

# Cryptography

## Lecture 11

# Announcements

- HW5 due on Monday, 3/13

# Agenda

- Last time:
  - MACs (K/L 4.1, 4.2, 4.3)
- This time:
  - Domain Extension for MACs (K/L 4.4) and Class Exercise solutions
  - CCA security (K/L 3.7)
  - Authenticated Encryption (K/L 4.5)

# Message Authentication Codes

Definition: A message authentication code (MAC) consists of three probabilistic polynomial-time algorithms  $(Gen, Mac, Vrfy)$  such that:

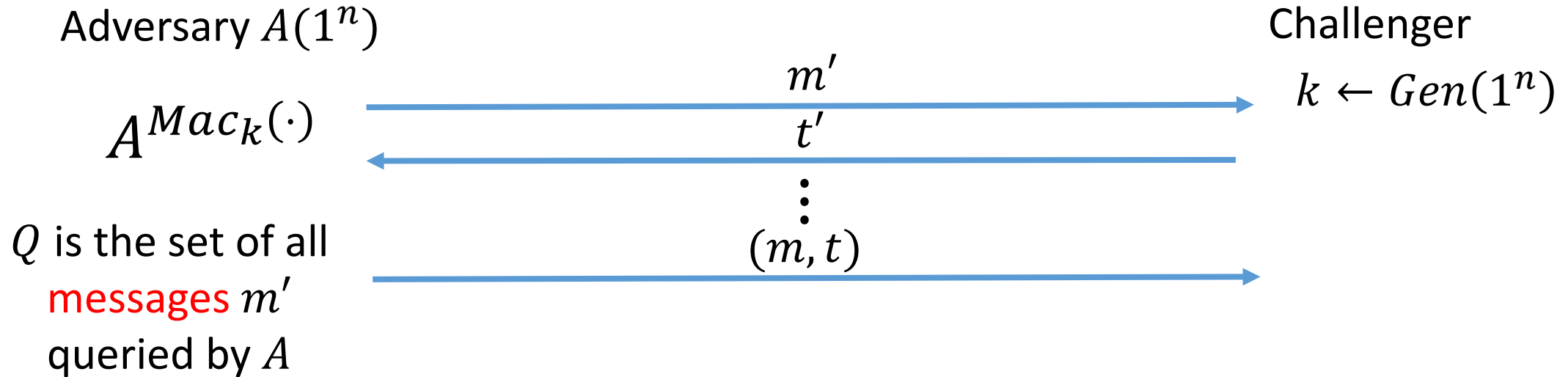
1. The key-generation algorithm  $Gen$  takes as input the security parameter  $1^n$  and outputs a key  $k$  with  $|k| \geq n$ .
2. The tag-generation algorithm  $Mac$  takes as input a key  $k$  and a message  $m \in \{0,1\}^*$ , and outputs a tag  $t$ .  
 $t \leftarrow Mac_k(m)$ .
3. The deterministic verification algorithm  $Vrfy$  takes as input a key  $k$ , a message  $m$ , and a tag  $t$ . It outputs a bit  $b$  with  $b = 1$  meaning valid and  $b = 0$  meaning invalid.  
 $b := Vrfy_k(m, t)$ .

It is required that for every  $n$ , every key  $k$  output by  $Gen(1^n)$ , and every  $m \in \{0,1\}^*$ , it holds that  $Vrfy_k(m, Mac_k(m)) = 1$ .

# Unforgeability for MACs

Consider a message authentication code  $\Pi = (Gen, Mac, Vrfy)$ , any adversary  $A$ , and any value  $n$  for the security parameter.

Experiment  $MACforge_{A,\Pi}(n)$



$MACforge_{A,\Pi}(n) = 1$  if both of the following hold:

1.  $m \notin Q$
2.  $Vrfy_k(m, t) = 1$

Otherwise,  $MACforge_{A,\Pi}(n) = 0$

# Security of MACs

The message authentication experiment  $MACforge_{A,\Pi}(n)$ :

1. A key  $k$  is generated by running  $Gen(1^n)$ .
2. The adversary  $A$  is given input  $1^n$  and oracle access to  $Mac_k(\cdot)$ . The adversary eventually outputs  $(m, t)$ . Let  $Q$  denote the set of all queries that  $A$  asked its oracle.
3.  $A$  succeeds if and only if (1)  $Vrfy_k(m, t) = 1$  and (2)  $m \notin Q$ . In that case, the output of the experiment is defined to be 1.

