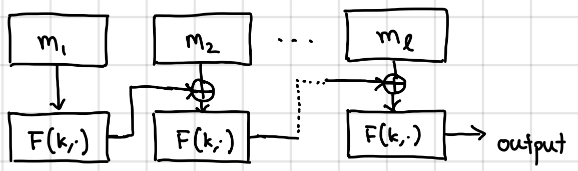
Another approach to construct MACs: domain extension for PRFs [small-domain PRF ⇒ large-domain PRF]

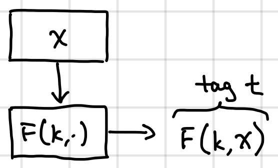
Approach 1: use CBC (without IV)

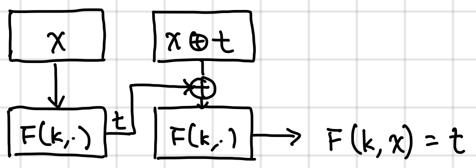


Not encrypting messages so no need for IV (or intermediate blocks)
↳ Mode often called "raw-CBC"

Raw-CBC is a way to build a <u>large-domain</u> PRF from a <u>small-domain</u> one
↳ Can show security for "prefix-free" messages [more precisely, raw-CBC is a prefix-free PRF: pseudorandom as long as PRF never evaluated on two values where one is a prefix of other]
↳ includes fixed-length messages as a special case

But <u>not</u> secure for <u>variable-length</u> messages: "Extension attack"
1. Query for MAC on arbitrary block x:



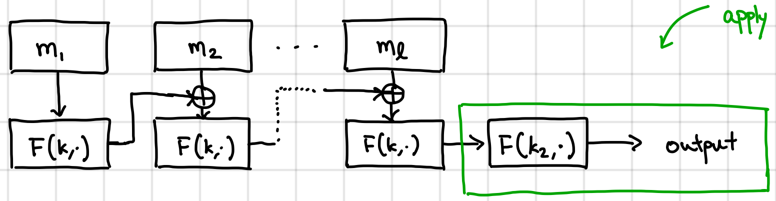


2. Output forgery on message $(x, x \oplus t)$ and tag t ⇒ t is a valid tag on <u>extended message</u> $(x, t \oplus x)$
↳ Adversary succeed with advantage 1

raw CBC can be used to build a MAC on fixed-length messages, but not variable-length messages
(more generally, prefix-free)

For variable-length messages, we use "encrypted CBC" (ECBC):
↳ variant used in $\underbrace{\text{ANSI X9.9, ANSI X19.9}}_{\text{standards for banking / financial services}}$ standards

apply another PRF with a <u>different</u> key to the output of rawCBC
critical for security (using the same key <u>not</u> secure)



To use encrypted CBC-MAC, we need to assume message length is even multiple of block size (similar to CBC encryption)
↳ to sign messages that are not a multiple of the block size, we need to first <u>pad</u> the message
↳ as was the case with encryption, padding must be injective
↳ in the case of encryption, injectivity needed for correctness
↳ in the case of integrity, injectivity needed for <u>security</u> [if $\text{pad}(m_0) = \text{pad}(m_1)$, m_0 and m_1 will have the same tag]

Standard approach to pad: append 1000…0 to fill up block [ANSI X9.9 and ANSI X9.19 standards]

- Note: if message is an even multiple of the block length, need to introduce a dummy block
  - ↳ Necessary for any injective function: $|\{0,1\}^{\leq n}| > |\{0,1\}^n|$
- This is a bit-padding scheme [PKCS #7 that we discuss previously in the context of CBC encryption is a byte-padding scheme]

Encrypted CBC-MAC drawbacks: always need at least 2 PRF evaluations (using different keys)
messages must be padded to block size
} especially bad for authenticating short (e.g., single-byte) messages

Better approach: raw CBC-MAC secure for prefix-free messages

↳ Can we apply a "prefix-free" encoding to the message?

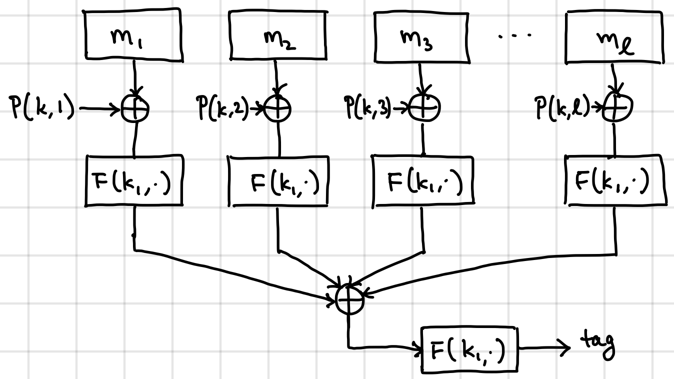
- Option 1: Prepend the message length to the message ← equal-length messages cannot have one be prefix of other; different-length messages differ in first block
  - Problematic if we do not know message length at the beginning (e.g., in a streaming setting)
  - Still requires padding message to multiple of block size)
- Option 2: Apply a random secret shift to the last block of the message

$$(x_1, x_2, \dots, x_\ell) \mapsto (x_1, x_2, \dots, x_\ell \oplus k) \quad \text{where } k \xleftarrow{R} X$$

Adversary that does not know k cannot construct two messages that are prefixes except with probability $1/|X|$ (by guessing k)

