ASYMMETRIC (PUBLIC-KEY) ENCRYPTION
Recommended Book


A non-technical account of the history of public-key cryptography and the colorful characters involved.
Recall Symmetric Cryptography

- Before Alice and Bob can communicate securely, they need to have a common secret key $K_{AB}$.
- If Alice wishes to also communicate with Charlie then she and Charlie must also have another common secret key $K_{AC}$.
- If Alice generates $K_{AB}, K_{AC}$, they must be communicated to her partners over private and authenticated channels.
Public Key Encryption

- Alice has a secret key that is shared with nobody, and an associated public key that is known to everybody.
- Anyone (Bob, Charlie, ... ) can use Alice’s public key to send her an encrypted message which only she can decrypt.

Think of the public key like a phone number that you can look up in a database
Public Key Encryption

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- Senders don’t need secrets
- There are no shared secrets
Syntax of PKE

A public-key (or asymmetric) encryption scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ consists of three algorithms, where
Let $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be an asymmetric encryption scheme. The correct decryption requirement is that

$$\Pr[\mathcal{D}(sk, \mathcal{E}(pk, M)) = M] = 1$$

for all $(pk, sk)$ that may be output by $\mathcal{K}$ and all messages $M$ in the message space of $\mathcal{AE}$. The probability is over the random choices of $\mathcal{E}$.

This simply says that decryption correctly reverses encryption to recover the message that was encrypted. When we specify schemes, we indicate what is the message space.
How it works

Step 1: Key generation
Alice locally computes \((pk, sk) \leftarrow \mathcal{K}\) and stores \(sk\).

Step 2: Alice enables any prospective sender to get \(pk\).

Step 3: The sender encrypts under \(pk\) and Alice decrypts under \(sk\).

We don’t require privacy of \(pk\) but we do require authenticity: the sender should be assured \(pk\) is really Alice’s key and not someone else’s. One could

- Put public keys in a trusted but public “phone book”, say a cryptographic DNS.
- Use certificates as we will see later.
Security of PKE Schemes

Same as for symmetric encryption, except for one new element: The adversary needs to be given the public key.

We formalize IND-CPA accordingly.
The games for IND-CPA

Let $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be a PKE scheme and $A$ an adversary.

### Game Left$_{\mathcal{AE}}$

- **procedure Initialize**
  
  $(pk, sk) \leftarrow \mathcal{K}$ ; return $pk$

- **procedure LR($M_0, M_1$)**
  
  Return $C \leftarrow \mathcal{E}_{pk}(M_0)$

### Game Right$_{\mathcal{AE}}$

- **procedure Initialize**
  
  $(pk, sk) \leftarrow \mathcal{K}$ ; return $pk$

- **procedure LR($M_0, M_1$)**
  
  Return $C \leftarrow \mathcal{E}_{pk}(M_1)$

Associated to $\mathcal{AE}$, $A$ are the probabilities

$$\Pr\left[\text{Left}_{\mathcal{AE}}^A \Rightarrow 1\right] \quad \text{and} \quad \Pr\left[\text{Right}_{\mathcal{AE}}^A \Rightarrow 1\right]$$

that $A$ outputs 1 in each world. The ind-cpa advantage of $A$ is

$$\text{Adv}^{\text{ind-cca}}_{\mathcal{AE}}(A) = \Pr\left[\text{Right}_{\mathcal{AE}}^A \Rightarrow 1\right] - \Pr\left[\text{Left}_{\mathcal{AE}}^A \Rightarrow 1\right]$$
The “return $pk$” statement in **Initialize** means the adversary $A$ gets the public key $pk$ as input. It does not get $sk$.

It can call **LR** with any equal-length messages $M_0, M_1$ of its choice to get back an encryption $C \leftarrow E_{pk}(M_b)$ of $M_b$ under $sk$, where $b = 0$ in game $\text{Left}_{AE}$ and $b = 1$ in game $\text{Right}_{AE}$. Notation indicates encryption algorithm may be randomized.

$A$ is not allowed to call **LR** with messages $M_0, M_1$ of unequal length. Any such $A$ is considered invalid and its advantage is undefined or 0.

It outputs a bit, and wins if this bit equals $b$. 
We would like security to result from the hardness of computing discrete logarithms.

