Running iOS in QEMU to an interactive bash shell (1): tutorial

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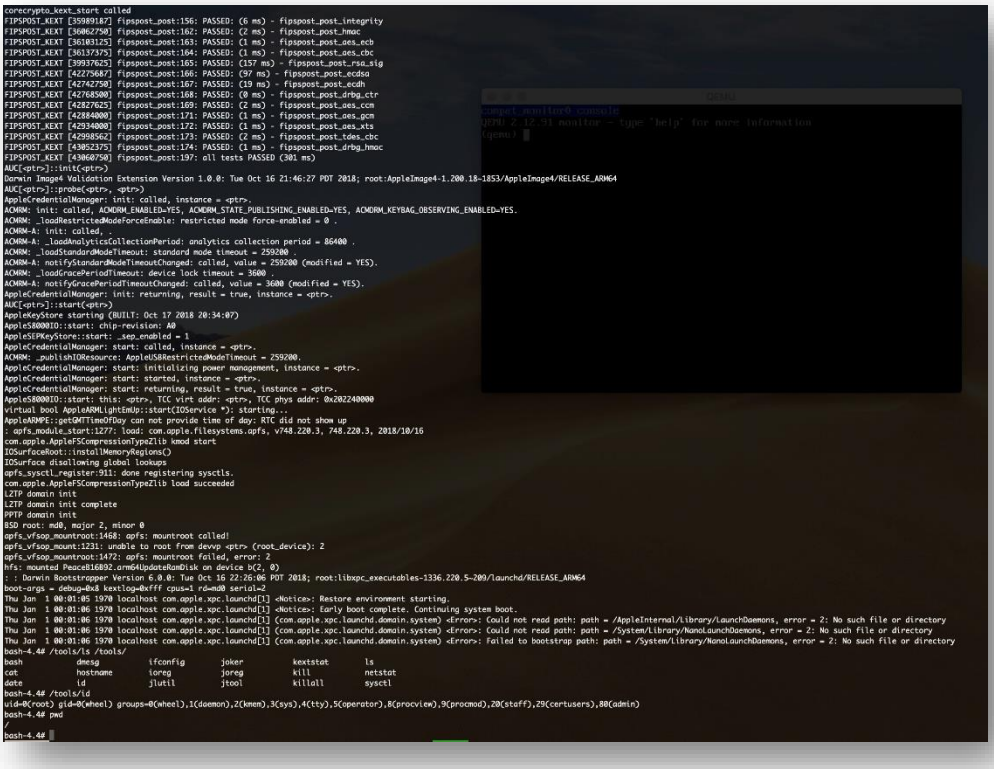
For better reading experience please follow the link to original blog posts (1) (2):

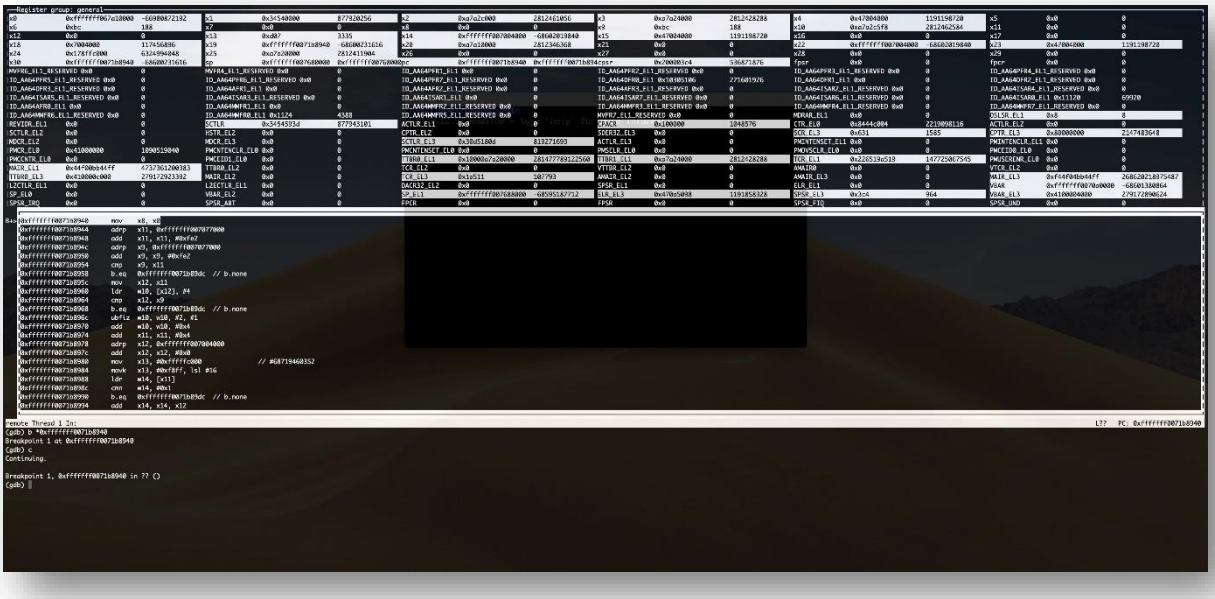
While wanting to do some iOS security research and inspired by the work done by **zhuowei**, I decided to try and get this emulation project further along the boot process. The goal was to get the system to boot without having to patch the kernel beforehand or during the boot process, have new modules that extend QEMU's capabilities to execute arm64 XNU systems and, get an interactive bash shell. This post is the first post in a 2-post series, in which I will present instructions for executing iOS on QEMU and launching an interactive bash shell. In the second post, I will detail some of the research that was required in order to get there. For this project, the iOS version and device that were chosen are iOS 12.1 and iPhone 6s Plus, because this specific iOS 12 image comes with a lot of symbols exported in the kernel image compared to other iOS kernel images that are usually stripped of most symbols. This presented some more challenges, because it is a non-KTRR device that uses a secure monitor image, and that required changes in the stages of the solution already done by zhuowei. Another change is that I wanted this feature to be in external modules that could later be extended and used to create modules for other iOS devices and versions, instead of having the code inside the core QEMU code.

Current Status

The project is now available at **qemu-aleph-git** with the required scripts at **qemu-scripts-aleph-git**. The current status allows booting to user mode with a read only mounted ram disk, to which new executables and launchd items can be added (before boot), and those can use the **dyld cache** from the main disk image copied to the ram disk and communicate with the user via the emulated UART channel. Here is a demonstration of running an interactive bash shell with this project:



This lets you execute whatever user mode process you want as root, with whatever entitlements you choose, and debug the process and/or the kernel with a kernel debugger:



Current Limitations

1. There is a long suspension where nothing happens for a few seconds before mounting the ram disk.
2. It only works with a ram disk image which is mounted as read only, and is limited to 2GB in size.
3. We can only communicate with the guest iOS over UART, and no other communication channels are currently available.
4. No devices emulation: screen, touch, wifi, BT or anything else.
5. Only a single emulated CPU is currently supported.

Tutorial

To start the process we first need to prepare a kernel image, a secure monitor image, a device tree, a static trust cache, and ram disk images. To get the images we first need to get the update file from Apple: **iOS 12.1 update file**. This is actually a zip file which we can extract:

```
Downloads jonathanafek$ unzip iPhone_5.5_12.1_16B92_Restore.ipsw
Archive:  iPhone_5.5_12.1_16B92_Restore.ipsw
   creating: Firmware/
  inflating: Restore.plist
   creating: Firmware/usr/
   creating: Firmware/usr/local/
  inflating: BuildManifest.plist
  inflating: Firmware/Mav10-7.21.00.Release.plist
   creating: Firmware/all_flash/
  inflating: Firmware/all_flash/DeviceTree.n66ap.im4p.plist
  inflating: Firmware/all_flash/LLB.n56.RELEASE.im4p
  inflating: Firmware/all_flash/batterylow1@3x~iphone.im4p
  inflating: Firmware/all_flash/batterycharging0@3x~iphone.im4p
  inflating: Firmware/all_flash/LLB.n66.RELEASE.im4p
  inflating: Firmware/all_flash/sep-firmware.n56.RELEASE.im4p.plist
  inflating: Firmware/all_flash/iBoot.n56.RELEASE.im4p.plist
  inflating: Firmware/all_flash/batteryfull@3x~iphone.im4p
  inflating: Firmware/all_flash/iBoot.n66m.RELEASE.im4p
  inflating: Firmware/all_flash/iBoot.n56.RELEASE.im4p
  inflating: Firmware/all_flash/DeviceTree.n66ap.im4p
  inflating: Firmware/all_flash/sep-firmware.n66m.RELEASE.im4p.plist
  inflating: Firmware/all_flash/applelogo@3x~iphone.im4p
```

```
  inflating: Firmware/all_flash/recoverymode@1920~iphone-lightning.im4p
   creating: Firmware/dfu/
  inflating: Firmware/dfu/iBSS.n56.RELEASE.im4p.plist
  inflating: Firmware/all_flash/glyphplugin@1920~iphone-lightning.im4p
  inflating: Firmware/all_flash/batterylow0@3x~iphone.im4p
  inflating: Firmware/dfu/iBEC.n66m.RELEASE.im4p.plist
  inflating: Firmware/dfu/iBSS.n66.RELEASE.im4p
  inflating: Firmware/048-32459-105.dmg.trustcache
  inflating: Firmware/dfu/iBSS.n66m.RELEASE.im4p
  inflating: Firmware/dfu/iBEC.n56.RELEASE.im4p.plist
  inflating: Firmware/all_flash/sep-firmware.n56.RELEASE.im4p
  inflating: Firmware/Mav13-5.21.00.Release.bbfw
  inflating: Firmware/all_flash/sep-firmware.n66m.RELEASE.im4p
  inflating: Firmware/all_flash/LLB.n66m.RELEASE.im4p.plist
  inflating: Firmware/all_flash/iBoot.n66.RELEASE.im4p.plist
  inflating: Firmware/dfu/iBSS.n56.RELEASE.im4p
  inflating: Firmware/all_flash/DeviceTree.n66map.im4p.plist
  inflating: Firmware/all_flash/DeviceTree.n56ap.im4p.plist
  inflating: Firmware/all_flash/LLB.n66.RELEASE.im4p.plist
   creating: Firmware/AOP/
  inflating: Firmware/AOP/aopfw-s8000aop.im4p
  inflating: Firmware/dfu/iBEC.n56.RELEASE.im4p
  inflating: Firmware/all_flash/LLB.n66m.RELEASE.im4p
  inflating: Firmware/all_flash/iBoot.n66.RELEASE.im4p
  inflating: Firmware/all_flash/sep-firmware.n66.RELEASE.im4p
  inflating: Firmware/048-31952-103.dmg.trustcache
  inflating: Firmware/all_flash/sep-firmware.n66.RELEASE.im4p.plist
  inflating: Firmware/dfu/iBSS.n66.RELEASE.im4p.plist
  inflating: Firmware/all_flash/DeviceTree.n66map.im4p
  inflating: Firmware/dfu/iBSS.n66m.RELEASE.im4p.plist
  inflating: Firmware/all_flash/batterycharging1@3x~iphone.im4p
  inflating: Firmware/all_flash/iBoot.n66m.RELEASE.im4p.plist
  inflating: 048-32651-104.dmg
  inflating: Firmware/all_flash/LLB.n56.RELEASE.im4p.plist
  inflating: Firmware/dfu/iBEC.n66.RELEASE.im4p
  inflating: Firmware/dfu/iBEC.n66.RELEASE.im4p.plist
  inflating: Firmware/dfu/iBEC.n66m.RELEASE.im4p
  inflating: kernelcache.release.iphone7
  inflating: Firmware/048-32651-104.dmg.trustcache
  inflating: Firmware/Mav13-5.21.00.Release.plist
  inflating: Firmware/all_flash/DeviceTree.n56ap.im4p
  inflating: Firmware/Mav10-7.21.00.Release.bbfw
  inflating: 048-32459-105.dmg
  inflating: kernelcache.release.n66
 extracting: 048-31952-103.dmg
```

Next, we need to clone the supporting scripts repository:

```
Downloads jonathanafek$ git clone git@github.com:alephsecurity/xnu-qemu-arm64-scripts.git
Cloning into 'xnu-qemu-arm64-scripts'...
remote: Enumerating objects: 16, done.
remote: Counting objects: 100% (16/16), done.
remote: Compressing objects: 100% (11/11), done.
remote: Total 16 (delta 4), reused 16 (delta 4), pack-reused 0
Receiving objects: 100% (16/16), 5.16 KiB | 5.16 MiB/s, done.
Resolving deltas: 100% (4/4), done.
```

And extract the ASN1 encoded kernel image:

```
Downloads jonathanafek$ python xnu-qemu-arm64-scripts/asn1kerneldecode.py kernelcache.release.n66
kernelcache.release.n66.asn1decoded
```

This decoded image now includes the compressed kernel and the secure monitor image. To extract both of them:

```
Downloads jonathanafek$ python xnu-qemu-arm64-scripts/decompress_lzss.py
kernelcache.release.n66.asn1decoded kernelcache.release.n66.out
Downloads jonathanafek$ python xnu-qemu-arm64-scripts/kernelcompressedextractmonitor.py
kernelcache.release.n66.asn1decoded securemonitor.out
```

Now let's prepare a device tree which we can boot with (more details about the device tree in the second post). First, extract it from the ASN1 encoded file:

```
Downloads jonathanafek$ python xnu-qemu-arm64-scripts/asn1dtredecode.py
Firmware/all_flash/DeviceTree.n66ap.im4p Firmware/all_flash/DeviceTree.n66ap.im4p.out
```

Then, parse it and modify it to make our kernel boot on QEMU:

```
Downloads jonathanafek$ python xnu-qemu-arm64-scripts/read_device_tree.py
Firmware/all_flash/DeviceTree.n66ap.im4p.out Firmware/all_flash/DeviceTree.n66ap.im4p.out.mod
```

Now we have to set up the ram disk. First, ASN1 decode it:

```
Downloads jonathanafek$ python xnu-qemu-arm64-scripts/asn1rdskdecode.py ./048-32651-104.dmg ./048-32651-
104.dmg.out
```

Next, resize it so it has room for the **dynamic loader cache file** (needed by bash and other executables), mount it, and force usage of file permissions on it:

```
Downloads jonathanafek$ hdiutil resize -size 1.5G -imagekey diskimage-class=CRawDiskImage 048-32651-
104.dmg.out
Downloads jonathanafek$ hdiutil attach -imagekey diskimage-class=CRawDiskImage 048-32651-104.dmg.out
Downloads jonathanafek$ sudo diskutil enableownership /Volumes/PeaceB16B92.arm64UpdateRamDisk/
```

Now let's mount the regular update disk image by double clicking on it: `048-31952-103.dmg` Create a directory for the dynamic loader cache in the ram disk, copy the cache from the update image and chown it to root:

```
Downloads jonathanafek$ sudo mkdir -p
/Volumes/PeaceB16B92.arm64UpdateRamDisk/System/Library/Caches/com.apple.dyld/
Downloads jonathanafek$ sudo cp
/Volumes/PeaceB16B92.N56N66OS/System/Library/Caches/com.apple.dyld/dyld_shared_cache_arm64
/Volumes/PeaceB16B92.arm64UpdateRamDisk/System/Library/Caches/com.apple.dyld/
Downloads jonathanafek$ sudo chown root
/Volumes/PeaceB16B92.arm64UpdateRamDisk/System/Library/Caches/com.apple.dyld/dyld_shared_cache_arm64
```

Get precompiled user mode tools for iOS, including bash, from **rootlessJB** and/or **iOSBinaries**. Alternatively, compile your own iOS console binaries as described **here**.

```
Downloads jonathanafek$ git clone https://github.com/jakeajames/rootlessJB
Cloning into 'rootlessJB'...
remote: Enumerating objects: 6, done.
remote: Counting objects: 100% (6/6), done.
remote: Compressing objects: 100% (6/6), done.
remote: Total 253 (delta 2), reused 0 (delta 0), pack-reused 247
Receiving objects: 100% (253/253), 7.83 MiB | 3.03 MiB/s, done.
Resolving deltas: 100% (73/73), done.

Downloads jonathanafek$ cd rootlessJB/rootlessJB/bootstrap/tars/
tars jonathanafek$ tar xvf iosbinpack.tar
tars jonathanafek$ sudo cp -R iosbinpack64 /Volumes/PeaceB16B92.arm64UpdateRamDisk/
tars jonathanafek$ cd -
```

Configure launchd to not execute any services:

```
Downloads jonathanafek$ sudo rm /Volumes/PeaceB16B92.arm64UpdateRamDisk/System/Library/LaunchDaemons/*
```

And now, configure it to launch the interactive bash shell by creating a new file under `/Volumes/PeaceB16B92.arm64UpdateRamDisk/System/Library/LaunchDaemons/com.apple.bash.plist` with the following contents:

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN" "http://www.apple.com/DTDs/PropertyList-1.0.dtd">
<plist version="1.0">
<dict>
        <key>EnablePressuredExit</key>
```

```
        <false/>
        <key>Label</key>
        <string>com.apple.bash</string>
        <key>POSIXSpawnType</key>
        <string>Interactive</string>
        <key>ProgramArguments</key>
        <array>
                <string>/iosbinpack64/bin/bash</string>
        </array>
        <key>RunAtLoad</key>
        <true/>
        <key>StandardErrorPath</key>
        <string>/dev/console</string>
        <key>StandardInPath</key>
        <string>/dev/console</string>
        <key>StandardOutPath</key>
        <string>/dev/console</string>
        <key>Umask</key>
        <integer>0</integer>
        <key>UserName</key>
        <string>root</string>
</dict>
</plist>
```

As a side note, you can always convert the binary plist files that you find natively in iOS images to text xml format and back to binary format with:

```
Downloads jonathanafek$ plutil -convert xml1 file.plist
Downloads jonathanafek$ vim file.plist
Downloads jonathanafek$ plutil -convert binary1 file.plist
```

For launch daemon, iOS accepts both xml and binary plist files.

Since the new binaries are signed, but not by Apple, they need to be trusted by the static trust cache that we will create. To do this, we need to get **jtool** (also available via **Homebrew**: `brew cask install jtool`). Once we have the tool, we have to run it on every binary we wish to be trusted, extract the first 40 characters of its CDHash, and put it in a new file named `tchashes`. A sample execution of jtool looks like this:

```
Downloads jonathanafek$ jtool --sig --ent /Volumes/PeaceB16B92.arm64UpdateRamDisk/iosbinpack64/bin/bash
Blob at offset: 1308032 (10912 bytes) is an embedded signature
Code Directory (10566 bytes)
                Version:     20001
                Flags:       none
                CodeLimit:   0x13f580
                Identifier:
/Users/jakejames/Desktop/jelbreks/multi_path/multi_path/iosbinpack64/bin/bash (0x58)
                CDHash:      7ad4d4c517938b6fdc0f5241cd300d17fbb52418b1a188e357148f8369bacad1 (computed)
                # of Hashes: 320 code + 5 special
                Hashes @326 size: 32 Type: SHA-256
 Empty requirement set (12 bytes)
Entitlements (279 bytes) :
--
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN" "http://www.apple.com/DTDs/PropertyList-1.0.dtd">
<plist version="1.0">
<dict>
    <key>platform-application</key>
    <true/>
    <key>com.apple.private.security.container-required</key>
    <false/>
</dict>
</plist>
```

In the above case, we need to write down `7ad4d4c517938b6fdc0f5241cd300d17fbb52418` in `tchashes`. For convenience, the following command will extract the correct part of the hash from each of the binaries we put in the image:

```
Downloads jonathanafek$ for filename in $(find /Volumes/PeaceB16B92.arm64UpdateRamDisk/iosbinpack64 -type
f); do jtool --sig --ent $filename 2&>/dev/null; done | grep CDHash | cut -d' ' -f6 | cut -c 1-40
ebe945ddbb4dbeb1ee9624e6ba1932d2ec61cfde
7ad4d4c517938b6fdc0f5241cd300d17fbb52418
0cf1b00e3bf76ab51c56da7ca888e89359f1d1c4
c9c1e21c3f3593c99f4e7c91c64d7f3106ad29ce
522dda7f40fe6aa6e2038bc66c9cb31660a43429
dc040d340f1fcfb493394e77d9944aa164e23ca3
f975cd0eec230299d1b8d9b0e3b54ae7cf660d92
728be7f7a78f400742e887f7ac93306145f822c0
4f4ca5aa3e506d145f344d59504630b85ddefffc
0d274c72cefbff705db0ed0fda29fb6f4cacf4c9
ebcf9073fd59db7c59a5212b0824faf1d7b30e39
cf784ea216e6b49f66a3cc81aeceaf7ac39b71d7
9d625c7eaadc8fd3eb57d9facca294b1a5afab8a
90c02c153e636cac74ca09e7e3dc89c0508a1393
59cba1c5ce169d4cd454d43e3a3c6fa824cf2764
9ff1194d135e979a632033ec2df63ba0cfe4682a
d11b49576e0f6645c4c9f234497f51219173dce8
7a01f3e7bcda18b26297c3936c9e256ddf8f9fe3
b7fd47df9b6652f2810cc789d5903a082af2570d
68a32f0a35bbb23f4f272ca99186521618c08d21
e04fa65a33c4b69d2338688ee72ea13d624a4255
b400373e16a7f82fa56d318038ec7b4b28e2593f
65859385e11b910de3841e53a833ab4c4b855282
2eae1b42c4f6bb95e3226aff8cb93a539c0a6263
c305e094747ba274f37e3063b826a5e41e5e2549
41620d4632bf6f071388033f8cf267123df16489
3bf1f6c49e3bcd775041864085893bf9b1ab3870
bb2d9c166635fc693e99355e84984aa61692c6f3
3bb79fd3568c3620a2bd7bad004ab759bec4e331
7c60ae6060d7bf2772c6b4b0c04b605c4e62a7a7
b904a692d548c3323621c17212121aca0c733088
6fe1d88bcbdd97d273533d695c04279f8ddf5e32
4165a869f1b35bdff90b74116499c1c210f27ddb
414ebc5e48c94d60b2018e4c83a323426bc0ac74
62b2b303c31e5fc9d5210b736d8d632eee28d24f
871e0ea84b71cd01e45e261542e9b2dd08fb81ab
0912c647e222bd04f05b837a8286519bd8ae2393
bd6d7d7f51b639da99e0581096534273b4f040ed
27ed9a3b21392bc459619293a6b36fe2c3b8ddac
e92565cbfdb0bd41d069384689ffae715e61b216
164fc2d96f9decd643ac33fc279b2078e51f5c88
3e0529b705d666af4f25c8c18fc7992f6934cf6f
176f273cb276085052519054d042508dc8d562b4
18762f5c54d935759f02248b032576bdc93be260
22d2f02d3be49da4819534553ad5ac37c0ace28c
e76bf6e8e84b656ee61b1ff10b38eab23607ae82
84bbc455477d6737f738b649c5afd3d4a069abee
57fe14db863b48f19cdec3c884c5dfad1bff6a12
e6ee59194bd768c3e3cc140009b6a729c7700a11
f1c25d5ac4e3924deaa3418a9ba309e15c09f502
e962bfddead7da46f23b6f4dc448df085e946940
26d34ca63bc69c8e81c15672258f3b8cbaf4ba4c
7fc69d2fc1f57ca555b07d6de51c82f74915c6bd
85f3c5263835d90b776886f92e8536ceb2f46036
0f1214d8a6138f170c2654a6f81c40586fbebaac
dc995e91bc0b67c52b969c91c1d68b09bbf94ec2
5d46a9681b4a3cc84a69083288e76aa969ec3a43
3c0db01f7aaf0a5b935dfcc51f6b2534013795ad
8422f07e41b2951e4138b88e013eab5773ae52f7
f9c4cca6b141064b7ae97131ff3969386d624718
259733b48f2f4fa88ba4f2e5f519bd40a6a3750d
8e06a919d28c3c0376b1207981d70b3bda99b6bc
68cd528c435b417c6f0022a132d459fc25d6e039
d176fa07a7ea5bfe88b9d2d703f3c65b4298b2e6
30f3d6e1d00614a0a9e8e8a3d4f31b8c68066091
698587325d71b9d51c22ae26e0c2de8ca70f6dc8
ccf27e4d7b62f1f839cfb9d70340efd1a2b77532
928a02f17cef27a5528ae055a467a18528f2aff5
4d24ada94fa70d27a684867541266f264261ce36
ab3e7808ee41f4536ece24091d1f166c5f0e9b63
e492332b87adc07406503ca857b6f3e2a3f0625d
```

d121b2de1778563183087238c4675316176f159d
12fe31a31132f7c0bab2857c0b3ac3c71cdb9dae
d6bc5428d129dd76695519b9b7f201daa9eb87de
685660477e1f851a90ace593670e5288d2168a24
94a493c2909f8b563e0076956bec7a1941455ed3
13c2e0251ba0469f2e1ec3d61da61c664822c791
e6332fc916f9b06f4987ecbaa23bbf4fa374c68f
1f6f82bcc994a4559d891d3a9e187268632da0b9
f864bd7891b9a0970f3ea05f13f7769289e62803
ba84abbeb198b91cbefec678096c8fd17387657d
d537ff6ab7d2bf38b0f18e964ad3525f2761b535
1acf88c15c1a08b3387b62969a34a95196632932
345d3b92a7f8a11c0872ec9ec439b5a6a2ada104
067b54e23cd6bc5b007113929dc4e2d2868228b6
11794790670afe1b651ed838362bb955e1503706
973674b1cf5f51119fa655ad2393df3dee9f44cc
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41c139fa86a3e67d49566d11a7d1d14fe375b564
b52692291cc4d9c9f09bc0ba650904d889674218
65713ffe304718b3b6a8b710b7db0467e52ca5aa
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cb08034d4647f2cc921b62ea648a76b5635fcc13
a9fc0262a6925ec1c18b0bf627c04c60fa5b5ecf
3736f93cc5f88d138f58016fdce2c3c3af979c43
183cd29cea8ba53f6e5d28d87e37b0cc603106c6
cd0281c8fa808c3f0f0b74db8c262a6997f52d03
e3016edd7acfa4d24d2eacec4918f3018d9d2449
ddd943f2a4192b3eabbb0580c64ff23ea7c31387
e3285e8252c44404675876ae0104f02cdc36574c
41c139fa86a3e67d49566d11a7d1d14fe375b564
b52692291cc4d9c9f09bc0ba650904d889674218
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73657606cb288c85f909da3ec4b92d7f8819ae79
918a3cf30a9c9d6ee2872c670421e528883221ae
dcf5eeaefc7ec3e7a0166676f6ee564761f78bc6
994ada738587ba622bfe36b987e9bfa246ff3858
d6f9c9107eb6dc237040d18debd4244c3e4c1320
f0e0c6a7e5c4545bac0d9ebf7811997f5c7076ad
38a790a40cca659fb8a0942ba140aa07309a17aa
070472831955773d78c9f33aff696c0a67b06bda
4ca98aac5e3b9174beaa2e4175e33fdcddee6866
44bd100692ded0637a763d324490db7435216f8c
a28a3640920332306045fd288cb503aedbdd072
bbbe8ea84bdc4f3004398895ee58979a55b744c0
a09ee84582821397aa68d81350ed07b9902d09cb
8f8f612996a91e4fb26deacf2c88b8eda42da7a2
504d7c5b0a0e72a3dc5177ec571f591f3dae2ade
c0b0dea10a283f9d904bad52c53e20b129ae278c
5b0894327103472 42dfb6ccfdfea6fc523d9fe60
40af3f97ae3dc743f638c82f4ed78bce13687c83
7b3d463b62ce306c86d88e7ec0e52964c073c223
580eb965a96782a1fd005bd8a27100abca8430e1
330efc667ea608575d863b10a41a73e49f31d1c6
5827c3ef16144d298fd04342fc7041dd3b20d35e
f9bce1706a98b2492750aaa977806549f7d010f7
eeeaeb163512c31c6462f41c6bc3b6a228224bee
2ae51c0fac8b5656ec91693e7f9846a9c4af8069
92c89c47a734cad1a36756155ea3043e406ae565
be0e71c532033d79d519951f0450cdca44f835c3
feff0ce891c71c69f581b19a70b30ffd4c407205
8b0f3f0c620f008d4b85b7aff69933d3aae6098e
296124c76c9f0201480678a012a1df2e6835c521
a1876907ad59843dc5ed1390c78c88698504b9d8
e3190fc3865f02092ab6725b25c485ea5c143e3b
8bbd9944ebc23ce2001a4837732ba082c040d0f4
6408ed0d9df71e7bdde2faa985e5c07911a43503
ca2b47f582135e00a9720215cc09881dd9b49b85
e7e478f2e7f9715d9b540c9f8d12993c83ece0c1
25ac265b51c484680decaf8903b0b3c12c5ff81c
5a37eb16c2eaba8dcb55d9edb3ba98a0ee09afd0

The above output should be saved in `tchashes`, and then we can create the static trust cache blob:

```
Downloads jonathanafek$ python xnu-qemu-arm64-scripts/create_trustcache.py tchashes static_tc
```

Now is a good time to unmount both volumes. We now have all the images and files prepared. Let's get the modified QEMU code (more detailed info on the work done in QEMU will be in the second post in the series):

```
Downloads jonathanafek$ git clone git@github.com:alephsecurity/xnu-qemu-arm64.git
Cloning into 'xnu-qemu-arm64'...
remote: Enumerating objects: 377340, done.
remote: Total 377340 (delta 0), reused 0 (delta 0), pack-reused 377340
Receiving objects: 100% (377340/377340), 187.68 MiB | 5.32 MiB/s, done.
Resolving deltas: 100% (304400/304400), done.
Checking out files: 100% (6324/6324), done.
```

and compile it:

```
Downloads jonathanafek$ cd xnu-qemu-arm64
xnu-qemu-arm64 jonathanafek$ ./configure --target-list=aarch64-softmmu --disable-capstone
Install prefix    /usr/local
BIOS directory    /usr/local/share/qemu
firmware path     /usr/local/share/qemu-firmware
binary directory  /usr/local/bin
library directory /usr/local/lib
module directory  /usr/local/lib/qemu
libexec directory /usr/local/libexec
include directory /usr/local/include
config directory  /usr/local/etc
local state directory   /usr/local/var
Manual directory  /usr/local/share/man
ELF interp prefix /usr/gnemul/qemu-%M
Source path       /Users/jonathanafek/Downloads/xnu-qemu-arm64
GIT binary        git
GIT submodules    ui/keycodemapdb dtc
C compiler        cc
Host C compiler   cc
C++ compiler      c++
Objective-C compiler clang
ARFLAGS           rv
CFLAGS            -O2 -g
QEMU_CFLAGS       -I/opt/local/include/pixman-1 -I$(SRC_PATH)/dtc/libfdt -D_REENTRANT -
I/opt/local/include/glib-2.0 -I/opt/local/lib/glib-2.0/include -I/opt/local/include -m64 -mcx16 -
DOS_OBJECT_USE_OBJC=0 -arch x86_64 -D_GNU_SOURCE -D_FILE_OFFSET_BITS=64 -D_LARGEFILE_SOURCE -Wstrict-
prototypes -Wredundant-decls -Wall -Wundef -Wwrite-strings -Wmissing-prototypes -fno-strict-aliasing -
fno-common -fwrapv  -Wno-error=address-of-packed-member -Wno-string-plus-int -Wno-initializer-overrides -
Wexpansion-to-defined -Wendif-labels -Wno-shift-negative-value -Wno-missing-include-dirs -Wempty-body -
Wnested-externs -Wformat-security -Wformat-y2k -Winit-self -Wignored-qualifiers -Wold-style-definition -
Wtype-limits -fstack-protector-strong -I/opt/local/include -I/opt/local/include/p11-kit-1 -
I/opt/local/include  -I/opt/local/include/libpng16 -I/opt/local/include
LDFLAGS           -framework Hypervisor -m64 -framework CoreFoundation -framework IOKit -arch x86_64 -g
QEMU_LDFLAGS      -L$(BUILD_DIR)/dtc/libfdt
make              make
install           install
python            python -B
smbd              /usr/sbin/smbd
module support    no
host CPU          x86_64
host big endian   no
target list       aarch64-softmmu
gprof enabled     no
sparse enabled    no
strip binaries    yes
profiler          no
static build      no
Cocoa support     yes
SDL support       no
GTK support       no
GTK GL support    no
VTE support       no
```

```
TLS priority      NORMAL
GNUTLS support    yes
GNUTLS rnd        yes
libgcrypt         no
libgcrypt kdf     no
nettle            yes (3.4.1)
nettle kdf        yes
libtasn1          yes
curses support    yes
virgl support     no
curl support      yes
mingw32 support   no
Audio drivers     coreaudio
Block whitelist (rw)
Block whitelist (ro)
VirtFS support    no
Multipath support no
VNC support       yes
VNC SASL support  yes
VNC JPEG support  no
VNC PNG support   yes
xen support       no
brlapi support    no
bluez  support    no
Documentation     yes
PIE               no
vde support       no
netmap support    no
Linux AIO support no
ATTR/XATTR support no
Install blobs     yes
KVM support       no
HAX support       yes
HVF support       yes
WHPX support      no
TCG support       yes
TCG debug enabled no
TCG interpreter   no
malloc trim support no
RDMA support      no
fdt support       git
membarrier        no
preadv support    no
fdatasync         no
madvise           yes
posix_madvise     yes
posix_memalign    yes
libcap-ng support no
vhost-net support no
vhost-crypto support no
vhost-scsi support no
vhost-vsock support no
vhost-user support yes
Trace backends    log
spice support     no
rbd support       no
xfsctl support    no
smartcard support no
libusb            no
usb net redir     no
OpenGL support    no
OpenGL dmabufs    no
libiscsi support  no
libnfs support    no
build guest agent yes
QGA VSS support   no
QGA w32 disk info no
QGA MSI support   no
seccomp support   no
coroutine backend sigaltstack
coroutine pool    yes
debug stack usage no
mutex debugging   no
```

```
crypto afalg      no
GlusterFS support no
gcov              gcov
gcov enabled      no
TPM support       yes
libssh2 support   no
TPM passthrough   no
TPM emulator      yes
QOM debugging     yes
Live block migration yes
lzo support       no
snappy support    no
bzip2 support     yes
NUMA host support no
libxml2           yes
tcmalloc support  no
jemalloc support  no
avx2 optimization no
replication support yes
VxHS block device no
capstone          no
docker            no

xnu-qemu-arm64 jonathanafek$ make -j16
xnu-qemu-arm64 jonathanafek$ cd -
```

And all there's left to do is execute:

```
Downloads jonathanafek$ ./xnu-qemu-arm64/aarch64-softmmu/qemu-system-aarch64 -M iPhone6splus-n66-
s8000,kernel-filename=kernelcache.release.n66.out,dtb-
filename=Firmware/all_flash/DeviceTree.n66ap.im4p.out.mod,secmon-filename=securemonitor.out,ramdisk-
filename=048-32651-104.dmg.out,tc-filename=static_tc,kern-cmd-args="debug=0x8 kextlog=0xfff cpus=1 rd=md0
serial=2" -cpu max -m 6G -serial mon:stdio
iBoot version:
corecrypto_kext_start called
FIPSPOST_KEXT [38130750] fipspost_post:156: PASSED: (6 ms) - fipspost_post_integrity
FIPSPOST_KEXT [38201250] fipspost_post:162: PASSED: (2 ms) - fipspost_post_hmac
FIPSPOST_KEXT [38233562] fipspost_post:163: PASSED: (0 ms) - fipspost_post_aes_ecb
FIPSPOST_KEXT [38275375] fipspost_post:164: PASSED: (1 ms) - fipspost_post_aes_cbc
FIPSPOST_KEXT [41967250] fipspost_post:165: PASSED: (153 ms) - fipspost_post_rsa_sig
FIPSPOST_KEXT [44373250] fipspost_post:166: PASSED: (99 ms) - fipspost_post_ecdsa
FIPSPOST_KEXT [44832437] fipspost_post:167: PASSED: (18 ms) - fipspost_post_ecdh
FIPSPOST_KEXT [44861312] fipspost_post:168: PASSED: (0 ms) - fipspost_post_drbg_ctr
FIPSPOST_KEXT [44922625] fipspost_post:169: PASSED: (2 ms) - fipspost_post_aes_ccm
FIPSPOST_KEXT [44994250] fipspost_post:171: PASSED: (2 ms) - fipspost_post_aes_gcm
FIPSPOST_KEXT [45042125] fipspost_post:172: PASSED: (1 ms) - fipspost_post_aes_xts
FIPSPOST_KEXT [45109687] fipspost_post:173: PASSED: (2 ms) - fipspost_post_tdes_cbc
FIPSPOST_KEXT [45167062] fipspost_post:174: PASSED: (1 ms) - fipspost_post_drbg_hmac
FIPSPOST_KEXT [45178250] fipspost_post:197: all tests PASSED (300 ms)
Darwin Image4 Validation Extension Version 1.0.0: Tue Oct 16 21:46:27 PDT 2018; root:AppleImage4-
1.200.18~1853/AppleImage4/RELEASE_ARM64
AppleS8000IO::start: chip-revision: A0
AppleS8000IO::start: this: <ptr>, TCC virt addr: <ptr>, TCC phys addr: 0x202240000
AUC[<ptr>]::init(<ptr>)
AUC[<ptr>]::probe(<ptr>, <ptr>)
AppleCredentialManager: init: called, instance = <ptr>.
ACMRM: init: called, ACMDRM_ENABLED=YES, ACMDRM_STATE_PUBLISHING_ENABLED=YES,
ACMDRM_KEYBAG_OBSERVING_ENABLED=YES.
ACMRM: _loadRestrictedModeForceEnable: restricted mode force-enabled = 0 .
ACMRM-A: init: called, .
ACMRM-A: _loadAnalyticsCollectionPeriod: analytics collection period = 86400 .
ACMRM: _loadStandardModeTimeout: standard mode timeout = 259200 .
ACMRM-A: notifyStandardModeTimeoutChanged: called, value = 259200 (modified = YES).
ACMRM: _loadGracePeriodTimeout: device lock timeout = 3600 .
ACMRM-A: notifyGracePeriodTimeoutChanged: called, value = 3600 (modified = YES).
AppleCredentialManager: init: returning, result = true, instance = <ptr>.
AUC[<ptr>]::start(<ptr>)
virtual bool AppleARMLightEmUp::start(IOService *): starting...
AppleKeyStore starting (BUILT: Oct 17 2018 20:34:07)
AppleSEPKeyStore::start: _sep_enabled = 1
AppleCredentialManager: start: called, instance = <ptr>.
ACMRM: _publishIOResource: AppleUSBRestrictedModeTimeout = 259200.
```

