# Self-Encrypting Deception:

## Weaknesses in the Encryption of Solid State Drives (SSDs)


**Carlo Meijer**
Radboud University Nijmegen
Midnight Blue Labs

**Bernard van Gastel**
Radboud University Nijmegen
Open University of the Netherlands

# whoami

Carlo Meijer

- PhD student at Radboud University Nijmegen
- Focused on analysis of crypto systems deployed in the wild
- Independent security researcher at Midnight Blue Labs

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https://cs.ru.nl/~cmeijer/
https://midnightbluelabs.com/

# whoami (2)

Bernard van Gastel

- Assistant professor at Open University of the Netherlands
- Focused on anaylsis and correctness of systems

b.vangastel@cs.ru.nl
https://sustailablesoftware.info/

# What is a Self-Encrypting Drive?

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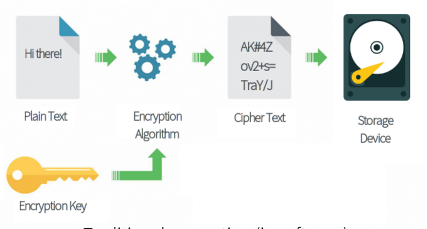


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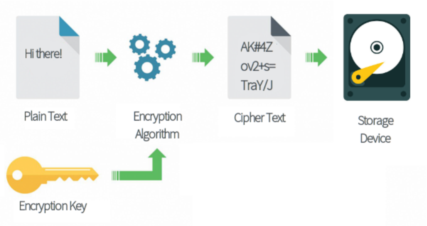


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# What is a Self-Encrypting Drive? (2)

**Samsung 840 EVO mSATA SSD Specifications:**

- Max capacity: 1TB
- Memory: 1GB LPDDDR2 DRAM
- Controller: Samsung MEX (3x ARM Cortex R4 cores @400MHz)
- NAND: 19nm Samsung TLC
- Interface: SATA
- Form Factor: mSATA
- Power Consumption
  - Start-up: 2.01W
  - Idle: 0.44W
- Dimensions Height x length x Thickness: 3cm x 5cm x 3.85mm
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The Marvell 88SS9189 controller supports high-speed NAND flash interfaces up to 200
channel and integrates a dual-core Marvell 88FR102 V5 CPU with shared DTCM and ITCM
can support up to eight NAND flash channels, ~500MBps sequential write performance,
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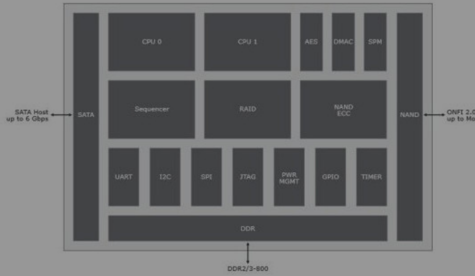

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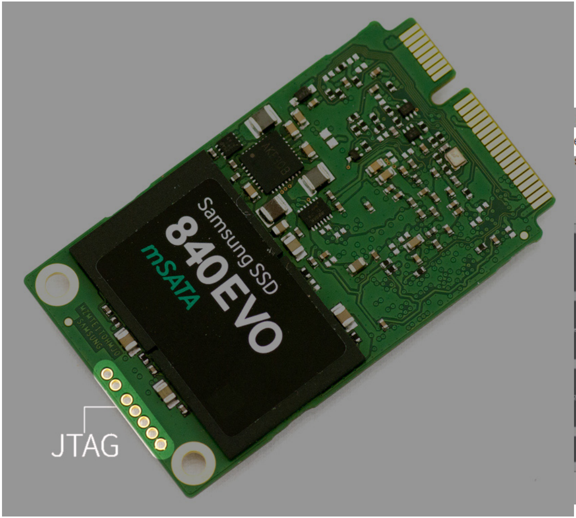


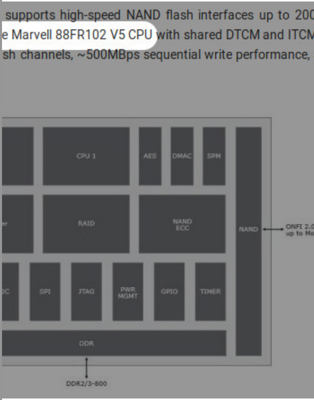


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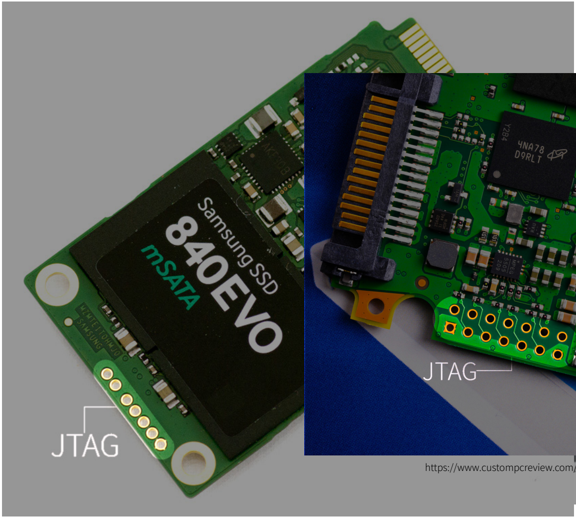


