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EUROPE 2023

Collide+Power

The Evolution of Software-based Power Side-Channels Attacks

Andreas Kogler
Graz University of Technology

6th December 2023

Whoami

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  - Software-based power side channels
  - Software-based fault attacks
  - Trusted execution environments

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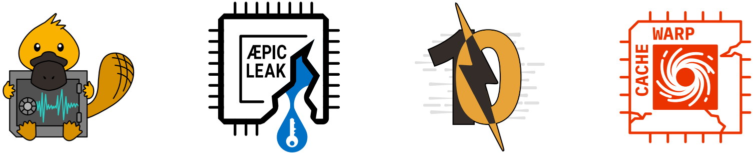

Motivation

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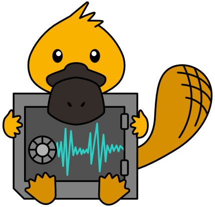

Software-based Power Side Channels

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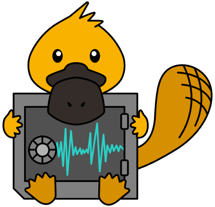

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- **Specific** targets: Algorithms

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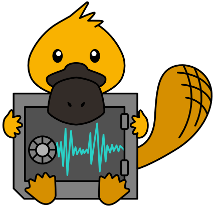

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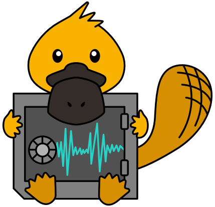

Software-based Power Side Channels

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- **Limited** to a side channels

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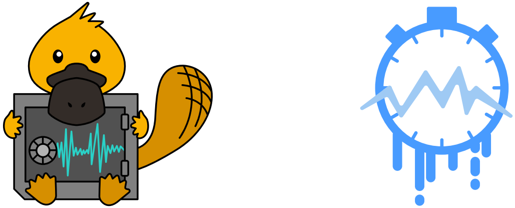

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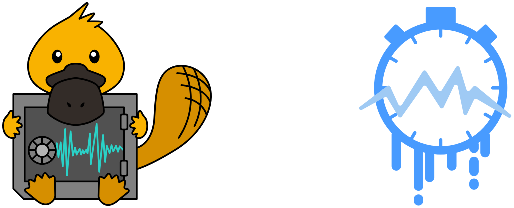

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Transient Execution Attacks

- **Generic** targets: CPU components

Motivation

Software-based Power Side Channels

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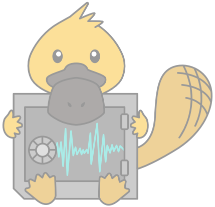

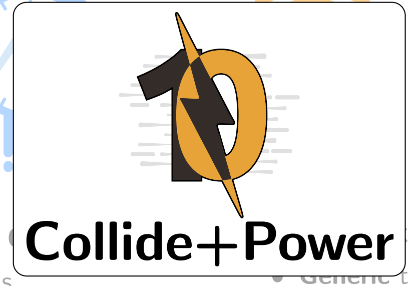

Software-based Power Side C

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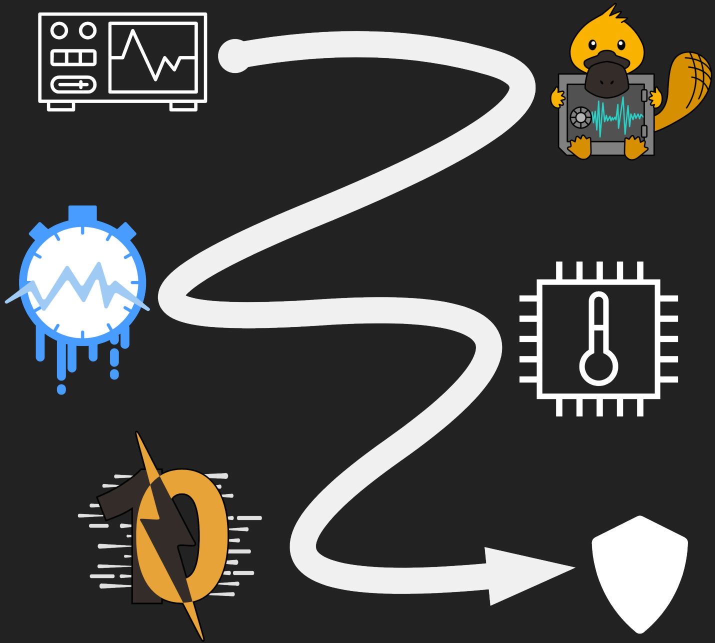
Can we build a generic software-based power side-channel attack independent of the targeted application?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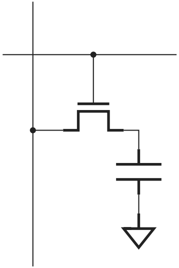
Power Leakage - Source



- **C**omplementary **M**etal **O**xide **S**emiconductor

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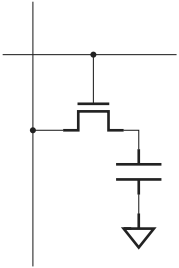

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- Low power consumption

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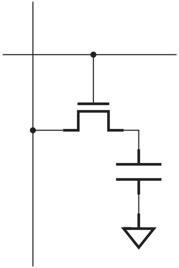

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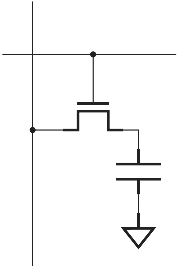

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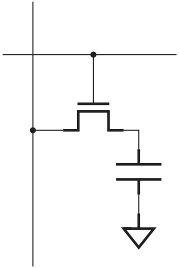

- **C**omplementary **M**etal **O**xide **S**emiconductor
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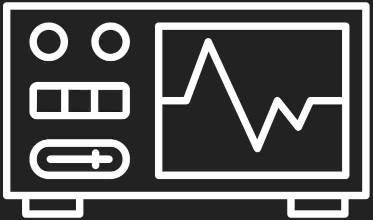
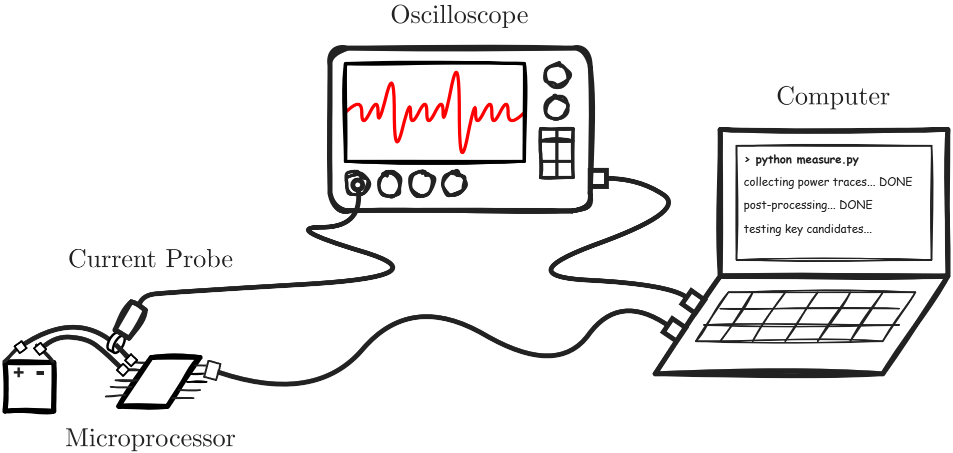
  - **Instruction** that is executed
  - **Data** that is being processed

Traditional Power Side Channels



Power Side Channel - Setup



Oscilloscope

Computer

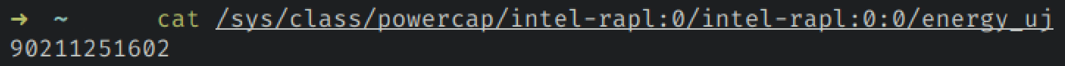
```
> python measure.py
collecting power traces... DONE
post-processing... DONE
testing key candidates...
```

Current Probe

Microprocessor

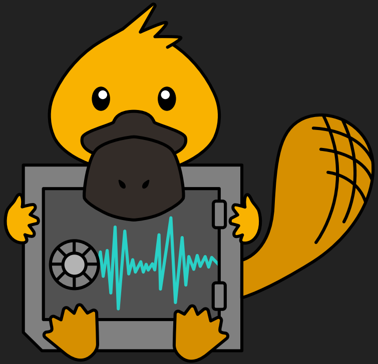
How can we measure the power consumption of a modern CPU?

