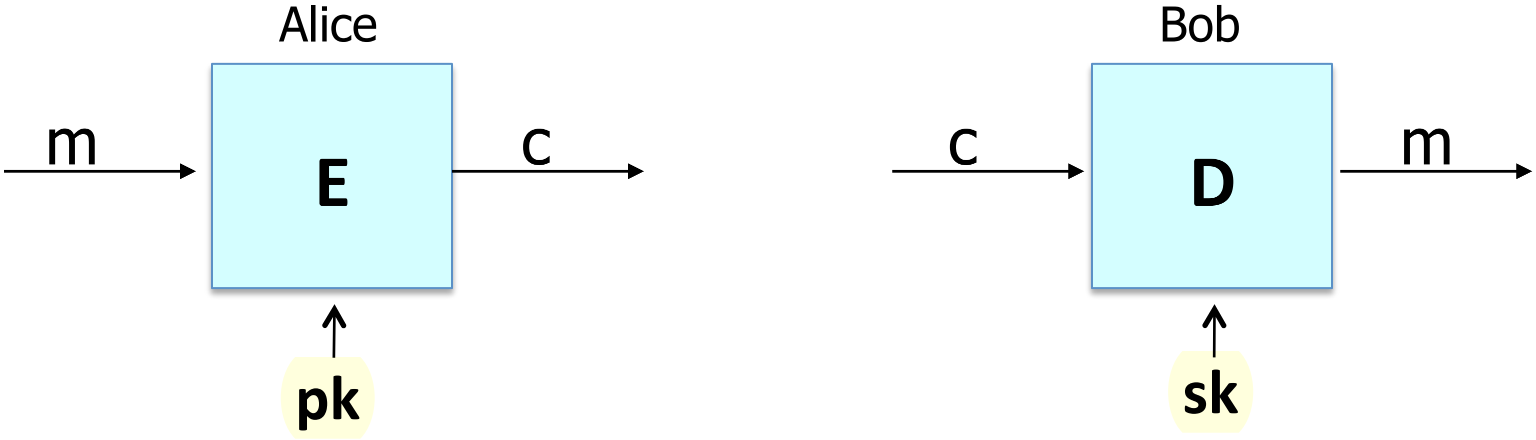
Public Key Encryption from trapdoor permutations

Public key encryption: definitions and security

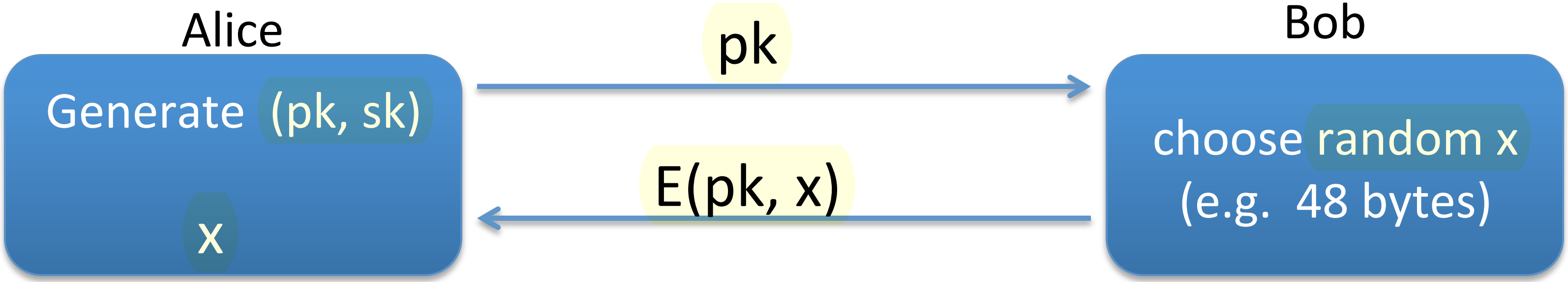
Public key encryption

Bob: generates (PK, SK) and gives PK to Alice



Applications

Session setup (for now, only eavesdropping security)



Alice

Generate (pk, sk)

x

pk

E(pk, x)

Bob

choose random x (e.g. 48 bytes)

Non-interactive applications: (e.g. Email)

- Bob sends email to Alice encrypted using pk_{alice}
- Note: Bob needs pk_{alice} (public key management)

Public key encryption

<u>Def</u>: a public-key encryption system is a triple of algs. (G, E, D)

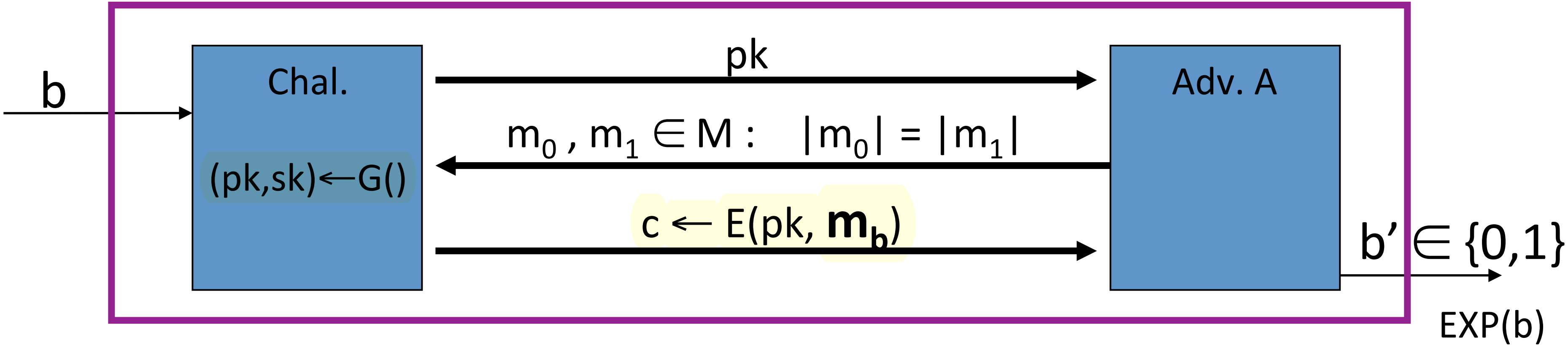
- G(): randomized alg. outputs a key pair (pk, sk)
- E(pk, m): randomized alg. that takes $m \in M$ and outputs $c \in C$
- D(sk,c): det. alg. that takes $c \in C$ and outputs $m \in M$ or $\perp$

