Distributed Operating Systems
Side-Channels

Marcus Hähnel (marcus.haehnel@kernkonzept.com)

29.06.2020
What is a Side-Channel?
What is a Side-Channel?

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.
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.

Phone example
- **Primary source**: Audio signal
- **Unintended source**: Visual information (e.g. facial expression, lip movement)
2001: A Space Odyssey — Video
## Side-Channel usage

### Internal Attack Vectors
- Malicious
  - Extracting... other customers data across virtual machines
  - Extracting... crypto keys from applications in different address spaces
  - Extracting... data from inaccessible processors

### External Attack Vectors
- Benign
  - Detecting rootkits
  - Detecting hardware trojans
Side-Channel usage

Malicious

Extracting ...

- ... other customers data across virtual machines
Side-Channel usage

Malicious

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Benign

- ... detecting rootkits
Side-Channel usage

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Benign

- ... detecting rootkits
- ... detecting hardware trojans
Typical Side-Channels

What is a suitable side-channel
Any measurable 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)
Typical Side-Channels

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Timing Channels

**Attack vector**

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

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

**Example - Graphics Processing**

Holidays
Day 1
Timing Channels

**Attack vector**

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

**Example - Graphics Processing**

- Holidays Day 1
Timing Channels

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

Example - Graphics Processing

Holidays Day 1

Convert to png: 1 s vs. 17 s
Cache Side-Channel

```
CPU

Core 1
  Thr 1
  L1I
  L1D
  L2 Cache

Core 2
  Thr 1
  L1I
  L1D
  L2 Cache

L3 Cache

DRAM Memory
```
Cache Side-Channel

<table>
<thead>
<tr>
<th>Level</th>
<th>Size</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1D</td>
<td>32 KiB</td>
<td>4</td>
</tr>
<tr>
<td>L1I</td>
<td>32 KiB</td>
<td>4</td>
</tr>
<tr>
<td>L2</td>
<td>256 KiB</td>
<td>12</td>
</tr>
<tr>
<td>L3</td>
<td>3 MiB</td>
<td>36</td>
</tr>
<tr>
<td>DRAM</td>
<td>large</td>
<td>250</td>
</tr>
</tbody>
</table>
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)

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

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

transact(Alice);
```

L1D 8-way set cache

<table>
<thead>
<tr>
<th></th>
<th>Tag (20)</th>
<th>Index (6)</th>
<th>Offset (6)</th>
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<td>(Alice)</td>
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Prime & Probe

Example (Victim)

```c
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Attacker

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L1D 8-way set cache

Set

Indices
Prime & Probe

Example (Victim)

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```

Attacker

Prime

L1D 8-way set cache

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Prime & Probe

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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
Evict & Time

Prime & Probe shortcomings

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

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Alternative: Evict & Time
- Possible if execution of victim code is under attacker control
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- Possible if execution of victim code is under attacker control
- Evict cache (by filling with known data)
Evict & Time

Prime & Probe shortcomings
- Hard with smart caches
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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 & 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
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
## 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.
Challenges

**Smart Caches**

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

**Prefetchers**

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

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**Prefetchers**

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
Pagefault Side-Channel

Assumption

Removing the OS from the TCB

Scenario: Shielding Systems

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

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
Pagefault Side-Channel

Assumption
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)

```c
// 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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Attackers Knowledge
Length = 0
Example: string length

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

- Heap not present
- Stack not present

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**Attackers Knowledge**

Length = 0
Example: string length

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Attackers Knowledge

Length = 1
Example: string length

Example (Source, simplified)

```
// str on heap
int strlen(char* str) {
    int len = 0; // Stack
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```

- Heap not present
- Stack not present

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Attackers Knowledge

Length = 1
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Attackers Knowledge

Length = 2
Example: string length

Example (Source, simplified)

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

- Heap not present
- Stack not present

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Attackers Knowledge

Length = 2
Example Results (PF vs. Cache Channel)
Example Results (PF vs. Cache Channel)
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

