SYNACKTIV

The printer goes brrrrr

CanSecWest

May 18-20, 2022

Agenda

- Introduction
- Bootloader Analysis
- Firmware Analysis
- Hunting for Bugs
- Exploitation Strategy
- Conclusion & Perspectives

Introduction

Who are we ?

- **Synacktiv**
  - Offensive security company
  - Offices in Paris, Lyon, Toulouse and Rennes
  - ~ 110 Ninjas
  - We are hiring!!!

- **Mehdi Talbi**

- **Rémi Jullian**

- **Thomas Jeunet**

SYNACKTIV

Pwn2Own Contest

- **International Contest organized by ZDI (Trend Micro)**
- **Pwn2Own Austin 2021**
  - 58 total entries
  - 22 different contestants
  - Won by Synacktiv (team of 11 members)
- **Phones, Printers, Nas and more**
  - 19 different devices

Pwn2Own Contest

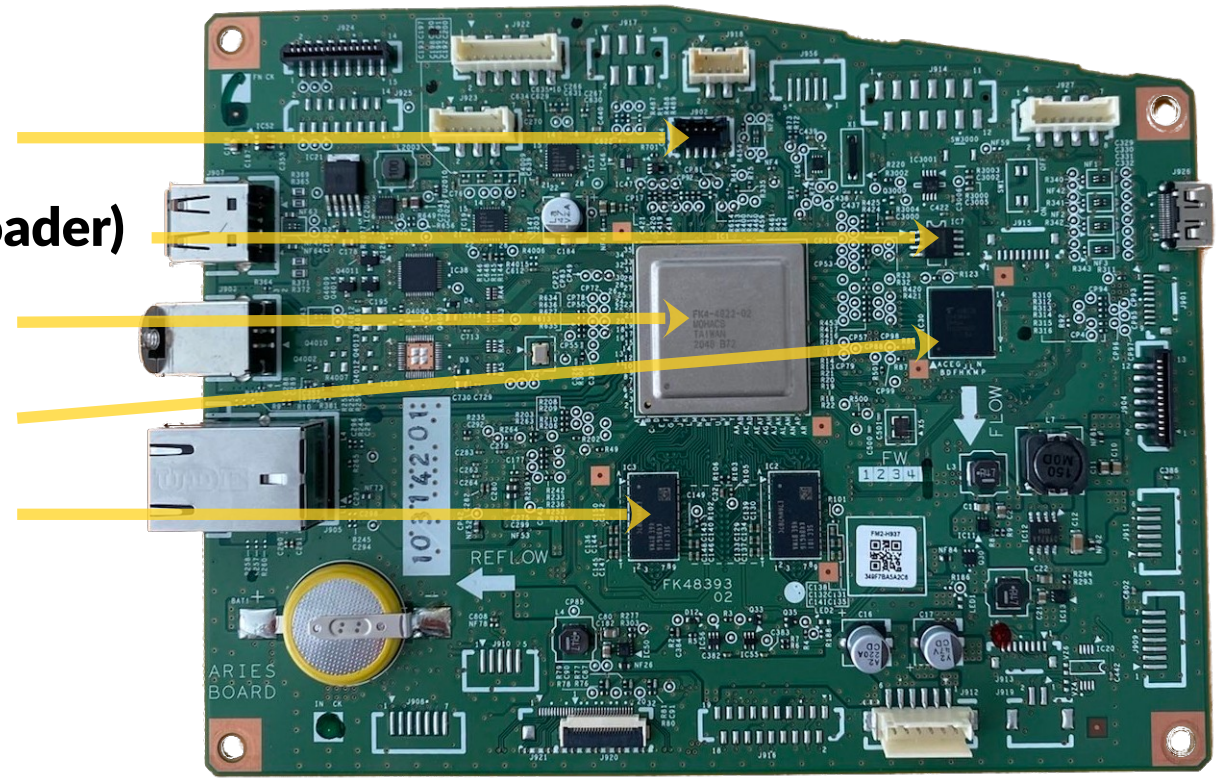
Pwn2Own Contest

Contestant	Cash	Points
Synacktiv	$197,500	20
DEVCORE	$180,000	18
STARLabs	$112,500	12
Sam Thomas	$90,000	9
THEORI	$80,000	8
Bien Pham	$52,500	6.5
NCC Group	$60,000	6
trichimtrich	$40,000	5
Martin Rakhmanov	$40,000	4
Flashback	$33,750	3.75