Consistency: $\forall$ (pk, sk) output by G :

$\forall m \in M$: D(sk, E(pk, m)) = m

Security: eavesdropping

For b=0,1 define experiments EXP(0) and EXP(1) as:



b
Chal.
(pk,sk)⟵G()
pk
m_0 , $m_1 \in$ M : $|m_0| = |m_1|$
c ⟵ E(pk, $\mathbf{m_b}$)
Adv. A
b' $\in$ {0,1}
EXP(b)

Def: E =(G,E,D) is sem. secure (a.k.a IND-CPA) if for all efficient A:

$$\text{Adv}_{SS}[A,E] = \left| \Pr[\text{EXP}(0)=1] - \Pr[\text{EXP}(1)=1] \right| < \text{negligible}$$

Relation to symmetric cipher security

Recall: for symmetric ciphers we had two security notions:

- One-time security and many-time security (CPA)
- We showed that one-time security $\not\Rightarrow$ many-time security

For public key encryption:

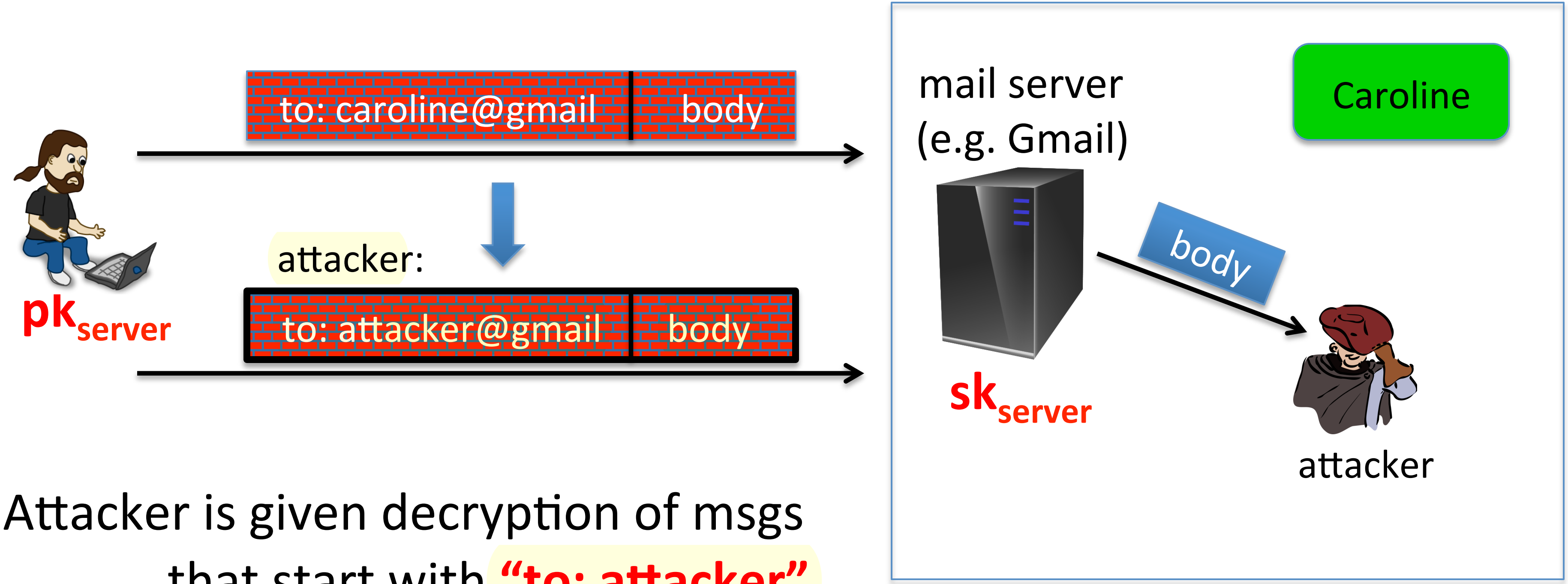
- One-time security ⇒ many-time security (CPA)

  (follows from the fact that attacker can encrypt by himself)

