Language-based software security, fourth lecture

Tempus fugit : timing attacks and cache attacks

Xavier Leroy

2022-03-31

Collège de France, chair of software sciences
xavier.leroy@college-de-france.fr

Execution time as an information channel

User experience with an old Unix system

```
login: dmr
password: *****
```

(two seconds later…)

```
Login incorrect
```

User experience with an old Unix system

```
login: dmr
password: *****
```

(two seconds later...)

```
Login incorrect
```

Second attempt:

```
login: foo
password: *****
```

(immediately)

```
Login incorrect
```

Why this difference in response time?

```
int check_login(char * username, char * password)
{
    struct passwd * userinfo = getpwnam(username);
    if (userinfo == NULL) return 0; // no user with this name
    char * hash = crypt(password);  // takes 2 seconds
    return (strcmp(hash, userinfo->pw_password) == 0);
}
```

The function terminates faster if there is no account named `username` than if there is one.

$\Longrightarrow$ Enables an attacker to easily check if a given account exists.

Checking a PIN

```
for (int i = 0; i < N; i++) {
    if (input[i] != pin[i]) return false;
}
return true;
```

This loop takes time proportional to the number of correct digits at the beginning of `input`.

$\Longrightarrow$ An attacker can find a N-digit PIN in time $10\,N$ instead of 10^N.

Checking a PIN

An alternate implementation where the loop always runs for N iterations:

```
valid = true;
for (int i = 0; i < N; i++) {
    if (input[i] != pin[i]) valid = false;
}
return valid;
```

Now, the execution time is $a + bn$, where n is the number of wrong digits (= number of assignments `valid = false`).

$\Longrightarrow$ An efficient attack remains possible.

Checking a PIN

Let's make the code more symmetrical by counting the number of correct digits and the number of wrong digits.

```
valid = 0; invalid = 0;
for (int i = 0; i < N; i++) {
    if (input[i] != pin[i]) ++invalid; else ++valid;
}
return (invalid == 0);
```

Branch prediction in the processor can still cause variations in execution time, but it's getting hard to exploit them.

Checking a PIN in constant time

The correct way to write this PIN-checking code is to use constant-time operations only, that is, operations that run in time independent of the values of their arguments.

```
d = 0;
for (int i = 0; i < N; i++) {
    d = d | (input[i] ^ pin[i]);
}
return (d == 0);
```

(Variable `d` accumulates the bits that differ between `input` and `password`; it remains 0 if and only if there are no differences.)

RSA encryption and signature

Based on modular exponentiation:

$$M \xrightarrow{\text{encryption}} C = M^e \bmod N \xrightarrow{\text{decryption}} C^d \bmod N$$

$$M \xrightarrow{\text{signature}} S = M^d \bmod N \xrightarrow{\text{verification}} S^e \bmod N$$

A modulus $N = pq$ product of two prime numbers p, q.

A secret exponent d and a public exponent e such that $de \bmod (p-1)(q-1) = 1$.

The public key is (N, e).

The secret key is d or sometimes (p, q, d).

Computing modular exponentation

The “Russian peasant” algorithm for fast exponentiation:

Decompose d in bits $d_n, \ldots, d_0$ $\quad (d = \sum_{i=0}^{n} d_i 2^i)$

$C := 1;\ \ z := M;$

`for` $i = 0$ `to` n `do`

`if` d_i `then` $C := C \cdot z \bmod N$

$z := z^2 \bmod N$

`done`

z takes successive values $M, M^2, M^4, M^8, \ldots, M^{2^n} \pmod{N}$.

At the end we have $C = \prod\{M^{2^i} \mid d_i = 1\} = M^{\sum\{2^i | d_i = 1\}} = M^d$

Running time of modular exponentiation

$\texttt{for}\ i = 0\ \texttt{to}\ n\ \texttt{do}$

$\quad \texttt{if}\ d_i\ \texttt{then}\ C := C \cdot z \bmod N$

$\quad z := z^2 \bmod N$

$\texttt{done}$

The running time of the loop depends on the d_i, obviously:
we perform $w + n + 1$ modular multiplications,
where w is the Hamming weight (number of 1 bits) of the secret d.

However, knowing w doesn't help to guess d.

Moreover, we can easily remove this dependence on w:

$\texttt{if}\ d_i\ \texttt{then}\ C := C \cdot z \bmod N\ \texttt{else}\ tmp := C \cdot z \bmod N$

Running time of modular exponentiation

for $i = 0$ to n do
  if d_i then $C := C \cdot z \bmod N$ else $tmp := C \cdot z \bmod N$
  $z := z^2 \bmod N$
done

The time it takes to compute $C \cdot z \bmod N$ depends significantly on the value of C, even more so if clever algorithms are used.

This suffices to mount attacks on RSA by observing execution times.

P. Kocher's timing attack (1996)

Take k random messages $M_1, \ldots, M_k$.

Have them signed: $S_i = M_i^d \bmod N$ and measure the time T_i.

