Distributed Operating Systems

Side-Channels

Marcus Hähnel

July 4, 2016

What is a Side-Channel?

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Visual side-channel

Which call has a positive connotation?

Definition

Side-Channel

A side-channel is an unintended information source which enables the extraction of information that is processed through a means of communication or computation.

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A side-channel is an unintended information source which enables the extraction of information that is processed through a means of communication or computation.

Phone example

Primary source	Audio signal
Unintended source	Visual information (e.g. facial expression, lip movement)

Side-Channel usage

Malicious

Extracting ...

- ... other customers data across virtual machines

Side-Channel usage

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- ... other customers data across virtual machines
- ... crypto keys from applications in different address spaces

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Benign

- ... detecting rootkits

Side-Channel usage

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Extracting ...

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- ... crypto keys from applications in different address spaces
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Benign

- ... detecting rootkits
- ... detecting hardware trojans

Typical Side-Channels

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Any measureable parameter of the system of of its individual operations that changes depending on the processed data.

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- Time (Duration)

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- Time (Duration)
- Error behavior (Out of memory? No more file handles?)

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What is a suitable side-channel

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Example parameters

- Time (Duration)
- Error behavior (Out of memory? No more file handles?)
- Power usage

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What is a suitable side-channel

Any measureable parameter of the system of of its individual operations that changes depending on the processed data.

Example parameters

- Time (Duration)
- Error behavior (Out of memory? No more file handles?)
- Power usage
- Radiation (Heat, EM-Radiation)

Typical Side-Channels

What is a suitable side-channel

Any measureable parameter of the system of of its individual operations that changes depending on the processed data.

Example parameters

- Time (Duration)
- Error behavior (Out of memory? No more file handles?)
- Power usage
- Radiation (Heat, EM-Radiation)
- Unexpected persistence of data (Cold-boot, memory re-use)

Attack vector

The duration of an attacker observable operation depends on the data processed by the victim

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Example - Graphics Processing

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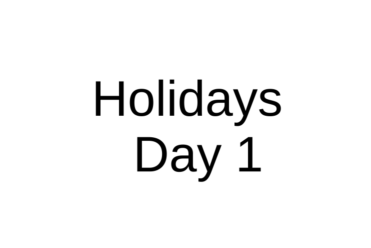
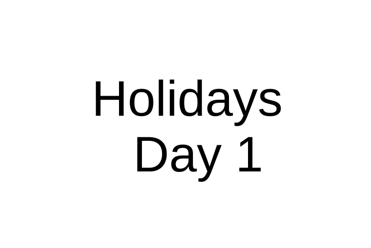
Example - Graphics Processing



Attack vector

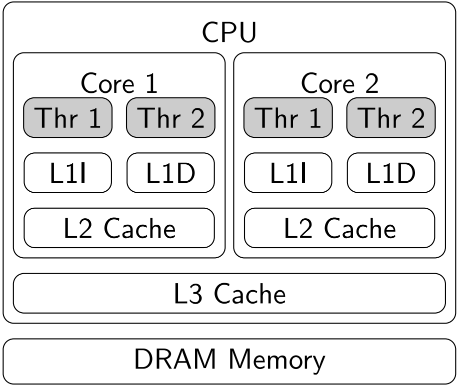
The duration of an attacker observable operation depends on the data processed by the victim

Example - Graphics Processing

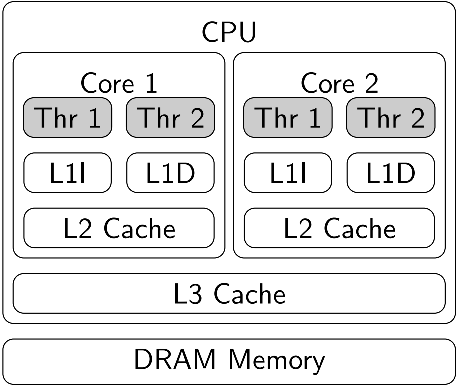


Convert to png: 1 s vs. 17 s

Cache Side-Channel



Cache Side-Channel



Level	Size	Cycles
L1D	32 KiB	4
L1I	32 KiB	4
L2	256 KiB	12
L3	3 MiB	36
DRAM	large	250

