Analyzing The ForcedEntry Zero-Click iPhone Exploit Used By Pegasus

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Exploits & Vulnerabilities

Citizen Lab has released a report on a new iPhone threat dubbed ForcedEntry. This zero-click exploit seems to be able to circumvent Apple's BlastDoor security, and allow attackers access to a device without user interaction.

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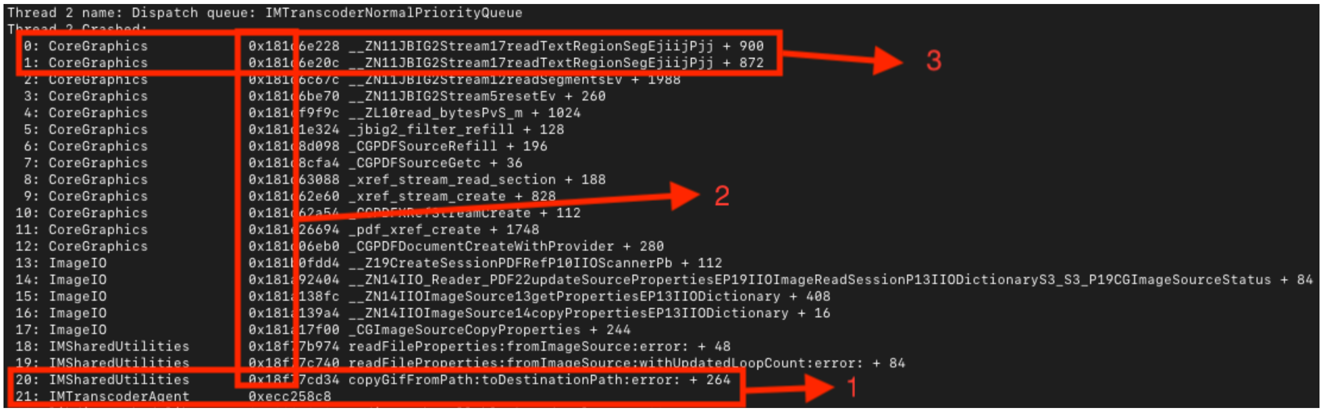
Citizen Lab has released a report detailing sophisticated iPhone exploits being used against nine Bahraini activists. The activists were reportedly hacked with the NSO Group’s Pegasus spyware using two zero-click iMessage exploits: Kismet, which was identified in 2020; and ForcedEntry, a new vulnerability that was identified in 2021. Zero-click attacks are labeled as sophisticated threats because unlike typical malware, they do not require user interaction to infect a device. The latter zero-click spyware is particularly notable because it can bypass security protections such as BlastDoor, which was designed by Apple to protect users against zero-click intrusions such as these.

According to Citizen Lab’s report, Kismet was used from July to September 2020 and was launched against devices running at least iOS 13.5.1 and 13.7. It was likely not effective against the iOS 14 update in September. Then, in February 2021, the NSO Group started deploying the zero-click exploit that managed to circumvent BlastDoor, which Citizen Lab calls ForcedEntry. Amnesty Tech, a global collective of digital rights advocates and security researchers, also observed zero-click iMessage exploit activity during this period and referred to it as Megalodon.

Diving into ForcedEntry

According to the report from Citizen Lab, when the ForcedEntry exploit was launched against the victim’s device, the device logs showed two types of crashes. The first crash apparently happened when invoking ImageIO’s functionality for rendering Adobe Photoshop PSD data.

