{\text{PRF-Ideal}}\) library from the PRF security definition.

Inlining \(\mathcal{L}_{\text{PRF-Real}}\) in the final hybrid, we see that the result is exactly \(\mathcal{L}_{\text{MAC-Fake}}\). Hence, we have shown that \(\mathcal{L}_{\text{MAC-Real}} \approx \mathcal{L}_{\text{MAC-Fake}}\), which completes the proof.

**Discussion**

**If PRFs are MACs, why do we even need a definition for MACs?** The simplest answer to this question is that the concepts of PRF and MAC are indeed different:

- Not every PRF is a MAC. **Only sufficiently long random values are hard to guess**, so only PRFs with long outputs \((\text{out} \geq \lambda)\) are MACs. It is perfectly reasonable to consider a PRF with short outputs.
Not every MAC is a PRF. Just like not every encryption scheme has pseudorandom ciphertexts, not every MAC scheme has pseudorandom tags. Imagine taking a secure MAC scheme and modifying it as \( \text{MAC}'(k, m) = \text{MAC}(k, m) || 0^\lambda \). Adding 0s to every tag prevents the tags from looking pseudorandom, but does not make the tags any easier to guess. **Something doesn’t have to be uniformly random in order to be hard to guess.**

It is true that in the vast majority of cases we will encounter MAC schemes with random tags, and PRFs with long outputs \((\text{out} \geq \lambda)\). But it is good practice to know whether you really need something that is pseudorandom or hard to guess.

### 10.3 MACs for Long Messages

Using a PRF as a MAC is useful only for short, fixed-length messages, since most PRFs that exist in practice are limited to such inputs. Can we somehow extend a PRF to construct a MAC scheme for long messages, similar to how we used block cipher modes to construct encryption for long messages?

**How NOT to do it**

To understand the challenges of constructing a MAC for long messages, we first explore some approaches that don’t work. The things that can go wrong in an insecure MAC are quite different in character to the things that can go wrong in a block cipher mode, so pay attention closely!

**Example** *Let \( F \) be a PRF with \( \text{in} = \text{out} = \lambda \). Below is a MAC approach for messages of length \( 2\lambda \). It is inspired by ECB mode, so you know it’s going to be a disaster:*

\[
\begin{align*}
\text{ECBMAC}(k, m_1 || m_2): & \\
t_1 := F(k, m_1) & \\
t_2 := F(k, m_2) & \\
\text{return } t_1 || t_2 & \\
\end{align*}
\]

One problem with this approach is that, although the PRF authenticates each block \( m_1, m_2 \) individually, it does nothing to authenticate that \( m_1 \) is the first block but \( m_2 \) is the second one. Translating this observation into an attack, an adversary can ask for the MAC tag of \( m_1 || m_2 \) and then predict/forge the tag for \( m_2 || m_1 \):

\[
\mathcal{A}: \\
t_1 || t_2 := \text{GETTAG}(0^\lambda || 1^\lambda) & \\
\text{return CHECKTAG}(1^\lambda || 0^\lambda, t_2 || t_1) & \\
\]

When \( \mathcal{A} \) is linked to \( \mathcal{L}_{\text{mac-real}} \), it always return true, since we can tell that \( t_2 || t_1 \) is indeed the valid tag for \( 1^\lambda || 0^\lambda \). When \( \mathcal{A} \) is linked to \( \mathcal{L}_{\text{mac-fake}} \), it always return false, since the calling program never called \( \text{GETTAG} \) with input \( 1^\lambda || 0^\lambda \). Hence, \( \mathcal{A} \) distinguishes the libraries with advantage 1.
This silly MAC construction treats both \( m_1 \) and \( m_2 \) identically, and an obvious way to try to fix the problem is to treat the different blocks differently somehow:

**Example**  
Let \( F \) be a PRF with \( \text{in} = \lambda + 1 \) and \( \text{out} = \lambda \). Below is another MAC approach for messages of length \( 2\lambda \):

\[
\text{ECB++MAC}(k, m_1 \parallel m_2):
\begin{align*}
  t_1 & := F(k, 0 \parallel m_1) \\
  t_2 & := F(k, 1 \parallel m_2) \\
  \text{return } t_1 \parallel t_2
\end{align*}
\]

This MAC construction does better, as it treats the two message blocks \( m_1 \) and \( m_2 \) differently. Certainly the previous attack of swapping the order of \( m_1 \) and \( m_2 \) doesn’t work anymore. (Can you see why?)