How would we ever do this remotely?



```
➜  ~      cat /sys/class/powercap/intel-rapl:0/intel-rapl:0:0/energy_uj
90211251602
```

PLATYPUS[1]



[1] Moritz Lipp, Andreas Kogler, David Oswald, Michael Schwarz, Catherine Easdon, Claudio Canella, and Daniel Gruss. PLATYPUS: Software-based Power Side-Channel Attacks on x86. In: S&P. 2021.

Running Average Power Limit (RAPL)

Unprivileged power meter

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No physical access

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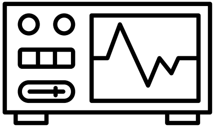
Unprivileged power meter

No physical access

Low refresh rate

External Measurement Equipment vs RAPL



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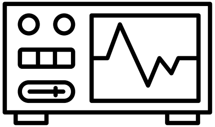

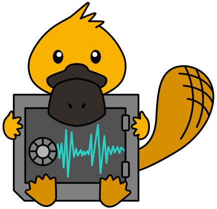

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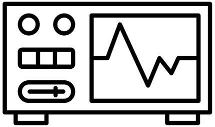

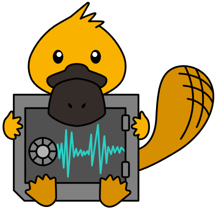

- **Full** Control

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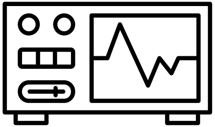

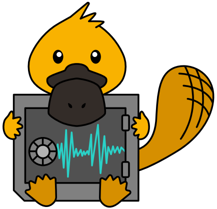

- **Full** Control
- **High** timing resolution

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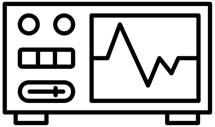

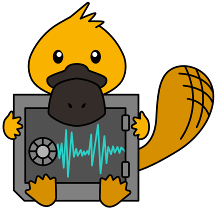

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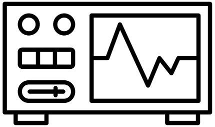

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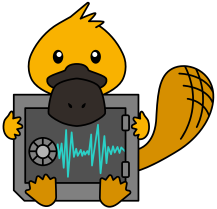

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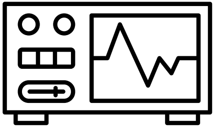

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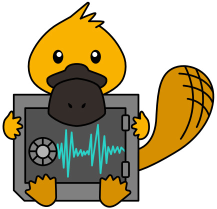

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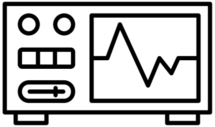

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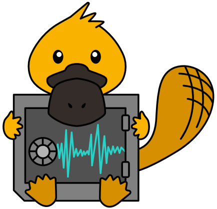

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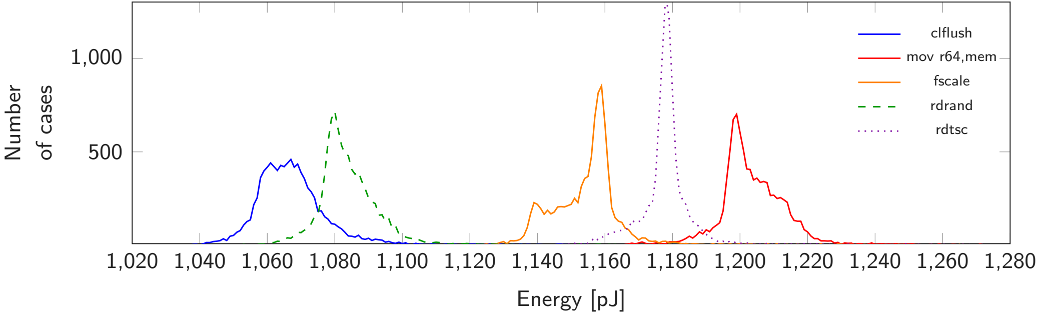
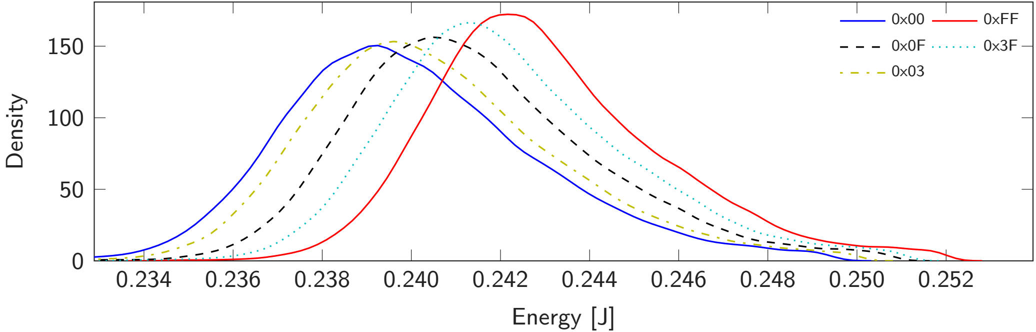
Distinguishing Instructions

- Measure the energy consumption of **different instructions**

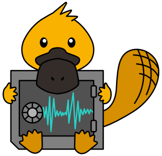


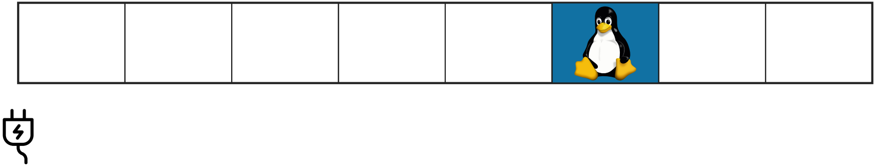
Distinguishing Operands

- Measure the energy consumption of **different operands**



Breaking KASLR





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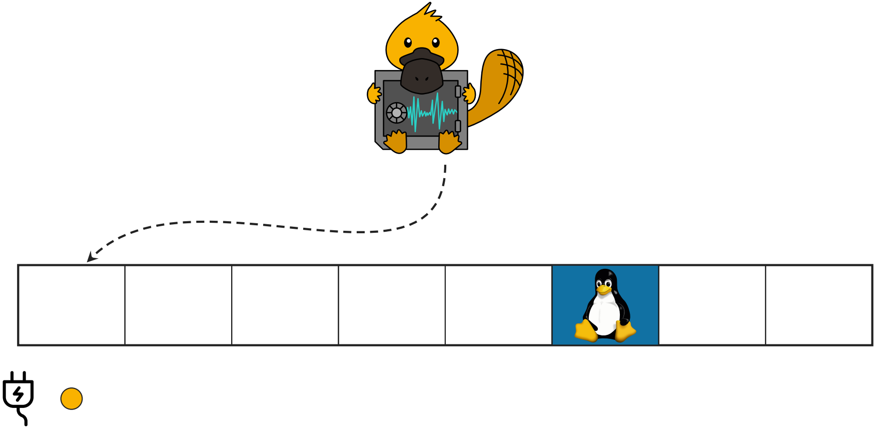

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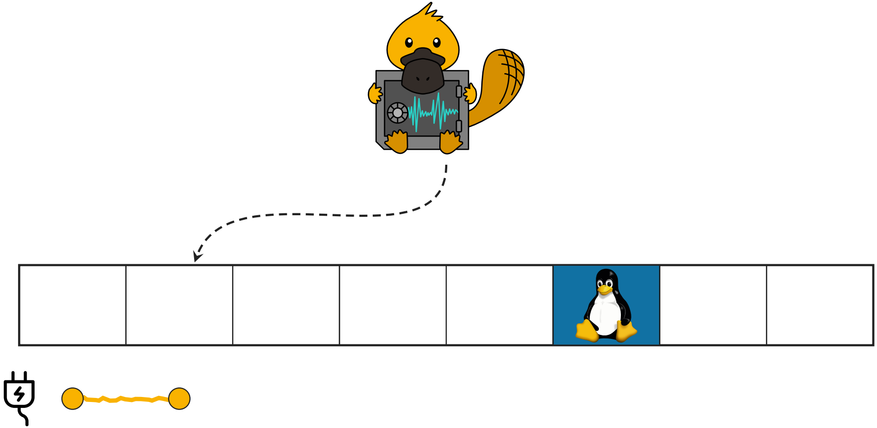