Our analysis focuses on the second crash, which is detailed in Figure 1. This crash happened when invoking CoreGraphics’ functionality for decoding JBIG2-encoded data in a PDF file. This analysis is solely based on samples from Citizen Lab; no new samples were obtained.



```
Thread 2 name: Dispatch queue: IMTranscoderNormalPriorityQueue
Thread 2 Crashed:
  0: CoreGraphics                 0x181d6e228 __ZN11JBIG2Stream17readTextRegionSegEjiijPjj + 900
  1: CoreGraphics                 0x181d6e20c __ZN11JBIG2Stream17readTextRegionSegEjiijPjj + 872
  2: CoreGraphics                 0x181d6c67c __ZN11JBIG2Stream12readSegmentsEv + 1988
  3: CoreGraphics                 0x181d6be70 __ZN11JBIG2Stream5resetEv + 260
  4: CoreGraphics                 0x181df9f9c __ZL10read_bytesPvS_m + 1024
  5: CoreGraphics                 0x181d1e324 _jbig2_filter_refill + 128
  6: CoreGraphics                 0x181d8d098 _CGPDFSourceRefill + 196
  7: CoreGraphics                 0x181d8cfa4 _CGPDFSourceGetc + 36
  8: CoreGraphics                 0x181d63088 _xref_stream_read_section + 188
  9: CoreGraphics                 0x181d62e60 _xref_stream_create + 828
 10: CoreGraphics                 0x181d62a54 _CGPDFXRefStreamCreate + 112
 11: CoreGraphics                 0x181d26694 _pdf_xref_create + 1748
 12: CoreGraphics                 0x181d06eb0 _CGPDFDocumentCreateWithProvider + 280
 13: ImageIO                      0x181b0fdd4 __Z19CreateSessionPDFRefP10IIOScannerPb + 112
 14: ImageIO                      0x181a92404 __ZN14IIO_Reader_PDF22updateSourcePropertiesEP19IIOImageReadSessionP13IIODictionaryS3_S3_P19CGImageSourceStatus + 84
 15: ImageIO                      0x181a138fc __ZN14IIOImageSource13getPropertiesEP13IIODictionary + 408
 16: ImageIO                      0x181a139a4 __ZN14IIOImageSource14copyPropertiesEP13IIODictionary + 16
 17: ImageIO                      0x181a17f00 _CGImageSourceCopyProperties + 244
 18: IMSharedUtilities            0x18f77b974 readFileProperties:fromImageSource:error: + 48
 19: IMSharedUtilities            0x18f77c740 readFileProperties:fromImageSource:withUpdatedLoopCount:error: + 84
 20: IMSharedUtilities            0x18f77cd34 copyGifFromPath:toDestinationPath:error: + 264
 21: IMTranscoderAgent            0xecc258c8
```

Figure 1. This image from Citizen Lab shows a Symbolicated Type Two crash for ForcedEntry on an iPhone 12 Pro Max running iOS 14.6. The red highlights from Trend Micro Research.

From this crash log, we can deduce three interesting points: First, the zero-click attack is dependent on iMessage attachment parsing. Next, the slide of dyld_shared_cache is 0, which means all the system modules are loaded into a fixed address. Lastly, the crash point 0x181d6e228 is not the first place of vulnerability exploitation. We discuss the details of these conclusions in the following sections.