Let the receiver’s public key be \( g \) where \( G = \langle g \rangle \) is a cyclic group. Let’s let the encryption of \( x \) be \( g^x \). Then

\[
\begin{align*}
g^x &\quad \text{hard} \quad \xrightarrow{} \quad x \\
\mathcal{E}_g(x) &\quad \text{so to recover } x, \text{ adversary must compute discrete logarithms, and we know it can’t, so are we done?}
\end{align*}
\]
Building a PKE Scheme

We would like security to result from the hardness of computing discrete logarithms.

Let the receiver’s public key be $g$ where $G = \langle g \rangle$ is a cyclic group. Let’s let the encryption of $x$ be $g^x$. Then

$$g^x \xrightarrow{\text{hard}} x$$

so to recover $x$, adversary must compute discrete logarithms, and we know it can’t, so are we done?

**Problem:** Legitimate receiver needs to compute discrete logarithm to decrypt too! But decryption needs to be feasible.

Above, receiver has no secret key!
Recall DH Secret Key Exchange

The following are assumed to be public: A large prime $p$ and a generator $g$ of $\mathbb{Z}_p^*$.  

\[
\begin{align*}
\text{Alice} & : \quad x \xleftarrow{\$} \mathbb{Z}_{p-1}; \quad X \leftarrow g^x \mod p \\
& \quad \xrightarrow{x} \quad \text{Bob} \\
& \quad y \xleftarrow{\$} \mathbb{Z}_{p-1}; \quad Y \leftarrow g^y \mod p \\
& \quad \xleftarrow{Y} \quad \text{Bob} \\
& \quad K_A \leftarrow Y^x \mod p \\
\end{align*}
\]

- $Y^x = (g^y)^x = g^{xy} = (g^x)^y = X^y \mod p$, so $K_A = K_B$
- Adversary is faced with the CDH problem.
We can turn DH key exchange into a public key encryption scheme via

- Let Alice have public key $g^x$ and secret key $x$
- If Bob wants to encrypt $M$ for Alice, he
  - Picks $y$ and sends $g^y$ to Alice
  - Encrypts $M$ under $g^{xy} = (g^x)^y$ and sends ciphertext to Alice.
- But Alice can recompute $g^{xy} = (g^y)^x$ because
  - $g^y$ is in the received ciphertext
  - $x$ is her secret key

Thus she can decrypt and adversary is still faced with CDH.
Let $G = \langle g \rangle$ be a cyclic group of order $m$ and $H: G \rightarrow \{0,1\}^k$ a (public) hash function. The DHIES PKE scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ is defined for messages $M \in \{0,1\}^k$ via

\[
\begin{align*}
\textbf{Alg } \& \mathcal{K} & \quad \quad \textbf{Alg } \mathcal{E}_X(M) & \quad \quad \textbf{Alg } \mathcal{D}_X(Y, W) \\
x & \leftarrow \$ Z_m & y & \leftarrow \$ Z_m; \ Y & \leftarrow g^y & K & \leftarrow X^y \\
X & \leftarrow g^x & \quad \quad \quad W & \leftarrow H(K) \oplus M & Y^x & \leftarrow Y^x \\
\text{return } (X, x) & \quad \quad \quad \quad \text{return } (Y, W) & M & \leftarrow H(K) \oplus W \\
\end{align*}
\]

Correct decryption is assured because $K = X^y = g^{xy} = Y^x$

**Note:** This is a simplified version of the actual scheme.
The DHIES scheme $\mathcal{AE} = (K, E, D)$ associated to cyclic group $G = \langle g \rangle$ and (public) hash function $H$ can be proven IND-CPA assuming

- CDH is hard in $G$, and
- $H$ is a “random oracle,” meaning a “perfect” hash function.

In practice, $H(K)$ could be the first $k$ bits of the sequence

$$\text{SHA256}(0^8 \parallel K) \parallel \text{SHA256}(0^71 \parallel K) \parallel \cdots$$
ECIES is DHIES with the group being an elliptic curve group.

