Reverse engineering hardware for software reversers: studying an encrypted external HDD

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AIRBUS GROUP


DATALOCKER


APRICORN
USB 3.0
FIPS
Level 2 Validated
140-2


LOCKDOWN


Bull


CORSAIR

Introduction

Why study encrypted hard drives?

- Initially: audit need inside Airbus Group
- Previous work revealed vulnerabilities
- Discover how to analyze hardware based on microcontrollers

Previous *epic fails* on this type of HW

- Kingston/SanDisk FIPS 140-2: magic unlocking packet (2010)
- Corsair Padlock: data not encrypted, reachable without PIN (2008)
- Corsair Padlock 2: brute-forceable PIN (2010)
- WD Passport (yesterday's talk by Gunnar Alendal and Christian Kison)

End goal

- Analyze the actual level of protection of user data
  $\Longrightarrow$ Validate security and cryptography implementations inside the enclosure

Introduction

This talk's objectives:

- Describe the study of an external encrypted HDD:
  - Explain the methodology in details
  - Show our various failures
  - Give leads to continue the analysis

Case study: Zalman ZM-VE400

- Enclosure: HDD is replaceable
- Optional AES-256 XTS encryption (physical keyboard)
- Can "mount" ISO as USB optical drive
- *Really* a rebranded iodd 2541

Context, first results

General security checks

- Verify basic crypto properties:
  - ECB mode? statistical tests OK?
  - Fixed key?
- More tests, to verify the key is not derived directly from the PIN:
  - The same PIN, on 2 different enclosures, **must** lead to different encryption
  - The same PIN, on the same enclosure, **must** lead to different encryption
- Secret material (keys, hashes) *should* be stored in tamper resistant hardware

VE400 results

- Basic crypto properties: OK
- Encryption does **not** depend on enclosure: **an encrypted HDD put in a new Zalman enclosure can be accessed with the right PIN**
- Activating encryption uses 10 sectors at the end of the HDD:
  - Not usable anymore
  - Contain a *blob* of 768 bytes, of high entropy, twice

Going forward

Important result: design failure

Everything needed to decrypt data is stored on the HDD itself.
$\Longrightarrow$ Efficient attacks are possible (*bruteforce*, key recovery)

New end goal

Understand the blob stored at the end of the disk: its data and its format, to implement an offline attack

How?

First by trying to access the *firmware* and/or by analyzing communications
Firmware updates are encrypted, so we need to attack the hardware

Hardware analysis

PCB analysis

- Components identification
- Traces and vias identification

$\Longrightarrow$ Logical view

Flash memories study

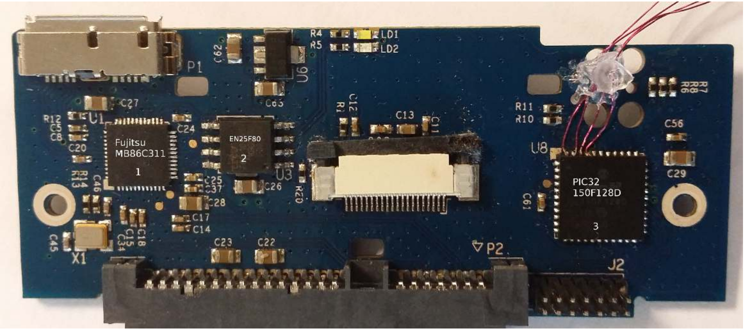
- Identify communication buses
- Flash content recovery

$\Longrightarrow$ Flash content analysis (hopefully cleartext code)

PCB: component identification 1/2

PCB: front side

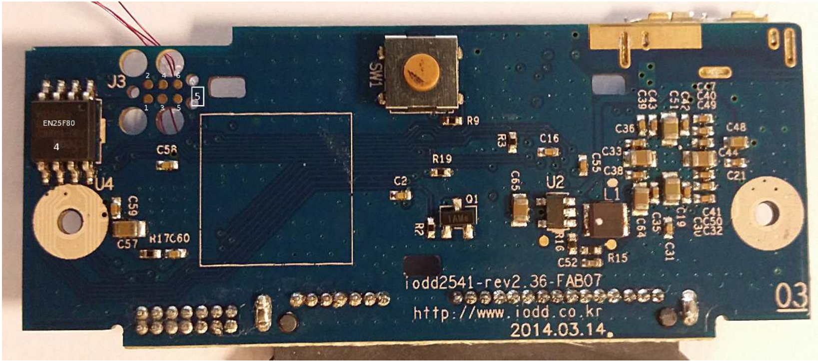
- *System on Chip* (SoC) Fujitsu MB86C311 USB3-SATA
- SPI flash EN25F80
- PIC32MX 150F128D microcontroller



PCB: component identification 2/2

PCB: back size

- SPI flash EN25F80



SoC and microcontroller

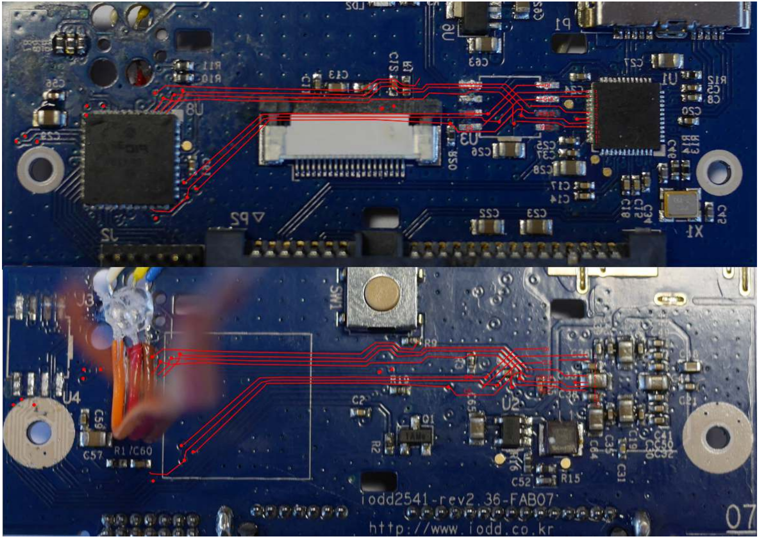
Fujitsu MB86C311

- USB3↔SATA controller
- AES-256 XTS encryption
- ARM core
- Internal ROM and external SPI firmware support (encrypted?)