Prime & Probe

Concept

- Fill cache with known data (Prime)
- Repeatedly measure how long it takes to access this data
- Longer duration means cache-line was ”stolen”

Prime & Probe

Example (Victim)

```
struct Person {
  char name[56];
  double account;
} Alice, Bob;

void transact(Person& p) {
  p.account += 4000;
}

transact(Alice);
```

L1D 8-way set cache

Tag (20)	Index (6)	Offset (6)
(Alice)	0	56
(Bob)	1	56

Prime & Probe

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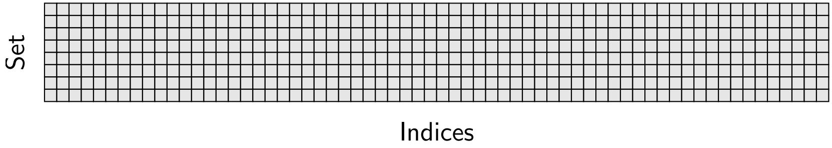
Attacker



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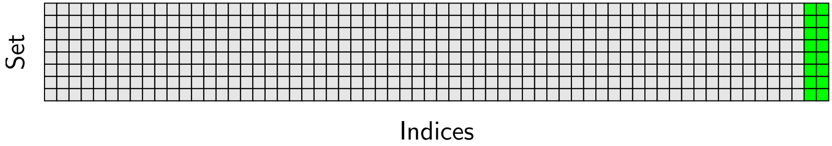

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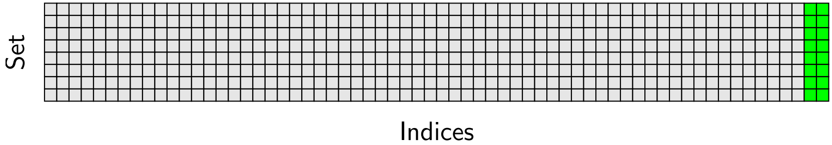

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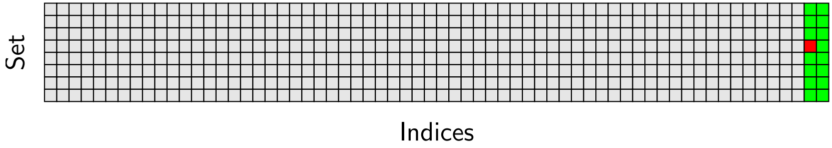
Attacker

Prime, Probe, Detect



Evict & Time

Prime & Probe shortcomings

- Hard with smart caches

Alternative: Evict & Time

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- Evict cache (by filling with known data)

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Alternative: Evict & Time

- Possible if execution of victim code is under attacker control
- Evict cache (by filling with known data)
- Run victim and measure runtime

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Alternative: Evict & Time

- Possible if execution of victim code is under attacker control
- Evict cache (by filling with known data)
- Run victim and measure runtime
- Evict most of the cache

Evict & Time

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Alternative: Evict & Time

- Possible if execution of victim code is under attacker control
- Evict cache (by filling with known data)
- Run victim and measure runtime
- Evict most of the cache
- Run victim again and measure time

Evict & Time

Prime & Probe shortcomings

- Hard with smart caches
- Probing is prone to many false positives

Alternative: Evict & Time

- Possible if execution of victim code is under attacker control
- Evict cache (by filling with known data)
- Run victim and measure runtime
- Evict most of the cache
- Run victim again and measure time
- Time difference tells if victim used non-evicted cache-line

Challenges

Smart Caches

Smart Caches "reserve" parts of the L3 cache for individual cores. This makes priming hard.

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Detect access patterns. Probing may cause prefetch of evicted line leading to false-negative.

