

CS 110

Computer Architecture

Security

Instructor:

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<https://robotics.shanghaitech.edu.cn/courses/ca22>

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Final Exam

- Time (90 minutes + 10 minutes)
 - 9:00am – 10:40am, 18th June
 - Any submission past **10:40:00** would not be evaluated
- **Twelve groups**, not 9 of mid-term exam
 - To be announced with 12 Tencent Meeting rooms
 - Set your name in the Meeting Room as **StudentID-Name**
- Check the email on final exams received on 1st June
 - Dual devices (双设备)
 - Do not be late for the exam
- **NO cheating, NO plagiarism**

Review: Hamming ECC

- Correct single-bit error, detect double-bit errors

Bit position	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Encoded data bits	p1	p2	d1	p4	d2	d3	d4	p8	d5	d6	d7	d8	d9	d10	d11
Parity bit coverage	p1	X		X		X		X		X		X		X	
	p2		X	X			X	X			X	X			X
	p4				X	X	X	X					X	X	X
	p8								X	X	X	X	X	X	X

An Example

- Valid codeword

0 1 1 1 0 0 1 0 1 0 1 0

- Two errors** happened

0 1 1 1 **1** **1** 1 0 1 0 1 0

- Checking

0 1 **1** 1 1 1 X

1 1 **1** 1 0 1 X

1 **1** **1** 1 0 ✓

0 1 0 1 0 ✓

One-bit error

0 1 **0** 1 0 0 1 0 1 0 1 0

Checking:

0 **0** 0 1 1 1 X

1 **0** 0 1 0 1 X

1 0 0 1 0 ✓

0 1 0 1 0 ✓

Add one XOR result of all bits
at the **MSB**

0 0 1 1 1 0 0 1 0 1 0 1 0

Outline

- The Lives of Others
 - Episode 1, over the air
 - Episode 2, very hard
- Inception
 - Plant a value with a hammer
- Mission Impossible
 - When, or where
- The Water Horse
 - Flush the Loch Ness
- Meltdown and Spectre

The Lives of Others

Over the air

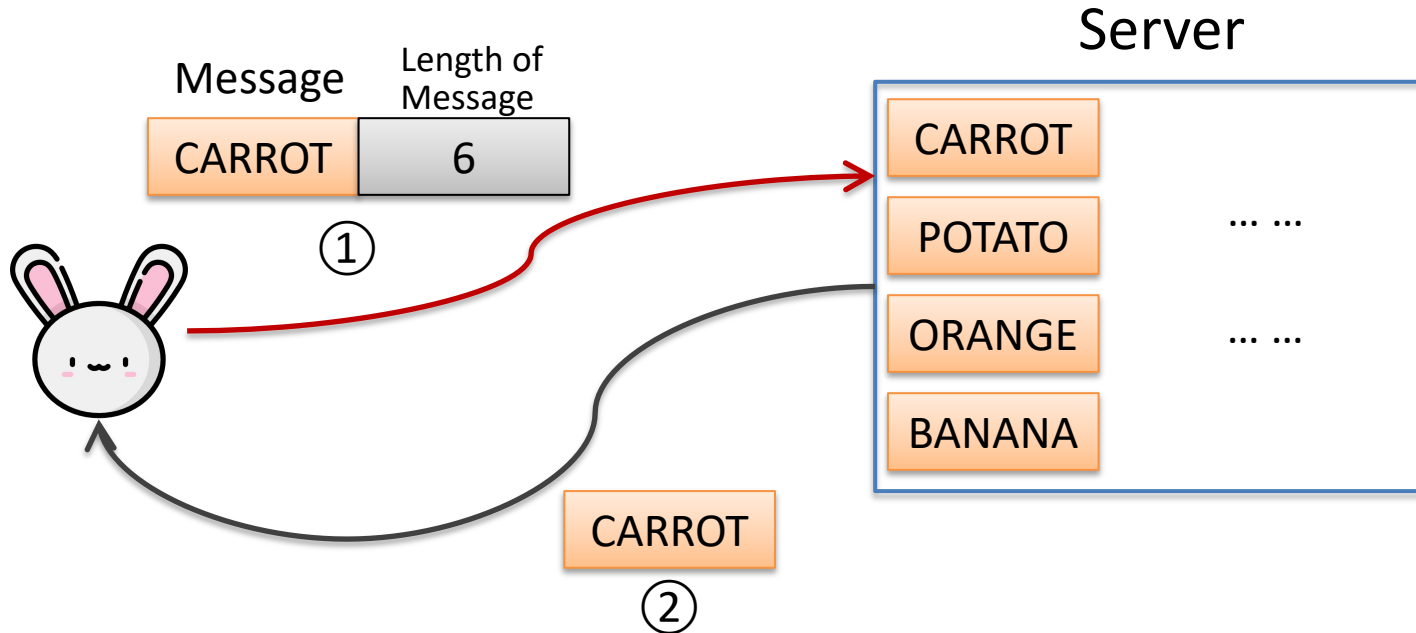
Heartbleed

- A network vulnerability uncovered in 2014 [1]
- Found in popular OpenSSL cryptographic software library
 - SSL/TLS: Secure Socket Layer (*deprecated*), and Transport Layer Security
 - Widely used in many applications
 - Email, VPN, WeChat, Taobao, 12306, Momo, etc. [1, 2]

[1] <https://heartbleed.com/>

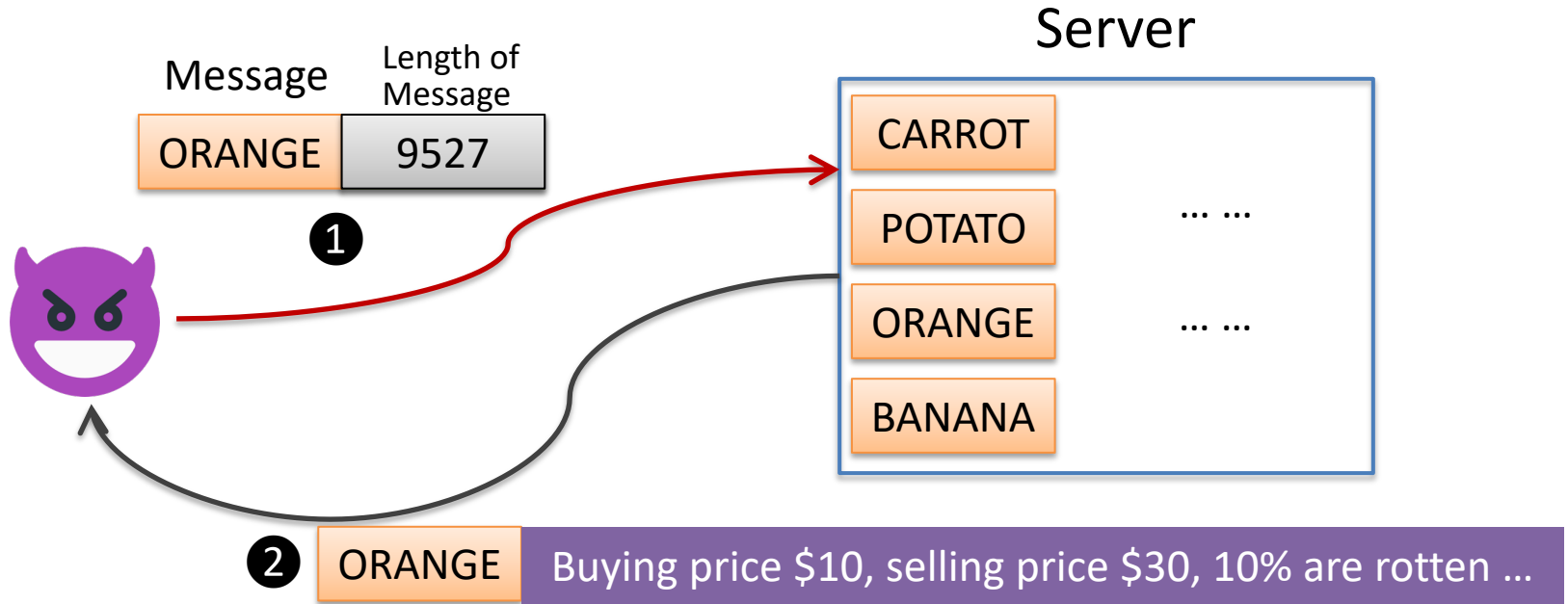
[2] <https://daily.zhihu.com/story/3824566>

