

# Cryptographic Primitives II

Brad Karp  
UCL Computer Science



CS GZ03 / M030  
17<sup>th</sup> November 2017

# Misuses of RSA Break Secrecy

- Example 1: when encrypting, what if plaintext drawn from **very small set** (e.g., {"yes", "no"})?
- Example 2: naïve escrow of encrypted documents for business continuity
- Example 3: **chosen ciphertext attack (CCA)**: eavesdrop a ciphertext  $c$ ; submit specially concocted messages for decryption; study resulting plaintexts; learn plaintext,  $m = c^d \bmod n$

# Misuse of RSA: Naïve Escrow of RSA-Encrypted Messages

- Company wants employees to encrypt their documents with RSA...
- ...but wants to make sure company can decrypt documents after employee fired or dies; ensures business continuity
- Naïve approach:
  - company has public key  $(e, n)$ , requires employees to encrypt their documents in  $(e, n)$  and give to company for storage
  - if employee dies, company decrypts plaintext document, gives to remaining employee

# Misuse of RSA: Naïve Escrow (2)

- Suppose employee A works on top-secret project, has encrypted document encrypted in  $(e, n)$ ; employees E and F want that document, but don't work on that project
- Employee E colludes with employee F as follows:
  - Employee E takes employee A's ciphertext encrypted in company's public key  $(e, n)$ :  
$$c = m^e \bmod n$$
  - Employee E computes  $c' = c^2 \bmod n$ , escrows  $c'$
  - Employee E gets fired (so many ways...)
  - Company releases  $(c^2)^d \bmod n = 2m$  to employee F!

# RSA: Not Quite Exponentiation

- At first glance, RSA operations appear to be raising a message to a power
- But they're not, really...the mod  $n$  means RSA in fact a **trap-door permutation**
  - Map one element,  $m$ , of set  $\{0, \dots, n-1\}$  to another,  $c$
  - Not invertible without knowing  $d$
- Non-invertibility applies to **whole of  $m$  and  $c$ ; not to individual bits of  $m$  and  $c$ , or other properties over  $m$  and  $c$ , e.g., parity of  $m$** 
  - In escrow attack, **multiplicative relationship among RSA ciphertexts exists**, despite non-invertibility
- It's possible that learning even **one bit of  $m$**  may help **recover all of  $m$  from  $c$**