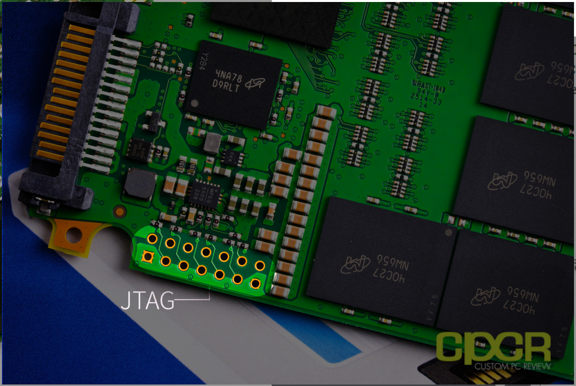


https://www.custompcreview.com/reviews/crucial-mx100-512gb-ssd-review/

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# Democratically proven

## The best way to enhance data security:

## Swap out vulnerable hard drives for self-encrypting SSDs

The best way to protect data stored on servers, desktops, or laptops is to encrypt it at the hardware level on a device's storage drive. This is just one of many standard data security steps, but it's critical – and often overlooked. The reason: New systems often come with low-grade, preinstalled hard drives, which often lack encryption technology. Or, if the hard drive offers encryption, it's typically software-based, which is one of the weakest forms of encryption and may severely slow system performance, plus it's also easier for hackers to attack. Here's why.


https://www.crucial.com/usa/en/how-self-encrypting-ssds-protect-your-business-and-enhance-data-security-and-limit-liability

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Hardware based encryption is very secure; far more secure than any software-based offering. Software can be corrupted or negated, while hardware cannot.

Software runs under an operating system that is vulnerable to viruses and other attacks. An operating system, by definition, provides open access to applications and thus exposes these access points to improper use.

Hardware based security can more effectively restrict access from the outside, especially to unauthorized use. Additionally, dedicated hardware can have superior performance compared to software.

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- **Ease of management:** No encryption key to manage; software vendors exploit standardized interface to manage SEDs, including remote management, pre-boot authentication, and password recovery
- **Disposal or re-purposing cost:** With an SED, erase on-board encryption key
- **Re-encryption:** With SED, there is no need to ever re-encrypt the data
- **Performance:** No degradation in SED performance; hardware-based
- **Standardization:** Whole drive industry is building to the TCG/SED Specifications
- **Simplified:** No interference with upstream processes

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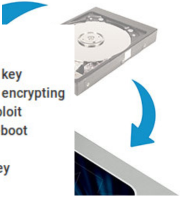

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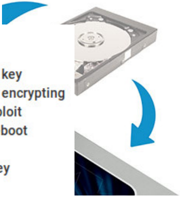

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BitLocker (built into Windows) opts for hardware encryption **by default** if available, software as a fall-back

# Security guarantees

of Self-Encrypting Drives

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Overall: Attack opportunities are more or less equivalent

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Overall: SEDs don't offer added protection → equivalent

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- Additional pitfalls that apply particularly to hardware (later)

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Thus, security guarantees are equivalent. **At best**.

# Standards

for Self-Encrypting Drives

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Two widely used standards exist

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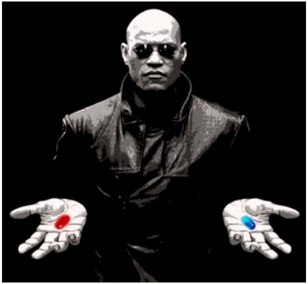
Originally designed for access control only



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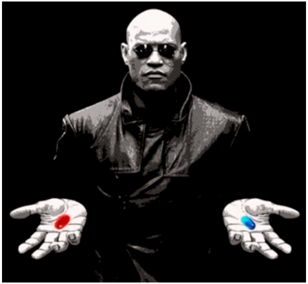

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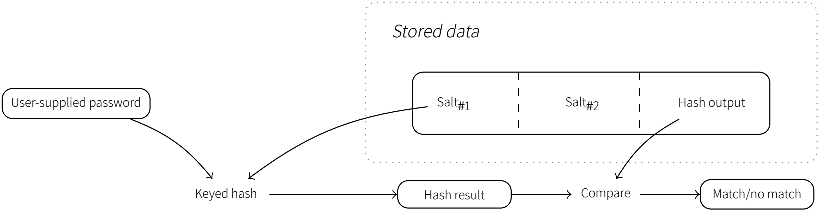

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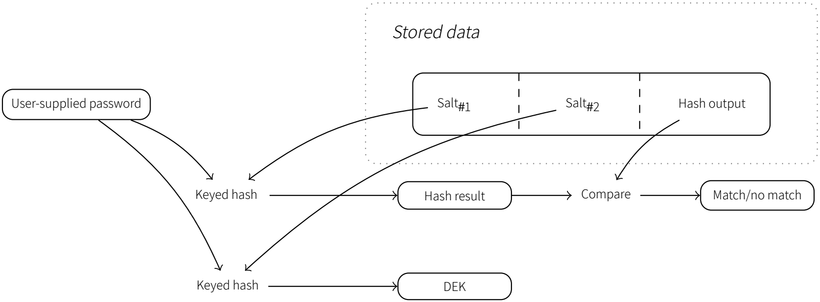

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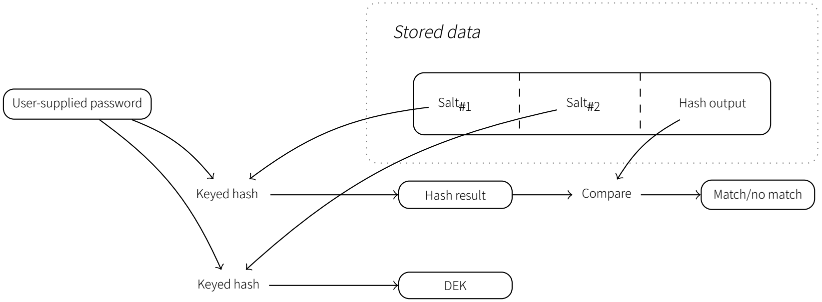