Root cause of CVE-2021-30860

The vulnerability is inside the function **JBIG2Stream::readTextRegionSeg** of CoreGraphics.framework The crash point **0x181d6e228** (as seen in box 3 in the preceding figure) is at line 161 of the function JBIG2Stream::readTextRegionSeg of the following screenshot:

```
  numSyms = 0;
  nRefSegs_1 = nRefSegs;
  refSegs_1 = (int *)refSegs;
  v28 = nRefSegs;
  do
  {
    Segment = (JBIG2SymbolDict *)JBIG2Stream::findSegment(this, *refSegs_1);
    if ( !Segment )
    {
      v47 = (*(__int64 (__fastcall **)(JBIG2Stream *))(*(_QWORD *)this + 40LL))(this);
      error(v47, "Invalid segment reference in JBIG2 text region");
      j__free(*(void **)v106);
      operator delete(v106);
      return;
    }
    v30 = Segment;
    if ( Segment->vfptr->getType(Segment) == jbig2SegSymbolDict )
    {
      numSyms += v30->size;
    }
    else if ( v30->vfptr->getType(v30) == jbig2SegCodeTable )
    {
      GList::append(v106, v30);
    }
    ++refSegs_1;
    --v28;
  }
  while ( v28 );
  v89 = v12;
  v91 = v14;
  v31 = 0;
  if...
  syms = (_QWORD *)gmallocn(numSyms, 8u);
  i_1 = 0LL;
  k = 0LL;
  do
  {
    seg = (JBIG2SymbolDict *)JBIG2Stream::findSegment(this, refSegs[i_1]);
    if ( seg
      && (symbolDict = seg, seg->vfptr->getType(seg) == jbig2SegSymbolDict)
      && (size = symbolDict->size, (_DWORD)size) )
    {
      bitmaps = symbolDict->bitmaps;
      do
      {
        v40 = (__int64)*bitmaps++;
        kk = (unsigned int)(k + 1);
        syms[(unsigned int)k] = v40;          // crash here !!!
        LODWORD(k) = k + 1;
        --size;
      }
      while ( size );
    }
    else
    {
      kk = k;
    }
    ++i_1;
    k = kk;
  }
  while ( i_1 != nRefSegs_1 );
```

```
00085228 __ZN11JBIG2Stream17readTextRegionSegEjiijPjj:161 (181D6E228)
```

Figure 2. Screenshot of the function JBIG2Stream::readTextRegionSeg showing the crash point

First, it calculates the *numSyms* according to the JBIG2SymbolDict segment:

```
  numSyms = 0;
  for (i = 0; i < nRefSegs; ++i) {
    if ((seg = findSegment(refSegs[i]))) {
      if (seg->getType() == jbig2SegSymbolDict) {
            numSyms += ((JBIG2SymbolDict *)seg)->getSize();
      } else if (seg->getType() == jbig2SegCodeTable) {
            codeTables->append(seg);
      }
    } else {
      error(getPos(), "Invalid segment reference in JBIG2 text region")
;
      delete codeTables;
      return;
    }
  }
```

The type of *numSyms* is unsigned int, and the return type of function *seg->getSize()* is also unsigned int. Therefore, *numSyms* could be smaller than the size of one JBIG2Segment due to integer overflow. One example is *numSyms=1=(0x80000000+0x80000001) < 0x80000000.*

Then, it allocates the heap buffer **syms**, with the size **numSyms * 8** :

```
syms = (JBIG2Bitmap **)gmallocn(numSyms, sizeof(JBIG2Bitmap *));
```

Finally, it fills the *syms* with the value from bitmap:

```
  kk = 0;
  for (i = 0; i < nRefSegs; ++i) {
    if ((seg = findSegment(refSegs[i]))) {
      if (seg->getType() == jbig2SegSymbolDict) {    //seg->getType() i
s a virtual function
            symbolDict = (JBIG2SymbolDict *)seg;
            for (k = 0; k < symbolDict->getSize(); ++k) {
                  syms[kk++] = symbolDict->getBitmap(k);    // crashed h
ere
            }
      }
    }
  }
```

The loop times are dependent on the JBIG2Segment size, which could be larger than the buffer *syms* size. This leads to the out-of-bounds write access for the heap buffer *syms*.

Looking at Apple’s fix

Apple patched the function in iOS 14.8:

```
syms = (_QWORD *)gmallocn(numSyms, 8);
i_1 = 0LL;
kk = 0;
do
{
  seg = (JBIG2SymbolDict *)JBIG2Stream::findSegment(this, refSegs[i_1]);
  if ( seg )
  {
    symbolDict = seg;
    v37 = seg→vfptr→getType(seg) ≠ jbig2SegSymbolDict || kk ≥ numSyms;
    if ( !v37 )
    {
      k = 0LL;
      size = symbolDict→size;
      do
      {
        if ( size == k )
          break;
        syms[kk + k] = symbolDict→bitmaps[k];
        ++k;
      }
      while ( numSyms - (unsigned __int64)kk ≠ k );
      kk += k;
    }
  }
  ++i_1;
}
while ( i_1 ≠ nRefSegs );
v40 = syms;
v12 = v86;
000850AC __ZN11JBIG2Stream17readTextRegionSegEjiijPjj:158 (181D710AC)
```

Figure 3. Screenshot of the same function JBIG2Stream::readTextRegionSeg with fixes in place

We can see that Apple adds two new boundary checks (the red box in Figure 3), to avoid overflowing the *syms* buffer.

