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1. Consider the following five events: **1 / 1 point**

1. Correctly guessing a random 128-bit AES key on the first try.
2. Winning a lottery with 1 million contestants (the probability is $1/10^6$).
3. Winning a lottery with 1 million contestants 5 times in a row (the probability is $(1/10^6)^5$).
4. Winning a lottery with 1 million contestants 6 times in a row.
5. Winning a lottery with 1 million contestants 7 times in a row.

What is the order of these events from most likely to least likely?

- ○ 2, 4, 3, 1, 5
- ◉ 2, 3, 4, 1, 5
- ○ 2, 3, 5, 4, 1
- ○ 3, 2, 5, 4, 1

Correct

- The probability of event (1) is 1/2^128.
- The probability of event (5) is 1/(10^6)^7 which is about 1/2^{139}. Therefore, event (5) is the least likely.
- The probability of event (4) is 1/(10^6)^6 which is about 1/2^{119.5} which is more likely than event (1).
- The remaining events are all more likely than event (4).

2. Suppose that using commodity hardware it is possible to build a computer **1 / 1 point**

for about $200 that can brute force about 1 billion AES keys per second.

Suppose an organization wants to run an exhaustive search for a single

128-bit AES key and was willing to spend 4 trillion dollars to buy these

machines (this is more than the annual US federal budget). How long would

it take the organization to brute force this single 128-bit AES key with

these machines? Ignore additional costs such as power and maintenance.

- ○ More than a million years but less than a billion (10^9) years
- ○ More than a day but less than a week
- ○ More than a 100 years but less than a million years

- [x] More than a billion (10^9) years
- [ ] More than a month but less than a year

Correct
The answer is about 540 billion years.

- # machines = 4*10^12/200 = 2*10^10
- # keys processed per sec = 10^9 * (2*10^10) = 2*10^19
- # seconds = 2^128 / (2*10^19) = 1.7*10^19

This many seconds is about 540 billion years.

3. Let $F : \{0,1\}^n \times \{0,1\}^n \to \{0,1\}^n$ be a secure PRF (i.e. a PRF where the key space, input space, and output space are all $\{0,1\}^n$) and say $n = 128$. **1 / 1 point**

Which of the following is a secure PRF (there is more than one correct answer):

- [x] $$F'((k_1, k_2),\ x) = \begin{cases} F(k_1, x) & \text{when } x \neq 0^n \\ k_2 & \text{otherwise} \end{cases}$$

Correct
Correct. A distinguisher for F' gives a distinguisher for F.

- [ ] $F'(k, x) = F(k, x) \ \| \ 0$

(here $\|$ denotes concatenation)

- [x] $F'((k_1, k_2),\ x) = F(k_1, x) \ \| \ F(k_2, x)$ (here $\|$ denotes concatenation)

Correct
Correct. A distinguisher for F' gives a distinguisher for F.

- [ ] $F'(k, x) = F(k,\ x) \bigoplus F(k,\ x \oplus 1^n)$
- [ ] $F'(k,\ x) = k \bigoplus x$
- [x] $F'(k, x) = F(k, x)[0, \ldots, n-2]$

(i.e., $F'(k, x)$ drops the last bit of $F(k, x)$)

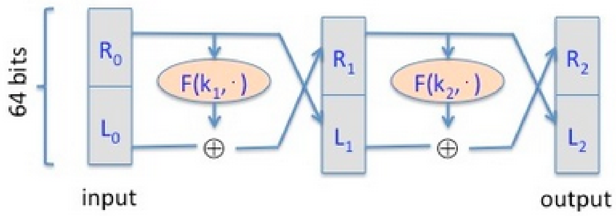
Correct
Correct. A distinguisher for F' gives a distinguisher for F.

4. Recall that the Luby-Rackoff theorem discussed in The Data Encryption Standard lecture states that applying a **three** round Feistel network to a secure PRF gives a secure block cipher. Let's see what goes wrong if we only use a **two** round Feistel. **1 / 1 point**

Let $F : K \times \{0,1\}^{32} \to \{0,1\}^{32}$ be a secure PRF.

Recall that a 2-round Feistel defines the following PRP

$F_2 : K^2 \times \{0,1\}^{64} \to \{0,1\}^{64}$:



Here R_0 is the right 32 bits of the 64-bit input and L_0 is the left 32 bits.

One of the following lines is the output of this PRP F_2 using a random key, while the other three are the output of a truly random permutation $f : \{0,1\}^{64} \to \{0,1\}^{64}$. All 64-bit outputs are encoded as 16 hex characters.

Can you say which is the output of the PRP? Note that since you are able to distinguish the output of F_2 from random, F_2 is not a secure block cipher, which is what we wanted to show.

Hint: First argue that there is a detectable pattern in the xor of $F_2(\cdot,\ 0^{64})$ and $F_2(\cdot,\ 1^{32}0^{32})$. Then try to detect this pattern in the given outputs.

- [x] On input 0^{64} the output is "290b6e3a 39155d6f".

  On input $1^{32}0^{32}$ the output is "d6f491c5 b645c008".
- [ ] On input 0^{64} the output is "5f67abaf 5210722b".

  On input $1^{32}0^{32}$ the output is "bbe033c0 0bc9330e".
- [ ] On input 0^{64} the output is "9d1a4f78 cb28d863".