Guess the bits of d one after the other:

- $d_0 = 1$ always.
- Assume $d_1 = 1$. Then, the computation of S_i would start by computing $M_i \cdot M_i^2 \bmod N$.
    - Measure the times t_i to compute $M_i \cdot M_i^2 \bmod N$.
    - If the t_i are correlated with the T_i, we do have $d_1 = 1$.
    - If there's no correlation, we have $d_1 = 0$.
- Iterate for the following bits.

D. Brumley and D. Boneh's timing attack on OpenSSL (2003)

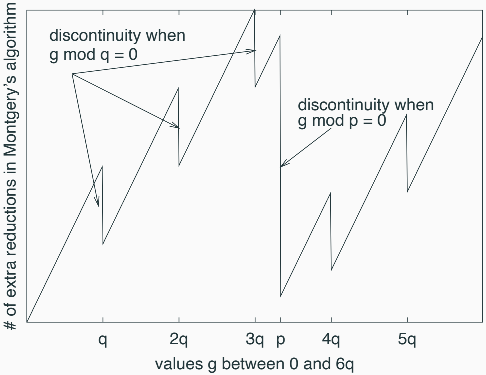
OpenSSL has a more efficient implementation of RSA:

- Uses the Chinese remainder theorem:
  compute $M^d \bmod p$ and $M^d \bmod q$, then combine the results to obtain $M^d \bmod N$ (with $N = pq$).
- Uses Montgomery's representation to speed up modular multiplications $C \cdot z \bmod q$.
- Several multiplication algorithms, selected based on the sizes of the arguments.

Each of these features contributes to leak more information through execution times…

Execution time for Montgomery multiplication

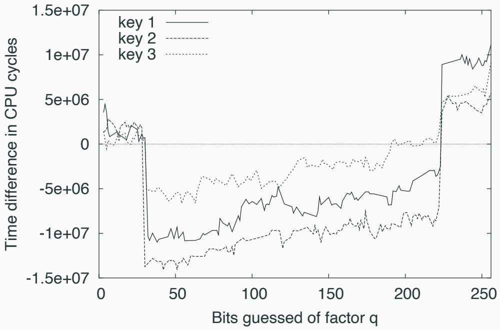
Montgomery's algorithm performs additional reduction steps when the product g gets close to the modulus p or q.



(Brumley & Boneh, 2003)

D. Brumley and D. Boneh's timing attack

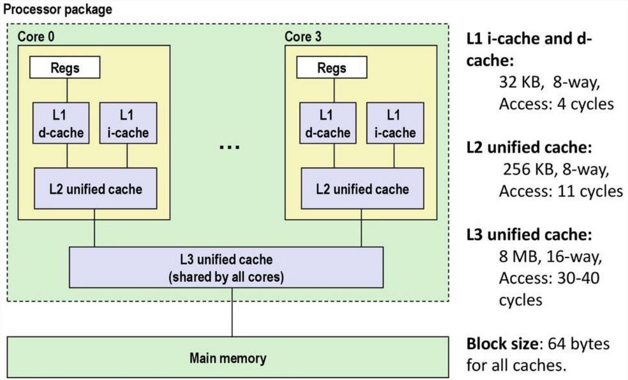
A binary search that identifies the most significant bits of the q factor. Once half the bits are known, Coppersmith's algorithm recovers the whole secret key.



The attack can be conducted across a network connection!

Cache memory
as an information channel

Cache memory



Speed up accesses to a memory location that has been accessed recently (temporal locality), or that is near a recently-accessed location (spatial locality).

Cache attacks

The time taken by a memory read varies greatly whether a data at a nearby location has been accessed recently.

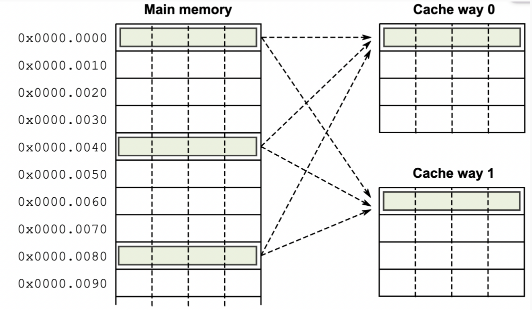
Overall structure of a cache attach:

1. Flush the cache (L1 or more) (`clflush` instruction, etc)
2. Execute privileged code that manipulates secret data.
3. Measure access times for several memory locations.
4. Infer which locations were accessed by the privileged code.
5. Deduce information on the secret data.

(In step 1-, instead of emptying the cache, we can also pre-fill it with locations that conflict with the locations we want to observe.)

(2- and 3- can take place concurrently.)

Cache attacks



Note: it is not necessary to have read and write permissions on the memory area we want to observe. We can use any memory area that shares the same cache entries.

Example: normalizing a character string

Put letters in uppercase and normalize non-printable characters.