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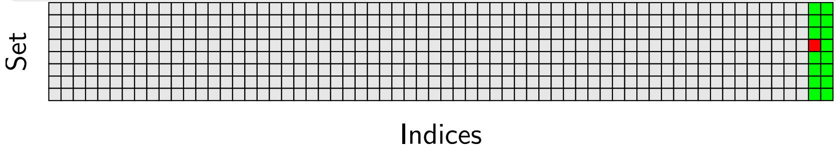

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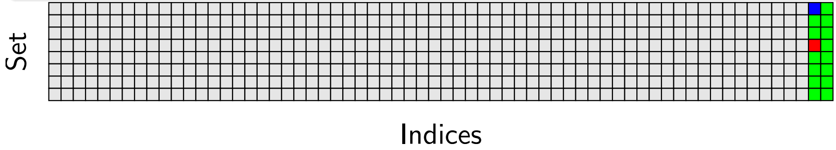

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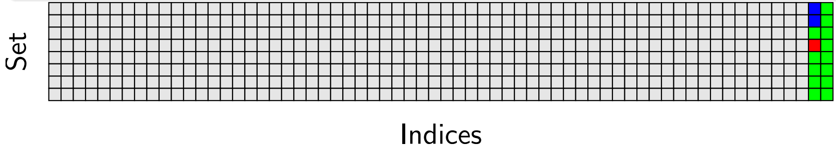

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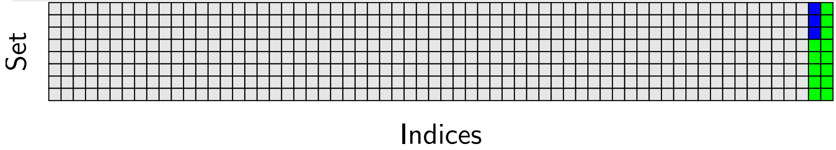

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Detect access patterns. Probing may cause prefetch of evicted line leading to false-negative.

Scheduling

May evict primed data leading to 'blind times'

Pagefault Side-Channel

Assumption

Removing the OS from the TCB

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Scenario: Shielding Systems

- InkTag: Hypervisor / paging based isolation between OS and Application

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- Intel SGX: Hardware-based isolation through read-protected memory

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Removing the OS from the TCB

Scenario: Shielding Systems

- InkTag: Hypervisor / paging based isolation between OS and Application
- Intel SGX: Hardware-based isolation through read-protected memory

Vulnerability

- These systems don't trust OS but use it to configure hardware
- OS makes a powerful adversary

Controlled Channel Attacks

First attack vector against Intel SGX

Controlled-Channel Attacks: Deterministic Side Channels for Untrusted Operating Systems

Yuanzhong Xu, Weidong Cui, and Marcus Peinado, MSR

System Model

- OS cannot directly observe memory or registers of application
- OS controls virtual memory

Example: string length

Example (Source, simplified)

```
//str on heap
int strlen(char* str) {
  int len = 0; //Stack
  while (*(str++) != '\0')
    len++;
  return len;
}
```

- Heap not present

Example: string length

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	Phys-Addr	other Flags	P
Heap	...	...	0
Stack	...	...	0

Attackers Knowledge

Length = 0

Example: string length

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Example: string length

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//str on heap
int strlen(char* str) {
  int len = 0; //Stack
  while (*(str++) != '\0')
    len++;
  return len;
}
```

- Heap not present
- Stack not present

	Phys-Addr	other Flags	P
Heap	...	...	1
Stack	...	...	0

Attackers Knowledge

Length = 0

Example: string length

Example (Source, simplified)

```
//str on heap
int strlen(char* str) {
  int len = 0; //Stack
  while (*(str++) != '\0')
    len++;
  return len;
}
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- Heap not present
- Stack not present

	Phys-Addr	other Flags	P
Heap	...	...	1
! Stack	...	...	0

Attackers Knowledge

Length = 1

Example: string length

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//str on heap
int strlen(char* str) {
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  while (*(str++) != '\0')
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- Heap not present
- Stack not present