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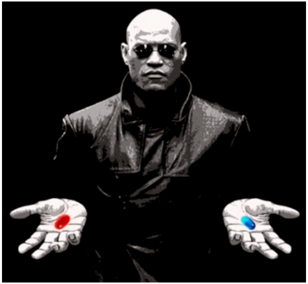

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  In practice, even this is almost always insufficient (later)

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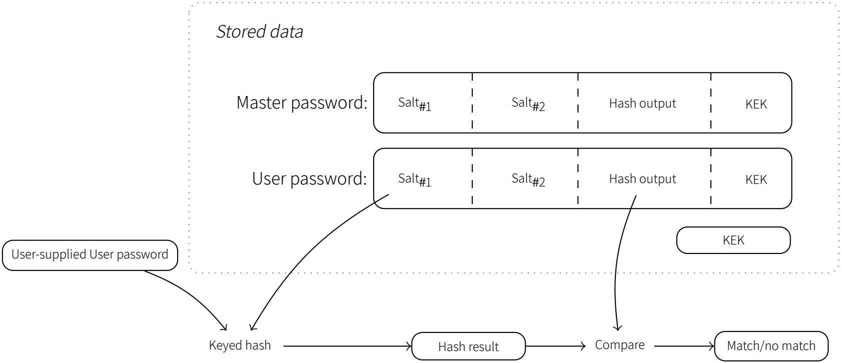

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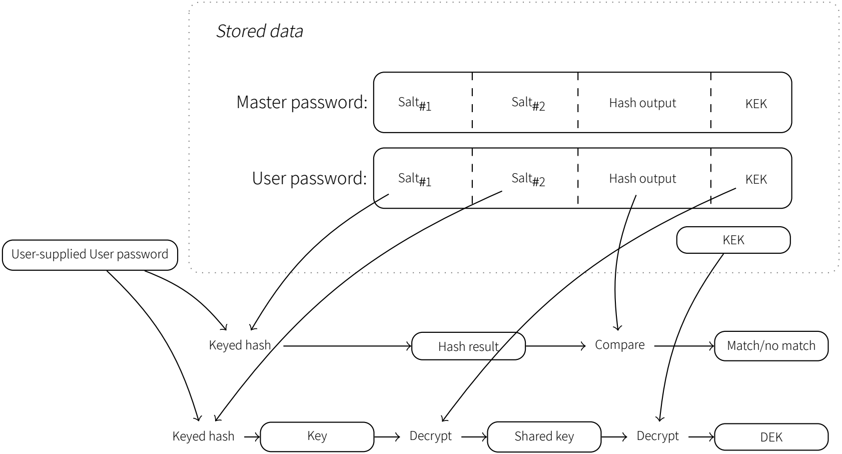

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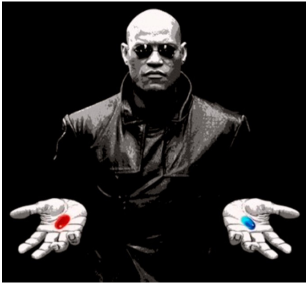

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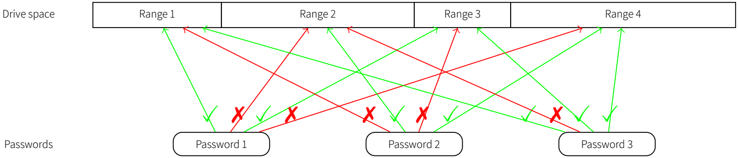

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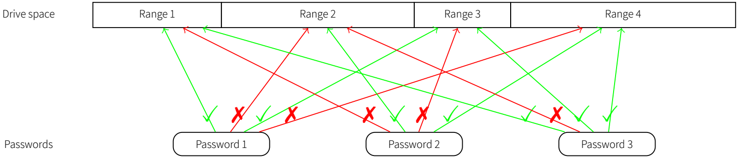

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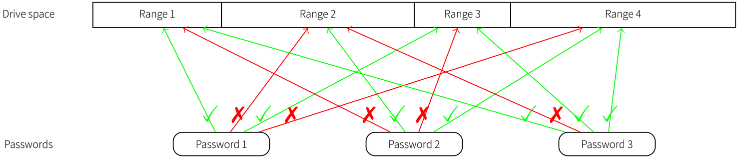
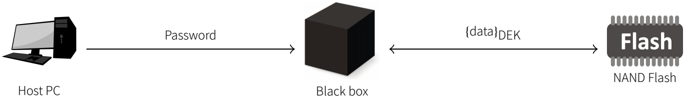


# Pitfalls

# Pitfall 1: DEK not derived from password



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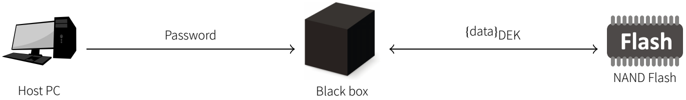


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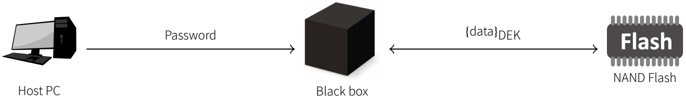


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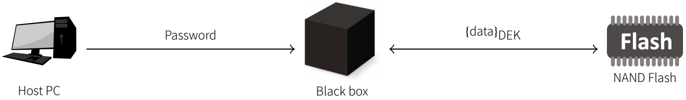


- Password unlocks drive and DEK is used to encrypt data
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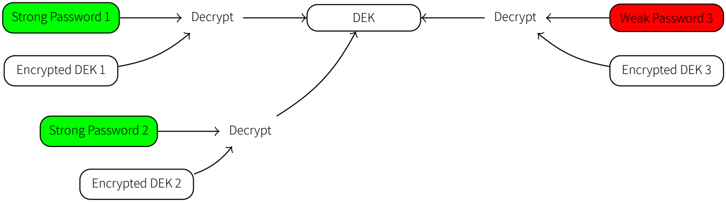
- They might **not be related at all**

