NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

FDTC 2021 Fault Diagnosis and Tolerance in Cryptography

PACE

Are Cold Boot Attacks Still Feasible:
A Case Study on Raspberry Pi With Stacked Memory

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14:00~14:15 (CEST), 17.Sep.2021.

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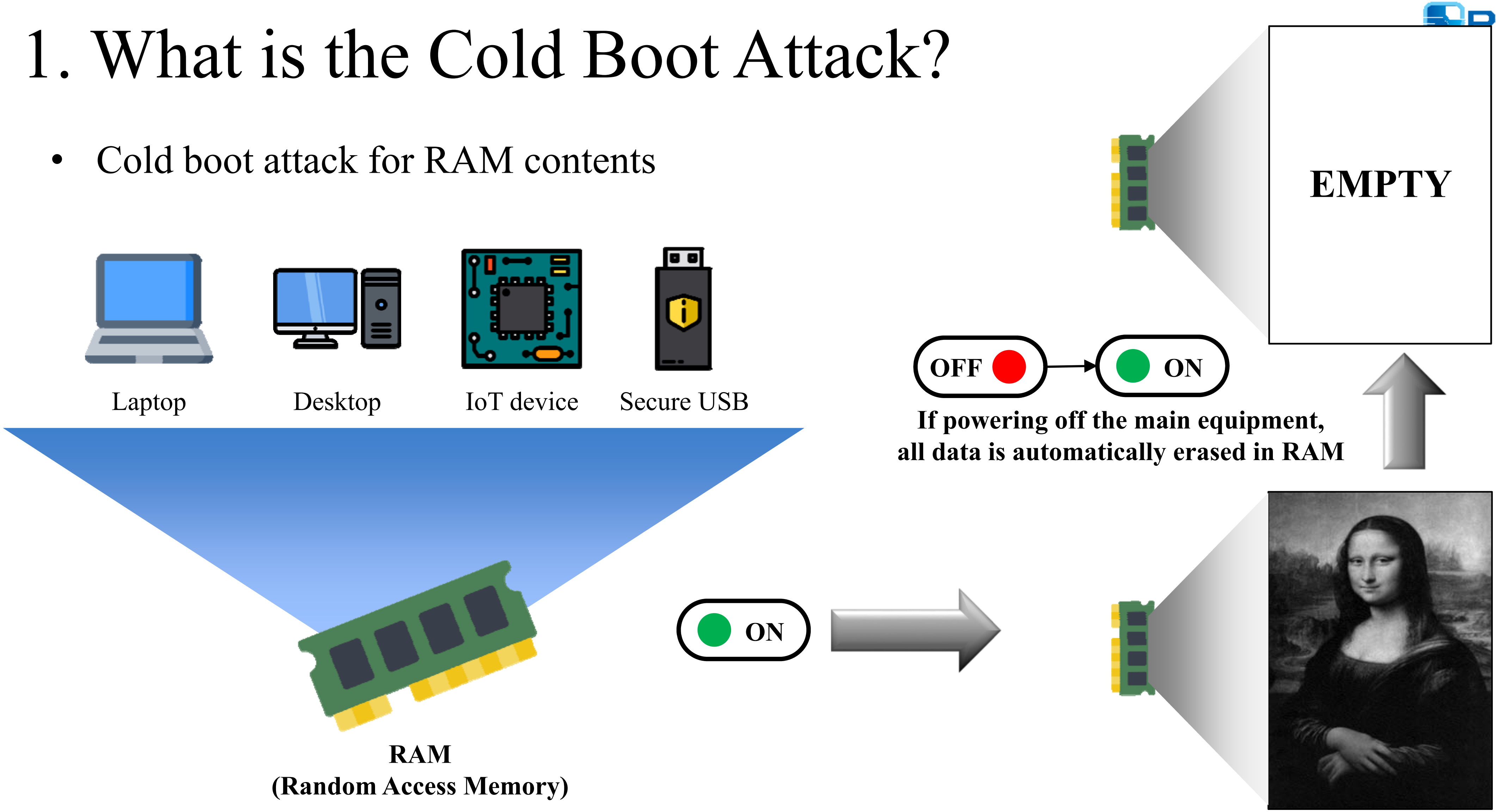
(2) Cold Boot Attack on Raspberry Pi