	Phys-Addr	other Flags	P
Heap	...	...	0
Stack	...	...	1

Attackers Knowledge

Length = 1

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Stack	...	...	1

Attackers Knowledge

Length = 1

Example: string length

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  while (*(str++) != '\0')
    len++;
  return len;
}
```

- Heap not present
- Stack not present

	Phys-Addr	other Flags	P
Heap	...	...	1
Stack	...	...	0

Attackers Knowledge

Length = 1

Example: string length

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    len++;
  return len;
}
```

- Heap not present
- Stack not present

	Phys-Addr	other Flags	P
Heap	...	...	1
! Stack	...	...	0

Attackers Knowledge

Length = 2

Example: string length

Example (Source, simplified)

```
//str on heap
int strlen(char* str) {
  int len = 0; //Stack
  while (*(str++) != '\0')
    len++;
  return len;
}
```

- Heap not present
- Stack not present

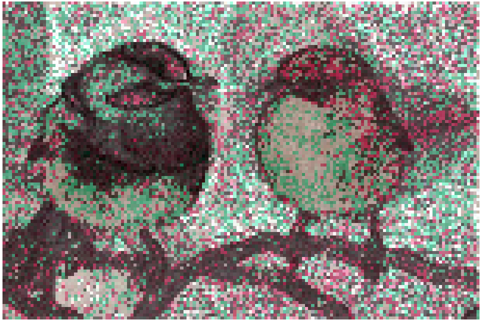
	Phys-Addr	other Flags	P
Heap	...	...	0
Stack	...	...	1

Attackers Knowledge

Length = 2

Example Results

Example Results



Example Results

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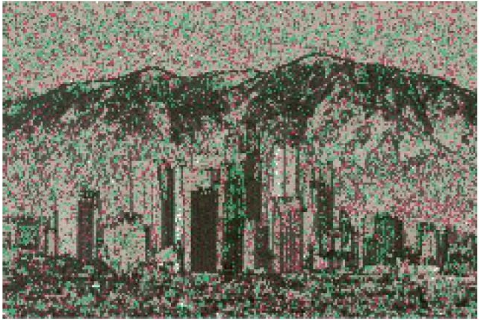

Example Results

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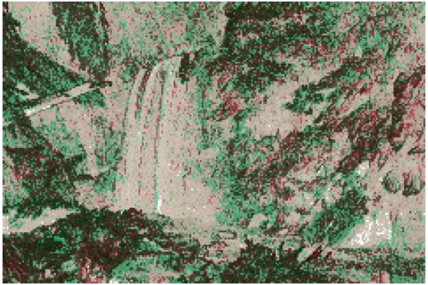

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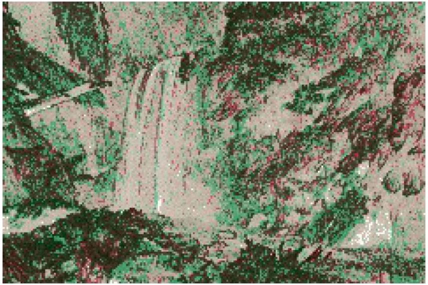

Power channels

Features

- Requires no capability to run code
- Hard to detect
- In theory usable remotely

Power channels

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- Requires no capability to run code
- Hard to detect
- In theory usable remotely

Requirements

- (very) high-resolution power measurement
- physical access to power supply
- detailed knowledge about exact processor used

Example

Example (Square-And-Multiply)

```
int exp(int base, int e) {
  int res = 1;
  while (e != 0) {
    res *= res; //square
    if (e & 1) res *= base; //multiply
    e >>= 1;
  }
  return res;
}
```