- Public key encryption **must** be randomized

Security against active attacks

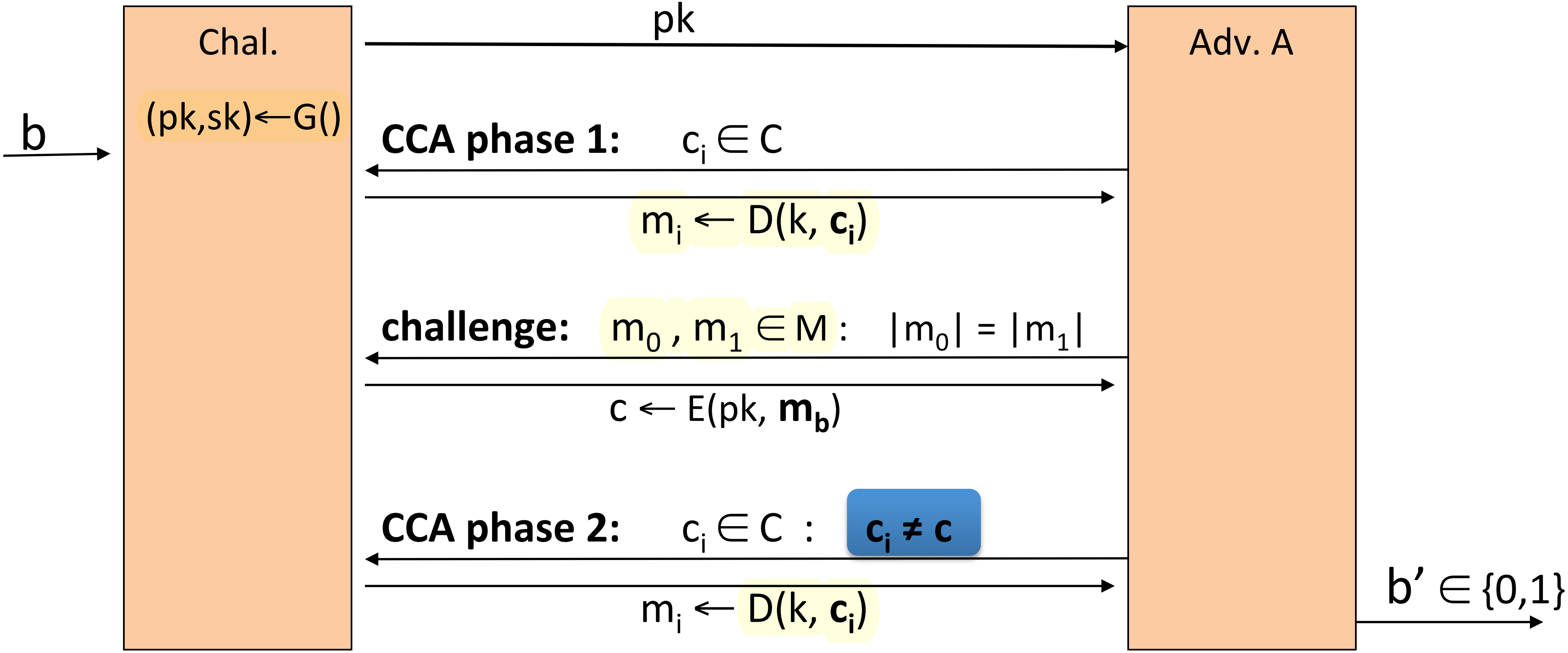
What if attacker can tamper with ciphertext?



Attacker is given decryption of msgs that start with **“to: attacker”**

(pub-key) Chosen Ciphertext Security: definition

$\mathbb{E}$ = (G,E,D) public-key enc. over (M,C). For b=0,1 define EXP(b):



Chal.

Adv. A

pk

b

(pk,sk)⟵G()

CCA phase 1: $c_i \in C$

$m_i \leftarrow D(k, \mathbf{c_i})$

challenge: $m_0 , m_1 \in M$: $|m_0| = |m_1|$

$c \leftarrow E(pk, \mathbf{m_b})$

CCA phase 2: $c_i \in C$: $\mathbf{c_i \neq c}$

$m_i \leftarrow D(k, \mathbf{c_i})$

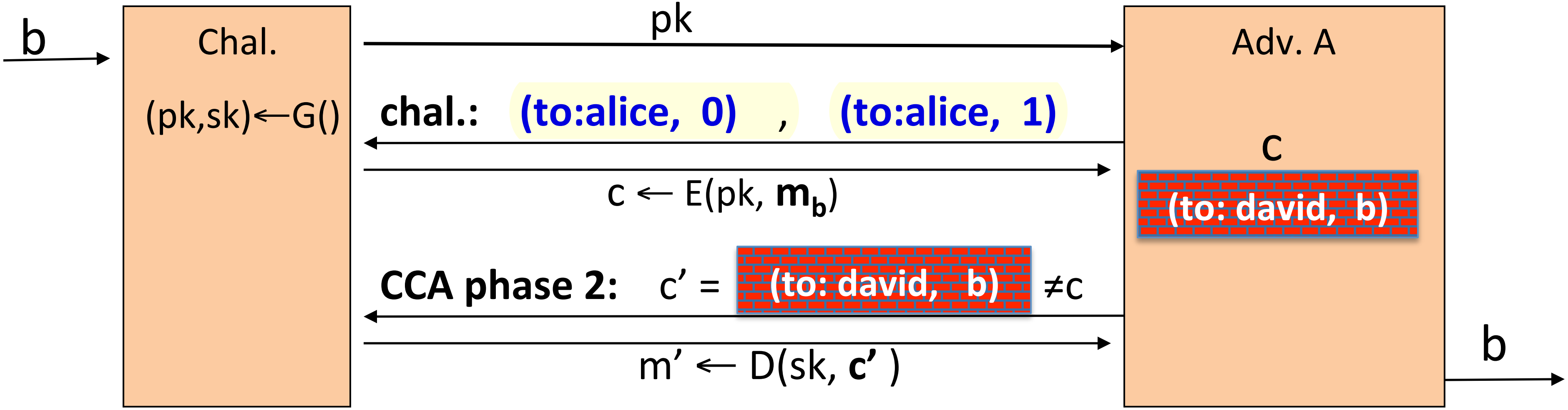
$b' \in \{0,1\}$

Chosen ciphertext security: definition

Def: E is CCA secure (a.k.a IND-CCA) if for all efficient A:

$\mathrm{Adv}_{\mathrm{CCA}}[A,E] = \left| \Pr[\mathrm{EXP}(0)=1] - \Pr[\mathrm{EXP}(1)=1] \right|$ is negligible.

Example: Suppose (to: alice, body) ⟶ (to: david, body)



b

Chal.