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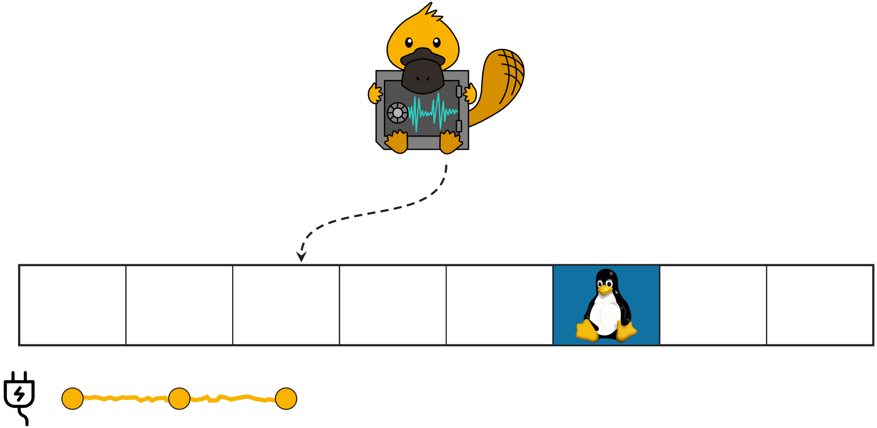

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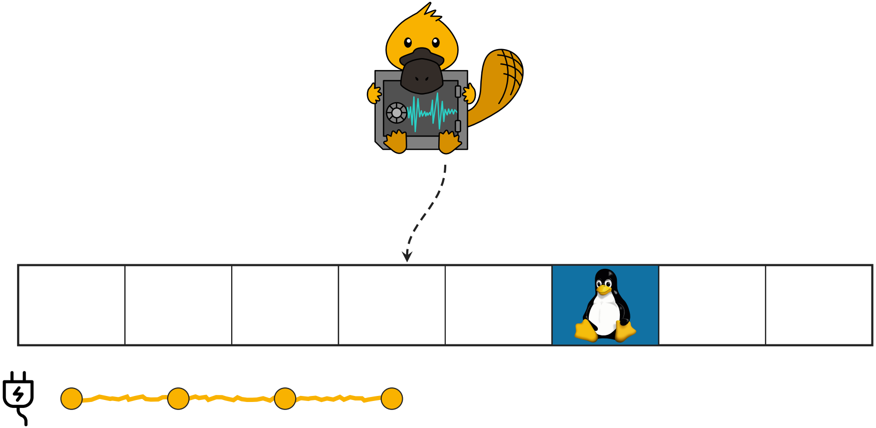

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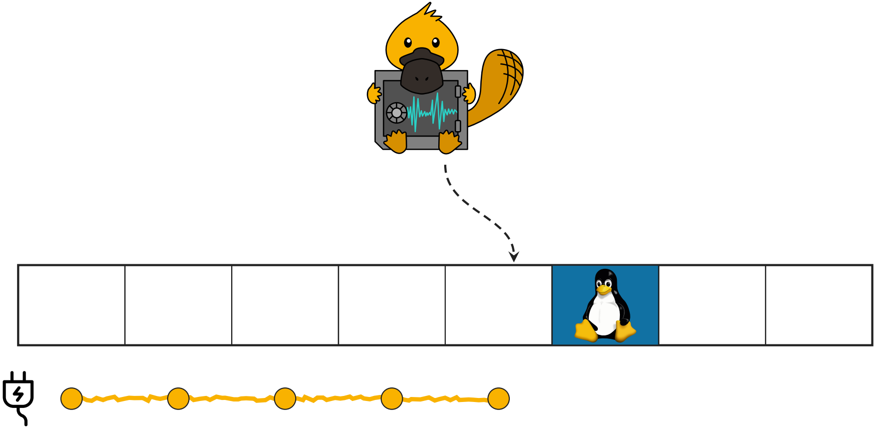

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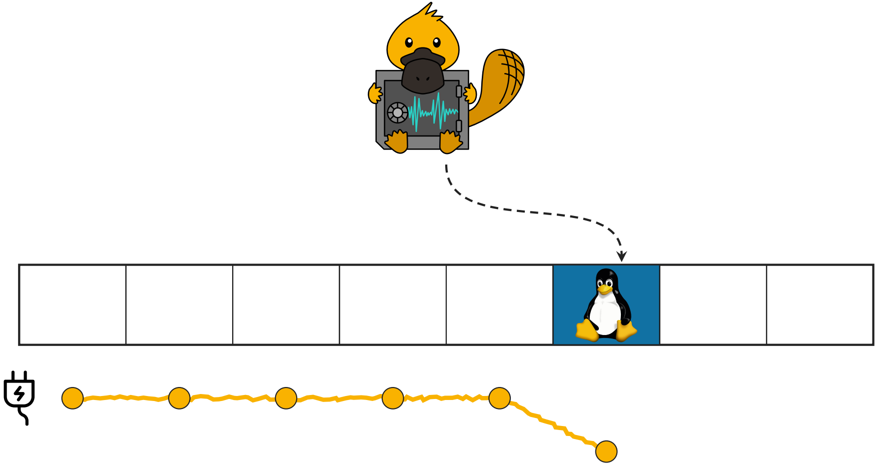

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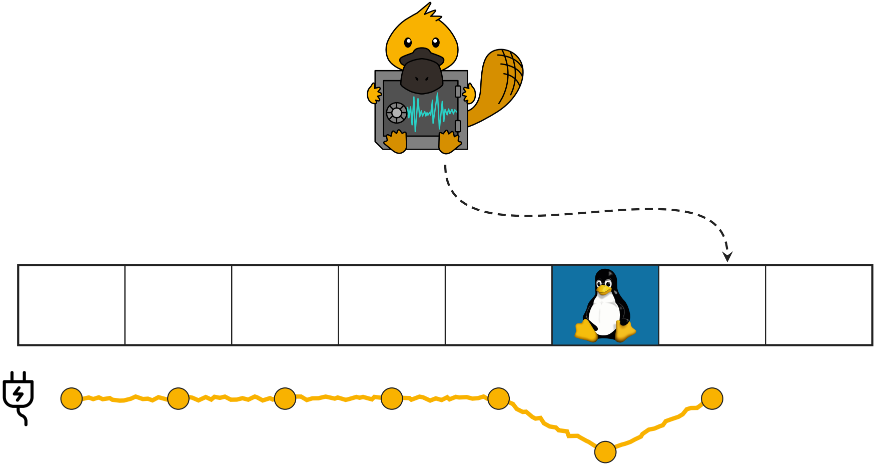

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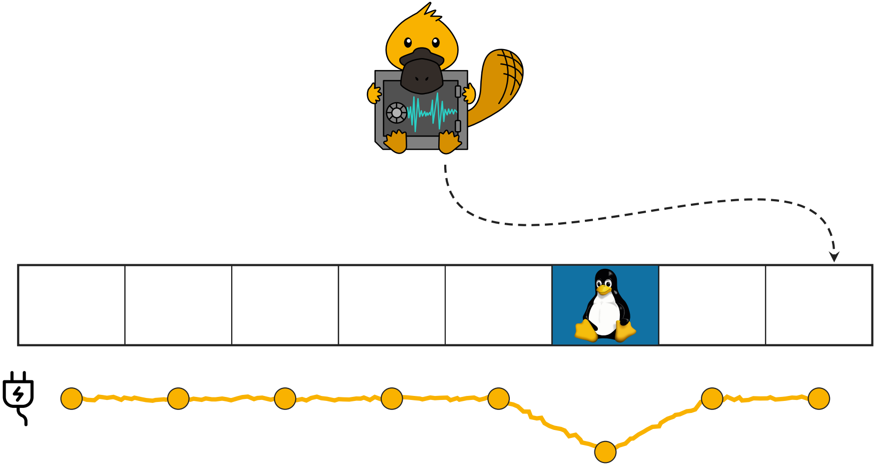
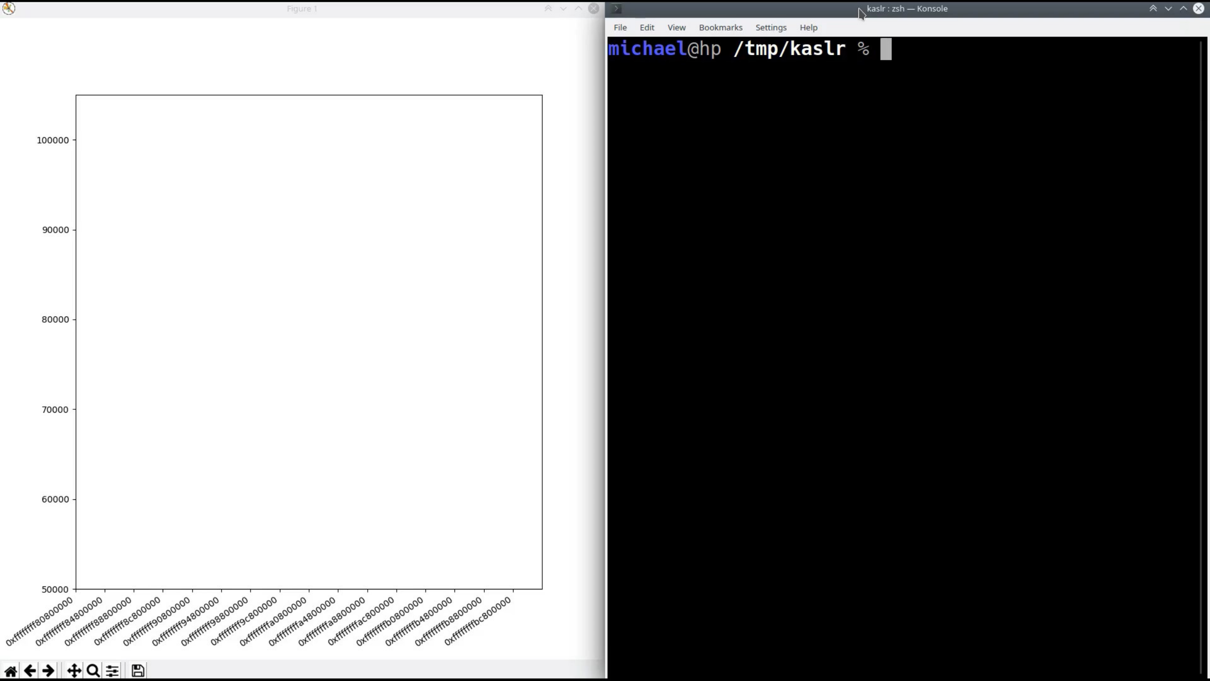
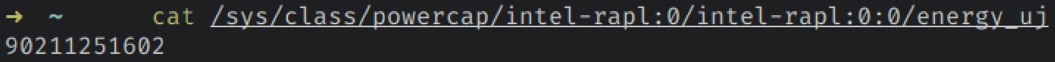




```
michael@hp /tmp/kaslr %
```



