Cinema time!

Andrey Labunets

Nikita Tarakanov

Hexacon

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#WhoWeAre

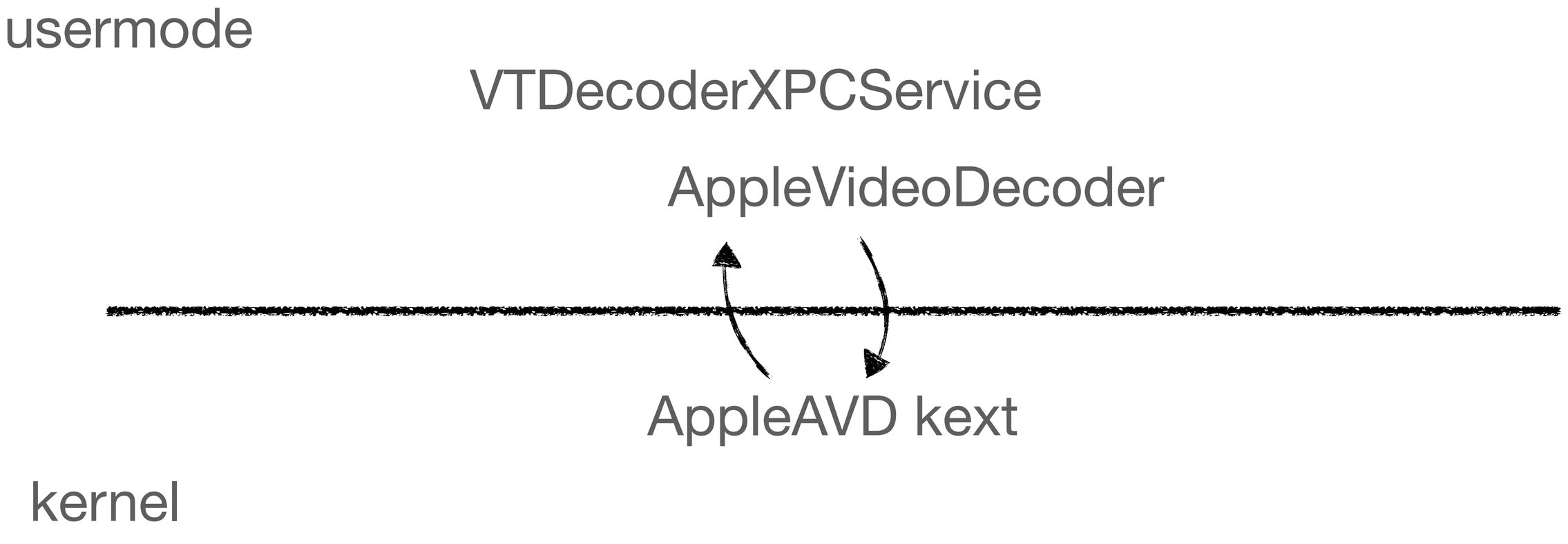
- Nikita Tarakanov is an independent security researcher. He has worked as a security researcher in Positive Technologies, Vupen Security, Intel corporation and Huawei. He likes writing exploits, especially for OS kernels. He won the PHDays Hack2Own contest in 2011 and 2012. He has published a few papers about kernel mode drivers and their exploitation. He is currently engaged in reverse engineering research and vulnerability search automation.
- Andrey Labunets is a security researcher with more than a decade of experience in vulnerability research and reverse engineering.

Agenda

- Video decoding subsystem overview
- AppleAVD internals and attack surface
- Previously disclosed vulnerabilities & Exploitation
- Fuzzing approach
- Results
- Discussion
- Q&A

Video decoding subsystem

macOS Monterey



Video decoding subsystem

- Out of scope today - hardware components
- Main focus is AppleAVD kext internals on

  macOS Monterey

- You can find some info on AVD hardware here:
  - https://twitter.com/rqou_/status/1577967077955993600
  - https://github.com/rqou/m1-avd-reverse-engineering/blob/main/avd_emu.py