# Security of MACs

Definition: A message authentication code  $\Pi = (Gen, Mac, Vrfy)$  is existentially unforgeable under an adaptive chosen message attack if for all probabilistic polynomial-time adversaries  $A$ , there is a negligible function  $neg$  such that:

$$\Pr[MACforge_{A,\Pi}(n) = 1] \leq neg(n).$$

# Strong Unforgeability for MACs

Consider a message authentication code  $\Pi = (Gen, Mac, Vrfy)$ , any adversary  $A$ , and any value  $n$  for the security parameter.

Experiment  $MACsforge_{A,\Pi}(n)$

Adversary  $A(1^n)$

Challenger

$A^{Mac_k(\cdot)}$

$k \leftarrow Gen(1^n)$

$m'$

$t'$

$\vdots$

$(m, t)$

$Q$  is the set of all  
message, tag pairs

$(m', t')$

queried/received  
by  $A$

$MACsforge_{A,\Pi}(n) = 1$  if both of the following hold:

1.  $m \notin Q$
2.  $Vrfy_k(m, t) = 1$

Otherwise,  $MACsforge_{A,\Pi}(n) = 0$



# Strong MACs

The strong message authentication experiment  $MACsforge_{A,\Pi}(n)$ :

1. A key  $k$  is generated by running  $Gen(1^n)$ .
2. The adversary  $A$  is given input  $1^n$  and oracle access to  $Mac_k(\cdot)$ . The adversary eventually outputs  $(m, t)$ . Let  $Q$  denote the set of all pairs  $(m, t)$  that  $A$  asked its oracle.
3.  $A$  succeeds if and only if (1)  $Vrfy_k(m, t) = 1$  and (2)  $(m, t) \notin Q$ . In that case, the output of the experiment is defined to be 1.

# Strong MACs

Definition: A message authentication code  $\Pi = (Gen, Mac, Vrfy)$  is a strong MAC if for all probabilistic polynomial-time adversaries  $A$ , there is a negligible function  $neg$  such that:

$$\Pr[MACsforge_{A,\Pi}(n) = 1] \leq neg(n).$$

# Domain Extension for MACs

# CBC-MAC

Let  $F$  be a pseudorandom function, and fix a length function  $\ell$ . The basic CBC-MAC construction is as follows:

- *Mac*: on input a key  $k \in \{0,1\}^n$  and a message  $m$  of length  $\ell(n) \cdot n$ , do the following:
  1. Parse  $m$  as  $m = m_1, \dots, m_\ell$  where each  $m_i$  is of length  $n$ .
  2. Set  $t_0 := 0^n$ . Then, for  $i = 1$  to  $\ell$ :  
Set  $t_i := F_k(t_{i-1} \oplus m_i)$ .Output  $t_\ell$  as the tag.
- *Vrfy*: on input a key  $k \in \{0,1\}^n$ , a message  $m$ , and a tag  $t$ , do: If  $m$  is not of length  $\ell(n) \cdot n$  then output 0. Otherwise, output 1 if and only if  $t = \text{Mac}_k(m)$ .