# Pitfall 2: Single DEK for entire drive



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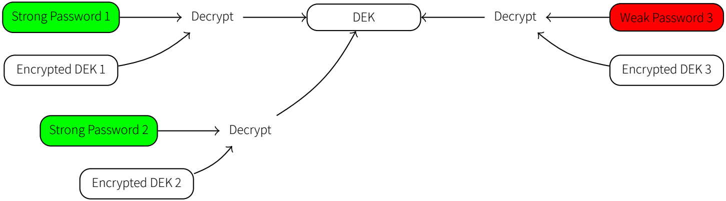


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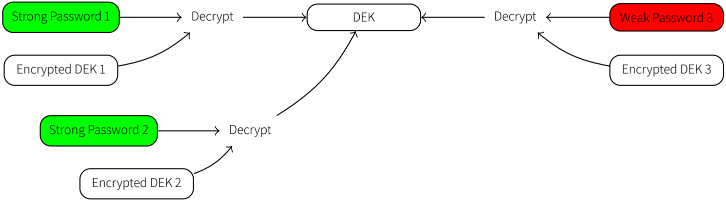


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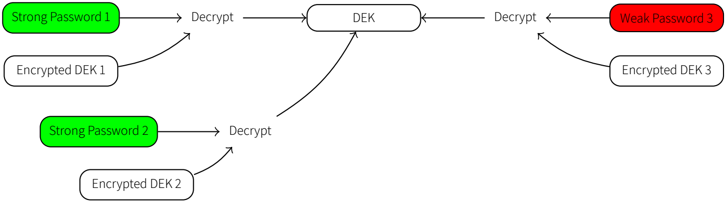


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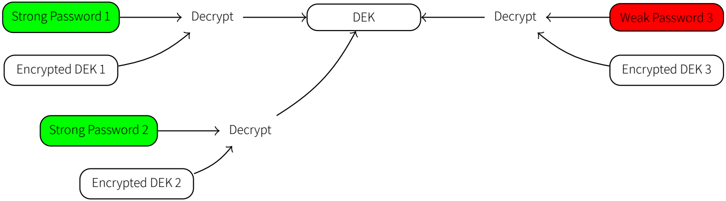


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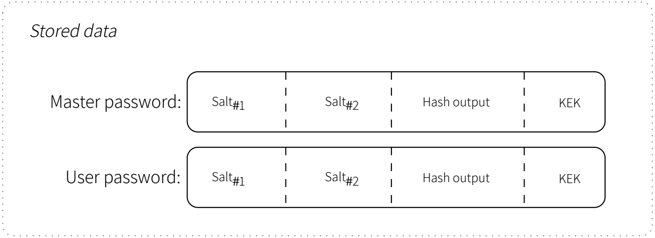
  - → Thus, in this case, DEK is recoverable **without** a password

# Pitfall 3: ATA Master password re-enable



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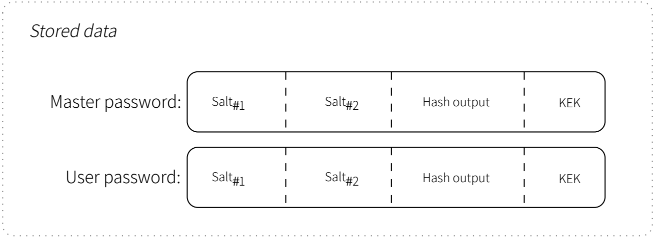


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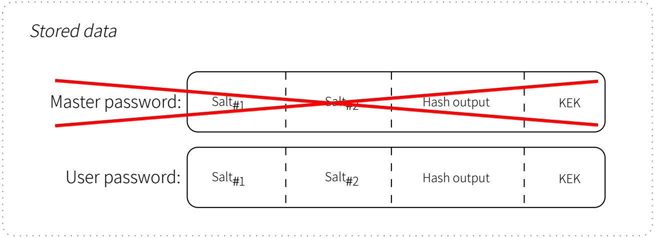


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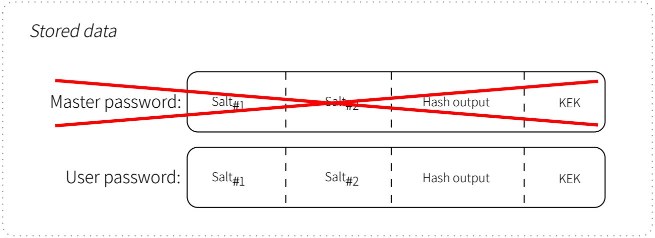


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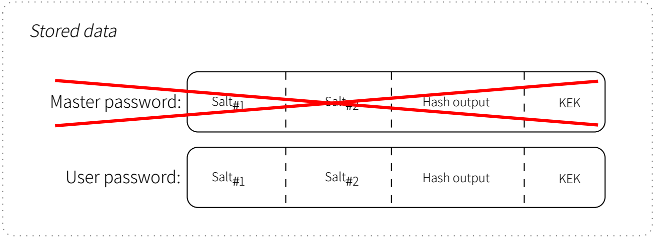


- Recall: You should set the MASTER PASSWORD CAPABILITY to *Max*
- Ideally, this erases key material
- However, the standard allows resetting it to *High*, using only the **user** password
- In practice, key material remains stored. If unchanged, **factory default master password** allows data to be recovered

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Multiple writes to the *same* logical sector trigger writes to *different* physical sectors

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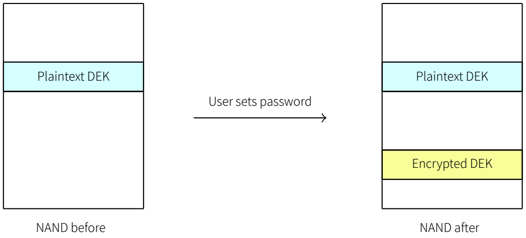