**ECIES features:**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>encryption</td>
<td>2 160-bit exp</td>
</tr>
<tr>
<td>decryption</td>
<td>1 160-bit exp</td>
</tr>
<tr>
<td>ciphertext expansion</td>
<td>160-bits</td>
</tr>
</tbody>
</table>

\[
\text{ciphertext expansion} = (\text{length of ciphertext}) - (\text{length of plaintext})
\]
Let $p \geq 3$ be a prime, $g \in \mathbb{Z}_p^*$ a generator of $\mathbb{Z}_p^*$ and $H: \mathbb{G} \rightarrow \{0, 1\}^k$ a hash function. (These are all public.) Consider the key-generation and encryption algorithms below, where $M \in \{0, 1\}^k$:

<table>
<thead>
<tr>
<th>Alg $\mathcal{K}$</th>
<th>Alg $\mathcal{E}(X, M)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x \leftarrow \mathbb{Z}_{p-1}^*$</td>
<td>$y \leftarrow \mathbb{Z}_{p-1}$; $Y \leftarrow g^y \mod p$</td>
</tr>
<tr>
<td>$X \leftarrow g^x \mod p$</td>
<td>$Z \leftarrow X^y \mod p$; $W \leftarrow H(Y) \oplus M$</td>
</tr>
<tr>
<td>return $(X, x)$</td>
<td>Return $(Z, W)$</td>
</tr>
</tbody>
</table>

Specify a $O(|p|^3 + k)$-time decryption algorithm $\mathcal{D}$ such that $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ is an asymmetric encryption scheme satisfying the correct decryption property, and prove this is the case.
Recall that $\varphi(N) = |\mathbb{Z}_N^*|$. 

**Claim:** Suppose $e, d \in \mathbb{Z}_N^*$ satisfy $ed \equiv 1 \pmod{\varphi(N)}$. Then for any $x \in \mathbb{Z}_N^*$ we have

$$(x^e)^d \equiv x \pmod{N}$$

**Proof:**

$$(x^e)^d \equiv x^{ed} \pmod{\varphi(N)} \equiv x^1 \equiv x$$

modulo $N$
The RSA function

A modulus $N$ and encryption exponent $e$ define the RSA function $f : \mathbb{Z}_N^* \to \mathbb{Z}_N^*$ defined by

$$f(x) = x^e \mod N$$

for all $x \in \mathbb{Z}_N^*$.

A value $d \in \mathbb{Z}_{\varphi(N)}^*$ satisfying $ed \equiv 1 \pmod{\varphi(N)}$ is called a decryption exponent.

**Claim:** The RSA function $f : \mathbb{Z}_N^* \to \mathbb{Z}_N^*$ is a permutation with inverse $f^{-1} : \mathbb{Z}_N^* \to \mathbb{Z}_N^*$ given by

$$f^{-1}(y) = y^d \mod N$$

**Proof:** For all $x \in \mathbb{Z}_N^*$ we have

$$f^{-1}(f(x)) \equiv (x^e)^d \equiv x \pmod{N}$$

by previous claim.
Let $N = 15$. So

$$Z_N^* = \{ 1, 2, 4, 7, 8, 11, 13, 14 \}$$

$$\varphi(N) = 8$$

$$Z_{\varphi(N)}^* = \{ 1, 3, 5, 7 \}$$
Example

Let $N = 15$. So

$$\mathbb{Z}_N^* = \{1, 2, 4, 7, 8, 11, 13, 14\}$$

$$\varphi(N) = 8$$

$$\mathbb{Z}_{\varphi(N)}^* = \{1, 3, 5, 7\}$$

Let $e = 3$ and $d = 3$. Then

$$ed \equiv 9 \equiv 1 \pmod{8}$$

Let

$$f(x) = x^3 \mod 15$$

$$g(y) = y^3 \mod 15$$

<table>
<thead>
<tr>
<th>$x$</th>
<th>$f(x)$</th>
<th>$g(f(x))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>8</td>
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<tr>
<td>11</td>
<td>11</td>
<td>11</td>
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<tr>
<td>13</td>
<td>7</td>
<td>13</td>
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<tr>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

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UCSD
1. List all possible encryption exponents for RSA modulus 35:

2. The decryption exponent corresponding to RSA modulus 187 and encryption exponent 107 is
RSA usage

- $pk = N, e; \ sk = N, d$
- $\mathcal{E}_{pk}(x) = x^e \ mod \ N = f(x)$
- $\mathcal{D}_{sk}(y) = y^d \ mod \ N = f^{-1}(y)$

Security will rely on it being hard to compute $f^{-1}$ without knowing $d$.