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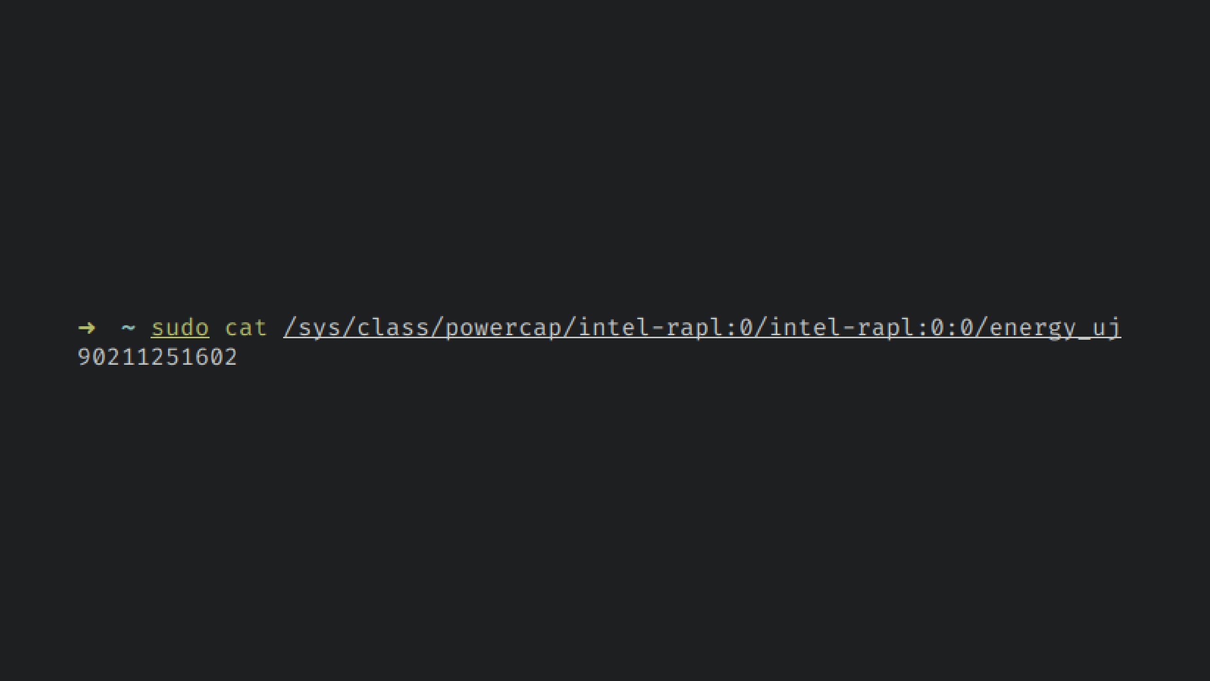

