

**Q1** *Bob's Birthday*

(11 points)

It's Bob's birthday! Alice wants to send an encrypted birthday message to Bob using ElGamal.

Recall the definition of ElGamal encryption:

- $b$  is the private key, and  $B = g^b \bmod p$  is the public key.
- $\text{Enc}(B, M) = (C_1, C_2)$ , where  $C_1 = g^r \bmod p$  and  $C_2 = M \times B^r \bmod p$
- $\text{Dec}(b, C_1, C_2) = C_1^{-b} \times C_2 \bmod p$

Q1.1 (2 points) Mallory wants to tamper with Alice's message to Bob. In response, Alice decides to sign her message with an RSA digital signature. Bob receives the signed message and verifies the signature successfully. Can he be sure the message is from Alice?

- Yes, because RSA digital signatures are unforgeable.
- Yes, because RSA encryption is IND-CPA secure.
- No, because Mallory could have blocked Alice's message and replaced it with a different one.
- No, because Mallory could find a different message with the same hash as Alice's original message.

**Solution:** RSA digital signatures, when paired with a secure hash function, are believed to be unforgeable. See the textbook for a game-based definition of what exactly we mean by unforgeable.

As we discussed in class, ElGamal is malleable, meaning that a man-in-the-middle can change a message in a *predictable* manner, such as producing the ciphertext of the message  $2 \times M$  given the ciphertext of  $M$ .

Q1.2 (3 points) Consider the following modification to ElGamal: Encrypt as normal, but further encrypt portions of the ciphertext with a block cipher  $E$ , which has a block size equal to the number of bits in  $p$ . In this scheme, Alice and Bob share a symmetric key  $K_{\text{sym}}$  known to no one else.

Under this modified scheme,  $C_1$  is computed as  $E_{K_{\text{sym}}}(g^r \bmod p)$  and  $C_2$  is computed as  $E_{K_{\text{sym}}}(M \times B^r \bmod p)$ . Is this scheme still malleable?

- Yes, because block ciphers are not IND-CPA secure encryption schemes
- Yes, because the adversary can still forge  $k \times C_2$  to produce  $k \times M$
- No, because block ciphers are a pseudorandom permutation
- No, because the adversary isn't able to learn anything about the message  $M$

**Solution:** While block ciphers aren't IND-CPA secure, they are secure when encrypting "random-looking" values because of their properties as pseudorandom permutations. As long as the values you encrypt are unique, the output of the block cipher will always be secure. ElGamal's  $C_1$  and  $C_2$  both appear random.

Additionally, because block ciphers are a PRP, the scheme is no longer malleable, because modifying the ciphertext in any way causes an unpredictable change to the result of decrypting the block cipher with  $D_{K_{\text{sym}}}$ .

The remaining parts are independent of the previous part.

For Bob's birthday, Mallory hacks into Bob's computer, which stores Bob's private key  $b$ . She isn't able to read  $b$  or overwrite  $b$  with an arbitrary value, but she can multiply the stored value of  $b$  by a random value  $z$  known to Mallory.

Mallory wants to send a message to Bob that appears to decrypt as normal, but **using the modified key**  $b \cdot z$ . Give a new encryption formula for  $C_1$  and  $C_2$  that Mallory should use. Make sure you only use values known to Mallory!

*Clarification during exam:* For subparts 3 and 4, assume that the value of  $B$  is unchanged.

Q1.3 (3 points) Give a formula to produce  $C_1$ , encrypting  $M$ .

**Solution:** Mallory should send  $g^r$  with some randomly chosen  $r$ , as usual.

Q1.4 (3 points) Give a formula to produce  $C_2$ , encrypting  $M$ .

**Solution:** Mallory should send  $C_2 = m \times B^{rz} \pmod p$ .

**Q2 ElGamal and friends****(0 points)**

Bob wants his pipes fixed and invites independent plumbers to send him bids for their services (*i.e.*, the fees they charge). Alice is a plumber and wants to submit a bid to Bob. Alice and Bob want to preserve the confidentiality of Alice's bid, but the communication channel between them is insecure. Therefore, they decide to use the ElGamal public key encryption scheme in order to communicate privately.

Instead of using the traditional version of the ElGamal scheme, Alice and Bob use the following variant. As usual, Bob's private key is  $x$  and his public key is  $PK = (p, g, h)$ , where  $h = g^x \pmod p$ . However, to send a message  $M$  to Bob, Alice encrypts  $M$  as  $Enc_{PK}(M) = (s, t)$ , where  $s = g^r \pmod p$  and  $t = g^M \times h^r \pmod p$ , for a randomly chosen  $r$ .

Q2.1 Consider two distinct messages  $m_1$  and  $m_2$ . Let  $Enc_{PK}(m_1) = (s_1, t_1)$  and  $Enc_{PK}(m_2) = (s_2, t_2)$ . For the given variant of the ElGamal scheme, which of the following is true?

- (A)  $(s_1 + s_2 \pmod p, t_1 + t_2 \pmod p)$  is a possible value for  $Enc_{PK}(m_1 + m_2)$ .
  (D)  $(s_1 + s_2 \pmod p, t_1 + t_2 \pmod p)$  is a possible value for  $Enc_{PK}(m_1 \times m_2)$ .
- (B)  $(s_1 \times s_2 \pmod p, t_1 \times t_2 \pmod p)$  is a possible value for  $Enc_{PK}(m_1 + m_2)$ .
  (E) None of these
- (C)  $(s_1 \times s_2 \pmod p, t_1 \times t_2 \pmod p)$  is a possible value for  $Enc_{PK}(m_1 \times m_2)$ .
  (F) —

Q2.2 In order to decrypt a ciphertext  $(s, t)$ , Bob starts by calculating  $q = ts^{-x} \pmod p$ . Assume that the message  $M$  is between 0 and 1000. How can Bob recover  $M$  from  $q$ ?

**Solution:** If Bob knows the possible set of messages, then he can pre-compute a lookup table for values of  $q = g^M \pmod p$ .

Q2.3 Explain why Bob cannot efficiently recover  $M$  from  $q$  if  $M$  is randomly chosen such that  $0 \leq M < p$ .

**Solution:** Requires solving the discrete log mod  $p$ , which is thought to be computationally hard.

Q2.4 Suppose Alice sends Bob a bid  $M_0 = 500$ , encrypted under Bob's public key. We let  $C_0 = (s, t)$  be the ciphertext here.

Mallory is an active man-in-the-middle attacker who knows Alice's bid is  $M_0 = 500$ . Mallory wants to replace Alice's bid with  $M_1 = 999$ . To do that, Mallory intercepts  $C_0$  and replaces it with another ciphertext  $C_1$ . Mallory wishes that when Bob decrypts  $C_1$ , Bob sees  $M_1 = 999$ .

Describe how Mallory creates  $C_1$  in each of the following situations:

1. Mallory didn't obtain  $C_0$ , but knows Bob's public key  $\text{PK} = (p, g, h)$ .

**Solution:** Mallory can simply encrypt  $M$  of her choice using Bob's public key and replace the ciphertext.

2. Mallory knows Alice's ciphertext  $C_0$ , but only knows  $p$  and  $g$  in Bob's public key  $\text{PK} = (p, g, h)$ . (That is to say, Mallory does not know  $h$ .)

**Solution:** Mallory can create  $(s', t') = (s, tg^{499}) \pmod{p}$ .