RSA is a trapdoor, one-way permutation:
- Easy to invert given trapdoor $d$
- Hard to invert given only $N, e$
An RSA generator with security parameter $k$ is an algorithm $\mathcal{K}_{rsa}$ that returns $N, p, q, e, d$ satisfying

- $p, q$ are distinct odd primes
- $N = pq$ and is called the (RSA) modulus
- $|N| = k$, meaning $2^{k-1} \leq N \leq 2^k$
- $e \in \mathbb{Z}^*_\varphi(N)$ is called the encryption exponent
- $d \in \mathbb{Z}^*_\varphi(N)$ is called the decryption exponent
- $ed \equiv 1 \pmod{\varphi(N)}$
Plan

- Building RSA generators
- Basic RSA security
- Encryption with RSA
Fact: Suppose $N = pq$ for distinct primes $p$ and $q$. Then

$$\varphi(N) = (p - 1)(q - 1).$$

Example: Let $N = 15 = 3 \cdot 5$. Then the Fact says that

$$\varphi(15) = (3 - 1)(5 - 1) = 8.$$  

As a check, $\mathbb{Z}_{15}^* = \{1, 2, 4, 7, 8, 11, 13, 14\}$ indeed has size 8.
A more general formula for Phi

Fact: Suppose $N \geq 1$ factors as

$$N = p_1^{\alpha_1} \cdot p_2^{\alpha_2} \cdot \ldots \cdot p_n^{\alpha_n}$$

where $p_1 < p_2 < \ldots < p_n$ are primes and $\alpha_1, \ldots, \alpha_n \geq 1$ are integers. Then

$$\varphi(N) = p_1^{\alpha_1-1}(p_1 - 1) \cdot p_2^{\alpha_2-1}(p_2 - 1) \cdot \ldots \cdot p_n^{\alpha_n-1}(p_n - 1).$$

Note prior Fact is a special case of the above. (Make sure you understand why!)

Example: Let $N = 45 = 3^2 \cdot 5^1$. Then the Fact says that

$$\varphi(45) = 3^1(3 - 1) \cdot 5^0(5 - 1) = 24$$
Recall

Given $\varphi(N)$ and $e \in \mathbb{Z}_{\varphi(N)}^*$, we can compute $d \in \mathbb{Z}_{\varphi(N)}^*$ satisfying $ed \equiv 1 \pmod{\varphi(N)}$ via

$$d \leftarrow \text{MOD-INV}(e, \varphi(N)).$$

We have algorithms to efficiently test whether a number is prime, and a random number has a pretty good chance of being a prime.
Say we wish to have $e = 3$ (for efficiency). The generator $\mathcal{K}_{rsa}^3$ with (even) security parameter $k$:

repeat

\[ p, q \leftarrow \{2^{k/2-1}, \ldots, 2^{k/2} - 1\}; \ N \leftarrow pq; \ M \leftarrow (p - 1)(q - 1) \]

until

\[ N \geq 2^{k-1} \text{ and } p, q \text{ are prime and } gcd(e, M) = 1 \]

\[ d \leftarrow \text{MOD-INV}(e, M) \]

return $N, p, q, e, d$
The following should be hard:

Given: $N, e, y$ where $y = f(x) = x^e \mod N$

Find: $x$

Formalism picks $x$ at random and generates $N, e$ via an RSA generator.
One-wayness of RSA, formally

Let $\mathcal{K}_\text{rsa}$ be a RSA generator and $I$ an adversary.

**Game $\text{OW}_{\mathcal{K}_\text{rsa}}$**

**procedure Initialize**

$(N, p, q, e, d) \leftarrow^$ $\mathcal{K}_\text{rsa}$

$x \leftarrow^$ $\mathbb{Z}_N^*$; $y \leftarrow x^e \mod N$

return $N, e, y$

**procedure Finalize($x'$)**

return $(x = x')$

The ow-advantage of $I$ is

$$\text{Adv}_{\mathcal{K}_\text{rsa}}^{\text{OW}} (I) = \Pr \left[ \text{OW}'_{\mathcal{K}_\text{rsa}} \Rightarrow \text{true} \right]$$
Inverting RSA : given $N$, $e$, $y$ find $x$ such that $x^e \equiv y \pmod{N}$
Inverting RSA : given $N, e, y$ find $x$ such that $x^e \equiv y \pmod{N}$