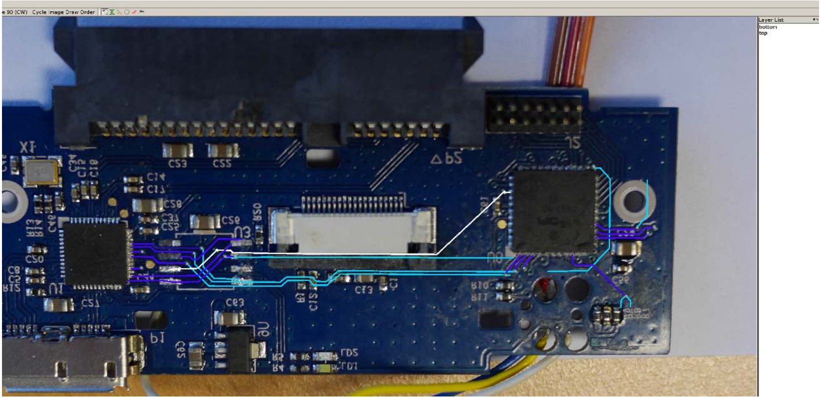
PIC32MX 150F128D

- MIPS32 CPU (with MIPS16e support)
- 128 Ki of internal flash
- 32 Ki of RAM
- Supports ICSP and EJTAG
- Protection bits to disable external access

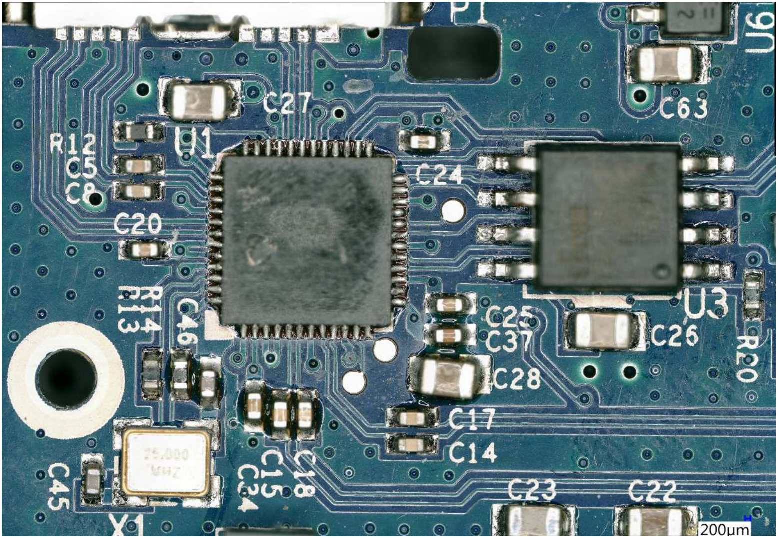
PCB: traces analysis (1/5): Hobo mode with GIMP



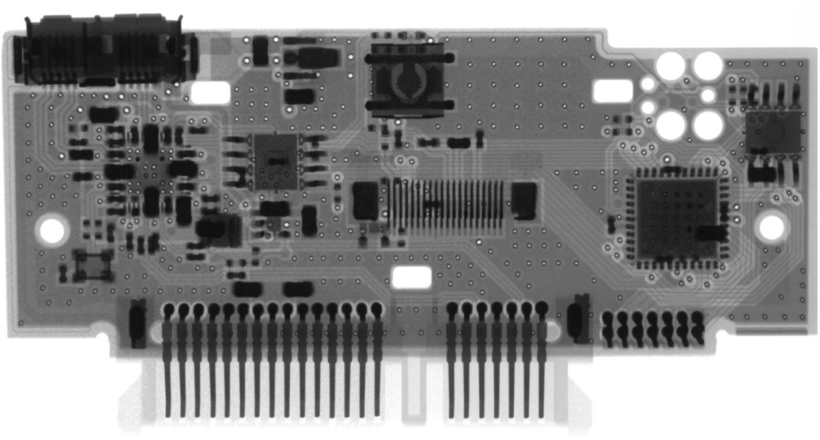
PCB: traces analysis (2/5): getting real with PCBRE [5]



PCB: traces analysis (3/5): leveling up: optical microscope



PCB: traces analysis (4/5): level cap: X-rays



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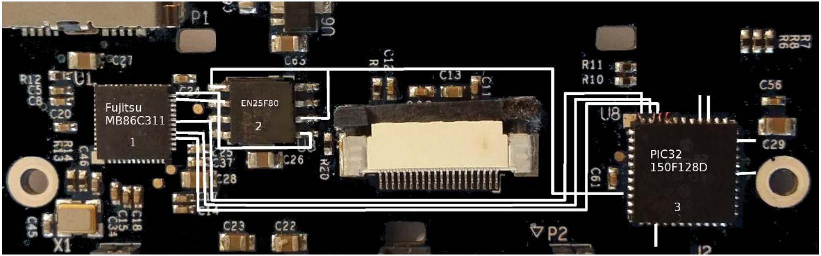
PCB: traces analysis (5/5)



In the end

- One flash dedicated to the USB-SATA controller (SoC)
- One flash dedicated to the PIC32
- One link between the SoC and the PIC, (partially) shared with the SoC flash

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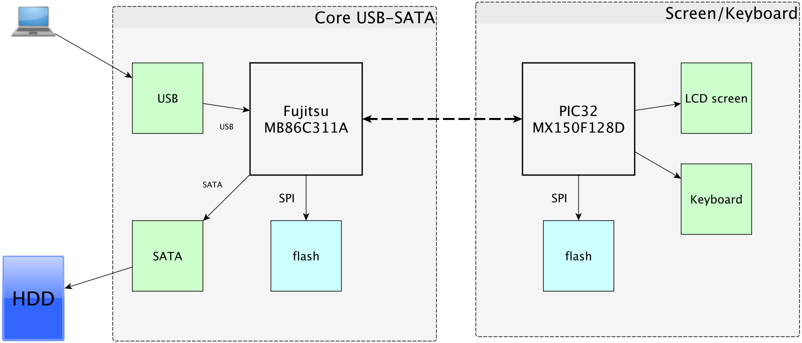
PCB: logic view



What's inside the flash chips?

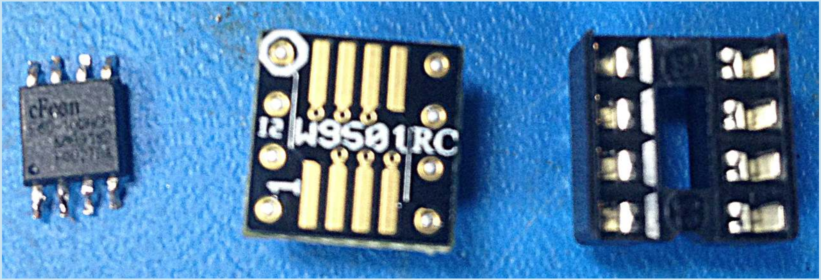
Maybe the code is in cleartext?

$\Longrightarrow$ Let's get their contents!

