Timing Attacks and Countermeasures

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June 10, 2016

Summer school on real-world crypto and privacy
Šibenik, Croatia
Secure Crypto

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- AES-256 block cipher
- AES-CBC + HMAC-SHA256 authenticated encryption
- RSA-2048 public-key encryption
- ECDSA signatures with the secp256k1 curve (used in Bitcoin)
Secure Crypto?

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Those attacks all don’t break the math!
Timing Attacks

General idea of those attacks

- Secret data has influence on timing of software
- Attacker measures timing
- Attacker computes influence\(^{-1}\) to obtain secret data
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Two kinds of remote...

- Timing attacks are a type of side-channel attacks
- Unlike other side-channel attacks, they work remotely:
  - Some need to run attack code in parallel to the target software
  - Attacker can log in remotely (ssh)
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  - Some attacks work by measuring network delays
  - Attacker does not even need an account on the target machine
- Can’t protect against timing attacks by locking a room
if(secret)
{
    do_A();
}
else
{
    do_B();
}
Square-and-multiply

- Core operation in RSA decryption: \( a^d \mod n \) with secret key \( d \)
- Very similar operation involved in ElGamal, DSA, and ECC

```c
typedef unsigned long long uint64;
typedef uint32_t uint32;

/* This really wants to be done with long integers */
uint32 modexp(uint32 a, uint32 mod, const unsigned char exp[4])
{
    int i,j;
    uint32 r = 1;
    for(i=3;i>=0;i--)
    {
        for(j=7;j>=0;j--)
        {
            r = ((uint64)r*r) % mod;
            if((exp[i] >> j) & 1)
                r = ((uint64)a*r) % mod;
        }
    }
    return r;
}
```
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Square-and-multiply-always

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        for (j = 7; j >= 0; j--) {
            r = ((uint64)r * r) % mod;
            if (((exp[i] >> j) & 1)
                r = ((uint64)a * r) % mod;
            else
                t = ((uint64)a * r) % mod;
        }
    }
    return r;
}

Compiler may optimize else clause away, but can avoid that
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            else
                t = ((uint64)a*r) % mod;
        }
    }
    return r;
}

- Compiler may optimize else clause away, but can avoid that
- Still not constant time, reasons:
  - Branch prediction
  - Instruction cache
Eliminating branches

- So, what do we do with code like this?

```plaintext
if s then
  r ← A
else
  r ← B
end if
```
Eliminating branches

- So, what do we do with code like this?
  
  ```
  if \( s \) then
    r ← A
  else
    r ← B
  end if
  ```

- Replace by

  \[
  r ← sA + (1 - s)B
  \]
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  ```c
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- Can expand \( s \) to all-one/all-zero mask and use XOR instead of addition, AND instead of multiplication
Eliminating branches

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```

▷ Can expand $s$ to all-one/all-zero mask and use XOR instead of addition, AND instead of multiplication

▷ For very fast $A$ and $B$ this can even be faster
Fixing Square-and-multiply-always

```c
uint32 modexp(uint32 a, uint32 mod, const unsigned char exp[4]) {
    int i,j;
    uint32 r = 1, t;
    for(i=3;i>=0;i--) {
        for(j=7;j>=0;j--) {
            r = ((uint64)r*r) % mod;
            t = ((uint64)a*r) % mod;
            cmov(&r, &t, (exp[i] >> j) & 1);
        }
    }
    return r;
}
```
void cmov(uint32 *r, const uint32 *a, uint32 b)
{
    uint32 t;

    b = -b; /* Now b is either 0 or 0xffffffff */
    t = (*r ^ *a) & b;
    *r ^= t;
}
Problem No. 2

table[secret]
The Advanced Encryption Standard (AES)

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- AES with \( n \) rounds uses \( n + 1 \) 16-byte rounds keys \( K_0, \ldots, K_n \)
- Four operations per round: SubBytes, ShiftRows, MixColumns, and AddRoundKey
- Last round does not have MixColumns
Implementing AES on 32-bit machines