Bootloader

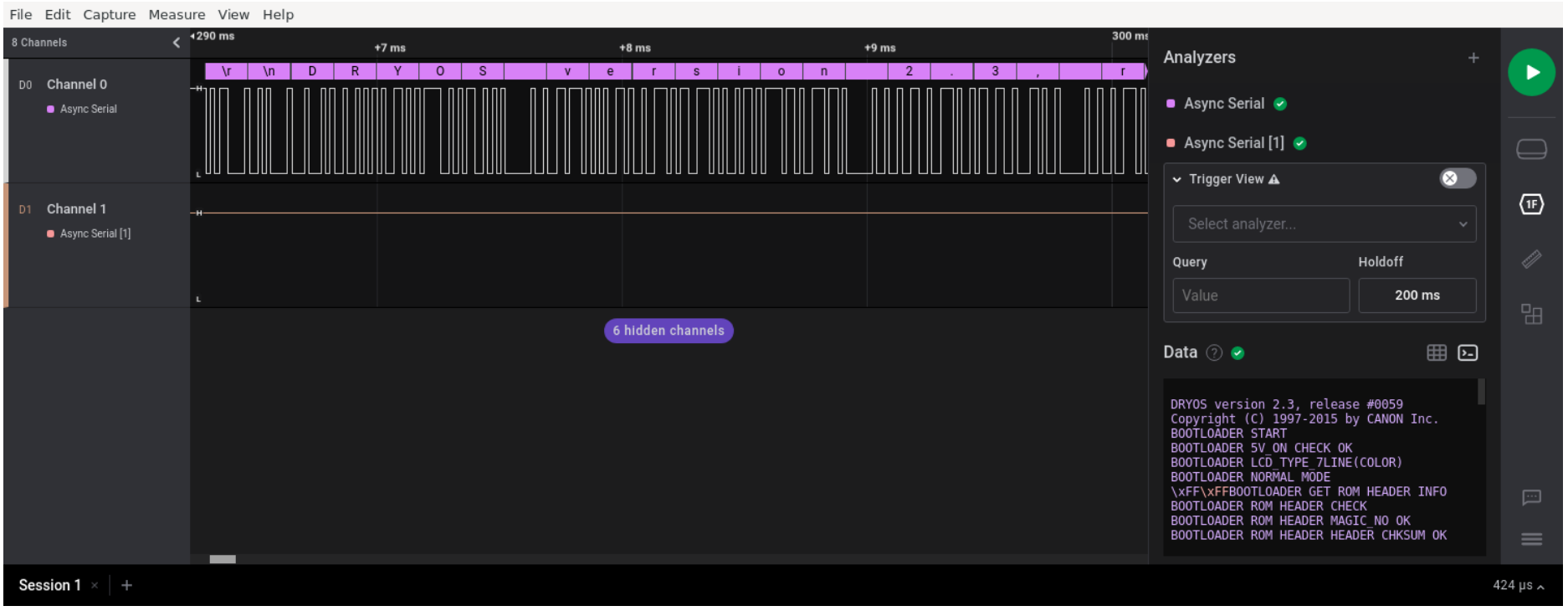
PCB Identification

- UART Connector
- NOR Flash memory (bootloader)
- ARM CPU
- eMMC memory (firmware)
- 2GB DRAM



Bootloader Start Sequence

UART



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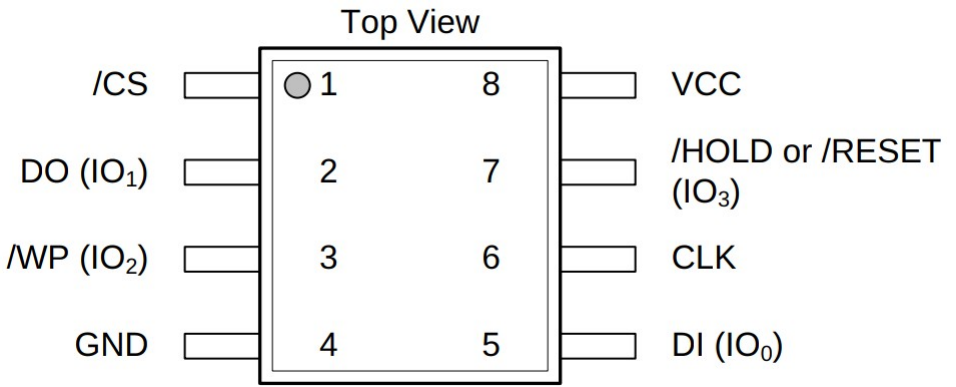
Dumping the bootloader

- The Flash model is W25Q16JV
- Dump the ARM bootloader
- Flashrom + SOP8 clip + CH341



Bootloader analysis (1/2)

- The bootloader is able to “download” a firmware to the eMMC
- The firmware is stored on the eMMC at 0x1500000
- It is mapped in RAM memory at 0x40b00000

```
if ( emmc_direct_read(0x40B00000, 0x1500000u, 0x40u) != 0x40 )
{
  log("BOOTABLE HEADER READ ERROR\n");
  return -1;
}
```

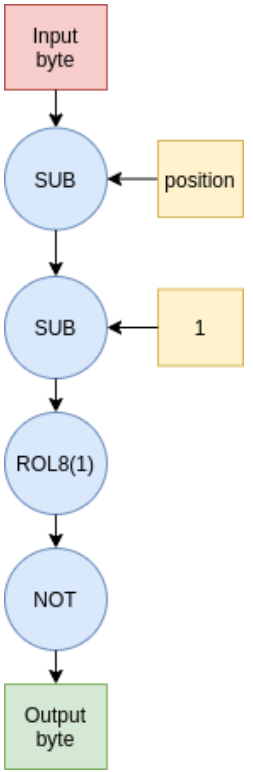
- A deobfuscation routine is found

Bootloader analysis (2/2)

