Internet Security

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Side Channel attacks against CRYPTO
General Model

- A
- B
- E
- ??
- public key
- private key
- secret key
- secret key
- public key
General Model
Side Channel Cryptanalysis

Definition: Any attack on a cryptosystem using information leaked given off as a byproduct of the physical implementation of the cryptosystem, rather than a theoretical weakness.

Exploitable side-channels:
- Power usage
- Cache accesses
- Noise
- Heat
- Time
- ...
**Brief History of Timing Attacks**

Timing attacks consider variability in the time taken to perform an encryption due to secret data.

- Paul Kocher demonstrated timing attacks against Diffie-Hellman, RSA, DSS, etc. at CRYPTO ’96
- Dan Boneh, David Brumley demonstrate first *remote* timing attack against RSA in 2003
- Public Key systems are vulnerable due to their use of lengthy mathematical operations
Reading (for this part)


- Many more exist ...
Attacking Cryptographic Schemes

- Cryptanalysis
  - Find mathematical weaknesses in constructions
  - Statistical analysis of plaintext / ciphertext pairs

- Side channel attacks
  - Exploit characteristics of implementations
  - Power analysis
  - Electromagnetic radiation analysis
  - Acoustic analysis
  - Timing analysis
    - Many variants, ...
Timing Attack

- Basic idea: learn the secret key by observing how long it takes to perform various computations.

- Typical goal: extract private key.

- Extremely powerful because isolation doesn’t help:
  - Victim could be remote.
  - Victim could be inside its own virtual machine.
  - Keys could be in tamper-proof storage or smartcard.

- Attacker wins simply by measuring response times.
RSA Cryptosystem

Key generation:
- Generate large (say, 512-bit) primes $p$, $q$
- Compute $n=pq$ and $\varphi(n)=(p-1)(q-1)$
- Choose small $e$, relatively prime to $\varphi(n)$
  - Typically, $e=3$ (may be vulnerable) or $e=2^{16}+1=65537$ (why?)
- Compute unique $d$ such that $e \cdot d = 1 \mod \varphi(n)$
- Public key = $(e, n)$; private key = $d$
  - Security relies on the assumption that it is difficult to compute roots modulo $n$ without knowing $p$ and $q$

Encryption of $m$ (simplified!): $c = m^e \mod n$

Decryption of $c$: $c^d \mod n = (m^e)^d \mod n = m$
How Does RSA Decryption Work?

- RSA decryption: compute $y^x \mod n$
  - This is a modular exponentiation operation

- Naïve algorithm: square and multiply

Let $s_0 = 1$.
For $k = 0$ upto $w - 1$:
  If (bit $k$ of $x$) is 1 then
    Let $R_k = (s_k \cdot y) \mod n$.
  Else
    Let $R_k = s_k$.
  Let $s_{k+1} = R_k^2 \mod n$.
EndFor.
Return $(R_{w-1})$. 
Kocher’s Observation

Let \( s_0 = 1 \).

For \( k = 0 \) upto \( w - 1 \):

- If (bit \( k \) of \( x \)) is 1 then
  - Let \( R_k = (s_k \cdot y) \mod n \).
- Else
  - Let \( R_k = s_k \).

Let \( s_{k+1} = R_k^2 \mod n \).

EndFor.

Return \( (R_{w-1}) \).

Whether iteration takes a long time depends on the \( k^{th} \) bit of secret exponent.

This takes a while to compute.

This is instantaneous.
Outline of Kocher’s Attack

- Idea: guess some bits of the exponent and predict how long decryption will take

- If guess is correct, will observe correlation; if incorrect, then prediction will look random
  - This is a signal detection problem, where signal is timing variation due to guessed exponent bits
  - The more bits you already know, the stronger the signal, thus easier to detect (error-correction property)

- Start by guessing a few top bits, look at correlations for each guess, pick the most promising candidate and continue
RSA in OpenSSL

- OpenSSL is a popular open-source toolkit
  - mod_SSL (in Apache = 28% of HTTPS market)
  - stunnel (secure TCP/IP servers)
  - sNFS (secure NFS)
  - Many more applications

- Kocher’s attack doesn’t work against OpenSSL
  - Instead of square-and-multiply, OpenSSL uses CRT, sliding windows and two different multiplication algorithms for modular exponentiation
    - CRT = Chinese Remainder Theorem
    - Secret exponent is processed in chunks, not bit-by-bit
Chinese Remainder Theorem

- $n = n_1 n_2 \ldots n_k$
  
  where $gcd(n_i, n_j) = 1$ for $i \neq j$

- The system of congruences
  
  $x = x_1 \mod n_1 = \ldots = x_k \mod n_k$
  
  - Has a simultaneous solution $x$ to all congruences
  - There exists exactly one solution $x$ between 0 and $n-1$

- For RSA modulus $n = pq$, to compute $x \mod n$
  it’s enough to know $x \mod p$ and $x \mod q$
RSA Decryption With CRT

- To decrypt \( c \), need to compute \( m = c^d \mod n \)
- Use Chinese Remainder Theorem (why?)
  - \( d_1 = d \mod (p-1) \)
  - \( d_2 = d \mod (q-1) \)
  - \( qinv = q^{-1} \mod p \)
  - \( qinv \) these are precomputed
  - Compute \( m_1 = c^{d_1} \mod p; m_2 = c^{d_2} \mod q \)
  - Compute \( m = m_2 + (qinv \times (m_1 - m_2) \mod p) \times q \)