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The first round of AES in C

- Input: 32-bit integers $y_0, y_1, y_2, y_3$
- Output: 32-bit integers $z_0, z_1, z_2, z_3$
- Round keys in 32-bit-integer array $rk[44]$

```
z0 = T0[ y0 >> 24 ] ^ T1[(y1 >> 16) & 0xff] ^ T2[(y2 >> 8) & 0xff] ^ T3[ y3 & 0xff] ^ rk[4];
z1 = T0[ y1 >> 24 ] ^ T1[(y2 >> 16) & 0xff] ^ T2[(y3 >> 8) & 0xff] ^ T3[ y0 & 0xff] ^ rk[5];
z2 = T0[ y2 >> 24 ] ^ T1[(y3 >> 16) & 0xff] ^ T2[(y0 >> 8) & 0xff] ^ T3[ y1 & 0xff] ^ rk[6];
z3 = T0[ y3 >> 24 ] ^ T1[(y0 >> 16) & 0xff] ^ T2[(y1 >> 8) & 0xff] ^ T3[ y2 & 0xff] ^ rk[7];
```
Cache-timing attacks

- AES and the attackers program run on the same CPU
- Tables are in cache
## Cache-timing attacks

- AES and the attackers program run on the same CPU
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- The attacker’s program replaces some cache lines

<table>
<thead>
<tr>
<th>T0[0] ... T0[15]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0[16] ... T0[31]</td>
</tr>
<tr>
<td>attacker’s data</td>
</tr>
<tr>
<td>attacker’s data</td>
</tr>
<tr>
<td>T0[64] ... T0[79]</td>
</tr>
<tr>
<td>T0[80] ... T0[95]</td>
</tr>
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<td>attacker’s data</td>
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<td>T0[160] ... T0[175]</td>
</tr>
<tr>
<td>T0[176] ... T0[191]</td>
</tr>
<tr>
<td>T0[192] ... T0[207]</td>
</tr>
<tr>
<td>T0[208] ... T0[223]</td>
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- Tables are in cache
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- AES continues, loads from table again
- Attacker loads his data:
  - Fast: cache hit (AES did not just load from this line)
  - Slow: cache miss (AES just loaded from this line)
The general case

Loads from and stores to addresses that depend on secret data leak secret data.
“Countermeasure”

- Observation: This simple *cache-timing attack* does not reveal the secret address, only the cache line
- Idea: Lookups *within one cache line* should be safe
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- Yarom, Genkin, Heninger: CacheBleed attack “is able to recover both 2048-bit and 4096-bit RSA secret keys from OpenSSL 1.0.2f running on Intel Sandy Bridge processors after observing only 16,000 secret-key operations (decryption, signatures).”
uint32 table[TABLE_LENGTH];

uint32 lookup(size_t pos)
{
    size_t i;
    int b;
    uint32 r = table[0];
    for(i=1;i<TABLE_LENGTH;i++)
    {
        b = (i == pos);
        cmov(&r, &table[i], b);
    }
    return r;
}
Countermeasure

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{
    size_t i;
    int b;
    uint32 r = table[0];
    for(i=1;i<TABLE_LENGTH;i++)
    {
        b = (i == pos); /* DON’T! Compiler may do funny things! */
        cmov(&r, &table[i], b);
    }
    return r;
}
uint32 table[TABLE_LENGTH];

uint32 lookup(size_t pos)
{
    size_t i;
    int b;
    uint32 r = table[0];
    for(i=1;i<TABLE_LENGTH;i++)
    {
        b = isequal(i, pos);
        cmov(&r, &table[i], b);
    }
    return r;
}
int isequal(uint32 a, uint32 b) {
    size_t i; uint32 r = 0;
    unsigned char *ta = (unsigned char *)&a;
    unsigned char *tb = (unsigned char *)&b;
    for(i=0;i<sizeof(uint32);i++)
    {
        r |= (ta[i] ^ tb[i]);
    }
    r = (-r) >> 31;
    return (int)(1-r);
}
How could AES be chosen?