```
AppleCredentialManager: start: initializing power management, instance = <ptr>.
AppleCredentialManager: start: started, instance = <ptr>.
AppleCredentialManager: start: returning, result = true, instance = <ptr>.
AppleARMPE::getGMTTimeOfDay can not provide time of day: RTC did not show up
: apfs_module_start:1277: load: com.apple.filesystems.apfs, v748.220.3, 748.220.3, 2018/10/16
com.apple.AppleFSCompressionTypeZlib kmod start
IOSurfaceRoot::installMemoryRegions()
IOSurface disallowing global lookups
apfs_sysctl_register:911: done registering sysctls.
com.apple.AppleFSCompressionTypeZlib load succeeded
L2TP domain init
L2TP domain init complete
PPTP domain init
BSD root: md0, major 2, minor 0
apfs_vfsop_mountroot:1468: apfs: mountroot called!
apfs_vfsop_mount:1231: unable to root from devvp <ptr> (root_device): 2
apfs_vfsop_mountroot:1472: apfs: mountroot failed, error: 2
hfs: mounted PeaceB16B92.arm64UpdateRamDisk on device b(2, 0)
: : Darwin Bootstrapper Version 6.0.0: Tue Oct 16 22:26:06 PDT 2018; root:libxpc_executables-
1336.220.5~209/launchd/RELEASE_ARM64
boot-args = debug=0x8 kextlog=0xfff cpus=1 rd=md0 serial=2
Thu Jan  1 00:01:05 1970 localhost com.apple.xpc.launchd[1] <Notice>: Restore environment starting.
Thu Jan  1 00:01:05 1970 localhost com.apple.xpc.launchd[1] <Notice>: Early boot complete. Continuing
system boot.
Thu Jan  1 00:01:06 1970 localhost com.apple.xpc.launchd[1] (com.apple.xpc.launchd.domain.system)
<Error>: Could not read path: path = /AppleInternal/Library/LaunchDaemons, error = 2: No such file or
directory
Thu Jan  1 00:01:06 1970 localhost com.apple.xpc.launchd[1] (com.apple.xpc.launchd.domain.system)
<Error>: Could not read path: path = /System/Library/NanoLaunchDaemons, error = 2: No such file or
directory
Thu Jan  1 00:01:06 1970 localhost com.apple.xpc.launchd[1] (com.apple.xpc.launchd.domain.system)
<Error>: Failed to bootstrap path: path = /System/Library/NanoLaunchDaemons, error = 2: No such file or
directory
bash-4.4# export
PATH=$PATH:/iosbinpack64/usr/bin:/iosbinpack64/bin:/iosbinpack64/usr/sbin:/iosbinpack64/sbin
bash-4.4# id
uid=0(root) gid=0(wheel)
groups=0(wheel),1(daemon),2(kmem),3(sys),4(tty),5(operator),8(procview),9(procmod),20(staff),29(certusers
),80(admin)
bash-4.4# pwd
/
bash-4.4# ls -la
total 18
drwxr-xr-x  17 root    wheel  748 Jun 10  2019 .
drwxr-xr-x  17 root    wheel  748 Jun 10  2019 ..
-rw-r--r--   1 root    wheel    0 Oct 20  2018 .Trashes
drwx------   2 mobile  staff  170 Jun 10  2019 .fseventsd
drwxr-xr-x   4 root    wheel  136 Oct 20  2018 System
drwxr-xr-x   2 root    wheel  272 Oct 20  2018 bin
dr-xr-xr-x   3 root    wheel  660 Jan  1 00:01 dev
lrwxr-xr-x   1 root    wheel   11 Oct 20  2018 etc -> private/etc
drwxr-xr-x   7 root    wheel  374 Jun 10  2019 iosbinpack64
drwxr-xr-x   2 root    wheel   68 Oct 20  2018 mnt1
drwxr-xr-x   2 root    wheel   68 Oct 20  2018 mnt2
drwxr-xr-x   2 root    wheel   68 Oct 20  2018 mnt3
drwxr-xr-x   2 root    wheel   68 Oct 20  2018 mnt4
drwxr-xr-x   2 root    wheel   68 Oct 20  2018 mnt5
drwxr-xr-x   2 root    wheel   68 Oct 20  2018 mnt6
drwxr-xr-x   2 root    wheel   68 Oct 20  2018 mnt7
drwxr-xr-x   4 root    wheel  136 Oct 20  2018 private
drwxr-xr-x   2 root    wheel  510 Oct 20  2018 sbin
drwxr-xr-x   9 root    wheel  306 Oct 20  2018 usr
lrwxr-xr-x   1 root    admin   11 Oct 20  2018 var -> private/var
bash-4.4#
```

And we have an interactive bash shell! :)

Note that the last flag (`-serial mon:stdio`) will forward all shell combinations (such as `Ctrl`+`C`) to the shell. To shut down QEMU, close its (empty) window.

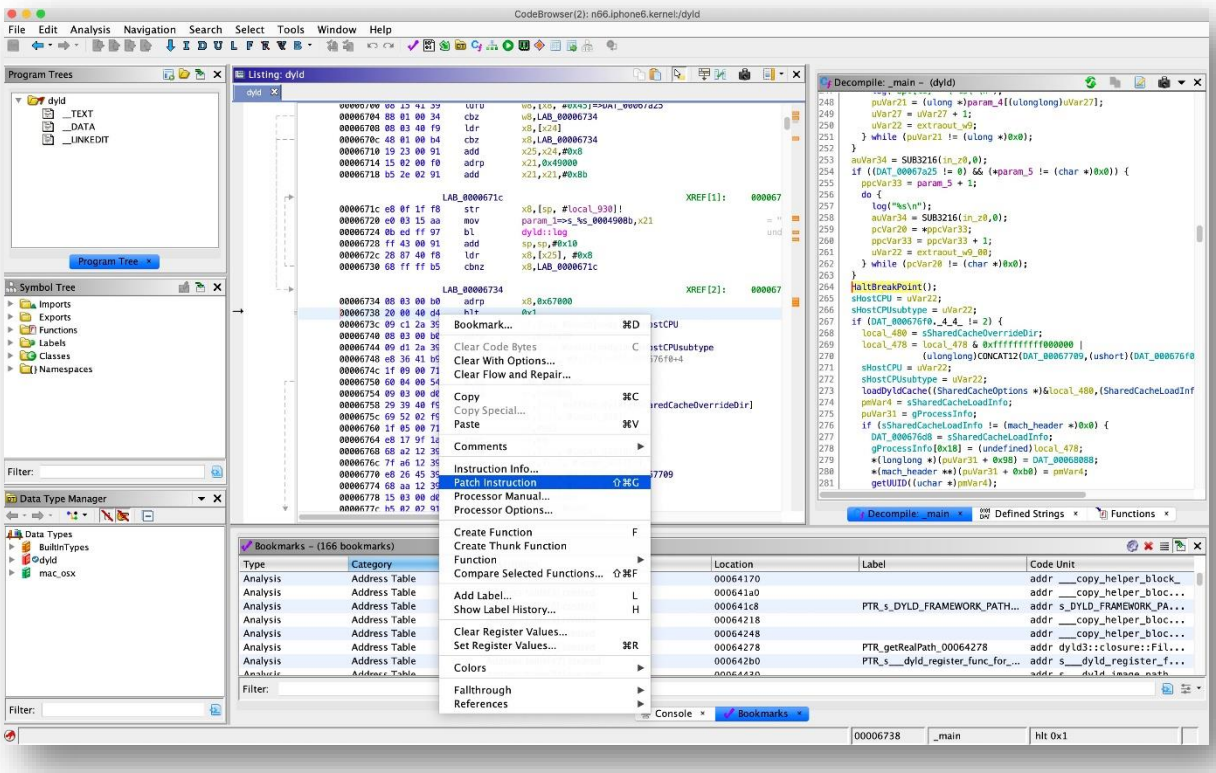
To get a kernel debugger, `-S -s` should be added to the QEMU command line, and then it's possible to execute `target remote :1234` in a gdb console which supports this architecture. More details on how to get this gdb and perform this can be found in **here**. You can also get the relevant gdb on OSX with **mac ports**, while adding the `multiarch` and `python27` options to the gdb port.

Future Improvements

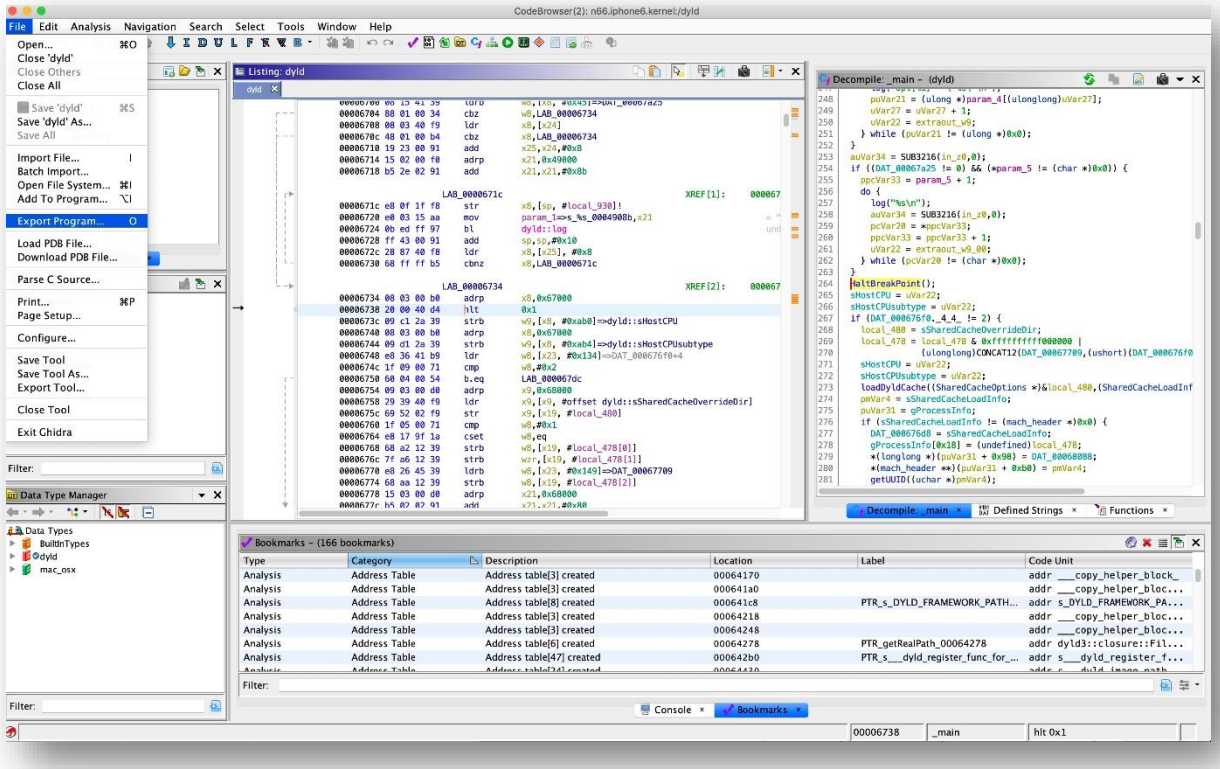
1. Make this boot much faster, without a long suspension before mounting the ram disk.
2. Add support to emulate the iOS as a USB device and communicate over usbmuxd. This will enable us to connect over SSH and therefore copy files using scp, have a more robust terminal, conduct security research for network protocols, use **gdbserver** to debug user mode applications and more.
3. Add support for emulated physical storage to work with a r/w mounted disk, that won't be a ram disk and will not be limited to 2GB.
4. Add support for devices such as screen, touch, wifi, BT, etc…
5. Add support for more iDevices and iOS versions.

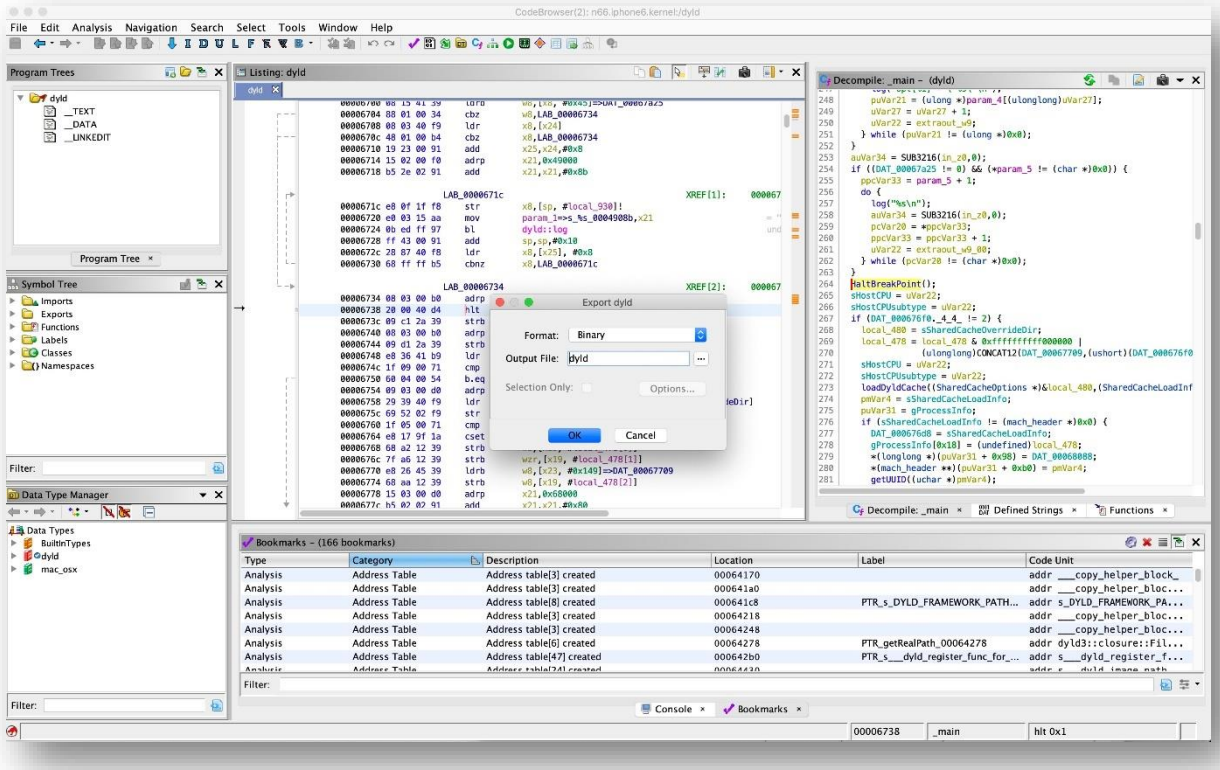
Fun Feature

User applications get loaded at different addresses every boot because of ASLR, and can share virtual addresses with one another, so using a regular breakpoint on a static virtual address in gdb can be challenging, when debugging user mode applications. Therefore, I added another fun feature to help debug user mode applications in this kernel debugger. When QEMU encounters the HLT aarch64 instruction, it breaks in gdb just as if it was a gdb breakpoint, so all you have to do to debug user mode applications in the kernel debugger is to patch the application with an HLT instruction, using ghidra,



for example:



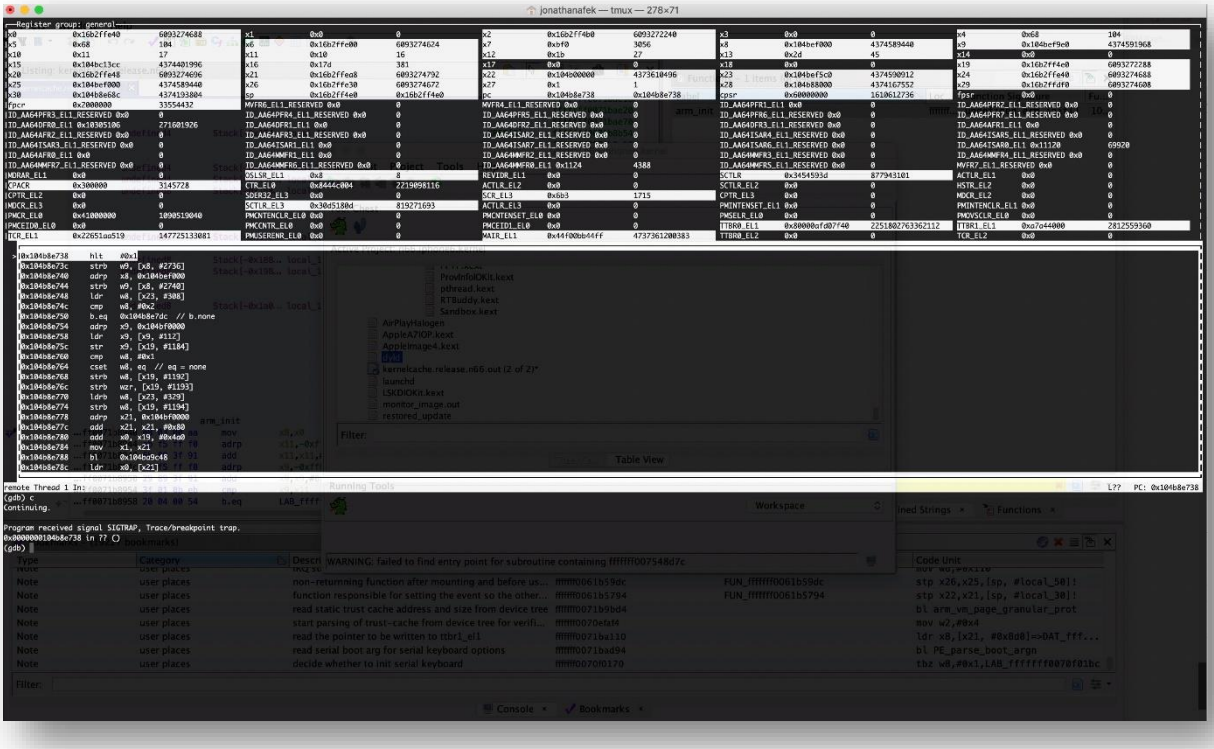


and then sign it using jtool with any required entitlements:

```
Downloads jonathanafek$ ./jtool/jtool --sign --ent ent.xml --inplace bin
```

After that, you need to add the new CDHash to the `tchashes` file, and recreate the static trust cache.

Following that, gdb will break when it encounters the HLT instruction in the user mode application so we can debug the application in the kernel debugger:



Running iOS in QEMU to an interactive bash shell (2): research

By Jonathan Afek (@JonathanAfek)

June 25, 2019

This is the second post in a 2-post series about the work I did to boot a non-patched iOS 12.1 kernel on QEMU emulating iPhone 6s plus and getting an interactive bash shell on the emulated iPhone. To see the code and the explanation on how to use it, please refer to the **first post**. In this post, I will present some of the research that was done in order to make this happen. This research was based on the work done by **zhuowei** as a starting point. Based on the work done by zhuowei, I already had a way to boot an iOS kernel of a slightly different version on a different iPhone without a secure monitor, while patching the kernel at runtime to make it boot, running the launchd services that pre-existed on the ramdisk image and without interactive I/O. In this post I will present:

1. How the code was inserted in the QEMU project as a new machine type.
2. How the kernel was booted without patching the kernel either at runtime or beforehand.
3. How the secure monitor image was loaded and executed in EL3.
4. How a new static trust cache was added so self signed executables could be executed.
5. How a new launchd item was added for executing an interactive shell instead of the existing services on the ramdisk.
6. How full serial I/O was established.

The project is now available at **qemu-aleph-git** with the required scripts at **qemu-scripts-aleph-git**.

QEMU code

In order to be able to later rebase the code on more recent versions of QEMU and to add support for other iDevices and iOS versions, I moved all the QEMU code changes into new modules. I now have the module `hw/arm/n66_iphone6splus.c` that is the main module for the iPhone 6s plus (n66ap) iDevice in QEMU that is responsible for:

1. Define a new machine type.
2. Define the memory layout of the UART memory mapped I/O, the loaded kernel, secure monitor, boot args, device tree, trust cache in different exception levels' memory.
3. Define the iDevice's proprietary registers (currently do nothing and just operate as general purpose registers).
4. Define the machine's capabilities and properties like having EL3 support and start execution in it at the secure monitor entry point.
5. Connect the builtin timer interrupt to FIQ.
6. Get command line parameters for defining the files for: kernel image, secure monitor image, device tree, ramdisk, static trust cache, kernel boot args.

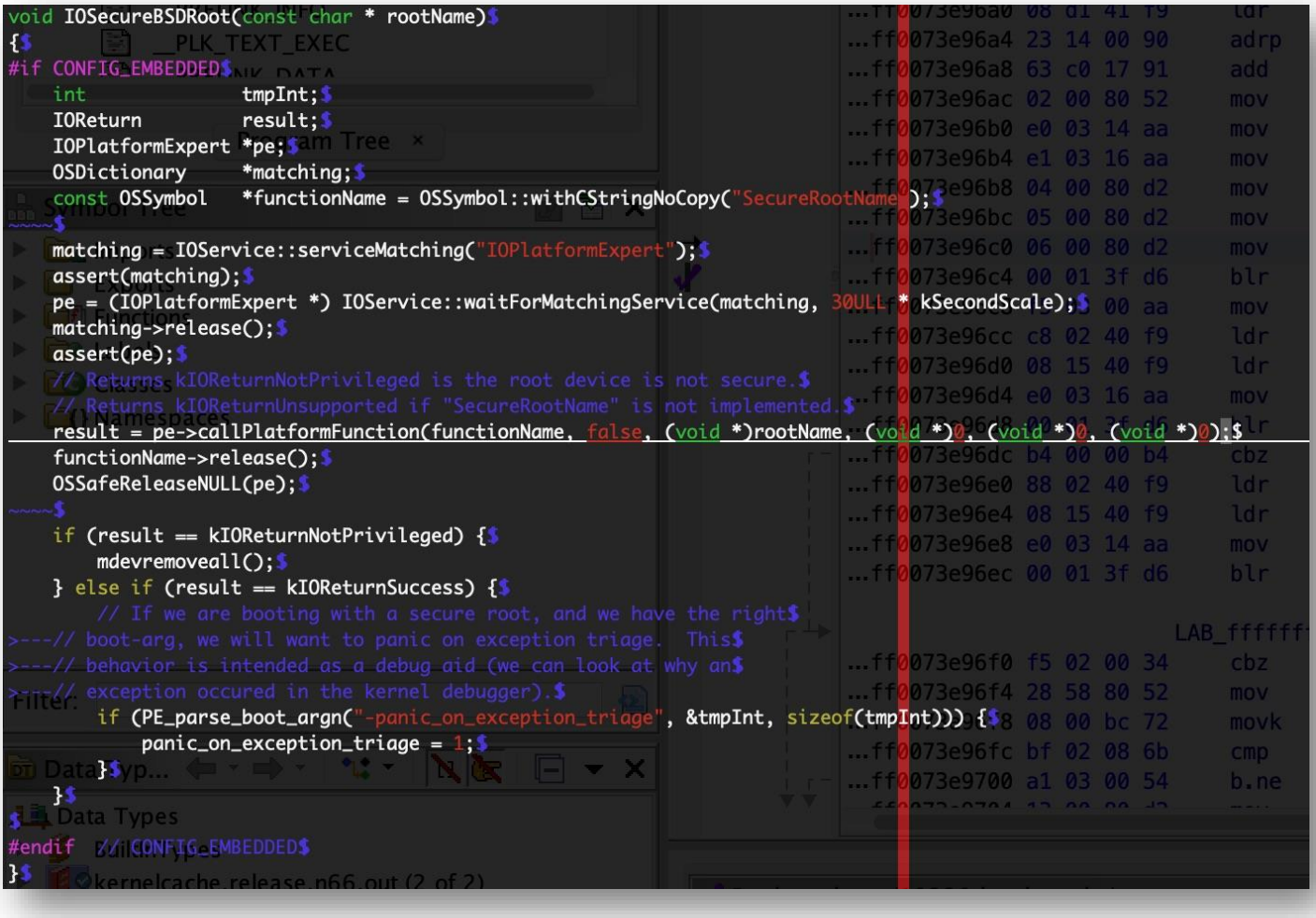
The other main module is `hw/arm/xnu.c` and it is responsible for:

1. Loading the device tree into memory and adding the ramdisk and the static trust cache addresses to the device tree where they are actually loaded.

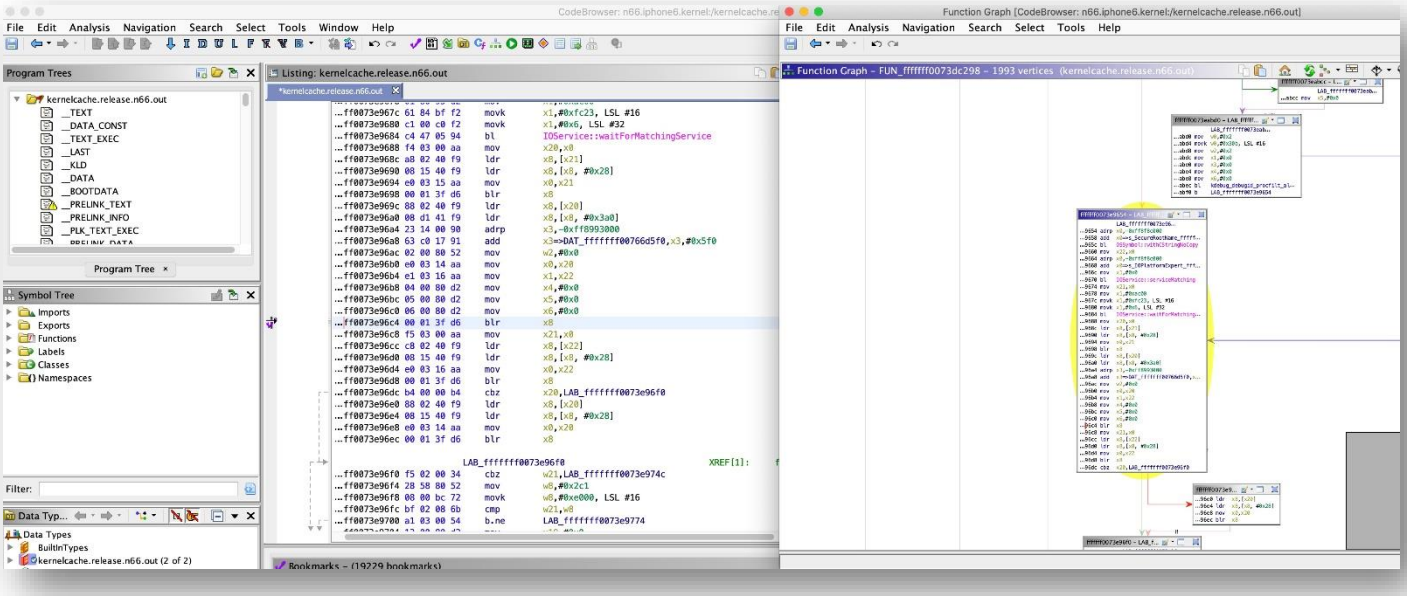
2. Loading the ramdisk into memory.
3. Loading the static trust cache into memory.
4. Loading the kernel image into memory.
5. Loading the secure monitor image into memory.
6. Loading and setting the kernel and secure monitor boot args.

Booting the kernel with no patches

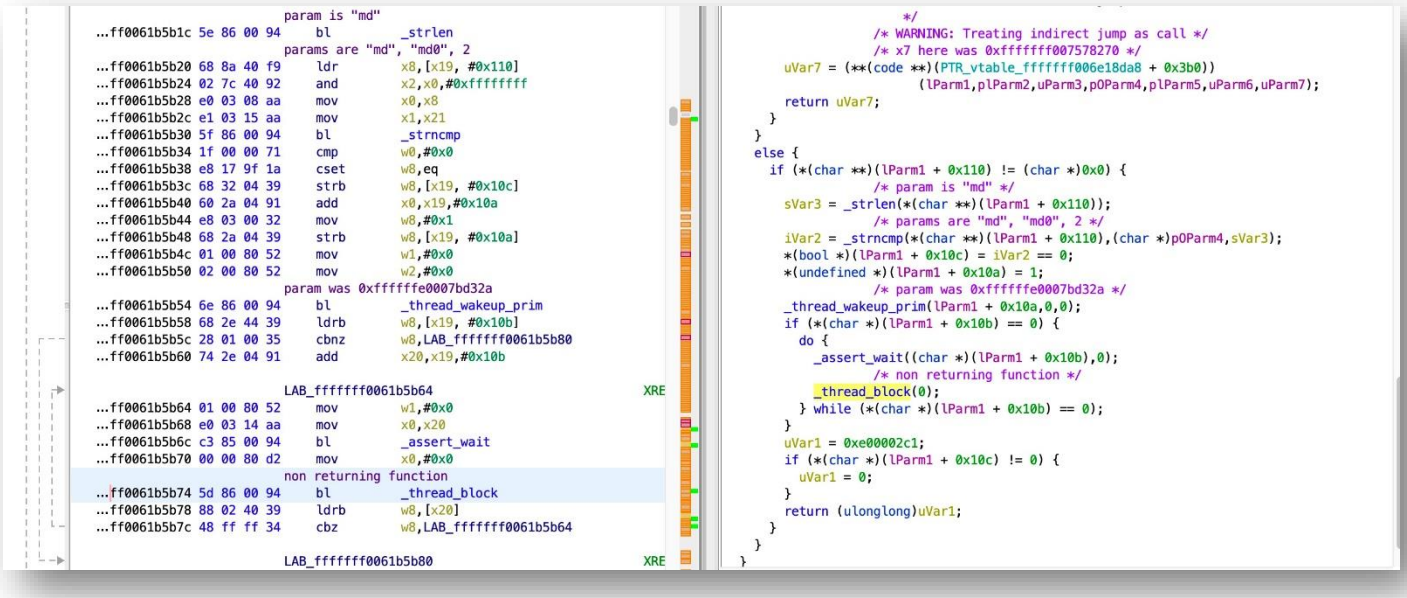
Basing the work on **zhuowei**, I already had the ability to boot to user mode with a different iOS version and for a different iPhone while patching the kernel at runtime using the kernel debugger. The need to patch comes from the fact that after changing the device tree and booting from a ramdisk we encounter a non-returning function waiting for an event that never comes. By placing breakpoints all over and single stepping in the kernel debugger I found that the non-returning function is `IOSecureBSDRoot()` which can be found in the **XNU code published by Apple** in version `xnu-4903.221.2`:



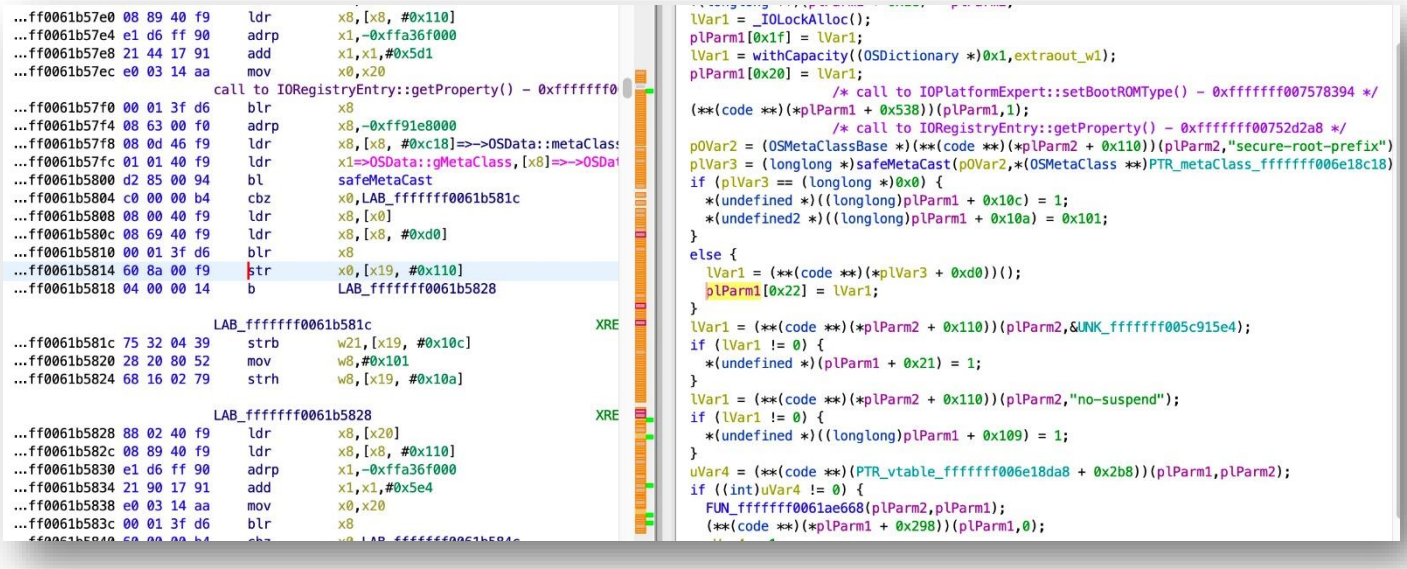
and at runtime, when debugging the kernel itself:



This function doesn't return, because the call to `pe->callPlatformFunction()` doesn't return. For this function I don't have any reference code, so the kernel is disassembled:



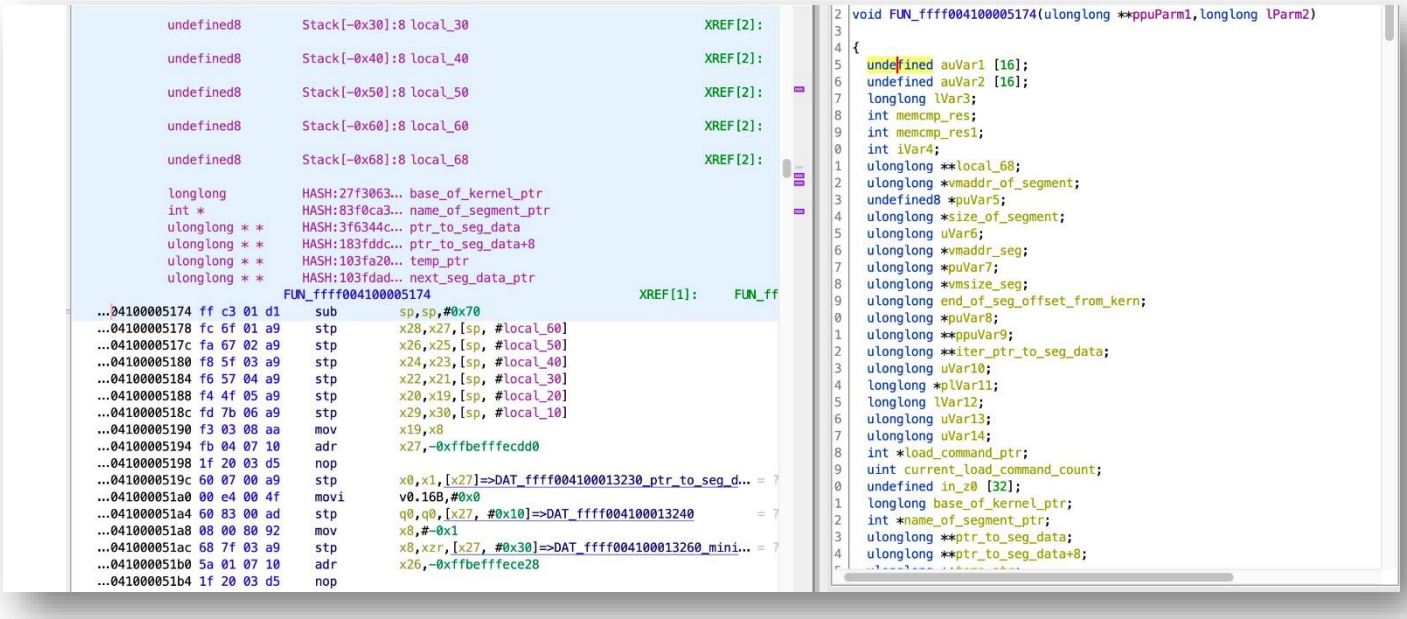
By examining the function, we can see that the non-returning function deals a lot with specific members of the object in x19, and the flow changes depending on these members. I tried a few approaches to understand what these members mean, and where their values are set, but with no luck. These members do seem to be at special offsets, so after a while I tried my luck and used Ghidra to search the whole kernel for functions that use objects and their members at offsets 0x10a, 0x10c and 0x110 - and I got lucky! I found this function, that deals with the exact same object and these members:



In this function, it is easy to see that when the prop `secure-root-prefix` is not in the device tree, the member at offset 0x110 is kept untouched with the value 0, and then the original function I looked at (`pe->callPlatformFunction()`) just returns, and voila - there no need to patch the kernel.

Loading the secure monitor image

Where we left off with the work done by **zhuowei**, I was able to boot an iPhone X image to user mode. This image boots straight into EL1 and has no secure monitor. I decided to work with another image for iPhone 6s plus, as Apple left off a lot of symbols in there and I thought it would make the research simpler. It turns out that **KPP** (Kernel Patch Protection) based devices with no **KTRR** (Kernel Text Readonly Region) have a secure monitor image that needs to be loaded with its own boot args, and executed in EL3. This part of the project was about finding the secure monitor image embedded in the kernel file, loading it, understanding the boot args structure, and loading the image and configuring QEMU to start executing the entry point in EL3. After completing these steps, things still didn't work. The reason seemed to be that the secure monitor image tries to parse the kernel mach-o header at the kernel base (read from the kernel boot args), and I didn't have a kernel image at that base address, so it failed with a data-abort. This all happens in this function:



I believe this function is responsible for the KPP functionality because it keeps a map of kernel sections based on the permissions they should have, but this assumption still needs to be verified.

As can be seen in the code from **zhuowei**, the `virt_base` arg was pointing to the lowest segment of the loaded kernel:

```
static uint64_t arm_load_macho(struct arm_boot_info *info, uint64_t *pentry, AddressSpace *as)
{
    hwaddr kernel_load_offset = 0x00000000;
    hwaddr mem_base = info->loader_start;

    uint8_t *data = NULL;
    gsize len;
    bool ret = false;
    uint8_t* rom_buf = NULL;
    if (!g_file_get_contents(info->kernel_filename, (char**) &data, &len, NULL)) {
        goto out;
    }
    struct mach_header_64* mh = (struct mach_header_64*)data;
    struct load_command* cmd = (struct load_command*)(data + sizeof(struct mach_header_64));
    // iterate through all the segments once to find highest and lowest addresses
    uint64_t pc = 0;
    uint64_t low_addr_temp;
    uint64_t high_addr_temp;
    macho_highest_lowest(mh, &low_addr_temp, &high_addr_temp);
    uint64_t rom_buf_size = high_addr_temp - low_addr_temp;
    rom_buf = g_malloc0(rom_buf_size);
    for (unsigned int index = 0; index < mh->ncmds; index++) {
        switch (cmd->cmd) {
            case LC_SEGMENT_64: {
                struct segment_command_64* segCmd = (struct segment_command_64*)cmd;
                memcpy(rom_buf + (segCmd->vmaddr - low_addr_temp), data + segCmd->fileoff, segCmd-
>filesize);
                break;
            }
            case LC_UNIXTHREAD: {
                // grab just the entry point PC
                uint64_t* ptrPc = (uint64_t*)((char*)cmd + 0x110); // for arm64 only.
                pc = VAtoPA(*ptrPc);
                break;
            }
        }
```

```
        cmd = (struct load_command*)((char*)cmd + cmd->cmdsize);
    }
    hwaddr rom_base = VAtoPA(low_addr_temp);
    rom_add_blob_fixed_as("macho", rom_buf, rom_buf_size, rom_base, as);
    ret = true;

    uint64_t load_extra_offset = high_addr_temp;

    uint64_t ramdisk_address = load_extra_offset;
    gsize ramdisk_size = 0;

    // load ramdisk if exists
    if (info->initrd_filename) {
        uint8_t* ramdisk_data = NULL;
        if (g_file_get_contents(info->initrd_filename, (char**) &ramdisk_data, &ramdisk_size, NULL)) {
            info->initrd_filename = NULL;
            rom_add_blob_fixed_as("xnu_ramdisk", ramdisk_data, ramdisk_size, VAtoPA(ramdisk_address),
as);
            load_extra_offset = (load_extra_offset + ramdisk_size + 0xfffull) & ~0xfffull;
            g_free(ramdisk_data);
        } else {
            fprintf(stderr, "ramdisk failed?!\n");
            abort();
        }
    }

    uint64_t dtb_address = load_extra_offset;
    gsize dtb_size = 0;
    // load device tree
    if (info->dtb_filename) {
        uint8_t* dtb_data = NULL;
        if (g_file_get_contents(info->dtb_filename, (char**) &dtb_data, &dtb_size, NULL)) {
            info->dtb_filename = NULL;
            if (ramdisk_size != 0) {
                macho_add_ramdisk_to_dtb(dtb_data, dtb_size, VAtoPA(ramdisk_address), ramdisk_size);
            }
            rom_add_blob_fixed_as("xnu_dtb", dtb_data, dtb_size, VAtoPA(dtb_address), as);
            load_extra_offset = (load_extra_offset + dtb_size + 0xfffull) & ~0xfffull;
            g_free(dtb_data);
        } else {
            fprintf(stderr, "dtb failed?!\n");
            abort();
        }
    }