The construction authenticates (in some sense) the fact that \( m_1 \) is the first message block, and \( m_2 \) is the second block. However, this construction doesn’t authenticate **the fact that this particular \( m_1 \) and \( m_2 \) belong together**. More concretely, we can “mix and match” blocks of the tag corresponding to different messages:

\[
\mathcal{A}:
\begin{align*}
  t_1 || t_2 & := \text{GETTAG}(0^{2\lambda}) \\
  t'_1 || t'_2 & := \text{GETTAG}(1^{2\lambda}) \\
  \text{return } \text{CHECKTAG}(0^{\lambda} \parallel 1^{\lambda}, t_1 || t'_2)
\end{align*}
\]

In this attack, we combine the \( t_1 \) block from the first tag and the \( t_2 \) block from the second tag.

We are starting to see the challenges involved in constructing a MAC scheme for long messages. A secure MAC should authenticate each message block, the order of the message blocks, and the fact that these particular message blocks are appearing in a single message. In short, it must authenticate the entirety of the message.

Think about how authentication is significantly different than privacy/hiding in this respect. At least for CPA security, we can hide an entire plaintext by hiding each individual piece of the plaintext separately (encrypting it with a CPA-secure encryption). Authentication is fundamentally different.

**How to do it: CBC-MAC**

We have seen some insecure ways to construct a MAC for longer messages. Now let’s see a secure way. A common approach to constructing a MAC for long messages involves the CBC block cipher mode.

**Construction 10.5 (CBC-MAC)**  
Let \( F \) be a PRF with \( \text{in} = \text{out} = \lambda \). CBC-MAC refers to the following MAC scheme:
Unlike CBC encryption, CBC-MAC uses no initialization vector (or, you can think of it as using the all-zeroes IV), and it outputs only the last block.

**Theorem 10.6** If \( F \) is a secure PRF with \( \text{in} = \text{out} = \lambda \), then for any fixed \( \ell \), CBC-MAC is a secure MAC when used with message space \( \mathcal{M} = \{0,1\}^{\lambda \ell} \).

Pay close attention to the security statement. It says that if you only ever authenticate 4-block messages, CBC-MAC is secure. If you only ever authenticate 24-block messages, CBC-MAC is secure. However, if you want to authenticate both 4-block and 24-block messages (i.e., under the same key), then CBC-MAC is not secure. In particular, seeing the CBC-MAC of several 4-block messages allows an attacker to generate a forgery of a 24-block message. The exercises explore this property.

**More Robust CBC-MAC**

If CBC-MAC is so fragile, is there a way to extend it to work for messages of mixed lengths? One approach is called ECBC-MAC, and is shown below. It works by treating the last block differently — specifically, it uses an independent PRF key for the last block in the CBC chain.

**Construction 10.7** (ECBC-MAC)

Let \( F \) be a PRF with \( \text{in} = \text{out} = \lambda \). ECBC-MAC refers to the following scheme:

**Theorem 10.8** If \( F \) is a secure PRF with \( \text{in} = \text{out} = \lambda \), then ECBC-MAC is a secure MAC for message space \( \mathcal{M} = (\{0,1\}^{\lambda})^* \).

