Digging Deep: Finding 0days in Embedded Systems with Code Coverage Guided Fuzzing

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About us - NGUYEN Anh Quynh

- NGUYEN Anh Quynh, aquynh -at- gmail.com

  - 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 us - Kai Jern 'xwings' LAU

- Kai Jern 'xwings' LAU, xwings -at- hitb.org
  - The Shepherd Lab, JD.com
  - IoT research, Blockchain research
  - HackInTheBox, CodeGate, VXRL, QCon, KCon, DC852, DC010, beVX, Brucon, H2HC, etc
  - Founder of Hackersbadge.com, RE & CTF fan
  - HackInTheBox crew & Review Board

Agenda

1. Coverage Guided Fuzzer vs Embedded Systems
2. Emulating Firmware
3. Skorpio Dynamic Binary Instrumentation
4. Guided Fuzzer for Embedded
5. Demos
6. Conclusions

Guided Fuzzer vs Embedded Systems

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?
  - Restricted system
  - Binary only (no source code)
  - Lack support for embedded hardware

Emulating Firmware

Emulating firmware for fuzzing

- Extract firmware of the target device
- Extract the target binary from firmware
- Run the target binary on Virtual machine on QEMU
  - Fix missing dependency (standard system binary, SO files, etc)
  - Emulate wireless device
  - Emulate NVRAM

Skorpio Dynamic Binary Instrumentation

Dynamic Binary Instrumentation (DBI)