    // fixup boot args
    // note: device tree and args must follow kernel and be included in the kernel data size.
    // macho_setup_bootargs takes care of adding the size for the args
    // osfmk/arm64/arm_vm_init.c:arm_vm_prot_init
    uint64_t bootargs_addr = VAtoPA(load_extra_offset);
    uint64_t phys_base = (mem_base + kernel_load_offset);
    uint64_t virt_base = low_addr_temp & ~0x3fffffffull;
    macho_setup_bootargs(info, as, bootargs_addr, virt_base, phys_base, VAtoPA(load_extra_offset),
dtb_address, dtb_size);

    // write bootloader
    uint32_t fixupcontext[FIXUP_MAX];
    fixupcontext[FIXUP_ARGPTR] = bootargs_addr;
    fixupcontext[FIXUP_ENTRYPOINT] = pc;
    write_bootloader("bootloader", info->loader_start,
                     bootloader_aarch64, fixupcontext, as);
    *pentry = info->loader_start;

    out:
    if (data) {
        g_free(data);
    }
    if (rom_buf) {
        g_free(rom_buf);
    }
    return ret? high_addr_temp - low_addr_temp : -1;
}
```

This segment, in our case, was mapped below the address of the loaded mach-o header. This means that the `virt_base` does not point to the kernel mach-o header, and therefore doesn't work with the secure monitor code as presented above. One way I tried solving this was by setting the `virt_base` to the address of the mach-o header, but this made some kernel drivers code load below `virt_base`, which messed up a lot of stuff, like the following function:

```
vm_offset_t
ml_static_vtop(vm_offset_t va)
{
        for (size_t i = 0; (i < PTOV_TABLE_SIZE) && (ptov_table[i].len != 0); i++) {
                if ((va >= ptov_table[i].va) && (va < (ptov_table[i].va + ptov_table[i].len)))
                        return (va - ptov_table[i].va + ptov_table[i].pa);
        }
        if (((vm_address_t)(va) - gVirtBase) >= gPhysSize)
                panic("ml_static_vtop(): illegal VA: %p\n", (void*)va);
        return ((vm_address_t)(va) - gVirtBase + gPhysBase);
}
```

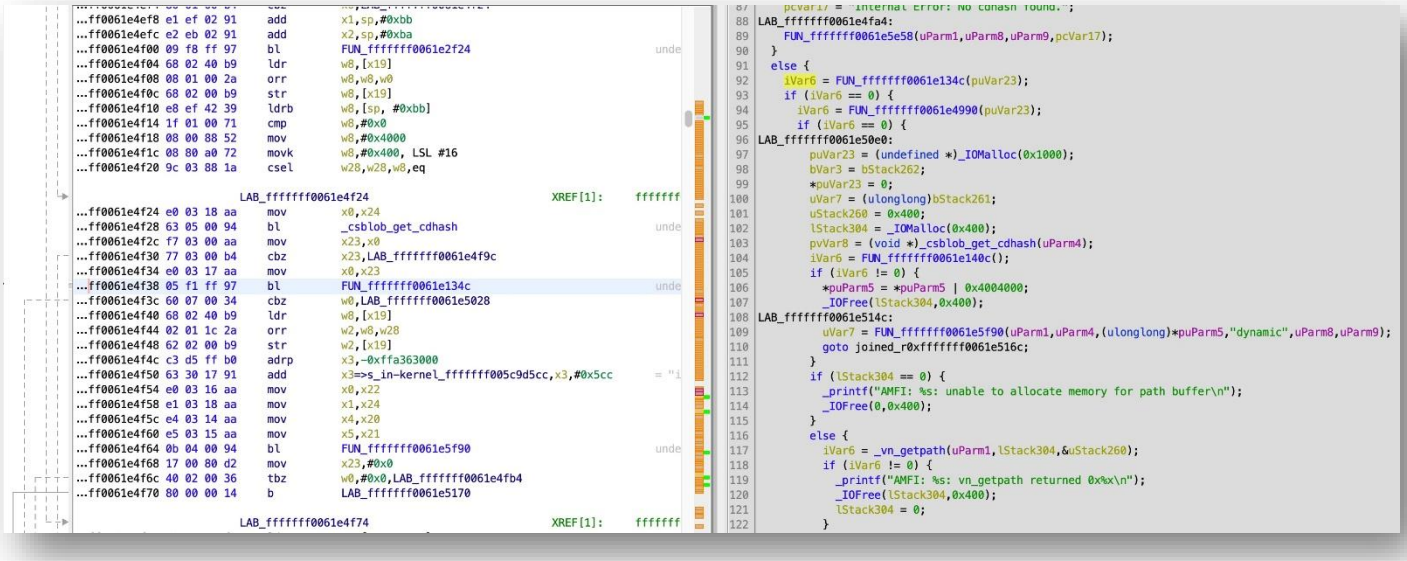
Another approach I tried was to skip the execution of the secure monitor, and start straight from the kernel entry point in EL1. This worked until I hit the first SMC instruction. It might have been possible to solve this by patching the kernel at points where SMC is used, but I didn't want to go this way, as I opted for no patches at all (if possible), and you never know where not having some secure monitor functionality might hit you again. What eventually worked was setting the `virt_base` to a lower address below the lowest loaded segment, and just have another copy of the whole raw kernelcache file at this place (in addition to the copy loaded segment by segment where the code is actually executed from). This solution satisfied all the conditions of having the `virt_base` below all the virtual addresses actually used in the kernel, having it point to the kernel mach-o header, and having the kernel loaded at its preferred address segment by segment, where it is actually executed from.

Trust Cache

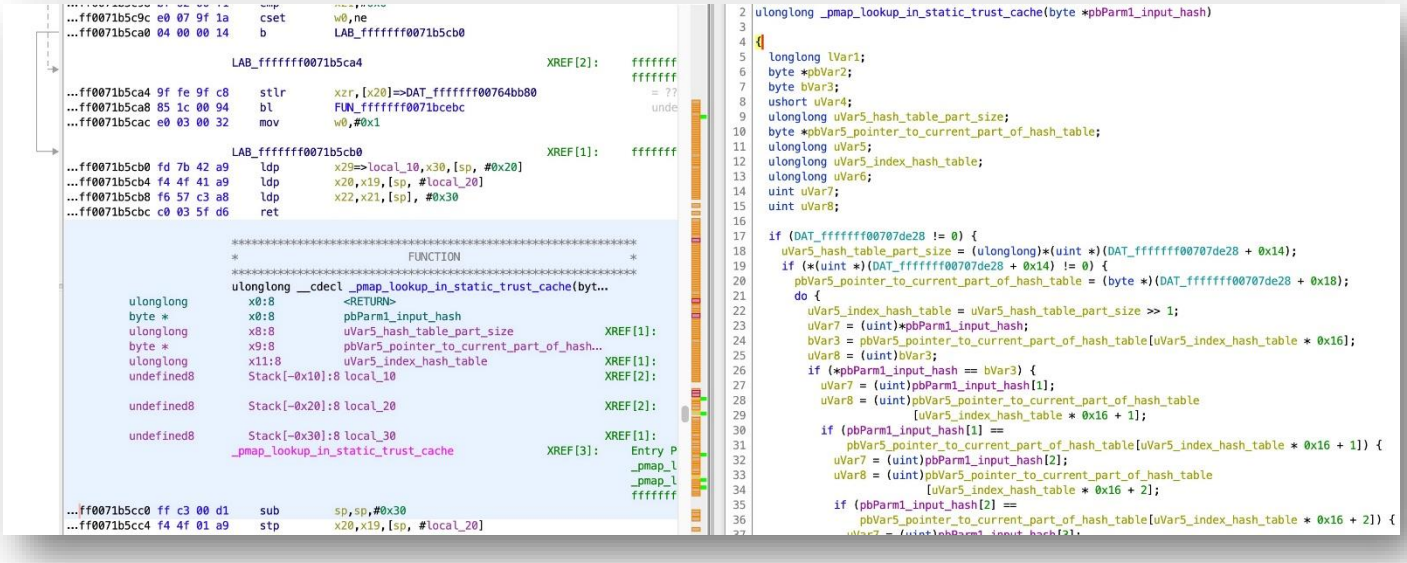
In this section, I will present the work that was done to load non-Apple, self-signed executables. iOS systems normally will only execute trusted executables that are either in a trust cache, or signed by Apple or an installed profile. More background on the subject can be found **here**, as well as other writeups on the web and in books. In general, there are 3 types of trust caches:

1. A trust cache hardcoded in the kernelcache.
2. A trust cache that can be loaded at runtime from a file.
3. A trust cache in memory pointed to from the device tree.

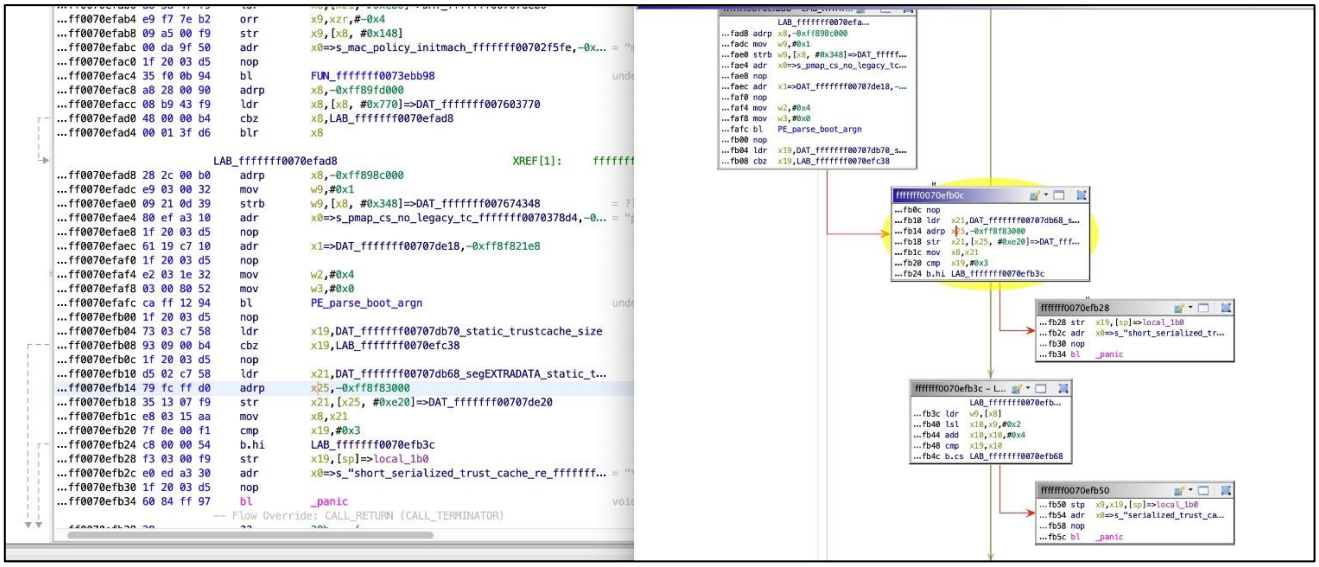
I decided to go after the 3rd one. The following function contains the top level logic for checking whether an executable has a code signature that is approved for execution, based on trust cahces or otherwise:



If we drill down deeper, we finally get to this function, that checks the static trust cache:



From there, we can see, using XREFs, that the values are set here:

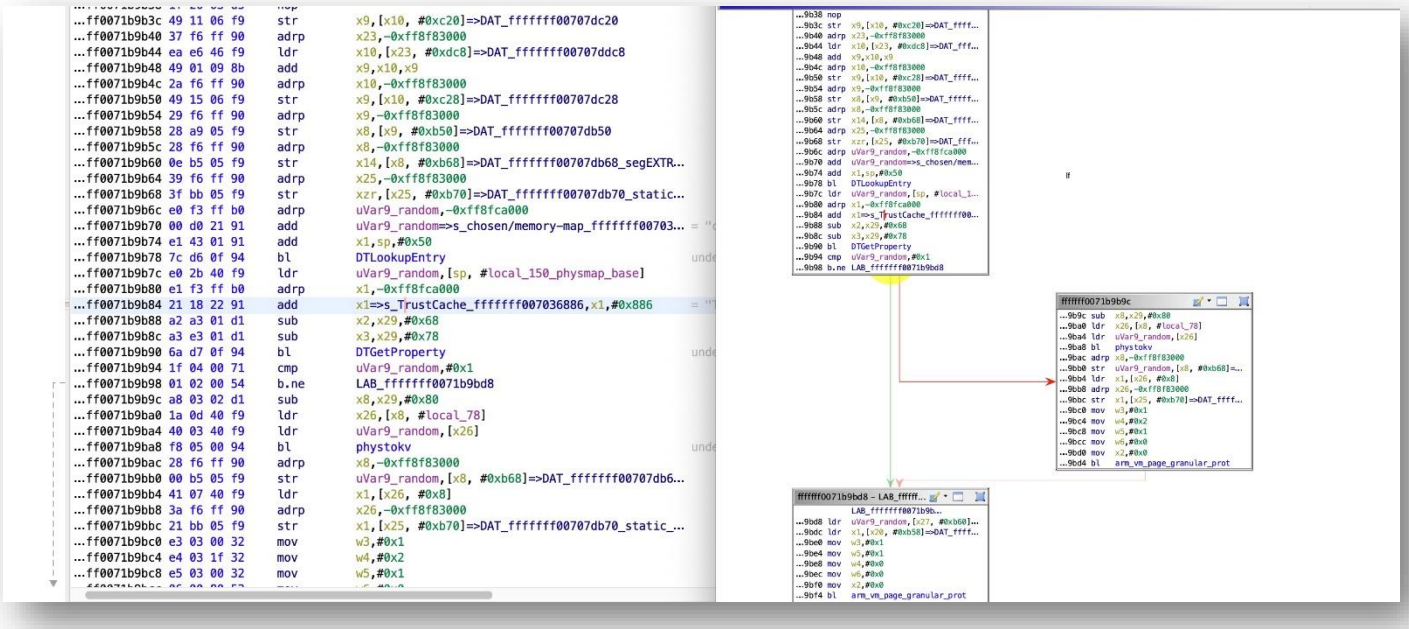


The function above parses the raw trust cache format. It is left as an exercise to the reader to follow the code and the error messages, to conclude that the trust cache format is:

```
struct cdhash {
    uint8_t hash[20]; //first 20 bytes of the cdhash
    uint8_t hash_type; //left as 0
    uint8_t hash_flags; //left as 0
};

struct static_trust_cache_entry {
    uint64_t trust_cache_version; //should be 1
    uint64_t unknown1; //left as 0
    uint64_t unknown2; //left as 0
    uint64_t unknown3; //left as 0
    uint64_t unknown4; //left as 0
    uint64_t number_of_cdhashes;
    struct cdhash[];
};

struct static_trust_cache_buffer {
    uint64_t number_of_trust_caches_in_buffer;
    uint64_t offsets_to_trust_caches_from_beginning_of_buffer[];
    struct static_trust_cache_entry entries[];
};
```

And it seems that even though the structure supports multiple trust caches in the buffer, the code actually limits the size to 1.

Following XREFS from this function leads us to the following code:



This data is, therefore, read from the device tree.

Now, all that's left to do is load the trust cache into memory, and point to it from the device tree. I have to decide where to place it in memory. There is a kernel boot arg `top of kernel data` which points to the address after the kernel, ramdisk, device tree and the boot args. The first location I tried was near this `top of kernel data` address (before and after it). This didn't go so well because of the following code which is the code ~matching the above assembly:

```
void
arm_vm_prot_init(boot_args * args)
{

	segLOWESTTEXT = UINT64_MAX;
	if (segSizePRELINKTEXT  && (segPRELINKTEXTB < segLOWESTTEXT)) segLOWESTTEXT = segPRELINKTEXTB;
	assert(segSizeTEXT);
	if (segTEXTB < segLOWESTTEXT) segLOWESTTEXT = segTEXTB;
	assert(segLOWESTTEXT < UINT64_MAX);

	segEXTRADATA = segLOWESTTEXT;
	segSizeEXTRADATA = 0;

	DTEntry memory_map;
	MemoryMapFileInfo *trustCacheRange;
	unsigned int trustCacheRangeSize;
	int err;

	err = DTLookupEntry(NULL, "chosen/memory-map", &memory_map);
	assert(err == kSuccess);

	err = DTGetProperty(memory_map, "TrustCache", (void**)&trustCacheRange, &trustCacheRangeSize);
	if (err == kSuccess) {
		assert(trustCacheRangeSize == sizeof(MemoryMapFileInfo));

		segEXTRADATA = phystokv(trustCacheRange->paddr);
		segSizeEXTRADATA = trustCacheRange->length;

		arm_vm_page_granular_RNX(segEXTRADATA, segSizeEXTRADATA, FALSE);
	}

	/* Map coalesced kext TEXT segment RWNX for now */
	arm_vm_page_granular_RWNX(segPRELINKTEXTB, segSizePRELINKTEXT, FALSE); // Refined in
OSKext::readPrelinkedExtensions

	/* Map coalesced kext DATA_CONST segment RWNX (could be empty) */
	arm_vm_page_granular_RWNX(segPLKDATACONSTB, segSizePLKDATACONST, FALSE); // Refined in
OSKext::readPrelinkedExtensions

	/* Map coalesced kext TEXT_EXEC segment RWX (could be empty) */
	arm_vm_page_granular_ROX(segPLKTEXTEXECB, segSizePLKTEXTEXEC, FALSE); // Refined in
OSKext::readPrelinkedExtensions

	/* if new segments not present, set space between PRELINK_TEXT and xnu TEXT to RWNX
	 * otherwise we no longer expect any space between the coalesced kext read only segments and xnu
rosegments
	 */
	if (!segSizePLKDATACONST && !segSizePLKTEXTEXEC) {
		if (segSizePRELINKTEXT)
			arm_vm_page_granular_RWNX(segPRELINKTEXTB + segSizePRELINKTEXT, segTEXTB -
(segPRELINKTEXTB + segSizePRELINKTEXT), FALSE);
	} else {
		/*
		 * If we have the new segments, we should still protect the gap between kext
		 * read-only pages and kernel read-only pages, in the event that this gap
		 * exists.
		 */
		if ((segPLKDATACONSTB + segSizePLKDATACONST) < segTEXTB) {
			arm_vm_page_granular_RWNX(segPLKDATACONSTB + segSizePLKDATACONST, segTEXTB -
(segPLKDATACONSTB + segSizePLKDATACONST), FALSE);
		}
	}

	/*
	 * Protection on kernel text is loose here to allow shenanigans early on.  These
	 * protections are tightened in arm_vm_prot_finalize().  This is necessary because
	 * we currently patch LowResetVectorBase in cpu.c.
	 *
	 * TEXT segment contains mach headers and other non-executable data. This will become RONX
later.
	 */
	arm_vm_page_granular_RNX(segTEXTB, segSizeTEXT, FALSE);
```

```
        /* Can DATACONST start out and stay RNX?
         * NO, stuff in this segment gets modified during startup (viz.
mac_policy_init()/mac_policy_list)
         * Make RNX in prot_finalize
         */
        arm_vm_page_granular_RWNX(segDATACONSTB, segSizeDATACONST, FALSE);

        /* TEXTEXEC contains read only executable code: becomes ROX in prot_finalize */
        arm_vm_page_granular_RWX(segTEXTEXECB, segSizeTEXTEXEC, FALSE);


