Problem 1 Let’s explore why in the RSA public key system each person has to be assigned a different modulus $N = pq$. Suppose we try to use the same modulus $N = pq$ for everyone. Each person is assigned a public exponent $e_i$ and a private exponent $d_i$ such that $e_i \cdot d_i = 1 \mod \varphi(N)$. At first this appears to work fine: to encrypt a message to Bob, Alice computes $C = M^{e_{bob}}$ and sends $C$ to Bob. An eavesdropper Eve, not knowing $d_{bob}$ appears to be unable to decrypt $C$. Let’s show that using $e_{eve}$ and $d_{eve}$ Eve can very easily decrypt $C$.

a. Show that given $e_{eve}$ and $d_{eve}$ Eve can obtain a multiple of $\varphi(N)$.

b. Show that given an integer $K$ which is a multiple of $\varphi(N)$ Eve can factor the modulus $N$. Deduce that Eve can decrypt any RSA ciphertext encrypted using the modulus $N$ intended for Alice or Bob.

Hint: Consider the sequence $g^K, g^{K/2}, g^{K/4}, \ldots g^{K/\tau(K)} \mod N$ where $g$ is random in $\mathbb{Z}_N$ and $\tau(N)$ is the largest power of 2 dividing $K$. Use the the left most element in this sequence which is not equal to $\pm 1 \mod N$.

Problem 2 Recall that a simple RSA signature $S = H(M)^d \mod N$ is computed by first computing $S_1 = H(M)^d \mod p$ and $S_2 = H(M)^d \mod q$. The signature $S$ is then found by combining $S_1$ and $S_2$ using the Chinese Remainder Theorem (CRT). Now, suppose a Certificate Authority (CA) is about to sign a certain certificate $C$. While the CA is computing $S_1 = H(C)^d \mod p$, a glitch on the CA’s machine causes it to produce the wrong value $\tilde{S}_1$ which is not equal to $S_1$. The CA computes $S_2 = H(C)^d \mod q$ correctly. Clearly the resulting signature $\tilde{S}$ is invalid. The CA then proceeds to publish the newly generated certificate with the invalid signature $\tilde{S}$.

a. Show that any person who obtains the certificate $C$ along with the invalid signature $\tilde{S}$ is able to factor the CA’s modulus.

Hint: Use the fact that $\tilde{S}^e = H(C) \mod q$. Here $e$ is the public verification exponent.

b. Suggest some method by which the CA can defend itself against this danger.

Problem 3 Commitment schemes. A commitment scheme enables Alice to commit a value $x$ to Bob. The scheme is secure if the commitment does not reveal to Bob any information about the committed value $x$. At a later time Alice may open the commitment and convince Bob that the committed value is $x$. The commitment is binding if Alice cannot convince Bob that the committed value is some $x' \neq x$. Here is an example commitment scheme:
Public values: (1) a 1024 bit prime \( p \), and (2) two elements \( g \) and \( h \) of \( \mathbb{Z}_p^* \) of prime order \( q \).

Commitment: To commit to an integer \( x \in [0, q - 1] \) Alice does the following: (1) she picks a random \( r \in [0, q - 1] \), (2) she computes \( b = g^x \cdot h^r \mod p \), and (3) she sends \( b \) to Bob as her commitment to \( x \).

Open: To open the commitment Alice sends \((x, r)\) to Bob. Bob verifies that 
\[
b = g^x \cdot h^r \mod p.
\]

Show that this scheme is secure and binding.

a. To prove security show that \( b \) does not reveal any information to Bob about \( x \). In other words, show that given \( b \), the committed value can be any integer \( x' \) in \([0, q - 1]\).

Hint: show that for any \( x' \) there exists a unique \( r' \in [0, q - 1] \) so that \( b = g^{x'} h^{r'} \).

b. To prove the binding property show that if Alice can open the commitment as \((x', r')\) where \( x \neq x' \) then Alice can compute the discrete log of \( h \) base \( g \). In other words, show that if Alice can find an \((x', r')\) such that \( b = g^{x'} h^{r'} \mod p \) then she can find the discrete log of \( h \) base \( g \). Recall that Alice also knows the \((x, r)\) used to create \( b \).