Example

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int exp(int base, int e) {
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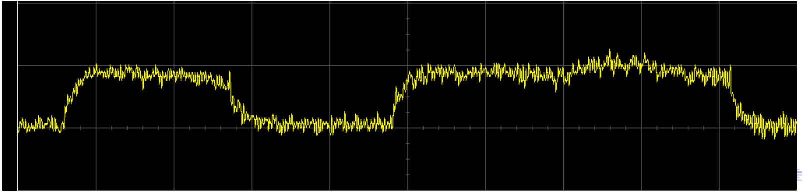

Acoustic channels

Features

- Requires no capability to run code
- Hard to detect
- Usable remotely, bugs

Acoustic channels

Features

- Requires no capability to run code
- Hard to detect
- Usable remotely, bugs

Requirements

- Good audio equipement
- Reliable audio filters
- Knowledge about typing style
- Knowledge about hardware used

Example

Password typing attack

Keyboard Acoustic Emanations Revisited
*L*i Zhuang, Feng Zhou, J. D. Tygar
University of California, Berkeley

Example

Password typing attack

Keyboard Acoustic Emanations Revisited

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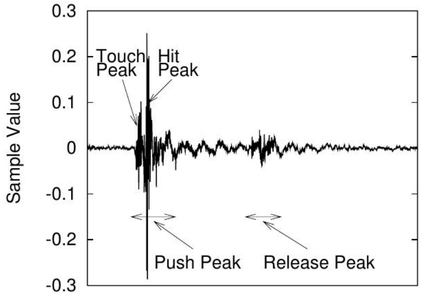

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Keyboard Acoustic Emanations Revisited

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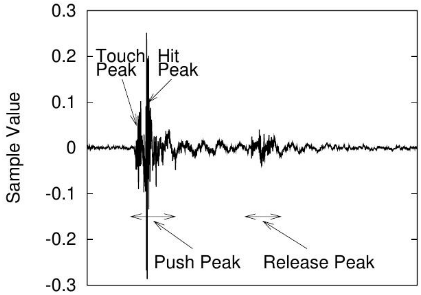

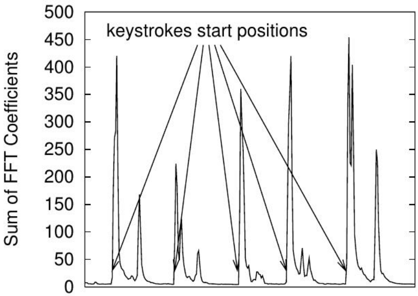

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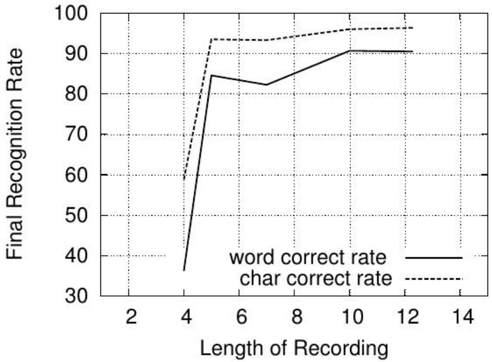
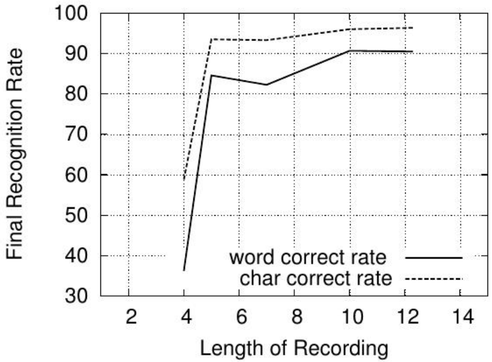

Final Recognition Rate
100
90
80
70
60
50
40
30
2
4
6
8
10
12
14
Length of Recording
word correct rate
char correct rate

Results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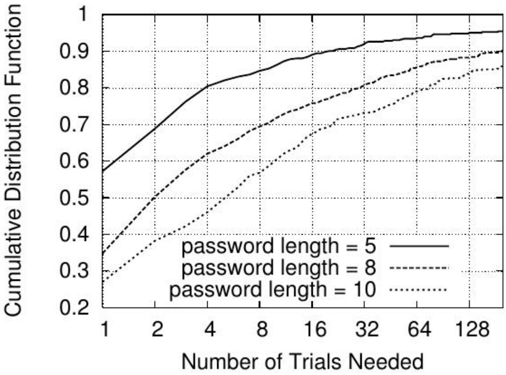