        /* DATA segment will remain RWNX */
        arm_vm_page_granular_RWNX(segDATAB, segSizeDATA, FALSE);

        arm_vm_page_granular_RWNX(segBOOTDATAB, segSizeBOOTDATA, TRUE);
        arm_vm_page_granular_RNX((vm_offset_t)&intstack_low_guard, PAGE_MAX_SIZE, TRUE);
        arm_vm_page_granular_RNX((vm_offset_t)&intstack_high_guard, PAGE_MAX_SIZE, TRUE);
        arm_vm_page_granular_RNX((vm_offset_t)&excepstack_high_guard, PAGE_MAX_SIZE, TRUE);

        arm_vm_page_granular_ROX(segKLDB, segSizeKLD, FALSE);
        arm_vm_page_granular_RWNX(segLINKB, segSizeLINK, FALSE);
        arm_vm_page_granular_RWNX(segPLKLINKEDITB, segSizePLKLINKEDIT, FALSE); // Coalesced kext
LINKEDIT segment
        arm_vm_page_granular_ROX(segLASTB, segSizeLAST, FALSE); // __LAST may be empty, but we cannot
assume this

        arm_vm_page_granular_RWNX(segPRELINKDATAB, segSizePRELINKDATA, FALSE); // Prelink __DATA for
kexts (RW data)

        if (segSizePLKLLVMCOV > 0)
                arm_vm_page_granular_RWNX(segPLKLLVMCOVB, segSizePLKLLVMCOV, FALSE); // LLVM code
coverage data

        arm_vm_page_granular_RWNX(segPRELINKINFOB, segSizePRELINKINFO, FALSE); /* PreLinkInfoDictionary
*/

        arm_vm_page_granular_RNX(phystokv(args->topOfKernelData), BOOTSTRAP_TABLE_SIZE, FALSE); // Boot
page tables; they should not be mutable.
}
```

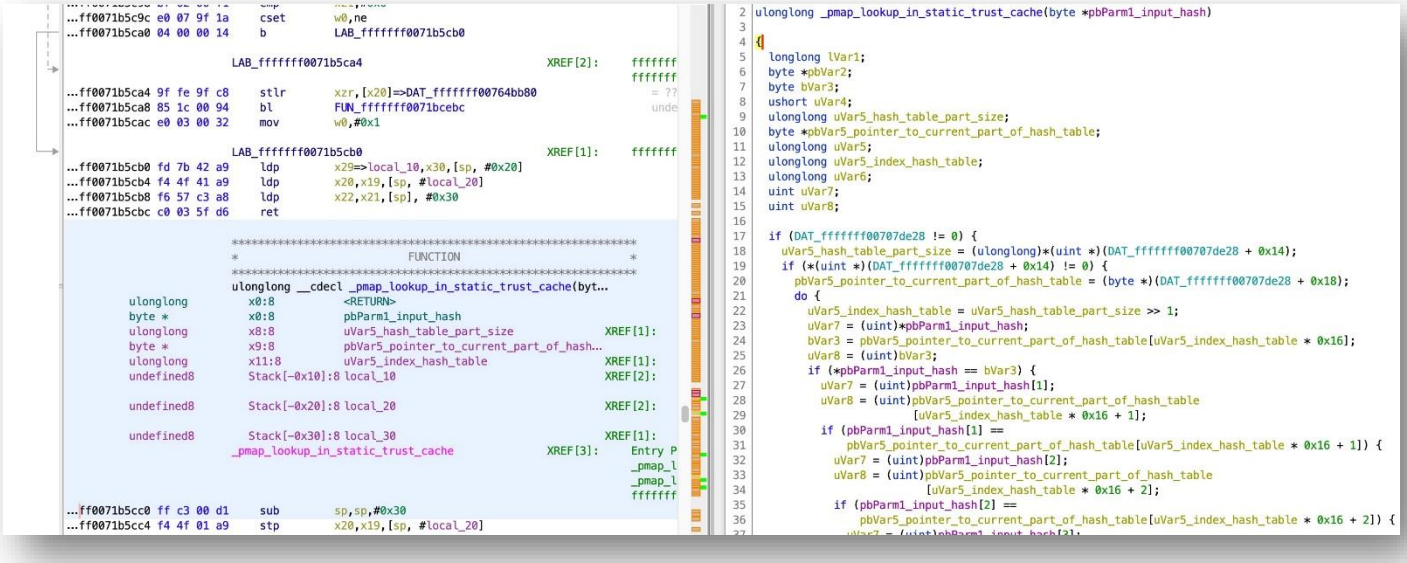
Here we can see that when we have a static trust cache, `segEXTRADATA` is set to the trust cache buffer, instead of `segLOWESTTEXT`.
In the following 2 functions we can see that if the data between `gVirtBase` and `segEXTRADATA` holds anything meaningful, terrible things happen:

```
static void
arm_vm_physmap_init(boot_args *args, vm_map_address_t physmap_base, vm_map_address_t dynamic_memory_begin
__unused)
{
        ptov_table_entry temp_ptov_table[PTOV_TABLE_SIZE];
        bzero(temp_ptov_table, sizeof(temp_ptov_table));

        // Will be handed back to VM layer through ml_static_mfree() in arm_vm_prot_finalize()
        arm_vm_physmap_slide(temp_ptov_table, physmap_base, gVirtBase, segEXTRADATA - gVirtBase,
AP_RWNA, FALSE);

        arm_vm_page_granular_RWNX(end_kern, phystokv(args->topOfKernelData) - end_kern, FALSE); /*
Device Tree, RAM Disk (if present), bootArgs */

        arm_vm_physmap_slide(temp_ptov_table, physmap_base, (args->topOfKernelData +
BOOTSTRAP_TABLE_SIZE - gPhysBase + gVirtBase),
                             real_avail_end - (args->topOfKernelData + BOOTSTRAP_TABLE_SIZE),
AP_RWNA, FALSE); // rest of physmem

        assert((temp_ptov_table[ptov_index - 1].va + temp_ptov_table[ptov_index - 1].len) <=
dynamic_memory_begin);

        // Sort in descending order of segment length.  LUT traversal is linear, so largest (most likely
used)
        // segments should be placed earliest in the table to optimize lookup performance.
```

```
	qsort(temp_ptov_table, PTOV_TABLE_SIZE, sizeof(temp_ptov_table[0]), cmp_ptov_entries);

	memcpy(ptov_table, temp_ptov_table, sizeof(ptov_table));
}


void
arm_vm_prot_finalize(boot_args * args __unused)
{
	/*
	 * At this point, we are far enough along in the boot process that it will be
	 * safe to free up all of the memory preceeding the kernel.  It may in fact
	 * be safe to do this earlier.
	 *
	 * This keeps the memory in the V-to-P mapping, but advertises it to the VM
	 * as usable.
	 */

	/*
	 * if old style PRELINK segment exists, free memory before it, and after it before XNU text
	 * otherwise we're dealing with a new style kernel cache, so we should just free the
	 * memory before PRELINK_TEXT segment, since the rest of the KEXT read only data segments
	 * should be immediately followed by XNU's TEXT segment
	 */

	ml_static_mfree(phystokv(gPhysBase), segEXTRADATA - gVirtBase);

	/*
	 * KTRR support means we will be mucking with these pages and trying to
	 * protect them; we cannot free the pages to the VM if we do this.
	 */
	if (!segSizePLKDATACONST && !segSizePLKTEXTEXEC && segSizePRELINKTEXT) {
		/* If new segments not present, PRELINK_TEXT is not dynamically sized, free DRAM
between it and xnu TEXT */
		ml_static_mfree(segPRELINKTEXTB + segSizePRELINKTEXT, segTEXTB - (segPRELINKTEXTB +
segSizePRELINKTEXT));
	}

	/*
	 * LowResetVectorBase patching should be done by now, so tighten executable
	 * protections.
	 */
	arm_vm_page_granular_ROX(segTEXTEXECB, segSizeTEXTEXEC, FALSE);

	/* tighten permissions on kext read only data and code */
	if (segSizePLKDATACONST && segSizePLKTEXTEXEC) {
		arm_vm_page_granular_RNX(segPRELINKTEXTB, segSizePRELINKTEXT, FALSE);
		arm_vm_page_granular_ROX(segPLKTEXTEXECB, segSizePLKTEXTEXEC, FALSE);
		arm_vm_page_granular_RNX(segPLKDATACONSTB, segSizePLKDATACONST, FALSE);
	}

	cpu_stack_alloc(&BootCpuData);
	arm64_replace_bootstack(&BootCpuData);
	ml_static_mfree(phystokv(segBOOTDATAB - gVirtBase + gPhysBase), segSizeBOOTDATA);

#if __ARM_KERNEL_PROTECT__
	arm_vm_populate_kernel_el0_mappings();
#endif /* __ARM_KERNEL_PROTECT__ */


#if defined(KERNEL_INTEGRITY_KTRR)
	/*
	 * __LAST,__pinst should no longer be executable.
	 */
	arm_vm_page_granular_RNX(segLASTB, segSizeLAST, FALSE);

	/*
	 * Must wait until all other region permissions are set before locking down DATA_CONST
	 * as the kernel static page tables live in DATA_CONST on KTRR enabled systems
	 * and will become immutable.
	 */
#endif
```

```
        arm_vm_page_granular_RNX(segDATACONSTB, segSizeDATACONST, FALSE);

#ifndef __ARM_L1_PTW__
        FlushPoC_Dcache();
#endif
        __builtin_arm_dsb(DSB_ISH);
        flush_mmu_tlb();
}
```

Alright, so now, based on the above observation, I decided to place the trust cache buffer right after the raw kernel file I placed at `virt_base`. This, of course, still didn't work. Following the code that sets the page table, I found where this memory location gets unloaded from the table, and finally understood that a few pages after the end of the raw kernel file get unloaded from memory at some point. Therefore, I placed it a few MBs above that address, and it finally worked (partially).
Looking at the code at:



It is left to the reader to read the function and see that a binary search is implemented there. After sorting the hashes in the buffer, it finally worked properly.

Bash launchd item

At this point, I have the ability to execute our own self-signed, non-Apple executables, so I wanted launchd to execute bash instead of the services that exist on the ramdisk. To do so, I deleted all the files in `/System/Library/LaunchDaemons/` and added a new file `com.apple.bash.plist`, with the following content:

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN" "http://www.apple.com/DTDs/PropertyList-1.0.dtd">
<plist version="1.0">
<dict>
        <key>EnablePressuredExit</key>
        <false/>
        <key>Label</key>
        <string>com.apple.bash</string>
        <key>POSIXSpawnType</key>
        <string>Interactive</string>
        <key>ProgramArguments</key>
        <array>
```

```
                <string>/iosbinpack64/bin/bash</string>
        </array>
        <key>RunAtLoad</key>
        <true/>
        <key>StandardErrorPath</key>
        <string>/dev/console</string>
        <key>StandardInPath</key>
        <string>/dev/console</string>
        <key>StandardOutPath</key>
        <string>/dev/console</string>
        <key>Umask</key>
        <integer>0</integer>
        <key>UserName</key>
        <string>root</string>
</dict>
</plist>
```

This made launchd try and execute bash, but still no go. It seems that the ramdisk comes without the dynamic loader cache on it. To solve this, I copied the dyld cache from the full disk image to the ramdisk (after resizing the ramdisk so it would have enough space for it). Alas, it still didn't work and it seemed the problem was still the same missing libraries, even with the dyld cache in place. To debug this, I needed to better understand where the failure happens. I found out that loading the cache happens inside **dyld** in:

```
static void mapSharedCache()
{
        uint64_t cacheBaseAddress = 0;
        // quick check if a cache is already mapped into shared region
        if ( _shared_region_check_np(&cacheBaseAddress) == 0 ) {
                sSharedCache = (dyld_cache_header*)cacheBaseAddress;
                // if we don't understand the currently mapped shared cache, then ignore
#if __x86_64__
                const char* magic = (sHaswell ? ARCH_CACHE_MAGIC_H : ARCH_CACHE_MAGIC);
#else
                const char* magic = ARCH_CACHE_MAGIC;
#endif
                if ( strcmp(sSharedCache->magic, magic) != 0 ) {
                        sSharedCache = NULL;
                        if ( gLinkContext.verboseMapping ) {
                                dyld::log("dyld: existing shared cached in memory is not
compatible\n");
                                return;
                        }
                }
                // check if cache file is slidable
                const dyld_cache_header* header = sSharedCache;
                if ( (header->mappingOffset >= 0x48) && (header->slideInfoSize != 0) ) {
                        // solve for slide by comparing loaded address to address of first region
                        const uint8_t* loadedAddress = (uint8_t*)sSharedCache;
                        const dyld_cache_mapping_info* const mappings =
(dyld_cache_mapping_info*)(loadedAddress+header->mappingOffset);
                        const uint8_t* preferedLoadAddress = (uint8_t*)(long)(mappings[0].address);
                        sSharedCacheSlide = loadedAddress - preferedLoadAddress;
                        dyld::gProcessInfo->sharedCacheSlide = sSharedCacheSlide;
                        //dyld::log("sSharedCacheSlide=0x%08lX, loadedAddress=%p,
preferedLoadAddress=%p\n", sSharedCacheSlide, loadedAddress, preferedLoadAddress);
                }
                // if cache has a uuid, copy it
                if ( header->mappingOffset >= 0x68 ) {
                        memcpy(dyld::gProcessInfo->sharedCacheUUID, header->uuid, 16);
                }
                // verbose logging
                if ( gLinkContext.verboseMapping ) {
                        dyld::log("dyld: re-using existing shared cache mapping\n");
                }
        }
        else {
#if __i386__ || __x86_64__
```

```
                // <rdar://problem/5925940> Safe Boot should disable dyld shared cache
                // if we are in safe-boot mode and the cache was not made during this boot cycle,
                // delete the cache file
                uint32_t safeBootValue = 0;
                size_t           safeBootValueSize = sizeof(safeBootValue);
                if ( (sysctlbyname("kern.safeboot", &safeBootValue, &safeBootValueSize, NULL, 0) == 0)
&& (safeBootValue != 0) ) {
                        // user booted machine in safe-boot mode
                        struct stat dyldCacheStatInfo;
                        //  Don't use custom DYLD_SHARED_CACHE_DIR if provided, use standard path
                        if ( my_stat(MACOSX_DYLD_SHARED_CACHE_DIR DYLD_SHARED_CACHE_BASE_NAME
ARCH_NAME, &dyldCacheStatInfo) == 0 ) {
                                struct timeval bootTimeValue;
                                size_t bootTimeValueSize = sizeof(bootTimeValue);
                                if ( (sysctlbyname("kern.boottime", &bootTimeValue,
&bootTimeValueSize, NULL, 0) == 0) && (bootTimeValue.tv_sec != 0) ) {
                                        // if the cache file was created before this boot, then
throw it away and let it rebuild itself
                                        if ( dyldCacheStatInfo.st_mtime < bootTimeValue.tv_sec ) {
                                                ::unlink(MACOSX_DYLD_SHARED_CACHE_DIR
DYLD_SHARED_CACHE_BASE_NAME ARCH_NAME);
                                                gLinkContext.sharedRegionMode =
ImageLoader::kDontUseSharedRegion;
                                                return;
                                        }
                                }
                        }
                }
#endif
                // map in shared cache to shared region
                int fd = openSharedCacheFile();
                if ( fd != -1 ) {
                        uint8_t firstPages[8192];
                        if ( ::read(fd, firstPages, 8192) == 8192 ) {
                                dyld_cache_header* header = (dyld_cache_header*)firstPages;
                #if __x86_64__
                                const char* magic = (sHaswell ? ARCH_CACHE_MAGIC_H :
ARCH_CACHE_MAGIC);
                #else
                                const char* magic = ARCH_CACHE_MAGIC;
                #endif
                                if ( strcmp(header->magic, magic) == 0 ) {
                                        const dyld_cache_mapping_info* const fileMappingsStart =
(dyld_cache_mapping_info*)&firstPages[header->mappingOffset];
                                        const dyld_cache_mapping_info* const fileMappingsEnd =
&fileMappingsStart[header->mappingCount];
                                        shared_file_mapping_np      mappings[header-
>mappingCount+1]; // add room for code-sig
                                        unsigned int mappingCount = header->mappingCount;
                                        int codeSignatureMappingIndex = -1;
                                        int readWriteMappingIndex = -1;
                                        int readOnlyMappingIndex = -1;
                                        // validate that the cache file has not been truncated
                                        bool goodCache = false;
                                        struct stat stat_buf;
                                        if ( fstat(fd, &stat_buf) == 0 ) {
                                                goodCache = true;
                                                int i=0;
                                                for (const dyld_cache_mapping_info* p =
fileMappingsStart; p < fileMappingsEnd; ++p, ++i) {
                                                        mappings[i].sfm_address              =
p->address;
                                                        mappings[i].sfm_size                 =
p->size;
                                                        mappings[i].sfm_file_offset = p-
>fileOffset;
                                                        mappings[i].sfm_max_prot    = p->maxProt;
                                                        mappings[i].sfm_init_prot   = p-
>initProt;
                                                        // rdar://problem/5694507 old
update_dyld_shared_cache tool could make a cache file
                                                        // that is not page aligned, but
otherwise ok.
```