Flash content recovery (1/2)

Reading flash content

- SPI
- Chip desoldering needed to avoid interferences
- Interface using a SOIC↔DIP adapter to keep the board working



Flash content recovery (2/2)

SPI tools

- GoodFET with `goodfet.spiflash` (recommended)
- Bus Pirate
- Raspberry Pi with *spidev*

Results: flashes content

USB-SATA controller:

- Plaintext configuration data (USB descriptors, etc.)
- Code, **encrypted**

PIC32 microcontroller:

- A font, for the LCD screen
- Code, **encrypted**

Results

Code access: *fail*

All the code is encrypted, so we cannot reverse engineer the firmware

What can we do now?

As in network reversing, we will analyze communications (black box)

How?

By using a logic analyzer to capture communications

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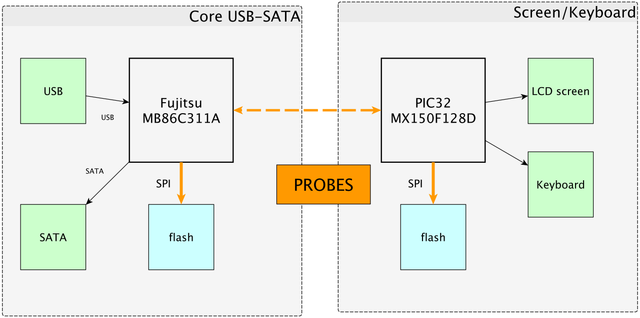
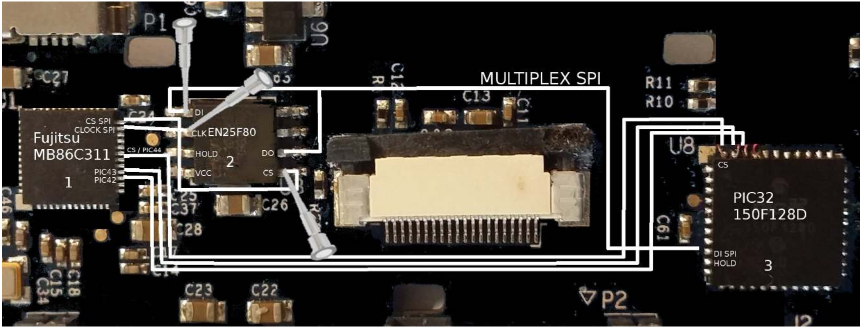
Hardware and probe placement

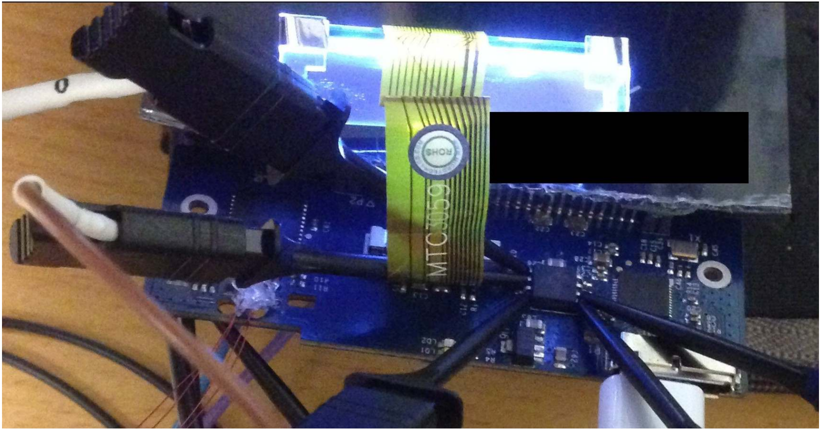


Saleae Logic Pro 16 logic analyzer

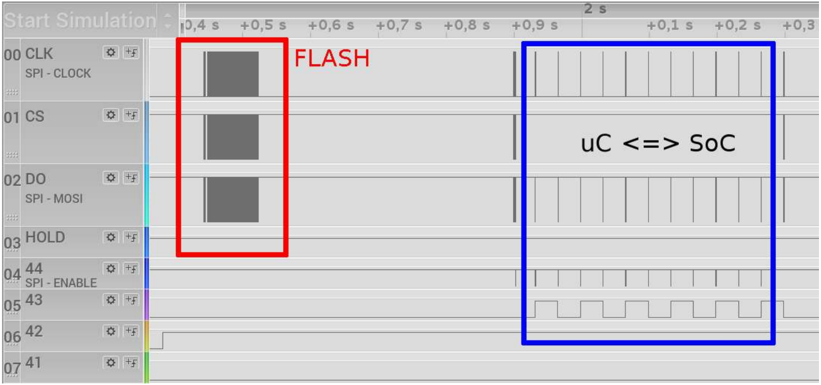
PCB traces and components pinout



Probe placement



Screenshot


Start Simulation
0,4 s
+0,5 s
+0,6 s
+0,7 s
+0,8 s
+0,9 s
2 s
+0,1 s
+0,2 s
+0,3
00 CLK
SPI - CLOCK
01 CS
02 DO
SPI - MOSI
03 HOLD
04 44
SPI - ENABLE
05 43
06 42
07 41
FLASH
uC <=> SoC

Analyzing flash SPI communications

USB-SATA/PIC to flash

- Placing the 4 probes: simply on flash pins
- SPI decoding parameters: “standard” (cf. datasheet)
- Sampling speed: 50MS/s **min**, 100MS/s recommended (25MHz quartz)

Post-treatment

- CSV export of decoded SPI data
- Ruby script to interpret flash commands:
  - Text display
  - Binary dump rebuilding

Results

- PIC never writes to its external flash
- *USB-SATA controller writes data when the PIN is validated*

Analyzing SoC ↔ PIC communications

USB-SATA controller ↔ PIC

- Probes placement: on the SOC flash pins (cf. PCB traces)
- Sampling speed: 50MS/s **min**, 100MS/s recommended
- Protocol: *unknown*

Post-treatment

SPI based protocol:

- Low level decoding with Saleae, then CSV export
- Application-layer data must be reversed engineered

Custom protocol

Reverse engineering

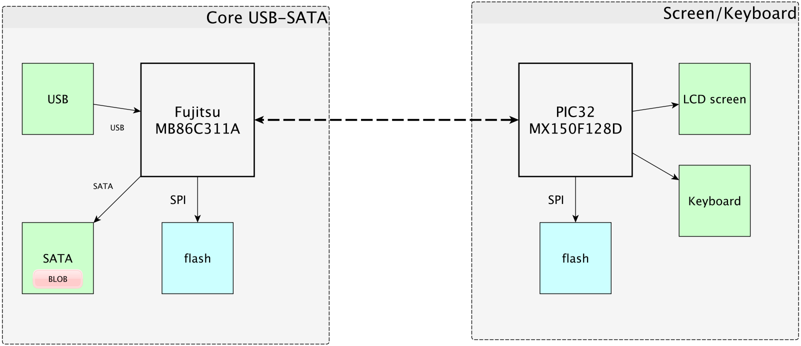
- Preambles: `AA AA AA AA 55` (SoC → PIC) and `A5 A5 A5 5A` (PIC → SoC)
- *Type, Length, Value*
- Frames are numbered and acknowledged
- Unknown 16bits checksum