In other words, ECBC-MAC is safe to use with messages of any length (that is a multiple of the block length).
To extend ECBC-MAC to messages of any length (not necessarily a multiple of the block length), one can use a padding scheme as in the case of encryption.\(^1\)

### 10.4 Encrypt-Then-MAC

Our motivation for studying MACs is that they seem useful in constructing a CCA-secure encryption scheme. The idea is to add a MAC to a CPA-secure encryption scheme. The decryption algorithm can raise an error if the MAC is invalid, thereby ensuring that adversarially-generated (or adversarially-modified) ciphertexts are not accepted. There are several natural ways to combine a MAC and encryption scheme, but not all are secure! (See the exercises.) The safest way is known as encrypt-then-MAC:

**Construction 10.9 (Enc-then-MAC)** Let \( E \) denote an encryption scheme, and \( M \) denote a MAC scheme where \( E.C \subseteq M\.M \) (i.e., the MAC scheme is capable of generating MACs of ciphertexts in the \( E \) scheme). Then let \( E_tM \) denote the **encrypt-then-MAC** construction given below:

| \( K = E.K \times M.K \) | **Enc**((\( k_e, k_m \)), \( m \)):
| \( M = E.M \) | \( c := E.\text{Enc}(k_e, m) \)
| \( C = E.C \times M.T \) | \( t := M.\text{MAC}(k_m, c) \)
| **KeyGen**:
| \( k_e \leftarrow E.\text{KeyGen} \)
| \( k_m \leftarrow M.\text{KeyGen} \)
| return \((k_e, k_m)\) | return \((c, t)\)
| **Dec**((\( k_e, k_m \)), (\( c, t \))):
| if \( t \neq M.\text{MAC}(k_m, c) \):
| return \text{err} | return \text{err}
| return \text{err} | return \text{E.\text{Dec}}(k_e, c) |

Importantly, the scheme computes a MAC of the CPA ciphertext, and not of the plaintext! The result is a CCA-secure encryption scheme:

**Claim 10.10** If \( E \) has CPA security and \( M \) is a secure MAC, then \( E_tM \) (**Construction 10.9**) has CCA security.

**Proof** As usual, we prove the claim with a sequence of hybrid libraries:

---

\(^1\)Note that if the message is already a multiple of the block length, then padding adds an extra block. There exist clever ways to avoid an extra padding block in the case of MACs, which we don’t discuss further.
The starting point is $\mathcal{L}^{EtM}_{\text{cca-L}}$, shown here with the details of the encrypt-then-MAC construction highlighted. Our goal is to eventually swap $m_L$ with $m_R$. But the CPA security of $E$ should allow us to do just that, so what’s the catch?

To apply the CPA-security of $E$, we must factor out the relevant call to $E.\text{Enc}$ in terms of the CPA library $\mathcal{L}^E_{\text{cpa-L}}$. This means that $k_e$ becomes private to the $\mathcal{L}_{\text{cpa-L}}$ library. But $k_e$ is also used in the last line of the library as $E.\text{Dec}(k_e, c)$. The CPA security library for $E$ provides no way to carry out such $E.\text{Dec}$ statements!

The operations of the MAC scheme have been factored out in terms of $\mathcal{L}^M_{\text{mac-real}}$. Notably, in the $\text{DEC}$ subroutine the condition "$t \neq M.\text{MAC}(k_m, c)$" has been replaced with "not $\text{CHECKTAG}(c, t)$."
CHAPTER 10. MESSAGE AUTHENTICATION CODES

$k_e \leftarrow E.KeyGen$

$S := \emptyset$

Eavesdrop($m_L, m_R$):

if $|m_L| \neq |m_R|$

return null

c := E.Enc($k_e, m_L$)

t := GETTAG(c)

$S := S \cup \{(c, t)\}$

return $(c, t)$

Dec($c, t$):

if $(c, t) \in S$

return null

if not CHECKTAG($c, t$):

return err

return E.Dec($k_e, c$)

\[ L^{M}_{\text{mac-fake}} \]

\[ k_m \leftarrow M.KeyGen \]

\[ T := \emptyset \]

GETTAG(c):

\[ t := M.MAC(k_m, c) \]

\[ T := T \cup \{(c, t)\} \]

return t

CHECKTAG($c, t$):

\[ (c, t) \not\in T \]

We have applied the security of the MAC scheme, and replaced $L_{\text{mac-real}}$ with $L_{\text{mac-fake}}$.

We have inlined the $L_{\text{mac-fake}}$ library. This library keeps track of a set $S$ of values for the purpose of the CCA interface, but also a set $T$ of values for the purposes of the MAC. However, it is clear from the code of this library that $S$ and $T$ always have the same contents.

