# Timing Attacks and Countermeasures

Peter Schwabe

June 10, 2016

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

# Secure Crypto

Research over the past decades has produced several secure crypto algorithms:

- AES-256 block cipher

# Secure Crypto

Research over the past decades has produced several secure crypto algorithms:

- AES-256 block cipher
- AES-CBC + HMAC-SHA256 authenticated encryption

# Secure Crypto

Research over the past decades has produced several secure crypto algorithms:

- AES-256 block cipher
- AES-CBC + HMAC-SHA256 authenticated encryption
- RSA-2048 public-key encryption

# Secure Crypto

Research over the past decades has produced several secure crypto algorithms:

- 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?

- Osvik, Shamir, Tromer, 2006: Recover AES-256 secret key of Linux's `dmcrypt` in just 65 ms

# Secure Crypto?

- Osvik, Shamir, Tromer, 2006: Recover AES-256 secret key of Linux's `dmcrypt` in just 65 ms
- AlFardan, Paterson, 2013: "Lucky13" recovers plaintext of CBC-mode encryption in pretty much all TLS implementations

# Secure Crypto?

- Osvik, Shamir, Tromer, 2006: Recover AES-256 secret key of Linux's `dmcrypt` in just 65 ms
- AlFardan, Paterson, 2013: "Lucky13" recovers plaintext of CBC-mode encryption in pretty much all TLS implementations
- Yarom, Falkner, 2014: Attack against RSA-2048 in GnuPG 1.4.13: *"On average, the attack is able to recover 96.7% of the bits of the secret key by observing a single signature or decryption round."*

# Secure Crypto?

- Osvik, Shamir, Tromer, 2006: Recover AES-256 secret key of Linux's `dmcrypt` in just 65 ms
- AlFardan, Paterson, 2013: "Lucky13" recovers plaintext of CBC-mode encryption in pretty much all TLS implementations
- Yarom, Falkner, 2014: Attack against RSA-2048 in GnuPG 1.4.13: *"On average, the attack is able to recover 96.7% of the bits of the secret key by observing a single signature or decryption round."*
- Benger, van de Pol, Smart, Yarom, 2014: *"reasonable level of success in recovering the secret key"* for OpenSSL ECDSA using secp256k1 *"with as little as 200 signatures"*

# Secure Crypto?

- Osvik, Shamir, Tromer, 2006: Recover AES-256 secret key of Linux's `dmcrypt` in just 65 ms
- AlFardan, Paterson, 2013: "Lucky13" recovers plaintext of CBC-mode encryption in pretty much all TLS implementations
- Yarom, Falkner, 2014: Attack against RSA-2048 in GnuPG 1.4.13: *"On average, the attack is able to recover 96.7% of the bits of the secret key by observing a single signature or decryption round."*
- Benger, van de Pol, Smart, Yarom, 2014: *"reasonable level of success in recovering the secret key"* for OpenSSL ECDSA using secp256k1 *"with as little as 200 signatures"*

**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

# 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

## 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)

# 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

## 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)
  - Some attacks work by measuring network delays
  - Attacker does not even need an account on the target machine

# 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

## 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)
  - 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]) {
  int i,j;
  uint32 r = 1,t;
  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;
      else
        t = ((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]) {
  int i,j;
  uint32 r = 1,t;
  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;
      else
        t = ((uint64)a*r) % mod;
    }
  }
  return r;
}
```

- Compiler may optimize `else` clause away, but can avoid that

# Square-and-multiply-always

```
/* 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,t;
  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;
      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?