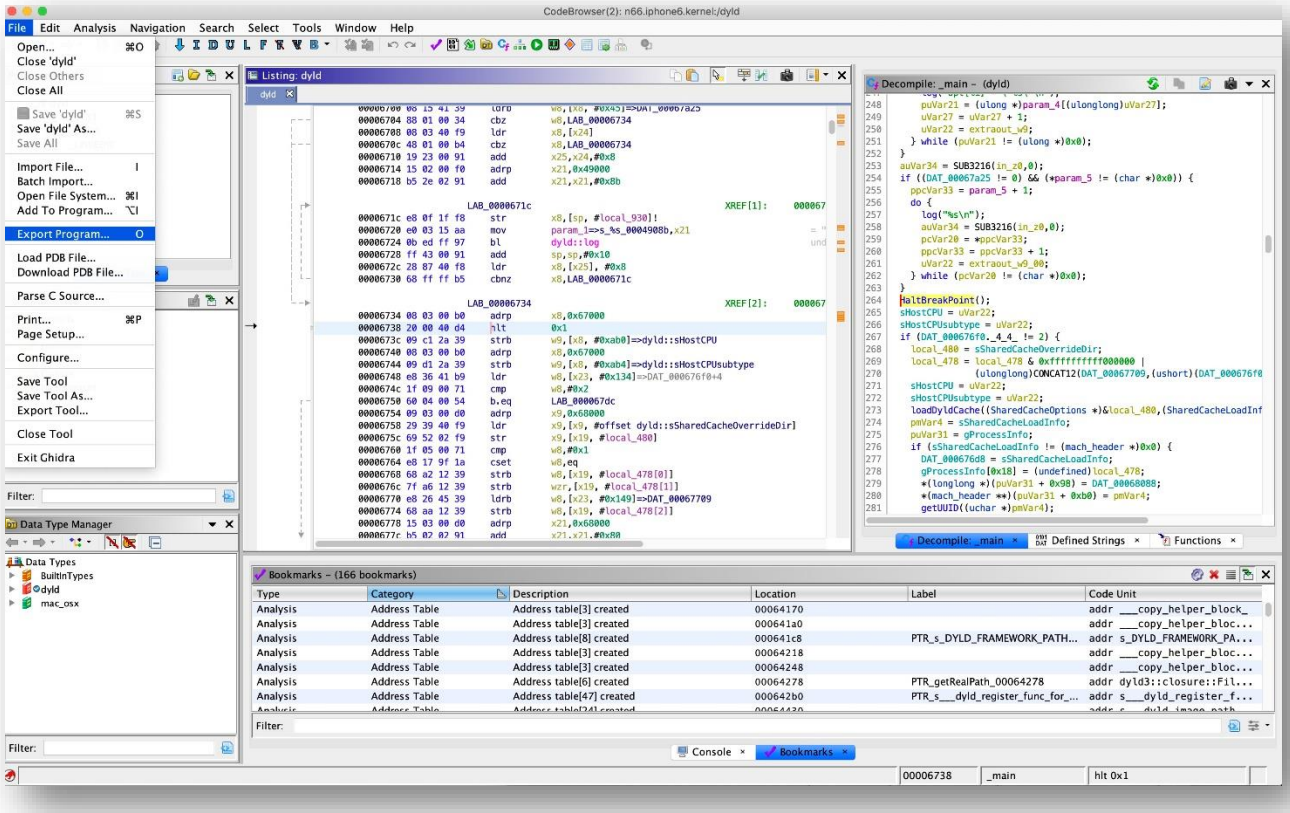
```
                                                        if ( p->fileOffset+p->size >
(uint64_t)(stat_buf.st_size+4095 & (-4096)) ) {
                                                                dyld::log("dyld: shared cached
file is corrupt: %s" DYLD_SHARED_CACHE_BASE_NAME ARCH_NAME "\n", sSharedCacheDir);
                                                                goodCache = false;
                                                        }
                                                        if ( (mappings[i].sfm_init_prot &
(VM_PROT_READ|VM_PROT_WRITE)) == (VM_PROT_READ|VM_PROT_WRITE) ) {
                                                                readWriteMappingIndex = i;
                                                        }
                                                        if ( mappings[i].sfm_init_prot ==
VM_PROT_READ ) {
                                                                readOnlyMappingIndex = i;
                                                        }
                                                }
                                                // if shared cache is code signed, add a mapping
for the code signature
                                                uint64_t signatureSize = header-
>codeSignatureSize;
                                                // zero size in header means signature runs to
end-of-file
                                                if ( signatureSize == 0 )
                                                        signatureSize = stat_buf.st_size -
header->codeSignatureOffset;
                                                if ( signatureSize != 0 ) {
                                int linkeditMapping = mappingCount-1;
                                                        codeSignatureMappingIndex =
mappingCount++;

                mappings[codeSignatureMappingIndex].sfm_address                 =
mappings[linkeditMapping].sfm_address + mappings[linkeditMapping].sfm_size;
#if __arm__ || __arm64__

                mappings[codeSignatureMappingIndex].sfm_size            = (signatureSize+16383) & (-16384);
#else

                mappings[codeSignatureMappingIndex].sfm_size            = (signatureSize+4095) & (-4096);
#endif

                mappings[codeSignatureMappingIndex].sfm_file_offset     = header->codeSignatureOffset;

                mappings[codeSignatureMappingIndex].sfm_max_prot        = VM_PROT_READ;

                mappings[codeSignatureMappingIndex].sfm_init_prot       = VM_PROT_READ;
                                                }
                                        }
#if __MAC_OS_X_VERSION_MIN_REQUIRED
                                        // sanity check that /usr/lib/libSystem.B.dylib stat() info
matches cache
                                        if ( header->imagesCount * sizeof(dyld_cache_image_info) +
header->imagesOffset < 8192 ) {
                                                bool foundLibSystem = false;
                                                if ( my_stat("/usr/lib/libSystem.B.dylib",
&stat_buf) == 0 ) {
                                                        const dyld_cache_image_info* images =
(dyld_cache_image_info*)&firstPages[header->imagesOffset];
                                                        const dyld_cache_image_info* const
imagesEnd = &images[header->imagesCount];
                                                        for (const dyld_cache_image_info* p =
images; p < imagesEnd; ++p) {
                                                                if ( ((time_t)p->modTime ==
stat_buf.st_mtime) && ((ino_t)p->inode == stat_buf.st_ino) ) {
                                                                        foundLibSystem = true;
                                                                        break;
                                                                }
                                                        }

                                                }
                                                if ( !sSharedCacheIgnoreInodeAndTimeStamp &&
!foundLibSystem ) {
                                                        dyld::log("dyld: shared cached file was
built against a different libSystem.dylib, ignoring cache.\n"
```

```
                                                                                "to update dyld shared
cache run: 'sudo update_dyld_shared_cache' then reboot.\n");
                                                                        goodCache = false;
                                                                }
                                                        }
#endif
#if __IPHONE_OS_VERSION_MIN_REQUIRED
                                                        {
                                                                uint64_t lowAddress;
                                                                uint64_t highAddress;
                                                                getCacheBounds(mappingCount, mappings, lowAddress,
highAddress);
                                                                if ( (highAddress-lowAddress) > SHARED_REGION_SIZE
)
                                                                        throw "dyld shared cache is too big to
fit in shared region";
                                                        }
#endif

                                                        if ( goodCache && (readWriteMappingIndex == -1) ) {
                                                                dyld::log("dyld: shared cached file is missing
read/write mapping: %s" DYLD_SHARED_CACHE_BASE_NAME ARCH_NAME "\n", sSharedCacheDir);
                                                                goodCache = false;
                                                        }
                                                        if ( goodCache && (readOnlyMappingIndex == -1) ) {
                                                                dyld::log("dyld: shared cached file is missing
read-only mapping: %s" DYLD_SHARED_CACHE_BASE_NAME ARCH_NAME "\n", sSharedCacheDir);
                                                                goodCache = false;
                                                        }
                                                        if ( goodCache ) {
                                                                long cacheSlide = 0;
                                                                void* slideInfo = NULL;
                                                                uint64_t slideInfoSize = 0;
                                                                // check if shared cache contains slid info
                                                                if ( header->slideInfoSize != 0 ) {
                                                                        // <rdar://problem/8611968> don't slide
shared cache if ASLR disabled (main executable didn't slide)
                                                                        if ( sMainExecutable-
>isPositionIndependentExecutable() && (sMainExecutable->getSlide() == 0) )
                                                                                cacheSlide = 0;
                                                                        else {
                                                                                // generate random slide amount
                                                                                cacheSlide =
pickCacheSlide(mappingCount, mappings);
                                                                                slideInfo =
(void*)(long)(mappings[readOnlyMappingIndex].sfm_address + (header->slideInfoOffset -
mappings[readOnlyMappingIndex].sfm_file_offset));
                                                                                slideInfoSize = header-
>slideInfoSize;
                                                                                // add VM_PROT_SLIDE bit to
__DATA area of cache

        mappings[readWriteMappingIndex].sfm_max_prot  |= VM_PROT_SLIDE;

        mappings[readWriteMappingIndex].sfm_init_prot |= VM_PROT_SLIDE;
                                                                        }
                                                                }
                                                                if ( gLinkContext.verboseMapping ) {
                                                                        dyld::log("dyld: calling
_shared_region_map_and_slide_np() with regions:\n");
                                                                        for (int i=0; i < mappingCount; ++i) {
                                                                                dyld::log("   address=0x%08llX,
size=0x%08llX, fileOffset=0x%08llX\n", mappings[i].sfm_address, mappings[i].sfm_size,
mappings[i].sfm_file_offset);
                                                                        }
                                                                }
                                                                if (_shared_region_map_and_slide_np(fd,
mappingCount, mappings, codeSignatureMappingIndex, cacheSlide, slideInfo, slideInfoSize) == 0) {
                                                                        // successfully mapped cache into shared
region
                                                                        sSharedCache =
(dyld_cache_header*)mappings[0].sfm_address;
                                                                        sSharedCacheSlide = cacheSlide;
```

```
                                                                dyld::gProcessInfo->sharedCacheSlide =
cacheSlide;
                                                                //dyld::log("sSharedCache=%p
sSharedCacheSlide=0x%08lX\n", sSharedCache, sSharedCacheSlide);
                                                                // if cache has a uuid, copy it
                                                                if ( header->mappingOffset >= 0x68 ) {
                                                                        memcpy(dyld::gProcessInfo-
>sharedCacheUUID, header->uuid, 16);
                                                                }
                                                        }
                                                        else {
#if __IPHONE_OS_VERSION_MIN_REQUIRED
                                                                throw "dyld shared cache could not be
mapped";
#endif
                                                                if ( gLinkContext.verboseMapping )
                                                                        dyld::log("dyld: shared cached
file could not be mapped\n");
                                                        }
                                                }
                                        }
                                        else {
                                                if ( gLinkContext.verboseMapping )
                                                        dyld::log("dyld: shared cached file is
invalid\n");
                                        }
                                }
                                else {
                                        if ( gLinkContext.verboseMapping )
                                                dyld::log("dyld: shared cached file cannot be read\n");
                                }
                                close(fd);
                        }
                        else {
                                if ( gLinkContext.verboseMapping )
                                        dyld::log("dyld: shared cached file cannot be opened\n");
                        }
                }

                // remember if dyld loaded at same address as when cache built
                if ( sSharedCache != NULL ) {
                        gLinkContext.dyldLoadedAtSameAddressNeededBySharedCache = ((uintptr_t)(sSharedCache-
>dyldBaseAddress) == (uintptr_t)&_mh_dylinker_header);
                }

                // tell gdb where the shared cache is
                if ( sSharedCache != NULL ) {
                        const dyld_cache_mapping_info* const start =
(dyld_cache_mapping_info*)((uint8_t*)sSharedCache + sSharedCache->mappingOffset);
                        dyld_shared_cache_ranges.sharedRegionsCount = sSharedCache->mappingCount;
                        // only room to tell gdb about first four regions
                        if ( dyld_shared_cache_ranges.sharedRegionsCount > 4 )
                                dyld_shared_cache_ranges.sharedRegionsCount = 4;
                        const dyld_cache_mapping_info* const end =
&start[dyld_shared_cache_ranges.sharedRegionsCount];
                        int index = 0;
                        for (const dyld_cache_mapping_info* p = start; p < end; ++p, ++index ) {
                                dyld_shared_cache_ranges.ranges[index].start = p->address+sSharedCacheSlide;
                                dyld_shared_cache_ranges.ranges[index].length = p->size;
                                if ( gLinkContext.verboseMapping ) {
                                        dyld::log("        0x%08llX->0x%08llX %s%s%s init=%x, max=%x\n",
                                                p->address+sSharedCacheSlide, p-
>address+sSharedCacheSlide+p->size-1,
                                                ((p->initProt & VM_PROT_READ) ? "read " : ""),
                                                ((p->initProt & VM_PROT_WRITE) ? "write " : ""),
                                                ((p->initProt & VM_PROT_EXECUTE) ? "execute " : ""),  p-
>initProt, p->maxProt);
                                }
                        #if __i386__
                                // If a non-writable and executable region is found in the R/W shared region,
then this is __IMPORT segments
                                // This is an old cache.  Make writable.  dyld no longer supports turn W on
and off as it binds
```

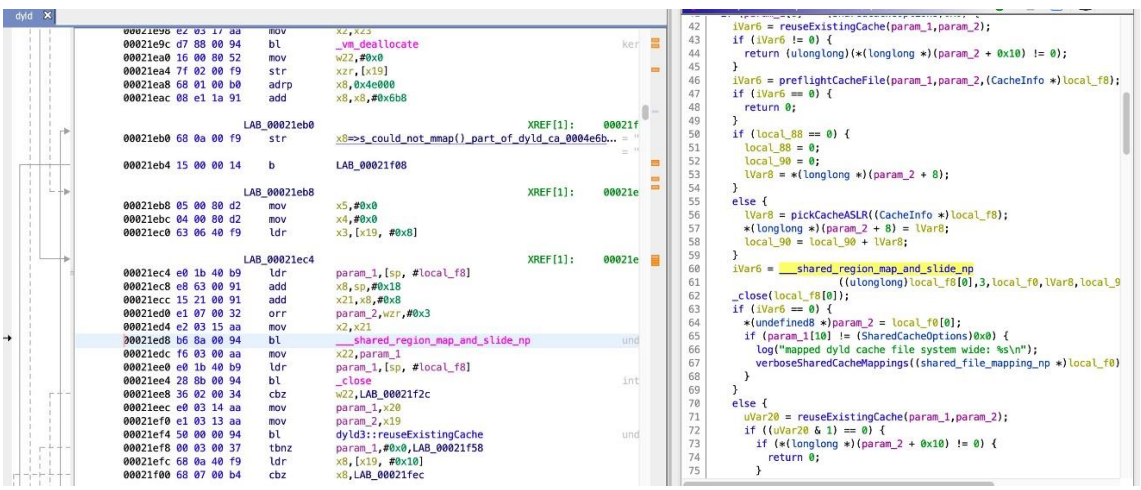
```
                        if ( (p->initProt == (VM_PROT_READ|VM_PROT_EXECUTE)) && ((p->address &
0xF0000000) == 0xA0000000) ) {
                                if ( p->size != 0 ) {
                                        vm_prot_t prot = VM_PROT_EXECUTE | PROT_READ |
VM_PROT_WRITE;
                                        vm_protect(mach_task_self(), p->address, p->size, false,
prot);
                                        if ( gLinkContext.verboseMapping ) {
                                                dyld::log("%18s at 0x%08llX->0x%08llX altered
permissions to %c%c%c\n", "", p->address,
                                                                p->address+p->size-1,
                                                                (prot & PROT_READ) ? 'r' : '.',  (prot &
PROT_WRITE) ? 'w' : '.',  (prot & PROT_EXEC) ? 'x' : '.' );
                                        }
                                }
                        }
                #endif
                }
                if ( gLinkContext.verboseMapping ) {
                        // list the code blob
                        dyld_cache_header* header = (dyld_cache_header*)sSharedCache;
                        uint64_t signatureSize = header->codeSignatureSize;
                        // zero size in header means signature runs to end-of-file
                        if ( signatureSize == 0 ) {
                                struct stat stat_buf;
                                // FIXME: need size of cache file actually used
                                if ( my_stat(IPHONE_DYLD_SHARED_CACHE_DIR
DYLD_SHARED_CACHE_BASE_NAME ARCH_NAME, &stat_buf) == 0 )
                                        signatureSize = stat_buf.st_size - header-
>codeSignatureOffset;
                        }
                        if ( signatureSize != 0 ) {
                                const dyld_cache_mapping_info* const last =
&start[dyld_shared_cache_ranges.sharedRegionsCount-1];
                                uint64_t codeBlobStart = last->address + last->size;
                                dyld::log("        0x%08llX->0x%08llX (code signature)\n",
codeBlobStart, codeBlobStart+signatureSize);
                        }
                }
#if __IPHONE_OS_VERSION_MIN_REQUIRED
                // check for file that enables dyld shared cache dylibs to be overridden
                struct stat enableStatBuf;
                // check file size to determine if correct file is in place.
                // See <rdar://problem/13591370> Need a way to disable roots without removing
/S/L/C/com.apple.dyld/enable...
                sDylibsOverrideCache = ( (my_stat(IPHONE_DYLD_SHARED_CACHE_DIR "enable-dylibs-to-
override-cache", &enableStatBuf) == 0)
                                                                                        &&
(enableStatBuf.st_size < ENABLE_DYLIBS_TO_OVERRIDE_CACHE_SIZE) );
#endif
        }
}
```

By using the fun feature from the **previous post**, which lets us debug user mode apps in the gdb kernel debugger, I was able to debug, by stepping through this function, and seeing what fails. To do this, I patched dyld with an `HLT` instruction, which our modified QEMU treats as a breakpoint. I then re-signed the executable with `jtool`, and added the new signature to the static trust cache:



This showed me that actually the failure is in:

```
        if (_shared_region_map_and_slide_np(fd, mappingCount, mappings, codeSignatureMappingIndex,
cacheSlide, slideInfo, slideInfoSize) == 0) {
                // successfully mapped cache into shared region
                sSharedCache = (dyld_cache_header*)mappings[0].sfm_address;
                sSharedCacheSlide = cacheSlide;
                dyld::gProcessInfo->sharedCacheSlide = cacheSlide;
        //dyld::log("sSharedCache=%p sSharedCacheSlide=0x%08lX\n", sSharedCache, sSharedCacheSlide);
        // if cache has a uuid, copy it
                if ( header->mappingOffset >= 0x68 ) {
                        memcpy(dyld::gProcessInfo->sharedCacheUUID, header->uuid, 16);
                }
        }
        else {
#if __IPHONE_OS_VERSION_MIN_REQUIRED
        throw "dyld shared cache could not be mapped";
#endif
        if ( gLinkContext.verboseMapping )
                dyld::log("dyld: shared cached file could not be mapped\n");
        }
```



Good thing I am running a kernel debugger, so I can step right into the kernel system call and see where it fails. And another good thing is that I have some version of the **code**:

```
int
shared_region_map_and_slide_np(
	struct proc                                     *p,
	struct shared_region_map_and_slide_np_args      *uap,
	__unused int                                                    *retvalp)
{
	struct shared_file_mapping_np        *mappings;
	unsigned int                         mappings_count = uap->count;
	kern_return_t                        kr = KERN_SUCCESS;
	uint32_t                    slide = uap->slide;

#define SFM_MAX_STACK       8
	struct shared_file_mapping_np        stack_mappings[SFM_MAX_STACK];

	/* Is the process chrooted?? */
	if (p->p_fd->fd_rdir != NULL) {
		kr = EINVAL;
		goto done;
	}

	if ((kr = vm_shared_region_sliding_valid(slide)) != KERN_SUCCESS) {
		if (kr == KERN_INVALID_ARGUMENT) {
			/*
			 * This will happen if we request sliding again
			 * with the same slide value that was used earlier
			 * for the very first sliding.
			 */
			kr = KERN_SUCCESS;
		}
		goto done;
	}

	if (mappings_count == 0) {
		SHARED_REGION_TRACE_INFO(
			("shared_region: %p [%d(%s)] map(): "
			 "no mappings\n",
			 (void *)VM_KERNEL_ADDRPERM(current_thread()),
			 p->p_pid, p->p_comm));
		kr = 0;  /* no mappings: we're done ! */
		goto done;
	} else if (mappings_count <= SFM_MAX_STACK) {
		mappings = &stack_mappings[0];
	} else {
		SHARED_REGION_TRACE_ERROR(
			("shared_region: %p [%d(%s)] map(): "
			 "too many mappings (%d)\n",
			 (void *)VM_KERNEL_ADDRPERM(current_thread()),
			 p->p_pid, p->p_comm,
			 mappings_count));
		kr = KERN_FAILURE;
		goto done;
	}

	if ( (kr = shared_region_copyin_mappings(p, uap->mappings, uap->count, mappings))) {
		goto done;
	}


	kr = _shared_region_map_and_slide(p, uap->fd, mappings_count, mappings,
					  slide,
					  uap->slide_start, uap->slide_size);
	if (kr != KERN_SUCCESS) {
		return kr;
	}

done:
	return kr;
}
```

