Distributed Operating Systems

Side-Channels

Marcus Hähnel (marcus.haehnel@kernkonzept.com)

29.06.2020

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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Phone example

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

2001: A Space Odysee — Video

Side-Channel usage

Side-Channel usage

Malicious

Extracting ...

- ... other customers data across virtual machines

Side-Channel usage

Malicious

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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

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Benign

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

Typical Side-Channels

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

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- Microarchitectural state

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- Microarchitectural state
- Power usage
- Radiation (Heat, EM-Radiation)

Typical Side-Channels

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

Example parameters

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

Timing Channels

Attack vector

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

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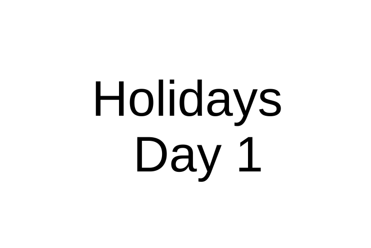
The duration of an attacker observable operation depends on the data processed by the victim

Example - Graphics Processing



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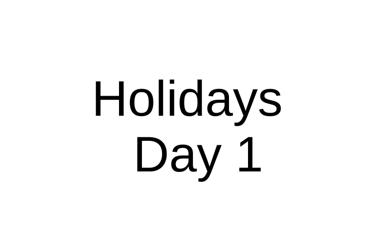

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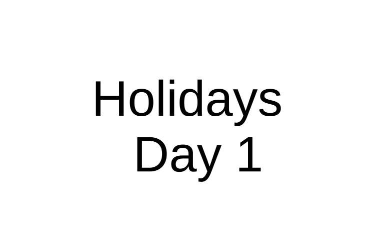
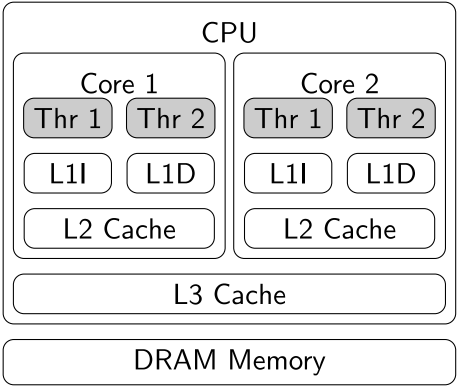


Convert to png: 1 s vs. 17 s

Cache Side-Channel



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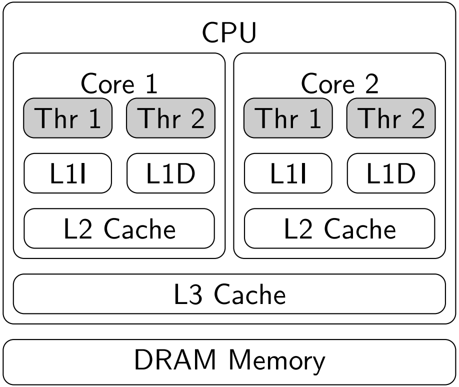

Level	Size	Cycles
L1D	32 KiB	4
L1I	32 KiB	4
L2	256 KiB	12
L3	3 MiB	36
DRAM	large	250

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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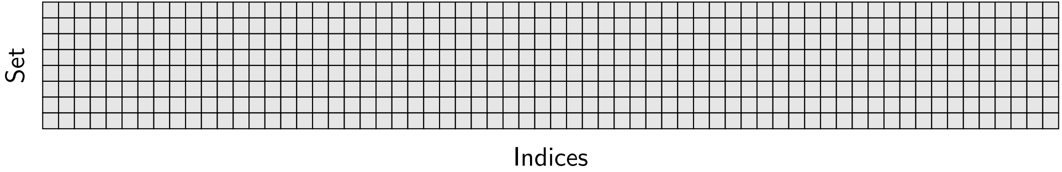

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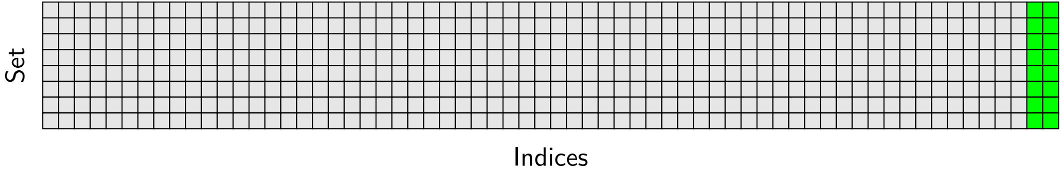