Deobfuscation Routine

- Deobfuscation is routine is quite simple

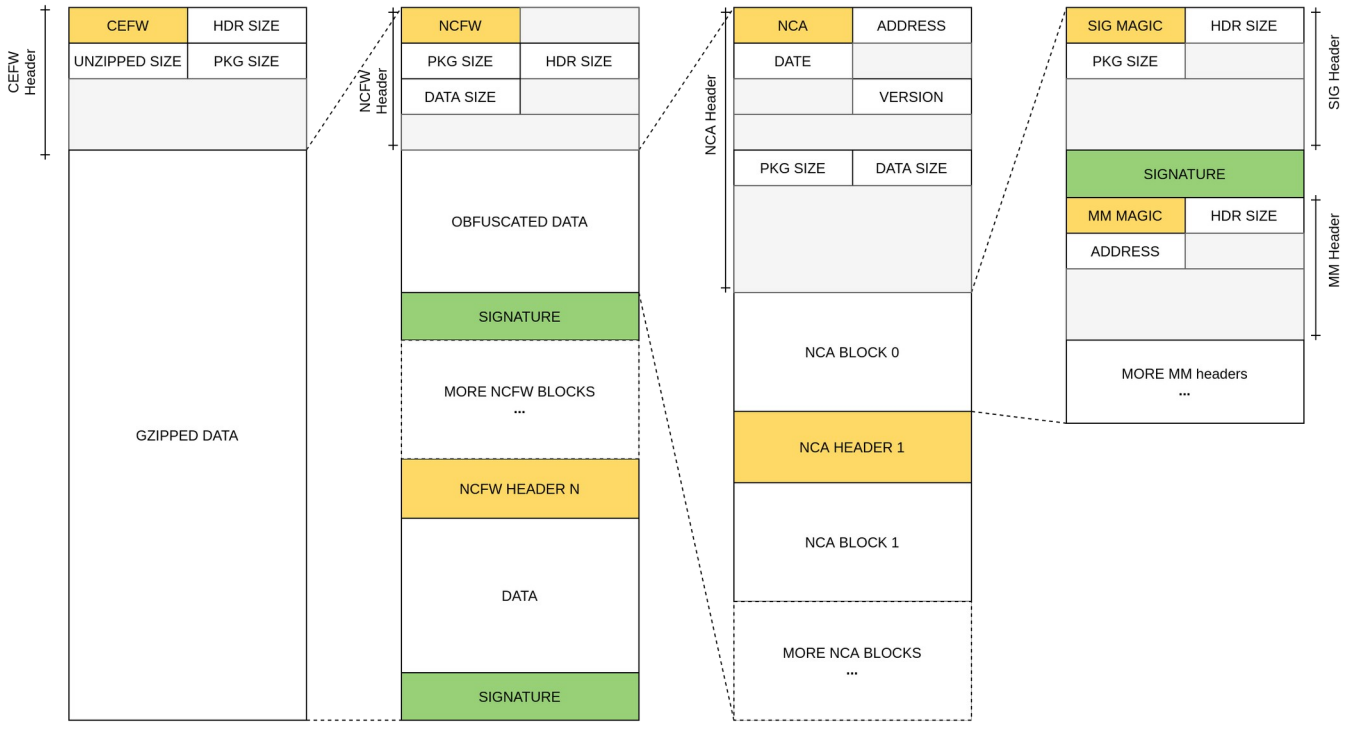
```
_BYTE *__fastcall NCFW_deobfuscate(_BYTE *data, unsigned int size, char offset)
{
  unsigned int i; // r3
  unsigned int tmp; // r4

  for ( i = 0; i < size; ++i )
  {
    tmp = (unsigned __int8)(data[i] - (offset + i) - 1);
    data[i] = ~((2 * tmp) | (tmp >> 7));
  }
  return data;
}
```



Getting the firmware

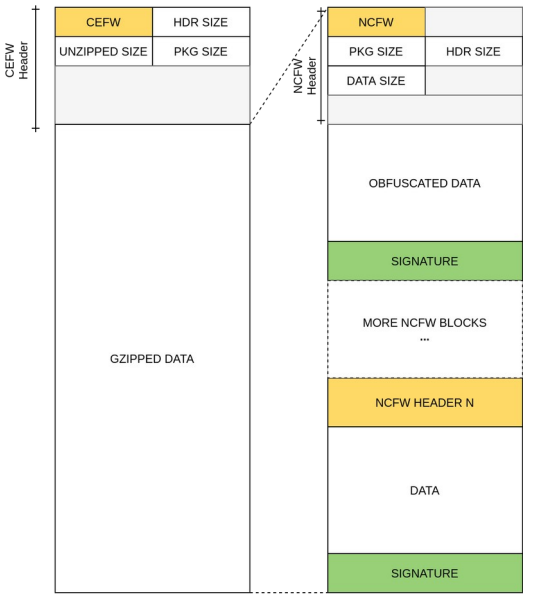
- **The hard way**
  - Dump the eMMC
- **The easy way**
  1) Setup a HTTP proxy
  2) Intercept the URL updates
- **Alternative easy way**
  - Download "MF63Cdw/ MF641Cw Firmware Update Tool" from Canon support website
  - Extract the firmware

Package Image Format (1/3)



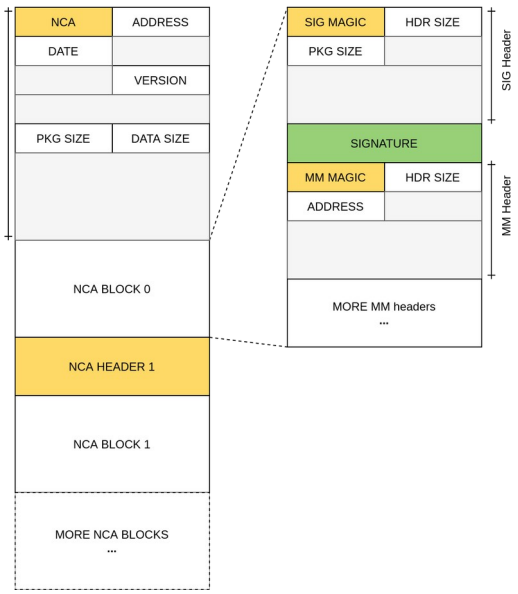
Firmware Image Format (2/3)

- **CEFW Block**
  - Only present in packages downloaded from Canon website
  - Gzipped content
  - Multiple NCFW blocks (once uncompressed)
- **NCFW Block**
  - Obfuscated data with routine identified in the bootloader
  - Multiple NCA blocks (once deobfuscated)



Firmware Image Format (3/3)

- **NCA Block**
  - Block of data written on the eMMC
  - Headers:
    - Version & Release date
    - eMMC address
    - RAM loading address
    - Etc.
- **NCA Block 0**
  - SIG Block + Multiple MM headers (one per further NCA blocks)



IDA Loader

- Parse Canon package format
- Code on Synacktiv's Github repository

```
Output
Detected file format: Canon firmware binary
[*] handling CEFW block
    pkg size: 0x7948c39 (0x91092a5)
    decompressing… done
[*] handling NCFW block
    pkg size: 0x85d367d
    deobfuscating… done
[*] handling NCA  block
    blk addr: 0x08d00600 size: 0x220
    version: 01.00 (20210914)
    kind: 01 flags: none
[*]     handling Sig block
[*]     handling Mm block
[*]     handling Mm block
[*]     handling Mm block
[*]     handling Mm block
[*]     handling Mm block
[*]     handling Mm block
[*] handling NCA  block
    blk addr: 0x01500000 size: 0x53a79a4
    version: 10.03 (20210914)
    kind: 01 flags: code
[*] handling NCA  block
Python
```

