Question 1 ***Public Key Encryption*** ()

The El Gamal encryption scheme is reproduced below:

- **Key Generation**: public key $= (g, h, p)$, where $h = g^k \pmod p$, private key $= k$
- **Encryption**: $c = (c_1, c_2) = (g^r \bmod p, m \times h^r \bmod p)$, where r is randomly sampled from $\{1, \ldots, p-1\}$.
- **Decryption**: $m = c_1^{-k} \times c_2 \pmod p$

Look at each scenario below and select the appropriate options.

Q1.1 With El Gamal, it is not a problem if the adversary can learn the value of g somehow.

◯ (A) True
◯ (B) False
◯ (C) ——
◯ (D) ——
◯ (E) ——
◯ (F) ——

Q1.2 With El Gamal, it is not a problem if the value r used during encryption is accidentally revealed after the encryption is complete.

◯ (G) True
◯ (H) False
◯ (I) ——
◯ (J) ——
◯ (K) ——
◯ (L) ——

Now imagine that Alice (A) and Bob (B) want to communicate over an insecure network and they know each other's public key. Consider the following message exchange:

A: Hey Bob, it's Alice. How many dollars do I owe you?
B: 10000

The message is encrypted with Alice's public key using ElGamal encryption.
Alice decrypted this successfully, but suddenly remembered that she only owed Bob $100.

Q1.1 Assume Bob would not lie. How did an attacker tamper with the message?

Q1.2 What could Bob have additionally sent that would've stopped this attack?

Question 2 ***Why do RSA signatures need a hash?*** **()**

To generate RSA signatures, Alice first creates a standard RSA key pair: (n, e) is the RSA public key and d is the RSA private key, where n is the RSA modulus. For standard RSA signatures, we typically set e to a small prime value such as 3; for this problem, let $e = 3$.

Suppose we used a **simplified** scheme for RSA signatures that skips using a hash function and instead uses message M directly, so the signature S on a message M is $S = M^d \bmod n$. In other words, if Alice wants to send a signed message to Bob, she will send (M, S) to Bob where $S = M^d \bmod n$ is computed using her private signing key d.

Q2.1 With this **simplified** RSA scheme, how can Bob verify whether S is a valid signature on message M? In other words, what equation should he check, to confirm whether M was validly signed by Alice?

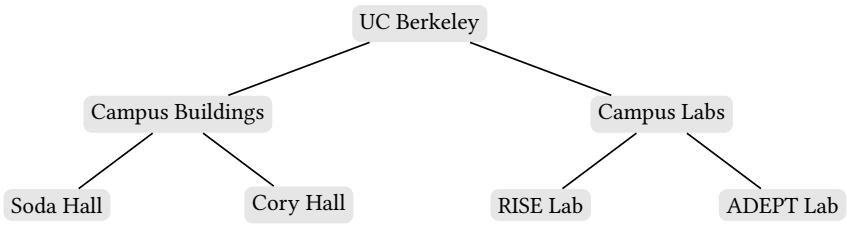
Q2.2 Mallory learns that Alice and Bob are using the **simplified** signature scheme described above and decides to trick Bob into beliving that one of Mallory's messages is from Alice. Explain how Mallory can find an (M, S) pair such that S will be a valid signature on M.

You should assume that Mallory knows Alice's public key n, but not Alice's private key d. The message M does not have to be chosen in advance and can be gibberish.

Q2.3 Is the attack in Q3.2 possible against the **standard** RSA signature scheme (the one that includes the cryptographic hash function)? Why or why not?

Question 3 ***RISELab Shenanigans*** ()

Certificate authorities of UC Berkeley are organized in a hierarchy as follows:



Alice is a student in RISELab at UC Berkeley and wants to obtain a certificate for her public key. Assume that only RISELab is allowed to issue certificates to Alice.

Q3.1 (2 min) Which of the following values are included in the certificate issued to Alice? Select all that apply.

☐ (A) Alice's public key

☐ (B) Alice's private key

☐ (C) A signature on Alice's *public* key, signed by RISELab's private key

☐ (D) A signature on Alice's *private* key, signed by RISELab's private key

☐ (E) None of the above

☐ (F) ——

Q3.2 (2 min) Assume that the only public key you trust is UC Berkeley's public key. Which certificates do you need to verify in order to be sure that you have Alice's public key? Select all that apply.

☐ (G) Certificate for Alice

☐ (H) Certificate for Soda Hall

☐ (I) Certificate for RISELab

☐ (J) Certificate for Campus Labs

☐ (K) None of the above

☐ (L) ——

Q3.3 (4 min) RISELab issues a certificate to Alice that expires in 1 hour. Which of the following statements are true about using such a short expiration date? Select all that apply.

☐ (A) It mitigates attacks where Alice's private key is stolen

☐ (B) It mitigates attacks where RISELab's private key is stolen

☐ (C) It mitigates attacks where Campus Labs' private key is stolen

☐ (D) It forces Alice to renew the certificate more often

☐ (E) None of the above

☐ (F) ——

The following subparts are independent from the previous subparts.

Passwords on the RISELab website are six-digit codes, where each digit is one of 0–9 (repeat digits are allowed). An attacker steals the password database, which includes Alice's hashed password, and wants to learn Alice's password.

For each password storage scheme, *in the worst case*, how much time would it take for the attacker to brute-force Alice's password?

Assumptions:

- The attacker tries passwords one at a time.
- H is a hash function that takes 1 second to compute.
- The time required for all other operations is negligible.

Q3.4 (2 min) Passwords are stored as $H(\mathsf{pwd})$.

◯ (G) $10^6 \cdot 2 \cdot 8$ seconds ◯ (I) $10^6 \cdot 2^8$ seconds ◯ (K) 2^8 seconds

◯ (H) $6 \cdot 10 \cdot 2^8$ seconds ◯ (J) 10^6 seconds ◯ (L) ——

Q3.5 (2 min) Passwords are stored as $(\mathsf{salt}, H(\mathsf{salt}\|\mathsf{pwd}))$, where salt is an 8-bit random string.

◯ (A) $10^6 \cdot 2 \cdot 8$ seconds ◯ (C) $10^6 \cdot 2^8$ seconds ◯ (E) 2^8 seconds

◯ (B) $6 \cdot 10 \cdot 2^8$ seconds ◯ (D) 10^6 seconds ◯ (F) ——

Q3.6 (4 min) Assume that the attacker is conducting an **online** brute-force attack against Alice's account. Which of the following changes, if implemented individually, would make it more difficult for the attacker to access Alice's account? Select all that apply.

☐ (G) Alice uses a random, alphanumeric, 32-character password instead of a 6-digit numeric password

☐ (H) Alice enables two-factor authentication on her account

☐ (I) RISELab imposes a timeout which doubles after each password attempt

☐ (J) RISELab enables TLS for its login page

☐ (K) None of the above

◯ (L) ——