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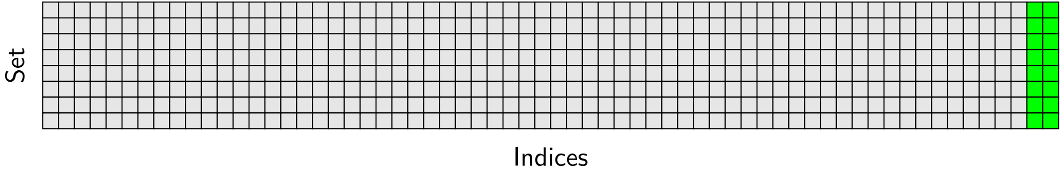

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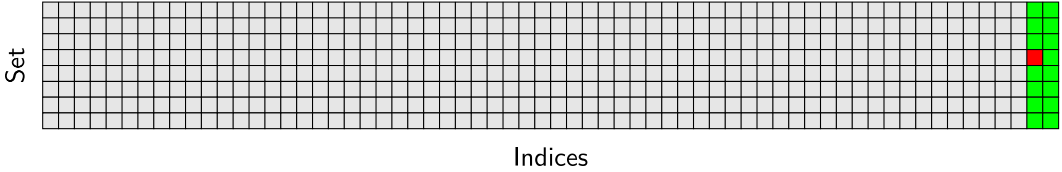
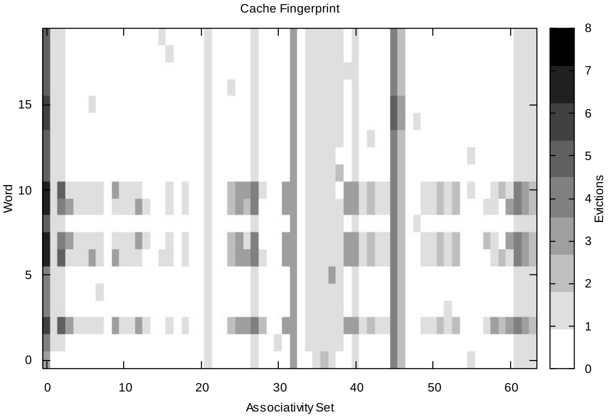
Attacker

Prime, Probe, Detect





Results of prime-probe observations for 20 distinct words (rows). Darker fields indicate more evicted ways within an 8-way associativity set. Vertical lines identify cache addresses evicted in every observation.

Evict & Time

Prime & Probe shortcomings

- Hard with smart caches

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- Run victim and measure runtime

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- Possible if execution of victim code is under attacker control
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- Evict most of the cache

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- Run victim and measure runtime
- Evict most of the cache
- Run victim again and measure time

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
- 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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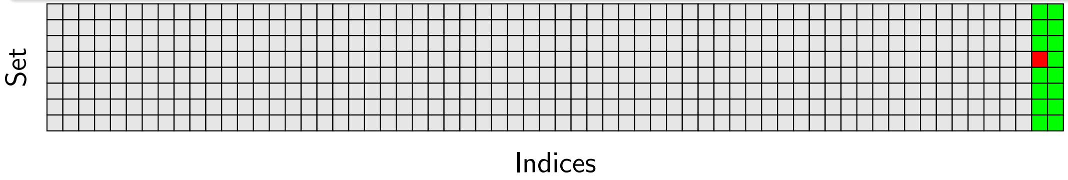

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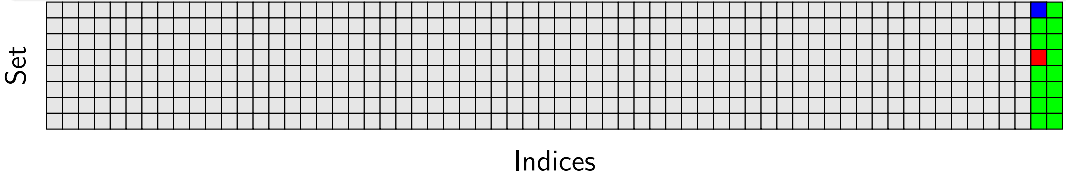

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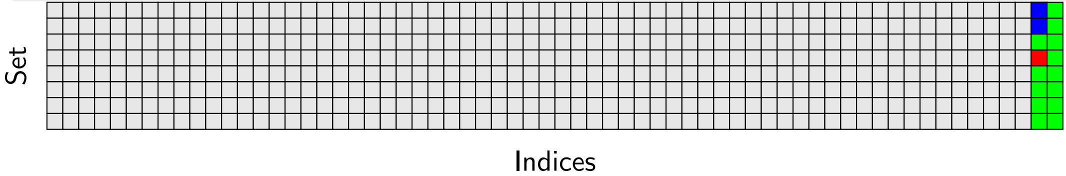

