Eliminating Timing Side-Channels.
A Tutorial.

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Secure Crypto

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- 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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  - Attacker can log in remotely (ssh)
  - 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();
}
```

Exponentiation

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

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- $105 = 1 \cdot 2^6 + 1 \cdot 2^5 + 0 \cdot 2^4 + 1 \cdot 2^3 + 0 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0$

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- $105 = ((((((((((1 \cdot 2 + 1) \cdot 2) + 0) \cdot 2) + 1) \cdot 2) + 0) \cdot 2) + 0) \cdot 2) + 1$ (Horner's rule)
- $a^{105} = ((((((((((a^2 \cdot a)^2) \cdot 1)^2) \cdot a)^2) \cdot 1)^2) \cdot 1)^2) \cdot a$

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- $a^{105} = ((((((((((a^2 \cdot a)^2) \cdot 1)^2) \cdot a)^2) \cdot 1)^2) \cdot 1)^2) \cdot a$
- Cost: 6 squarings, 3 multiplications
- More generally: 1 squaring per bit, 1 multiplication per 1-bit

Square-and-multiply

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

/* This really wants to be done with long integers */
uint32 modexp(uint32 a, uint32 mod, 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] & (1<<j))
        r = ((uint64)a*r) % mod;
    }
  }
  return r;
}
```

Square-and-multiply-always

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

- 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**
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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

```
uint32 modexp(uint32 a, uint32 mod, 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] & (1<<j)) >> j);
    }
  }
  return r;
}
```

cmov

```
/* decision bit b has to be either 0 or 1 */
void cmov(uint32 *r, 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]`

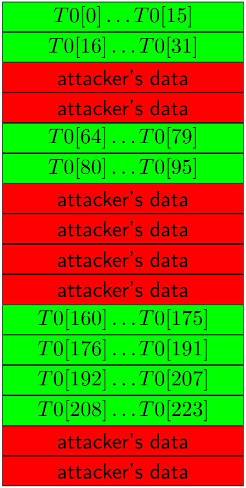
```
z0 = T0[ y0 >> 24       ] ^ T1[(y1 >> 16) & 0xff] \
   ^ T2[(y2 >>  8) & 0xff] ^ T3[ y3        & 0xff] ^ rk[4];
z1 = T0[ y1 >> 24       ] ^ T1[(y2 >> 16) & 0xff] \
   ^ T2[(y3 >>  8) & 0xff] ^ T3[ y0        & 0xff] ^ rk[5];
z2 = T0[ y2 >> 24       ] ^ T1[(y3 >> 16) & 0xff] \
   ^ T2[(y0 >>  8) &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

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

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

Cache-timing attacks



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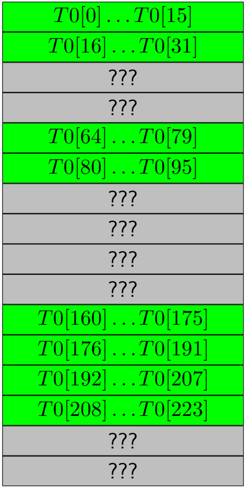

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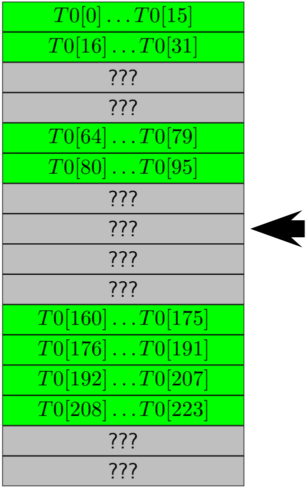

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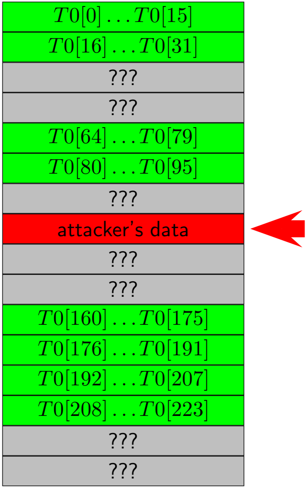

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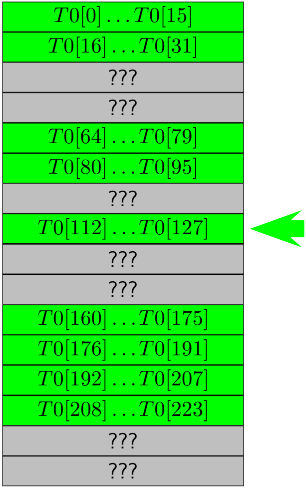

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- The attacker's program replaces some cache lines
- AES continues, loads from table again
- Attacker loads his data:
  - Fast: cache hit (AES did not just load from this line)
  - Slow: cache miss (AES just loaded from this line)

The general case

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

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- Bernstein, Schwabe, 2013: Demonstrate timing variability for access within one cache line
- TODO: Real attack against, e.g., OpenSSL

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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  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;
}
```

Countermeasure

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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

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- 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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- Think of them as vectors of bits
- 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]);
}
```

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- Avoid all data flow from secrets to branch conditions and memory addresses
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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)

- `DIV`, `IDIV`, `FDIV` on pretty much all Intel/AMD CPUs
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Solution

- Avoid these instructions
- Make sure that inputs to the instructions don't leak timing information

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