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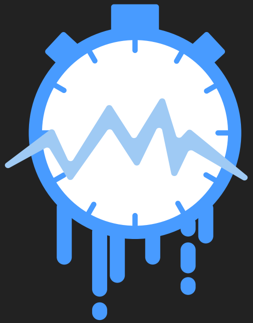
```

The end?

Hertzbleed[2][3]



[2] Yingchen Wang, Riccardo Paccagnella, Elizabeth He, Hovav Shacham, Christopher W. Fletcher, and David Kohlbrenner. Hertzbleed: Turning Power Side-Channel Attacks Into Remote Timing Attacks on x86. In: USENIX Security. 2022.

[3] Chen Liu, Abhishek Chakraborty, Nikhil Chawla, and Neer Roggel. Frequency throttling side-channel attack. In: CCS. 2022.

CPU Power Management

- CPU power management is complex

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- In order to save power, you can . . .

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Shut down resources

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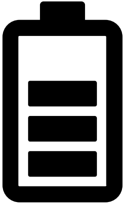
Hertzbleed Effect



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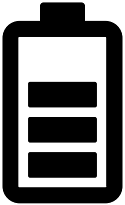
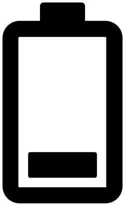


- Consumes **more** energy



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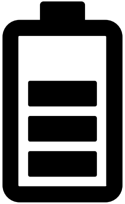

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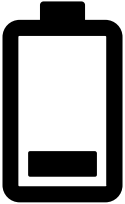

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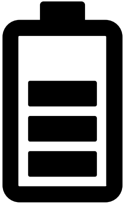
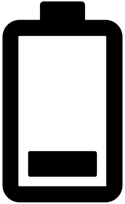


- Consumes **more** energy
- **Reaches** power limit after some time



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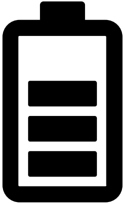

- Consumes **more** energy
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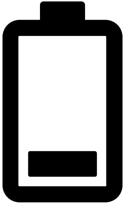
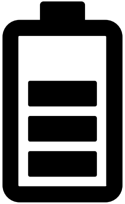
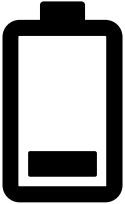


- Consumes **less** energy
- **Never reaches** power limit

Hertzbleed Effect



- Consumes **more** energy
- **Reaches** power limit after some time
- Throttling occurs



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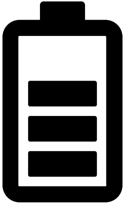

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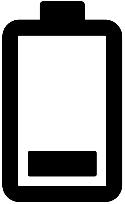

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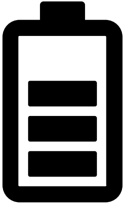

- Consumes **more** energy
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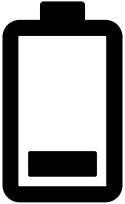
→ Slowdown



- Consumes **less** energy
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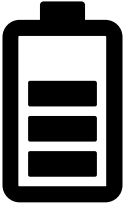
Hertzbleed Effect



- Consumes **more** energy
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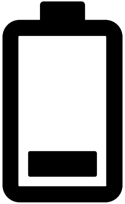
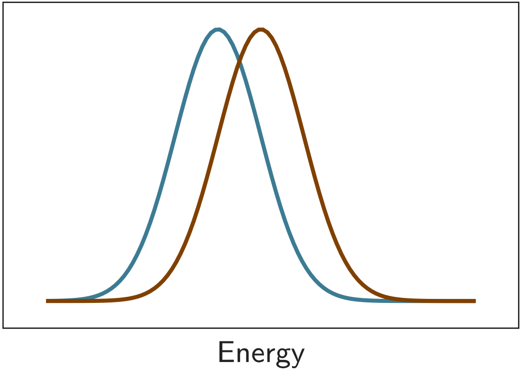
→ Slowdown

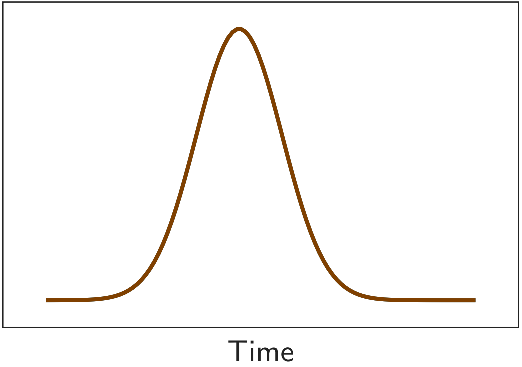


- Consumes **less** energy
- **Never reaches** power limit
- No throttling

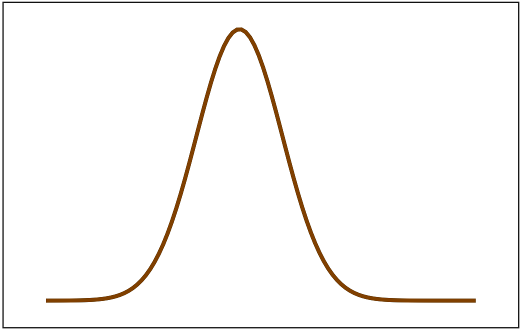
→ No slowdown

Hertzbleed Effect - Without Power Limit

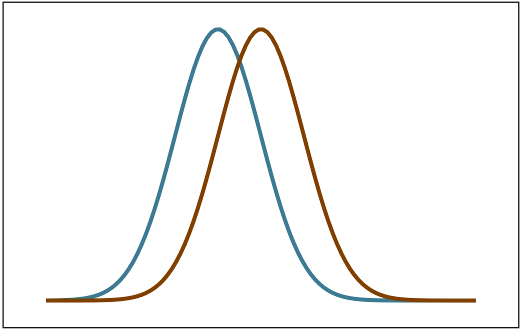




Hertzbleed Effect - With Power Limit



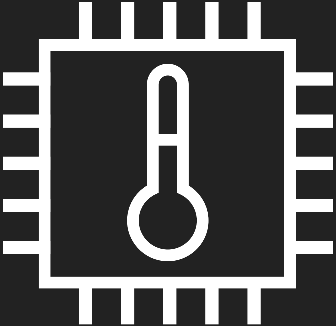
Energy



Time

NYPD
POWER
TIME
imgflip.com

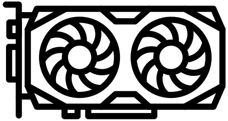
GPU Throttling[4][5]



[4] Yingchen Wang, Riccardo Paccagnella, Alan Wandke, Zhao Gang, Grant Garrett-Grossman, Christopher W Fletcher, David Kohlbrenner, and Hovav Shacham. DVFS frequently leaks secrets: Hertzbleed attacks beyond SIKE, cryptography, and CPU-only data. In: S&P. 2023.