(3) Conclusion & Mitigation

1. What is the Cold Boot Attack?

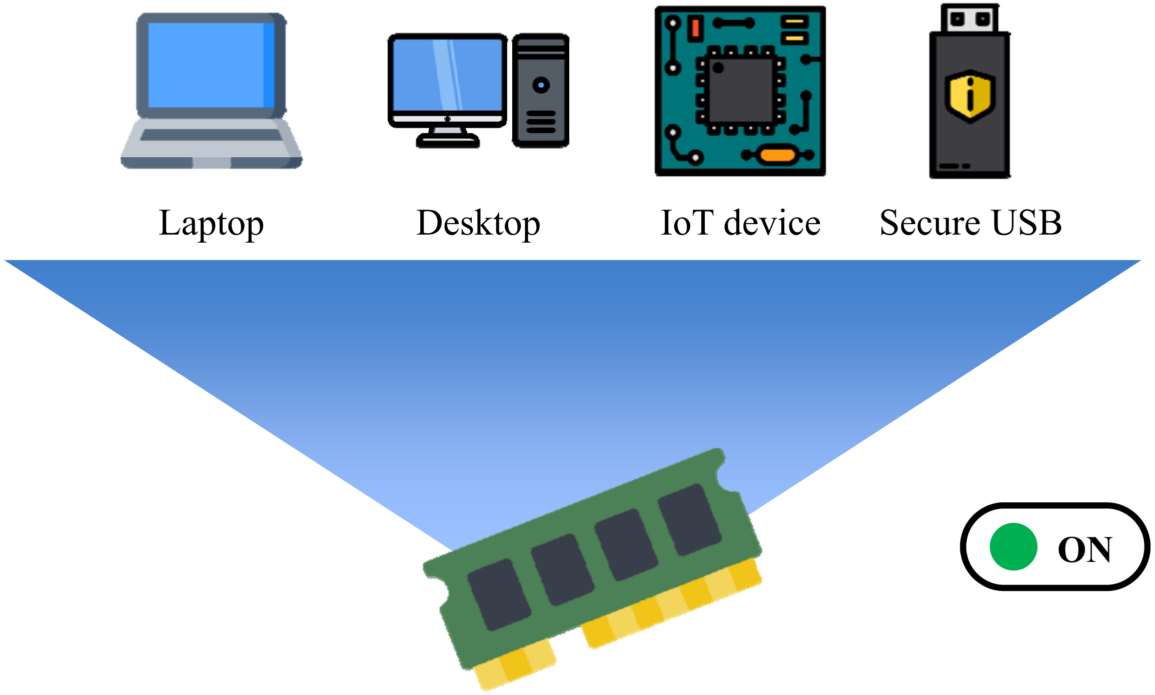
- Cold boot attack for RAM contents



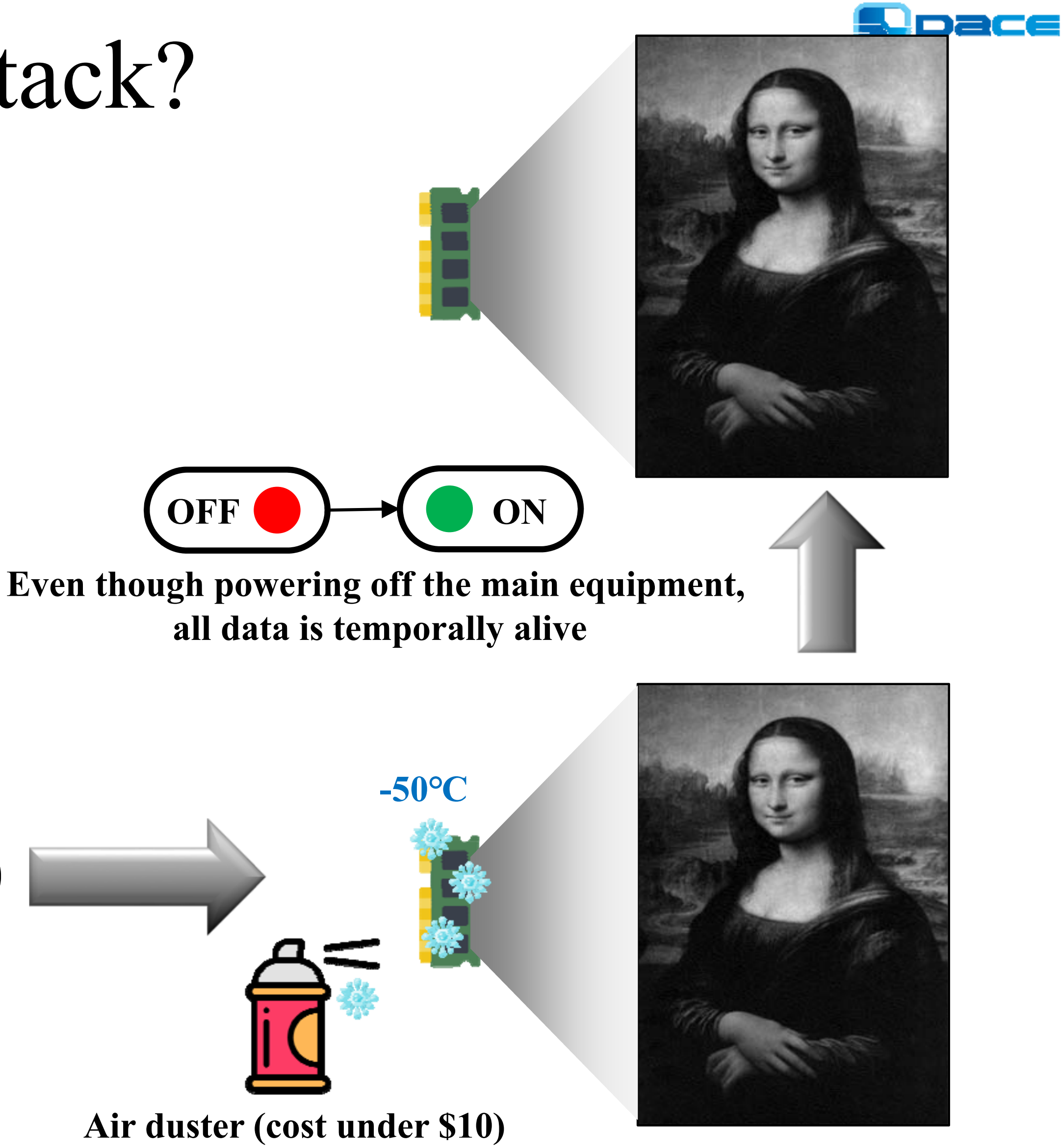
If powering off the main equipment, all data is automatically erased in RAM