⟹ Ruby script to decode data from the CSV produced by Saleae

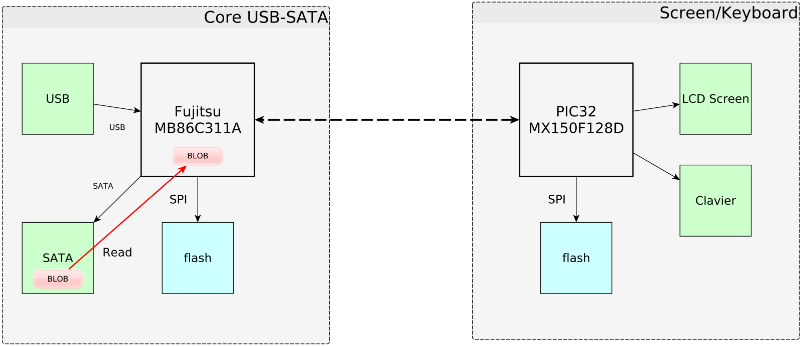
Decoded example: PIN request

```
0.00000000 SoC->PIC T: 0x33, ID: 0x14 | 01,01,10,01
0.00003861 PIC->SoC        RESP: 0x14 | 06,00,01,00,09,4d,01,cb,
                                        0e,00,00,00,89,0f,3a,7a
```

Summary: communication sequence



Summary: communication sequence



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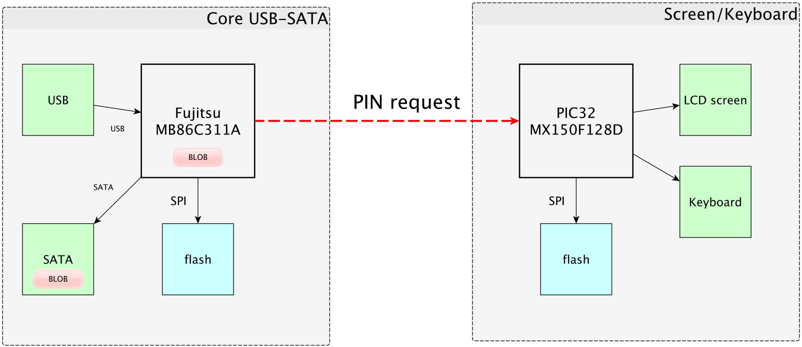
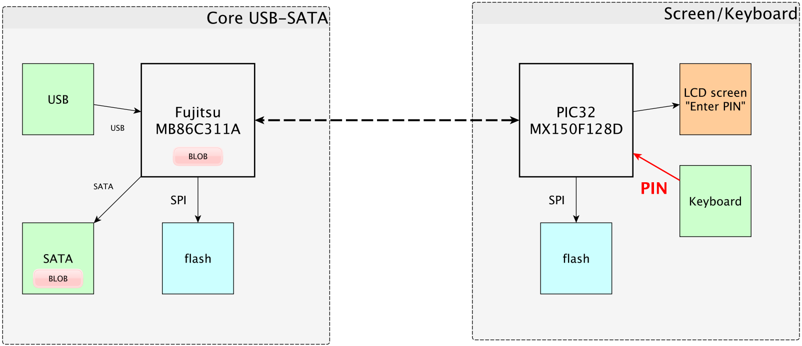
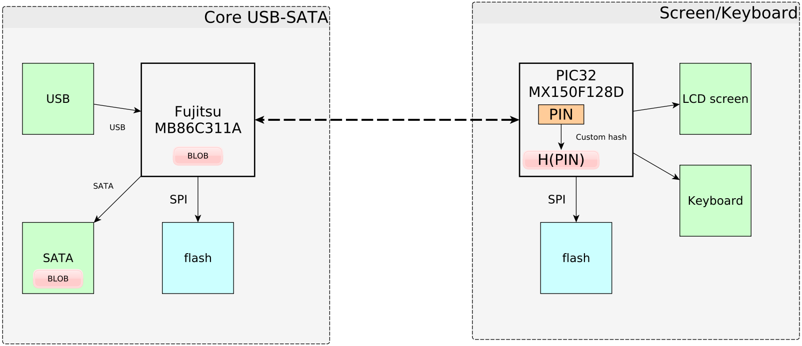


Summary: communication sequence



Summary: communication sequence



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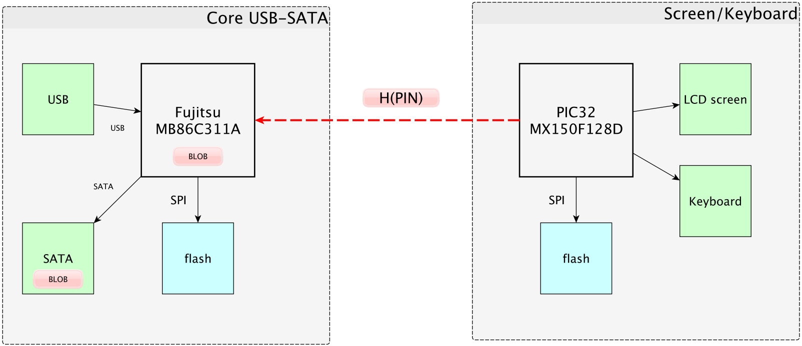
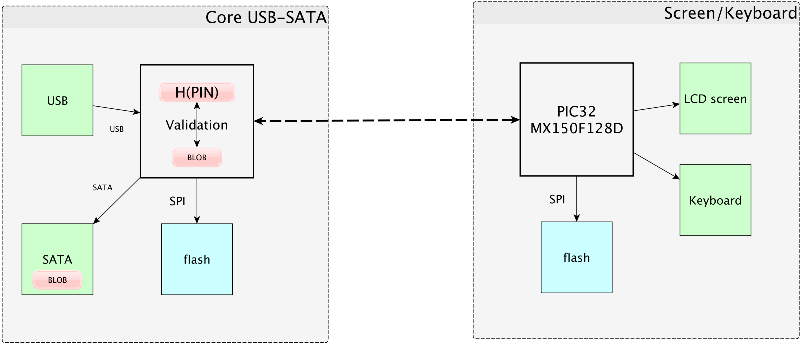