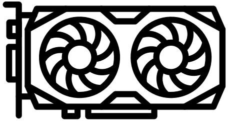
[5] Hritvik Taneja, Jason Kim, Jie Jeff Xu, Stephan van Schaik, Daniel Genkin, and Yuval Yarom. Hot Pixels: Frequency, Power, and Temperature Attacks on GPUs and ARM SoCs. In: USENIX Security.

GPU Throttling



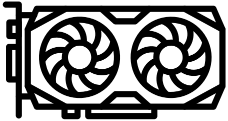
- **Integrated** GPUs share power limits with the CPU

GPU Throttling



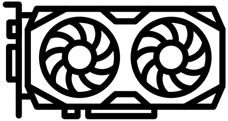
- **Integrated** GPUs share power limits with the CPU
  → **CPU throttling** indicates high GPU consumption

GPU Throttling



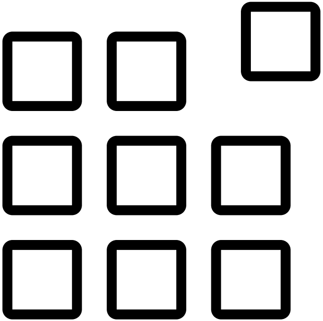
- **Integrated** GPUs share power limits with the CPU
  → **CPU throttling** indicates high GPU consumption
- **Dedicated** GPUs have power limits too

GPU Throttling



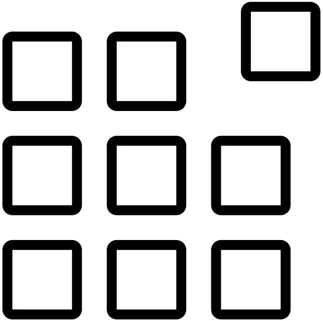
- **Integrated** GPUs share power limits with the CPU
  → **CPU throttling** indicates high GPU consumption
- **Dedicated** GPUs have power limits too
  → **Observable** by timing a GPU workload

Pixel Stealing



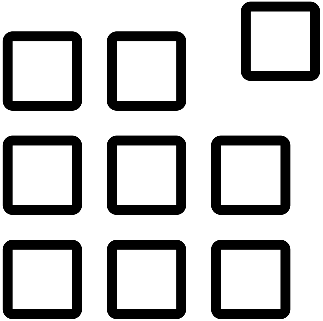
- What secrets are *“inside”* a GPU?

Pixel Stealing



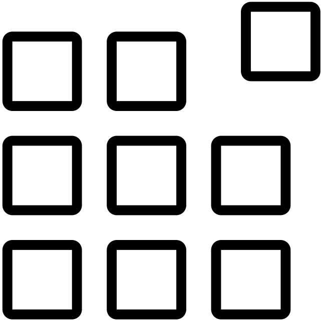
- What secrets are *“inside”* a GPU?
    - GPU renders windows and screen

Pixel Stealing



- What secrets are *"inside"* a GPU?
  - GPU renders windows and screen
  - → **Privacy** related information

Pixel Stealing



- What secrets are *“inside”* a GPU?
  - GPU renders windows and screen
  - → **Privacy** related information
- **Pixel** color represents the information

Pixel Stealing

- **Post-processing** without revealing the pixels

Pixel Stealing

- **Post-processing** without revealing the pixels
- Pixel value is the **data operand**

Pixel Stealing

- **Post-processing** without revealing the pixels
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- **Post-processing** without revealing the pixels
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  - **Bright** pixel → less power

Pixel Stealing

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  - **Bright** pixel → less power
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Pixel Stealing

- **Post-processing** without revealing the pixels
- Pixel value is the **data operand**
- Distinguishable power consumption
  - **Bright** pixel → less power
  - **Dark** pixel → more power

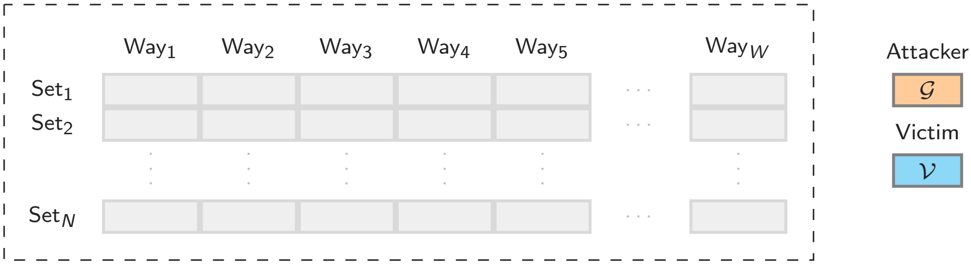
→ Measure timing and infer pixel value

How can we transform power side channels towards a broader scope?

Collide+Power[6]

[6] Andreas Kogler, Jonas Juffinger, Lukas Giner, Lukas Gerlach, Martin Schwarzl, Michael Schwarz, Daniel Gruss, and Stefan Mangard. Collide+Power: Leaking Inaccessible Data with Software-based Power Side Channels. In: USENIX Security. 2023.

Collide+Power - Memory Subsystem



Way$_1$ Way$_2$ Way$_3$ Way$_4$ Way$_5$ ... Way$_W$

Set$_1$

Set$_2$

Set$_N$

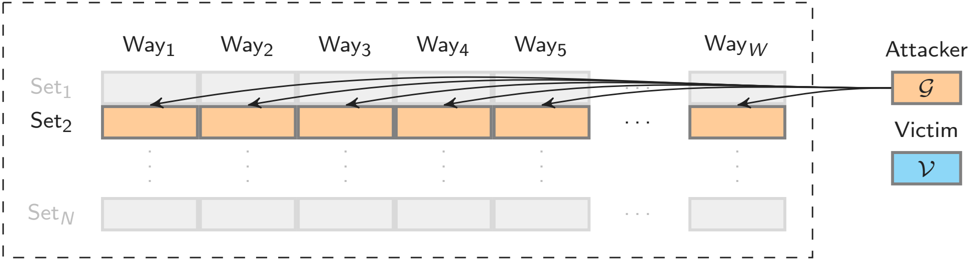
Attacker

$\mathcal{G}$

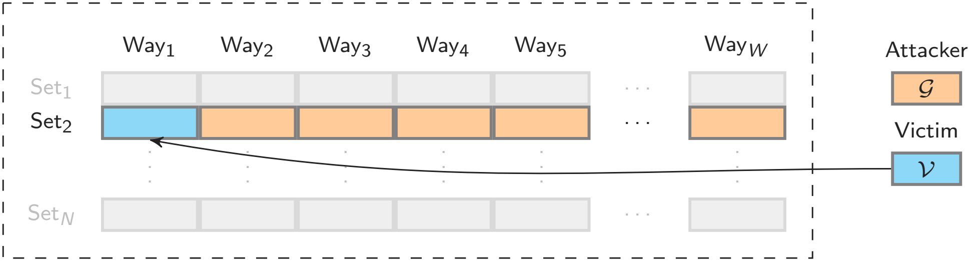
Victim

$\mathcal{V}$

Collide+Power - Memory Subsystem



Collide+Power - Memory Subsystem



Way_1 Way_2 Way_3 Way_4 Way_5 Way_W

Set_1

Set_2

Set_N

Attacker