How Heartbeat Works



The rule: one side sends a message with a length, and the other side replies with *the same* message according to *the length*.

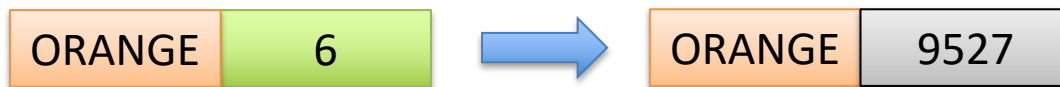
How Heartbleed Works



The rule: one side sends a message with a length, and the other side replies with *the same* message according to *the length*.

Why “Heartbleed”?

- Found in TLS Heartbeat extension
 - To check whether a connection is still alive
 - One device confirms the other's continued presence by sending a specific payload in a packet that the other device sends back
 - Not only user to server, also possible server to user
 - Heartbleed happens if the packet's length is not validated.



Heartbleed

- The impact
 - Without using any privileged information or credentials, attackers can steal the victim's secrets, including user names and passwords, instant messages, emails and business critical documents and communication.
- Is it a design flaw of SSL/TLS?
 - No. It is an implementation flaw.

How to fix it?

The Lives of Others

Very hard

Eavesdropping

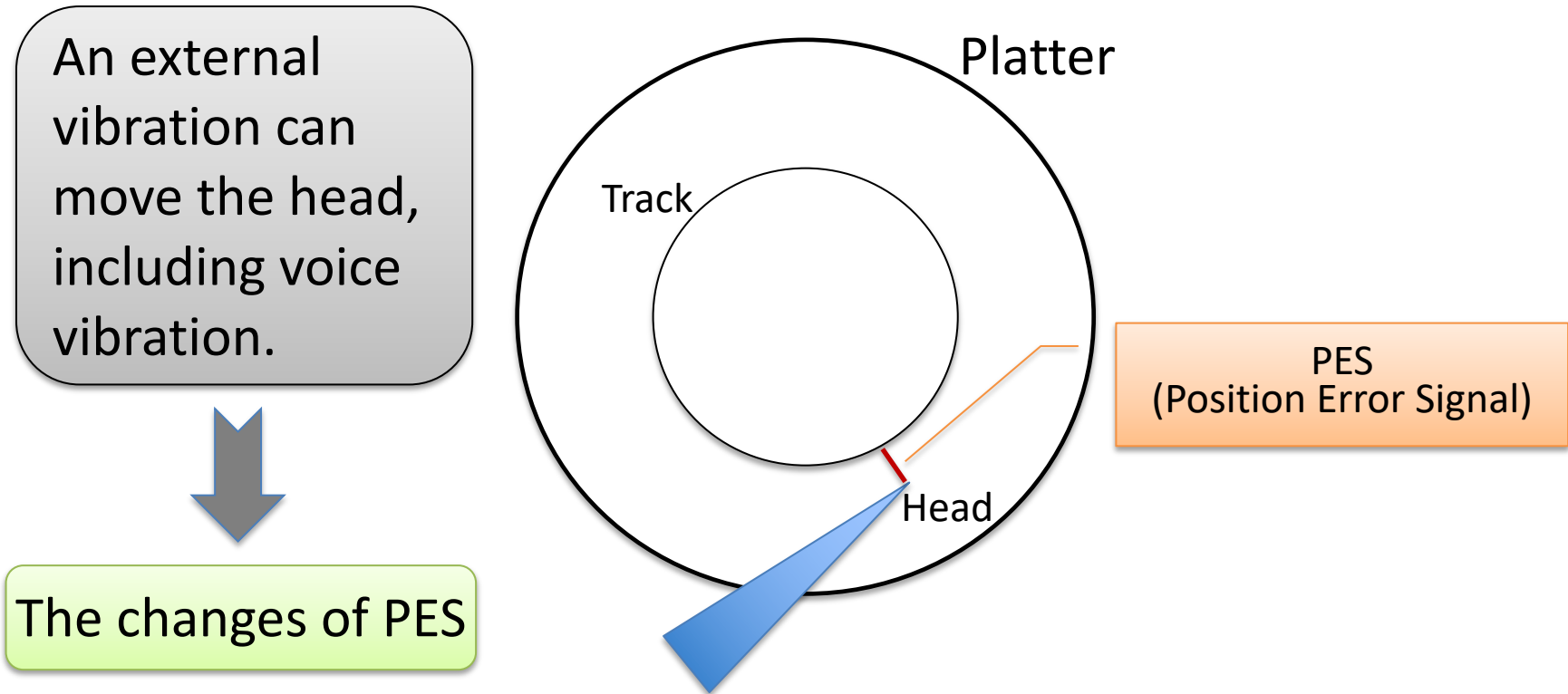


Hacking a Hard Disk is Doable

- Hard disk is controlled by firmware
 - Remember the “controller processing time”?
 - Let’s hack it
- Re-flashing a disk’s firmware
- Or maliciously leaving a stealthy backdoor