“Table lookup: not vulnerable to timing attacks; relatively easy to effect a defense against power attacks by software balancing of the lookup address.”

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- Intel’s answer: let’s do it in hardware (AES-NI, since Westmere)
- ARM’s answer: let’s do it in hardware (crypto extension in ARMv8)
- Solutions in software:
  - AES with vector-permute instructions (Hamburg, 2009)
  - Bitslicing (Biham, 1997, for DES)
Bitslicing

- Imagine registers that have only one bit
- Perform arithmetic on those registers using XOR, AND, OR
- Essentially the same as hardware implementations
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- But wait, registers are longer!
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- Perform the simulated hardware implementations on many independent data streams
- Bitslicing works for every algorithm
- Bitslicing is inherently protected against timing attacks
- Efficient bitslicing needs a huge amount of data-level parallelism
Bitslicing binary polynomials

4-coefficient binary polynomials
\((a_3x^3 + a_2x^2 + a_1x + a_0), \text{ with } a_i \in \{0, 1\}\)

4-coefficient bitsliced binary polynomials

typedef unsigned char poly4; /* 4 coefficients in the low 4 bits */
typedef unsigned long long poly4x64[4];

void poly4_bitslice(poly4x64 r, const poly4 x[64])
{
    int i, j;
    for(i=0; i<4; i++)
    {
        r[i] = 0;
        for(j=0; j<64; j++)
            r[i] |= (unsigned long long)(1 & (x[j] >> i))<<j;
    }
}
typedef unsigned long long poly4x64[4];
typedef unsigned long long poly7x64[7];

void poly4x64_mul(poly7x64 r, const poly4x64 a, const poly4x64 b) {
    r[0] = a[0] & b[0];
    r[1] = (a[0] & b[1]) ^ (a[1] & b[0]);
    r[2] = (a[0] & b[2]) ^ (a[1] & b[1]) ^ (a[2] & b[0]);
}
Sorting and permuting

- So far:
  - Generic technique to eliminate branches
  - Generic technique to eliminate secretly indexed lookups
  - Bitslicing as generic technique to “hardwarize” software implementations
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Standard algorithms use **lots of** branches or memory access
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Naively applying our generic techniques can even result in terribly inefficient running time for simple, every-day tasks!
Expanding our toolbox

A sorting network sorts an array $S$ of elements by using a fixed sequence of comparators.

- A comparator can be expressed by a pair of indices $(i, j)$.
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- Efficient sorting network: Batcher sort (Batcher, 1968)

Batcher sorting network for sorting 8 elements

http://en.wikipedia.org/wiki/Batcher%27s_sort
The comparison operator...

- Intuition of sorting: use $c(v_i, v_j) = v_i > v_j$ operator
- Can use different comparison operator
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- Random permutation: sort tuples $(v_i, r_i)$ by $r_i$
- Example of arbitrary permutation:

  Computing $b_3, b_2, b_1$ from $b_1, b_2, b_3$ can be done by sorting the key-value pairs $(3, b_1), (2, b_2), (1, b_3)$ the output is $(1, b_3), (2, b_2), (3, b_1)$
The comparison operator...

- Intuition of sorting: use $c(v_i, v_j) = v_i > v_j$ operator
- Can use different comparison operator
- Random permutation: sort tuples $(v_i, r_i)$ by $r_i$
- Example of arbitrary permutation:

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- Pick values $< 61445$: use $c(v_i, v_j) = v_i \geq 61445$
Is that all?

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- Can *always* be done; cost highly depends on the algorithm
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“So the argument to the \texttt{DIV} instruction was smaller and \texttt{DIV}, on Intel, takes a variable amount of time depending on its arguments!”

—Langley, Feb. 2013
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- DIV, IDIV, FDIV on pretty much all Intel/AMD CPUs
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Timing Attacks and Countermeasures
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Solution

- Avoid these instructions
- Make sure that inputs to the instructions don’t leak timing information
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Questions?

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