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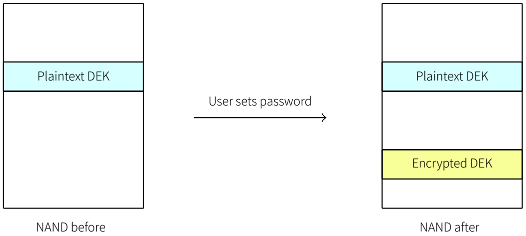


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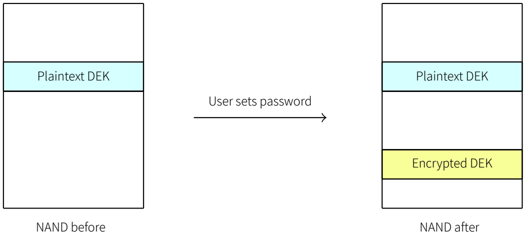


- Set password → overwrite of unprotected DEK with encrypted variant
- Unprotected DEK may still be present in physical flash

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  Mode of operation (ECB, CBC, CTR, XTS) , Side channels, Key derivation, etc.

# Methodology

Radboud University

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dword_10222A58 = sub_1003E390();
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v129 = 7;
*(_BYTE *)sub_1002D920(v15, v14, &v129) = 37;
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Decompilation of Samsung Magician tool

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(ii) Pull the firmware from RAM through JTAG (next)

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Decompilation of Samsung Magician tool

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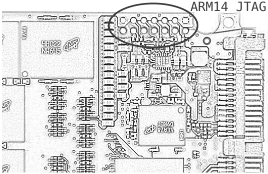


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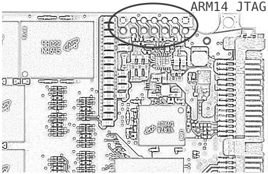


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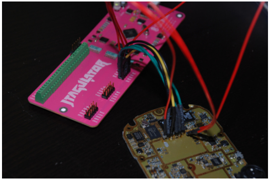


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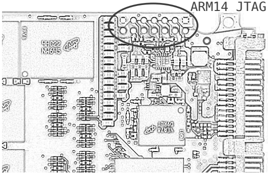


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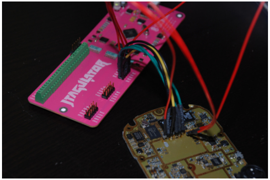

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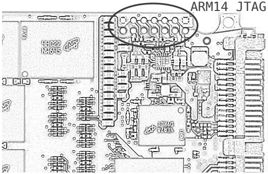


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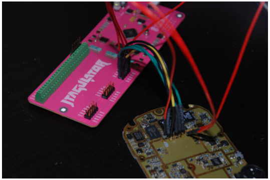


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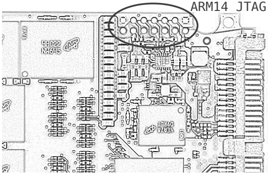


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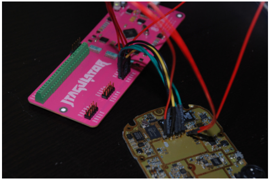

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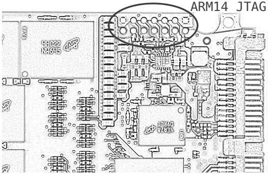


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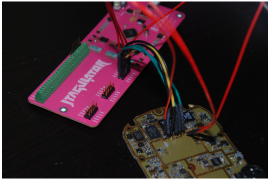

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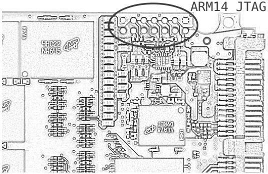
- Bypass cryptographic signatures with fault injection

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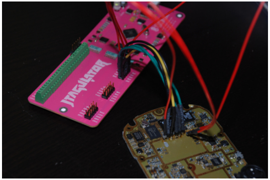

JTAGulator

# Methodology

General approach

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# Analyze the firmware

(i) Figure out the section information

# Analyze the firmware

```
user@pinacolada:~/Documents/ssdproject/crucial$ php parse_fw.php firmware_mx300/M0CR060.bin
[+] found MCRN header -- B0KB
[*] [segment] [type] [source] [dest] [size]
[*]     0    0  0x00000010 0x00000000 117456
[*]     1    0  0x0001cae0 0x0001fa00 352
[*]     2    0  0x0001cc40 0x04002100 2488
[*]     3    0  0x0001d5f8 0x80001000 240
[*]     4    0  0x00000000 0x80000000 16
[*]     5    0  0x0001d6e8 0x80041000 264
[*]     6    0  0x0001d7f0 0x801c4000 1035224
[*]   255  255  0xffffffff 0xffffffff 4294967295
[*]   255  255  0xffffffff 0xffffffff 4294967295
[*]   255  255  0xffffffff 0xffffffff 4294967295
[*]   255  255  0xffffffff 0xffffffff 4294967295
[*] new offset : 0x11aa00
[*] new offset : 0x133c00
[*] new offset : 0xfa540c00
user@pinacolada:~/Documents/ssdproject/crucial$ 
```