1. What is the Cold Boot Attack?

- Cold boot attack for RAM contents



RAM
(Random Access Memory)



Even though powering off the main equipment, all data is temporally alive

Air duster (cost under $10)

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(1) What is the Cold Boot Attack?

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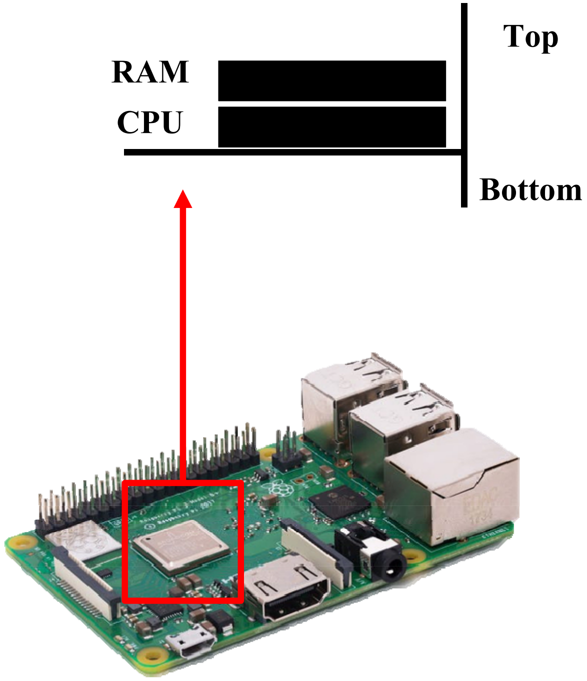
2. Cold Boot Attack on Raspberry Pi

1) Identifying the Target & Potential Vulnerabilities

✓ Main Target: Raspberry Pi Model B+



Raspberry Pi model B+

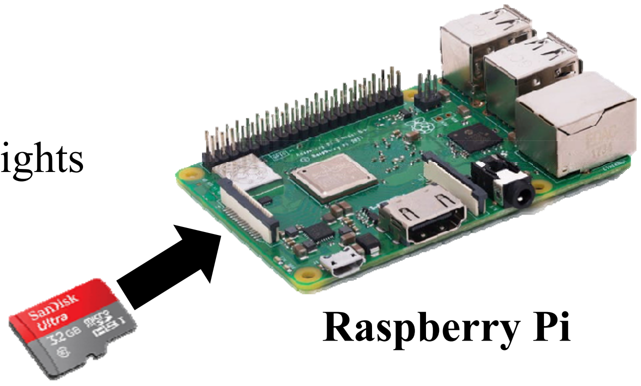
Target	Raspberry Pi model B+
SoC	Broadcom BCM2835 (Technology: 65nm)
CPU	700 MHz ARM1176JZF-S single core
GPU	Broadcom VideoCore IV @ 250 MHz OpenGL ES 2.0 (24 GFLOPS) MPEG-2 and VC-1 (with license), 1080p30 H.264/MPEG-4 AVC high-profile decoder and encoder (L2 cache of 128 KB)
Memory (SDRAM)	LPDDR2 512 MB (shared with GPU) (SAMSUNG k4p4g324eq-rgc2)

