Timing Attacks and Countermeasures

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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)

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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
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Two kinds of remote...

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- Unlike other side-channel attacks, they work remotely:
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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

Problem No. 1

```
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

```
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;
}
```

Square-and-multiply-always

```
/* This really wants to be done with long integers */
uint32 modexp(uint32 a, uint32 mod, const unsigned char exp[4]) {
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    }
  }
  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?

  if s **then**
  $r \leftarrow A$
  else
  $r \leftarrow B$
  end if

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$$r \leftarrow sA + (1 - s)B$$

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$$r \leftarrow sA + (1 - s)B$$

- 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

```
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;
}
```

cmov

```
/* decision bit b has to be either 0 or 1 */
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

"The different steps of the round transformation can be combined in a single set of table lookups, allowing for very fast implementations on processors with word length 32 or above."

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The first round of AES in C

- Input: 32-bit integers `y0`, `y1`, `y2`, `y3`
- Output: 32-bit integers `z0`, `z1`, `z2`, `z3`
- Round keys in 32-bit-integer array `rk[44]`

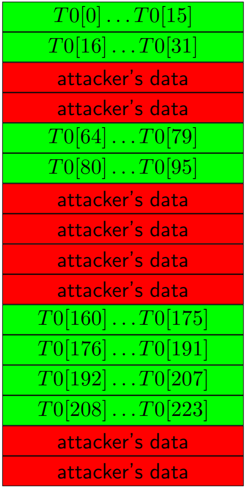
```
z0 = T0[ y0 >> 24        ] ^ T1[(y1 >> 16) & 0xff] \
   ^ T2[(y2 >>  8) & 0xff] ^ T3[ y3        & 0xff] ^ rk[4];
z1 = T0[ y1 >> 24        ] ^ T1[(y2 >> 16) & 0xff] \
   ^ T2[(y3 >>  8) & 0xff] ^ T3[ y0        & 0xff] ^ rk[5];
z2 = T0[ y2 >> 24        ] ^ T1[(y3 >> 16) & 0xff] \
   ^ T2[(y0 >>  8) & 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

$T0[0] \dots T0[15]$
$T0[16] \dots T0[31]$
$T0[32] \dots T0[47]$
$T0[48] \dots T0[63]$
$T0[64] \dots T0[79]$
$T0[80] \dots T0[95]$
$T0[96] \dots T0[111]$
$T0[112] \dots T0[127]$
$T0[128] \dots T0[143]$
$T0[144] \dots T0[159]$
$T0[160] \dots T0[175]$
$T0[176] \dots T0[191]$
$T0[192] \dots T0[207]$
$T0[208] \dots T0[223]$
$T0[224] \dots T0[239]$
$T0[240] \dots T0[255]$

- AES and the attackers program run on the same CPU
- Tables are in cache

Cache-timing attacks



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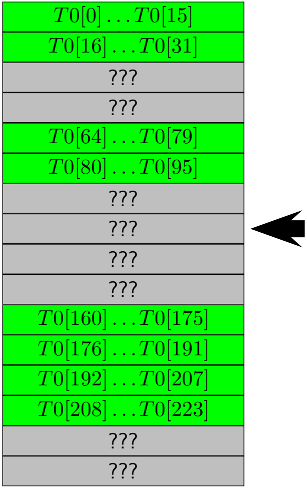

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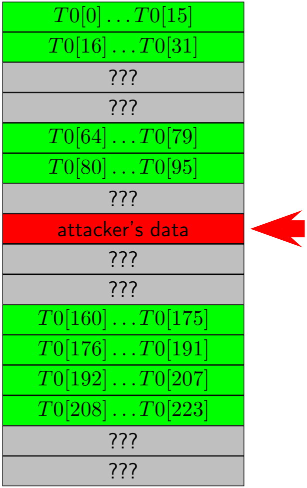

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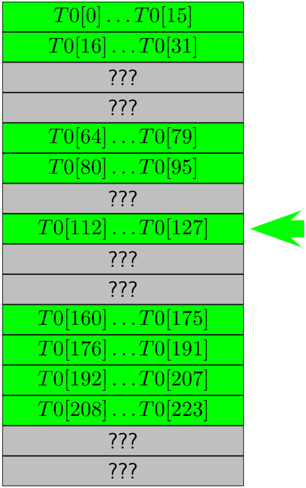

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- The attacker's program replaces some cache lines
- AES continues, loads from table again
- Attacker loads his data:
  - Fast: cache hit (AES did not just load from this line)
  - Slow: cache miss (AES just loaded from this line)

The general case

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

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- Observation: This simple *cache-timing attack* does not reveal the secret address, only the cache line
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Countermeasure

```
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;
}
```

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

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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;
}
```

Countermeasure, part 2

```
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);
}
```

Back to AES

How could AES be chosen?

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- It's horribly inefficient
- 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
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- Perform the simulated hardware implementations on many independent data streams

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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

$(a_3x^3 + a_2x^2 + a_1x + a_0)$, 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;
  }
}
```

Bitsliced binary-polynomial multiplication

```
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]);
  r[3] = (a[0] & b[3]) ^ (a[1] & b[2]) ^ (a[2] & b[1]) ^ (a[3] & b[0]);
  r[4] = (a[1] & b[3]) ^ (a[2] & b[2]) ^ (a[3] & b[1]);
  r[5] = (a[2] & b[3]) ^ (a[3] & b[2]);
  r[6] = (a[3] & b[3]);
}
```

Sorting and permuting

- So far:
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  - Generic technique to eliminate secretly indexed lookups
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- Take integer array of length 1024, sort it

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Funny problems

- Take integer array of length 1024, sort it
- Compute random permutation of $\{0, \ldots, 1023\}$

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- Take integer array of length 1024, sort it
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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).
- A comparator swaps $S[i]$ and $S[j]$ if $S[i] > S[j]$.

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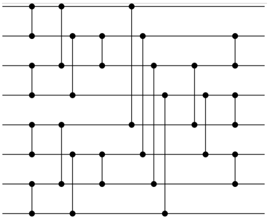
- Efficient sorting network: Batcher sort (Batcher, 1968)



Batcher sorting network for sorting 8 elements
http://en.wikipedia.org/wiki/Batcher%27s_sort

The comparison operator...

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

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"So the argument to the `DIV` instruction was smaller and `DIV`, on Intel, takes a variable amount of time depending on its arguments!"

—Langley, Feb. 2013

Dangerous arithmetic (examples)

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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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