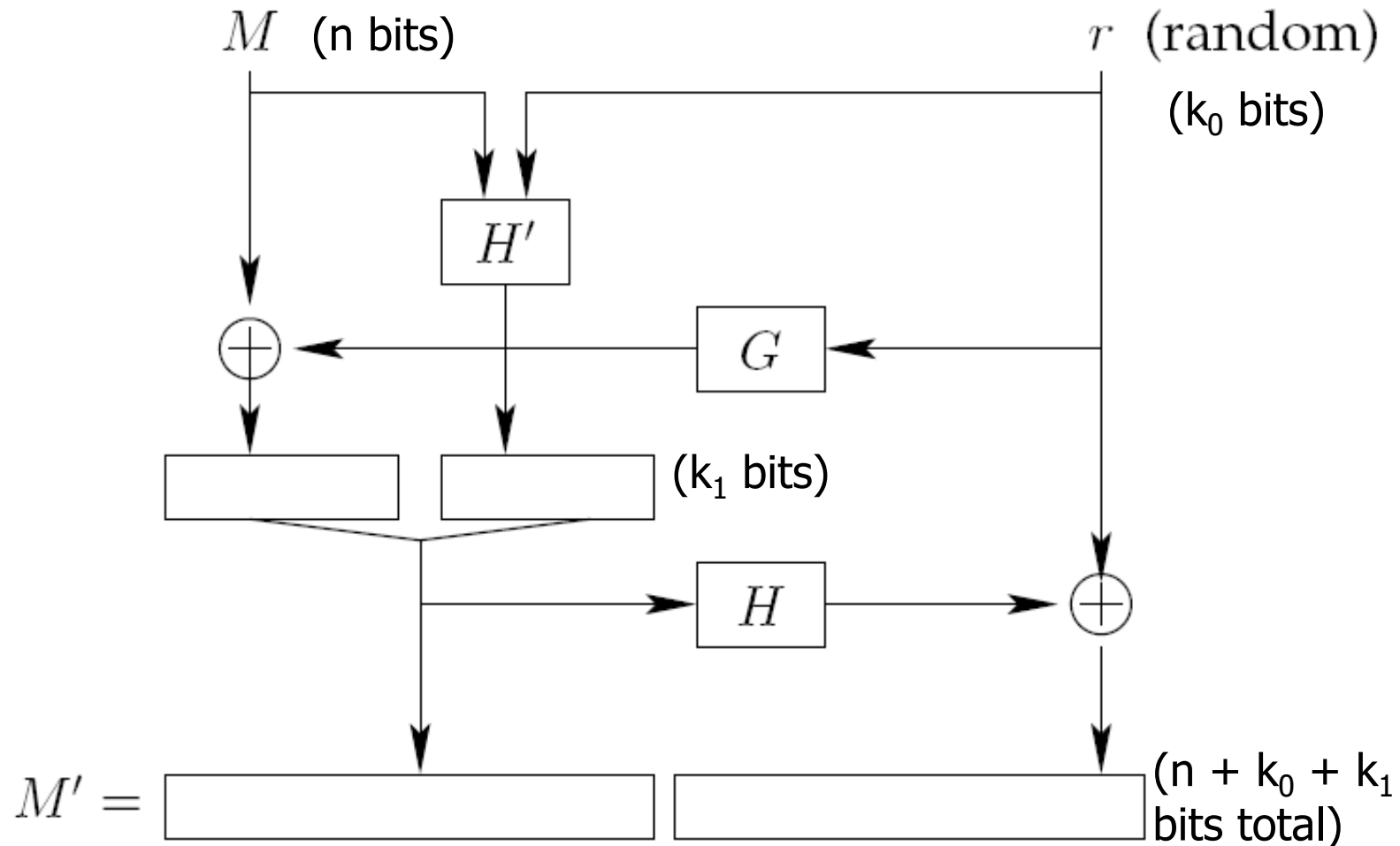
# Adaptive Chosen Ciphertext Attack on RSA in SSL 3.0

- SSL 3.0 encrypted with RSA by padding plaintext into blocks using PKCS #1 standard, as follows:
  - 0x00 | 0x02 |  
8 or more non-zero random bytes | 0x00 |  
plaintext block
- SSL decrypts received ciphertext, checks if result in this format; **returns "format error" if not!**
- Bleichenbacher's **adaptive CCA attack**: with about one million messages to server, attacker can recover  $m$  for previously eavesdropped ciphertext  $c = m^e \bmod n$ 
  - When chosen ciphertext accepted by server, attacker knows first two plaintext bytes with certainty!

# Making RSA Secure Against Adaptive CCA Attacks

- Intuition: want plaintext input to RSA to be **all-or-nothing transform** of actual message
  - e.g., so that multiplicative property over ciphertexts doesn't reveal message, and knowing one bit doesn't reveal anything about whole message
- Desirable transform properties:
  - **Randomness**: unique ciphertext for repeated identical messages
  - **Redundancy**: make most strings invalid ciphertexts
  - **Entanglement**: knowing partial information about input to RSA should reveal nothing about message
  - **Invertibility**: of course, must be able to recover original message when decrypting

# Practical Padding for RSA: OAEP+ [Shoup]



- Transforms  $n$ -bit message  $M$  into  $n+k_0+k_1$ -bit RSA input  $M'$
- Not proven adaptive CCA secure, but heuristically so