→ basis for CMAC (standardized by NIST in 2005)

A parallelizable MAC (PMAC) — general idea:



derived as $F(k_1, 0^n)$ — so key is just k_1

$P(k,\cdot)$ are important — otherwise, adversary can <u>permute</u> the blocks

↳ "mask" term is of the form $\gamma_i \cdot k$ where multiplication is done over $GF(2^n)$ where n is the block size (constants γ_i carefully chosen for efficient evaluation)

Can use similar ideas as CMAC (randomized prefix-free encoding) to support messages that is not constant multiple of block size

Parallel structure of PMAC makes it easily updateable (assuming F is a PRP)

↳ suppose we change block i from $m[i]$ to $m'[i]$:

compute $F^{-1}(k_1, \text{tag}) \oplus \underbrace{F(k_1, m[i] \oplus P(k,i))}_{\text{old value}} \oplus \underbrace{F(k_1, m'[i] \oplus P(k,i))}_{\text{new value}}$

} PMAC is "incremental": can make local updates without full recomputation

In terms of performance:

- On sequential machine, PMAC comparable to ECBC, NMAC, CMAC
- On parallel machine, PMAC much better

} Best MAC we've seen so far, but not used... <u>Reason</u>: patents :([not patented anymore!]

<u>Summary</u>: Many techniques to build a large-domain PRF from a small-domain one (domain extension for PRF)

↳ Each method (ECBC, CMAC, PMAC) gives a MAC on <u>variable-length</u> messages

↳ Many of these designs (or their variants) are <u>standardized</u>

How do we combine confidentiality and integrity?

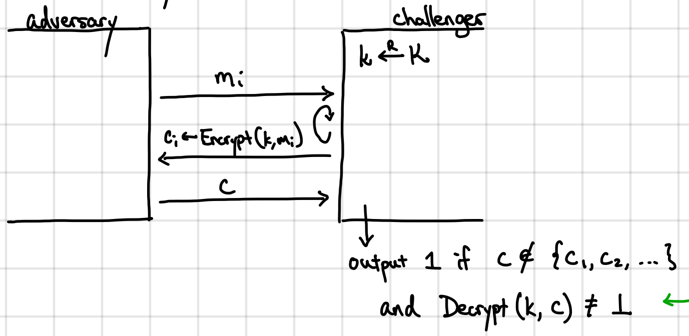
↳ Systems with both guarantees are called authenticated encryption schemes – gold standard for symmetric encryption

Two natural options:

1. Encrypt-then MAC (TLS 1.2+, IPsec) ← guaranteed to be secure if we instantiate using CPA-secure encryption and a secure MAC
2. MAC-then-encrypt (SSL 3.0/TLS 1.0, 802.11i) ← as we will see, not always secure

Definition. An encryption scheme $\Pi_{SE} = (\text{Encrypt}, \text{Decrypt})$ is an authenticated encryption scheme if it satisfies the following two properties:

- CPA security [confidentiality]
- ciphertext integrity [integrity]



adversary
challenger
$k \xleftarrow{R} \mathcal{K}$
m_i
$c_i \leftarrow \text{Encrypt}(k, m_i)$
c
output 1 if $c \notin \{c_1, c_2, \ldots\}$
and $\text{Decrypt}(k, c) \neq \perp$

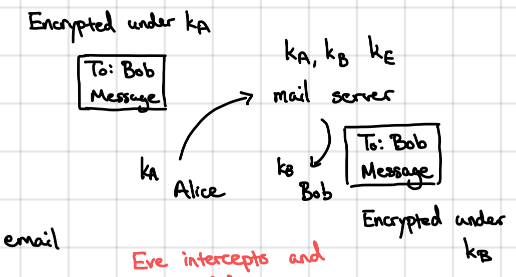
special symbol $\perp$ to denote invalid ciphertext

Define $\text{CIAdv}[\mathcal{A}, \Pi_{SE}]$ to be the probability that output of above experiment is 1. The scheme Π_{SE} satisfies ciphertext integrity if for all efficient adversaries $\mathcal{A}$,

$$\text{CIAdv}[\mathcal{A}, \Pi_{SE}] = \text{negl}(\lambda)$$

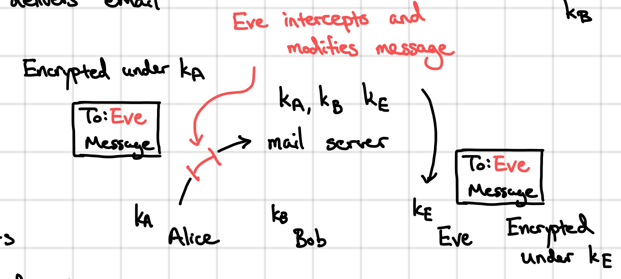
↑ security parameter determines key length

Ciphertext integrity says adversary cannot come up with a new ciphertext: only ciphertexts it can generate are those that are already valid. Why do we want this property?



Consider the following active attack scenario:

- Each user shares a key with a mail server
- To send mail, user encrypts contents and send to mail server
- Mail server decrypts the email, re-encrypts it under recipient's key and delivers email



If Eve is able to tamper with the encrypted message, then she is able to learn the encrypted contents (even if the scheme is CPA-secure)

↳ More broadly, an adversary can tamper and inject ciphertexts into a system and observe the user's behavior to learn information about the decrypted values – against active attackers, we need stronger notion of security