Summary: communication sequence



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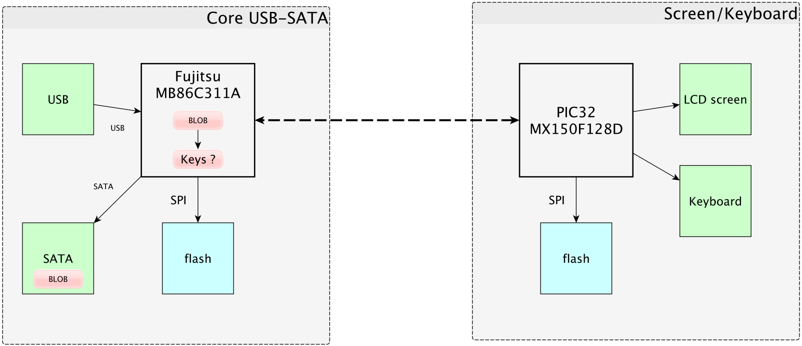
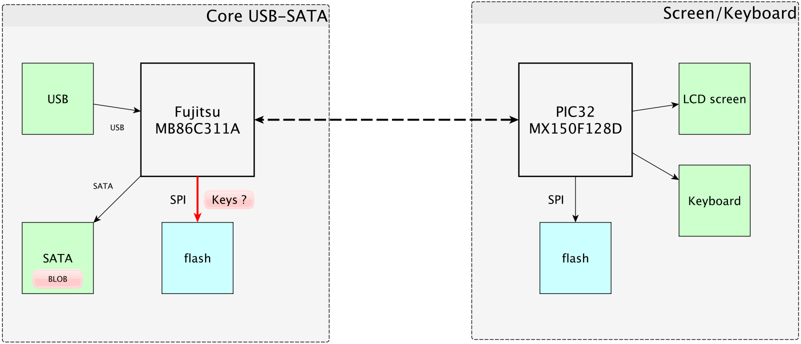


Summary: communication sequence



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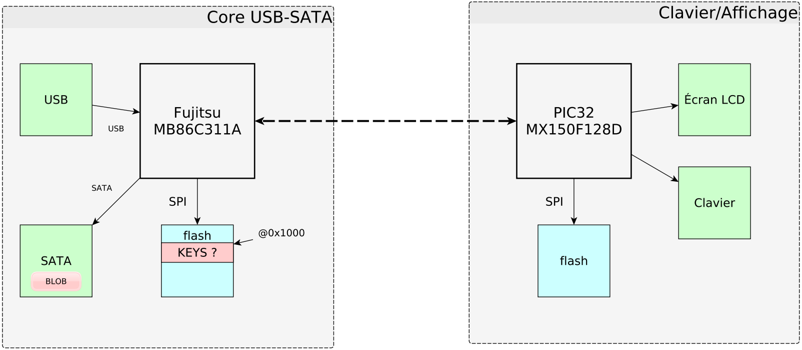
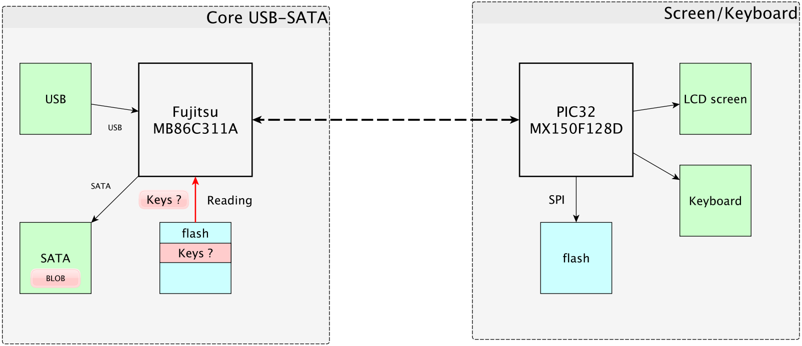
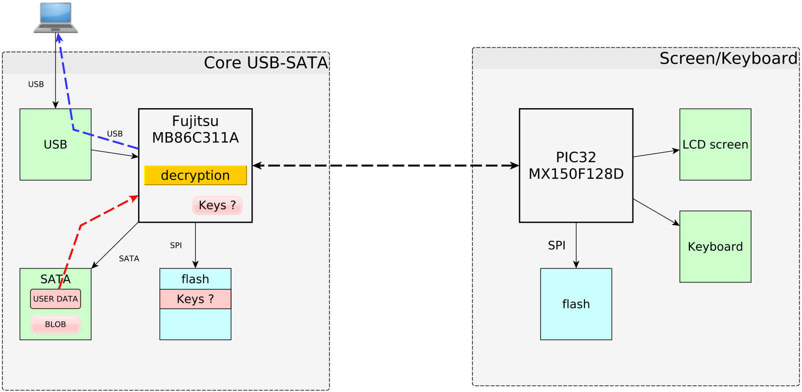
Summary: communication sequence



Summary: communication sequence



Summary: communication sequence



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And now?

Remaining questions

- Can we do a hardware bruteforcer? (PIC+Keyboard emulator)
  - No, because the hash algorithm is unknown
- What is inside the block at 0x1000 in the SoC flash?

Flash block at 0x1000

Properties:

- Written when:
  - Enabling encryption
  - Entering a *valid* PIN
- *Erased* when encryption is disabled
- Contains 3 different blocks of data of high entropy:
  1. 512 bits, AES-256-XTS key 1, encrypted?
  2. 512 bits, AES-256-XTS key 2, encrypted?
  3. SHA256 of previous data (1 and 2)

Designing an attack

Hypothesis

The block at 0x1000 seems to **contain AES-XTS encryption keys**, in an encrypted or obfuscated form

Implications?

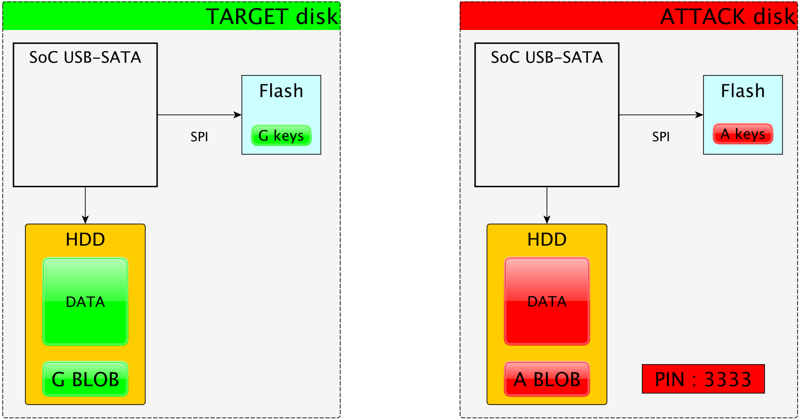
Can we use this block to mount an attack?