Cumulative Distribution Function
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
2
4
8
16
32
64
128
Number of Trials Needed
password length = 5
password length = 8
password length = 10

Electro Magnetic (EM) Radiation

Features

- Requires no capability to run code
- Hard to detect
- No "wire-cutting" needed

Electro Magnetic (EM) Radiation

Features

- Requires no capability to run code
- Hard to detect
- No "wire-cutting" needed

Requirements

- Expensive detection equipement (antenna, scope)
- Detailed knowledge about hardware used

Warning

- NOT a classical side-channel
- no indirect observance of data $\rightarrow$ direct

Warning

- NOT a classical side-channel
- no indirect observance of data $\rightarrow$ direct
- is still interesting

Warning

- NOT a classical side-channel
- no indirect observance of data → direct
- is still interesting

Features

- Access to data you thought is gone
- Usually if you get data it is pretty good

Examples

Example (Your friend, the compiler)

```
void secret() {
  char* buf = (char*)malloc(1024);
  // put sth. secret into buf
  free(buf);
}
```

Problem

Examples

Example (Your friend, the compiler)

```
void secret() {
  char* buf = (char*)malloc(1024);
  // put sth. secret into buf
  free(buf);
}
```

Problem

What if someone gets the same memory?

Examples

Example (Your friend, the compiler)

```
void secret() {
  char* buf = (char*)malloc(1024);
  // put sth. secret into buf
  memset(buf,'\0',1024);
  free(buf);
}
```

Problem

?

Examples

Example (Your friend, the compiler)

```
void secret() {
  char* buf = (char*)malloc(1024);
  // put sth. secret into buf
  memset(buf,'\0',1024);
  free(buf);
}
```

Problem

The compiler could optimize the memset out

Cold Boot

Lest We Remember: Cold Boot Attacks on Encryption Keys

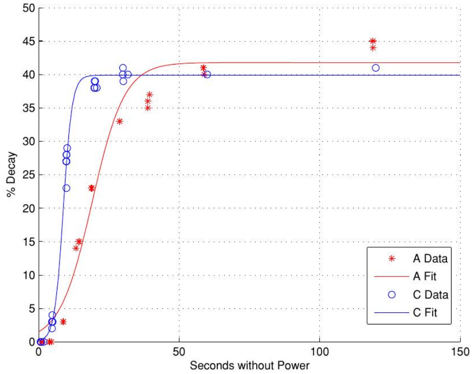
J. Alex Halderman, Seth D. Schoen, Nadia Heninger, William Clarkson, William Paul, Joseph A. Calandrino , Ariel J. Feldman, Jacob Appelbaum, and Edward W. Felten
Princeton University, Electronic Frontier Foundation, Wind River Systems

Performance

	Seconds w/o power	Error % at operating temp.	Error % at -50 °C
A	60	41	(no errors)
	300	50	0.000095
B	360	50	(no errors)
	600	50	0.000036
C	120	41	0.00105
	360	42	0.00144
D	40	50	0.025
	80	50	0.18

Performance

	Seconds w/o power	Error % at operating temp.	Error % at -50 °C
A	60	41	(no errors)
	300	50	0.000095
B	360	50	(no errors)
	600	50	0.000036
C	120	41	0.00105
	360	42	0.00144
D	40	50	0.025
	80	50	0.18