(pk,sk)←G()

pk

Adv. A

chal.: (to:alice, 0) , (to:alice, 1)

c

(to: david, b)

$c \leftarrow E(pk, \mathbf{m_b})$

CCA phase 2: c’ = (to: david, b) ≠c

$m' \leftarrow D(sk, \mathbf{c'})$

b

Active attacks: symmetric vs. pub-key

Recall: secure symmetric cipher provides **authenticated encryption**

[chosen plaintext security & ciphertext integrity]

- Roughly speaking: **attacker cannot create new ciphertexts**
- Implies security against chosen ciphertext attacks

In public-key settings:

- Attacker **can** create new ciphertexts using pk !!
- So instead: we directly require chosen ciphertext security

This and next module:

constructing CCA secure pub-key systems

End of Segment

Public Key Encryption from trapdoor permutations

Constructions

Goal: construct chosen-ciphertext secure public-key encryption

Trapdoor functions (TDF)

Def: a trapdoor func. $X \longrightarrow Y$ is a triple of efficient algs. (G, F, F^{-1})

- $G()$: randomized alg. outputs a key pair (pk, sk)
- $F(pk, \cdot)$: det. alg. that defines a function $X \longrightarrow Y$
- $F^{-1}(sk, \cdot)$: defines a function $Y \longrightarrow X$ that inverts $F(pk, \cdot)$

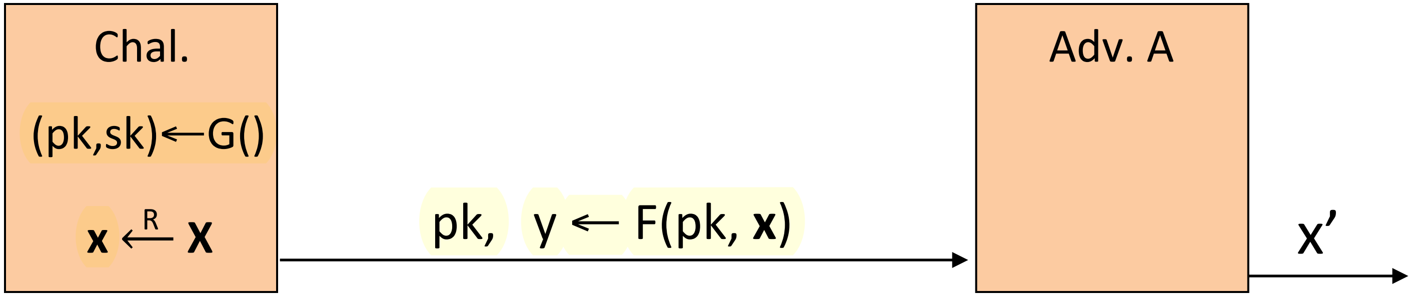
More precisely: $\forall (pk, sk)$ output by G

$$\forall x \in X: \quad F^{-1}(sk, F(pk, x)) = x$$

Secure Trapdoor Functions (TDFs)

(G, F, F^{-1}) is secure if $F(pk, \cdot)$ is a "one-way" function:

can be evaluated, but cannot be inverted without sk



Chal.

$(pk,sk) \leftarrow G()$

$\mathbf{x} \xleftarrow{R} \mathbf{X}$

$pk,\ \ y \leftarrow F(pk, \mathbf{x})$

Adv. A

x'

Def: (G, F, F^{-1}) is a secure TDF if for all efficient A:

$$\mathrm{Adv}_{\mathrm{OW}}[A,F] = \mathbf{Pr[\ x = x'\ ]} < \text{negligible}$$

Public-key encryption from TDFs

- (G, F, F^{-1}): secure TDF $X \longrightarrow Y$
- (E_s, D_s) : symmetric auth. encryption defined over (K,M,C)
- $H: X \longrightarrow K$ a hash function

We construct a pub-key enc. system (G, E, D):

Key generation G: same as G for TDF

Public-key encryption from TDFs

- (G, F, F^{-1}):   secure TDF $X \longrightarrow Y$
- (E_s, D_s) :   symmetric auth. encryption defined over (K,M,C)
- $H: X \longrightarrow K$ a hash function

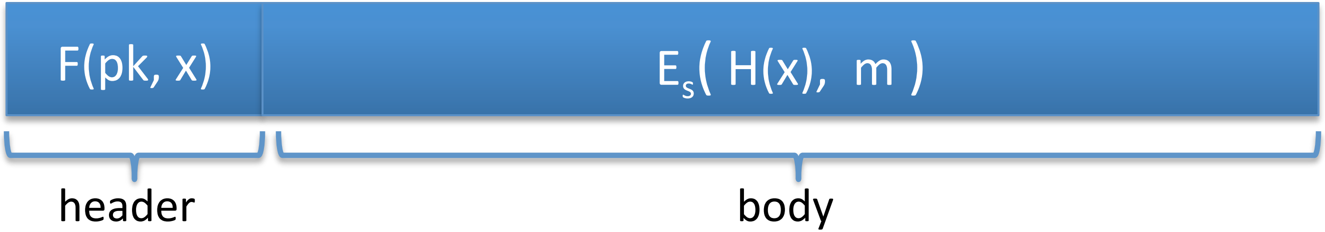
<u>E(pk, m)</u> :

```
    $x \xleftarrow{R} X$,        $y \longleftarrow F(pk, x)$
    $k \longleftarrow H(x)$,    $c \longleftarrow E_s(k, m)$
    output   $(y, c)$
```

<u>D(sk, (y,c))</u> :

```
    $x \longleftarrow F^{-1}(sk, y)$,
    $k \longleftarrow H(x)$,    $m \longleftarrow D_s(k, c)$
    output   $m$
```

In pictures:



$F(pk, x)$

$E_s(\,H(x),\ m\,)$

header

body

<u>Security Theorem</u>:

If **(G, F, $\mathbf{F^{-1}}$)** is a secure TDF, **($\mathbf{E_s}$, $\mathbf{D_s}$)** provides auth. enc.

and **H:** $X \longrightarrow K$ is a "random oracle"

then **(G,E,D)** is $\mathrm{CCA}^{\mathrm{ro}}$ secure.