The idea

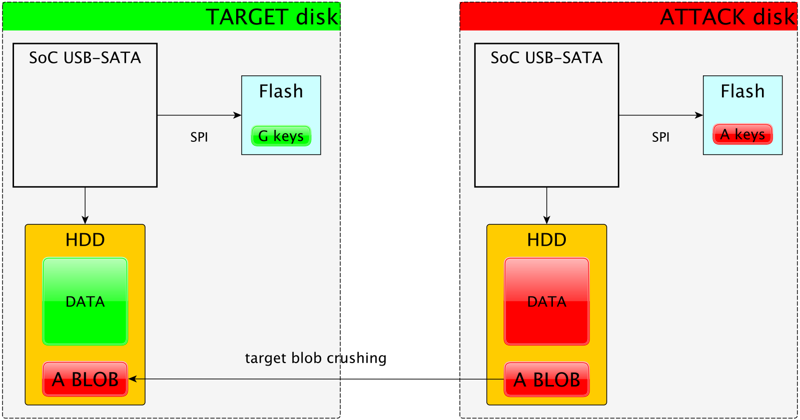
Assuming the block at 0x1000 contains decryption keys:

- We will try to keep the one of the target drive intact, in the flash . . .
- while validating the PIN against a chosen blob, stored on the HDD

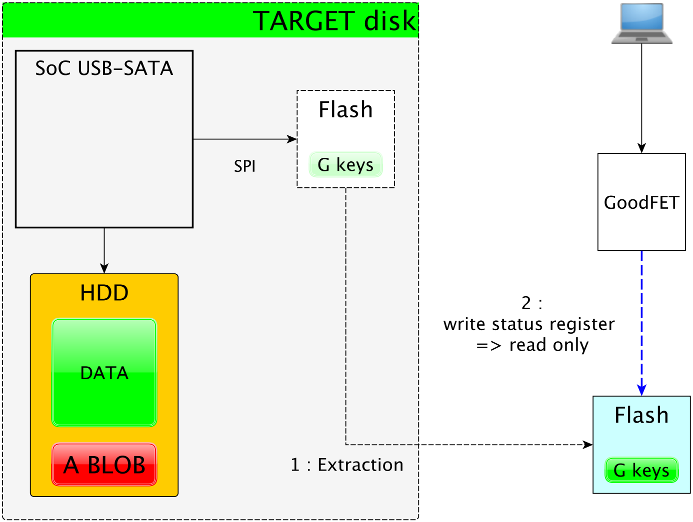
Theoretical steps



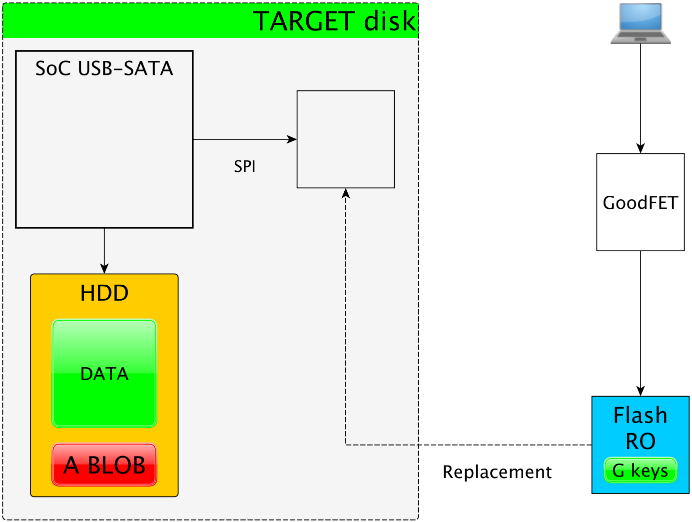
Theoretical steps



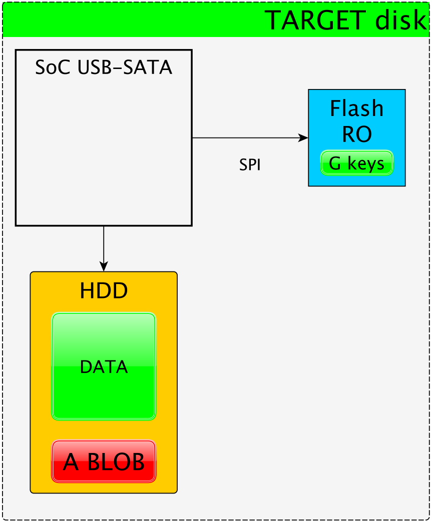
Theoretical steps



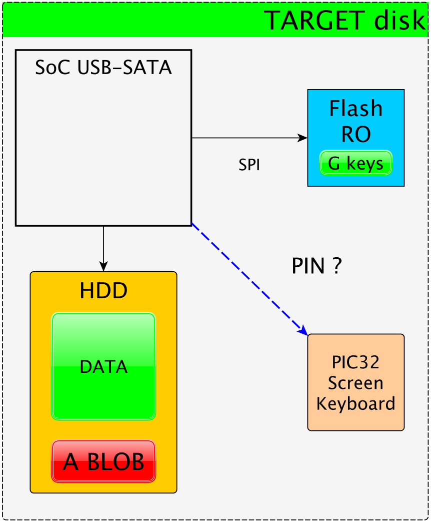
Theoretical steps



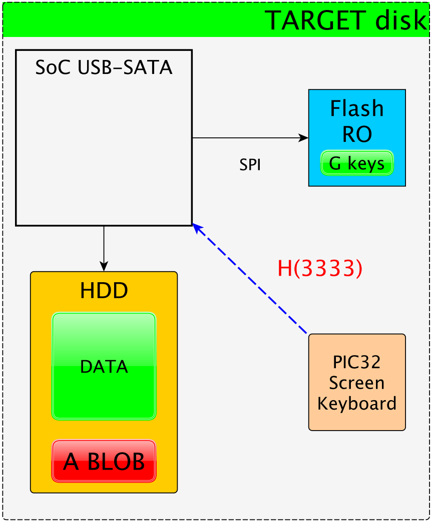
Theoretical steps



Theoretical steps



Theoretical steps



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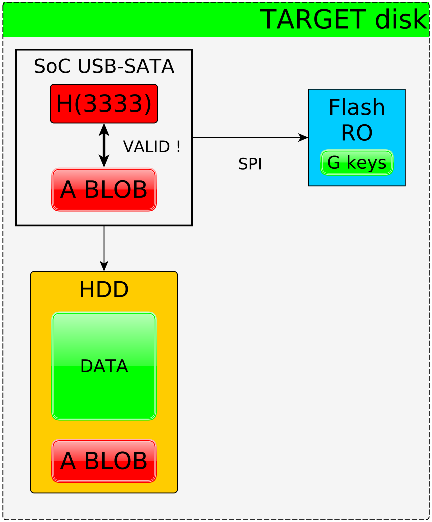