By stepping through the code in the debugger, I found that the call to `_shared_region_map_and_slide()` is what actually fails:

```
/*
 * shared_region_map_np()
 *
 * This system call is intended for dyld.
 *
 * dyld uses this to map a shared cache file into a shared region.
 * This is usually done only the first time a shared cache is needed.
 * Subsequent processes will just use the populated shared region without
 * requiring any further setup.
 */
int
_shared_region_map_and_slide(
        struct proc                             *p,
        int                                     fd,
        uint32_t                        mappings_count,
        struct shared_file_mapping_np           *mappings,
        uint32_t                        slide,
        user_addr_t                             slide_start,
        user_addr_t                             slide_size)
{
        int                             error;
        kern_return_t                   kr;
        struct fileproc                 *fp;
        struct vnode                    *vp, *root_vp, *scdir_vp;
        struct vnode_attr               va;
        off_t                           fs;
        memory_object_size_t            file_size;
#if CONFIG_MACF
        vm_prot_t                       maxprot = VM_PROT_ALL;
#endif
        memory_object_control_t         file_control;
        struct vm_shared_region         *shared_region;
        uint32_t                        i;

        SHARED_REGION_TRACE_DEBUG(
                ("shared_region: %p [%d(%s)] -> map\n",
                 (void *)VM_KERNEL_ADDRPERM(current_thread()),
                 p->p_pid, p->p_comm));

        shared_region = NULL;
        fp = NULL;
        vp = NULL;
        scdir_vp = NULL;

        /* get file structure from file descriptor */
        error = fp_lookup(p, fd, &fp, 0);
        if (error) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map: "
                         "fd=%d lookup failed (error=%d)\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm, fd, error));
                goto done;
        }

        /* make sure we're attempting to map a vnode */
        if (FILEGLOB_DTYPE(fp->f_fglob) != DTYPE_VNODE) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map: "
                         "fd=%d not a vnode (type=%d)\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         fd, FILEGLOB_DTYPE(fp->f_fglob)));
                error = EINVAL;
                goto done;
        }

        /* we need at least read permission on the file */
```

```
        if (! (fp->f_fglob->fg_flag & FREAD)) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map: "
                         "fd=%d not readable\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm, fd));
                error = EPERM;
                goto done;
        }

        /* get vnode from file structure */
        error = vnode_getwithref((vnode_t) fp->f_fglob->fg_data);
        if (error) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map: "
                         "fd=%d getwithref failed (error=%d)\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm, fd, error));
                goto done;
        }
        vp = (struct vnode *) fp->f_fglob->fg_data;

        /* make sure the vnode is a regular file */
        if (vp->v_type != VREG) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "not a file (type=%d)\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp),
                         vp->v_name, vp->v_type));
                error = EINVAL;
                goto done;
        }

#if CONFIG_MACF
        /* pass in 0 for the offset argument because AMFI does not need the offset
                of the shared cache */
        error = mac_file_check_mmap(vfs_context_ucred(vfs_context_current()),
                        fp->f_fglob, VM_PROT_ALL, MAP_FILE, 0, &maxprot);
        if (error) {
                goto done;
        }
#endif /* MAC */

        /* make sure vnode is on the process's root volume */
        root_vp = p->p_fd->fd_rdir;
        if (root_vp == NULL) {
                root_vp = rootvnode;
        } else {
                /*
                 * Chroot-ed processes can't use the shared_region.
                 */
                error = EINVAL;
                goto done;
        }

        if (vp->v_mount != root_vp->v_mount) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "not on process's root volume\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name));
                error = EPERM;
                goto done;
        }

        /* make sure vnode is owned by "root" */
        VATTR_INIT(&va);
        VATTR_WANTED(&va, va_uid);
        error = vnode_getattr(vp, &va, vfs_context_current());
        if (error) {
```

```
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "vnode_getattr(%p) failed (error=%d)\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name,
                         (void *)VM_KERNEL_ADDRPERM(vp), error));
                goto done;
        }
        if (va.va_uid != 0) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "owned by uid=%d instead of 0\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp),
                         vp->v_name, va.va_uid));
                error = EPERM;
                goto done;
        }

        if (scdir_enforce) {
                /* get vnode for scdir_path */
                error = vnode_lookup(scdir_path, 0, &scdir_vp, vfs_context_current());
                if (error) {
                        SHARED_REGION_TRACE_ERROR(
                                ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                                 "vnode_lookup(%s) failed (error=%d)\n",
                                 (void *)VM_KERNEL_ADDRPERM(current_thread()),
                                 p->p_pid, p->p_comm,
                                 (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name,
                                 scdir_path, error));
                        goto done;
                }

                /* ensure parent is scdir_vp */
                if (vnode_parent(vp) != scdir_vp) {
                        SHARED_REGION_TRACE_ERROR(
                                ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                                 "shared cache file not in %s\n",
                                 (void *)VM_KERNEL_ADDRPERM(current_thread()),
                                 p->p_pid, p->p_comm,
                                 (void *)VM_KERNEL_ADDRPERM(vp),
                                 vp->v_name, scdir_path));
                        error = EPERM;
                        goto done;
                }
        }

        /* get vnode size */
        error = vnode_size(vp, &fs, vfs_context_current());
        if (error) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "vnode_size(%p) failed (error=%d)\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name,
                         (void *)VM_KERNEL_ADDRPERM(vp), error));
                goto done;
        }
        file_size = fs;

        /* get the file's memory object handle */
        file_control = ubc_getobject(vp, UBC_HOLDOBJECT);
        if (file_control == MEMORY_OBJECT_CONTROL_NULL) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "no memory object\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name));
                error = EINVAL;
```

```
                goto done;
        }

        /* check that the mappings are properly covered by code signatures */
        if (!cs_system_enforcement()) {
                /* code signing is not enforced: no need to check */
        } else for (i = 0; i < mappings_count; i++) {
                if (mappings[i].sfm_init_prot & VM_PROT_ZF) {
                        /* zero-filled mapping: not backed by the file */
                        continue;
                }
                if (ubc_cs_is_range_codesigned(vp,
                                               mappings[i].sfm_file_offset,
                                               mappings[i].sfm_size)) {
                        /* this mapping is fully covered by code signatures */
                        continue;
                }
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "mapping #%d/%d [0x%llx:0x%llx:0x%llx:0x%x:0x%x] "
                         "is not code-signed\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name,
                         i, mappings_count,
                         mappings[i].sfm_address,
                         mappings[i].sfm_size,
                         mappings[i].sfm_file_offset,
                         mappings[i].sfm_max_prot,
                         mappings[i].sfm_init_prot));
                error = EINVAL;
                goto done;
        }

        /* get the process's shared region (setup in vm_map_exec()) */
        shared_region = vm_shared_region_trim_and_get(current_task());
        if (shared_region == NULL) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "no shared region\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name));
                error = EINVAL;
                goto done;
        }

        /* map the file into that shared region's submap */
        kr = vm_shared_region_map_file(shared_region,
                                       mappings_count,
                                       mappings,
                                       file_control,
                                       file_size,
                                       (void *) p->p_fd->fd_rdir,
                                       slide,
                                       slide_start,
                                       slide_size);
        if (kr != KERN_SUCCESS) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "vm_shared_region_map_file() failed kr=0x%x\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name, kr));
                switch (kr) {
                case KERN_INVALID_ADDRESS:
                        error = EFAULT;
                        break;
                case KERN_PROTECTION_FAILURE:
                        error = EPERM;
                        break;
                case KERN_NO_SPACE:
                        error = ENOMEM;
```

```
                        break;
                case KERN_FAILURE:
                case KERN_INVALID_ARGUMENT:
                default:
                        error = EINVAL;
                        break;
                }
                goto done;
        }

        error = 0;

        vnode_lock_spin(vp);

        vp->v_flag |= VSHARED_DYLD;

        vnode_unlock(vp);

        /* update the vnode's access time */
        if (! (vnode_vfsvisflags(vp) & MNT_NOATIME)) {
                VATTR_INIT(&va);
                nanotime(&va.va_access_time);
                VATTR_SET_ACTIVE(&va, va_access_time);
                vnode_setattr(vp, &va, vfs_context_current());
        }

        if (p->p_flag & P_NOSHLIB) {
                /* signal that this process is now using split libraries */
                OSBitAndAtomic(~((uint32_t)P_NOSHLIB), &p->p_flag);
        }

done:
        if (vp != NULL) {
                /*
                 * release the vnode...
                 * ubc_map() still holds it for us in the non-error case
                 */
                (void) vnode_put(vp);
                vp = NULL;
        }
        if (fp != NULL) {
                /* release the file descriptor */
                fp_drop(p, fd, fp, 0);
                fp = NULL;
        }
        if (scdir_vp != NULL) {
                (void)vnode_put(scdir_vp);
                scdir_vp = NULL;
        }

        if (shared_region != NULL) {
                vm_shared_region_deallocate(shared_region);
        }

        SHARED_REGION_TRACE_DEBUG(
                ("shared_region: %p [%d(%s)] <- map\n",
                 (void *)VM_KERNEL_ADDRPERM(current_thread()),
                 p->p_pid, p->p_comm));

        return error;
}
```

And by stepping through this function in the kernel debugger, I found that the failure is in this `part:`

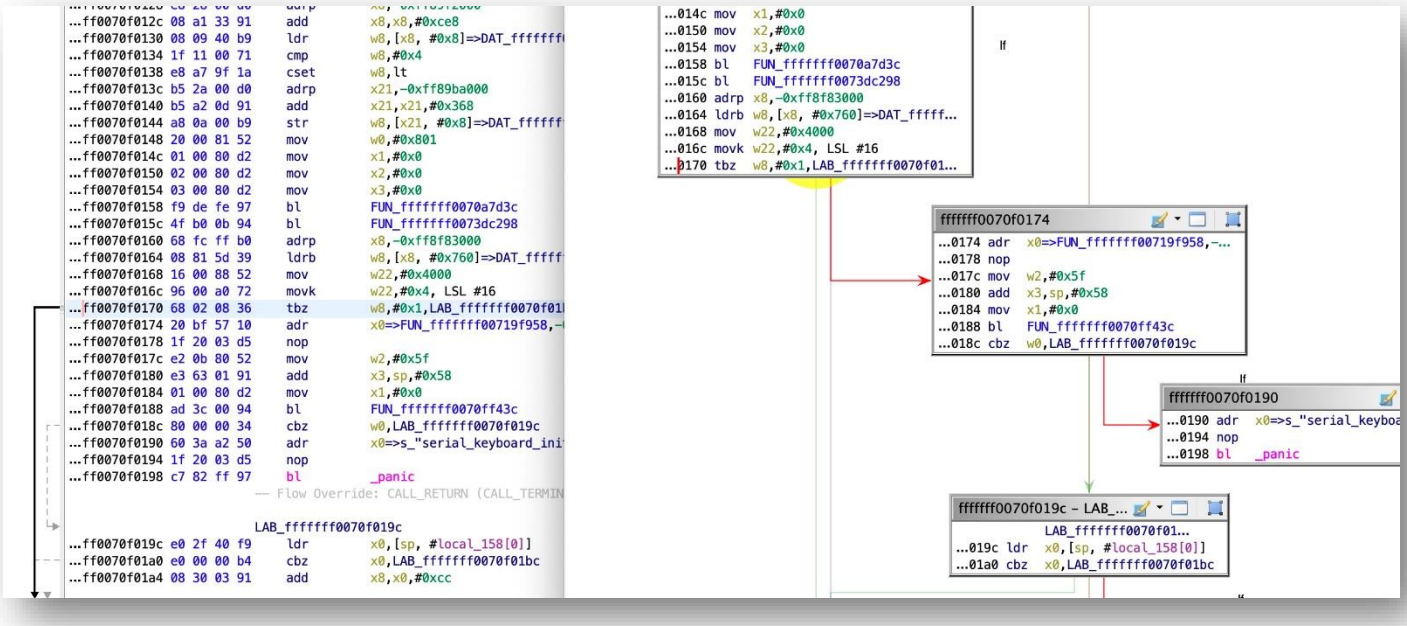
```
        /* make sure vnode is owned by "root" */
        VATTR_INIT(&va);
        VATTR_WANTED(&va, va_uid);
        error = vnode_getattr(vp, &va, vfs_context_current());
        if (error) {
                SHARED_REGION_TRACE_ERROR(
```

```
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "vnode_getattr(%p) failed (error=%d)\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name,
                         (void *)VM_KERNEL_ADDRPERM(vp), error));
                goto done;
        }
        if (va.va_uid != 0) {
                SHARED_REGION_TRACE_ERROR(
                        ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                         "owned by uid=%d instead of 0\n",
                         (void *)VM_KERNEL_ADDRPERM(current_thread()),
                         p->p_pid, p->p_comm,
                         (void *)VM_KERNEL_ADDRPERM(vp),
                         vp->v_name, va.va_uid));
                error = EPERM;
                goto done;
        }
```

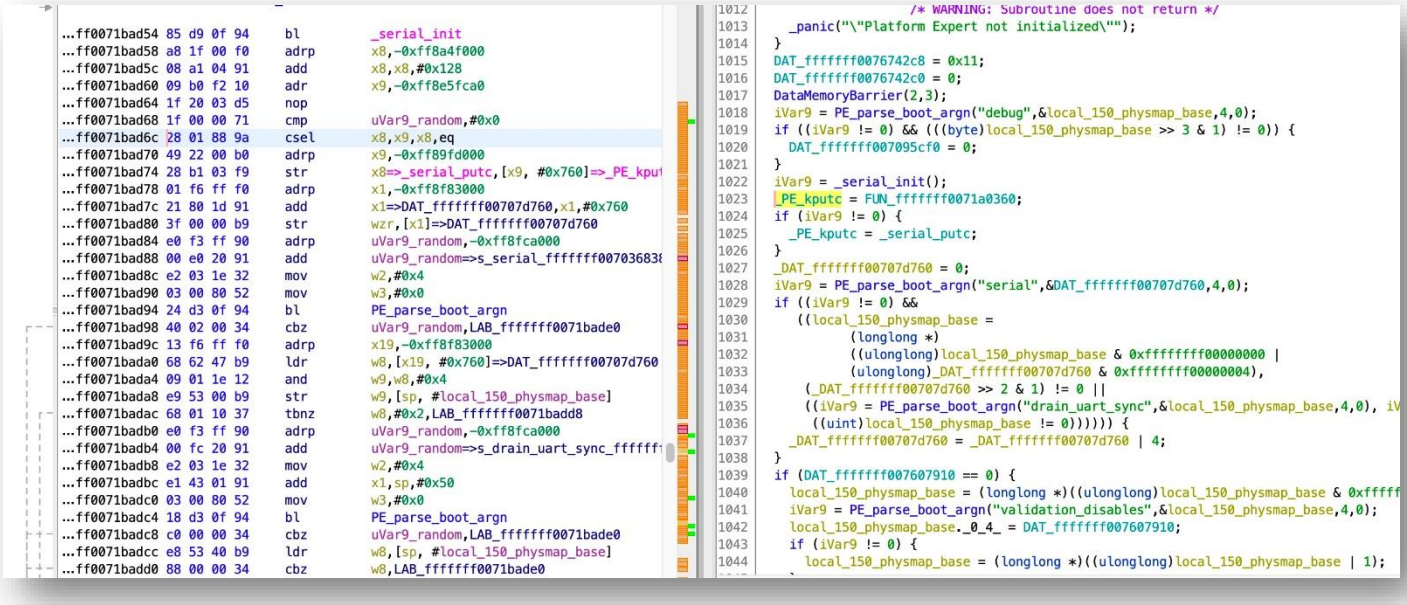
And the problem is that the cache file isn't owned by root, so I found a way to mount the ramdisk on OSX with file permissions enabled, and `chown`ed the file. This made bash work! Now we only have stdout, but no input support.

UART interactive I/O

Now, all that's left is enabling UART input. After going over and reversing some of the serial I/O handling code I found this place, which decides whether to enable the UART input (which is off by default):



This code reads a global value, and checks bit #1. If it is on, UART input is enabled. By examining this global, we can see that it is set here:



```
...ff0071bad54 85 d9 0f 94     bl        _serial_init
...ff0071bad58 a8 1f 00 f0     adrp      x8,-0xff8a4f000
...ff0071bad5c 08 a1 04 91     add       x8,x8,#0x128
...ff0071bad60 09 b0 f2 10     adr       x9,-0xff8e5fca0
...ff0071bad64 1f 20 03 d5     nop
...ff0071bad68 1f 00 00 71     cmp       uVar9_random,#0x0
...ff0071bad6c 28 01 88 9a     csel      x8,x9,x8,eq
...ff0071bad70 49 22 00 b0     adrp      x9,-0xff89fd000
...ff0071bad74 28 b1 03 f9     str       x8=>_serial_putc,[x9, #0x760]=>_PE_kput
...ff0071bad78 01 f6 ff f0     adrp      x1,-0xff8f83000
...ff0071bad7c 21 80 1d 91     add       x1=>DAT_fffffff00707d760,x1,#0x760
...ff0071bad80 3f 00 00 b9     str       wzr,[x1]=>DAT_fffffff00707d760
...ff0071bad84 e0 f3 ff 90     adrp      uVar9_random,-0xff8fca000
...ff0071bad88 00 e0 20 91     add       uVar9_random=>s_serial_fffffff00703683
...ff0071bad8c e2 03 1e 32     mov       w2,#0x4
...ff0071bad90 03 00 80 52     mov       w3,#0x0
...ff0071bad94 24 d3 0f 94     bl        PE_parse_boot_argn
...ff0071bad98 40 02 00 34     cbz       uVar9_random,LAB_fffffff0071bade0
...ff0071bad9c 13 f6 ff f0     adrp      x19,-0xff8f83000
...ff0071bada0 68 62 47 b9     ldr       w8,[x19, #0x760]=>DAT_fffffff00707d760
...ff0071bada4 09 01 1e 12     and       w9,w8,#0x4
...ff0071bada8 e9 53 00 b9     str       w9,[sp, #local_150_physmap_base]
...ff0071badac 68 01 10 37     tbnz      w8,#0x2,LAB_fffffff0071badd8
...ff0071badb0 e0 f3 ff 90     adrp      uVar9_random,-0xff8fca000
...ff0071badb4 00 fc 20 91     add       uVar9_random=>s_drain_uart_sync_fffffff
...ff0071badb8 e2 03 1e 32     mov       w2,#0x4
...ff0071badbc e1 43 01 91     add       x1,sp,#0x50
...ff0071badc0 03 00 80 52     mov       w3,#0x0
...ff0071badc4 18 d3 0f 94     bl        PE_parse_boot_argn
...ff0071badc8 c0 00 00 34     cbz       uVar9_random,LAB_fffffff0071bade0
...ff0071badcc e8 53 40 b9     ldr       w8,[sp, #local_150_physmap_base]
...ff0071badd0 88 00 00 34     cbz       w8,LAB_fffffff0071bade0
```

```
1012                    /* WARNING: Subroutine does not return */
1013    _panic("\"Platform Expert not initialized\"");
1014  }
1015  DAT_fffffff0076742c8 = 0x11;
1016  DAT_fffffff0076742c0 = 0;
1017  DataMemoryBarrier(2,3);
1018  iVar9 = PE_parse_boot_argn("debug",&local_150_physmap_base,4,0);
1019  if ((iVar9 != 0) && (((byte)local_150_physmap_base >> 3 & 1) != 0)) {
1020    DAT_fffffff007095cf0 = 0;
1021  }
1022  iVar9 = _serial_init();
1023  _PE_kputc = FUN_fffffff0071a0360;
1024  if (iVar9 != 0) {
1025    _PE_kputc = _serial_putc;
1026  }
1027  _DAT_fffffff00707d760 = 0;
1028  iVar9 = PE_parse_boot_argn("serial",&DAT_fffffff00707d760,4,0);
1029  if ((iVar9 != 0) &&
1030     ((local_150_physmap_base =
1031             (longlong *)
1032             ((ulonglong)local_150_physmap_base & 0xffffffff00000000 |
1033             (ulonglong)_DAT_fffffff00707d760 & 0xffffffff00000004),
1034      (_DAT_fffffff00707d760 >> 2 & 1) != 0 ||
1035      ((iVar9 = PE_parse_boot_argn("drain_uart_sync",&local_150_physmap_base,4,0), iV
1036       ((uint)local_150_physmap_base != 0))))) {
1037    _DAT_fffffff00707d760 = _DAT_fffffff00707d760 | 4;
1038  }
1039  if (DAT_fffffff007607910 == 0) {
1040    local_150_physmap_base = (longlong *)((ulonglong)local_150_physmap_base & 0xffff
1041    iVar9 = PE_parse_boot_argn("validation_disables",&local_150_physmap_base,4,0);
1042    local_150_physmap_base._0_4_ = DAT_fffffff007607910;
1043    if (iVar9 != 0) {
1044      local_150_physmap_base = (longlong *)((ulonglong)local_150_physmap_base | 1);
```

The value is taken from the `serial` boot arg. So finally, by setting the `serial` boot arg to `2` (bit #1 on) I got an interactive bash shell!

Conclusion

This project was a lot of fun and the team plans to keep working on it and expand the features displayed out in the previous post. This post shows some of the details of some of the interesting parts of the work, but as I worked very sparsely on this project for the past few months, and documentation during the research lacked some details, not all the details are here. With that in mind, all the functionality is in the code which does include comments in non-trivial places. I got into iOS internals only through this project, so some parts can possibly be improved, and I already received some improvement suggestions. If you have any comments/ideas/suggestions for this project, please contact me.