AppleAVD internals

Codebase overview

- AppleAVD - one of the largest kexts in macOS
  - **~120 KLOC** in IDA decompiler
- Large part of this codebase are actual decoders, which process parts of media input in kernel space

```
  if ( (_DWORD)a3 == 301 )
  {
    createLilyDLghDecoder(this);
  }
  else
  {
    if ( (_DWORD)a3 != 308 )
      goto LABEL_39;
    createDahliaLghDecoder(this);
  }
}
else
{
  switch ( (_DWORD)a3 )
  {
    case 0x13C:
      createRadishLghDecoder(this);
      break;
    case 0x144:
      v10 = createClaryLghDecoder(this);
      break;
    case 0x190:
      v10 = createIxoraLghDecoder(this);
      break;
    default:
```

AppleAVD internals

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```
{
  createCloverLghDecoder(this);
  goto LABEL_4;
}
if ( (int)a3 <= 300 )
{
  switch ( (int)a3 )
  {
    case 20:
      v10 = createSalviaA0LghDecoder(this);
      goto LABEL_4;
    case 21:
      v10 = createSalviaLghDecoder(this);
      goto LABEL_4;
    case 22:
    case 23:
    case 24:
    case 25:
    case 27:
      goto LABEL_39;
    case 26:
      createViolaLghDecoder(this);
      goto LABEL_4;
    case 28:
      v10 = createLotusLghDecoder(this);
      goto LABEL_4;
    default:
      if ( (_DWORD)a3 != 300 )
        goto LABEL_39;
      createLilyCLghDecoder(this);
      break;
  }
```

AppleAVD internals

Entry points (external methods)

- Accessed through AppleAVDUserClient
- Most interesting external methods:
  - AppleAVDUserClient::createDecoder
  - AppleAVDUserClient::decodeFrameFig
- Message passing between user / kernel (media data, NAL units, etc)
  - IOSurface

AppleAVD internals

Entry points (external methods)

- This set of external methods covers most of the kext functionality:
  - AppleAVDUserClient::setCallback
  - AppleAVDUserClient::createDecoder
  - AppleAVDUserClient::setCryptSession
  - AppleAVDUserClient::decodeFrameFig

AppleAVD internals

createDecoder

- Sets up one of 3 decoders of our choice

```
codec_type = (unsigned __int8)in->codec_type;
*(_DWORD *)&this->m_AppleAVDUserClient.codec_type = codec_type;
*(_DWORD *)&this->m_AppleAVDUserClient.field7892_0x1ed4 = in->pad0x24;
this->m_AppleAVDUserClient.decoder = 0LL;
switch ( codec_type )
{
  case 1:
    if ( this->m_AppleAVDUserClient.deviceType < 0xDu )
      goto LABEL_41;
    v21 = (CAVDAvcDecoder *)operator new(0x8642B0uLL);
    decoder = CAVDAvcDecoder::CAVDAvcDecoder(
                v21,
                this,
                (unsigned int)this->m_AppleAVDUserClient.deviceType,
                in->pad0x1B != 0);
    break;
  case 3:
    v22 = (CAVDLghDecoder *)operator new(0x65C0uLL);
    decoder = (CAVDAvcDecoder *)CAVDLghDecoder::CAVDLghDecoder(
                                  v22,
                                  this,
                                  this->m_AppleAVDUserClient.deviceType,
                                  in->pad0x1B != 0);
    break;
  case 2:
    v19 = (CAVDHevcDecoder *)operator new(0x21CBB8uLL);
    CAVDHevcDecoder::CAVDHevcDecoder(v19, this, this->m_AppleAVDUserClient.deviceType, in->pad0x1B != 0);
    break;
  default:
```

```
struct _sAppleAVDCreateDecoderIn
{
  _DWORD width;
  _DWORD height;
  _DWORD nal_buf_len;
  _DWORD val0xc;
  _BYTE val0x10[9];
  _BYTE codec_type;
  _BYTE pad0x1A;
  _BYTE pad0x1B;
  _BYTE pad0x1C;
  _BYTE pad0x1D;
  _BYTE ichat_usage_mode;
  _BYTE pad0x1F;
  _BYTE memCacheMode;
  _BYTE val0x21;
  _BYTE val0x22;
  _BYTE val0x23;
  _DWORD pad0x24;
  _DWORD pad0x28;
  _DWORD pad0x2c;
  _DWORD val0x30;
  _DWORD wsk[33];
  _DWORD surface_id;
  _DWORD decrypt_mode;
  _DWORD sleepWakeTransitionTimeout;
  _BYTE pmgrRequestTimeout[20];
};
```

AppleAVD internals

decodeFrameFig

- Processes plaintext frames…

```
process_plaintext_frame:

    _reference_index = in->reference_index;
    *&this->m_AppleAVDUserClient._reference_index = _reference_index;
    deviceType = this->m_AppleAVDUserClient.deviceType;
    if ( (deviceType == 28 || deviceType >= 0x12F) && (this->m_AppleAVDUserClient.field
    {
      (this->m_AppleAVDUserClient.decoder->__vftable->VASetParams)(
        this->m_AppleAVDUserClient.decoder,
        43LL,
        *&this->m_AppleAVDUserClient.field7296_0x1c80 + ((in->framenumber << 9) & 0x1E0
      _reference_index = in->reference_index;
    }

    kernel_debug(0x2B680050u, _reference_index, in->display_index, in->index_target2, 0

    res = (this->m_AppleAVDUserClient.decoder->__vftable->VADecodeFrame)(
            this->m_AppleAVDUserClient.decoder,
            buf,
            in->dataLength,
            in->framenumber,
            in->display_index,
            in->reference_index,
            in->index_target2,
            out + 3552);
```

```
/* 110 */
struct __attribute__((aligned(4))) _sAppleAVDDecodeFrameFigIn
{
  _QWORD mapPixBuf_address;
  _DWORD dataLength;
  _DWORD framenumber;
  _DWORD display_index;
  _DWORD reference_index;
  _DWORD index_target2;
  _DWORD decrypt_byte_offset;
  _DWORD allocSize;
  _BYTE VASetDisableSkipToIDR_val;
  _BYTE val0x25;
  _BYTE val0x26;
  _BYTE val0x27;
  _BYTE isEncrypted;
  _BYTE val0x29;
  _BYTE val0x2a;
  _BYTE val0x2b;
  _DWORD initialClearBytes;
  _DWORD ivSize;
```

AppleAVD internals

decodeFrameFig -> decodeFrameFigHelper_DecryptFrame

- Processes plaintext frames…
- …and DRM content
  - Likely it's FairPlay Streaming
  - FairPlay code obfuscation complicates some analysis

```
__int64 __fastcall AppleAVDUserClient::decodeFrameFigHelper_DecryptFrame(
{
  char *plaintext_buffer; // x1
  unsigned __int8 *buffer; // x2
  __int64 v6; // x0
  __int64 res; // x21
  AppleAVD *v8; // x0
  unsigned int dataLength; // w3
  __int64 contextID; // x4
  int v11; // w5

  plaintext_buffer = this->m_AppleAVDUserClient.plaintext_buffer;
  buffer = this->m_AppleAVDUserClient.buffer;
  switch ( *&this->m_AppleAVDUserClient.decrypt_mode )
  {
    case 0:
      v6 = AppleAVD::decryptFrame(
             this->m_AppleAVDUserClient.appleAVD,
             plaintext_buffer,
             buffer,
             in->dataLength,
             *&this->m_AppleAVDUserClient.contextID);
      goto LABEL_10;
    case 1:
      v8 = this->m_AppleAVDUserClient.appleAVD;
      dataLength = in->dataLength;
      contextID = *&this->m_AppleAVDUserClient.contextID;
```

AppleAVD internals

setCryptSession

- Allocates data buffers for (decrypted?) data, initializes session parameters
- From AppleVideoDecoder:

```
67  struct _sAppleAVDSetCryptSessionIn
68  {
69    _QWORD crypt_ref;
70    uint8_t decrypt_mode;
71    uint8_t pad0x9;
72    uint8_t pad0xa;
73    uint8_t pad0xb;
74    uint8_t pad0xc;
75    uint8_t pad0xd;
76    uint8_t pad0xe;
77    uint8_t pad0xf;
78    _QWORD pad0x10;
79  };
80
```