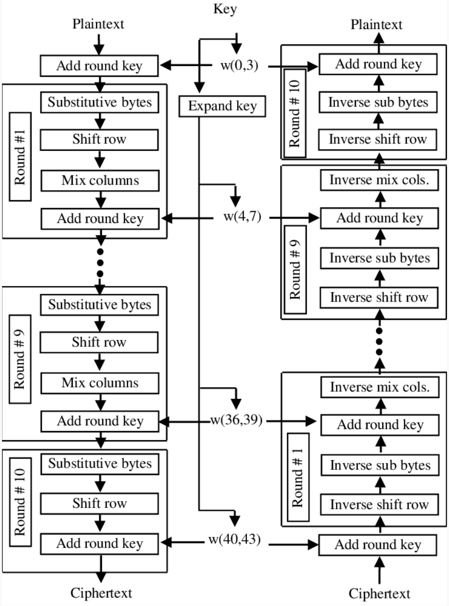
```c
void normalize(unsigned char * s, size_t len)
{
    static const unsigned char tbl[256] = "\
\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\
\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\
 !\"#$%&'()*+,-./0123456789:;<=>?\
@ABCDEFGHIJKLMNOPQRSTUVWXYZ[\\]^_\
`ABCDEFGHIJKLMNOPQRSTUVWXYZ{|}~";

    for (size_t i = 0; i < len; i++) s[i] = tbl[s[i]];
}
```

An example of a cache attack

`get_hashed_password`: a protected function that reads a password from the keyboard, normalizes it with `normalize`, and hashes it.

1. Flush the cache.
2. Call `get_hashed_password`.
3. Measure the time taken by `normalize` on inputs `"a"`, `"b"`, `"c"`, etc.
4. Infer the elements of the `tbl` array accessed by `normalize` when called from `get_hash_password`.
   (Assuming cache lines of size 1 byte.)
5. Deduce which letters `a`, `b`, `c`, etc, appear in the password.

The AES-128 symmetric cipher



(A. G. Wadday et al, 2018)

Software implementations of AES usually tabulate the subst/shift/mix steps.

T_0, T_1, T_2, T_3: tables of 256 32-bit constants.

$x_0, \ldots, x_{15}$: the 16 bytes of the current state.

$$
\begin{aligned}
(x'_0, x'_1, x'_2, x'_3) &= T_0[x_0] \oplus T_1[x_5] \oplus T_2[x_{10}] \oplus T_3[x_{15}] \oplus K_0 \\
(x'_4, x'_5, x'_6, x'_7) &= T_0[x_4] \oplus T_1[x_9] \oplus T_2[x_{14}] \oplus T_3[x_3] \oplus K_1 \\
(x'_8, x'_9, x'_{10}, x'_{11}) &= T_0[x_8] \oplus T_1[x_{13}] \oplus T_2[x_2] \oplus T_3[x_7] \oplus K_2 \\
(x'_{12}, x'_{13}, x'_{14}, x'_{15}) &= T_0[x_{12}] \oplus T_1[x_1] \oplus T_2[x_6] \oplus T_3[x_{11}] \oplus K_3
\end{aligned}
$$

Cache attack on AES

(Osvik, Shamir, Tromer, *Cache attacks and countermeasures: the case of AES*, 2005. Ashokummar, Giri, Menezes, *Highly efficient algorithms for AES key retrieval in cache access attacks*, 2016.)

$$(x'_0, x'_1, x'_2, x'_3) = T_0[x_0] \oplus T_1[x_5] \oplus T_2[x_{10}] \oplus T_3[x_{15}] \oplus K_0$$
$$(x'_4, x'_5, x'_6, x'_7) = T_0[x_4] \oplus T_1[x_9] \oplus T_2[x_{14}] \oplus T_3[x_3] \oplus K_1$$
$$(x'_8, x'_9, x'_{10}, x'_{11}) = T_0[x_8] \oplus T_1[x_{13}] \oplus T_2[x_2] \oplus T_3[x_7] \oplus K_2$$
$$(x'_{12}, x'_{13}, x'_{14}, x'_{15}) = T_0[x_{12}] \oplus T_1[x_1] \oplus T_2[x_6] \oplus T_3[x_{11}] \oplus K_3$$

Assuming cache lines are 4 32-bit words, each access $T_i[x_j]$ “leaks” the 4 most significant bits of x_j.

First round: $x =$ chosen text $\oplus$ key, hence we can recover the 4 most significant bits of each byte of the key.

Cache attack on AES

(Osvik, Shamir, Tromer, *Cache attacks and countermeasures: the case of AES*, 2005. Ashokummar, Giri, Menezes, *Highly efficient algorithms for AES key retrieval in cache access attacks*, 2016.)

$$
\begin{aligned}
(x'_0, x'_1, x'_2, x'_3) &= T_0[x_0] \oplus T_1[x_5] \oplus T_2[x_{10}] \oplus T_3[x_{15}] \oplus K_0 \\
(x'_4, x'_5, x'_6, x'_7) &= T_0[x_4] \oplus T_1[x_9] \oplus T_2[x_{14}] \oplus T_3[x_3] \oplus K_1 \\
(x'_8, x'_9, x'_{10}, x'_{11}) &= T_0[x_8] \oplus T_1[x_{13}] \oplus T_2[x_2] \oplus T_3[x_7] \oplus K_2 \\
(x'_{12}, x'_{13}, x'_{14}, x'_{15}) &= T_0[x_{12}] \oplus T_1[x_1] \oplus T_2[x_6] \oplus T_3[x_{11}] \oplus K_3
\end{aligned}
$$

Assuming cache lines are 4 32-bit words, each access $T_i[x_j]$ “leaks” the 4 most significant bits of x_j.