Incorrect use of a Trapdoor Function (TDF)

Never encrypt by applying F directly to plaintext:

```
E( pk, m) :
    output   c ⟵ F(pk, m)
```

```
D( sk,  c ) :
    output   $F^{-1}$(sk, c)
```

Problems:

- Deterministic: cannot be semantically secure !!
- Many attacks exist   (next segment)

Next step: construct a TDF

End of Segment

Public Key Encryption from trapdoor permutations

The RSA trapdoor permutation

Review: trapdoor permutations

Three algorithms: (G, F, F^{-1})

- G: outputs pk, sk. pk defines a function $F(pk, \cdot): X \rightarrow X$
- $F(pk, x)$: evaluates the function at x
- $F^{-1}(sk, y)$: inverts the function at y using sk

Secure trapdoor permutation:

The function $F(pk, \cdot)$ is one-way without the trapdoor sk

Review: arithmetic mod composites

Let $N = p \cdot q$ where p,q are prime

$Z_N = \{0,1,2,\ldots,N-1\}$; $(Z_N)^*$ = {invertible elements in Z_N}

<u>Facts</u>: $x \in Z_N$ is invertible $\Leftrightarrow$ $\gcd(x,N) = 1$

– Number of elements in $(Z_N)^*$ is $\varphi(N) = (p-1)(q-1) = N-p-q+1$

<u>Euler's thm</u>: $\boxed{\forall\, x \in (Z_N)^* \; : \; x^{\varphi(N)} = 1}$

The RSA trapdoor permutation

First published: Scientific American, Aug. 1977.

Very widely used:

- SSL/TLS: certificates and key-exchange
- Secure e-mail and file systems

… many others

The RSA trapdoor permutation

G(): choose random primes p,q ≈1024 bits. Set **N=pq**.

choose integers **e , d** s.t. $\mathbf{e \cdot d = 1}$ $\mathbf{(\bmod\ \varphi(N)\ )}$

output pk = (N, e) , sk = (N, d)

F(pk, x): $\mathbb{Z}_N^* \to \mathbb{Z}_N^*$; $\mathbf{RSA(x) = x^e}$ (in Z_N)

$\mathbf{F^{-1}(sk, y)} = y^d$; $y^d = \mathbf{RSA(x)^d} = x^{ed} = x^{k\varphi(N)+1} = \left(x^{\varphi(N)}\right)^k \cdot \mathbf{x} =$ x

The RSA assumption

RSA assumption: RSA is one-way permutation

For all efficient algs. A:

$$\Pr\left[\ A(N,e,y) = y^{1/e}\ \right] < \text{negligible}$$

where $p,q \xleftarrow{R}$ n-bit primes, $N \leftarrow pq$, $y \xleftarrow{R} Z_N^*$

Review: RSA pub-key encryption (ISO std)

(E_s, D_s): symmetric enc. scheme providing auth. encryption.

$H: Z_N \rightarrow K$ where K is key space of (E_s, D_s)

- **G**(): generate RSA params: pk = (N,e), sk = (N,d)
- **E**(pk, m):
  (1) choose random x in Z_N
  (2) $y \leftarrow RSA(x) = x^e$, $k \leftarrow H(x)$
  (3) output $(y , E_s(k,m))$
- **D**(sk, (y, c)): output $D_s\big(H\big(RSA^{-1}(y)\big) , c\big)$

Textbook RSA is insecure

Textbook RSA encryption:

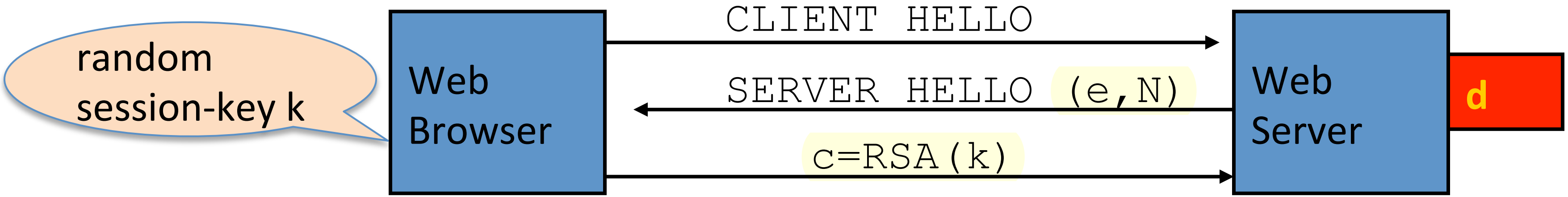
- public key: **(N,e)** Encrypt: $\mathbf{c} \longleftarrow \mathbf{m}^{\mathbf{e}}$ (in Z_N)
- secret key: **(N,d)** Decrypt: $\mathbf{c}^{\mathbf{d}} \longrightarrow \mathbf{m}$

Insecure cryptosystem !!

- Is not semantically secure and many attacks exist

⇒ The RSA trapdoor permutation is not an encryption scheme !

A simple attack on textbook RSA



Suppose k is 64 bits: $k \in \{0,\ldots,2^{64}\}$. Eve sees: $c = k^e$ in Z_N

If $\mathbf{k = k_1 \cdot k_2}$ where $k_1, k_2 < 2^{34}$ (prob. ≈20%) then $\mathbf{c/k_1^e = k_2^e}$ in Z_N

Step 1: build table: $c/1^e, c/2^e, c/3^e, \ldots, c/2^{34e}$. time: 2^{34}

Step 2: for $k_2 = 0,\ldots, 2^{34}$ test if k_2^e is in table. time: 2^{34}

Output matching (k_1, k_2). Total attack time: $\approx 2^{40} << 2^{64}$

End of Segment

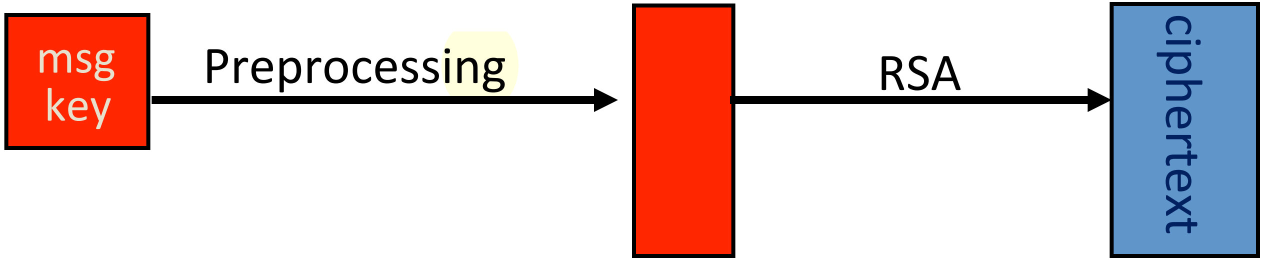
Public Key Encryption from trapdoor permutations

PKCS 1

RSA encryption in practice

Never use textbook RSA.