```
241
242         // set_parameter later calls AppleAVD setCryptsession external method
243         v39 = set_parameter(*(unknown2 **)&v11[80].__opaque[40], 22, (unsigned __int8 *)v116.value);
244         if ( (_DWORD)v39 )
245         {
246           v33 = v39;
247           syslog_DARWIN_EXTSN(
248             3LL,
249             "AppleAVD: AppleAVD_HEVCVideoDecoder: frame# %d, Could not set kAppleAVDSetCryptRef, err %d\n");
250           goto LABEL_59;
251         }
0004D5E8 AppleAVDWrapperHEVCDecoderDecodeFrame:235 (55E8)
```

AppleAVD attack surface

- AppleAVD media processing is performed with *stateless* decoders and *stateful* logic
  - Stateless components might be easier to attack remotely
  - Attacking stateful logic might require more control over kernel objects, achieved with local privilege escalation (LPE)

AppleAVD attack surface

- To find or rule out the most straightforward remote vectors, we extracted stateless components and tested them directly with a coverage-guided fuzzer
- To investigate the rest, we reviewed stateful parts by reconstructing the logic of external methods and reviewing object initialization and interaction between components
- We left all firmware and hardware vectors out of scope

Fuzzing decoders

- AppleAVD decoders process media data, such as Network Abstraction Layer (NAL) units, parameter sets (SPS, PPS)
- This code is implemented in CAVDAvcDecoder, CAVDLghDecoder, CAVDHevcDecoder
- Parsing is done inside virtual VAStartDecode and VADecodeFrame

Fuzzing decoders

Seed corpus generation

- First, we fuzzed ffmpeg with a small set of publicly available templates
- ffmpeg fuzzer generated a sufficient seed corpus for AppleAVD
- AppleAVD expects NAL units in a special format:
  - <next_NAL_unit_offset><current_NAL_unit>…

Fuzzing decoders

Target code setup and fuzzing

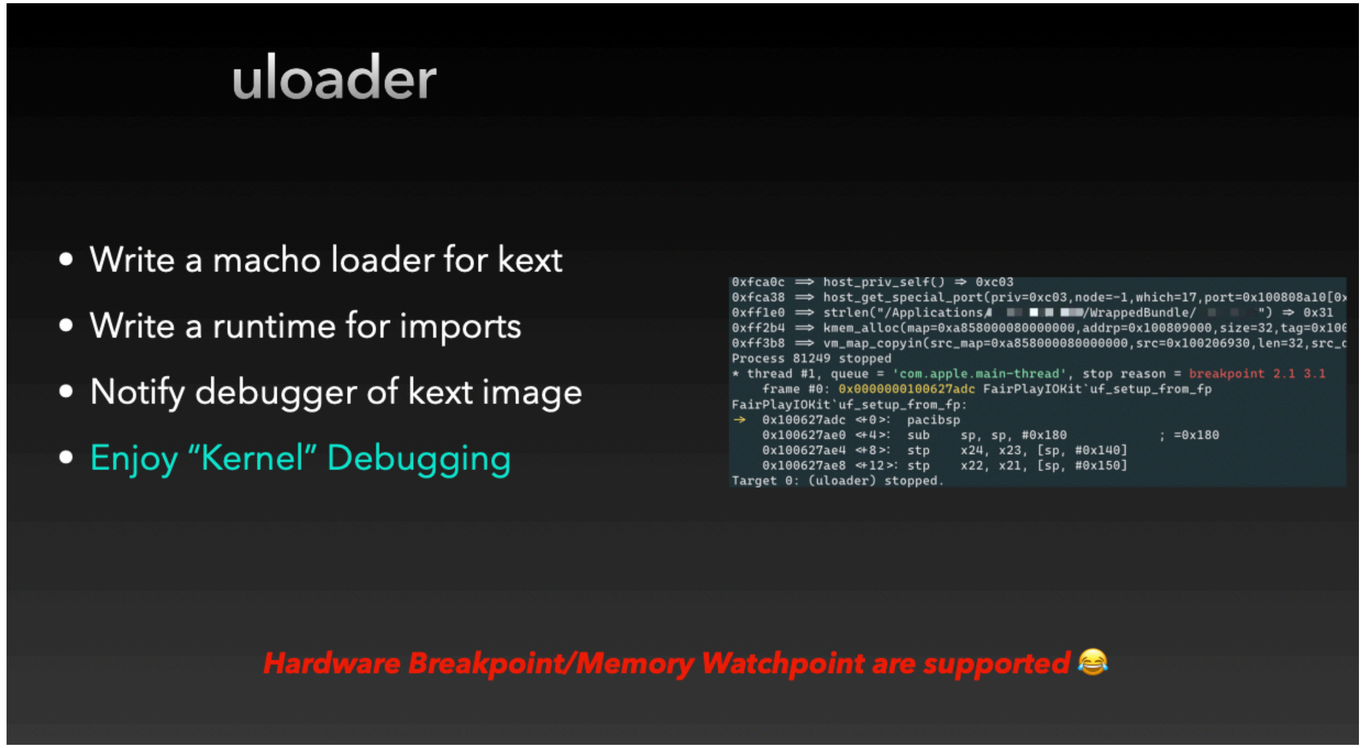
- We build the target from extracted IDA decompiler pseudocode
  - In our experiments with AppleAVD and other macOS subsystems, the control flow does not differ from the original machine code
- A tiny shim handles IDA types, reimplements ARM intrinsics and selected pieces of kernel library code
- Fuzzing ~3KLOC of CAVDAVCDecoder+AVC_RBSP with AFL++ resulted in a single unexploitable crash (an artifact of fuzzing setup) and 96% coverage

Fuzzing decoders

Road not taken - alternative fuzzing setup

- Another approach by Junzhi Lu, Xindi Wang, Ju Zhuto runs kexts in user mode with a custom macho loader for debugging, but could be useful for fuzzing too.

- Our approach with code extraction gives source code-level flexibility to fuzz selected code paths with debug symbols.



https://github.com/pwn0rz/fairplay_research

Manual analysis

- Analysis of 3 external methods revealed an issue with inconsistent checks
- More details to come

On Sat, Oct 15, 2022 at 5:35 AM product-security@apple.com <product-security@apple.com> wrote:

> Hi Andrey,
>
> Thank you for providing the details about your presentation tomorrow. We are investigating the issue reported. To avoid placing our customers at risk, we would appreciate you not disclosing this information until our investigation is complete and, any necessary updates are available.

AppleAVD attack surface

- Results:
  - Fuzzed one of three decoders - 1 non-exploitable crash (fuzzing setup at fault), not an issue
  - Reviewed control flow and interaction between 3 external methods - 1 unverified finding, possibly an issue
  - Limited results suggests interaction between stateful components in AVD is more error-prone

Previously discovered vulnerabilities

- CVE-2018-4348 - memory corruption
- CVE-2020-9958 - out-of-bound write
- **CVE-2022-22675 - overflow in parseHRD**
- **CVE-2022-32788 - overflow in parseSliceHeader**

Overflow in parseHRD

- cpb_cnt_minus1 = Read_byte_from_stream();
- *HRD_data_in_spsList = cpb_cnt_minus1;
- HRD_arrays = HRD_data_in_spsList + 0x104;
- Index = 0
- do {
- *(_DWORD *)&HRD_arrays[4 * index - 0x100] = Read_dword_from_stream();
- *(_DWORD *)&HRD_arrays[4 * index - 0x80] = Read_dword_from_stream();
- HRD_arrays[index] = = Read_byte_from_stream();
- } while (index++ < *HRD_data_in_spsList);

Overflow in parseHRD

- Size of array is 0x20 elements we can copy up-to 0x100 elements
- We can overflow adjacent element in spsList array
- We can overflow adjacent memory to spsList array (first element in ppsList)

Overflow in parseSliceHeaders