  On input $1^{32}0^{32}$ the output is "75e5e3ea 773ec3e6".
- [ ] On input 0^{64} the output is "7b50baab 07640c3d".

  On input $1^{32}0^{32}$ the output is "ac343a22 cea46d60".

Correct

Observe that the two round Feistel has the property that

the left of $F(\cdot, 0^{64}) \bigoplus F(\cdot, 1^{32}0^{32})$ is 1^{32}.

The two outputs in this answer are the only ones with this property.

5. Nonce-based CBC. Recall that in Lecture 4.4 we said that if one wants to use CBC encryption with a non-random unique nonce then the nonce must first be encrypted with an **independent** PRP key and the result then used as the CBC IV. **1 / 1 point**

Let's see what goes wrong if one encrypts the nonce with the **same** PRP key as the key used for CBC encryption.

Let $F : K \times \{0,1\}^{\ell} \to \{0,1\}^{\ell}$ be a secure PRP with, say, $\ell = 128$. Let n be a nonce and suppose one encrypts a message m by first computing $IV = F(k, n)$ and then using this IV in CBC encryption using $F(k, \cdot)$. Note that the same key k is used for computing the IV and for CBC encryption. We show that the resulting system is not nonce-based CPA secure.

The attacker begins by asking for the encryption of the two block message $m = (0^\ell, 0^\ell)$ with nonce $n = 0^\ell$. It receives back a two block ciphertext (c_0, c_1). Observe that by definition of CBC we know that $c_1 = F(k, c_0)$.

Next, the attacker asks for the encryption of the one block message $m_1 = c_0 \bigoplus c_1$ with nonce $n = c_0$. It receives back a one block ciphertext c_0'.

What relation holds between c_0, c_1, c_0'? Note that this relation lets the adversary win the nonce-based CPA game with advantage 1.

- (selected) $c_1 = c_0'$
- $c_0' = c_0 \bigoplus 1^\ell$
- $c_0 = c_1 \bigoplus c_0'$
- $c_1 = c_0$

Correct
This follows from the definition of CBC with an encrypted nonce

as defined in the question.

6. Let m be a message consisting of ℓ AES blocks **1 / 1 point**

(say $\ell = 100$). Alice encrypts m using CBC mode and transmits

the resulting ciphertext to Bob. Due to a network error,

ciphertext block number $\ell/2$ is corrupted during transmission.

All other ciphertext blocks are transmitted and received correctly.

Once Bob decrypts the received ciphertext, how many plaintext blocks

will be corrupted?

- $\ell/2$
- 3
- (selected) 2
- 0
- ℓ

Correct
Take a look at the CBC decryption circuit. Each ciphertext

blocks affects only the current plaintext block and the next.

7. Let m be a message consisting of ℓ AES blocks (say $\ell = 100$). Alice encrypts m using randomized counter mode and **1 / 1 point**

transmits the resulting ciphertext to Bob. Due to a network error transmits the resulting ciphertext to Bob. Due to a network error,

ciphertext block number $\ell/2$ is corrupted during transmission.

All other ciphertext blocks are transmitted and received correctly.

Once Bob decrypts the received ciphertext, how many plaintext blocks

will be corrupted?

- ( ) $1+\ell/2$
- ( ) 0
- ( ) $\ell/2$
- (•) 1
- ( ) 3

Correct
Take a look at the counter mode decryption circuit. Each

ciphertext block affects only the current plaintext block.

8. Recall that encryption systems do not fully hide the **length** of

1 / 1 point

transmitted messages. Leaking the length of web requests hasbeen used to eavesdrop on encrypted HTTPS traffic to a number of

web sites, such as tax preparation sites, Google searches, and

healthcare sites.

Suppose an attacker intercepts a packet where he knows that the

packet payload is encrypted using AES in CBC mode with a random IV. The

encrypted packet payload is 128 bytes. Which of the following

messages is plausibly the decryption of the payload:

- ( ) 'The significance of this general conjecture, assuming its truth, is

  easy to see. It means that it may be feasible to design ciphers that

  are effectively unbreakable.'
- (•) 'In this letter I make some remarks on a general principle

  relevant to enciphering in general and my machine.'
- ( ) 'If qualified opinions incline to believe in the exponential

  conjecture, then I think we cannot afford not to make use of it.'
- ( ) 'The most direct computation would be for the enemy to try

  all 2^r possible keys, one by one.'

Correct
The length of the string is 107 bytes, which after padding becomes 112 bytes,

and after prepending the IV becomes 128 bytes.

9. Let $R := \{0,1\}^4$ and consider the following PRF $F : R^5 \times R \to R$ defined as follows: **1 / 1 point**

$$F(k,x) := \begin{cases} t = k[0] \\ \text{for i=1 to 4 do} \\ \qquad \text{if } (x[i-1] == 1) \quad t = t \oplus k[i] \\ \text{output } t \end{cases}$$

That is, the key is $k = (k[0], k[1], k[2], k[3], k[4])$ in R^5 and the function at, for example, 0101 is defined as $F(k, 0101) = k[0] \oplus k[2] \oplus k[4]$.

For a random key k unknown to you, you learn that

$$F(k, 0110) = 0011 \text{ and } F(k, 0101) = 1010 \text{ and } F(k, 1110) = 0110 \,.$$

What is the value of $F(k, 1101)$? Note that since you are able to predict the function at a new point, this PRF is insecure.

1111

Correct