Therefore, the two conditions "$(c, t) \in S$" and "$(c, t) \notin T$" in the Dec subroutine are exhaustive! The final line of Dec is unreachable. This hybrid highlights the intuitive idea that an adversary can either query Dec with a ciphertext generated by Eavesdrop (the $(c, t) \in S$ case) — in which case the response is null — or with a different ciphertext — in which case the response will be err since the MAC will not verify.


\[
\begin{align*}
  k_e &\leftarrow E.\text{KeyGen} \\
  k_m &\leftarrow M.\text{KeyGen} \\
  S &:= \emptyset \\

\text{EAVESDROP}(m_L, m_R): & \\
  &\text{if } |m_L| \neq |m_R| \\
  &\quad \text{return null} \\
  c &:= E.\text{Enc}(k_e, m_L) \\
  t &:= M.\text{MAC}(k_m, c) \\
  S &:= S \cup \{(c, t)\} \\
  &\text{return } (c, t) \\

\text{DEC}(c, t): & \\
  &\text{if } (c, t) \in S \\
  &\quad \text{return null} \\
  &\text{if } (c, t) \notin S: \\
  &\quad \text{return } \text{err} \\
  &\quad \text{// unreachable}
\end{align*}
\]

The unreachable statement has been removed and the redundant variables \(S\) and \(T\) have been unified. Note that this hybrid library never uses \(E.\text{Dec}\), making it possible to express its use of the \(E\) encryption scheme in terms of \(L_{\text{cpa-L}}\).

\[
\begin{align*}
  &k_m \leftarrow M.\text{KeyGen} \\
  &S := \emptyset \\

\text{EAVESDROP}(m_L, m_R): & \\
  &\text{if } |m_L| \neq |m_R| \\
  &\quad \text{return null} \\
  c &:= \text{CPA.EAVESDROP}(m_L, m_R) \\
  t &:= M.\text{MAC}(k_m, c) \\
  S &:= S \cup \{(c, t)\} \\
  &\text{return } (c, t) \\

\text{DEC}(c, t): & \\
  &\text{if } (c, t) \in S \\
  &\quad \text{return null} \\
  &\text{if } (c, t) \notin S: \\
  &\quad \text{return } \text{err}
\end{align*}
\]

The statements involving the encryption scheme \(E\) have been factored out in terms of \(L_{\text{cpa-L}}\).

We have now reached the half-way point of the proof. The proof proceeds by replacing \(L_{\text{cpa-L}}\) with \(L_{\text{cpa-R}}\) (so that \(m_R\) rather than \(m_L\) is encrypted), applying the same modifications as before (but in reverse order), to finally arrive at \(L_{\text{cca-R}}\). The repetitive details have been omitted, but we mention that when listing the same steps in reverse, the changes appear very bizarre indeed. For instance, we add an unreachable statement to the \(\text{DEC}\) subroutine; we create a redundant variable \(T\) whose contents are the same as \(S\); we mysteriously change one instance of \(S\) (the condition of the second if-statement in \(\text{DEC}\)) to refer to the other variable \(T\). Of course, all of this is so that we can factor out the statements referring to the MAC scheme (along with \(T\)) in terms of \(L_{\text{mac-fake}}\) and finally
replace $L_{\text{mac-fake}}$ with $L_{\text{mac-real}}$. 

Exercises

10.1. Consider the following MAC scheme, where $F$ is a secure PRF with $in = out = \lambda$:

```
KeyGen: 
\[ k \leftarrow \{0,1\}^\lambda \]
\[ \text{return } k \]
MAC(k, m_1 \| \cdots \| m_\ell): // each $m_i$ is $\lambda$ bits
\[ m^* := 0^\lambda \]
\[ \text{for } i = 1 \text{ to } \ell: \]
\[ m^* := m^* \oplus m_i \]
\[ \text{return } F(k, m^*) \]
```

Show that the scheme is not a secure MAC. Describe a distinguisher and compute its advantage.