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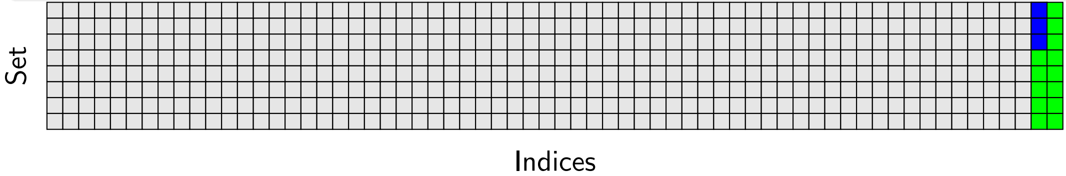

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Detect access patterns. Probing may cause prefetch of evicted line leading to false-negative.

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

Attackers Knowledge

Length = 0

Example: string length

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Length = 0

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  return len;
}
```

- Heap not present
- Stack not present

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

Attackers Knowledge

Length = 0

Example: string length

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//str on heap
int strlen(char* str) {
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	Phys-Addr	other Flags	P
Heap	...	...	1
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Attackers Knowledge

Length = 1

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Attackers Knowledge

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Attackers Knowledge

Length = 2

Example: string length

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	Phys-Addr	other Flags	P
Heap	...	...	0
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Attackers Knowledge

Length = 2

Example Results (PF vs. Cache Channel)

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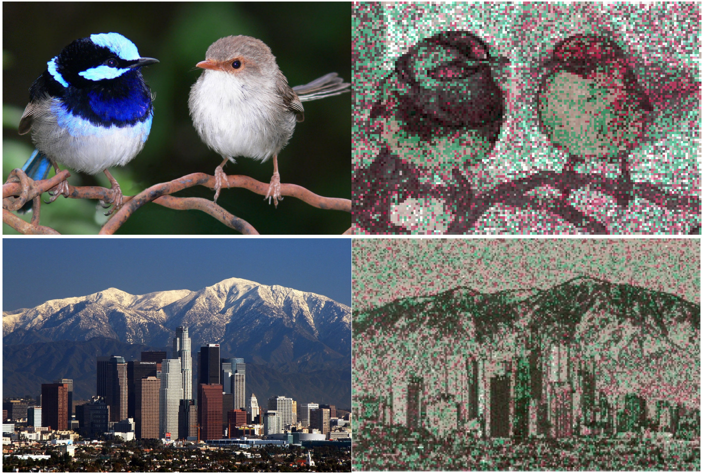
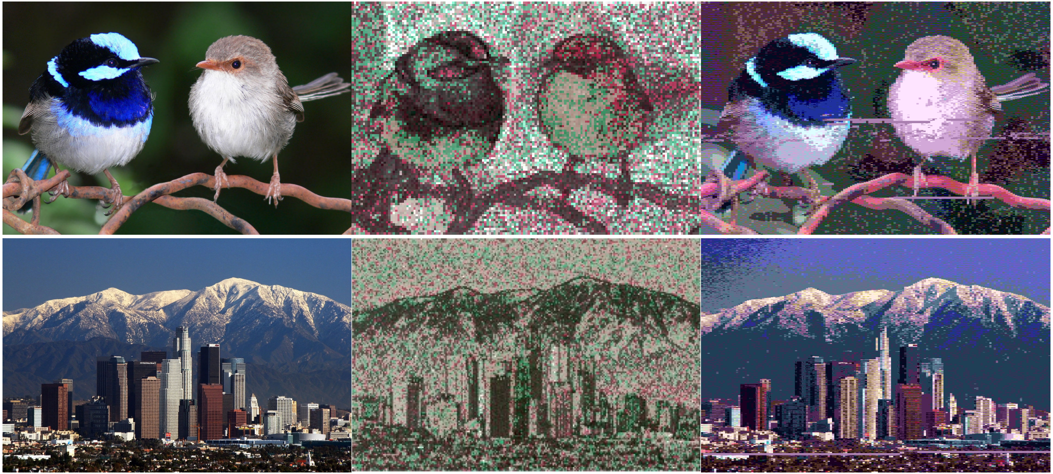


Example Results (PF vs. Cache Channel)



Microarchitectural Channels

Leaking speculative CPU-state to attackers

Moritz Lipp, Michael Schwarz, Daniel Gruss, Thomas Prescher, Werner Haas, Stefan Mangard, Paul Kocher, Daniel Genkin, Yuval Yarom, Mike Hamburg

Examples and figures taken from the Meltdown paper

Meltdown

Spectre

Side-Effects of Out-of-Order execution

Toy Example