Firmware Analysis

Preliminary Firmware Analysis

- **ARM instruction set**
- **DryOs Operating System**
- **> 100k functions!!**
- **Script to rename the functions**
  - Based on logging API
  - More than 2700 functions renamed

```
logf(2802, 3, "[CPC] %s ERROR [Fail getOperationParam]\n", "pjcc_act_checkUserPassword2");
logf(3604, 3, "[CADM] %s: cadmMessage.message.pEventMessage is NULL", "cadm_sendEventMessage");
logf(3520, 6, "[USBD] %s EPNo = 0x%X EPNoSS = 0x%X\n", "ScanBULK Out", (unsigned __int8)v14[0], v1)
```

DryOs

- **DryOs**
  - Canon custom Real Time Operating System
  - Used for printers, DSL cameras, …
  - Older release identified on a Canon MX920 series
- **Based on µITRON**
  - Micro Industrial TRON
  - Japanese RTOS
  - Specification publicly available

```
sub_40C9F5BC("DRYOS version 2.3, release #0059");

/* … */

sub_414FDE88("  Dry-ITRON4.0 object name : isem, iflg, idtq,
imbx, impf, impl, icyc\n");
```

DryOs
Mitigations

- The whole system is linked into a single module
- No ASLR
- No stack-cookies
- No W^X protection
- No security assertion
- … and obviously no modern protections (CFI, …)

DryOs
DryShell (1/2)

- **Debug shell**
- **Available via the UART**
- **413 unique commands**
  - 46 command families
    - System utilities
    - Network
    - Debug
    - Etc.

```
Dry> vers
DRYOS version 2.3, release #0059
  Dry-MK 2.66
  Dry-DM 1.21
  Dry-FSM 0.10
  Dry-EFAT 1.22
  Dry-stdlib 1.57
  Dry-PX 1.15
  Dry-drylib 1.22
  Dry-shell 1.19
  Dry-command alpha 065
```

DryOs
DryShell (1/2)

- **Memory access (useful for exploitation)**
  - xd : Dump memory
  - xm : Modify memory
- **EMMC Dumping**

```
Dry> emmc_dump 1500000 64
read address = 0x01500000.

dump size = 64.
        |+0 +1 +2 +3 +4 +5 +6 +7 +8 +9 +A +B +C +D +E +F
01500000|AF AF 9C 9C 01 50 00 00 20 21 09 14 00 00 00 01
01500010|58 58 78 78 10 03 01 01 05 3A 79 A4 05 3A 79 64
01500020|00 00 00 00 40 B0 00 00 00 00 00 00 00 00 00 00
01500030|00 00 00 00 00 00 00 00 00 00 00 00 08 63 7A A0
01500040|
```

Hunting for Vulnerabilities

DryOs-
Attack surface

Service	Port	Notes
HTTP/HTTPS	80/TCP, 443/TCP	Canon HTTP Server
LPD	515/TCP	Line Printer Daemon Protocol
IPP/IPPS	631/TCP,10443/TCP	Internet Printing Protocol
Jetdirect	9100/TCP	Allow printing using PDL
Canon MFNP	8610/TCP 8610/UDP	Print/Scan jobs
Canon CADM	9007/TCP 9013/TCP 47545/TCP 47547/TCP (SSL) 47545/UDP	Canon administration proprietary protocol

DryOs-
Attack surface

Service	Port	Notes
NetBIOS	137/UDP, 138/UDP	NetBIOS
SNMP	161/UDP	Simple Network Management Protocol
SLP	427/UDP	Service Location Protocol
WSD	3702/UDP	Web Services Dynamic Discovery
Zeroconf	5353/UDP	Multicast DNS (Bonjour Apple)

Overview

- **Heap-based overflow in the CADM service**
- **CVE-2022-24672**
- **Timeline**
  - 2022-01-21: Vulnerability reported (by ZDI) to vendor
  - 2022-03-18: Coordinated public release of advisory

CADM Service

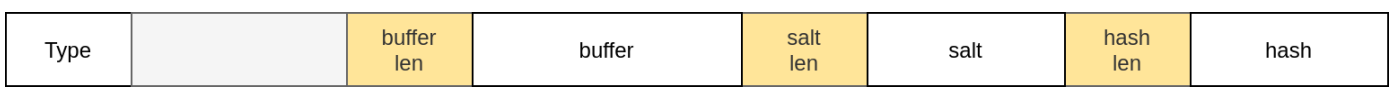
- **Canon ADMinistration?**
- **41 supported operations**
  - Add new user
  - Start job
  - Shutdown device
  - Etc.

CADM Message Format

magic (0xCDCA)	version	flag
operation code	block number	
param len		
	channel number	
data		

The Vulnerability (1/2)

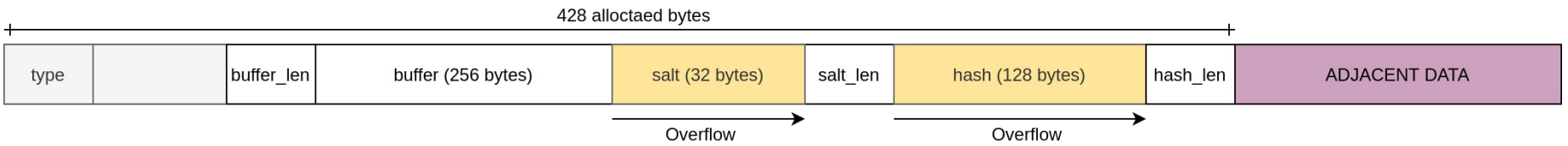

```
uint32_t pjcc_dec_ope_checkUserPassword2(int *pkt, int a2, int *a3)
{
    /* ... */

    alloc = (pjcc_checkpassword_payload *)pjcc_zeroAlloc(428);
    pjcc_checkpass_obj = alloc;

    v7 = pjcc_dec_ubyte(pkt, alloc);
    v12 = pjcc_dec_ulong(pkt, (int)&pjcc_checkpass_obj->field_4);

    v14 = pjcc_dec_ubyte(pkt, &pjcc_checkpass_obj->buffer_len);
    v17 = pjcc_dec_buffer(pkt, pjcc_checkpass_obj->buffer_len, (char *)
        pjcc_checkpass_obj->buffer, v15);

    v19 = pjcc_dec_ubyte(pkt, &pjcc_checkpass_obj->salt_len);
    v22 = pjcc_dec_buffer(pkt, pjcc_checkpass_obj->salt_len, (char *)
        pjcc_checkpass_obj->salt, v20);

    v24 = pjcc_dec_ubyte(pkt, &pjcc_checkpass_obj->hash_len);

    result = pjcc_dec_buffer(pkt, pjcc_checkpass_obj->hash_len, (char *)
        pjcc_checkpass_obj->hash, v25);

    /* ... */
}
```