$\mathcal{G}$

Victim

$\mathcal{V}$

Power Leakage - Model Components

Power Leakage - Model Components

Hamming Weight: $\mathrm{hw}(x)$

Power Leakage - Model Components

Hamming Weight: $\mathrm{hw}(x)$

Number of set bits

Power Leakage - Model Components

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$\mathrm{hw}(11_2) = 2$

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Hamming Distance: $\mathrm{hd}(x, y)$

Number of different bits

Power Leakage - Model Components

Hamming Weight: $\mathrm{hw}(x)$

Number of set bits

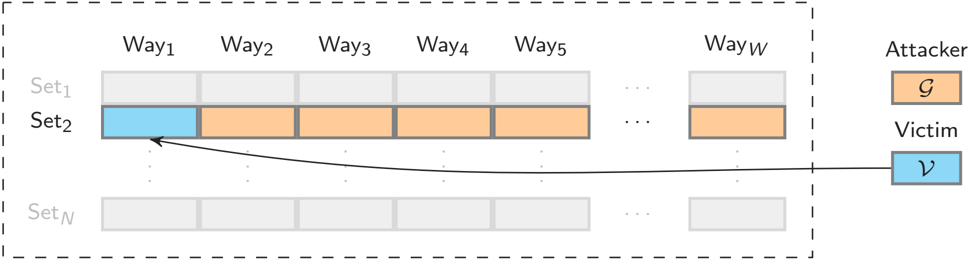
$\mathrm{hw}(11_2) = 2$

Hamming Distance: $\mathrm{hd}(x, y)$

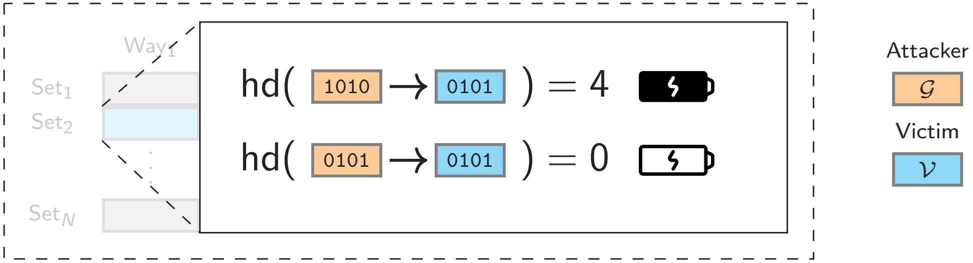
Number of different bits

$\mathrm{hd}(11_2, 01_2) = 1$

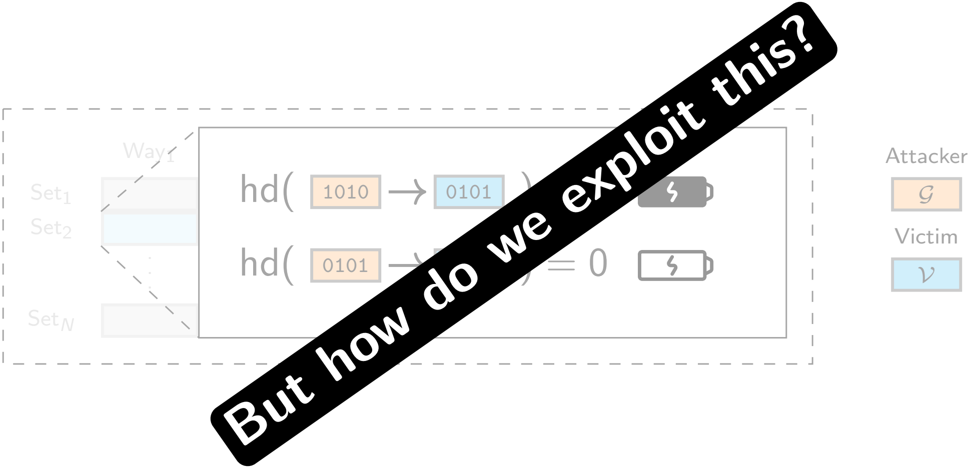
Collide+Power - Memory Subsystem



Collide+Power - Memory Subsystem



Collide+Power - Memory Subsystem



But how do we exploit this?

Collide+Power - Intuition

$$\mathcal{P}(\mathcal{G}, \mathcal{V}) \approx \ldots$$

Collide+Power - Intuition

$$\mathcal{P}(\mathcal{G}, \mathcal{V}) \approx \mathrm{hd}(\mathcal{G}, \mathcal{V})$$

Collide+Power - Intuition

$$\mathcal{P}(\mathcal{G}, \mathcal{V}) \approx \mathrm{hd}(\mathcal{G}, \mathcal{V})$$

Collide+Power - Intuition

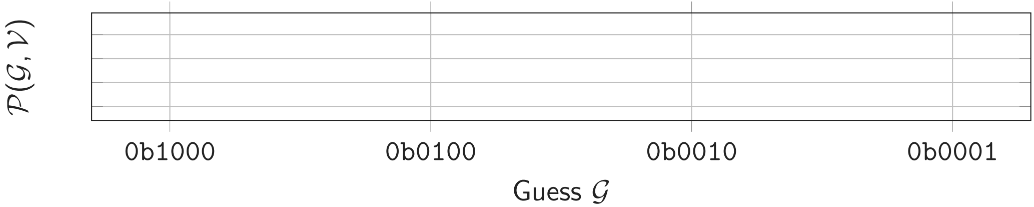
$$\underbrace{\mathcal{P}(\mathcal{G}, \mathcal{V})}_{\text{model}} \approx \mathrm{hd}(\mathcal{G}, \mathcal{V})$$

Collide+Power - Intuition

$$\underbrace{\mathcal{P}(\mathcal{G}, \mathcal{V})}_{\text{model}} \approx \underbrace{\mathrm{hd}(\mathcal{G}, \mathcal{V})}_{\text{signal}}$$

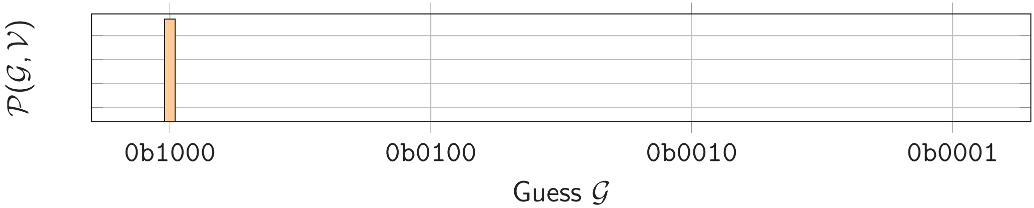
Collide+Power - Example

$$\mathcal{P}(\mathcal{G}, 0101_2) \approx \mathrm{hd}(\mathcal{G}, 0101_2)$$



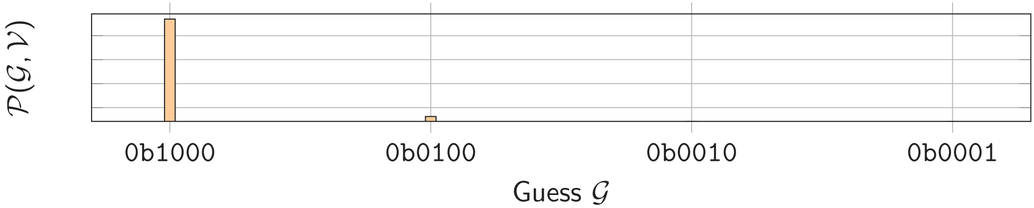
Collide+Power - Example

$$\mathcal{P}(1000_2, 0101_2) \approx \mathrm{hd}(\mathbf{1}000_2, \mathbf{0}101_2) = 3$$



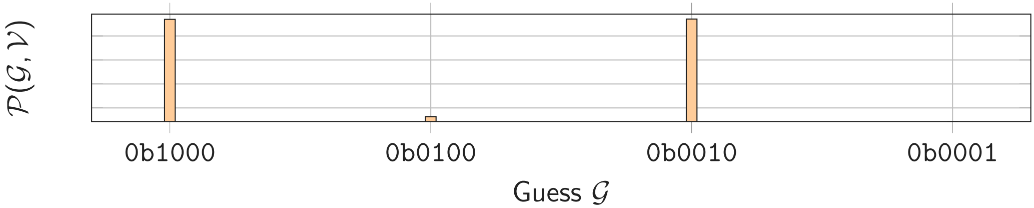
Collide+Power - Example

$$\mathcal{P}(0100_2, 0101_2) \approx \mathrm{hd}(0\mathbf{1}00_2, 0\mathbf{1}01_2) = 1$$



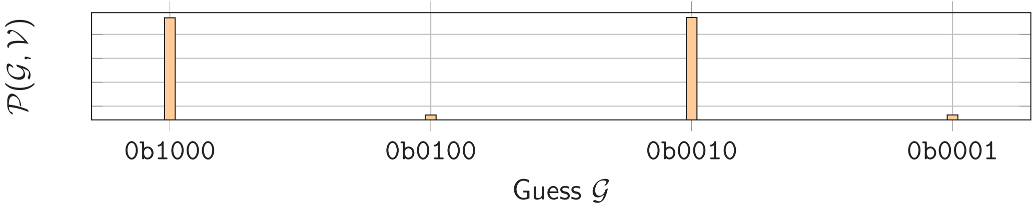
Collide+Power - Example

$$\mathcal{P}(0010_2, 0101_2) \approx \mathrm{hd}(00\mathbf{1}0_2, 01\mathbf{0}1_2) = 3$$



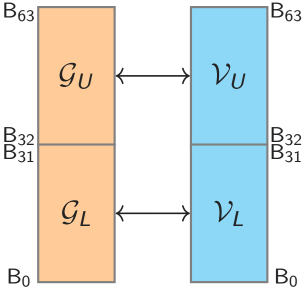
Collide+Power - Example

$$\mathcal{P}(0001_2, 0101_2) \approx \text{hd}(000\mathbf{1}_2, 010\mathbf{1}_2) = 1$$

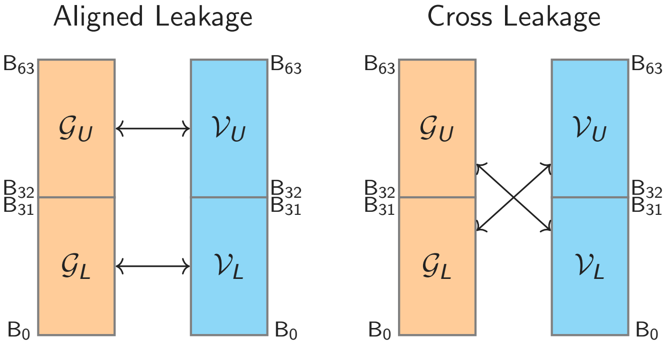


Leakage Analysis - Generalization

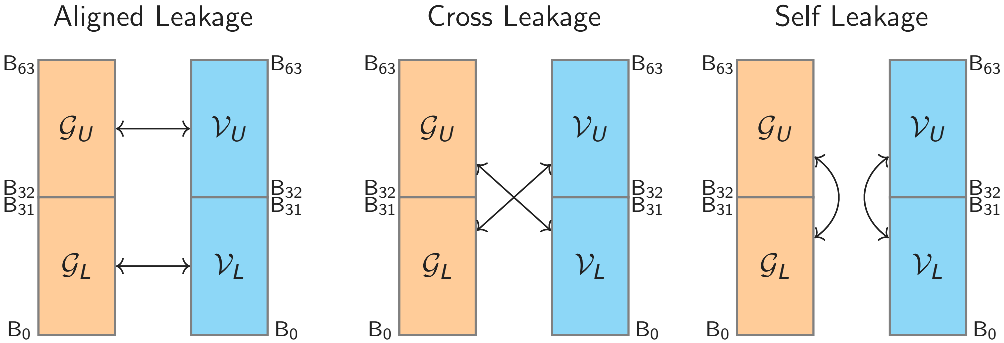
Aligned Leakage



Leakage Analysis - Generalization



Leakage Analysis - Generalization



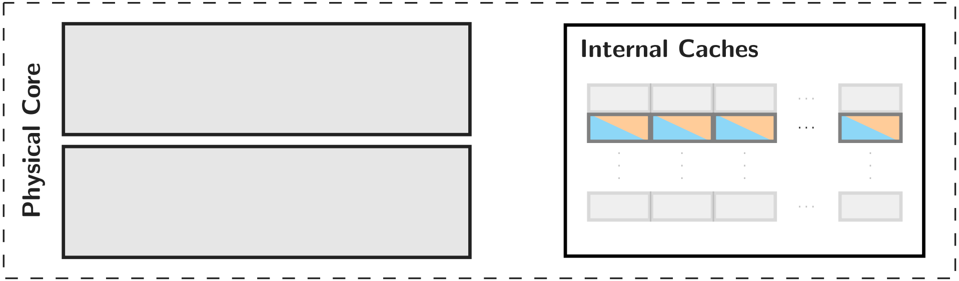
Leakage Analysis: Results

Inst.	Evict.	Effectiveness $\hat{\rho}$ $\cdot 1$	 SNR$_A$ $\cdot 10^{-3}$	Aligned Leakage hd(v_L, g_L) a_0 in μW	 hd(v_U, g_U) a_1 in μW	Cross Leakage hd(v_L, g_U) c_0 in μW	 hd(v_U, g_L) c_1 in μW	Self Leakage hd(v_L, v_U) s_0 in μW	 hd(g_L, g_U) s_1 in μW	Weights hw(v_L) [illegible]	 [illegible](v_U) [illegible]W	 hw(g_L) w_2 in μW	 hw(g_U) w_3 in μW
Load	None	0.311	72.004	544.5	4.2	1.1	0.5	0.0	[illegible]	[illegible]	0.0	362.6	0.0
	L1	0.907	7.873	598.3	278.8	0.0	0.0	[illegible]	[illegible]	0.0	0.0	6124.4	2696.9