# CBC-MAC

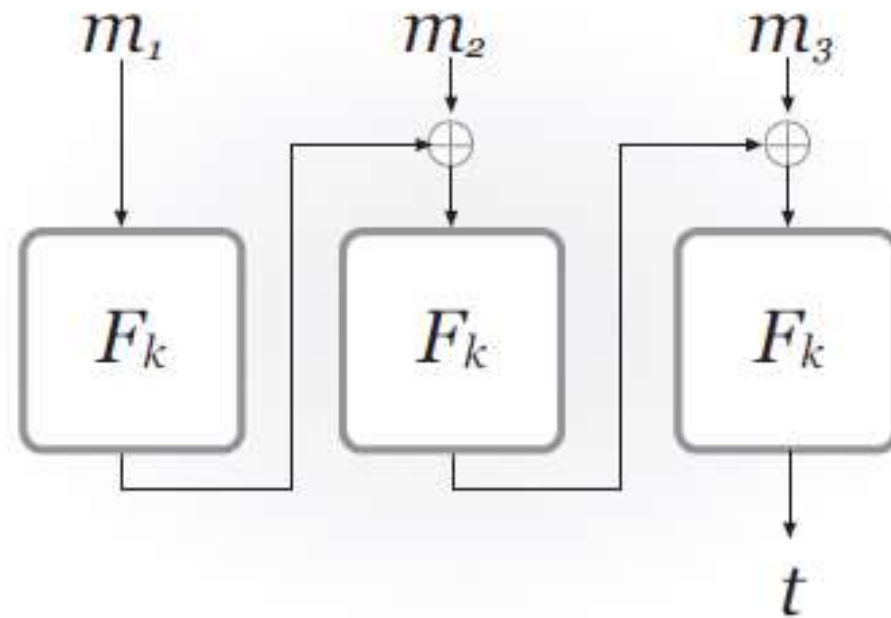


FIGURE 4.1: Basic CBC-MAC (for fixed-length messages).





# Chosen Ciphertext Security



# CCA Security\*

Consider a private-key encryption scheme  $\Pi = (Gen, Enc, Dec)$ , any adversary  $A$ , and any value  $n$  for the security parameter.

Experiment  $PrivK_{A,\Pi}^{cca}(n)$

Adversary  $A(1^n)$

Challenger

# CCA Security\*

Consider a private-key encryption scheme  $\Pi = (Gen, Enc, Dec)$ , any adversary  $A$ , and any value  $n$  for the security parameter.

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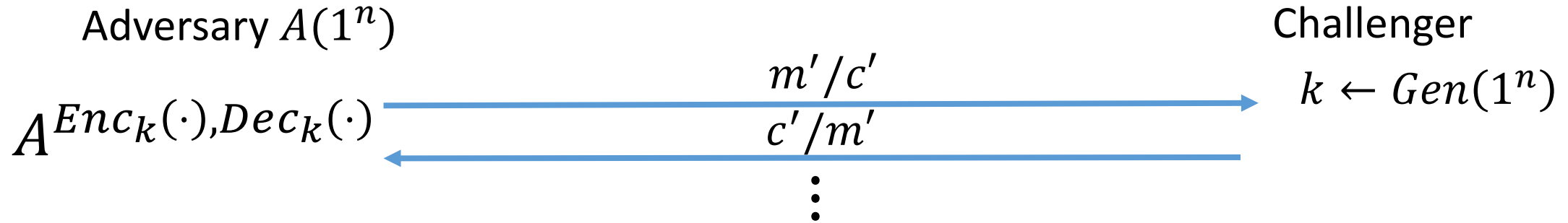
Challenger