Finer analysis of the second round lets us recover the whole key using a small number of encryptions (10 to 1000).

Protections against timing attacks

Protections against timing attacks

How can we avoid leaking information through execution time?

Various approaches:

- "Constant-time" programming.
- Prevent precise time measurements.
- Quantize execution or communication times.
- Blinding secrets with random noise.

Precise time measurements

Many timing attacks cannot be conducted remotely: the attacker must run on the same machine as the attacked code.

To measure elapsed time precisely, the attacker needs

- access to a high-resolution hardware clock
  (e.g. the Time Stamp Counter register on x86 processors);
- or parallel execution of two threads.

$$
\begin{array}{l}
\texttt{while true do} \\
\quad \texttt{time} := \texttt{time} + 1 \\
\texttt{done}
\end{array}
\quad \Bigg\| \quad
\begin{array}{l}
T_0 := \texttt{time}; \\
\text{computation to be timed}; \\
T_1 := \texttt{time}
\end{array}
$$

Prevent precise time measurements

The operating system or the execution environment can:

- Prohibit access to high-resolution clocks
  (e.g. block the `rdtsc` x86 instruction).
- Force the threads of the attacker to run on the same processor core as the attacked code, by interleaving.
- Schedule threads independently from execution time.

Scheduling based on instruction counts

(Stefan et al, *Eliminating cache-based timing attacks with instruction-based scheduling*, 2013.)

$$\texttt{fillArray}(L);$$

$$\begin{array}{l} \texttt{if } \mathit{secret} \texttt{ then} \\ \quad \texttt{fillArray}(H) \\ \texttt{else} \\ \quad \texttt{skip} \end{array} \;\Bigg\|\; \begin{array}{l} \texttt{for } i = 1 \texttt{ to } n \\ \texttt{do skip done;} \\ \texttt{readArray}(L); \\ x := 1 \end{array} \;\Bigg\|\; \begin{array}{l} \texttt{for } i = 1 \texttt{ to } n + m \\ \texttt{do skip done;} \\ x := 0 \end{array}$$

With a schedule based on time slices (preemption after a fixed time T), we terminate with $x = 0$ or $x = 1$ depending on the running time of $\texttt{readArray}(L)$, which depends on the state of the cache.

Scheduling based on instruction counts

(Stefan et al, *Eliminating cache-based timing attacks with instruction-based scheduling*, 2013.)

$$\texttt{fillArray}(L);$$

`if` $secret$ `then`	`for` $i = 1$ `to` n	`for` $i = 1$ `to` $n + m$
`fillArray`(H)	`do skip done`;	`do skip done`;
`else`	`readArray`(L);	$x := 0$
`skip`	$x := 1$	

With a schedule based on instruction counts (preemption after N instructions were executed), the final value of x is independent from the cache state.

Time quantization

Add a delay at the end of computation to guarantee that it runs in constant time D_{max}.

$T_0 := \texttt{now}$;
$\texttt{for}\ i = 0\ \texttt{to}\ n\ \texttt{do}$
  $\texttt{if}\ d_i\ \texttt{then}\ C := C \cdot z \bmod N\ \texttt{else}\ tmp := C \cdot z \bmod N$
  $z := z^2 \bmod N$
$\texttt{done}$
$D = \texttt{now} - T_0$;
$\texttt{sleep}(D_{max} - D)$

No more temporal leaks!

… at the cost of slowing down all computations.

D_{max} can be hard to determine *a priori*.

Time quantization

Variation: adjust running time to an integer multiple of Δ.
(E.g. $\Delta = 10^7$ cycles for the Brumley-Boney attack.)

$T_0 := \mathtt{now};$

$\dots$

$D = \mathtt{now} - T_0;$

$\mathtt{sleep}(\mathtt{ceil}(D/\Delta) \times \Delta - D)$

Time Quantization

(Askarov, Zhang, Myers, *Predictive black-box mitigation of timing channels*, 2010.)

Variation: adjust D_{max} on the fly, following an exponential law.

$T_0 := \texttt{now};$

$\ldots$

$D = \texttt{now} - T_0;$

$\texttt{if}\ \ D > D_{max}\ \ \texttt{then}\ \ D_{max} := D_{max} \times (1 + \varepsilon)$

$\qquad\qquad\qquad \texttt{else}\ \texttt{sleep}(D_{max} - D)$

The attacker gains one bit of information each time $D > D_{max}$.
This happens at most one by time slice of duration $(1 + \varepsilon)^k$.
Hence, information leakage is $O(\log^2 t)$.