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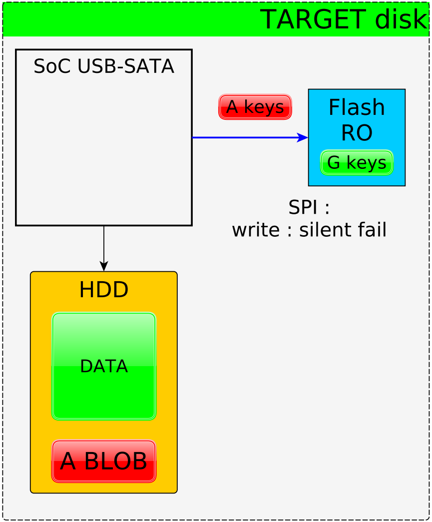

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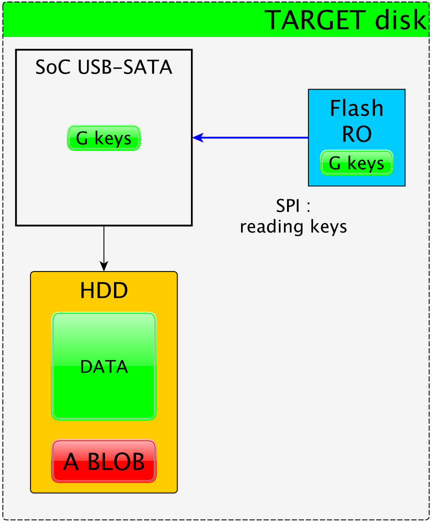


In practice

First fail

The flash *status register* is reset to 0 during startup

Attack, second version

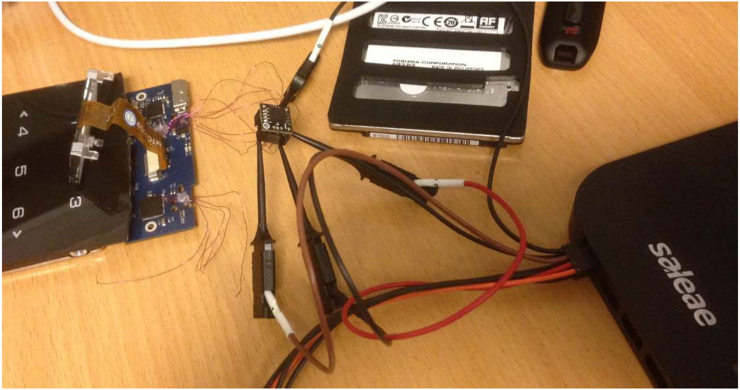
The flash is put in read only after startup:

1. Connect the enclosure
2. Unplug flash
3. Put it in read only using GoodFET
4. Plug it back
5. Continue the attack: enter the known PIN

Final result

Fail. PIN code is not valid (*Not match* on screen)
$\Longrightarrow$ There's probably an unidentified check

Final attack: demo



Conclusion

Encrypted data security

The whole security relies on:

- The security of the blob at the end of the disk
- The security of the block at 0x1000 in the flash

$\Longrightarrow$ Everything relies on the fact that the Fujitsu firmware is “secret”

iodd’s feedback (original board dev)

Firmware evolution (version 077):

- PIN hash is now non-deterministic

The rest is not fixable:

- Customer support choice: data can survive broken enclosure
- Opaque handling of the blob at the end of the HDD: binary code provided by Fujitsu

Conclusion: going further

Access the code of the USB-SATA controller

- Find a JTAG? (unlikely)
- The firmware encryption is the same on **all** chips:
  - “Buy” the SDK? (probable NDA)
  - Find someone generous ;)

Emulate the SoC SPI flash

- Allows subtle modifications of block 0x1000
- Try blind ARM code modifications

Dump PIC32 code

Use semi-invasive attack to reset protection fuse
$\Longrightarrow$ Hardware bruteforcer by emulating the whole keyboard/screen part

End

Questions?

References

[1] http://support.ironkey.com/article/AA-02513/

[2] http://www.h-online.com/security/features/USB-stick-with-PIN-code-746169.html