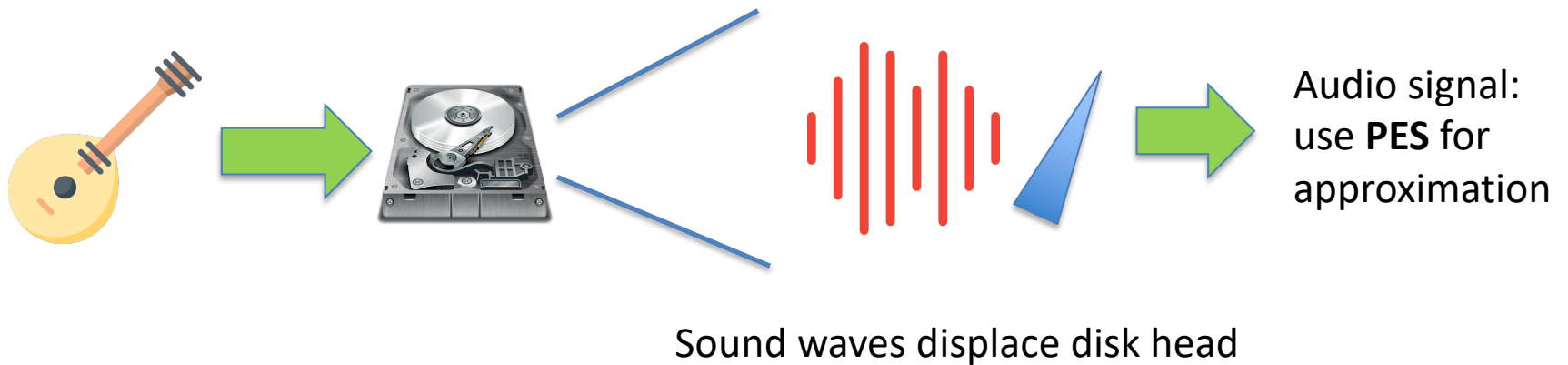
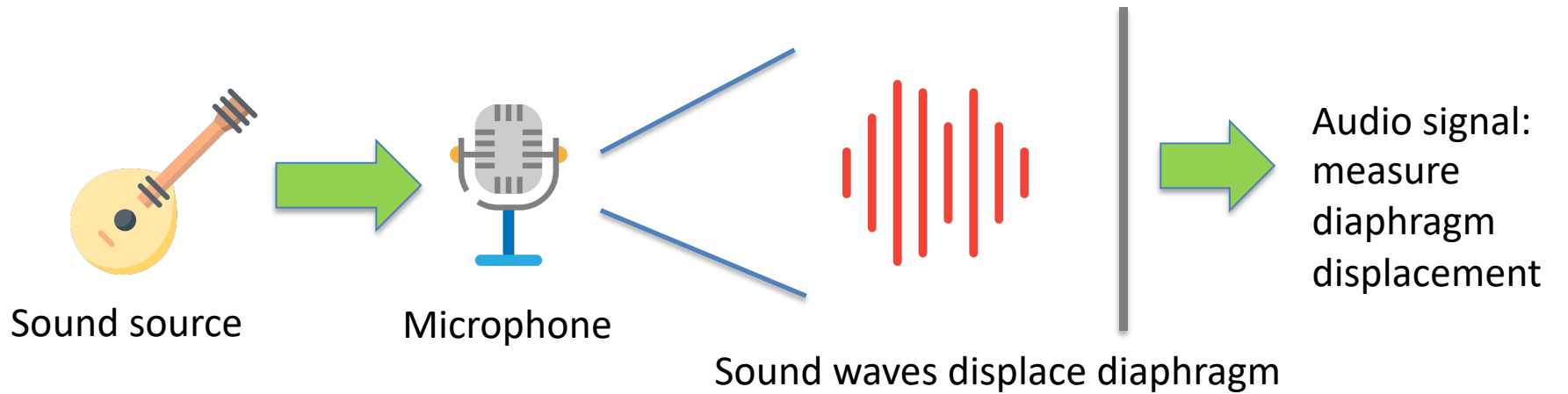
How to transform a hard disk to be a microphone?

Disk Head and Vibration



The bit density is very high for a hard disk drive. PES utilizes feedback-control loop to keep the head on track. It is a signal that can be read out with efforts.

To be a Microphone



It can work, but

- Required higher volume (90 dB)
- Audio can be recovered
 - Quality not very good
- How to defend?
 - Discard your disks? ← No.
 - Mask sound, secure future disks, etc. ← Yes.

Source: <https://spqrlab1.github.io/papers/Kwong-HDDphone-IEEE-SP-2019.pdf>

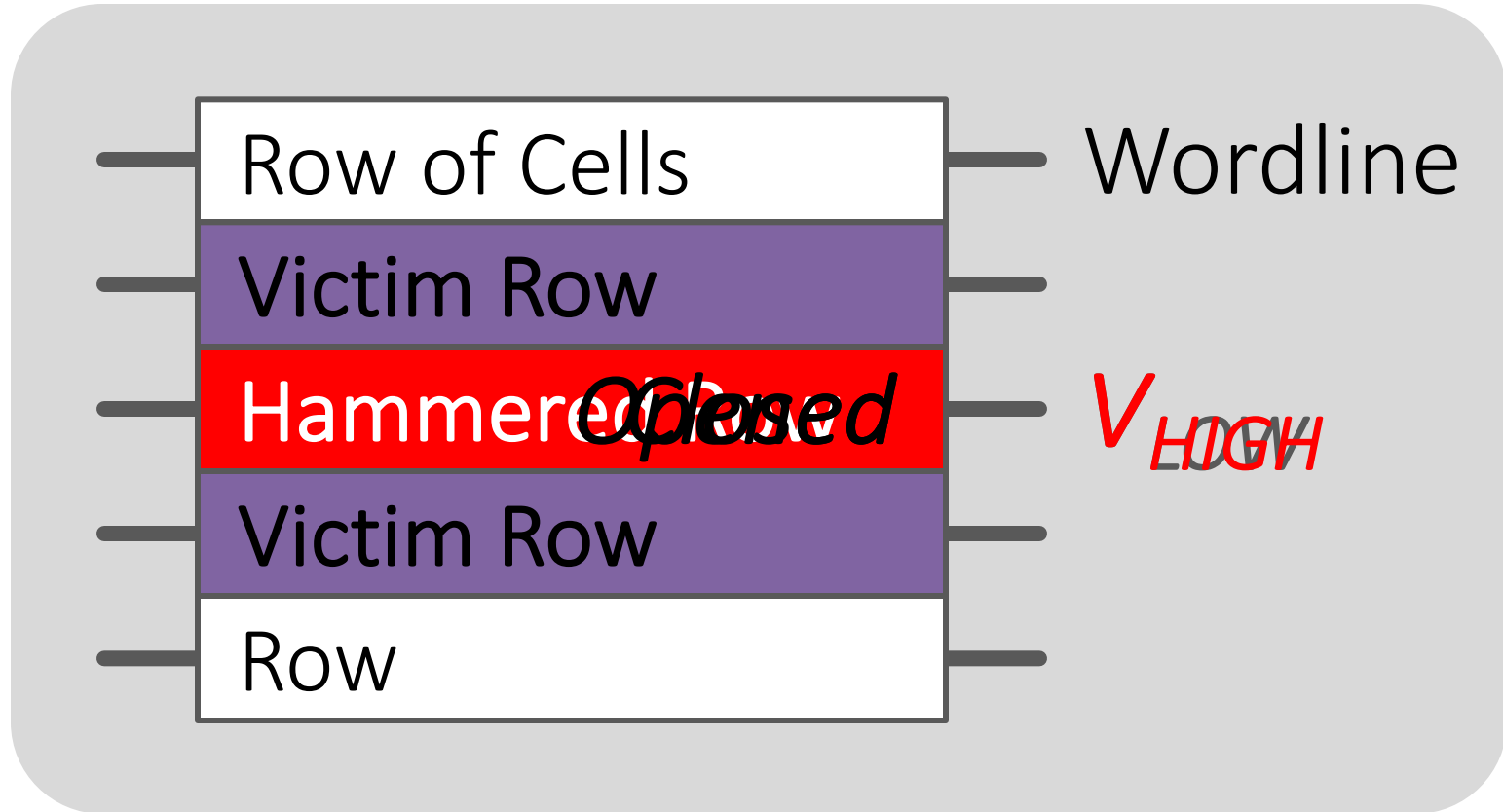
Inception

Plant a value with a hammer

Slides based on Onur Mutlu's Slides

<https://people.inf.ethz.ch/omutlu/talks.htm>

DRAM is Prone to Disturbance Errors



Repeatedly reading a row enough times (before memory gets refreshed) induces **disturbance errors** in adjacent rows in **most real DRAM chips you can buy today**

[Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors](#), (Kim et al., ISCA 2014)

Why Rowhammer Happens?