	L1+L2	0.822	5.632	339.3	141.7	106.6	[illegible]	[illegible]	0.0	0.0	0.0	3750.7	1435.0
Prefetch	None	0.003	0.000	0.0	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0	0.0	1.7	2.8
	L1	0.370	11.365	[illegible]	[illegible]	[illegible]	0.1	0.0	0.0	0.0	0.0	454.1	455.5
	L1+L2	0.300	5.294	[illegible]	[illegible]	40.9	43.0	0.0	0.0	0.0	0.0	334.0	332.5
Store	None	0.003	0.000	[illegible]	0.0	0.0	3.1	0.0	0.0	0.0	0.0	7.0	0.0
	L1	0.241	3.876	63.3	74.5	4.9	9.6	0.0	0.0	0.0	0.0	204.6	303.2
	L1+L2	0.450	6.457	133.7	169.0	84.7	86.2	0.0	0.0	0.0	0.0	347.1	1130.5

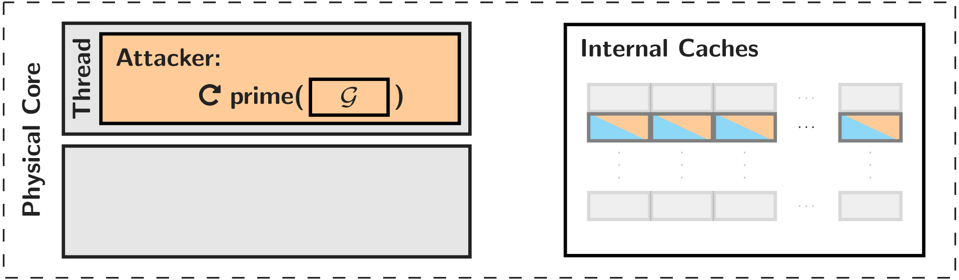
Do not start reading this!

Generic Attacks

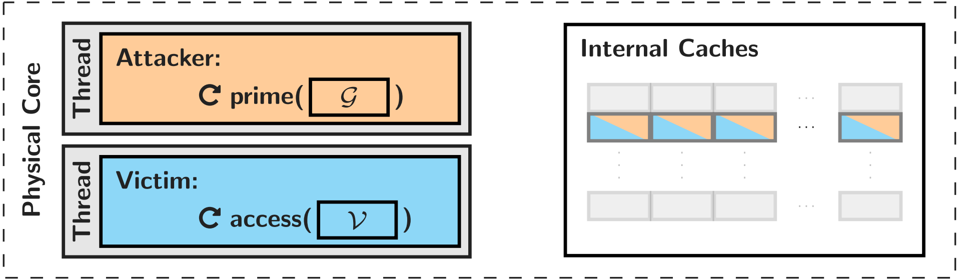
MDS-style Attack



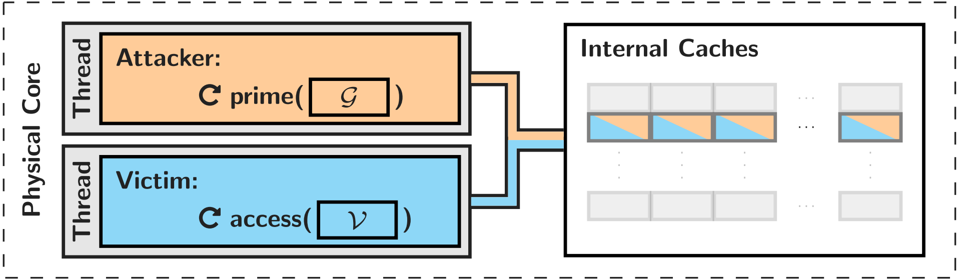
MDS-style Attack



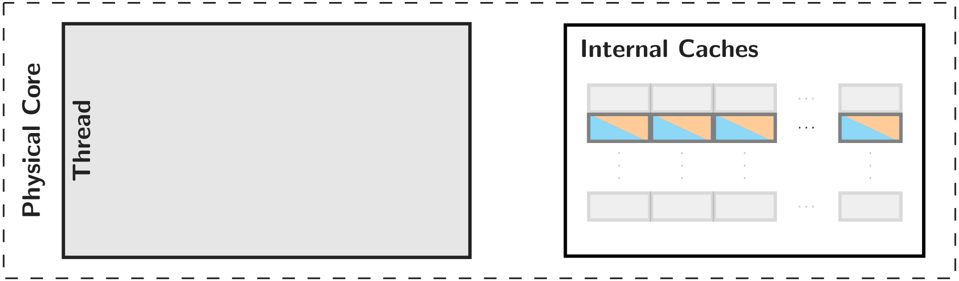
MDS-style Attack



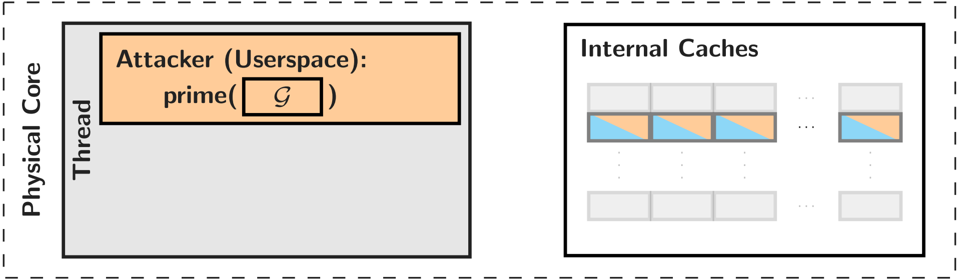
MDS-style Attack



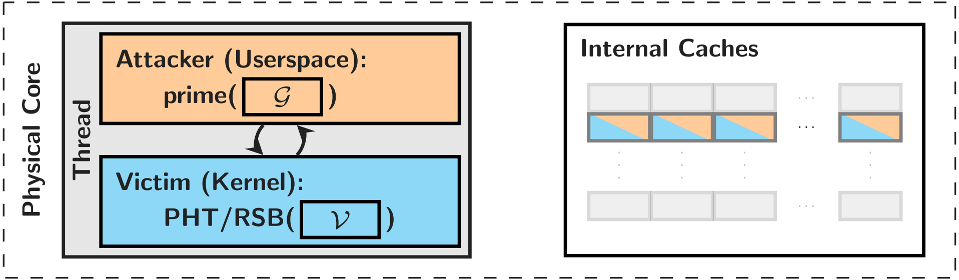
Meltdown-style Attack



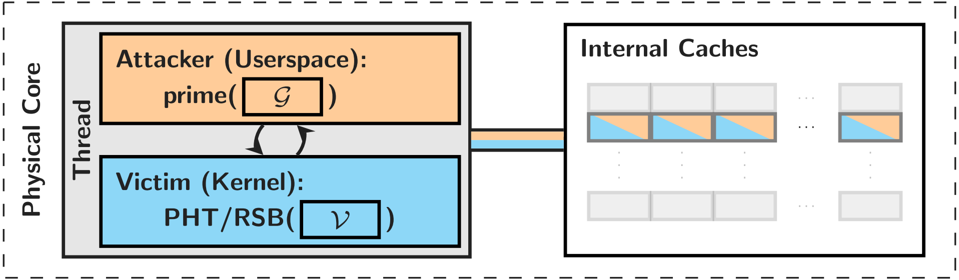
Meltdown-style Attack



Meltdown-style Attack



Meltdown-style Attack



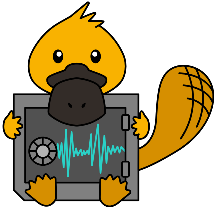
This must be slow?

NO!

It is EXTREMELY slow![7]

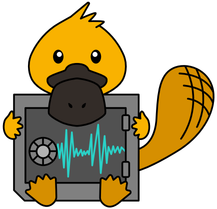
[7] With the current state-of-the-art.

Software-based Power Side Channels



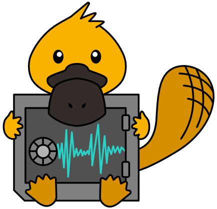
- **MDS-style:**
  4.82 bit/h

Software-based Power Side Channels



- **MDS-style:**
  4.82 bit/h
- **Meltdown-style (RSB):**
  0.84 bit/h

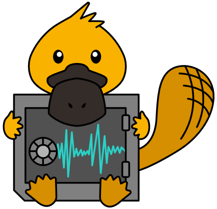
Software-based Power Side Channels



- **MDS-style:**
  4.82 bit/h
- **Meltdown-style (RSB):**
  0.84 bit/h

- **MDS-style:**
  0.065 to 0.68 bit/h

Software-based Power Side Channels



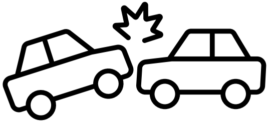
- **MDS-style:**
  4.82 bit/h
- **Meltdown-style (RSB):**
  0.84 bit/h

- **MDS-style:**
  0.065 to 0.68 bit/h
- **Meltdown-style estimate (PHT):**
  99.95 days/bit to 2.86 years/bit

DEMO

Mitigations

Mitigations



- **Preventing data collisions:**
  - **Redesign** of the complete shared data path
  - **Costly** to deploy
  - **Missed** components re-enable Collide+Power

Mitigations

- **Preventing observable power consumption:**
  - **Restricting** all direct power interfaces
- **Mitigating** Hertzbleed is challenging
  - Thermal and power management is required

→ **Collide+Power** is slow but unmitigated on modern CPUs!

Black Hat Sound Bytes

- **Unrestricted** power interfaces are a threat for system security

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- **Unrestricted** power interfaces are a threat for system security
- **Indirect interfaces** still expose exploitable information

Black Hat Sound Bytes

- **Unrestricted** power interfaces are a threat for system security
- **Indirect interfaces** still expose exploitable information
- **Software-based power side channels** can leak arbitrary data

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- **Unrestricted** power interfaces are a threat for system security
- **Indirect interfaces** still expose exploitable information
- **Software-based power side channels** can leak arbitrary data
- **Many more details** in the papers

  `https://collidepower.com`

  `https://hertzbleed.com`

  `https://platypusattack.com/`