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

# Eliminating branches

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

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

- Replace by

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

# Eliminating branches

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

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

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

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

# Eliminating branches

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

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

- Replace by

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

- 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)

- Block cipher Rijndael proposed by Rijmen, Daemen in 1998
- Selected as AES by NIST in October 2000

# The Advanced Encryption Standard (AES)

- Block cipher Rijndael proposed by Rijmen, Daemen in 1998
- Selected as AES by NIST in October 2000
- Block size: $128$ bits (AES state: $4 \times 4$ matrix of $16$ bytes)
- Key size $128/192/256$ bits (resp. $10/12/14$ rounds)

# The Advanced Encryption Standard (AES)

- Block cipher Rijndael proposed by Rijmen, Daemen in 1998
- Selected as AES by NIST in October 2000
- Block size: $128$ bits (AES state: $4 \times 4$ matrix of $16$ bytes)
- Key size $128/192/256$ bits (resp. $10/12/14$ rounds)
- AES with $n$ rounds uses $n + 1$ $16$-byte rounds keys $K_0, \ldots, K_n$

# The Advanced Encryption Standard (AES)

- Block cipher Rijndael proposed by Rijmen, Daemen in 1998
- Selected as AES by NIST in October 2000
- Block size: $128$ bits (AES state: $4 \times 4$ matrix of $16$ bytes)
- Key size $128/192/256$ bits (resp. $10/12/14$ rounds)
- 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."*

—Daemen, Rijmen. **AES Proposal**: Rijndael, 1999.

# 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."*

—Daemen, Rijmen. **AES Proposal**: Rijndael, 1999.

## 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

| |
|---|
| $T0[0] \dots T0[15]$ |
| $T0[16] \dots T0[31]$ |
| attacker's data |
| attacker's data |
| $T0[64] \dots T0[79]$ |
| $T0[80] \dots T0[95]$ |
| attacker's data |
| attacker's data |
| attacker's data |
| attacker's data |
| $T0[160] \dots T0[175]$ |
| $T0[176] \dots T0[191]$ |
| $T0[192] \dots T0[207]$ |
| $T0[208] \dots T0[223]$ |
| attacker's data |
| attacker's data |

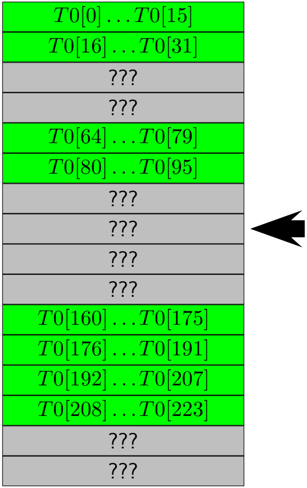
- AES and the attackers program run on the same CPU
- Tables are in cache
- The attacker's program replaces some cache lines

# Cache-timing attacks

| |
|---|
| $T0[0] \dots T0[15]$ |
| $T0[16] \dots T0[31]$ |
| ??? |
| ??? |
| $T0[64] \dots T0[79]$ |
| $T0[80] \dots T0[95]$ |
| ??? |
| ??? |
| ??? |
| ??? |
| $T0[160] \dots T0[175]$ |
| $T0[176] \dots T0[191]$ |
| $T0[192] \dots T0[207]$ |
| $T0[208] \dots T0[223]$ |
| ??? |
| ??? |

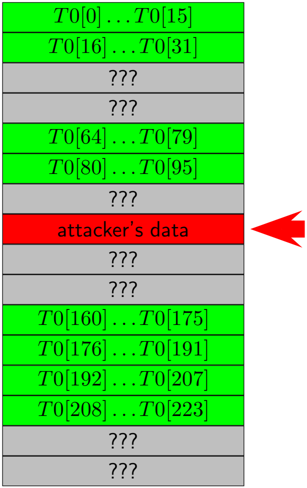
- AES and the attackers program run on the same CPU
- Tables are in cache
- The attacker's program replaces some cache lines
- AES continues, loads from table again