2. Cold Boot Attack on Raspberry Pi

1) Identifying the Target & Potential Vulnerabilities

✓ Adversary Assumption

- No one can access the RAM while victim's program (burned on a SD card) is in operation except for an authorized person
- An adversary can physically access the Raspberry Pi and can replace the victim's SD card by adversary SD card and vice versa
- Victim's SD card reveals no sensitive information owing to lack of access rights

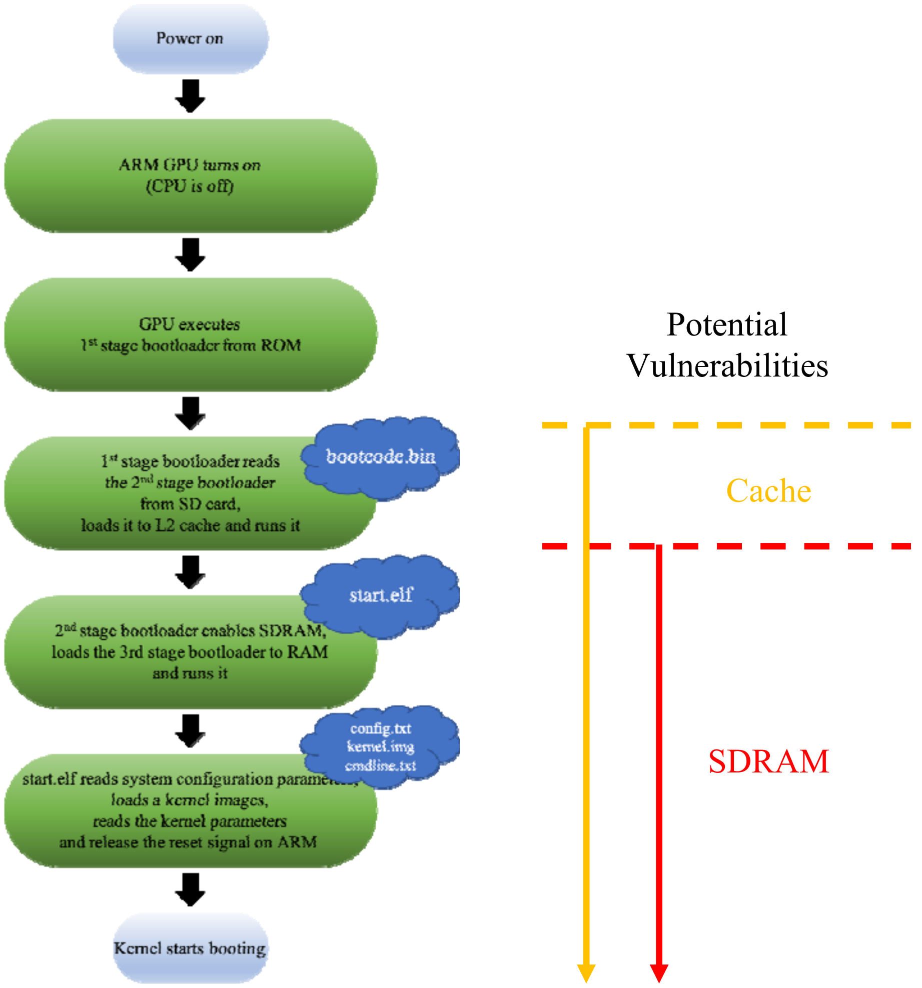


2. Cold Boot Attack on Raspberry Pi

1) Identifying the Target & Potential Vulnerabilities

- ✓ L2 cache memory
  - Attack point: Minimum 1st stage bootloader

- ✓ RAM
  - Attack point: Minimum 2nd stage bootloader



Power on

ARM GPU turns on
(CPU is off)

GPU executes
1st stage bootloader from ROM

1st stage bootloader reads
the 2nd stage bootloader
from SD card,
loads it to L2 cache and runs it

bootcode.bin

2nd stage bootloader enables SDRAM,
loads the 3rd stage bootloader to RAM
and runs it

start.elf

start.elf reads system configuration parameters,
loads a kernel images,
reads the kernel parameters
and release the reset signal on ARM