More subtle laws can be used, see Askarov *et al*.

Blinding

Inject randomness in the computation so that running time is no longer correlated with the value of the secret.

Artificial example:
checking a PIN code using a random permutation.

```
// draw a random permutation S of {0, ..., n − 1}
for (int i = 0; i < N; i++) {
    if (input[S[i]] != pin[S[i]]) return false;
}
return true;
```

The running time for one execution only gives a lower bound on the number of correct digits.

RSA with message blinding

If M is the message to be signed, we can blind it using a random number R before modular exponentiation.

$$C \stackrel{def}{=} (R^e \cdot M)^d = (R^e)^d \cdot M^d = R^{ed} \cdot M^d = R \cdot M^d \pmod N$$

since $ed \bmod \varphi(N) = 1$ and $R^{\varphi(N)} = 1 \pmod N$ (Euler's theorem).

Then, we can un-blind, obtaining the correct result:

$$S \stackrel{def}{=} R^{-1} \cdot C \pmod N$$

The time it takes to compute $(R^e \cdot M)^d$ gives no information to the attackers, since they choose M but not R.

Constant-time programming

Constant-time programming

A programming discipline to write programs that run in time independent from secret data.

Relies on a classification of the base operations of the programming language / of the instructions of the processor:

- Constant-time operations: same execution time regardless of the values of the arguments of the operation and of the state of the processor.
- Variable-time operations: timing is sensitive to the values of the arguments or to the processor state (caches, branch predictors, etc).

A standard classification

<table>
<tr><th></th><th>Constant time</th><th>Variable time</th></tr>
<tr><td>Integer arithmetic ([1])</td><td><code>+ - * & | ^</code>
shifts, comparisons</td><td>division, modulus</td></tr>
<tr><td>Memory reads and writes ([2])</td><td></td><td><code>x[i] *p</code></td></tr>
<tr><td>Conditional branches</td><td></td><td><code>if while</code>
<code>&& ||</code></td></tr>
</table>

(1) Some processors have variable-time integer multiplication.

(2) For writes `x[i] = v` and `*p = v`, execution time depends on `x`, `i`, `p` (the accessed address) but not on `v` (the stored value).

The “constant-time” criterion

An information flow property:

> A value at level H (secret) must not be used
> as argument to a non-constant-time operation.

Examples:

✔ $\mathtt{z}^H \mathrel{\mathtt{:=}} \mathtt{x}^H \mathtt{+} \mathtt{y}^H$ ✘ $\mathtt{z}^H \mathrel{\mathtt{:=}} \mathtt{x}^H \mathtt{/} \mathtt{y}^H$

✘ $\mathtt{if}\ \mathtt{x}^H < \mathtt{y}^H\ \mathtt{then}\ \mathtt{z}^H \mathrel{\mathtt{:=}} \mathtt{1}$

✘ $\mathtt{x}^H \mathrel{\mathtt{:=}} \mathtt{t}^L\mathtt{[i}^H\mathtt{]}$

Typing rules for constant time

In the style of the type systems for information flow of lecture #2.

$$\frac{\vdash a_1 : \ell \qquad a_2 : \ell}{\vdash a_1 + a_2 : \ell} \qquad \frac{\vdash a_1 : L \qquad a_2 : L}{\vdash a_1 / a_2 : \ell}$$

$$\frac{\vdash b : L \qquad \vdash c_1 : * \qquad \vdash c_2 : *}{\vdash \texttt{if}\ b\ \texttt{then}\ c_1\ \texttt{else}\ c_2 : *} \qquad \frac{\vdash b : L \qquad \vdash c : *}{\vdash \texttt{while}\ b\ \texttt{do}\ c}$$

Note: indirect flows ($\texttt{if}\ b^H\ \texttt{then}\ x^L := 1\ \texttt{else}\ x^L := 0$) are automatically excluded; no need to trace the *pc* level any longer.

A semantics for timing leaks

We can materialize information leaks caused by non-constant-time operations by a program transformation:

$$
\begin{aligned}
[\![z := x + y]\!] &= z := x + y \\
[\![z := x / y]\!] &= \mathtt{out}(x); \mathtt{out}(y); z := x / y \\
[\![\mathtt{if}\ x < y\ \ \mathtt{then}\ c_1\ \mathtt{else}\ c_2]\!] &= \mathtt{out}(x); \mathtt{out}(y); \\
&\ \mathtt{if}\ x < y\ \mathtt{then}\ [\![c_1]\!]\ \mathtt{else}\ [\![c_2]\!] \\
[\![\mathtt{while}\ x < y\ \mathtt{do}\ c\ \mathtt{done}]\!] &= \mathtt{out}(x); \mathtt{out}(y); \\
&\ \mathtt{while}\ x < y\ \mathtt{do} \\
&\ \quad [\![c]\!]; \mathtt{out}(x); \mathtt{out}(y) \\
&\ \mathtt{done}
\end{aligned}
$$

Non-interference in the presence of timing leaks

$$
\begin{tikzcd}[column sep=huge, row sep=huge]
\text{initial state 1} \arrow[r, dash, "\text{same values}", "\text{for the } x^L"'] \arrow[d, "\text{program execution (trace } T_1\text{)}"'] & \text{initial state 2} \arrow[d, "\text{program execution (trace } T_2\text{)}"] \\
\text{final state 1} \arrow[r, dash, "\text{same values for the } x^L", "\text{and same traces } T_1 = T_2"'] & \text{final state 2}
\end{tikzcd}
$$

Programming in “constant-time” style

On secret data: no conditionals, no array indexing,
just arithmetic and bitwise operations ≈ combinatorial circuits.