RSA in practice (since ISO standard is not often used) :

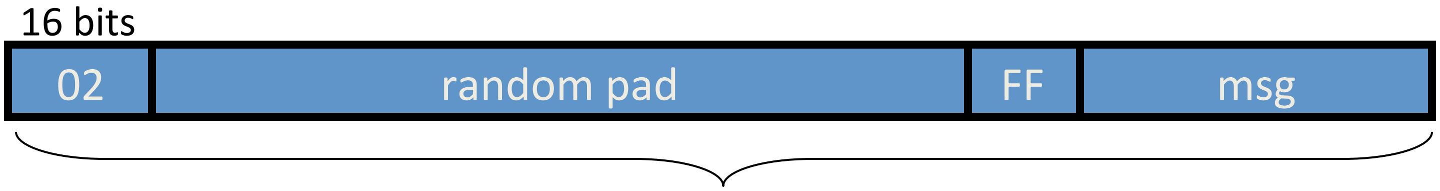


Main questions:

- How should the preprocessing be done?
- Can we argue about security of resulting system?

PKCS1 v1.5

PKCS1 mode 2: (encryption)

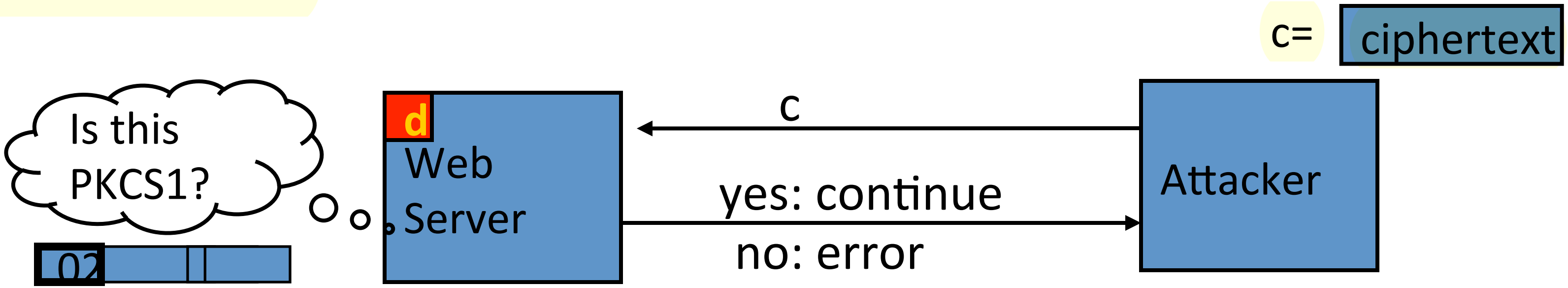


RSA modulus size (e.g. 2048 bits)

- Resulting value is RSA encrypted
- Widely deployed, e.g. in HTTPS

Attack on PKCS1 v1.5 (Bleichenbacher 1998)

PKCS1 used in HTTPS:

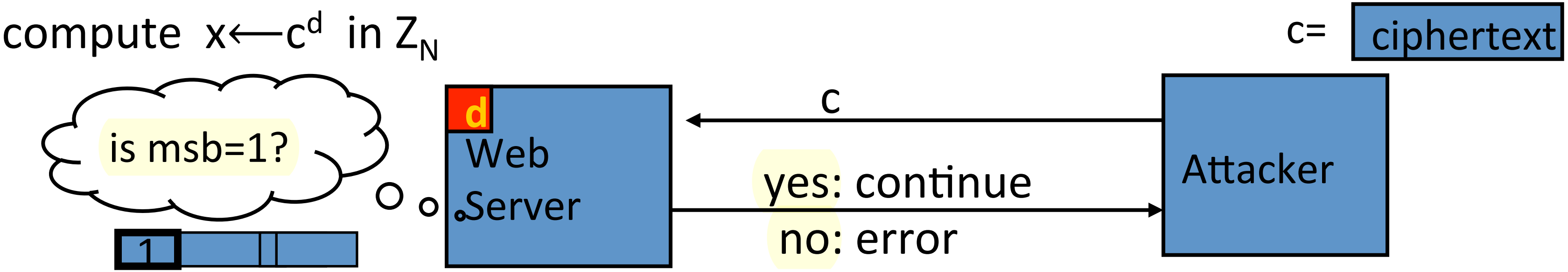


$\Rightarrow$ attacker can test if 16 MSBs of plaintext = '02'

Chosen-ciphertext attack: to decrypt a given ciphertext c do:

- Choose $r \in Z_N$. Compute $c' \leftarrow r^e \cdot c = (r \cdot \text{PKCS1}(m))^e$
- Send c' to web server and use response

Baby Bleichenbacher



Suppose N is $N = 2^n$ (an invalid RSA modulus). Then:

- Sending c reveals msb(x)
- Sending $\mathbf{2^e \cdot c = (2x)^e}$ in Z_N reveals msb(2x mod N) = $\mathbf{msb_2(x)}$
- Sending $\mathbf{4^e \cdot c = (4x)^e}$ in Z_N reveals msb(4x mod N) = $\mathbf{msb_3(x)}$
- … and so on to reveal all of x

HTTPS Defense (RFC 5246)

Attacks discovered by Bleichenbacher and Klima et al. … can be avoided by treating incorrectly formatted message blocks … in a manner indistinguishable from correctly formatted RSA blocks.