Attack this computation in order to learn \( q \). This is enough to learn private key (why?)
Montgomery Reduction

- Decryption requires computing \( m_2 = c^{d_2} \mod q \)
- This is done by repeated multiplication
  - Simple: square and multiply (process \( d_2 \) 1 bit at a time)
  - More clever: sliding windows (process \( d_2 \) in 5-bit blocks)
- In either case, many multiplications modulo \( q \)
- Multiplications use Montgomery reduction
  - Pick some \( R = 2^k \)
  - To compute \( x \times y \mod q \), convert \( x \) and \( y \) into their Montgomery form \( xR \mod q \) and \( yR \mod q \)
  - Compute \( (xR \times yR) \times R^{-1} = zR \mod q \)
    - Multiplication by \( R^{-1} \) can be done very efficiently
Schindler’s Observation

- At the end of Montgomery reduction, if \( zR > q \), then need to subtract \( q \)
  - Probability of this extra step is proportional to \( c \mod q \)
- If \( c \) is close to \( q \), a lot of subtractions will be done
- If \( c \mod q = 0 \), very few subtractions
  - Decryption will take longer as \( c \) gets closer to \( q \), then become fast as \( c \) passes a multiple of \( q \)
- By playing with different values of \( c \) and observing how long decryption takes, attacker can guess \( q \! \)
  - Doesn’t work directly against OpenSSL because of sliding windows and two multiplication algorithms
Reduction Timing Dependency

Decryption time

Value of ciphertext $c$

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Integer Multiplication Routines

- 30-40% of OpenSSL running time is spent on integer multiplication

- If integers have the same number of words $n$, OpenSSL uses Karatsuba multiplication
  - Takes $O(n^{\log_2 3})$ (square)

- If integers have unequal number of words $n$ and $m$, OpenSSL uses normal multiplication
  - Takes $O(nm)$ (multiply)
## Summary of Time Dependencies

<table>
<thead>
<tr>
<th>Montgomery effect</th>
<th>$g &gt; q$</th>
<th>$g &lt; q$</th>
</tr>
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<tbody>
<tr>
<td>Longer</td>
<td>Shorter</td>
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<tbody>
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<td>Longer</td>
<td></td>
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</tbody>
</table>

$g$ is the decryption value (same as $c$)

Different effects ... but one will always dominate!
Attack Is Binary Search

Decryption time

Value of ciphertext

$q$

#Reductions

Mult routine

0-1 Gap
Attack Overview

- Initial guess $g$ for $q$ between $2^{511}$ and $2^{512}$ (why?)
- Try all possible guesses for the top few bits
- Suppose we know $i-1$ top bits of $q$. Goal: $i^{th}$ bit
  - Set $g = \ldots$ known $i-1$ bits of $q \ldots 000000$
  - Set $g_{hi} = \ldots$ known $i-1$ bits of $q \ldots 100000$ (note: $g < g_{hi}$)
    - If $g < q < g_{hi}$ then the $i^{th}$ bit of $q$ is 0
    - If $g < g_{hi} < q$ then the $i^{th}$ bit of $q$ is 1
- Goal: decide whether $g < q < g_{hi}$ or $g < g_{hi} < q$
Two Possibilities for $g_{hi}$

Difference in decryption times between $g$ and $g_{hi}$ will be small
Timing Attack Details

- What is “large” and “small”?  
  - Know from attacking previous bits

- Decrypting just $g$ does not work because of sliding windows  
  - Decrypt a neighborhood of values near $g$  
  - Will increase difference between large and small values, resulting in larger 0-1 gap

- Attack requires only 2 hours, about 1.4 million queries to recover the private key  
  - Only need to recover most significant half bits of $q$
The 0-1 Gap
Extracting RSA Private Key

Montgomery reduction dominates

Zero-one gap

Multiplication routine dominates
Normal SSL Handshake

1. ClientHello
2. ServerHello (send public key)
3. ClientKeyExchange (encrypted under public key)

Exchange data encrypted with new shared key
Attacking SSL Handshake

1. ClientHello
2. ServerHello (send public key)
3. Record time $t_1$  
   Send guess $g$ or $g_{hi}$
4. Alert
5. Record time $t_2$  
   Compute $t_2 - t_1$
Works On The Network

Similar timing on WAN vs. LAN
Defenses

- Good: Use RSA blinding
- Worse: Require statically that all decryptions take the same time
  - For example, always do the extra "dummy" reduction
  - ... but what if compiler optimizes it away?
- Worse: Dynamically make all decryptions the same or multiples of the same time "quantum"
  - Now all decryptions have to be as slow as the slowest decryption
RSA Blinding

- Instead of decrypting ciphertext $c$, decrypt a random ciphertext related to $c$
  - Compute $x' = c^r \mod n$, $r$ is random
  - Decrypt $x'$ to obtain $m'$
    - Calculate original plaintext $m = m'/r \mod n$

- Since $r$ is random, decryption time is random
- 2–10% performance penalty
Blinding Works
Thank you for your attention!

Questions?
Papers to read for next lecture

- Whatever you can find about RSA ...