Example (reminder):

```
d = 0;
for (int i = 0; i < N; i++) {
    if (input[i] != pin[i]) d = 1; ✘
}
return (d == 0);
```

Programming in “constant-time” style

On secret data: no conditionals, no array indexing,
just arithmetic and bitwise operations ≈ combinatorial circuits.

Example (reminder):

```
d = 0;
for (int i = 0; i < N; i++) {
    d = d | (input[i] ^ pin[i]); ✔
}
return (d == 0);
```

Avoiding arrays and indexing

N-bit integers can replace arrays of N Booleans.

Example: a DES *S-box* = a function 6 bits $\rightarrow$ 4 bits.

The usual tabulated implementation:

```
int tbl[64] = { /* 64 4-bit integers */ };
int sbox(int x) { return tbl[x]; }
```

Tabulation using 4 64-bit integers:

```
uint64_t tbl0 = ..., tbl1 = ..., tbl2 = ..., tbl3 = ...;
int sbox(int x) {
    return (tbl0 >> x & 1) << 0 | (tbl1 >> x & 1) << 1 |
           (tbl2 >> x & 1) << 2 | (tbl3 >> x & 1) << 3;
}
```

(Constant-time… but much slower!)

IF-conversion: turning conditionals into selections

Base case:

$$\texttt{if}\ \ b\ \ \texttt{then}\ \ x := a_1\ \ \texttt{else}\ \ x := a_2 \quad\Longrightarrow\quad x := \texttt{sel}(b, a_1, a_2)$$

$$\texttt{if}\ \ b\ \ \texttt{then}\ \ x := a_1 \quad\Longrightarrow\quad x := \texttt{sel}(b, a_1, x)$$

The $\texttt{sel}(b, a_1, a_2)$ operator

- evaluates b, a_1 et a_2;
- returns the value of a_1 if b is true;
- returns the value of a_2 if b is false;

in time independent from the value of b (“constant time”).

IF-conversion: turning conditionals into selections

More generally:

- Execute both `then` and `else` branches, renaming the variables that are assigned.
- Select the final values for the variables using operator `sel`.

Example:

$$\texttt{if}\ \ b\ \ \texttt{then}\ \ (x := a_1; y := a_2)\ \ \texttt{else}\ \ (y := a_3; z := a_4)$$

$$\begin{aligned}
\Longrightarrow\quad & x_1 := a_1;\ \ y_1 := a_2[x \leftarrow x_1]; \\
& y_2 := a_3;\ \ z_2 := a_4[y \leftarrow y_2]; \\
& x := \texttt{sel}(b, x_1, x);\ \ y := \texttt{sel}(b, y_1, y_2);\ \ z := \texttt{sel}(b, z, z_2)
\end{aligned}$$

Limits of IF-conversion

This transformation applies only if the `then` and `else` branches

- always terminate;
- never trigger run-time errors;
- have no effects observable by the remainder of the program.

Problematic example:

$$\texttt{if}\ \ y \neq 0\ \ \texttt{then}\ \ z := x/y\ \ \texttt{else}\ \ \texttt{abort()}$$

$$\not\Longrightarrow \quad z_1 := x/y;\ \ \texttt{abort()};\ \ z := \texttt{sel}(y \neq 0, z_1, z)$$

Implementing the selection operator

Using specific processor instructions
(conditional move, predicated instructions, etc).

Portably, when b, a_1 and a_2 have type `bool`:

$$\texttt{sel}(b, a_1, a_2) = b \wedge a_1 \vee \neg b \wedge a_2$$

Portably, when a_1 and a_2 are integers and b = 0 or 1:

$$\texttt{sel}(b, a_1, a_2) = b \times a_1 + (1 - b) \times a_2$$

$$\texttt{sel}(b, a_1, a_2) = a_2 + b \times (a_1 - a_2)$$

$$\texttt{sel}(b, a_1, a_2) = (-b) \wedge a_1 \vee (b - 1) \wedge a_2$$

(If $b = 0$, we have $b - 1 = 11 \ldots 11$ and $-b = 00 \ldots 00$.
If $b = 1$, we have $b - 1 = 00 \ldots 00$ and $-b = 11 \ldots 11$.)