In other words:

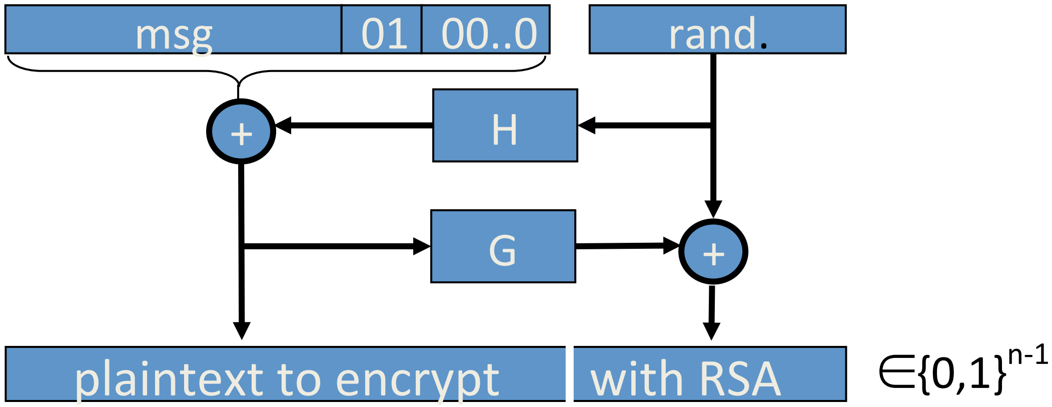
1. *Generate a string **R** of 46 random bytes*
2. *Decrypt the message to recover the plaintext M*
3. *If the PKCS#1 padding is not correct*

   *pre_master_secret = **R***

PKCS1 v2.0: OAEP

New preprocessing function: OAEP [BR94]

check pad
on decryption.
reject CT if invalid.



Thm [FOPS'01] : RSA is a trap-door permutation ⇒
RSA-OAEP is CCA secure when H,G are *random oracles*

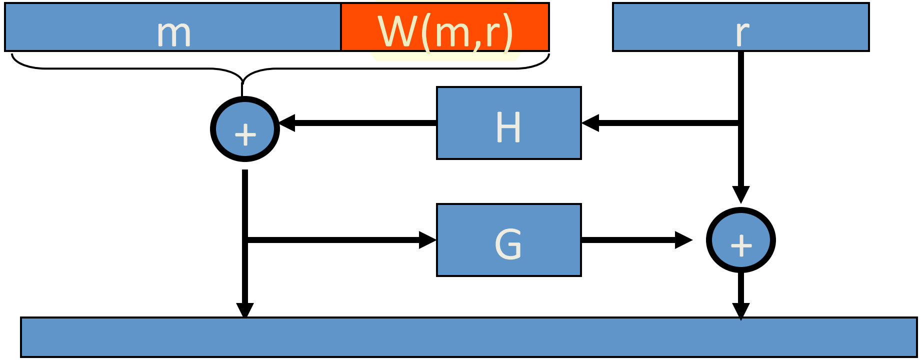
in practice: use SHA-256 for H and G

OAEP Improvements

OAEP+: [Shoup'01]

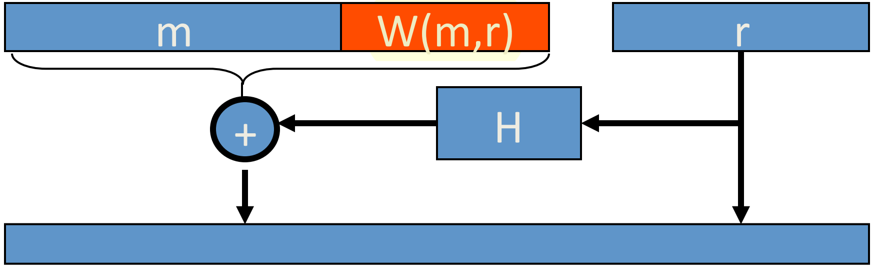
∀ trap-door permutation F
F-OAEP+ is CCA secure when
H,G,W are *random oracles*.

During decryption validate W(m,r) field.

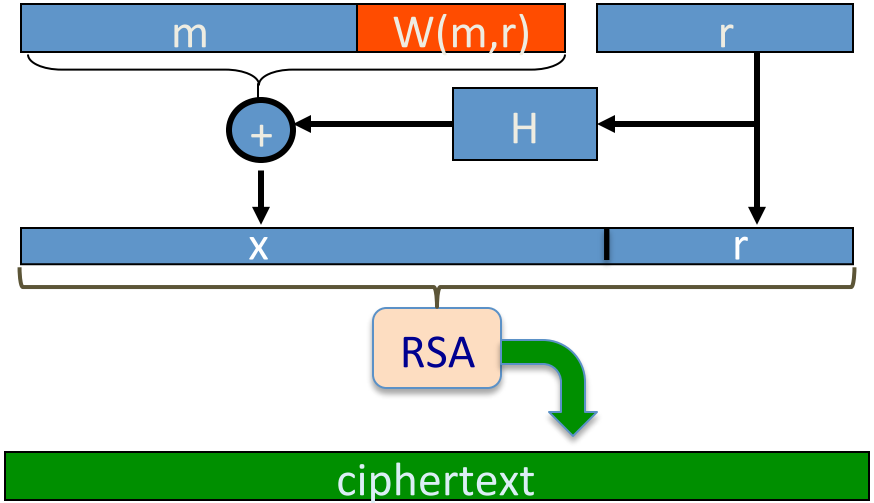


SAEP+: [B'01]

RSA (e=3) is a trap-door perm ⇒
RSA-SAEP+ is CCA secure when
H,W are *random oracle*.



How would you decrypt an SAEP ciphertext **ct** ?



[✓ ○ $(x,r) \longleftarrow \mathrm{RSA}^{-1}(sk,ct)$, $(m,w) \longleftarrow x \oplus H(r)$, output m if $w = W(m,r)$]

○ $(x,r) \longleftarrow \mathrm{RSA}^{-1}(sk,ct)$, $(m,w) \longleftarrow r \oplus H(x)$, output m if $w = W(m,r)$

○ $(x,r) \longleftarrow \mathrm{RSA}^{-1}(sk,ct)$, $(m,w) \longleftarrow x \oplus H(r)$, output m if $r = W(m,x)$

Subtleties in implementing OAEP [M ’00]

```
OAEP-decrypt(ct):
        error = 0;
        ........
        if ( $RSA^{-1}(ct) > 2^{n-1}$ )
            { error =1;  goto exit; }
        ........
        if ( $pad(OAEP^{-1}(RSA^{-1}(ct)))$ != “01000” )
            { error = 1;  goto exit; }
```

Problem: timing information leaks type of error

⇒ Attacker can decrypt any ciphertext

Lesson: Don’t implement RSA-OAEP yourself !