```
raise_exception();
// the line below is never reached
access(probe_array[data*4096]);
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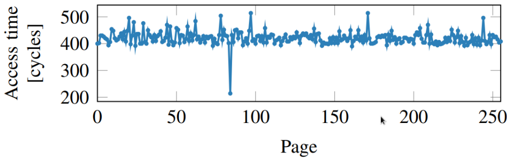

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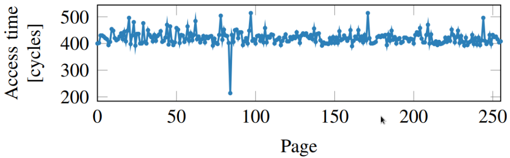

Constraints

- Raising the exception should be slow
- Accessing the array should be fast

Meltdown example code

```
; rcx = kernel address
; rbx = probe array
retry:
  MOV AL, byte [RCX]
  SHL RAX, 12
  JZ retry
MOV RBX, qword [RBX + RAX]
```

Power channels

Features

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

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- 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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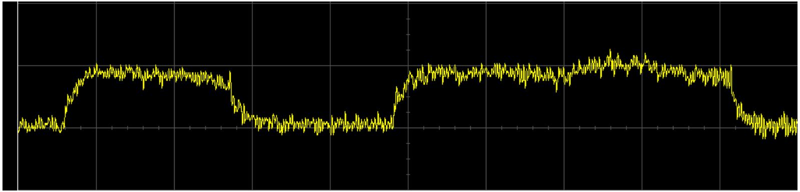

Source: https://commons.wikimedia.org/wiki/File:Power_attack.png

Acoustic channels

Features

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

Acoustic channels

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- Hard to detect
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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

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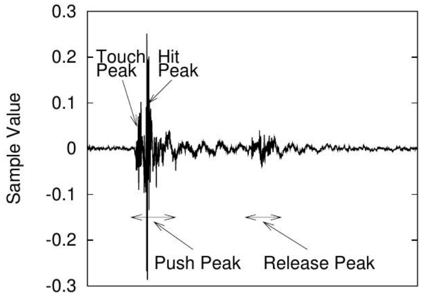

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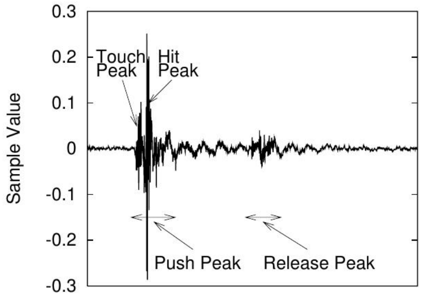
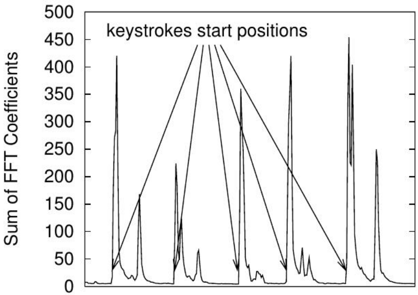
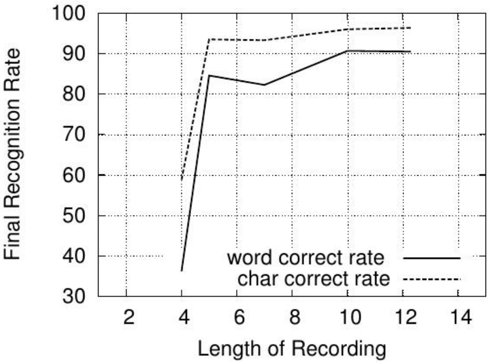
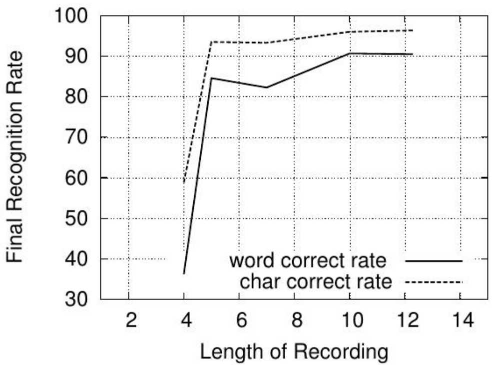