Resisting compiler optimizations

An optimizing compiler can perform “IF-conversion” itself, thus making certain conditionals constant-time:

$$\texttt{if}\ \ b\ \ \texttt{then}\ \ x := a_1\ \ \texttt{else}\ \ x := a_2 \quad\rightarrow\quad x := \texttt{sel}(b, a_1, a_2)$$

But it can also introduce conditional branches to compute arithmetic or logical expressions, such as our `sel` implementations!

$$x := b \times a_1 + (1 - b) \times a_2 \rightarrow \texttt{if}\ \ b\ \ \texttt{then}\ \ x := a_1\ \ \texttt{else}\ \ x := a_2$$

Resisting compiler optimizations

(Simon, Chisnall, Anderson, *What you get is what you C: controlling side effects in mainstream C compilers*, 2018).

Experiment: 4 implementations of `sel` in portable C, compiled for x86-32 by various versions of Clang.

		VERSION_1		VERSION_2		VERSION_3		VERSION_4	
		inlined	library	inlined	library	inlined	library	inlined	library
Clang 3.0	-O0	✓	✓	✓	✓	✓	✓	✓	✓
	-O1	✓	✓	✓	✓	✓	✓	✓	✗
	-O2	✓	✓	✓	✗	✗	✓	✓	✗
	-O3	✓	✓	✓	✗	✗	✓	✓	✗
Clang 3.3	-O0	✓	✓	✓	✓	✓	✓	✓	✓
	-O1	✓	✓	✓	✓	✓	✗	✓	✗
	-O2	✓	✓	✗	✗	✗	✗	✗	✗
	-O3	✓	✓	✗	✗	✗	✗	✗	✗
Clang 3.9	-O0	✓	✓	✓	✓	✓	✓	✓	✓
	-O1	✓	✓	✓	✓	✓	✗	✓	✗
	-O2	✓	✓	✗	✗	✗	✗	✗	✗
	-O3	✓	✓	✗	✗	✗	✗	✗	✗

✔ = constant-time code is generated.

✘ = a conditional branch is generated.

Attacks on speculative execution

Speculative execution in processors

Example: branch prediction.

```
        load x0, [x1]
        branch if x0 = 0 to L1
        mul x3, x2, x3
        add x4, x3, x4
        branch to L2
L1:     ...
```

Memory loads take a lot of time.

Speculative execution in processors

Example: branch prediction.

```
        load x0, [x1]
        branch if x0 = 0 to L1
        mul x3, x2, x3
        add x4, x3, x4
        branch to L2
L1:     ...
```

The processor predicts (based on previous executions) that `x0` will not be zero and the branch will not be taken.

Speculative execution in processors

Example: branch prediction.

```
        load x0, [x1]
        branch if x0 = 0 to L1
        mul x3, x2, x3
        add x4, x3, x4
        branch to L2
L1:     ...
```

The processor executes the following instructions speculatively, in a way that can be reversed if needed.

(For example, the initial values of `x3` and `x4` are kept somewhere.)

Speculative execution in processors

Example: branch prediction.

```
        load x0, [x1]
        branch if x0 = 0 to L1
        mul x3, x2, x3
        add x4, x3, x4
        branch to L2
L1:     ...
```

When the `load` terminates, the conditional branch is resolved.

If `x0` is 0, the prediction was wrong. The processor rolls back the speculative execution: the effects of the speculated instructions are ignored (e.g. registers `x3`, `x4` are reset to their initial values), and execution resumes at point `L1`.

Speculative execution in processors

Example: branch prediction.

```
        load x0, [x1]
        branch if x0 = 0 to L1
        mul x3, x2, x3
        add x4, x3, x4
        branch to L2
L1:     ...
```

If `x0` is not zero, the prediction is confirmed, and the processor *commits* the actions of the speculated instructions, then continues execution.

Speculative execution in processors

Many instructions can be executed speculatively:

- arithmetic and logical operations
- branches
- memory reads
- memory writes (as long as they stay in the write buffer).

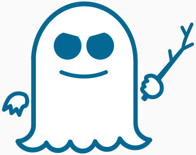
The processor can backtrack on these executions by rolling back the modified registers and the memory stores.

Speculative execution in processors

Many instructions can be executed speculatively:

- arithmetic and logical operations
- branches
- memory reads (incl. accessing and updating the caches)
- memory writes (as long as they stay in the write buffer).

The processor can backtrack on these executions by rolling back the modified registers and the memory stores.
However, the cache state is kept, not rolled back.



Principle:

A privileged piece of code, executed speculatively,
reads memory at an address that depends on a secret.

The attacker measures the state of the cache and infers part of the secret.

Spectre v1: circumventing array bounds checks

```c
const unsigned int len = ...;
unsigned char buf[len];

int f(unsigned int idx, int table[256 * CACHE_LINE_SIZE])
{
    int i;
    if (idx < len)
        return table[buf[idx] * CACHE_LINE_SIZE];
    else
        return -1;
}
```

Function `f` runs in privileged mode, e.g. within the kernel.

Parameters `idx` and `table` are controlled by the attacker.