checkUserPassword2 Format

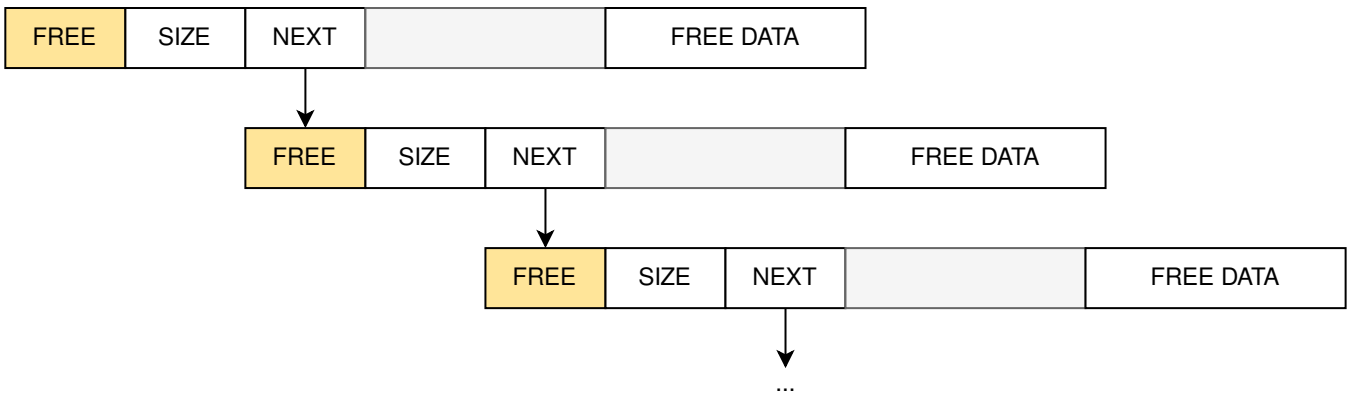
The Vulnerability (2/2)

- **Multiple copies without check size**
- **2 vulnerable buffers**
- **Overflow with:**
  - Controlled size
  - Controlled data



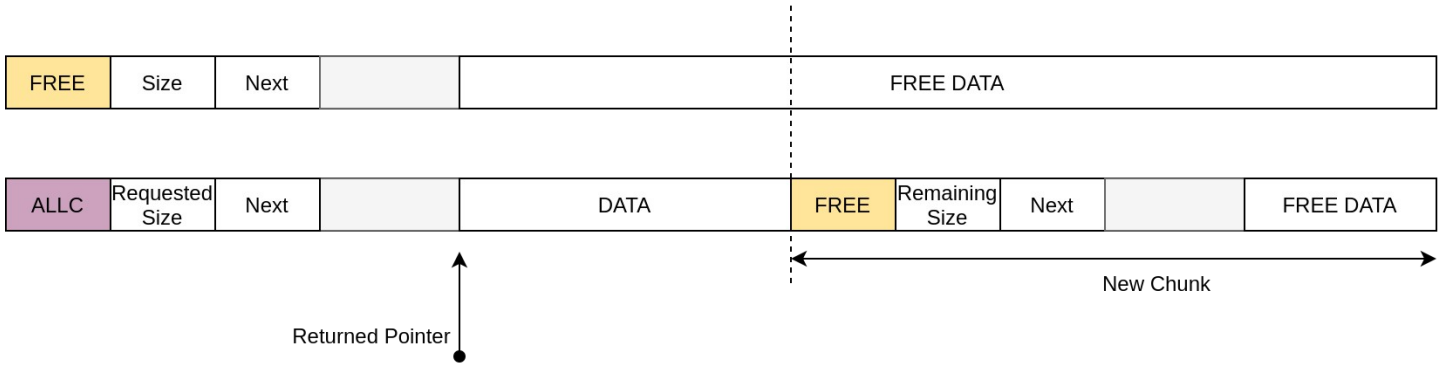
DryOs Allocator
Overview

- “best-fit” allocator
- Linked list of free chunks
- 40 bytes of metadata



DryOs Allocator
Allocation

- **Malloc returns the first free chunk that fulfills the requested size**
- **Create a new chunk with the remaining space**
  - IF chunk_size - request_size > metadata_size



- **Unlink the chunk from the freelist**

DryOs Allocator
Deallocation

- **Freed chunk inserted back in the freelist**
  - Free chunks ordered by their address
- **Chunk merged with adjacent free chunks**