Parsed header of MX300 FW image

(i) Figure out the section information

- From image header

# Analyze the firmware

```
user@pinacolada:~/Documents/ssdproject/crucial$ php parse_fw.php firmware_mx300/M0CR060.bin
[+] found MCRN header -- B0KB
[*] [segment] [type] [source] [dest] [size]
[*]     0    0  0x00000010 0x00000000 117456
[*]     1    0  0x0001cae0 0x0001fa00 352
[*]     2    0  0x0001cc40 0x04002100 2488
[*]     3    0  0x0001d5f8 0x80001000 240
[*]     4    0  0x00000000 0x80000000 16
[*]     5    0  0x0001d6e8 0x80041000 264
[*]     6    0  0x0001d7f0 0x801c4000 1035224
[*]   255  255  0xffffffff 0xffffffff 4294967295
[*]   255  255  0xffffffff 0xffffffff 4294967295
[*]   255  255  0xffffffff 0xffffffff 4294967295
[*]   255  255  0xffffffff 0xffffffff 4294967295
[*] new offset : 0x11aa00
[*] new offset : 0x133c00
[*] new offset : 0xfa540c00
user@pinacolada:~/Documents/ssdproject/crucial$
```

Parsed header of MX300 FW image

(i) Figure out the section information
  - From image header

(ii) Load the image into a disassembler

(We used IDA Pro for this purpose)

# Analyze the firmware

```
user@pinacolada:~/Documents/ssdproject/crucial$ php parse_fw.php firmware_mx300/M0CR060.bin
[+] found MCRN header -- B0KB
[*] [segment] [type] [source] [dest] [size]
[*]     0     0  0x00000010 0x00000000 117456
[*]     1     0  0x0001cae0 0x0001fa00 352
[*]     2     0  0x0001cc40 0x04002100 2488
[*]     3     0  0x0001d5f8 0x80001000 240
[*]     4     0  0x00000000 0x80000000 16
[*]     5     0  0x0001d6e8 0x80041000 264
[*]     6     0  0x0001d7f0 0x801c4000 1035224
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*] new offset : 0x11aa00
[*] new offset : 0x133c00
[*] new offset : 0xfa540c00
user@pinacolada:~/Documents/ssdproject/crucial$
```

Parsed header of MX300 FW image

(i) Figure out the section information

- From image header

(ii) Load the image into a disassembler

(We used IDA Pro for this purpose)

(iii) Figure out what the firmware does

# Analyze the firmware

```
user@pinacolada:~/Documents/ssdproject/crucial$ php parse_fw.php firmware_mx300/M0CR060.bin
[+] found MCRN header -- B0KB
[*] [segment] [type] [source] [dest] [size]
[*]     0     0  0x00000010 0x00000000 117456
[*]     1     0  0x0001cae0 0x0001fa00 352
[*]     2     0  0x0001cc40 0x04002100 2488
[*]     3     0  0x0001d5f8 0x80001000 240
[*]     4     0  0x00000000 0x80000000 16
[*]     5     0  0x0001d6e8 0x80041000 264
[*]     6     0  0x0001d7f0 0x801c4000 1035224
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*] new offset : 0x11aa00
[*] new offset : 0x133c00
[*] new offset : 0xfa540c00
user@pinacolada:~/Documents/ssdproject/crucial$
```

Parsed header of MX300 FW image

(i) Figure out the section information

- From image header

(ii) Load the image into a disassembler

(We used IDA Pro for this purpose)

(iii) Figure out what the firmware does

- Try to find the ATA dispatch table

```
AtaCommand <0x45, sub_80264DC0, 0x45DA0023>
AtaCommand <0xF1, sub_8022CA10, 0x47CB0000>
AtaCommand <0xF2, sub_8022CAE8, 0x7890000>
AtaCommand <0xF3, sub_8022C76C, 0x67C90000>
AtaCommand <0xF4, sub_8022C7F4, 0x67C90002>
AtaCommand <0xF5, sub_8022C98C, 0x7CA0000>
AtaCommand <0xF6, sub_8022C6C4, 0x47CB0000>
AtaCommand <0xB0, AtaSmart, 0x4880003>
AtaCommand <0x10, sub_80264CD0, 0x4CA0000>
AtaCommand <0x78, sub_801C6B00, 0x45CA0020>
AtaCommand <0xB4, sub_801C9D60, 0x2E880023>
AtaCommand <6, sub_801CBB74, 0x65DA0023>
AtaCommand <0xE7, sub_801CAF14, 0x45DA0000>
AtaCommand <0xEA, sub_801CAF14, 0x45DA0022>
AtaCommand <0xEF, sub_80264780, 0x5C80000>
AtaCommand <0xC6, sub_801CB3A8, 0x5C80000>
```

ATA Dispatch table in firmware

| Command feature set | | |
|---|---|---|
| Retired | 11h..1Fh, 71h..7Fh, 94h. | |
| Sanitize Device | B4h | O |
| SECURITY DISABLE PASSWORD | F6h | O |
| SECURITY ERASE PREPARE | F3h | O |
| SECURITY ERASE UNIT | F4h | O |
| SECURITY FREEZE LOCK | F5h | O |
| SECURITY SET PASSWORD | F1h | O |
| SECURITY UNLOCK | F2h | O |
| SET FEATURES | EFh | M |
| SET MAX ADDRESS | F9h | O |
| SET MAX ADDRESS EXT | 37h | O |
| SET MULTIPLE MODE | C6h | O |
| SLEEP | E6h | M |
| SMART | B0h | O |
| STANDBY | E2h | M |
| STANDBY IMMEDIATE | E0h | M |
| TRUSTED NON-DATA | 5Bh | O |
| TRUSTED RECEIVE | 5Ch | O |