[3] https://www.exploit-db.com/papers/15424/

[4] http://hardwear.io/speakers-kison-alendal/

[5] https://github.com/davidcarne/pcbre

[6] http://sigrok.org/wiki/Main_Page

[7] http://support.saleae.com/hc/en-us/articles/200672010

Blob comparison

```
bloc_ssd
0000 0000: 6E D1 40 A2 74 48 51 93  D1 5B 96 13 18 25 F7 67  n.@.tHQ. .[...%.g
0000 0010: CF 73 BB 45 0A 4F 02 11  35 34 C9 39 45 31 BE 44  .s.E.O.. 54.9E1.D
0000 0020: 03 93 32 E1 8A 64 69 2E  D6 1B 21 9F A5 51 88 8C  ..2..di. ..!..Q..
0000 0030: 16 57 FF 71 32 CA E8 82  69 68 6A 3A DE 77 EC 06  .W.q2... ihj:.w..
0000 0040: DB D9 35 2F 47 32 FC D8  30 9F 06 B7 87 C0 F3 87  ..5/G2.. 0.......
0000 0050: 66 22 4D 32 C0 58 98 65  6C 50 29 E2 FE CE A5 30  f"M2.X.e lP)....0
0000 0060: 23 D5 11 42 87 38 F5 8E  11 36 D1 8D 0C C6 67 63  #..B.8.. .6....gc
0000 0070: C1 7B 80 63 54 21 9C 7D  61 CB 33 5C 29 8C 1D DE  .{.cT!.} a.3\)...
0000 0080: B8 00 83 E9 36 50 FB FE  01 66 B5 EB F9 26 D7 64  ....6P.. .f...&.d
0000 0090: 7F FB 61 76 42 CE C7 06  74 28 EE 58 EB 3E 8C 26  ..avB... t(.X.>.&
0000 00A0: 0E 6B 94 99 7B 48 97 A3  73 33 58 A6 EE B6 9B 47  .k..{H.. s3X....G
0000 00B0: C8 81 F4 F8 C9 1B F5 8F  FB 2F 0C 73 B5 C9 CC 8E  ........ ./.s....
0000 00C0: AC B7 1E 03 FD 6D 9D E6  46 28 7F 2A 80 E1 17 01  .....m.. F(.*....
0000 00D0: 97 A7 D2 8F 33 17 A2 9E  9E BE 1C C6 AB CE E7 FC  ....3... ........
0000 00E0: 4D A6 74 27 D7 C9 3A 03  64 2C 3D 52 A4 2E A6 89  M.t'..:. d,=R....
```

```
bloc_toshiba
0000 0000: E5 91 D4 9A FD 40 12 21  1B DA 56 6D 67 AB 07 7C  .....@.! ..Vmg..|
0000 0010: 86 03 F4 AF BA 4D C3 72  D9 F4 61 F6 CF F0 28 84  .....M.r ..a...(.
0000 0020: AB EA 02 1C 08 3F 93 DB  69 BF 06 EA 8D 52 6D 16  .....?.. i....Rm.
0000 0030: 1F 7D 0A 44 7D 47 85 15  EE 43 27 74 3B CF 12 C0  .}.D}G.. .C't;...
0000 0040: E8 DC 87 82 FE 8E 40 14  D1 AC 1C 13 3F D0 84 C3  ......@. ....?...
0000 0050: 84 33 44 E4 9F 72 C3 F1  60 53 58 43 C1 6A D6 AC  .3D..r.. `SXC.j..
0000 0060: AD C8 94 88 BF 57 23 33  D4 46 77 12 3B 4C B1 AB  .....W#3 .Fw.;L..
0000 0070: E0 C7 37 ED 40 15 9C 09  60 3C 06 56 F1 F9 88 DD  ..7.@... `<.V....
0000 0080: 94 35 66 7B 5C 3C C0 51  DE A9 0F 20 B3 71 1D 17  .5f{\<.Q ... .q..
0000 0090: 52 17 6F 88 4B CF C6 E5  B8 54 C8 75 EF 93 F9 AA  R.o.K... .T.u....
0000 00A0: A7 74 E8 3D 66 D1 FB 4C  91 3F D5 2A 98 8C 75 B3  .t.=f..L .?.*..u.
0000 00B0: 04 C7 5C 53 53 7A 8E E3  AB FB 2B 2E 44 E1 98 27  ..\SSz.. ..+.D..'
0000 00C0: 9B 96 58 07 8A A8 60 19  DB 32 DE BF 26 58 1E 2A  ..X...`. .2..&X.*
0000 00D0: F4 05 34 88 2F F6 6B A1  50 01 FE 80 BA B8 1F 26  ..4./.k. P......&
0000 00E0: CD CC DD 80 77 EC 91 50  EE 25 50 79 56 18 DC C9  ....w..P .%PyV...
```

Firmware comparison: Zalman vs PS4

flash_controlerSATA

```
0000 20C0: A2 3E 19 19 F5 C8 85 41  B9 E4 92 15 9F F2 CA 77  .>.....A .......w
0000 20D0: 6C D3 BE 77 6F 17 0A 85  88 14 2E 49 3E 22 F5 05  l..wo... ...I>"..
0000 20E0: 96 B0 C1 3A 93 23 4C 51  7C 7A BB CD C3 19 13 7F  ...:.#LQ |z......
0000 20F0: B2 8F 34 59 B7 0E B4 F2  75 43 10 D5 5B 22 7D 86  ..4Y.... uC..["}.
0000 2100: 0E 93 D1 03 4E 37 BB D1  1C C9 DF 95 EC 7C 73 37  ....N7.. .....|s7
0000 2110: 83 90 A9 EF 89 A1 2B 12  BB 52 38 C2 4F 6B 8F DC  ......+. .R8.Ok..
0000 2120: 01 31 47 D6 9B 97 4F F1  3A 01 87 DC C6 50 18 95  .1G...O. :....P..
0000 2130: D7 0E 75 E0 17 83 32 A0  19 3D 46 5A DC 44 88 DF  ..u...2. .=FZ.D..
0000 2140: E4 D0 84 89 86 FC 9B BD  FA D7 F1 BE C5 79 EF C4  ........ .....y..
0000 2150: 96 2D D2 5C 5C F4 4C E8  24 83 93 CB 12 B1 18 04  .-.\\.L. $.......
0000 2160: 94 BD 16 44 49 C3 54 36  76 A6 4A D1 5D 4C BE E0  ...DI.T6 v.J.]L..
0000 2170: FF 60 7D 96 D3 DD 9C C7  9A 69 C0 60 C7 7F EB 8F  .`}..... .i.`....
0000 2180: DE F1 0E CB 7F C9 55 28  D7 23 7E 1F 98 10 00 4D  ......U( .#~....M
0000 2190: 53 8D CF 14 50 32 6C 6E  82 C6 E1 06 2B C6 22 B4  S...P2ln ....+.".
0000 21A0: 8A 23 ED EB F4 46 0F 15  02 EF 45 0A 77 59 A3 9B  .#...F.. ..E.wY..
```

PS4_dump.bin

```
0000 20C0: C0 15 19 19 81 19 85 41  09 6D 92 15 9F F2 CA 77  .......A .m.....w
0000 20D0: 60 EC BF 77 E7 90 0A 85  88 14 2E 49 3E 22 F5 05  `..w.... ...I>"..
0000 20E0: 96 B0 C1 3A 93 23 4C 51  7C 7A BB CD C3 19 09 7F  ...:.#LQ |z......
0000 20F0: B2 8F 34 59 B7 0E B4 F2  75 43 10 D5 5B 22 7D 86  ..4Y.... uC..["}.
0000 2100: 0E 93 D1 03 74 37 BB D1  1C C9 DF 95 EC 7C 73 37  ....t7.. .....|s7
0000 2110: 83 90 A9 EF 89 A1 2B 12  BB 52 38 C2 FB 08 8F DC  ......+. .R8.....
0000 2120: 55 52 47 D6 9B 97 4F F1  3A 01 87 DC C6 50 18 95  URG...O. :....P..
0000 2130: D7 0E 75 E0 17 83 32 A0  19 3D 46 5A DC 44 88 DF  ..u...2. .=FZ.D..
0000 2140: E4 D0 84 89 86 FC 9B BD  FA D7 F1 BE C5 79 EF C4  ........ .....y..
0000 2150: 96 2D D2 5C 5C F4 4C E8  24 83 93 CB 12 B1 18 04  .-.\\.L. $.......
0000 2160: 94 BD 16 44 49 C3 54 36  76 A6 4A D1 5D 4C BE E0  ...DI.T6 v.J.]L..
0000 2170: FF 60 7D 96 D3 DD 9C C7  9A 69 C0 60 C7 7F EB 8F  .`}..... .i.`....
0000 2180: DE F1 0E CB 7F C9 55 28  D7 23 7E 1F 98 10 00 4D  ......U( .#~....M
0000 2190: 53 8D CF 14 50 32 6C 6E  82 C6 E1 06 2B C6 22 B4  S...P2ln ....+.".
0000 21A0: 8A 23 ED EB F4 46 0F 15  02 EF 45 0A 77 59 A3 9B  .#...F.. ..E.wY..
```