# Cache-timing attacks



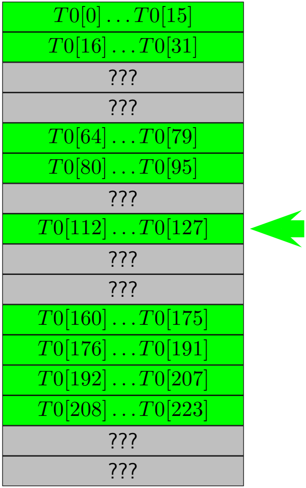

- AES and the attackers program run on the same CPU
- Tables are in cache
- The attacker's program replaces some cache lines
- AES continues, loads from table again
- Attacker loads his data:

# Cache-timing attacks




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

# Cache-timing attacks




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

# “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

# “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... or are they?

# “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... or are they?
- Bernstein, 2005: *“Does this guarantee constant-time S-box lookups? No!”*

# "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... or are they?
- Bernstein, 2005: *"Does this guarantee constant-time S-box lookups? No!"*
- Osvik, Shamir, Tromer, 2006: *"This is insufficient on processors which leak low address bits"*

# "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... or are they?
- Bernstein, 2005: *"Does this guarantee constant-time S-box lookups? No!"*
- Osvik, Shamir, Tromer, 2006: *"This is insufficient on processors which leak low address bits"*
- Reasons:
  - Cache-bank conflicts
  - Failed store-to-load forwarding
  - ...

# “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... or are they?
- Bernstein, 2005: *“Does this guarantee constant-time S-box lookups? No!”*
- Osvik, Shamir, Tromer, 2006: *“This is insufficient on processors which leak low address bits”*
- Reasons:
  - Cache-bank conflicts
  - Failed store-to-load forwarding
  - ...
- OpenSSL is using it in `BN_mod_exp_mont_consttime`

# “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... or are they?
- Bernstein, 2005: *“Does this guarantee constant-time S-box lookups? No!”*
- Osvik, Shamir, Tromer, 2006: *“This is insufficient on processors which leak low address bits”*
- Reasons:
  - Cache-bank conflicts
  - Failed store-to-load forwarding
  - ...
- OpenSSL is using it in `BN_mod_exp_mont_consttime`
- Brickell (Intel), 2011: yeah, it’s fine as a countermeasure

# “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... or are they?
- Bernstein, 2005: *“Does this guarantee constant-time S-box lookups? No!”*
- Osvik, Shamir, Tromer, 2006: *“This is insufficient on processors which leak low address bits”*
- Reasons:
  - Cache-bank conflicts
  - Failed store-to-load forwarding
  - ...
- OpenSSL is using it in `BN_mod_exp_mont_consttime`
- Brickell (Intel), 2011: yeah, it’s fine as a countermeasure
- Bernstein, Schwabe, 2013: Demonstrate timing variability for access within one cache line

# "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... or are they?
- Bernstein, 2005: *"Does this guarantee constant-time S-box lookups? No!"*
- Osvik, Shamir, Tromer, 2006: *"This is insufficient on processors which leak low address bits"*
- Reasons:
  - Cache-bank conflicts
  - Failed store-to-load forwarding
  - ...
- OpenSSL is using it in `BN_mod_exp_mont_consttime`
- Brickell (Intel), 2011: yeah, it's fine as a countermeasure
- Bernstein, Schwabe, 2013: Demonstrate timing variability for access within one cache line
- 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)."*

# 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;
}
```

# 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); /* DON'T! Compiler may do funny things! */
    cmov(&r, &table[i], b);
  }
  return r;
}
```

# 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 = 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?

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

—Report on the Development of the Advanced Encryption Standard (AES), October 2000

# Back to AES

## 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."*

—Report on the Development of the Advanced Encryption Standard (AES), October 2000

## What now?

- You *can* use generic constant-time lookups for AES tables
- It's horribly inefficient

# Back to AES

## 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."*

—Report on the Development of the Advanced Encryption Standard (AES), October 2000

## What now?

- You *can* use generic constant-time lookups for AES tables
- It's horribly inefficient
- Intel's answer: let's do it in hardware (AES-NI, since Westmere)