config.txt
kernel.img
cmdline.txt

Kernel starts booting

Potential
Vulnerabilities

Cache

SDRAM

2. Cold Boot Attack on Raspberry Pi

2) Recovery of image stored in RAM

1) Upload the Mona Lisa figure to RAM

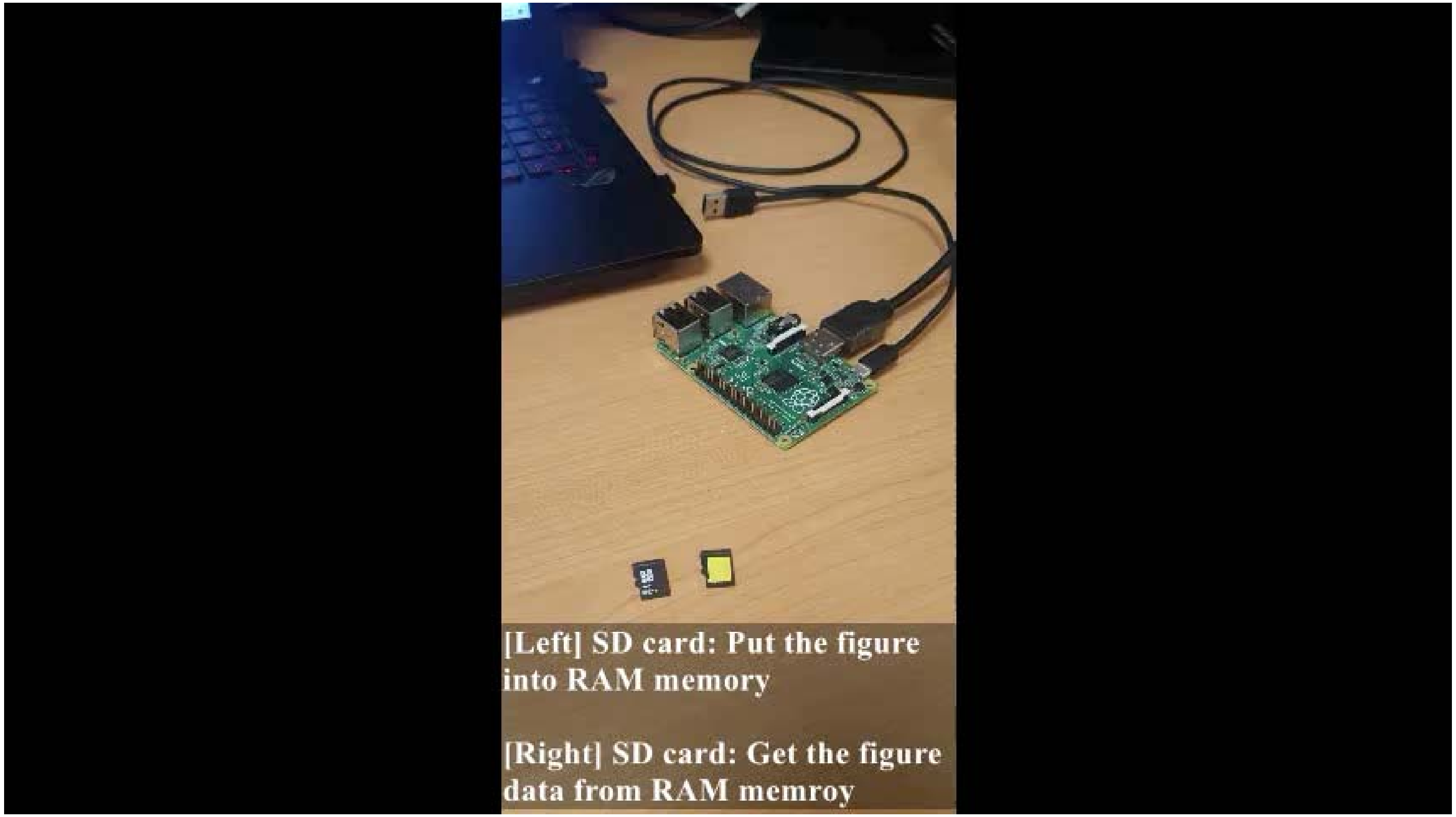
2) Freezing the RAM

3) Turn off and turn on the Raspberry pi

4) Read the RAM to show the figure

2. Cold Boot Attack on Raspberry Pi

2) Recovery of image stored in RAM



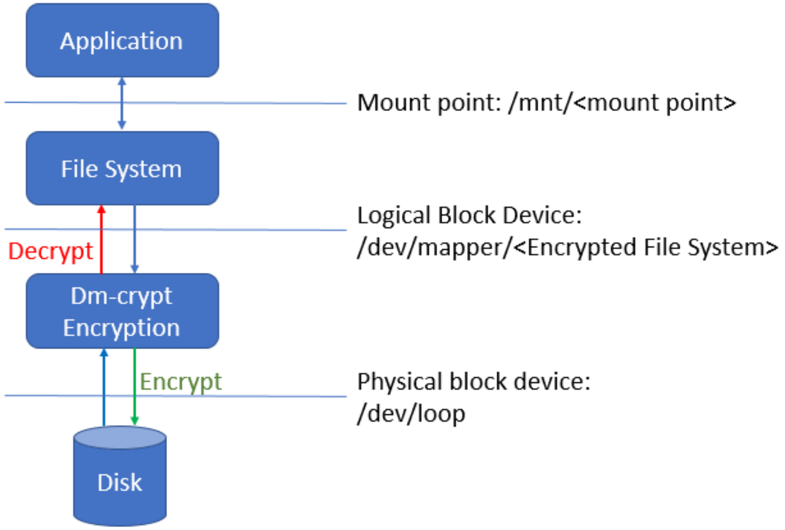
[Left] SD card: Put the figure into RAM memory

[Right] SD card: Get the figure data from RAM memroy

2. Cold Boot Attack on Raspberry Pi

3) Recovery of the dm-crypt master key