$k \leftarrow Gen(1^n)$

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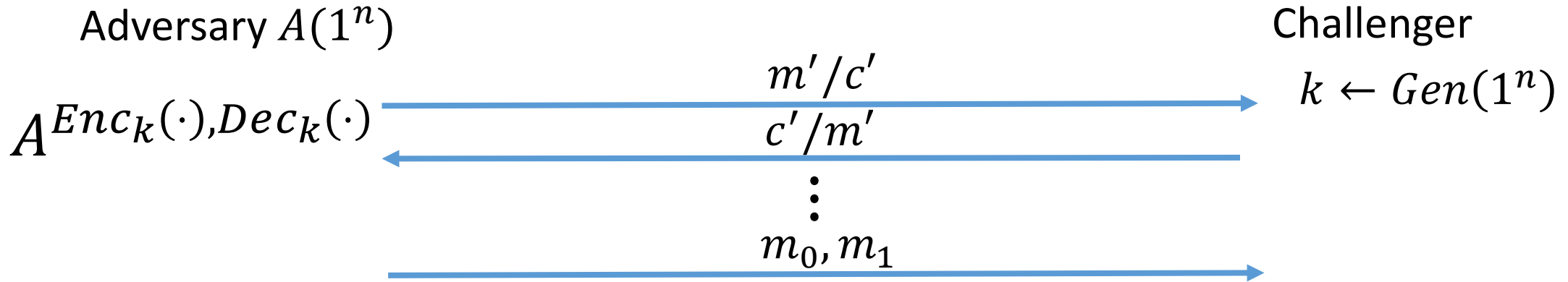
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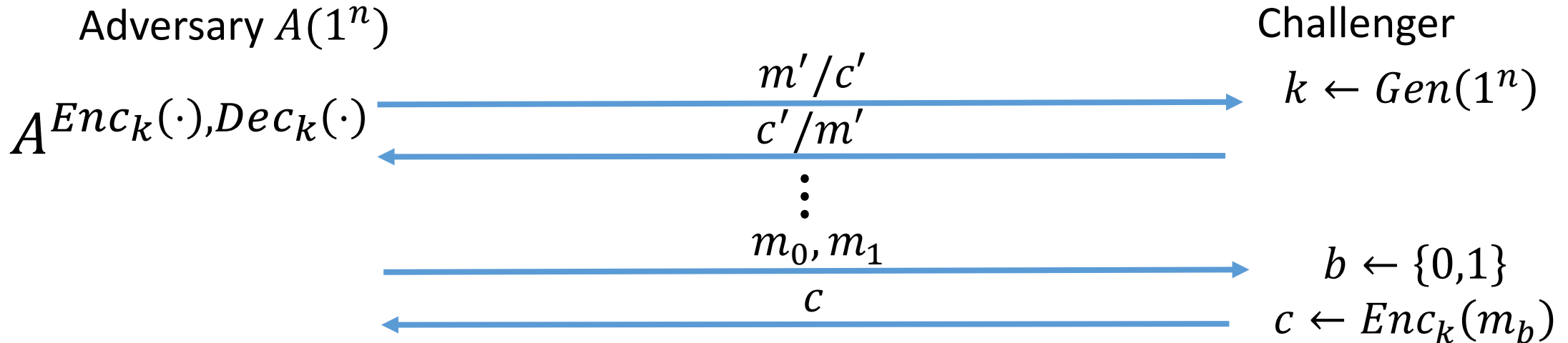
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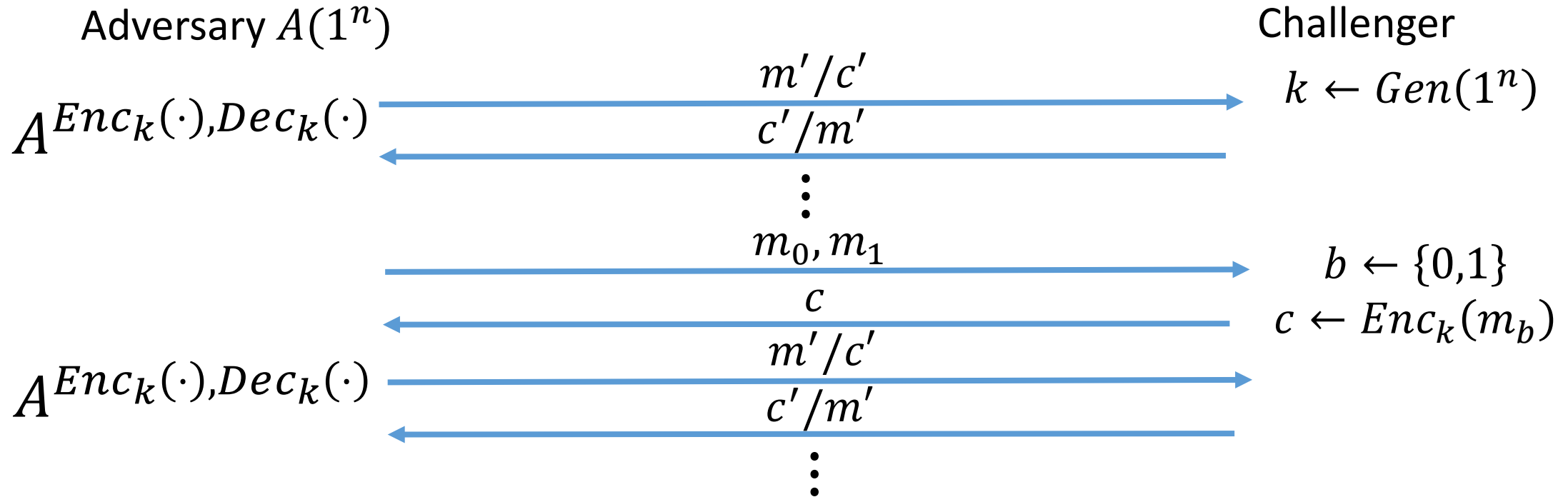