# Back to AES

## 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."*

—Report on the Development of the Advanced Encryption Standard (AES), October 2000

## What now?

- You *can* use generic constant-time lookups for AES tables
- 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)

# Back to AES

## 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."*

—Report on the Development of the Advanced Encryption Standard (AES), October 2000

## What now?

- You *can* use generic constant-time lookups for AES tables
- 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
- Perform arithmetic on those registers using `XOR`, `AND`, `OR`
- Essentially the same as hardware implementations

# Bitslicing

- Imagine registers that have only one bit
- Perform arithmetic on those registers using `XOR`, `AND`, `OR`
- Essentially the same as hardware implementations
- But wait, registers are longer!
- Think of them as vectors of bits
- Perform the simulated hardware implementations on many independent data streams

# Bitslicing

- Imagine registers that have only one bit
- Perform arithmetic on those registers using `XOR`, `AND`, `OR`
- Essentially the same as hardware implementations
- But wait, registers are longer!
- Think of them as vectors of bits
- 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:
  - Generic technique to eliminate branches
  - Generic technique to eliminate secretly indexed lookups
  - Bitslicing as generic technique to “hardwarize” software implementations

# 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

## Funny problems

- Take integer array of length $1024$, sort it

# 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

## Funny problems

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

# 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

## Funny problems

- Take integer array of length $1024$, sort it
- Compute random permutation of $\{0, \ldots, 1023\}$
- “Pick” all integers $< 61445$ from an array of $16$-bit integers

# 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

## Funny problems

- Take integer array of length $1024$, sort it
- Compute random permutation of $\{0, \ldots, 1023\}$
- "Pick" all integers $< 61445$ from an array of $16$-bit integers

Standard algorithms use **lots of** branches or memory access

# 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

## Funny problems

- Take integer array of length $1024$, sort it
- Compute random permutation of $\{0, \ldots, 1023\}$
- “Pick” all integers $< 61445$ from an array of $16$-bit integers

Standard algorithms use **lots of** branches or memory access

**Naively applying our generic techniques can even result in terribly inefficient running time for simple, every-day tasks!**

# Expanding our toolbox

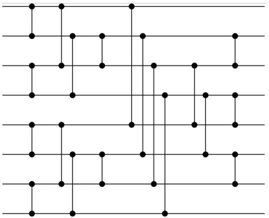
A *sorting network* sorts an array $S$ of elements by using a fixed sequence of *comparators*.

- A comparator can be expressed by a pair of indices $(i, j)$.
- A comparator swaps $S[i]$ and $S[j]$ if $S[i] > S[j]$.

# 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 $S[i] > S[j]$.
- 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

# 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 $r_i$

# 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:

  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:

  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 $(1, b_3), (2, b_2), (3, b_1)$
- Pick values $< 61445$: use $c(v_i, v_j) = v_i \geq 61445$

# Is that all?

## Lesson so far

- Avoid data flow from secrets to branch conditions and addresses
- Can *always* be done; cost highly depends on the algorithm

# Is that all?

## Lesson so far

- Avoid data flow from secrets to branch conditions and addresses
- Can *always* be done; cost highly depends on the algorithm
- Test this with `valgrind` and *uninitialized secret data* (or use Langley's `ctgrind`)

# Is that all?

## Lesson so far

- Avoid data flow from secrets to branch conditions and addresses
- Can *always* be done; cost highly depends on the algorithm
- Test this with `valgrind` and *uninitialized secret data* (or use Langley's `ctgrind`)
- More elegant: static analysis with Vagrant (Almeida, Barbosa, Barthe, Dupressoir, Emmi) https://github.com/imdea-software/verifying-constant-time

# Is that all?

## Lesson so far

- Avoid data flow from secrets to branch conditions and addresses
- Can *always* be done; cost highly depends on the algorithm
- Test this with `valgrind` and *uninitialized secret data* (or use Langley's `ctgrind`)
- More elegant: static analysis with Vagrant (Almeida, Barbosa, Barthe, Dupressoir, Emmi) https://github.com/imdea-software/verifying-constant-time