10.2. Consider the following MAC scheme, where $F$ is a secure PRF with $in = out = \lambda$:

```
KeyGen: 
\[ k \leftarrow \{0,1\}^\lambda \]
\[ \text{return } k \]
MAC(k, m_1 \| \cdots \| m_\ell): // each $m_i$ is $\lambda$ bits
\[ t := 0^\lambda \]
\[ \text{for } i = 1 \text{ to } \ell: \]
\[ t := t \oplus F(k, m_i) \]
\[ \text{return } t \]
```

Show that the scheme is not a secure MAC. Describe a distinguisher and compute its advantage.

10.3. Suppose MAC is a secure MAC algorithm. Define a new algorithm $\text{MAC}'(k,m) = \text{MAC}(k,m) \| \text{MAC}(k,m)$. Prove that $\text{MAC}'$ is also a secure MAC algorithm.

*Note: MAC’ cannot be a secure PRF. This shows that MAC security is different than PRF security.*

10.4. Suppose MAC is a secure MAC scheme, whose outputs are $\ell$ bits long. Show that there is an efficient adversary that breaks MAC security (i.e., distinguishes the relevant libraries) with advantage $\Theta(1/2^\ell)$. This implies that MAC tags must be reasonably long in order to be secure.

10.5. Suppose we use CBC-MAC with message space $\mathcal{M} = (\{0,1\}^\lambda)^\ast$. In other words, a single MAC key will be used on messages of any length that is an exact multiple of the block length. Show that the result is not a secure MAC. Construct a distinguisher and compute its advantage.

*Hint: Request a MAC on two single-block messages, then use the result to forge the MAC of a two-block message.*

10.6. Here is a different way to extend CBC-MAC for mixed-length messages, when the length of each message is known in advance. Assume that $F$ is a secure PRF with $in = out = \lambda$.

```
\text{NEWMAC}^F(k, m_1 \| \cdots \| m_\ell): 
\[ k^* := F(k, \ell) \]
\[ \text{return } \text{CBCMAC}^F(k^*, m_1 \| \cdots \| m_\ell) \]
```

193
10.7. Let $E$ be a CPA-secure encryption scheme and $M$ be a secure MAC. Show that the following encryption scheme (called encrypt & MAC) is not CCA-secure:

<table>
<thead>
<tr>
<th>$E&amp;M$.KeyGen:</th>
<th>$E&amp;M$.Enc($k_e$, $k_m$, $m$):</th>
<th>$E&amp;M$.Dec($k_e$, $k_m$, $c$, $t$):</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_e \leftarrow E$.KeyGen</td>
<td>$c := E$.Enc($k_e$, $m$)</td>
<td>$m := E$.Dec($k_e$, $c$)</td>
</tr>
<tr>
<td>$k_m \leftarrow M$.KeyGen</td>
<td>$t := M$.MAC($k_m$, $m$)</td>
<td>if $t \neq M$.MAC($k_m$, $m$):</td>
</tr>
<tr>
<td>return $(k_e$, $k_m$)</td>
<td>return $(c$, $t$)</td>
<td>return $err$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>return $m$</td>
</tr>
</tbody>
</table>

Describe a distinguisher and compute its advantage.

10.8. Let $E$ be a CPA-secure encryption scheme and $M$ be a secure MAC. Show that the following encryption scheme $\Sigma$ (which I call encrypt-and-encrypted-MAC) is not CCA-secure:

<table>
<thead>
<tr>
<th>$\Sigma$.KeyGen:</th>
<th>$\Sigma$.Enc($k_e$, $k_m$, $m$):</th>
<th>$\Sigma$.Dec($k_e$, $k_m$, $c$, $c'$):</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_e \leftarrow E$.KeyGen</td>
<td>$c := E$.Enc($k_e$, $m$)</td>
<td>$m := E$.Dec($k_e$, $c$)</td>
</tr>
<tr>
<td>$k_m \leftarrow M$.KeyGen</td>
<td>$t := M$.MAC($k_m$, $m$)</td>
<td>$t := E$.Dec($k_e$, $c'$)</td>
</tr>
<tr>
<td>return $(k_e$, $k_m$)</td>
<td>$c' := E$.Enc($k_e$, $t$)</td>
<td>if $t \neq M$.MAC($k_m$, $m$):</td>
</tr>
<tr>
<td></td>
<td>return $(c$, $c'$)</td>
<td>return $err$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>return $m$</td>
</tr>
</tbody>
</table>

Describe a distinguisher and compute its advantage.