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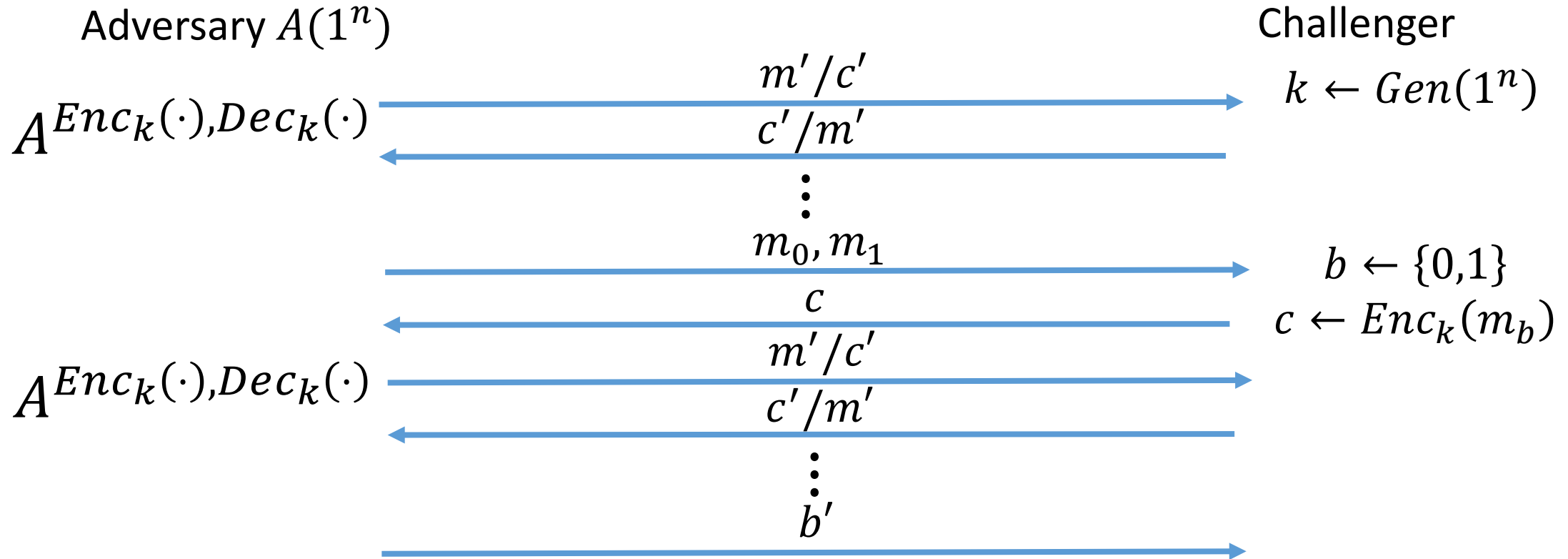
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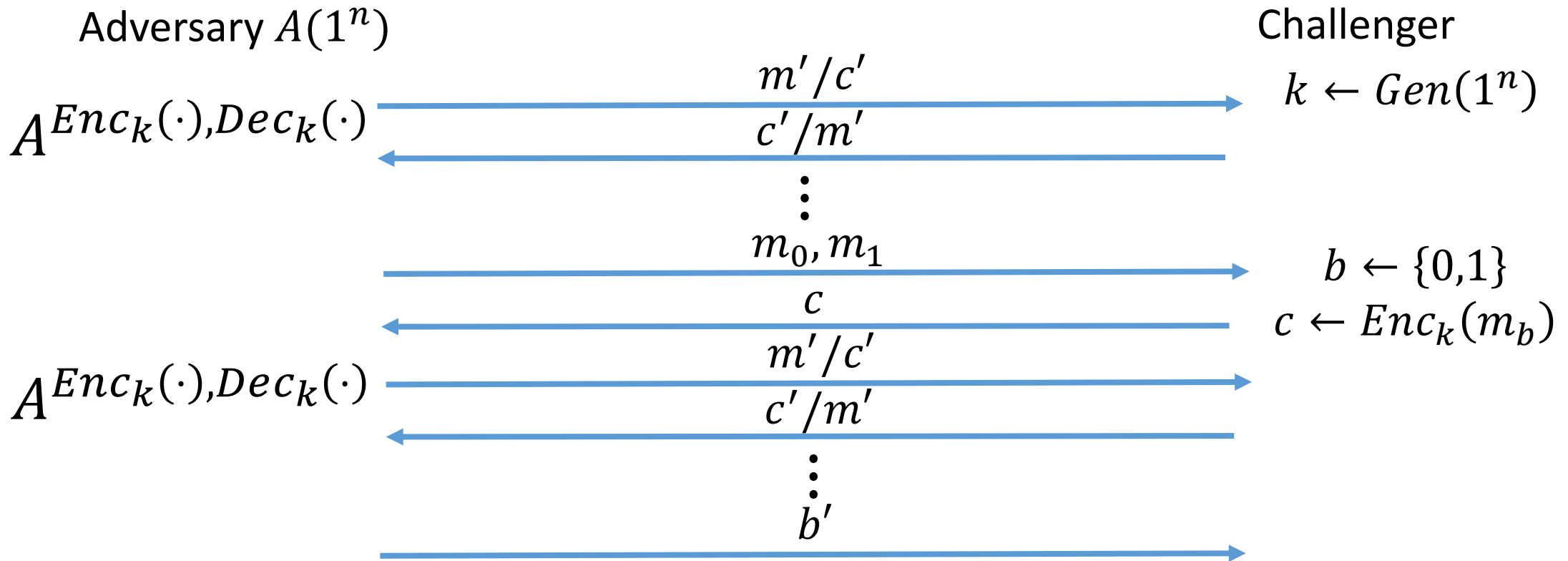
Experiment  $PrivK_{A,\Pi}^{cca}(n)$