- DRAM cells are too close to each other!
 - They are not electrically isolated from each other
- Access to one cell affects the value in nearby cells
 - due to **electrical interference** between
 - the cells
 - wires used for accessing the cells
 - Also called cell-to-cell coupling/interference
- Example: When we activate (apply high voltage) to a row, an adjacent row gets slightly activated as well
 - Vulnerable cells in that slightly-activated row lose a little bit of charge
 - If row hammer happens enough times, charge in such cells gets drained

How Rowhammer Becomes an Attack

- Picking a memory location
- Repeatedly accessing it **without caching**
- Adjacent rows in the same bank to be flipped
- An example to be exploited
 - Page table entry, containing a physical page no.
 - A bit of physical page no. flipped → another page

It sounds straightforward, but demands a lot of designs and tests.

The Impact of Rowhammer

Project Zero

[Exploiting the DRAM rowhammer bug to gain kernel privileges](#) (Seaborn, 2015)

News and updates from the Project Zero team at Google

<https://github.com/google/rowhammer-test>

Monday, March 9, 2015

Exploiting the DRAM rowhammer bug to gain kernel privileges

ANVIL: Software-Based Protection Against Next-Generation Rowhammer Attacks (ASPLOS 2016) <http://dl.acm.org/citation.cfm?doid=2872362.2872390>

CAN't Touch This: Software-only Mitigation against Rowhammer Attacks targeting Kernel Memory (USENIX Security 2017)

<https://www.usenix.org/system/files/conference/usenixsecurity17/sec17-brasser.pdf>

Another Flip in the Wall of Rowhammer Defenses (IEEE S&P 2018)

<https://ieeexplore.ieee.org/document/8418607>

Throwhammer: Rowhammer Attacks over the Network and Defenses (USENIX ATC 2018)

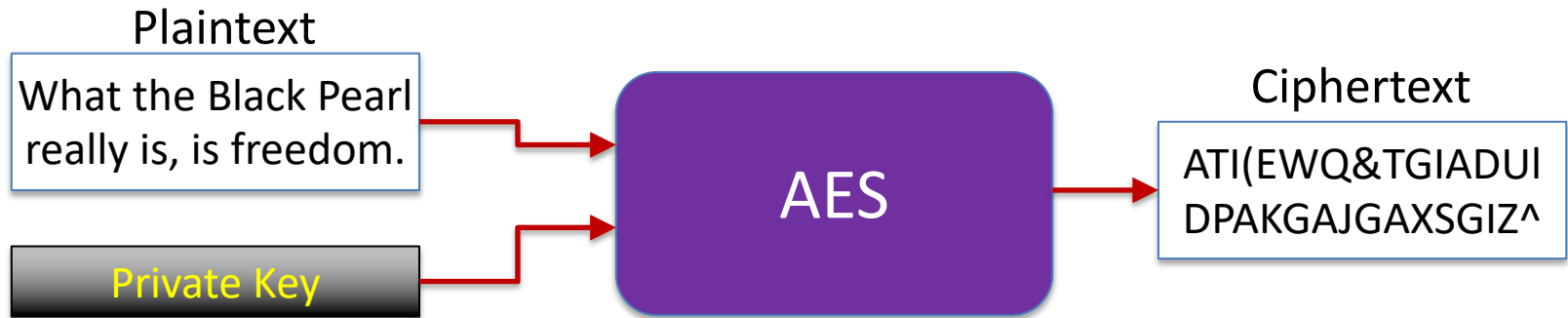
https://www.cs.vu.nl/~herbertb/download/papers/throwhammer_atc18.pdf

Mission Impossible

When, or where

Encryption and Decryption

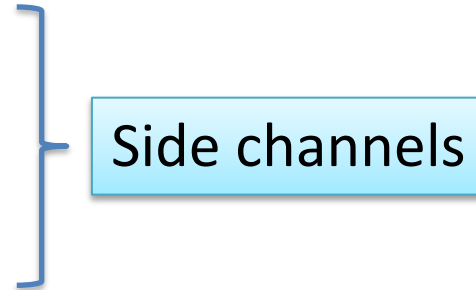
- Example: Advanced Encryption Standard (AES)
 - Used in OpenSSL and other applications



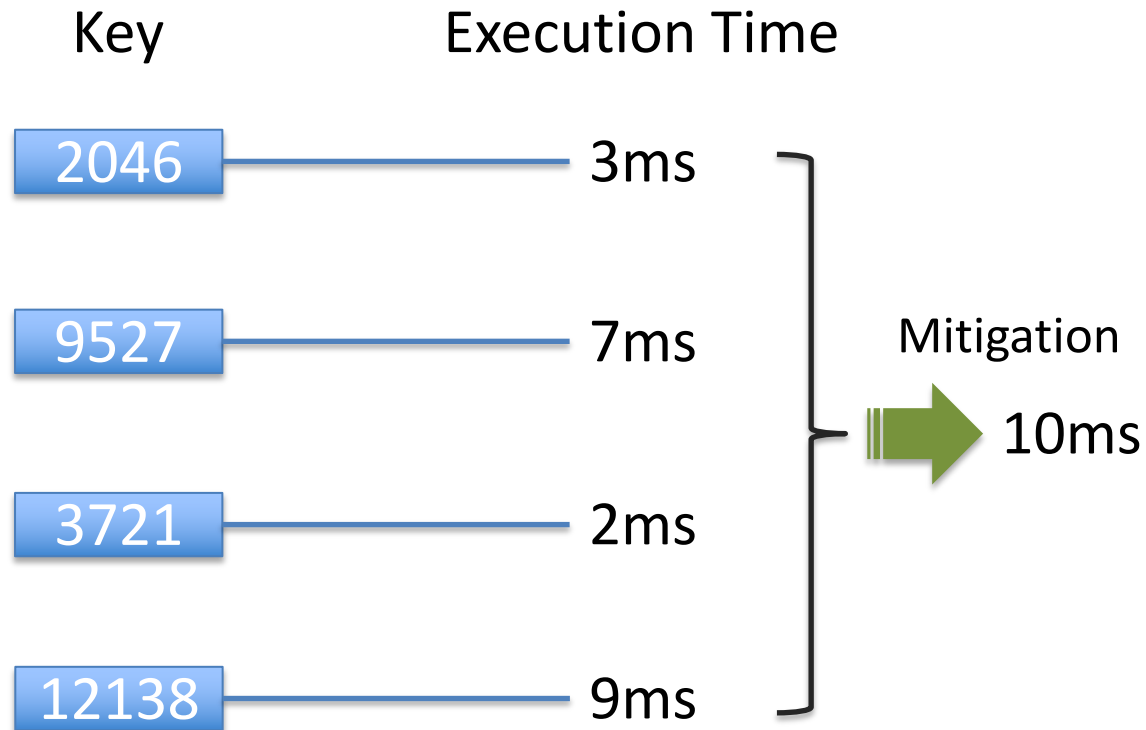
- A key can be 128, 192, or 256 bits.
- Is it possible to guess a key?
 - Well, it's a complicated question.
 - Brute-force?