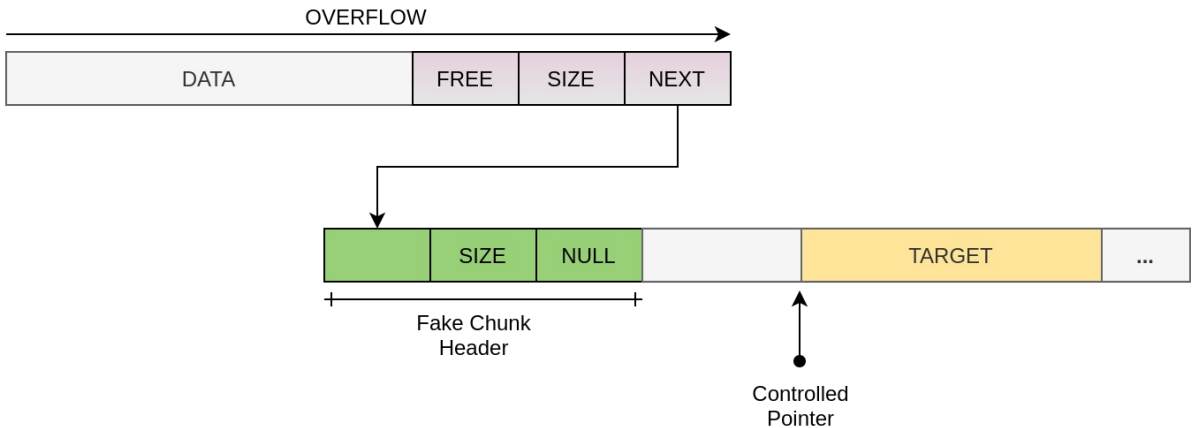
DryOS Allocator
Heap State

- **Custom DryShell command: !hd**
  - Iterate over the freelist
  - Use built-in ‘xd’ command to read memory

```
DryOs > !hd
magic = 0x0, size = 0x5ff930, next = 0x49c1dc88
magic = 0x46524545, size = 0x48, next = 0x49c1e7c0
magic = 0x46524545, size = 0x78, next = 0x49c30e50
magic = 0x46524545, size = 0x30, next = 0x49c30f10
magic = 0x46524545, size = 0x60, next = 0x49c35c98
magic = 0x46524545, size = 0x48, next = 0x49d0b578
magic = 0x46524545, size = 0x60, next = 0x49d14c70
magic = 0x46524545, size = 0x60, next = 0x49d15a18
magic = 0x46524545, size = 0x240, next = 0x49d22268
magic = 0x46524545, size = 0x2848, next = 0x49d24b68
magic = 0x46524545, size = 0x9198, next = 0x49d2ddd8
magic = 0x46524545, size = 0x292140, next = 0x0
```

Attacking the Allocator

- **No security checks!!**
  - All chunk's metadata can be corrupted
- **Arbitrary allocation**
  - Overwrite the 'Next' pointer



Exploitation Strategy

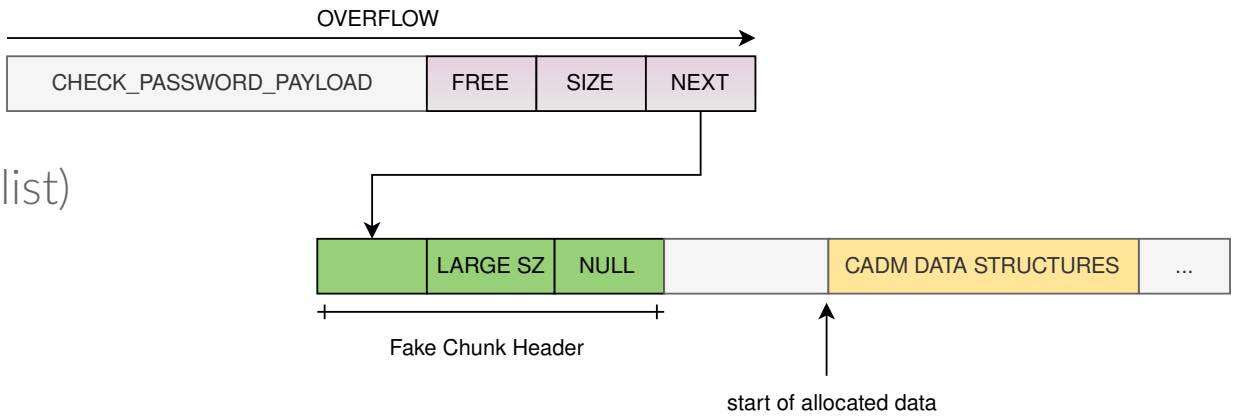
1) **Shape the heap**
2) **Trigger overflow**
   - Corrupt the 'Next' pointer of adjacent memory chunk
   - → Make it point to a memory region holding function pointers
3) **Allocate the fake chunk**
   - Write shellcode
   - Overwrite a function pointer
4) **Trigger code execution**
   - Jump to shellcode

Shaping the Heap

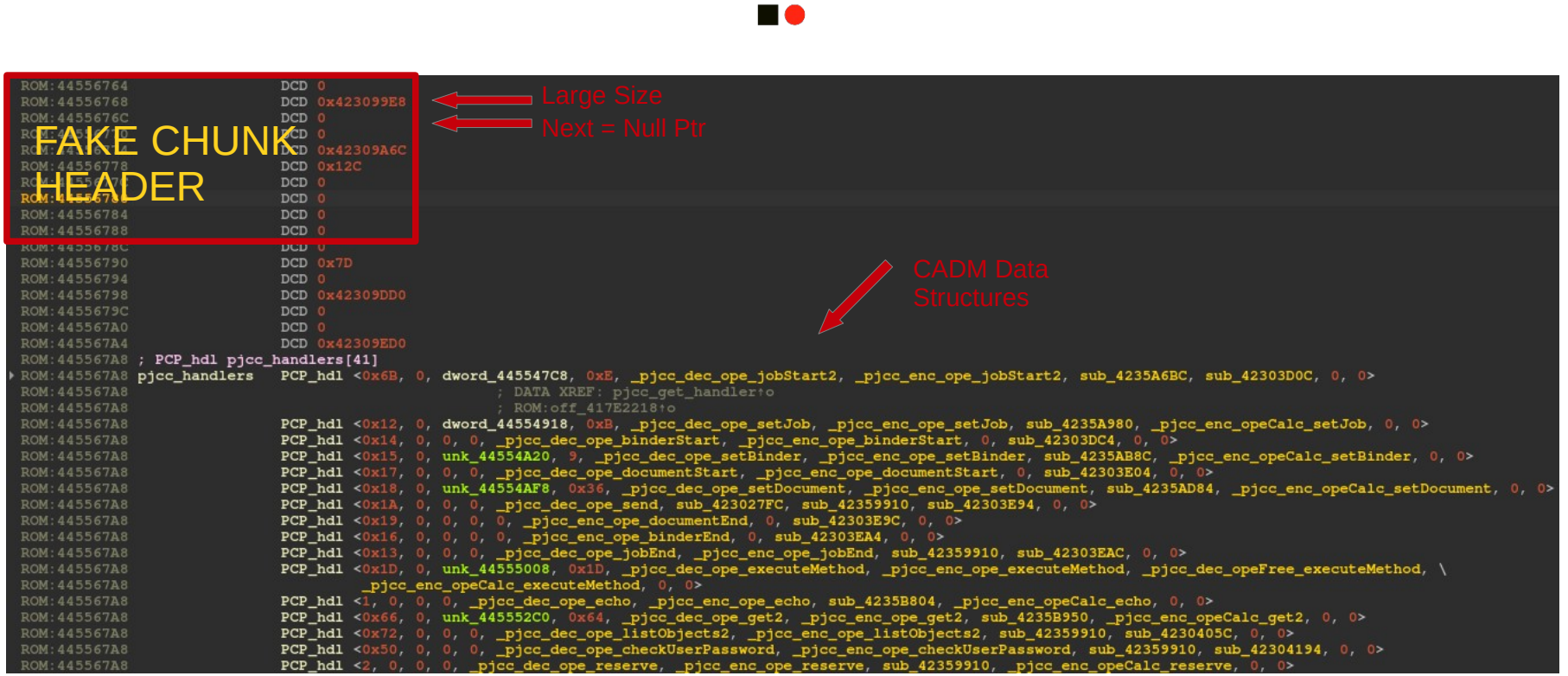
- **Goal:**
  - Force allocation from a large chunk
  - Prevent the allocator from serving our fake chunk at an early stage
- **How:**
  - Perform an HTTPS request will fragment the heap with large chunks
  - → Insert large chunks in the freelist