# CCA Security\*

Consider a private-key encryption scheme  $\Pi = (Gen, Enc, Dec)$ , any adversary  $A$ , and any value  $n$  for the security parameter.

Experiment  $PrivK_{A,\Pi}^{cca}(n)$



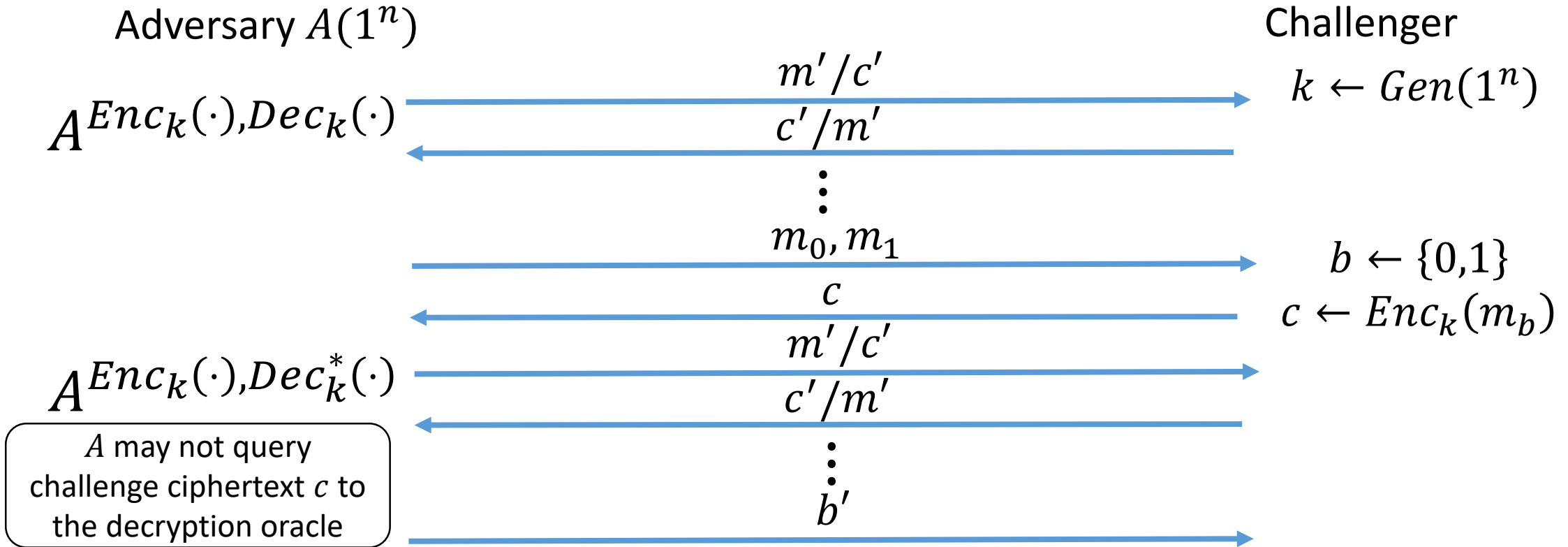
$PrivK_{A,\Pi}^{cca}(n) = 1$  if  $b' = b$  and  $PrivK_{A,\Pi}^{cca}(n) = 0$  if  $b' \neq b$ .