- ✓ Type of Disk encryption system
  - ➢ BitLocker – Windows OS
  - ➢ FileVault – Mac OS
  - ➢ TrueCrypt – Windows, Mac, Linux OS
  - ➢ dm-crypt – Linux OS
  - ➢ Loop-AES – Linux OS
- ✓ Application of Disk encryption system
  - ➢ Partition encryption/decryption
  - ➢ USB encryption/decryption

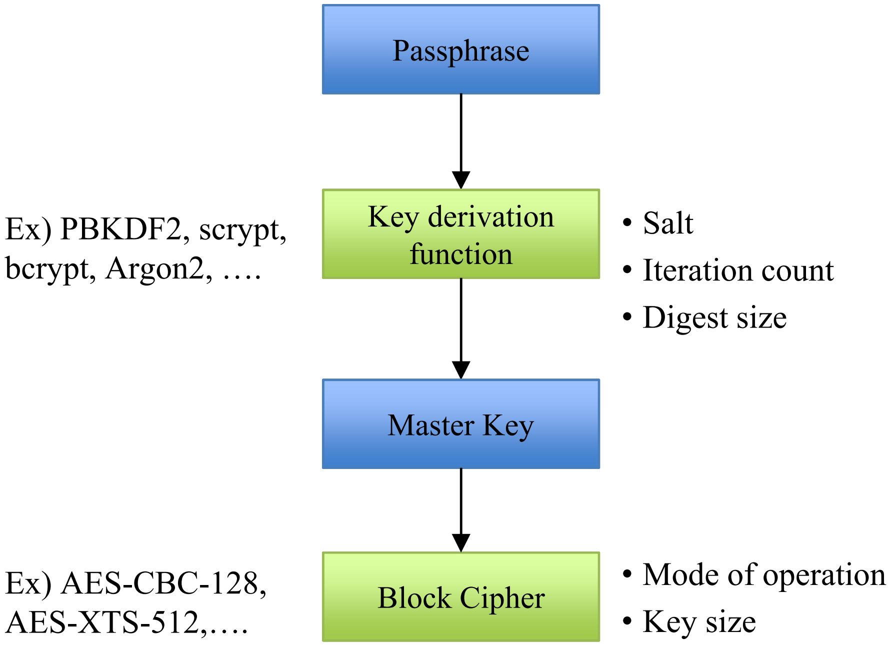


Overview of dm-crypt solution

2. Cold Boot Attack on Raspberry Pi

3) Recovery of the dm-crypt master key

✓ Encryption Method



Passphrase

Ex) PBKDF2, scrypt, bcrypt, Argon2, ….

Key derivation function

- Salt
- Iteration count
- Digest size

Master Key

Ex) AES-CBC-128, AES-XTS-512,….