```
counter_oob = 0;
while ( 1 ){
    *((_BYTE *)SliceHeaderBuffer + counter_oob + 47) = Read_byte_from_stream();
    *((_DWORD *)SliceHeaderBuffer + counter_oob + 55) = Read_dword_from_stream();
    *((_DWORD *)SliceHeaderBuffer + counter_oob + 21) = Read_dword_from_stream();
    counter_oob++;
    If ( *((_BYTE *)SliceHeaderBuffer + counter_oob + 47) == 0x3 ) {
        break;
    }
}
```

Overflow in parseSliceHeader

- Size of SliceHeader buffer is 0x480 located in CAVDAvcDecoder object
- We can overflow adjacent fields in CAVDAvcDecoder object
- CAVDAvcDecoder object is huge (0x8642B0 byes) in KHEAP_KEXT
- We can spray CAVDAvcDecoder objects and smash pointers in it
- Problem is that we have to win race between using vtable (PAC) and pointers to other objects

Discussion

- AppleAVD runs about ~100KLOC of parsers in kernel on all incoming media.
  - Can this functionality be moved to user land instead or isolated?

- Some input validation is spread across multiple external methods, processing is partially performed by an obfuscated FairplayKit.
  - Can we even inspect the security of Apple media pipeline in any meaningful way?

Thanks

- Thanks to Max Dmitriev (I_Greek) and to Berk Cem Göksel (@berkcgoksel)!

- Questions?