Let's Find a Side Channel

- Implementations have behaviours (observations) regarding different inputs
 - Timing
 - Accessed CPU cache lines
 - Power consumption
 - Sound
- Not theoretical properties of algorithm
- Side-channel attacks
- How to leverage a side channel?
 - First, to instrument, e.g., timing, power, etc.
 - More important, to figure out the relationship between observations via the side channel and inputs to the running program

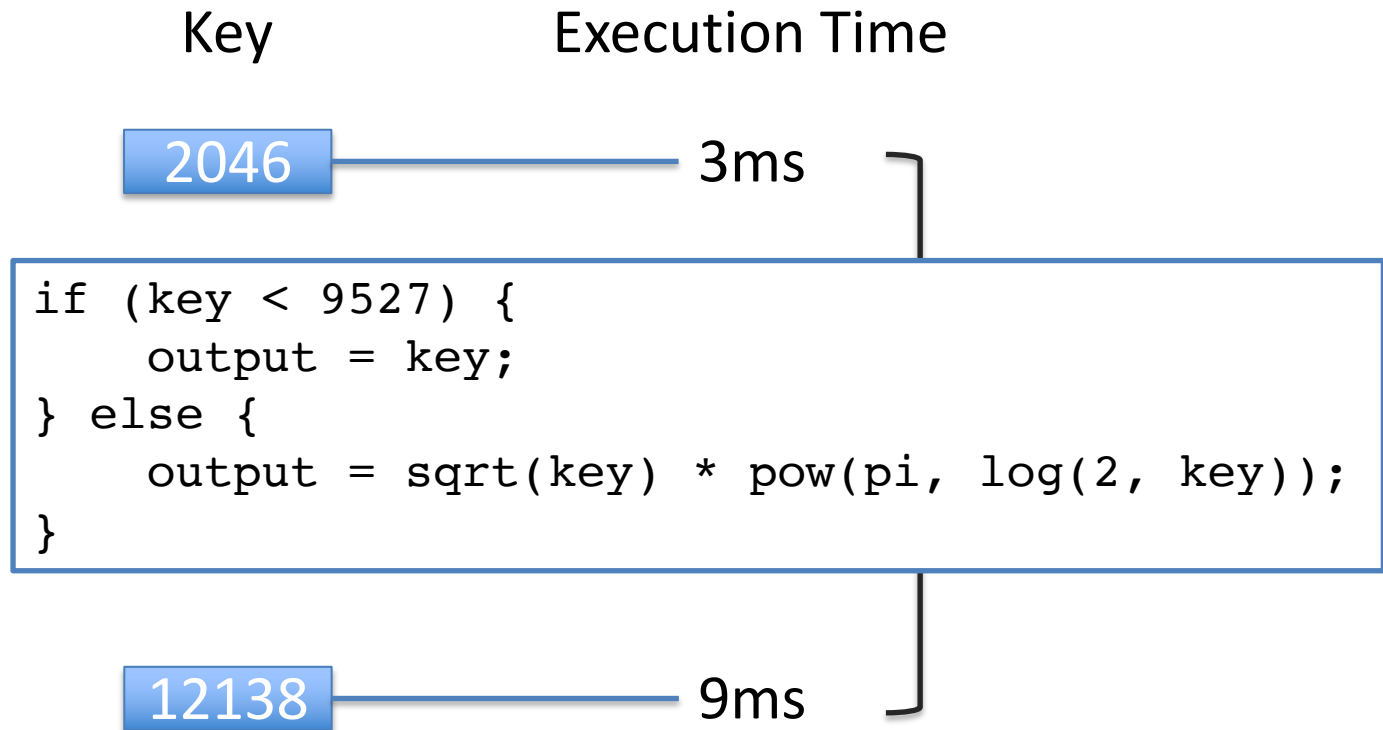


Timing-based Attack



When an implementation has data-dependent variations on its execution, it is prone to timing-based attacks.

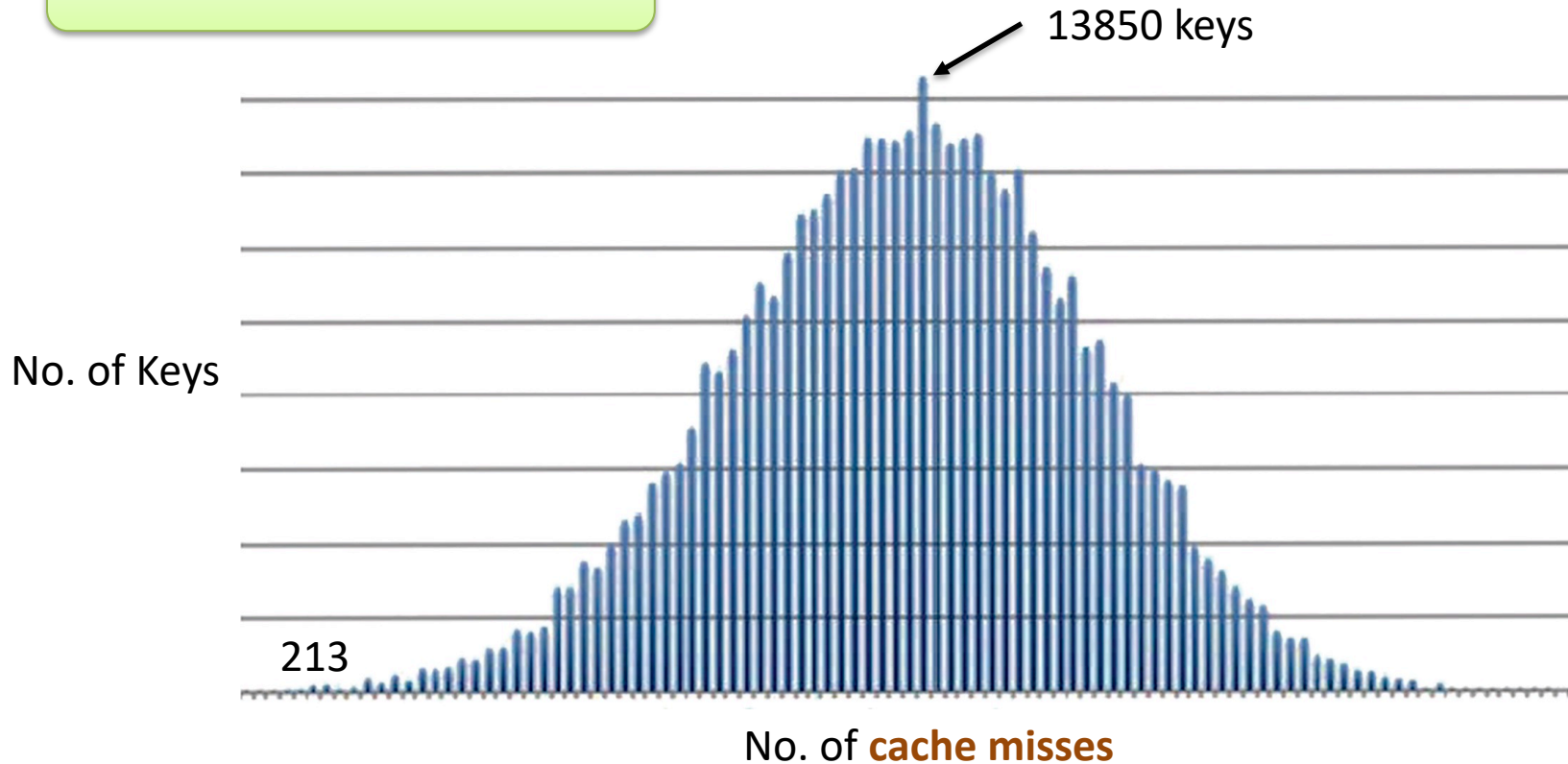
Timing-based Attack



When an implementation has data-dependent variations on its execution, it is prone to timing-based attacks.