# Digital Signatures with RSA

- RSA trap-door permutation also useful for **digital signatures**
- Public-key signature operations:
  - **Sign**:  $S(K^{-1}, m) \rightarrow \{m\}_K^{-1}$
  - **Verify**:  $V(K, \{m\}_K^{-1}, m) \rightarrow \{\text{true}, \text{false}\}$
- Provides **integrity**, like a MAC:
  - Cannot produce valid  $\langle m, \{m\}_K^{-1} \rangle$  pair without knowing  $K^{-1}$
- With RSA:
  - Sign using private key, using trap-door applied when **decrypting**
  - Verify using public key, using permutation applied when **encrypting**

# Multiplicative Attack Against RSA Signatures

- As in CCA, attacker may try to **exploit multiplicative relationship** among RSA permutation inputs and outputs, to decrypt eavesdropped ciphertexts
- Eve stores ciphertext  $c$  encrypted for Alice, wants to recover corresponding  $m$
- Using Alice's public key,  $\{n, e\}$ , Eve:
  - Chooses random number  $r < n$
  - Computes  $y = cr^e \bmod n$
  - Eve asks Alice to sign  $y$
  - Alice sends Eve  $y^d \bmod n = c^d r^{ed} \bmod n = rc^d \bmod n$
  - Eve computes  $r^{-1} \bmod n$ , then recovers  
 **$m = c^d \bmod n = r^{-1}rc^d \bmod n$**

# Multiplicative Attack Against RSA Signatures

- As in CCA, attacker may try to **exploit**

## Lesson:

**Don't sign whole messages presented to you by others!**

- Eve stores ciphertext  $c$  encrypted for Alice, wants to recover corresponding  $m$
- Using Alice's public key,  $\{n, e\}$ , Eve:
  - Chooses random number  $r < n$
  - Computes  $y = cr^e \bmod n$
  - Eve asks Alice to sign  $y$
  - Alice sends Eve  $y^d \bmod n = c^d r^{ed} \bmod n = rc^d \bmod n$
  - Eve computes  $r^{-1} \bmod n$ , then recovers
$$m = c^d \bmod n = r^{-1}rc^d \bmod n$$

# Only Sign Message Hashes with RSA!

- Again, want **all-or-nothing transform** over message before signing with trap door
- **Full-domain hash:**
  - Before signing message, compute hash of message sized to be same number of bits as RSA modulus  $n$
  - Sign the hash, not the message
  - Hash reveals nothing about underlying message, nor messages arithmetically related to it

# Costs of Cryptography

- Public-key operations **significantly more computationally expensive** than symmetric-key ones
- Modern CPU can symmetrically encrypt and MAC **faster than 1 Gbps**
- Public-key encryption typically **100X slower than symmetric crypto**
  - This relationship changes as hardware changes!
- Result: tend to use public-key encryption and signatures only on short messages

# Hybrid Cryptography

- Goal: mix **speed** of symmetric-key **flexibility** of public-key cryptography
- Send symmetric key encrypted with public key; message encrypted with symmetric key

# Pitfall: Public Key Provenance

- Suppose client wishes to know it's talking to particular server
- Where does client get server's public key?
- How does client know it has correct public key for real server, and not **attacker?**
- Man-in-the-middle attack:
  - Client connects to attacker
  - Attacker gives client **attacker's public key**
  - Client believes **communicating with real server**

# Further Reading

- The MIT Guide to Picking Locks
- Menezes, A., van Oorschot, P., and Vanstone, S., *Handbook of Applied Cryptography*,  
<http://www.cacr.math.uwaterloo.ca/hac/>
- Goldwasser, S. and Bellare, M., *Lecture Notes on Cryptography*,  
<http://cseweb.ucsd.edu/~mihir/papers/gb.pdf>
- Bleichenbacher, Daniel, Chosen Ciphertext Attacks Against Protocols Based on the RSA Encryption Standard PKCS #1, in *CRYPTO 1998*