10.9. In Construction 7.4, we encrypt one plaintext block into two ciphertext blocks. Imagine applying the Encrypt-then-MAC paradigm to this encryption scheme, but (erroneously) computing a MAC of only the second ciphertext block.

In other words, let $F$ be a PRF with $in = out = \lambda$, and let $M$ be a MAC scheme for message space $\{0, 1\}^\lambda$. Define the following encryption scheme:

<table>
<thead>
<tr>
<th>KeyGen:</th>
<th>Enc($k_e$, $k_m$, $m$):</th>
<th>Dec($k_e$, $k_m$, $r$, $x$, $t$):</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_e \leftarrow {0, 1}^\lambda$</td>
<td>$r \leftarrow {0, 1}^\lambda$</td>
<td>if $t \neq M$.MAC($k_m$, $x$):</td>
</tr>
<tr>
<td>$k_m \leftarrow M$.KeyGen</td>
<td>$x := F(k_e, r) \oplus m$</td>
<td>return $err$</td>
</tr>
<tr>
<td>return $(k_e$, $k_m$)</td>
<td>$t := M$.MAC($k_m$, $x$)</td>
<td>else return $F(k_e, r) \oplus x$</td>
</tr>
<tr>
<td></td>
<td>return $(r$, $x$, $t$)</td>
<td></td>
</tr>
</tbody>
</table>

Show that the scheme does not have CCA security. Describe a successful attack and compute its advantage.

*Hint:* Suppose $(r$, $x$, $t)$ and $(r'$, $x'$, $t')$ are valid encryptions, and consider:

$$\text{Dec}((k_e$, $k_m$), $(r'$, $x$, $t)) \oplus x \oplus x'.$$

10.10. When we combine different cryptographic ingredients (e.g., combining a CPA-secure encryption scheme with a MAC to obtain a CCA-secure scheme) we generally require the two ingredients to use separate, independent keys. It would be more convenient if the entire scheme just used a single $\lambda$-bit key.
(a) Suppose we are using Encrypt-then-MAC, where both the encryption scheme and MAC have keys that are $\lambda$ bits long. Refer to the proof of security of Claim 12.5 and describe where it breaks down when we modify Encrypt-then-MAC to use the same key for both the encryption & MAC components:

```
KeyGen:   Enc($k$, $m$):  Dec($k$, ($c$, $t$)):
  $k \leftarrow \{0, 1\}^{\lambda}$  $c := E.Enc(k, m)$  if $t \neq M.MAC(k, c)$:
  return $k$  $t := M.MAC(k, c)$  return $err$
return $k$  return $E.Dec(k, c)$
```

(b) While Encrypt-then-MAC requires independent keys $k_e$ and $k_m$ for the two components, show that they can both be derived from a single key using a PRF.

In more detail, let $F$ be a PRF with $in = 1$ and $out = \lambda$. Prove that the following modified Encrypt-then-MAC construction is CCA-secure:

```
KeyGen:   Enc($k^*$, $m$):  Dec($k^*$, ($c$, $t$)):
  $k^* \leftarrow \{0, 1\}^{\lambda}$  $k_e := F(k^*, 0)$  $k_e := F(k^*, 0)$
  $k_m := F(k^*, 1)$  $k_m := F(k^*, 1)$
  return $k^*$  $c := E.Enc(k_e, m)$  if $t \neq M.MAC(k_m, c)$:
return $k^*$  $t := M.MAC(k_m, c)$  return $err$
```

You should not have to re-prove all the tedious steps of the Encrypt-then-MAC security proof. Rather, you should apply the security of the PRF in order to reach the original Encrypt-then-MAC construction, whose security we already proved (so you don’t have to repeat).