Triggering Overflow

- **Send a crafted CADM CheckUserPassword Payload**
- **→ Corrupt adjacent memory chunk**
  - Overwrite 'Next' field with the address holding CADM Data structures (state machine, handlers, etc.)
- **Fake Chunk**
  - Large Size
  - Next = NULL (close the freelist)



Fake Chunk




```
ROM:44556764                    DCD 0
ROM:44556768                    DCD 0x423099E8
ROM:4455676C                    DCD 0
ROM:44556770                    DCD 0
ROM:44556774                    DCD 0x42309A6C
ROM:44556778                    DCD 0x12C
ROM:4455677C                    DCD 0
ROM:44556780                    DCD 0
ROM:44556784                    DCD 0
ROM:44556788                    DCD 0
ROM:4455678C                    DCD 0
ROM:44556790                    DCD 0x7D
ROM:44556794                    DCD 0
ROM:44556798                    DCD 0x42309DD0
ROM:4455679C                    DCD 0
ROM:445567A0                    DCD 0
ROM:445567A4                    DCD 0x42309ED0
ROM:445567A8 ; PCP_hdl pjcc_handlers[41]
ROM:445567A8 pjcc_handlers      PCP_hdl <0x6B, 0, dword_445547C8, 0xE, _pjcc_dec_ope_jobStart2, _pjcc_enc_ope_jobStart2, sub_4235A6BC, sub_42303D0C, 0, 0>
ROM:445567A8                                        ; DATA XREF: pjcc_get_handler↑o
ROM:445567A8                                        ; ROM:off_417E2218↑o
ROM:445567A8                    PCP_hdl <0x12, 0, dword_44554918, 0xB, _pjcc_dec_ope_setJob, _pjcc_enc_ope_setJob, sub_4235A980, _pjcc_enc_opeCalc_setJob, 0, 0>
ROM:445567A8                    PCP_hdl <0x14, 0, 0, 0, _pjcc_dec_ope_binderStart, _pjcc_enc_ope_binderStart, 0, sub_42303DC4, 0, 0>
ROM:445567A8                    PCP_hdl <0x15, 0, unk_44554A20, 9, _pjcc_dec_ope_setBinder, _pjcc_enc_ope_setBinder, sub_4235AB8C, _pjcc_enc_opeCalc_setBinder, 0, 0>
ROM:445567A8                    PCP_hdl <0x17, 0, 0, 0, _pjcc_dec_ope_documentStart, _pjcc_enc_ope_documentStart, 0, sub_42303E04, 0, 0>
ROM:445567A8                    PCP_hdl <0x18, 0, unk_44554AF8, 0x36, _pjcc_dec_ope_setDocument, _pjcc_enc_ope_setDocument, sub_4235AD84, _pjcc_enc_opeCalc_setDocument, 0, 0>
ROM:445567A8                    PCP_hdl <0x1A, 0, 0, 0, _pjcc_dec_ope_send, sub_423027FC, sub_42359910, sub_42303E94, 0, 0>
ROM:445567A8                    PCP_hdl <0x19, 0, 0, 0, 0, _pjcc_enc_ope_documentEnd, 0, sub_42303E9C, 0, 0>
ROM:445567A8                    PCP_hdl <0x16, 0, 0, 0, 0, _pjcc_enc_ope_binderEnd, 0, sub_42303EA4, 0, 0>
ROM:445567A8                    PCP_hdl <0x13, 0, 0, 0, _pjcc_dec_ope_jobEnd, _pjcc_enc_ope_jobEnd, sub_42359910, sub_42303EAC, 0, 0>
ROM:445567A8                    PCP_hdl <0x1D, 0, unk_44555008, 0x1D, _pjcc_dec_ope_executeMethod, _pjcc_enc_ope_executeMethod, _pjcc_dec_opeFree_executeMethod, \
ROM:445567A8                              _pjcc_enc_opeCalc_executeMethod, 0, 0>
ROM:445567A8                    PCP_hdl <1, 0, 0, 0, _pjcc_dec_ope_echo, _pjcc_enc_ope_echo, sub_4235B804, _pjcc_enc_opeCalc_echo, 0, 0>
ROM:445567A8                    PCP_hdl <0x66, 0, unk_445552C0, 0x64, _pjcc_dec_ope_get2, _pjcc_enc_ope_get2, sub_4235B950, _pjcc_enc_opeCalc_get2, 0, 0>
ROM:445567A8                    PCP_hdl <0x72, 0, 0, 0, _pjcc_dec_ope_listObjects2, _pjcc_enc_ope_listObjects2, sub_42359910, sub_4230405C, 0, 0>
ROM:445567A8                    PCP_hdl <0x50, 0, 0, 0, _pjcc_dec_ope_checkUserPassword, _pjcc_enc_ope_checkUserPassword, sub_42359910, sub_42304194, 0, 0>
ROM:445567A8                    PCP_hdl <2, 0, 0, 0, _pjcc_dec_ope_reserve, _pjcc_enc_ope_reserve, sub_42359910, _pjcc_enc_opeCalc_reserve, 0, 0>
```