*"In order for a function to be constant time, the branches taken and memory addresses accessed must be independent of any secret inputs. (That's assuming that the fundamental processor instructions are constant time, but that's true for all sane CPUs.)"*

—Langley, Apr. 2010

# Is that all?

## Lesson so far

- Avoid data flow from secrets to branch conditions and addresses
- Can *always* be done; cost highly depends on the algorithm
- Test this with `valgrind` and *uninitialized secret data* (or use Langley's `ctgrind`)
- More elegant: static analysis with Vagrant (Almeida, Barbosa, Barthe, Dupressoir, Emmi) https://github.com/imdea-software/verifying-constant-time

*"In order for a function to be constant time, the branches taken and memory addresses accessed must be independent of any secret inputs. (That's assuming that the fundamental processor instructions are constant time, but that's true for all sane CPUs.)"*

—Langley, Apr. 2010

*"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
- Various math instructions on Intel/AMD CPUs (`FSIN`, `FCOS`...)

# Dangerous arithmetic (examples)

- `DIV`, `IDIV`, `FDIV` on pretty much all Intel/AMD CPUs
- Various math instructions on Intel/AMD CPUs (`FSIN`, `FCOS`...)
- `MUL`, `MULHW`, `MULHWU` on many PowerPC CPUs
- `UMULL`, `SMULL`, `UMLAL`, and `SMLAL` on ARM Cortex-M3.

# Dangerous arithmetic (examples)

- `DIV`, `IDIV`, `FDIV` on pretty much all Intel/AMD CPUs
- Various math instructions on Intel/AMD CPUs (`FSIN`, `FCOS`...)
- `MUL`, `MULHW`, `MULHWU` on many PowerPC CPUs
- `UMULL`, `SMULL`, `UMLAL`, and `SMLAL` on ARM Cortex-M3.

## Solution

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

# References I


- Osvik, Shamir, Tromer, 2006: *Cache Attacks and Countermeasures: the Case of AES.*
  http://eprint.iacr.org/2005/271/
- AlFardan, Paterson, 2013: *Lucky Thirteen: Breaking the TLS and DTLS Record Protocols.*
  http://www.isg.rhul.ac.uk/tls/Lucky13.html
- Yarom, Falkner, 2014: FLUSH + RELOAD: *a High Resolution, Low Noise, L3 Cache Side-Channel Attack.*
  http://eprint.iacr.org/2013/448/
- Benger, van de Pol, Smart, Yarom, 2014: *"Ooh Aah... Just a Little Bit": A small amount of side channel can go a long way.*
  http://eprint.iacr.org/2014/161/

# References II


- Bernstein, 2005: *Cache-timing attacks on AES.*
  http://cr.yp.to/papers.html#cachetiming
- Brickell, 2011: *Technologies to Improve Platform Security.*
  http://www.chesworkshop.org/ches2011/presentations/Invited%201/CHES2011_Invited_1.pdf
- Bernstein, Schwabe, 2013: *A word of warning.*
  https://cryptojedi.org/peter/data/chesrump-20130822.pdf
  https://cryptojedi.org/peter/data/cacheline.tar.bz2
- Yarom, Genkin, Heninger, 2016: *CacheBleed: A Timing Attack on OpenSSL Constant Time RSA*
  https://ssrg.nicta.com.au/projects/TS/cachebleed/
- Hamburg, 2009: *Accelerating AES with Vector Permute Instructions.*
  http://mikehamburg.com/papers/vector_aes/vector_aes.pdf
- Biham, 1997: *"A Fast New DES Implementation in Software."*
  http://www.cs.technion.ac.il/users/wwwb/cgi-bin/tr-info.cgi?1997/CS/CS0891

# Questions?

https://cryptojedi.org