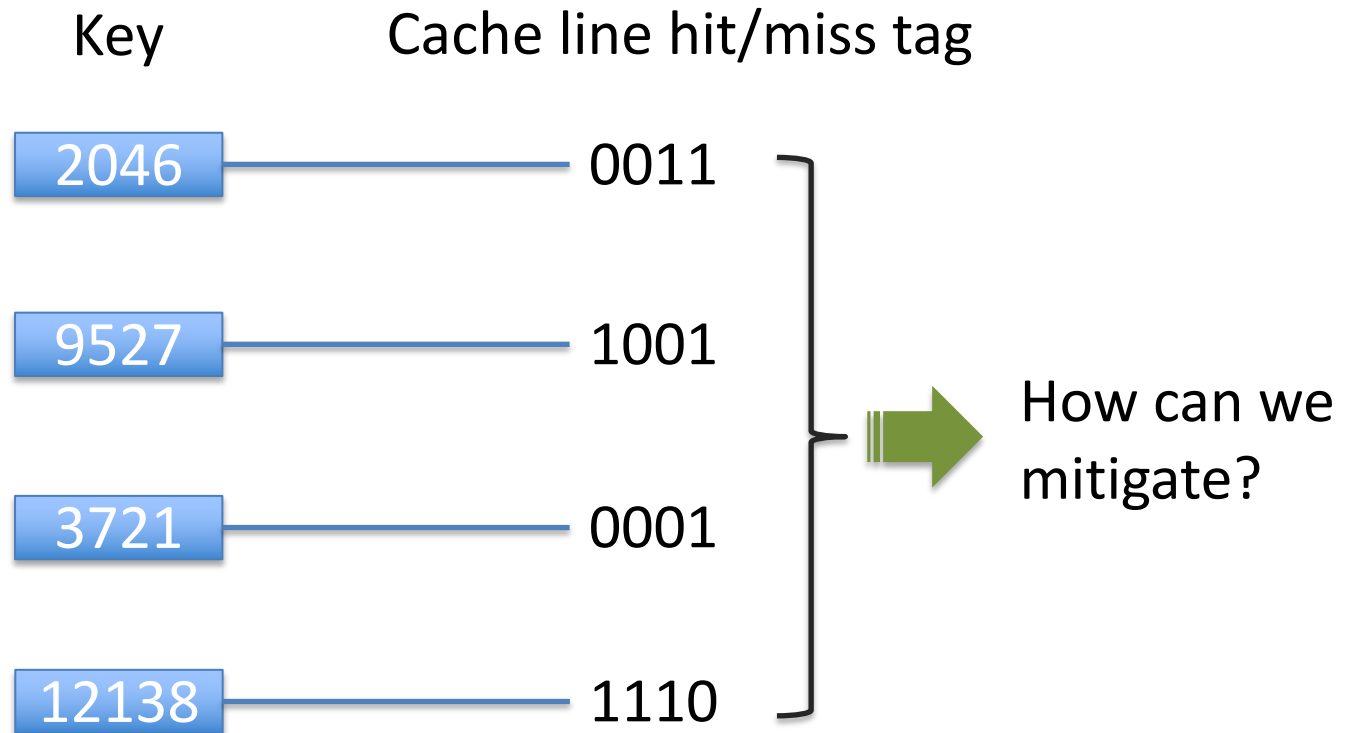
Timing-based Attack

NOT a uniform distribution



By executing AES-128 encryption with 256000 keys

Access-based Attack



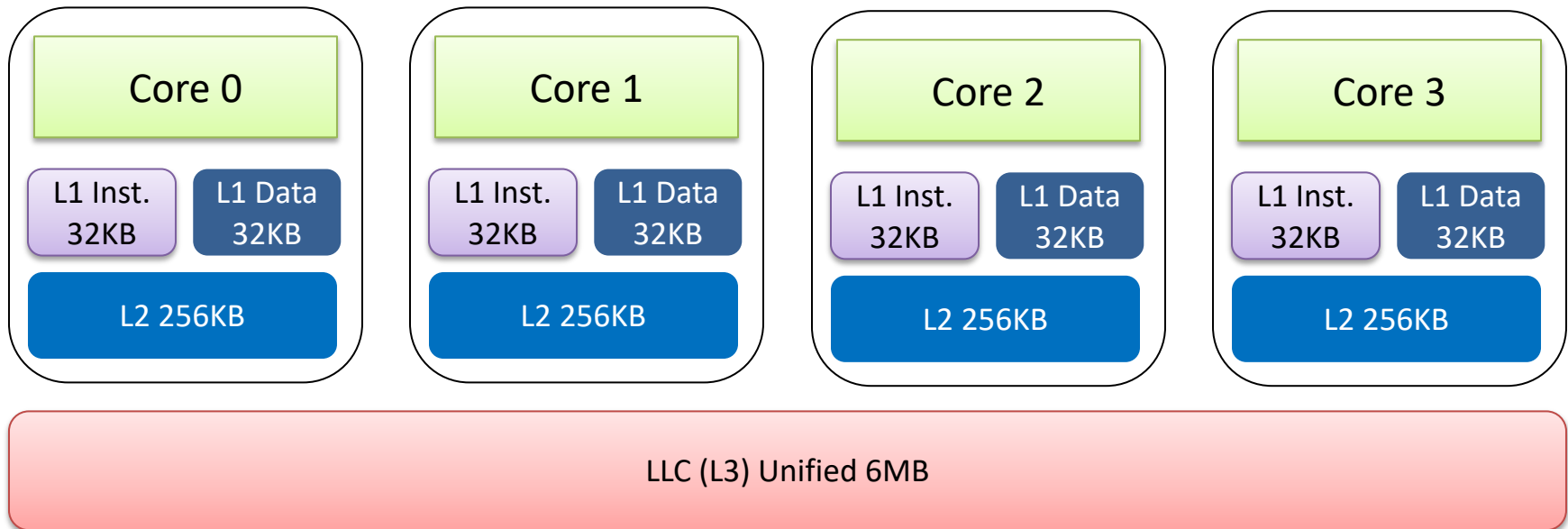
Hit/miss records of cache lines are also likely to leak secret.

An Example

- Cachebleed
 - Reported in March 2016
 - Timing-based attack
 - On RSA in OpenSSL
 - RSA is a public-**key** cryptographic system for encryption and decryption
 - By detecting cache-bank conflicts via timing variations → to reconstruct a **key**

The Water Horse
Flush the Loch Ness

Inclusive Cache and Shared Pages



Intel Ivy Bridge Cache Architecture (Core i5-3470)

1. For an inclusive cache, a cache line in higher-level caches are in LLC.
2. Programs may share memory pages, e.g., the same executable files.