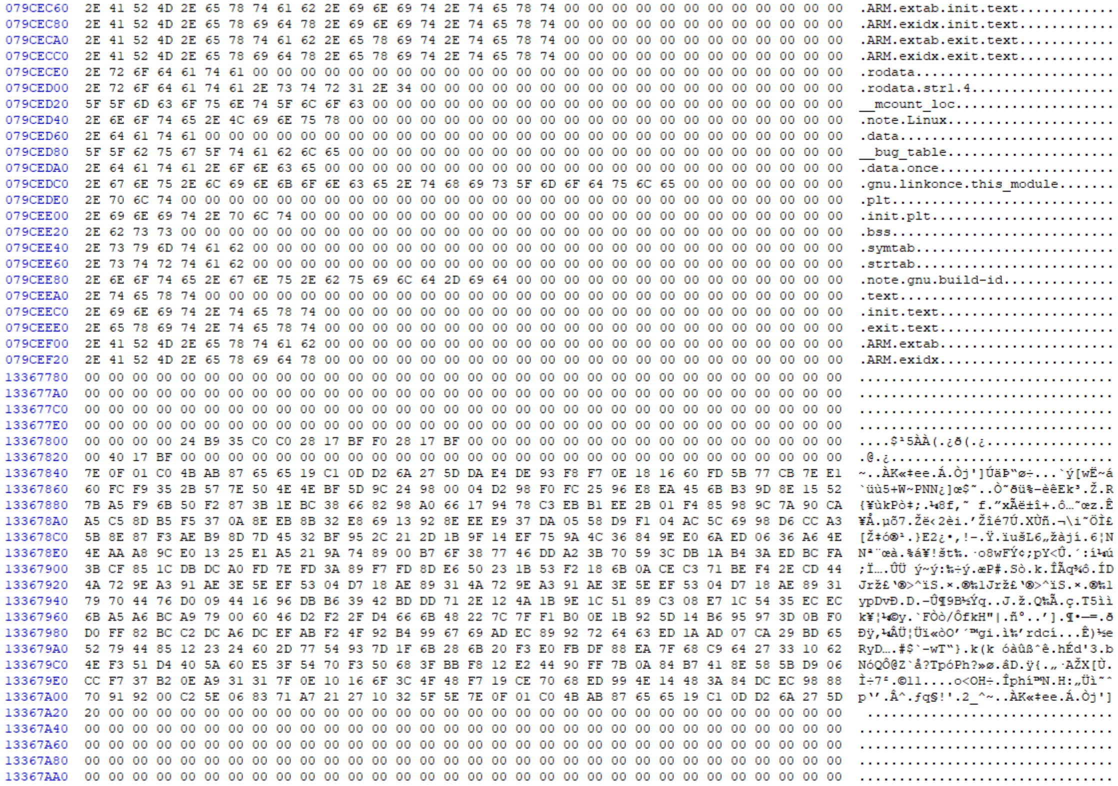
Block Cipher

- Mode of operation
- Key size

2. Cold Boot Attack on Raspberry Pi

3) Recovery of the dm-crypt master key

✓ Where is the master key in the RAM?



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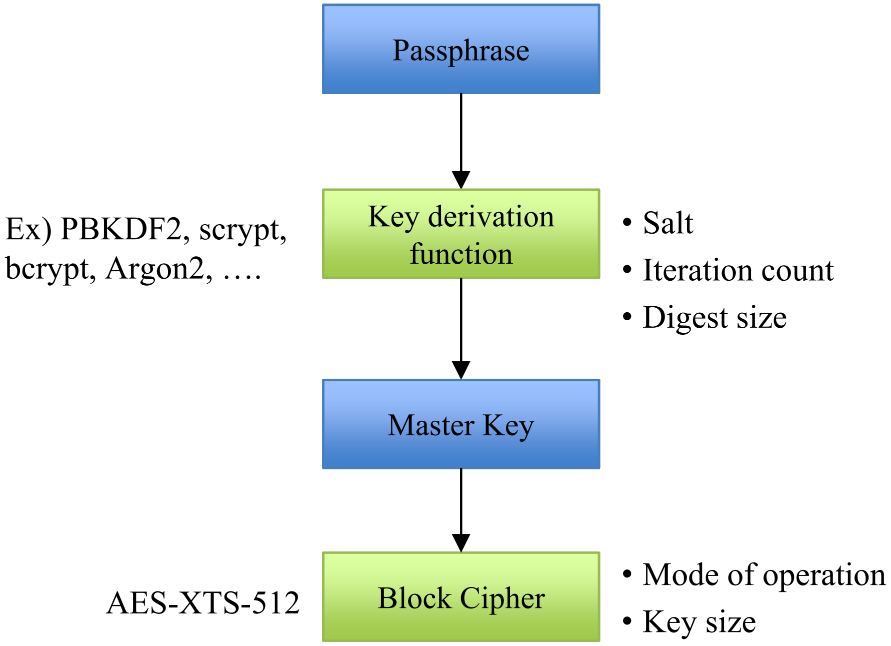


Ex) PBKDF2, scrypt, bcrypt, Argon2, ….