Allocating Fake Chunk

- **CADM Echo Operation**
  - Sends back identical copy of received data
- **→ Controlled allocation**
  - Controlled size
  - Controlled data

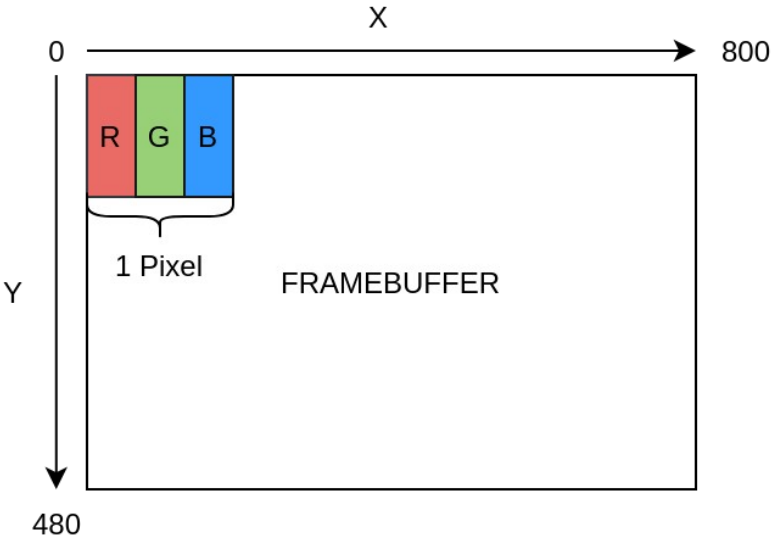
Getting Code Execution

- **Overwrite CADM data structures**
  - Copy shellcode
  - Overwrite the handler responsible for processing CADM Echo requests → Gives immediate code execution
  - Preserve the rest of the data to avoid early crashes due to a corrupted state machine internal data

Displaying a Ninja

- **800x480 LCD screen**
- **Frame Buffer**
  - Available at 0x40900000
  - 3 bytes used to encode 1 RGB pixel
- **Testing effect on LCD screen**
  - Use DryShell “xm” command

```
// String used in function close to
// frame buffer initialization
log("BOOTLOADER LCD_TYPE_%s\n", v0);
```



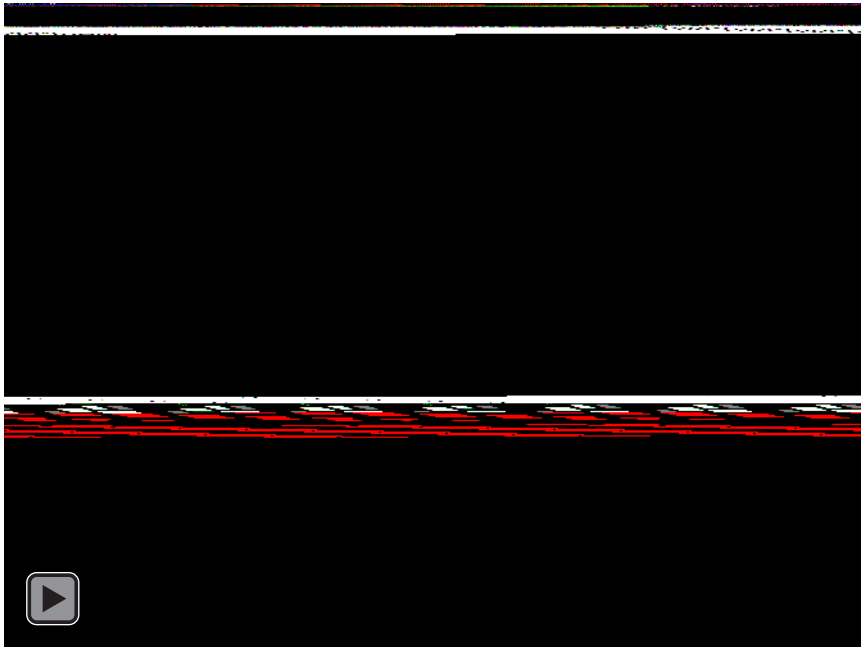
Displaying a Ninja

- **Shellcode used to read a picture from a socket**
  - Implemented in ARM assembly (binutils-arm-none-eabi)

```
struct sockaddr_in addr = {
 .sin_familly = AF_INET,
 .sin_port = htons(9000);
 .sin_addr = htonl(0xC0A80102); // 192.168.1.2
};
int sockfd = netSocket(1, 1, 0, 0);
netConnect(sockfd, addr, 8);

while (1)
{
   for (char *addr = 0x40900000; addr < 0x40a19400; addr +=3)
   {
      netRecv(sockfd, addr, 3, 0);
   }
   sedev_powerOnImgSns();
}
```

- **The server is a python script based on PIL**

DEMO



Conclusion & Perspectives

- **Conclusion**
  - First Pwn2Own participation, lots of fun!!
- **Perspectives**
  - Add persistence mechanism
  - Process continuation

Released tools and scripts

- **Available at https://github.com/synacktiv/canon-mf644/**
  - Exploit working on firmware v10.02
  - IDA Python loader for Canon firmware
  - IDA Python script for renaming functions

References

- Reversing a Japanese Wireless SD Card Zero to Code Execution
- THCON 2021 - Zombies ate my printer's ink
- µITRON4.0 Specification

https://www.linkedin.com/company/synacktiv
https://twitter.com/synacktiv
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