EASY because $f^{-1}(y) = y^d \pmod{N}$

Know $d$
Inverting RSA

Inverting RSA: given $N, e, y$ find $x$ such that $x^e \equiv y \pmod{N}$

- EASY because $f^{-1}(y) = y^d \pmod{N}$
- Know $d$
- EASY because $d = e^{-1} \pmod{\varphi(N)}$
- Know $\varphi(N)$
Inverting RSA

Inverting RSA: given $N, e, y$ find $x$ such that $x^e \equiv y \pmod{N}$

- EASY because $f^{-1}(y) = y^d \mod N$
- Know $d$
- EASY because $d = e^{-1} \mod \varphi(N)$
- Know $\varphi(N)$
- EASY because $\varphi(N) = (p - 1)(q - 1)$
- Know $p, q$
Inverting RSA : given \( N, e, y \) find \( x \) such that \( x^e \equiv y \pmod{N} \)

- **EASY** because \( f^{-1}(y) = y^d \pmod{N} \)
- Know \( d \)

- **EASY** because \( d = e^{-1} \pmod{\varphi(N)} \)
- Know \( \varphi(N) \)

- **EASY** because \( \varphi(N) = (p - 1)(q - 1) \)
- Know \( p, q \)

- ?
- Know \( N \)
Factoring Problem

Given: \( N \) where \( N = pq \) and \( p, q \) are prime

Find: \( p, q \)

If we can factor we can invert RSA. We do not know whether the converse is true, meaning whether or not one can invert RSA without factoring.
A factoring algorithm

Alg FACTOR(N)  // N = pq where p, q are primes
for i = 2, ..., \left\lceil \sqrt{N} \right\rceil \ do
  if N \mod i = 0 \ then
    p \leftarrow i; \ q \leftarrow N/i; \ return \ p, q
This algorithm works but takes time

\[ \mathcal{O}(\sqrt{N}) = \mathcal{O}(e^{0.5\ln N}) \]
which is prohibitive.
### Factoring algorithms

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Time taken to factor $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naive</td>
<td>$O(e^{0.5 \ln N})$</td>
</tr>
<tr>
<td>Quadratic Sieve (QS)</td>
<td>$O(e^{c(\ln N)^{1/2}(\ln \ln N)^{1/2}})$</td>
</tr>
<tr>
<td>Number Field Sieve (NFS)</td>
<td>$O(e^{1.92(\ln N)^{1/3}(\ln \ln N)^{2/3}})$</td>
</tr>
</tbody>
</table>
## Factoring records

<table>
<thead>
<tr>
<th>Number</th>
<th>bit-length</th>
<th>Factorization</th>
<th>alg</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSA-400</td>
<td>400</td>
<td>1993</td>
<td>QS</td>
</tr>
<tr>
<td>RSA-428</td>
<td>428</td>
<td>1994</td>
<td>QS</td>
</tr>
<tr>
<td>RSA-431</td>
<td>431</td>
<td>1996</td>
<td>NFS</td>
</tr>
<tr>
<td>RSA-465</td>
<td>465</td>
<td>1999</td>
<td>NFS</td>
</tr>
<tr>
<td>RSA-515</td>
<td>515</td>
<td>1999</td>
<td>NFS</td>
</tr>
<tr>
<td>RSA-576</td>
<td>576</td>
<td>2003</td>
<td>NFS</td>
</tr>
<tr>
<td>RSA-768</td>
<td>768</td>
<td>2009</td>
<td>NFS</td>
</tr>
</tbody>
</table>
Current wisdom: For 80-bit security, use a 1024 bit RSA modulus

80-bit security: Factoring takes $2^{80}$ time.

Factorization of RSA-1024 seems out of reach at present.