- Salt
- Iteration count
- Digest size

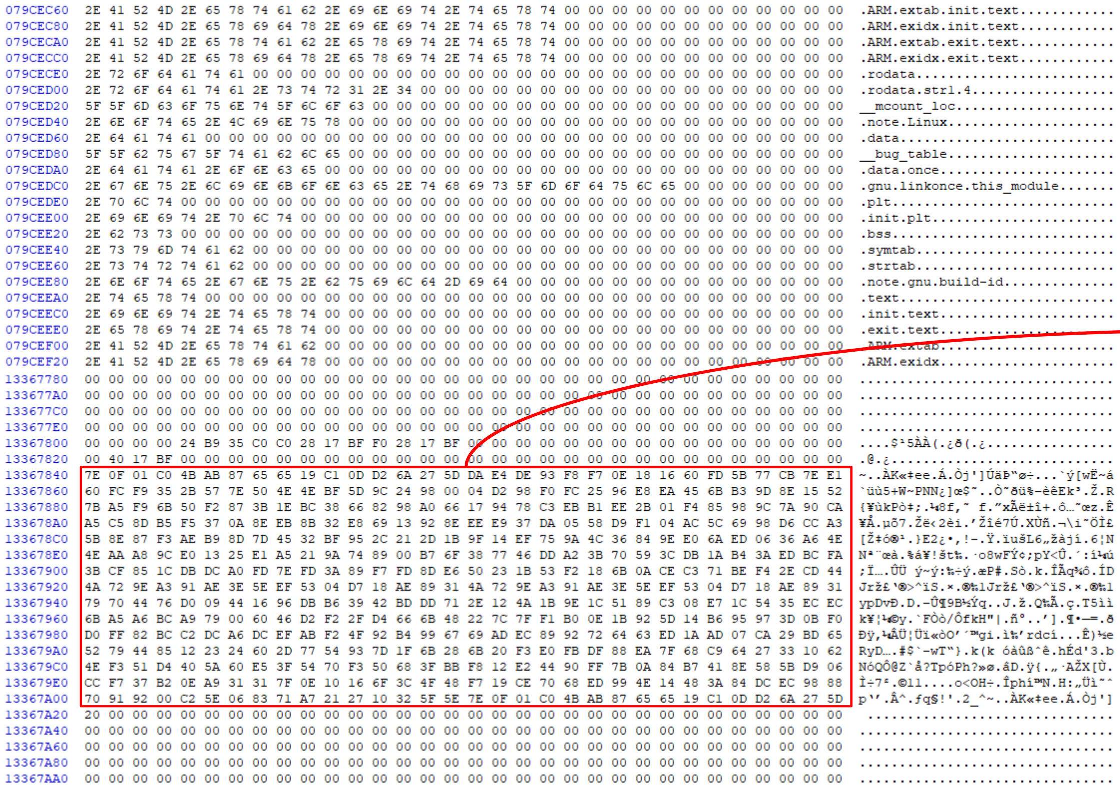
AES-XTS-512

- Mode of operation
- Key size

2. Cold Boot Attack on Raspberry Pi

3) Recovery of the dm-crypt master key

- ✓ Where is the master key in the RAM?



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133679C0  4E F3 51 D4 40 5A 60 E5 3F 54 70 F3 50 68 3F BB F8 12 E2 44 90 FF 7B 0A 84 B7 41 8E 58 5B D9 06  NóQÔ@Z`å?TpóPh?»ø.âD.ÿ{.„·AŽX[Ù.
133679E0  CC F7 37 B2 0E A9 31 31 7F 0E 10 16 6F 3C 4F 48 F7 19 CE 70 68 ED 99 4E 14 48 3A 84 DC EC 98 88  Ì÷7².©11....o<OH÷.Îphí™N.H:„Üì˜ˆ
13367A00  70 91 92 00 C2 5E 06 83 71 A7 21 27 10 32 5F 5E 7E 0F 01 C0 4B AB 87 65 65 19 C1 0D D2 6A 27 5D  p‘’.Â^.ƒq§!'.2_^~..ÀK«‡ee.Á.Òj']
13367A20  20 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ...............................
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13367AA0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................................
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AES-256 Round Keys

- ✓ We use *aeskeyfind* program to find round keys.

  https://citp.princeton.edu/our-work/memory/

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(1) What is the Cold Boot Attack?

(2) Cold Boot Attack on Raspberry Pi

(3) Conclusion & Mitigation

3. Conclusion & Mitigation

- The total cost of the reported attack is under $10

- It makes a serious threat against billions of IoT devices deployed into the wild.

- Secure boot process can be put in place to overcome such vulnerabilities, ensuring memory initialization and prevent unauthorized modification of boot sequence/firmware

- Even though the device is vulnerable to cold boot attacks, there are some solutions to protect the disk, utilizing the safe encryption solutions such as TRESOR* and ARMORED**

[*] T. Muller, F. C. Freiling, and A. Dewald, “Tresor runs encryption ¨ securely outside ram.” in USENIX Security Symposium, vol. 17, 2011.

[**] J. Gotzfried and T. M ¨ uller, “Armored: Cpu-bound encryption for ¨ android-driven arm devices,” in 2013 International Conference on Availability, Reliability and Security. IEEE, 2013, pp. 161–168

Q&A

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