Flush+Reload

- To build a side channel
- Manually share memory pages between attacker's and victim's programs
- Attacker forcefully flushes and reloads cache lines
 - To observe the victim's cache misses/hits
 - ➔ to speculate the victim's secret
- Why inclusive cache for study?
 - All levels would be flushed

Flush+Reload

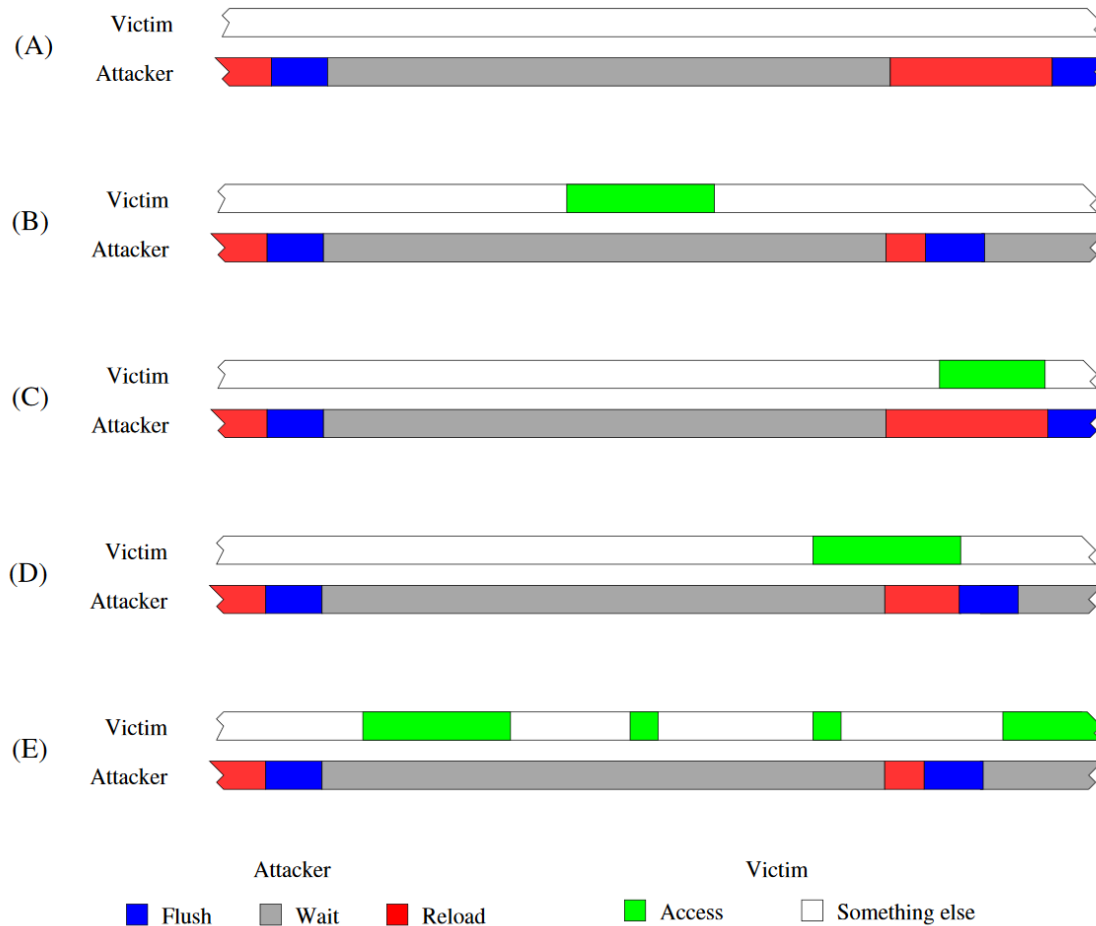


Figure 3: Timing of FLUSH+RELOAD. (A) No Victim Access (B) With Victim Access (C) Victim Access Overlap (D) Partial Overlap (E) Multiple Victim Accesses

Flush+Reload Example

- GNU Privacy Guard (GnuPG) with RSA
 - GnuPG is open-source
 - But key for encryption/decryption is private
- Attacker memory-maps victim's executable file to her/his memory space, to share pages
 - Flush and reload cache lines to observe
 - `clflush` for x86: cache line flush

Defence against Flush+Reload

- Permission check for `clflush`
- Disallowance of memory sharing
 - Contradictory to the increase of sharing in OS and virtual machines
- Tuning software programs

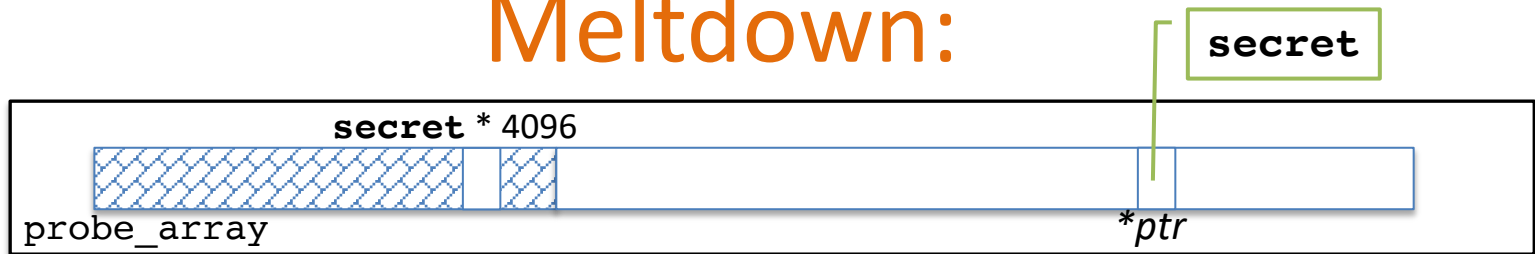
Meltdown and Spectre

Meltdown and Spectre

- Hardware vulnerability
 - Affecting Intel x86 microprocessors, IBM POWER processors, and some ARM-based microprocessors
- All Operating Systems affected!
- They are considered “catastrophic”!
- Allow to read all memory (e.g. from other process or other Virtual Machines (e.g. other users data on Amazon cloud service!))
- How Meltdown and Spectre work covers all knowledge of CA course:
 - Virtual Memory; Protection Levels; Instruction Pipelining; Out-of-order Execution; Speculative Execution; CPU Caching.



Meltdown:



- Out of order execution
 - Covered in L15@Spring 2022
 - *Some instructions executed in advance*

```
// secret is one-byte. probe_array is an array of char.  
1. raise_exception();  
2. // the line below is never reached  
3. access(probe_array[secret * 4096])
```

Why 4096?

probe_array should never be accessed, but accessed at some location probe_array + **secret** * 4096.

probe_array is fully controlled by attacker who can use Flush+Reload to see which cache line of probe_array is hit, so as to figure out the value of **secret**.