Estimates vary, and for more security, longer moduli are recommended.
http://www.youtube.com/watch?v=wXB-V_Keiu8
The RSA function $f(x) = x^e \mod N$ is a trapdoor one way permutation:

- Easy forward: given $N, e, x$ it is easy to compute $f(x)$
- Easy back with trapdoor: Given $N, d$ and $y = f(x)$ it is easy to compute $x = f^{-1}(y) = y^d \mod N$
- Hard back without trapdoor: Given $N, e$ and $y = f(x)$ it is hard to compute $x = f^{-1}(y)$
Plain-RSA encryption

The plain RSA PKE scheme \( \mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D}) \) associated to RSA generator \( \mathcal{K}_{rsa} \) is

\[
\begin{align*}
\textbf{Alg } \mathcal{K} \\
(N, p, q, e, d) & \leftarrow \mathcal{K}_{rsa} \\
pk & \leftarrow (N, e) ; \ sk & \leftarrow (N, d) \\
\text{return } (pk, sk)
\end{align*}
\]

\[
\begin{align*}
\textbf{Alg } \mathcal{E}_{pk}(M) \\
C & \leftarrow M^e \mod N \\
\text{return } C
\end{align*}
\]

\[
\begin{align*}
\textbf{Alg } \mathcal{D}_{sk}(C) \\
M & \leftarrow C^d \mod N \\
\text{return } M
\end{align*}
\]

\textbf{Decryption correctness:} The “easy-backwards with trapdoor” property implies that for all \( M \in \mathbb{Z}_{N}^{*} \) we have \( \mathcal{D}_{sk}(\mathcal{E}_{pk}(M)) = M \).

\textbf{Note:} The message space is \( \mathbb{Z}_{N}^{*} \). Messages are assumed to be all encoded as strings of the same length, for example length 4 if \( N = 15 \).
Plain-RSA encryption security

The plain RSA PKE scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ associated to RSA generator $\mathcal{K}_{rsa}$ is

<table>
<thead>
<tr>
<th>$\textbf{Alg } \mathcal{K}$</th>
<th>$\textbf{Alg } \mathcal{E}_{pk}(M)$</th>
<th>$\textbf{Alg } \mathcal{D}_{sk}(C)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(N, p, q, e, d) \leftarrow \mathcal{K}_{rsa}$</td>
<td>$C \leftarrow M^e \mod N$</td>
<td>$M \leftarrow C^d \mod N$</td>
</tr>
<tr>
<td>$pk \leftarrow (N, e)$ ; $sk \leftarrow (N, d)$</td>
<td>return $C$</td>
<td>return $M$</td>
</tr>
<tr>
<td>return $(pk, sk)$</td>
<td></td>
<td></td>
</tr>
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</table>
Plain-RSA encryption security

The plain RSA PKE scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ associated to RSA generator $\mathcal{K}_{rsa}$ is

$$\begin{align*}
\textbf{Alg } \mathcal{K} & \\
(N, p, q, e, d) & \leftarrow \mathcal{K}_{rsa} \\
\text{pk} & \leftarrow (N, e) \text{ ; } \text{sk} \leftarrow (N, d) \\
\text{return } (\text{pk}, \text{sk})
\end{align*}$$

$$\begin{align*}
\textbf{Alg } \mathcal{E}_{pk}(M) & \\
\text{C} & \leftarrow M^e \text{ mod } N \\
\text{return } \text{C}
\end{align*}$$

$$\begin{align*}
\textbf{Alg } \mathcal{D}_{sk}(C) & \\
\text{M} & \leftarrow C^d \text{ mod } N \\
\text{return } \text{M}
\end{align*}$$

Getting $\text{sk}$ from $\text{pk}$ involves factoring $N$. 
Plain-RSA encryption security

The plain RSA PKE scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ associated to RSA generator $\mathcal{K}_{\text{rsa}}$ is

$$\begin{align*}
\textbf{Alg } & \mathcal{K} \\
(N, p, q, e, d) & \leftarrow^{s} \mathcal{K}_{\text{rsa}} \\
pk & \leftarrow (N, e) ; sk \leftarrow (N, d) \\
\text{return } (pk, sk)
\end{align*}$$

$$\begin{align*}
\textbf{Alg } & \mathcal{E}_{pk}(M) \\
C & \leftarrow M^e \ mod \ N \\
\text{return } C
\end{align*}$$

$$\begin{align*}
\textbf{Alg } & \mathcal{D}_{sk}(C) \\
M & \leftarrow C^d \ mod \ N \\
\text{return } M
\end{align*}$$

Getting $sk$ from $pk$ involves factoring $N$.