End of Segment

Public Key Encryption from trapdoor permutations

Is RSA a one-way function?

Is RSA a one-way permutation?

To invert the RSA one-way func. (without d) attacker must compute:

x from $c = x^e$ (mod N).

How hard is computing e'th roots modulo N ??

Best known algorithm:

- Step 1: factor N (hard)
- Step 2: compute e'th roots modulo p and q (easy)

Shortcuts?

Must one factor N in order to compute e'th roots?

To prove no shortcut exists show a reduction:

- Efficient algorithm for e'th roots mod N

  ⇒ efficient algorithm for factoring N.

- Oldest problem in public key cryptography.

Some evidence no reduction exists: (BV'98)

- "Algebraic" reduction ⇒ factoring is easy.

How **not** to improve RSA's performance

To speed up RSA decryption use small private key d $(d \approx 2^{128})$

$$\boxed{c^d = m \pmod{N}}$$

Wiener'87: if $d < N^{0.25}$ then RSA is insecure.

BD'98: if $d < N^{0.292}$ then RSA is insecure (open: $d < N^{0.5}$)

<u>Insecure:</u> priv. key d can be found from (N,e)

Wiener's attack

Recall: $e\cdot d = 1 \pmod{\varphi(N)} \Rightarrow \exists\, k\in\mathbb{Z}: \quad e\cdot d = k\cdot\varphi(N) + 1$

$$\left|\frac{e}{\varphi(N)} - \frac{k}{d}\right| = \frac{1}{d\cdot\varphi(N)} \le \frac{1}{\sqrt{N}}$$

$\varphi(N) = N-p-q+1 \Rightarrow |N - \varphi(N)| \le p+q \le 3\sqrt{N}$

$d \le N^{0.25}/3 \Rightarrow$

$$\left|\frac{e}{N} - \frac{k}{d}\right| \le \underbrace{\left|\frac{e}{N} - \frac{e}{\varphi(N)}\right|}_{\le \frac{3\sqrt{N}}{N}\cdot\frac{e}{\varphi(N)} \le \frac{3}{\sqrt{N}} \le \frac{1}{2d^2} - \frac{1}{\sqrt{N}}} + \overbrace{\left|\frac{e}{\varphi(N)} - \frac{k}{d}\right|}^{\le 1/\sqrt{N}} \le \frac{1}{2d^2}$$

$$\frac{1}{2d^2} - \frac{1}{\sqrt{N}} \ge \frac{3}{\sqrt{N}}$$

$\Rightarrow$ Continued fraction expansion of e/N gives k/d.

$e\cdot d = 1 \pmod{k} \Rightarrow \gcd(d,k)=1 \Rightarrow$ can find d from k/d

End of Segment

Public Key Encryption from trapdoor permutations

RSA in practice

RSA With Low public exponent

To speed up RSA encryption use a small e: $c = m^e \pmod{N}$

- Minimum value: **e=3** ($\gcd(e, \varphi(N)) = 1$)
- Recommended value: **$e=65537=2^{16}+1$**

Encryption: 17 multiplications

<u>Asymmetry of RSA:</u> fast enc. / slow dec.

– ElGamal (next module): approx. same time for both.

Key lengths

Security of public key system should be comparable to security of symmetric cipher:

Cipher key-size	RSA Modulus size
80 bits	1024 bits
128 bits	3072 bits
256 bits (AES)	**15360** bits

Implementation attacks

Timing attack: [Kocher et al. 1997] , [BB'04]

The time it takes to compute $c^d \pmod N$ can expose d

Power attack: [Kocher et al. 1999)

The power consumption of a smartcard while it is computing $c^d \pmod N$ can expose d.

Faults attack: [BDL'97]

A computer error during $c^d \pmod N$ can expose d.

A common defense:: check output. 10% slowdown.

An Example Fault Attack on RSA (CRT)

A common implementation of RSA decryption: $x = c^d$ in Z_N

$$\left.\begin{array}{ll} \text{decrypt mod p:} & x_p = c^d \ \text{ in } Z_p \\ \text{decrypt mod q:} & x_q = c^d \ \text{ in } Z_q \end{array}\right\} \text{combine to get } x = c^d \text{ in } Z_N$$

Suppose error occurs when computing x_q, but no error in x_p

Then: output is x' where $x' = c^d$ in Z_p but $x' \neq c^d$ in Z_q

$\Rightarrow$ $(x')^e = c$ in Z_p but $(x')^e \neq c$ in Z_q $\Rightarrow$ $\gcd\big((x')^e - c , N \big) = p$

RSA Key Generation Trouble [Heninger et al./Lenstra et al.]

OpenSSL RSA key generation (abstract):

```
prng.seed(seed)
p = prng.generate_random_prime()
prng.add_randomness(bits)
q = prng.generate_random_prime()
N = p*q
```

Suppose poor entropy at startup:

- Same p will be generated by multiple devices, but different q
- N_1 , N_2 : RSA keys from different devices ⇒ $\gcd(N_1,N_2) = p$

RSA Key Generation Trouble [Heninger et al./Lenstra et al.]

Experiment: factors 0.4% of public HTTPS keys !!

Lesson:

- Make sure random number generator is properly seeded when generating keys

Further reading

- Why chosen ciphertext security matters, V. Shoup, 1998

- Twenty years of attacks on the RSA cryptosystem,
  D. Boneh, Notices of the AMS, 1999

- OAEP reconsidered, V. Shoup, Crypto 2001

- Key lengths, A. Lenstra, 2004

End of Segment