Results


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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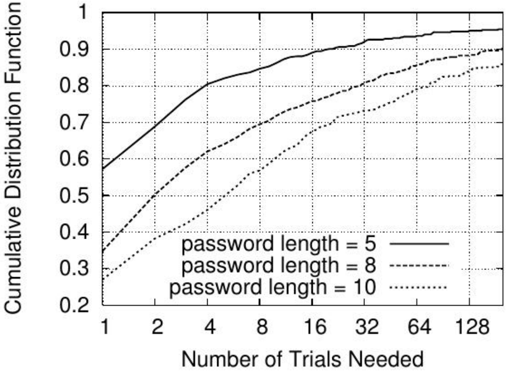

Cumulative Distribution Function
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
2
4
8
16
32
64
128
Number of Trials Needed
password length = 5
password length = 8
password length = 10

Electro Magnetic (EM) Radiation

Features

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

Electro Magnetic (EM) Radiation

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

Requirements

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

Data Remanence

Warning

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

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Features

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

Examples / Software

Example (Your friend, the compiler)

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

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

Problem

What if someone gets the same memory?

Examples / Software

Example (Your friend, the compiler)

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```
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

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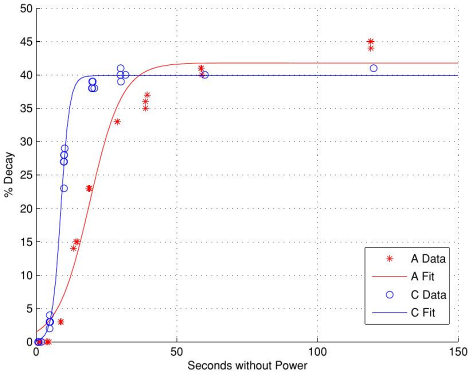

Results

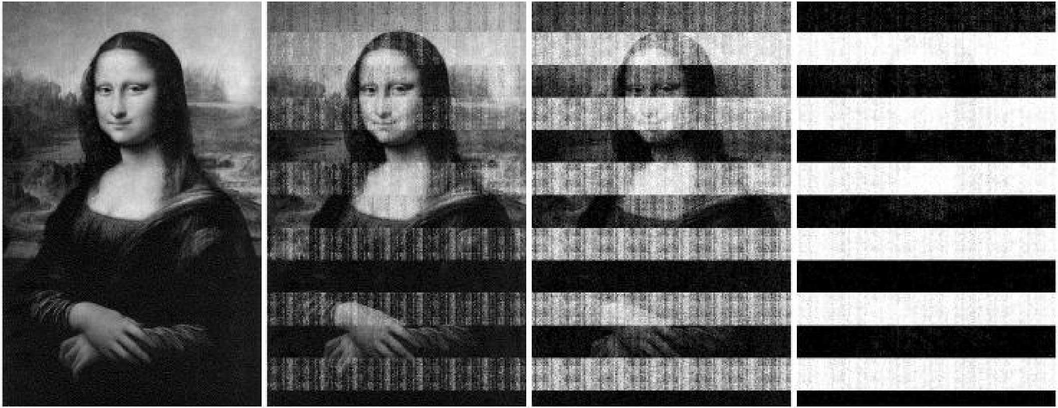

Image after 5, 30, 60 and 300 seconds

Defense mechanisms

Approach

Make all behavior that is observable independent of the input data

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Complete independence is not always achievable
(Algorithmic requirements, some channels hard to control)

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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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Example: Move different data processed in different branch targets to same cacheline

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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

Meltdown / Spectre

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- KPTI - Kernel Page Table Isolation
- HW: Don't speculate across protection boundarys

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Spectre

- Speculation Fences
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Power / Acoustic / EM

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- Use internal power source or high-capacitance in power path for sensitive instructions (low pass effect)
- Use same-complexity instructions for input-dependent code (mul instead of shift)

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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

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Attacks

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

- http://www.ieee-security.org/TC/SP2015/papers-archived/6949a640.pdf
- https://www.usenix.org/system/files/conference/atc17/atc17-hahnel.pdf

Microarchitectural Channels

- https://meltdownattack.com/meltdown.pdf
- https://spectreattack.com/spectre.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
- https://www.cc.gatech.edu/~slee3036/papers/shih:tsgx.pdf