Results

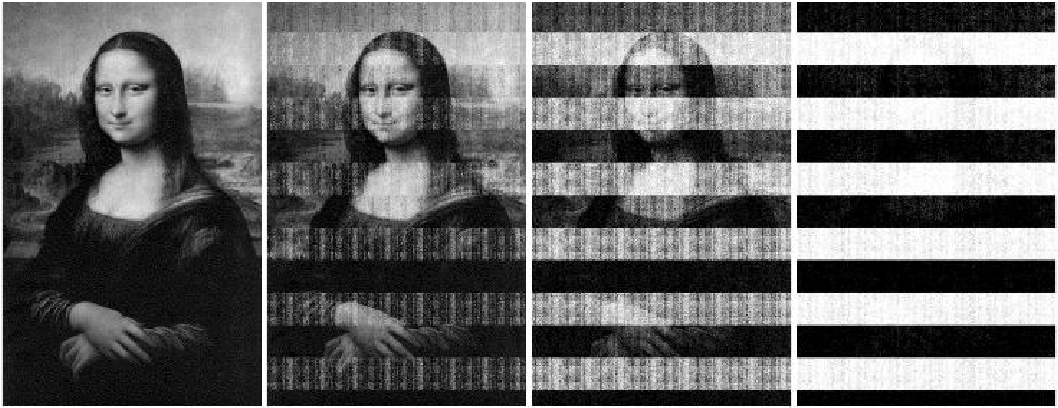


Figure: Image after 5, 30, 60 and 300 seconds

Defense mechanisms

Approach

Make all behavior that is observable independent of the input data

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Alternative

Remove ability to observe the given aspect

Timing channels

Blinding

- Modify data computed on in such a way that operation always takes equal time
- Requires inverse unblinding that can be performed after the operation
- Noise injection

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Prevent statistical analysis

Avoid running the same algorithm on attacker observable data multiple times.
Challenge-response is prone to this!

Page-Fault Channel / Fault channels

Detection

- Given a reliable time-source constant page-faults can be detected as unusually long program runtime
- SGX v2 can notify the protected program of page-faults. It may chose not to compute on secret data if such page-faults come unexpected

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Prevention

- Don't use paging. Require all memory to be mapped
- Avoid dynamic allocation of shared resources

Power / Acoustic / EM

Power Channel

- Use internal power source or high-capacitance in power path for sensitive instructions (low pass effect)
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Electro Magnetic Radiatiom

- Use EM shielding on chips
- Use EM shielding for case

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Cold Boot

- Combined with the above very hard! Use shut down and not hybernate / suspend. After a few seconds you should be fine.
- Idea: Write secret data to physical 0x7c00 - 0x7dFF! MBR is loaded there :)

Summary

Sidechannels

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There are a plethora of side-channels in every normal system! We only touched on a few methods! Your imagination is the limit.

Defense

... is very hard. The best way is to design algorithms from the ground up with side-channels in mind!

Overview

- http://csrc.nist.gov/groups/STM/cmvp/documents/fips140-3/physec/papers/physecpaper19.pdf

Cache Side-Channels

- https://www.usenix.org/system/files/conference/usenixsecurity14/sec14-paper-yarom.pdf

Page-fault Channel

- https://www.microsoft.com/en-us/research/wp-content/uploads/2016/02/ctrlchannels-oakland-2015.pdf

Acoustic Channels

- http://people.eecs.berkeley.edu/ tygar/papers/Keyboard_Acoustic_Emanations_Revisited/ccs.pdf

Cold Boot

- https://www.usenix.org/event/sec08/tech/full_papers/halderman/halderman.pdf

Remanence

- http://www.daemonology.net/blog/2014-09-04-how-to-zero-a-buffer.html
- http://www.daemonology.net/blog/2014-09-06-zeroing-buffers-is-insufficient.html

Defense

- https://www.blackhat.com/presentations/bh-usa-08/McGregor/BH_US_08_McGregor_Cold_Boot_Attacks.pdf
- http://fc16.ifca.ai/preproceedings/21_Anand.pdf
- https://www.semanticscholar.org/paper/Software-mitigations-to-hedge-AES-against-cache-Brickell-Graunke/11c6fddeff9e2f95c8cf238ea9f12f8ffae7cf8c/pdf