# CCA Security

Consider a private-key encryption scheme  $\Pi = (Gen, Enc, Dec)$ , any adversary  $A$ , and any value  $n$  for the security parameter.

Experiment  $PrivK_{A,\Pi}^{cca}(n)$



$PrivK_{A,\Pi}^{cca}(n) = 1$  if  $b' = b$  and  $PrivK_{A,\Pi}^{cca}(n) = 0$  if  $b' \neq b$ .

# CCA Security

The CCA Indistinguishability Experiment  $PrivK^{cca}_{A,\Pi}(n)$ :

1. A key  $k$  is generated by running  $Gen(1^n)$ .
2. The adversary  $A$  is given input  $1^n$  and oracle access to  $Enc_k(\cdot)$  and  $Dec_k(\cdot)$ , and outputs a pair of messages  $m_0, m_1$  of the same length.
3. A random bit  $b \leftarrow \{0,1\}$  is chosen, and then a challenge ciphertext  $c \leftarrow Enc_k(m_b)$  is computed and given to  $A$ .
4. The adversary  $A$  continues to have oracle access to  $Enc_k(\cdot)$  and  $Dec_k(\cdot)$ , but is not allowed to query the latter on the challenge ciphertext itself. Eventually,  $A$  outputs a bit  $b'$ .
5. The output of the experiment is defined to be 1 if  $b' = b$ , and 0 otherwise.

# CCA Security

A private-key encryption scheme

$\Pi = (Gen, Enc, Dec)$  has indistinguishable encryptions under a chosen-ciphertext attack if for all ppt adversaries  $A$  there exists a negligible function  $negl$  such that

$$\Pr \left[ PrivK^{cca}_{A, \Pi}(n) = 1 \right] \leq \frac{1}{2} + negl(n),$$

where the probability is taken over the random coins used by  $A$ , as well as the random coins used in the experiment.

# Authenticated Encryption

The unforgeable encryption experiment  $EncForge_{A,\Pi}(n)$ :

1. Run  $Gen(1^n)$  to obtain key  $k$ .
2. The adversary  $A$  is given input  $1^n$  and access to an encryption oracle  $Enc_k(\cdot)$ . The adversary outputs a ciphertext  $c$ .
3. Let  $m := Dec_k(c)$ , and let  $Q$  denote the set of all queries that  $A$  asked its encryption oracle. The output of the experiment is 1 if and only if (1)  $m \neq \perp$  and (2)  $m \notin Q$ .

# Authenticated Encryption

Definition: A private-key encryption scheme  $\Pi$  is unforgeable if for all ppt adversaries  $A$ , there is a negligible function  $neg$  such that:

$$\Pr[EncForge_{A,\Pi}(n) = 1] \leq neg(n).$$

Definition: A private-key encryption scheme is an authenticated encryption scheme if it is CCA-secure and unforgeable.