But $\mathcal{E}$ is deterministic so we can detect repeats and the scheme is not IND-CPA secure.
Let $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be the plain RSA asymmetric encryption scheme associated to RSA generator $\mathcal{K}_{rsa}$. Specify in pseudocode an adversary $A$ making one LR query and achieving $\text{Adv}^{\text{ind-cpa}}_{\mathcal{AE}}(A) = 1$. The messages in the LR query must both be in $\mathbb{Z}_N^*$ (assume they are encoded as strings of some common length), and the running time of $A$ should be $\mathcal{O}(k)$, where $k$ is the security parameter associated to $\mathcal{K}_{rsa}$ and the time taken by game procedures to execute is not counted in the time of $A$. 
Let \( k \) be an integer and let \( \mathcal{K}_{rsa} \) be an RSA generator with associated security parameter \( 8k \). Assume that if \((N, p, q, e, d)\) is an output of \( \mathcal{K}_{rsa} \) then \((p - 1)/2\) and \((q - 1)/2\) are primes larger than \(2^{2k}\). Let \( P \) denote the set of all odd primes smaller than \(2^k\). Consider the key-generation and encryption algorithms below, where the message \( M \) is in \( \mathbb{Z}_N^* \):

**Alg \( \mathcal{K} \)**

\[
(\ N, p, q, e, d) \leftarrow^\$ \mathcal{K}_{rsa} \\
pk \leftarrow N; \ sk \leftarrow (N, p, q) \\
\text{return } (pk, sk)
\]

**Alg \( \mathcal{E}_{pk}(M) \)**

\[
N \leftarrow pk; \ e \leftarrow^\$ P \\
C \leftarrow M^e \mod N \\
\text{return } (C, e)
\]
Exercise, continued

1. Prove that \( P \subseteq \mathbb{Z}_{\varphi(N)}^* \) for any \((N, p, q, e, d)\) output by \( K_{rsa} \).

2. Specify in pseudocode a \( O(k^3) \)-time decryption algorithm \( D \) such that \( AE = (K, E, D) \) is an asymmetric encryption scheme satisfying the correct decryption condition, and prove that this is indeed the case. Your pseudocode should explicitly invoke algorithms from the list in the Computational Number Theory slides and you should use part 1. above.

3. Specify in pseudocode an adversary \( A \) making one \( LR \) query and achieving \( \text{Adv}_{AE}^{\text{ind-cpa}}(A) = 1 \). The messages in the \( LR \) query must both be in \( \mathbb{Z}_{N}^* \), and the running time of \( A \) should be \( O(k) \), where the time taken by game procedures to execute is not counted in the time of \( A \).
The SRSA scheme

Encrypt $M$ unde $pk = N, e$ via:

- $x \leftarrow Z^*_N$; $C_a \leftarrow x^e \mod N$
- $K \leftarrow H(x)$
- $C_s \leftarrow K \oplus M$
- Ciphertext is $(C_a, C_s)$

Decrypt $(C_a, C_s)$ under $sk = N, d$ via:

- $x \leftarrow C_a^d \mod N$
- $K \leftarrow H(x)$
- $M \leftarrow C_s \oplus K$
The SRSA PKE scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ associated to RSA generator $\mathcal{K}_{\text{rsa}}$ and (public) hash function $H: \{0, 1\}^* \rightarrow \{0, 1\}^k$ encrypts $k$-bit messages via:

<table>
<thead>
<tr>
<th>$\text{Alg } \mathcal{K}$</th>
<th>$\text{Alg } \mathcal{E}_{N,e}(M)$</th>
<th>$\text{Alg } \mathcal{D}_{N,d}(C_a, C_s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(N, p, q, e, d) \leftarrow $ \mathcal{K}_{\text{rsa}}$</td>
<td>$x \leftarrow $ \mathbb{Z}_N^*$</td>
<td>$x \leftarrow C_a^d \text{ mod } N$</td>
</tr>
<tr>
<td>$pk \leftarrow (N, e)$</td>
<td>$K \leftarrow H(x)$</td>
<td>$K \leftarrow H(x)$</td>
</tr>
<tr>
<td>$sk \leftarrow (N, d)$</td>
<td>$C_a \leftarrow x^e \text{ mod } N$</td>
<td>$M \leftarrow C_s \oplus K$</td>
</tr>
<tr>
<td>return $(pk, sk)$</td>
<td>$C_s \leftarrow K \oplus M$</td>
<td>return $M$</td>
</tr>
</tbody>
</table>
The SRSA PKE scheme $\mathcal{AE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ associated to RSA generator $\mathcal{K}_{rsa}$ and (public) hash function $H$: $\{0, 1\}^* \rightarrow \{0, 1\}^k$ can be proven IND-CPA assuming