Problem 4 Access control and file sharing using RSA. In this problem \( N = pq \) is some RSA modulus. All arithmetic operations are done modulo \( N \).

a. Suppose we have a file system containing \( n \) files. Let \( e_1, \ldots, e_n \) be relatively prime integers that are also relatively prime to \( \varphi(N) \), i.e. \( \gcd(e_i, e_j) = \gcd(e_i, \varphi(N)) = 1 \) for all \( i \neq j \). The integers \( e_1, \ldots, e_n \) are public. Let \( R \in \mathbb{Z}_N^* \) and suppose each file \( F_i \) is encrypted using the key \( key_i = R^{1/e_i} \).

Now, let \( S \subseteq \{1, \ldots, n\} \) and set \( b = \prod_{i \in S} e_i \). Suppose user \( u \) is given \( K_u = R^{1/h} \). Show that user \( u \) can decrypt any file \( i \in S \). That is, show how user \( u \) using \( K_u \) can compute any key \( key_i \) for \( i \in S \).

This way, each user \( u_j \) can be given a key \( K_{u_j} \) enabling it to access those files to which it has access permission.

b. Next we need to show that using \( K_u \) user \( u \) cannot compute any key \( key_i \) for \( i \not\in S \).

To do so we first consider a simpler problem. Let \( d_1, d_2 \) be two integers relatively prime to \( \varphi(N) \) and relatively prime to each other. Suppose there is an efficient algorithm \( \mathcal{A} \) such that \( \mathcal{A}(R, R^{1/d_1}) = R^{1/d_2} \) for all \( R \in \mathbb{Z}_N^* \). In other words, given the \( d_1 \)'th root of \( R \in \mathbb{Z}_N^* \) algorithm \( \mathcal{A} \) is able to compute the \( d_2 \)'th root of \( R \). Show that there is an efficient algorithm \( \mathcal{B} \) to compute \( d_2 \)'th roots in \( \mathbb{Z}_N^* \). That is, \( \mathcal{B}(X) = X^{1/d_2} \) for all \( X \in \mathbb{Z}_N^* \). Algorithm \( \mathcal{B} \) uses \( \mathcal{A} \) as a subroutine.

c. Show using part (b) that user \( u \) cannot obtain the key \( key_i \) for any \( i \not\in S \) assuming that computing \( e \)'th roots modulo \( N \) is hard for any \( e \) such that \( \gcd(e, \varphi(N)) = 1 \).

(the contra-positive of this statement should follow from (b) directly).
Problem 5 In class we briefly noted that a one-time signature scheme can be converted into a many-time signature scheme. Let’s explore how to do it. The signer in our many-time scheme will maintain internal state and update it every time he signs a message. Let \((G, S, V)\) be a one-time signature scheme (i.e. a scheme secure as long as a public/secret pair is used to sign at most one message). To build a signature scheme for signing \(2^n\) messages (say \(n = 32\)) visualize a complete binary tree with \(2^n\) leaves. Every node in this tree stores a different public/secret key pair for the one-time system. 

The public key for our many-time scheme is the public key stored at the root of the tree. To sign message number \(i\) the signer uses the \(i\)th leaf in the tree (for \(1 \leq i \leq 2^n\)). Let \(u_0, \ldots, u_n\) be the \(n\) nodes on the path from the root to the \(i\)th leaf (\(u_0\) is the root of the tree, \(u_n\) is the leaf). To sign the message \(m\), first use the secret key in the leaf node \(u_n\) to sign \(m\). Let \(s_n\) be the resulting signature. Then for \(i = 0, \ldots, n - 1\) use the secret key in node \(u_i\) to sign the pair of public keys stored in its two children. Let \((s_0, \ldots, s_{n-1})\) be the resulting \(n\) one-time signatures. For \(1 \leq i \leq n\) let \(pk_i\) be the public key stored in node \(u_i\) and let \(pk'_i\) be the public key stored in the sibling of node \(u_i\). The many-time scheme outputs \((i, (s_0, pk_1, pk'_1), \ldots, (s_{n-1}, pk_n, pk'_n), s_n)\) as the signature on \(m\).

a. Write (short) pseudo-code to implement the signing and verification algorithms for the many-time scheme. Your signing code should maintain state containing at most \(2^n\) one-time public/private key pairs at any given time. Your verification code should be stateless.

b. Briefly explain why your implementation is secure. In other words, explain why your signing code never uses a one-time public-key to sign two distinct messages.

c. What is the size of the resulting signatures when using the Lamport one-time signature scheme discussed in class? How many applications of the one-way function are needed (on average) to generate a signature?