secret can be the value at any memory location, i.e., *ptr

The aim of Meltdown:
to leak/dump memory

The Impact of Meltdown

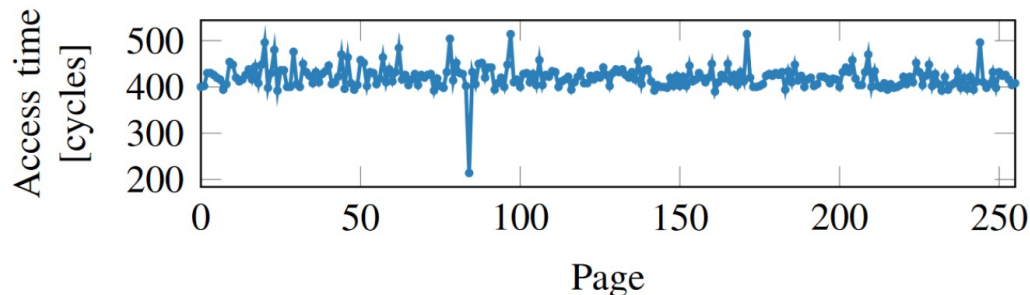


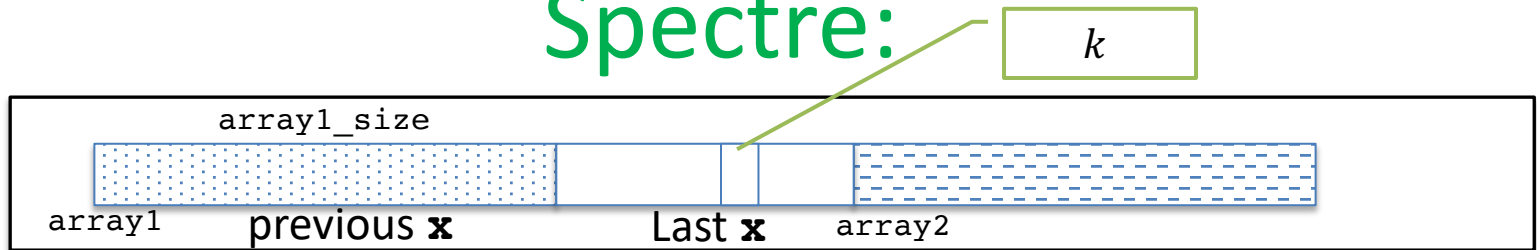
Figure 4: Even if a memory location is only accessed during out-of-order execution, it remains cached. Iterating over the 256 pages of `probe_array` shows one cache hit, exactly on the page that was accessed during the out-of-order execution.

Justification:

The researchers put a value of 84 in **secret** and managed to use Flush+Reload to get a cache hit at the 84th page.

The researchers developed competent programs to read memory locations that should be inaccessible to their program. They managed to dump the entire physical memory, for kernel and users.

Spectre:



- **Speculative execution**

- Example: branch prediction
- Covered in L13

Prerequisites:

- i. `array1[x]`, with an out-of-bound `x` larger than `array1_size`, resolves to a secret byte `k` that is cached;
- ii. `array1_size` and `array2` uncached.
- iii. Previous `x` values have been valid.

// `x` is controlled by attacker.

```
1. if (x < array1_size) ← cache miss, so run next line due to prediction history
2.  y = array2[array1[x] * 4096] ← array1[x] cache hit, as k is cached,
                                so load array2[k * 4096]
```

Regarding a misprediction with an illegal `x`, `array2[k * 4096]` will not be used, but has been loaded into CPU cache.

We can use Flush+Reload to guess `k` with `array2`.

The aim of Spectre:
to read out a victim's sensitive
information

The Impact of Spectre

- Processors can be tricked in speculative execution to modify cache state
 - Leaving attackers an exploitable opportunity
- Sensitive information of a victim program may be leaked
- Speculative Store Bypass
 - A newer variant of Spectre (v4) could allow an attacker to retrieve *older but stale values* in a CPU's stack or other memory locations.
 - <https://software.intel.com/security-software-guidance/software-guidance/speculative-store-bypass>

Meltdown and Spectre

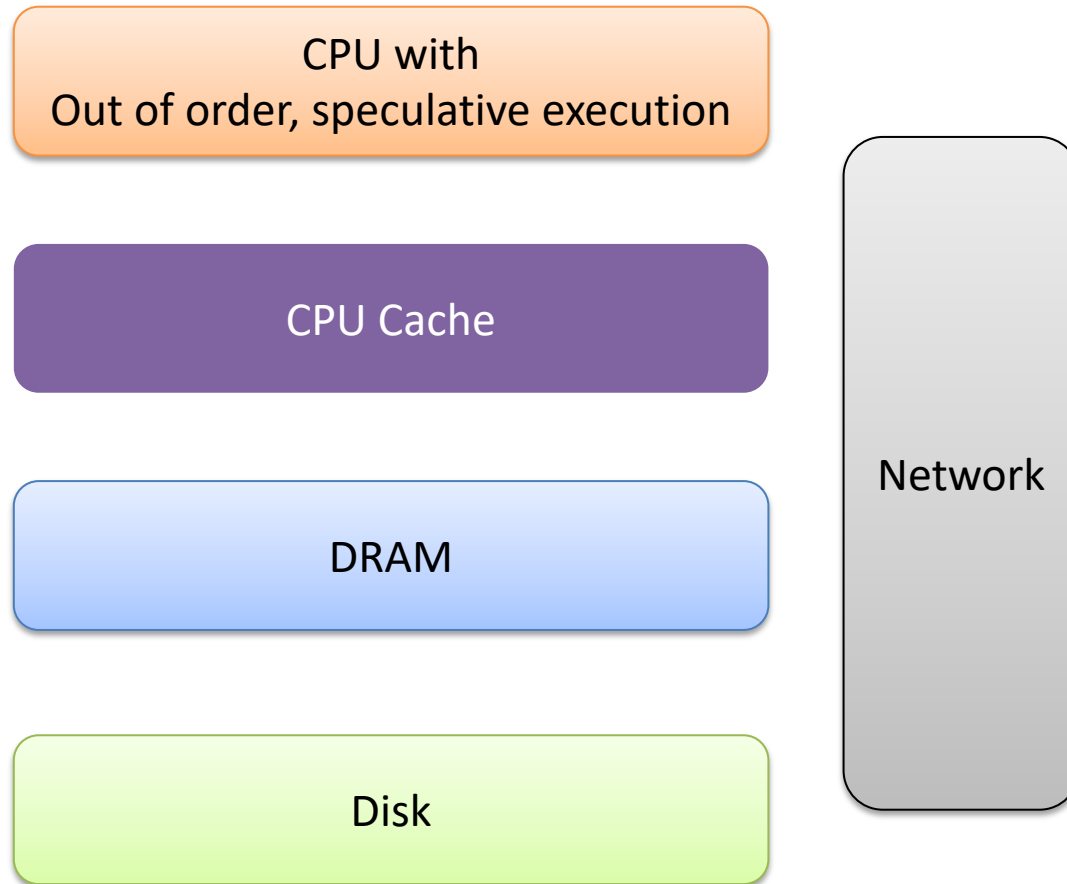
- More complicated than examples here
- Multiple variants today
- Many processors, OSes, applications affected
 - PC, mobile devices, cloud
- Many proposals to mitigate their impacts

No announced RISC-V silicon is susceptible, and the popular open-source RISC-V Rocket processor is unaffected as it does not perform memory accesses speculatively. <https://riscv.org/2018/01/more-secure-world-risc-v-isa/>

However, there is a workshop paper “*Replicating and Mitigating Spectre Attacks on a Open-Source RISC-V Microarchitecture*”

https://carrv.github.io/2019/papers/carrv2019_paper_5.pdf

Vulnerable Architecture



Conclusion

- Every part of a computer can be vulnerable
 - Be vigilant and attentive in designing and programming
- Security and privacy have different presences
 - More than DoS, DDoS, virus, Trojan, ransomware, spyware, and phishing emails
- The challenges for a computer architect
 - To rule out any possibility of vulnerabilities
 - To achieve both high performance and security