- $\mathcal{K}_{rsa}$ is one-way
- $H$ is a “random oracle,” meaning a “perfect” hash function.

In practice, $H(K)$ could be the first $k$ bits of the sequence

$$\text{SHA256}(0^8\|K)\|\text{SHA256}(0^71\|K)\| \cdots$$
OAEP [BR94]

Receiver keys: $pk = (N, e)$ and $sk = (N, d)$ where $|N| = 1024$
Hash functions: $G: \{0, 1\}^{128} \rightarrow \{0, 1\}^{894}$ and $H: \{0, 1\}^{894} \rightarrow \{0, 1\}^{128}$

**Algorithm $\mathcal{E}_{N,e}(M)$ // $|M| \leq 765$**

$r \leftarrow \{0, 1\}^{128}; p \leftarrow 765 - |M|$

- $128$
  - $r$
- $894$
  - $0^{128} \| M \| 10^p$

- $G$

- $H$

- $s$

- $t$

$x \leftarrow s \| t$
$C \leftarrow x^e \mod N$
return $C$

**Algorithm $\mathcal{D}_{N,d}(C)$ // $C \in \mathbb{Z}_N^*$**

$x \leftarrow C^d \mod N$
$s \| t \leftarrow x$

- $128$
  - $r$
- $894$
  - $a \| M \| 10^p$

- $G$

- $H$

- $s$

- $t$

if $a = 0^{128}$ then return $M$
else return ⊥
RSA OAEP usage

Protocols:

- SSL ver. 2.0, 3.0 / TLS ver. 1.0, 1.1
- SSH ver 1.0, 2.0
- ...

Standards:

- RSA PKCS #1 versions 1.5, 2.0
- IEEE P1363
- NESSIE (Europe)
- CRYPTREC (Japan)
- ...

Daniele Micciancio
Exercise

Let $m, k, \ell$ be integers such that $2 \leq m < k$ and $k \geq 2048$ and $\ell = k - m - 1$ and $\ell$ is even. Let $\mathcal{K}_{\text{rsa}}$ be a RSA generator with associated security parameter $k$. Consider the key-generation and encryption algorithms below, where $M \in \{0, 1\}^m$:

$$\text{Alg} \ \mathcal{K} \quad (N, e, d, p, q) \overset{\$}{\leftarrow} \mathcal{K}_{\text{rsa}} \quad \text{return } ((N, e), (N, d))$$

$$\text{Alg} \ E((N, e), M) \quad \text{Pad} \overset{\$}{\leftarrow} \{0, 1\}^\ell \ ; \ x \leftarrow 0 \ || \ \text{Pad} \ || \ M \quad C \leftarrow x^e \mod N \ ; \ \text{return } C$$

1. Specify a $O(k^3)$-time decryption algorithm $D$ such that $\mathcal{AE} = (\mathcal{K}, E, D)$ is an asymmetric encryption scheme satisfying the correct decryption property.

2. Specify an adversary $A$ making at most $2^{\ell/2}$ queries to its LR oracle and achieving $\text{Adv}^\text{ind-cca}_{\mathcal{AE}} (A) \geq 1/4$. Your adversary should have $O(\ell \cdot 2^{\ell/2})$ running time, not counting the time taken by game procedures to execute.
### PKE summary

<table>
<thead>
<tr>
<th>Scheme</th>
<th>IND-CPA?</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHIES</td>
<td>Yes</td>
</tr>
<tr>
<td>Plain RSA</td>
<td>No</td>
</tr>
<tr>
<td>SRSA</td>
<td>Yes</td>
</tr>
<tr>
<td>RSA OAEP</td>
<td>Yes</td>
</tr>
</tbody>
</table>