On the Pegasus spyware exploitation

Disabling ASLR

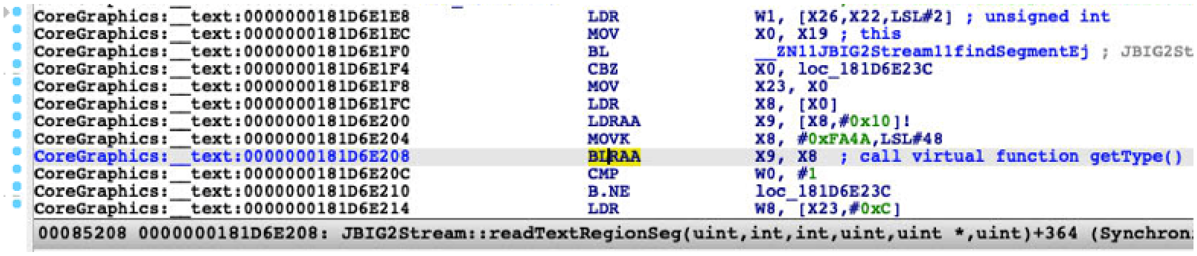
The **dyld_shared_cache** of version iOS 14.6 (18F72) was loaded into IDA Pro for static analysis, after which a surprising result emerged. We were able to go to the addresses on the call stack directly without rebasing the segment.

As deduced from the screenshot in Figure 1 (see box 2), the slide of dyld_shared_cache is **0**. However, in common crash scenarios, these addresses should be in **slide.**

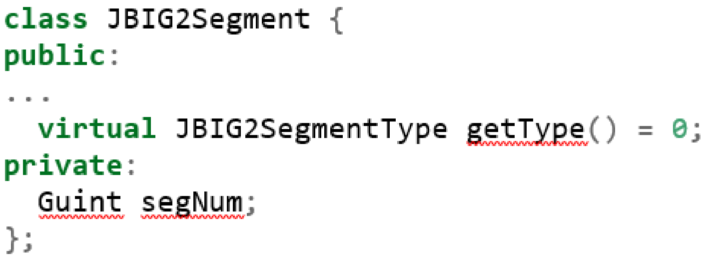
If the screenshot of the original crash log has not been modified, then the conclusion is worrying. It should be noted that Pegasus already disabled Address Space Layout Randomization (ASLR) before its exploitation.

Bypassing PAC

By inspecting the address **0x181d6e20c** from Frame 1 of the call stack trace, we can see that register x0, the return value of function JBIG2Stream::findSegment, is a subclass of JBIG2Segment:

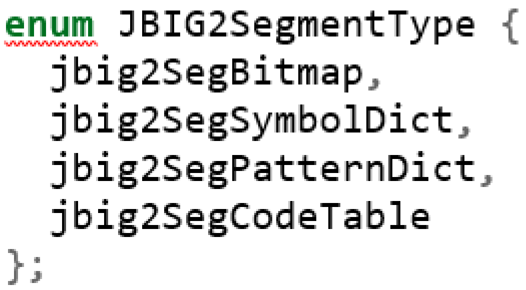


```
CoreGraphics:__text:0000000181D6E1E8                 LDR             W1, [X26,X22,LSL#2] ; unsigned int
CoreGraphics:__text:0000000181D6E1EC                 MOV             X0, X19 ; this
CoreGraphics:__text:0000000181D6E1F0                 BL              __ZN11JBIG2Stream11findSegmentEj ; JBIG2St
CoreGraphics:__text:0000000181D6E1F4                 CBZ             X0, loc_181D6E23C
CoreGraphics:__text:0000000181D6E1F8                 MOV             X23, X0
CoreGraphics:__text:0000000181D6E1FC                 LDR             X8, [X0]
CoreGraphics:__text:0000000181D6E200                 LDRAA           X9, [X8,#0x10]!
CoreGraphics:__text:0000000181D6E204                 MOVK            X8, #0xFA4A,LSL#48
CoreGraphics:__text:0000000181D6E208                 BLRAA           X9, X8  ; call virtual function getType()
CoreGraphics:__text:0000000181D6E20C                 CMP             W0, #1
CoreGraphics:__text:0000000181D6E210                 B.NE            loc_181D6E23C
CoreGraphics:__text:0000000181D6E214                 LDR             W8, [X23,#0xC]
00085208 0000000181D6E208: JBIG2Stream::readTextRegionSeg(uint,int,int,uint,uint *,uint)+364 (Synchron
```



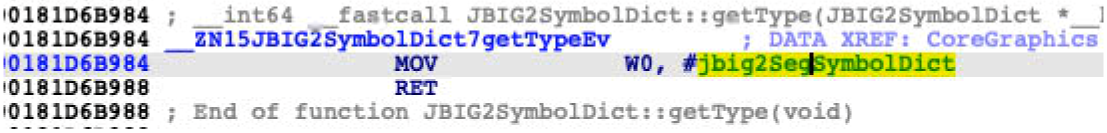
```
class JBIG2Segment {
public:
...
  virtual JBIG2SegmentType getType() = 0;
private:
  Guint segNum;
};
```

There are four kinds of subclasses that override the **getType()** virtual function, but the following code shows that they just return one of the enumerate values:



```
enum JBIG2SegmentType {
  jbig2SegBitmap,
  jbig2SegSymbolDict,
  jbig2SegPatternDict,
  jbig2SegCodeTable
};
```

For example, **JBIG2SymbolDict::getType** just returns **jbig2SegSymbolDict=1:**



```
0181D6B984 ; __int64 __fastcall JBIG2SymbolDict::getType(JBIG2SymbolDict *__
0181D6B984 __ZN15JBIG2SymbolDict7getTypeEv          ; DATA XREF: CoreGraphics
0181D6B984                 MOV             W0, #jbig2SegSymbolDict
0181D6B988                 RET
0181D6B988 ; End of function JBIG2SymbolDict::getType(void)
```

Therefore, the **frame 1** should have called the virtual function **seg->getType()**. But in actuality, it was already subverted to the current function itself **(frame 0)**.

This shows that the virtual functions table of the object **JBIG2Segment** had already been replaced, and the pointer authentication code (PAC) security feature was bypassed. This is significant because the PAC security mechanism was developed to help prevent zero-click hacking. This also shows that the crash point is not the first place of the vulnerability exploitation.

Conclusion and recommendations

From the view of attack technologies used, we can see that Pegasus is quite an advanced threat for iOS users. However, it seems that these attacks are being launched on very specific targets, rather than common users.

The information from the recent Pegasus attack is from the forensic analysis of Citizen Lab and Amnesty Tech, and we have not found Pegasus attack samples that are at large yet. We are actively searching and monitoring for these threats and will continue to share more details as our investigation continues.

Essentially, this attack is a very common file format parsing vulnerability. We previously discovered CVE-2020-9883, a vulnerability similar to ForcedEntry, which could be exploited to do the same as what Pegasus has done here. ForcedEntry's key point is the exploit technology as it is still unknown how it is able to bypass the PAC and disable ASLR.

In the meantime, we strongly recommendupdating your device to iOS 14.8. As stated previously, common iOS users are not the target for attacks using this spyware. However, there are simple security steps that users can take. For example, concerned users can block iMessages from unknown senders, while a more drastic step would be to disable the iMessage function completely in the device's Preferences.