Examples and figures taken from the Spectre paper
Side-Effects of Out-of-Order execution

Toy Example

```python
raise_exception();
// the line below is never reached
access(probe_array[data*4096]);
```
Side-Effects of Out-of-Order execution

Toy Example

```plaintext
raise_exception();
// the line below is never reached
access(probe_array[data*4096]);
```
Side-Effects of Out-of-Order execution

Toy Example

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

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
Power channels

Features
- 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 (Square-And-Multiply)

```c
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 (Square-And-Multiply)

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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;
}
```

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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<th>Requirements</th>
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<tr>
<td>Good audio equipment</td>
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<tr>
<td>Reliable audio filters</td>
</tr>
<tr>
<td>Knowledge about typing style</td>
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<tr>
<td>Knowledge about hardware used</td>
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Example

Password typing attack

Keyboard Acoustic Emanations Revisited
Li Zhuang, Feng Zhou, J. D. Tygar
University of California, Berkeley
Password typing attack

Keyboard Acoustic Emanations Revisited

Li Zhuang, Feng Zhou, J. D. Tygar
University of California, Berkeley

Sample Value

-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Touch Peak
Hit Peak
Push Peak
Release Peak
Example

Password typing attack

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

![Graph showing sample value and sum of FFT coefficients with labeled peaks and positions.](attachment:image.png)
Results

![Graph showing Final Recognition Rate vs Length of Recording with two lines: word correct rate and char correct rate.](image)
Results

- **Final Recognition Rate** vs Length of Recording
  - Word correct rate
  - Char correct rate

- **Cumulative Distribution Function** vs 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 equipment (antenna, scope)
- Detailed knowledge about hardware used
Data Remanence

Warning

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

Warning

- **Not** a classical side-channel
- no indirect observance of data $\rightarrow$ direct
- is still interesting
Data Remanence

Warning

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

Features

- Access to data you thought is gone
- Usually if you get data it is pretty good
Example (Your friend, the compiler)

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

Examples / Software
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Example (Your friend, the compiler)

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

What if someone gets the same memory?
Example (Your friend, the compiler)

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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

<table>
<thead>
<tr>
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<tr>
<td>A</td>
<td>60</td>
<td>41</td>
<td>(no errors) 0.000095</td>
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![Graph showing % Decay vs Seconds without Power](image-url)
Image after 5, 30, 60 and 300 seconds
Defense mechanisms

Approach

Make all behavior that is observable independent of the input data
Defense mechanisms

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**Caveat**

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

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Make all behavior that is observable independent of the input data

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

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
Timing channels

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Removes changes in runtime due to different operations depending on data
Example: Move different data processed in different branch targets to same cacheline
Timing channels

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Removes changes in runtime due to different operations depending on data
Example: Move different data processed in different branch targets to same cacheline

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
Page-Fault Channel / Fault channels

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**Prevention**
- Don’t use paging. Require all memory to be mapped
- Avoid dynamic allocation of shared resources
Meltdown / Spectre

**Meltdown**
- KPTI - Kernel Page Table Isolation
- HW: Don’t speculate across protection boundarys
## Meltdown / Spectre

### Meltdown
- KPTI - Kernel Page Table Isolation
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### Spectre
- Speculation Fences
Power / Acoustic / EM

**Power Channel**

- 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)
**Power / Acoustic / EM**

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## Electro Magnetic Radiation
- Use EM shielding on chips
- Use EM shielding for case
Data remanence

Zero memory

- Like really zero it! (memset_s for C11, SecureZeroMemory for Windows)
Data remanence

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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 :)

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## 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.
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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!
<table>
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<th>Overview</th>
<th>Cache Side-Channels</th>
<th>Page-fault Channel</th>
<th>Microarchitectural Channels</th>
<th>Acoustic Channels</th>
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Cold Boot


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.semanticscholar.org/paper/Software-mitigations-to-hedge-AES-against-cache-Brickell-Graunke/11c6fddeff9e2f95c8cf238ea9f12f8ffae7cf8c/pdf