Spectre v1: circumventing array bounds checks

```
const unsigned int len = ...;
unsigned char buf[len];

int f(unsigned int idx, int table[256 * CACHE_LINE_SIZE])
{
    int i;
    if (idx < len)
        return table[buf[idx] * CACHE_LINE_SIZE];
    else
        return -1;
}
```

The attacker calls `f` several times with valid `idx` values (to train branch prediction), then prepares the cache and calls `f` with `idx` too large.

Spectre v1: circumventing array bounds checks

```
const unsigned int len = ...;
unsigned char buf[len];

int f(unsigned int idx, int table[256 * CACHE_LINE_SIZE])
{
    int i;
    if (idx < len)
        return table[buf[idx] * CACHE_LINE_SIZE];
    else
        return -1;
}
```

The `then` branch of the `if` is executed speculatively.

The value of the byte at `buf + idx` leaks via the cache.

This makes it possible to read a good chunk of the kernel memory space.

Protections against Spectre v1

Harden array bounds checks against speculation (macros `_nospec` in the Linux kerne).

The usual access with bounds checking:

```
T safe_read(T * tbl, unsigned len, unsigned idx)
{
    if (idx >= len) abort();
    return tbl[idx];
}
```

Protections against Spectre v1

Harden array bounds checks against speculation (macros `_nospec` in the Linux kerne).

Access hardened against speculation:

```
T safe_read_nospec(T * tbl, unsigned len, unsigned idx)
{
    if (idx >= len) abort();
    return tbl[sel(idx < len, idx, 0)];
}
```

The effect of `sel(idx < len, idx, 0)` is to clip the `idx` value so that it is never too big during speculative execution.

During normal execution, `idx < len` and access takes place at index `idx`, as desired.

Variation: circumvent the BPF static code verifier

(Schlüter, Borkmann, Krysiuk, *BPF and Spectre* PRISC 2022.)

`r1`: valid pointer to a reachable variable.

`r2`: aribtrary integer, controlled by the attacker.

```
1:   if r0 != 0 goto line 3
2:   r1 = r2
3:   if r0 != 1 goto line 5
4:   r2 = load(r1)
5:   // leak the value of r2
```

The verifier knows that `r0` cannot be both 0 and 1. Therefore, `load(r1)` at line 4 is a load from a valid address.

If both conditional branches (lines 1 and 3) are predicted as not taken, the code speculatively reads address `r2`.

Generalization: attacks by transient executions

Many kinds of transient state in processors can leak data via timing channels.

→ Seminar by F. Piessens on 21/04.

Spectre v1 Bounds Check Bypass	2017-5753
Spectre v2 Branch Target Injection	2017-5715
SpectreRSB[25]**/ret2spec**[26] Return Mispredict	2018-15572
Meltdown Rogue Data Cache Load	2017-5754
Spectre-NG v3a	2018-3640
Spectre-NG v4 Speculative Store Bypass	2018-3639
Foreshadow L1 Terminal Fault, L1TF	2018-3615
Spectre-NG Lazy FP State Restore	2018-3665
Spectre-NG v1.1 Bounds Check Bypass Store	2018-3693
Spectre-NG v1.2 Read-only Protection Bypass (RPB)	
Foreshadow-OS L1 Terminal Fault (L1TF)	2018-3620
Foreshadow-VMM L1 Terminal Fault (L1TF)	2018-3646
RIDL/ZombieLoad Microarchitectural Fill Buffer Data Sampling (MFBDS)	2018-12130

RIDL Microarchitectural Load Port Data Sampling (MLPDS)	2018-12127
RIDL Microarchitectural Data Sampling Uncacheable Memory (MDSUM)	2019-11091
Fallout Microarchitectural Store Buffer Data Sampling (MSBDS)	2018-12126
Spectre SWAPGS[34][35][36]	2019-1125
RIDL/ZombieLoad v2 Transactional Asynchronous Abort (TAA)[37][38][39]	2019-11135
RIDL/CacheOut L1D Eviction Sampling (L1DES)[41][42][43]	2020-0549
RIDL Vector Register Sampling (VRS)[41][42]	2020-0548
Load Value Injection (LVI)[44][45][46][47]	2020-0551
Take a Way[48][49]	
CROSSTalk Special Register Buffer Data Sampling (SRBDS) [52][53][54]	2020-0543
Blindside[55]	
Branch History Injection (BHI)	CVE-2022-0001 CVE-2022-0002

Summary

Summary on timing attacks and cache attacks

Execution time is a significant source of information leaks.

These leaks are amplified by features of modern processors: caches, speculative execution, etc.

Some (mostly cryptographic) computations can be hardened against these attacks via constant-time programming, or blinding, or hardware assistance (crypto coprocessors).

Some (incomplete?) protections can be found in operating systems and in Web browsers (JavaScript execution engines).

Intel SGX enclaves are being retired, in part because they are too vulnerable to transient execution attacks.

Related attacks

By observation:

- Power consumption.
- Electromagnetic emission.
- And much more $\rightarrow$ Anderson, *Security Engineering*, chap. 19.

By perturbation:

- Fault injection $\rightarrow$ seminar by K. Heydemann on 07/04