ATA specification

# Analyze the firmware

```
user@pinacolada:~/Documents/ssdproject/crucial$ php parse_fw.php firmware_mx300/M0CR060.bin
[+] found MCRN header -- B0KB
[*] [segment] [type] [source] [dest] [size]
[*]     0     0  0x00000010 0x00000000 117456
[*]     1     0  0x0001cae0 0x0001fa00 352
[*]     2     0  0x0001cc40 0x04002100 2488
[*]     3     0  0x0001d5f8 0x80001000 240
[*]     4     0  0x00000000 0x80000000 16
[*]     5     0  0x0001d6e8 0x80041000 264
[*]     6     0  0x0001d7f0 0x801c4000 1035224
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*]   255   255  0xffffffff 0xffffffff 4294967295
[*] new offset : 0x11aa00
[*] new offset : 0x133c00
[*] new offset : 0xfa540c00
user@pinacolada:~/Documents/ssdproject/crucial$
```

Parsed header of MX300 FW image

```
AtaCommand <0x93, sub_80262F58, 0x454A0003>
AtaCommand <0x45, sub_80264DC0, 0x45DA0023>
AtaCommand <0xF1, sub_8022CA10, 0x47CB0000>
AtaCommand <0xF2, sub_8022CAE8, 0x7890000>
AtaCommand <0xF3, sub_8022C76C, 0x67C90000>
AtaCommand <0xF4, sub_8022C7F4, 0x67C90002>
AtaCommand <0xF5, sub_8022C98C, 0x7CA0000>
AtaCommand <0xF6, sub_8022C6C4, 0x47CB0000>
AtaCommand <0xB0, AtaSmart, 0x4880003>
AtaCommand <0x10, sub_80264CD0, 0x4CA0000>
AtaCommand <0x78, sub_801C6B00, 0x45CA0020>
AtaCommand <0xB4, sub_801C9D60, 0x2E880023>
AtaCommand <6, sub_801CBB74, 0x65DA0023>
AtaCommand <0xE7, sub_801CAF14, 0x45DA0000>
AtaCommand <0xEA, sub_801CAF14, 0x45DA0022>
AtaCommand <0xEF, sub_80264780, 0x5C80000>
AtaCommand <0xC6, sub_801CB3A8, 0x5C80000>
AtaCommand <0xEC, sub_802640C8, 0x4080000>
```

ATA Dispatch table in firmware

(i) Figure out the section information
- From image header

(ii) Load the image into a disassembler

(We used IDA Pro for this purpose)

(iii) Figure out what the firmware does
- Try to find the ATA dispatch table
- Look through functions with interesting opcodes

| Command feature set | | |
|---|---|---|
| Retired | 11h..1Fh, 71h..7Fh, 94h. | |
| Sanitize Device | B4h | O |
| SECURITY DISABLE PASSWORD | F6h | O |
| SECURITY ERASE PREPARE | F3h | O |
| SECURITY ERASE UNIT | F4h | O |
| SECURITY FREEZE LOCK | F5h | O |
| SECURITY SET PASSWORD | F1h | O |
| SECURITY UNLOCK | F2h | O |
| SET FEATURES | EFh | M |
| SET MAX ADDRESS | F9h | O |
| SET MAX ADDRESS EXT | 37h | O |
| SET MULTIPLE MODE | C6h | O |
| SLEEP | E6h | M |
| SMART | B0h | O |
| STANDBY | E2h | M |
| STANDBY IMMEDIATE | E0h | M |
| TRUSTED NON-DATA | 5Bh | O |
| TRUSTED RECEIVE | 5Ch | O |

ATA specification

# Results

# Results

- Models studied released in 2014-2018

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

[1] Derivation of the DEK from the password in ATA Security (High mode)
[2] Derivation of the DEK from the password in ATA Security (Max mode)
[3] Derivation of the DEK from the password in TCG Opal
[4] Derivation of the DEK from the password in proprietary standard
[5] No single key for entire disk
[6] Not vulnerable to ATA Master password re-enabling (only if derivation is present)
[7] Randomized DEK on sanitize and sufficient random entropy
[8] No wear leveling related issues
[9] No DEVSLP related issues

# Results

- Models studied released in 2014-2018
- Different form factors

  SATA, NVMe, USB

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

[1] Derivation of the DEK from the password in ATA Security (High mode)
[2] Derivation of the DEK from the password in ATA Security (Max mode)
[3] Derivation of the DEK from the password in TCG Opal
[4] Derivation of the DEK from the password in proprietary standard
[5] No single key for entire disk
[6] Not vulnerable to ATA Master password re-enabling (only if derivation is present)
[7] Randomized DEK on sanitize and sufficient random entropy
[8] No wear leveling related issues
[9] No DEVSLP related issues

# Results

- Models studied released in 2014-2018
- Different form factors
  - SATA, NVMe, USB
- Most have severe weaknesses

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

[1] Derivation of the DEK from the password in ATA Security (High mode)
[2] Derivation of the DEK from the password in ATA Security (Max mode)
[3] Derivation of the DEK from the password in TCG Opal
[4] Derivation of the DEK from the password in proprietary standard
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[7] Randomized DEK on sanitize and sufficient random entropy
[8] No wear leveling related issues
[9] No DEVSLP related issues

# Results

- Models studied released in 2014-2018
- Different form factors
  - SATA, NVMe, USB
- Most have severe weaknesses
- Best case scenario: security guarantees are equivalent to software FDE

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

1 Derivation of the DEK from the password in ATA Security (High mode)
2 Derivation of the DEK from the password in ATA Security (Max mode)
3 Derivation of the DEK from the password in TCG Opal
4 Derivation of the DEK from the password in proprietary standard
5 No single key for entire disk
6 Not vulnerable to ATA Master password re-enabling (only if derivation is present)
7 Randomized DEK on sanitize and sufficient random entropy
8 No wear leveling related issues
9 No DEVSLP related issues

# Results

- Models studied released in 2014-2018
- Different form factors
  - SATA, NVMe, USB
- Most have severe weaknesses
- Best case scenario: security guarantees are equivalent to software FDE
- Worst case: confidentiality relies on an **if-statement**

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

[1] Derivation of the DEK from the password in ATA Security (High mode)
[2] Derivation of the DEK from the password in ATA Security (Max mode)
[3] Derivation of the DEK from the password in TCG Opal
[4] Derivation of the DEK from the password in proprietary standard
[5] No single key for entire disk
[6] Not vulnerable to ATA Master password re-enabling (only if derivation is present)
[7] Randomized DEK on sanitize and sufficient random entropy
[8] No wear leveling related issues
[9] No DEVSLP related issues

# Results

- Models studied released in 2014-2018
- Different form factors
  - SATA, NVMe, USB
- Most have severe weaknesses
- Best case scenario: security guarantees are equivalent to software FDE
- Worst case: confidentiality relies on an **if-statement**
- BitLocker delegating trust amplifies the issue

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

[1] Derivation of the DEK from the password in ATA Security (High mode)
[2] Derivation of the DEK from the password in ATA Security (Max mode)
[3] Derivation of the DEK from the password in TCG Opal
[4] Derivation of the DEK from the password in proprietary standard
[5] No single key for entire disk
[6] Not vulnerable to ATA Master password re-enabling (only if derivation is present)
[7] Randomized DEK on sanitize and sufficient random entropy
[8] No wear leveling related issues
[9] No DEVSLP related issues

# Results

- TCG Opal is terrible

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

[1] Derivation of the DEK from the password in ATA Security (High mode)
[2] Derivation of the DEK from the password in ATA Security (Max mode)
[3] Derivation of the DEK from the password in TCG Opal
[4] Derivation of the DEK from the password in proprietary standard
[5] No single key for entire disk
[6] Not vulnerable to ATA Master password re-enabling (only if derivation is present)
[7] Randomized DEK on sanitize and sufficient random entropy
[8] No wear leveling related issues
[9] No DEVSLP related issues

# Results

- TCG Opal is terrible
  - Over-engineered

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

[1] Derivation of the DEK from the password in ATA Security (High mode)
[2] Derivation of the DEK from the password in ATA Security (Max mode)
[3] Derivation of the DEK from the password in TCG Opal
[4] Derivation of the DEK from the password in proprietary standard
[5] No single key for entire disk
[6] Not vulnerable to ATA Master password re-enabling (only if derivation is present)
[7] Randomized DEK on sanitize and sufficient random entropy
[8] No wear leveling related issues
[9] No DEVSLP related issues

# Results

- TCG Opal is terrible
  - Over-engineered
  - Security goals not clear

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

[1] Derivation of the DEK from the password in ATA Security (High mode)
[2] Derivation of the DEK from the password in ATA Security (Max mode)
[3] Derivation of the DEK from the password in TCG Opal
[4] Derivation of the DEK from the password in proprietary standard
[5] No single key for entire disk
[6] Not vulnerable to ATA Master password re-enabling (only if derivation is present)
[7] Randomized DEK on sanitize and sufficient random entropy
[8] No wear leveling related issues
[9] No DEVSLP related issues

# Results

- TCG Opal is terrible
  - Over-engineered
  - Security goals not clear
  - No reference implementation exists

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

[1] Derivation of the DEK from the password in ATA Security (High mode)
[2] Derivation of the DEK from the password in ATA Security (Max mode)
[3] Derivation of the DEK from the password in TCG Opal
[4] Derivation of the DEK from the password in proprietary standard
[5] No single key for entire disk
[6] Not vulnerable to ATA Master password re-enabling (only if derivation is present)
[7] Randomized DEK on sanitize and sufficient random entropy
[8] No wear leveling related issues
[9] No DEVSLP related issues

# Results

- TCG Opal is terrible
  - Over-engineered
  - Security goals not clear
  - No reference implementation exists
  - Implementation is not even part of complience tests

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

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# Results

- TCG Opal is terrible
  - Over-engineered
  - Security goals not clear
  - No reference implementation exists
  - Implementation is not even part of complience tests
  - Structural changes needed

| Drive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Crucial MX100 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX200 (all) | ✗ | ✗ | ✗ | | ✗ | | ✓ | ✓ | | Compromised |
| Crucial MX300 (all) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✓ | | Compromised |
| Sandisk X600 (SATA) | ✓ | ✓ | ✓ | | ✗ | ✗ | ✓ | ✗ | | Probably compromised |
| Samsung 840 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | Depends |
| Samsung 850 EVO (SATA) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Depends |
| Samsung 950 PRO (NVMe) | ✗ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Probably safe |
| Samsung T3 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |
| Samsung T5 (USB) | | | | ✗ | | | ✓ | ✓ | | Compromised |

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# Timeline

| | |
|---|---|
| Oct 2016 | First discovery – Crucial (Mciron) MX100 |
| Oct 2017 – Apr 2018 | Attempts made contacting vendors |
| Apr 2018 | Disclosure to Samsung – Meeting in The Hague, Netherlands |
| Apr 2018 | Disclosure to Micron |
| Nov 2018 | Draft paper published – Vendor responses published<br>Both vendors release firmware updates |
| Dec 2018 | Presentation at 35C3 |
| Dec 2018 | Discovery of Sandisk (Western Digital) models |

# Timeline (2)

Today:

- CVEs released (CVE-2019-10705, CVE-2019-10706, CVE-2019-10636, CVE-2019-11686)
- Western Digital releases firmware updates available at `https://www.westerndigital.com/productsecurity`
    - Reviewed by *Trail of Bits*
- "Western Digital thanks the Radboud researchers, NCSC, and CERT-CC for participating in the coordinated disclosure process. For more information on how we work with researchers - including contact details -, please go to `https://www.westerndigital.com/productsecurity`."

# Questions

See the paper ’Self-Encrypting Deception’


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