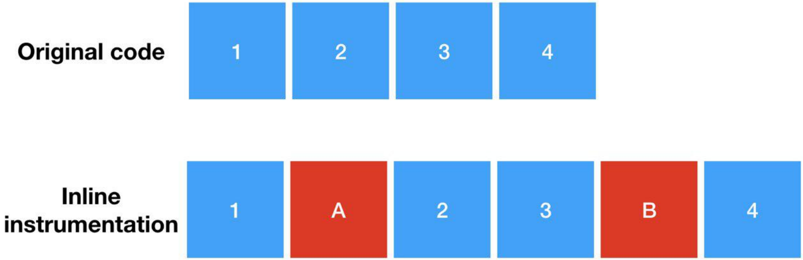
Definition

- 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

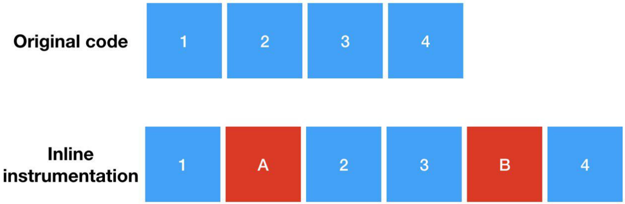


DBI techniques

- 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

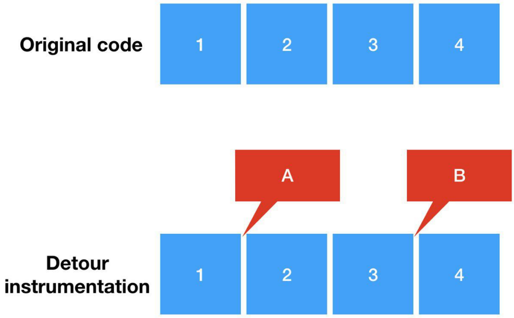
Hooking mechanisms - Inline

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



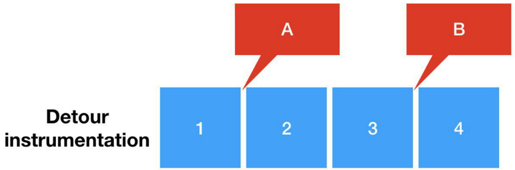
Hooking mechanisms - Detour

- 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

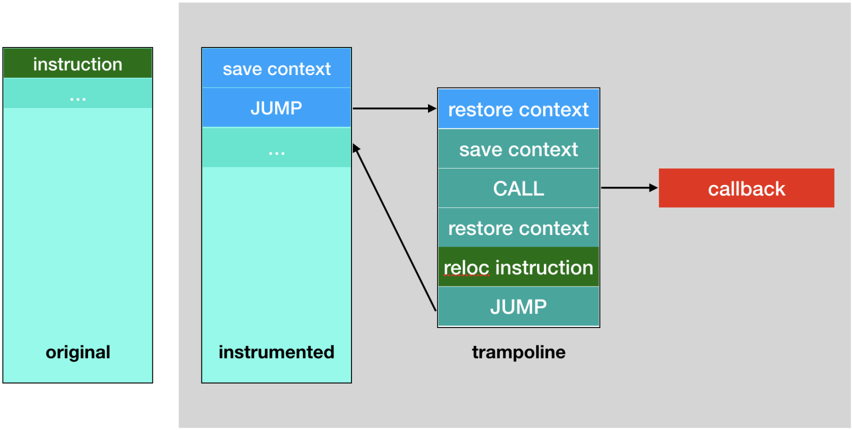


Detour injection mechanisms

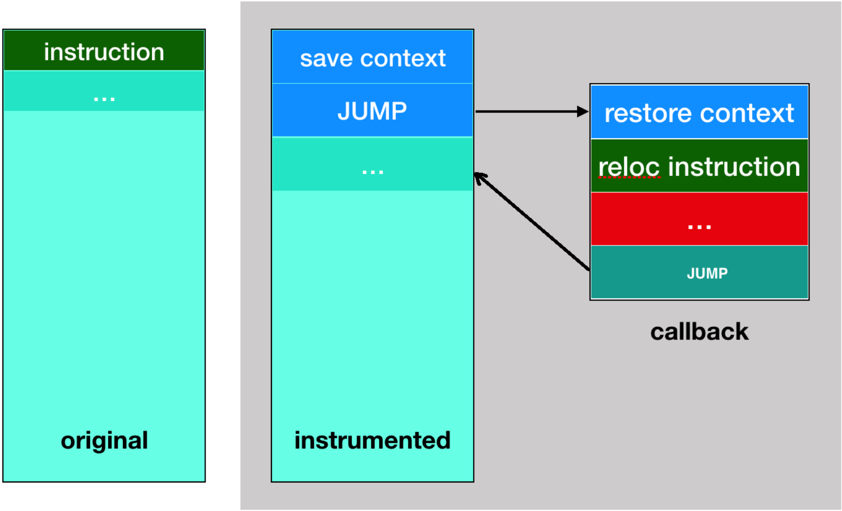
- Branch from original instruction to instrumented code
- Branch to trampoline, or directly to callback
  - Jump-trampoline technique
  - Jump-callback technique
  - Call-trampoline technique
  - Call-callback technique



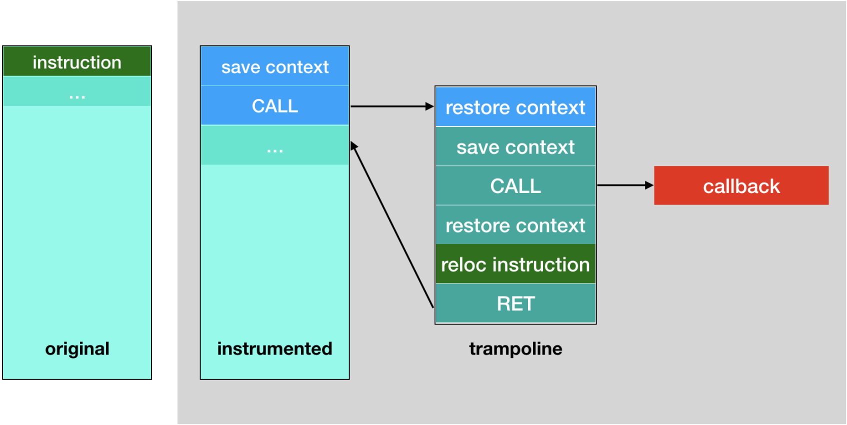
Jump-trampoline technique



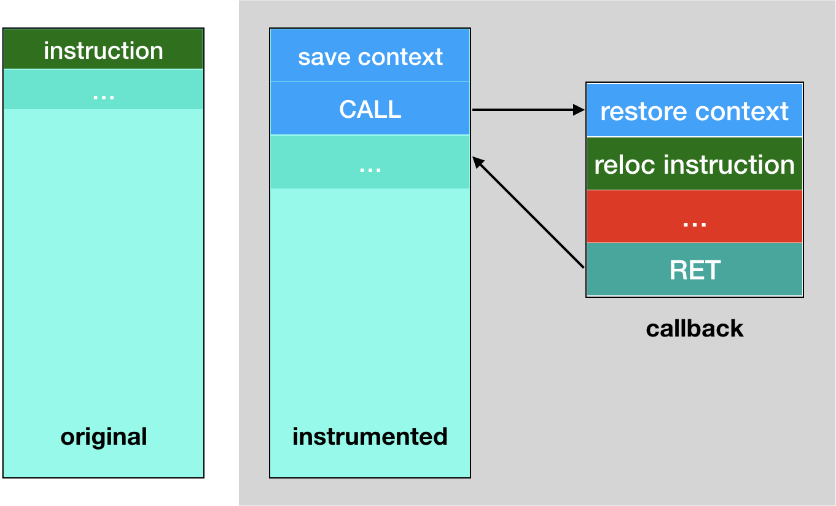
Jump-callback technique



Call-trampoline technique



Call-callback technique



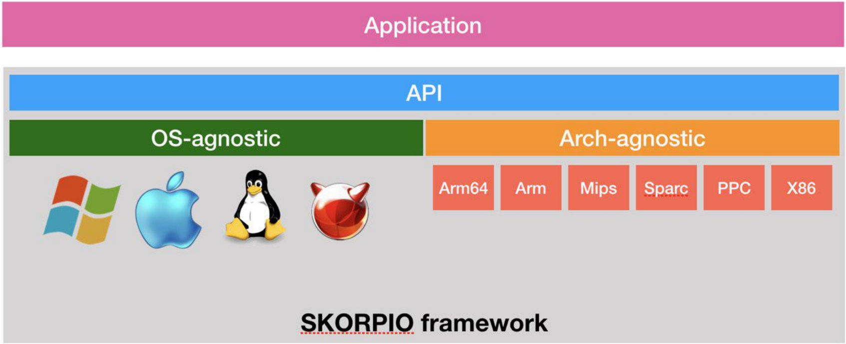
Problems of existing DBI

- 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

Guided Fuzzer for Embedded

Fuzzer Features

- Coverage guided 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 binary 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

Fuzzer Instrumentation

- LD_PRELOAD to dynamically inject instrumentation
  - Take place before main program runs
  - Linux: shared object file (.so)
- Inject hooks at SO initialisation time
  - Can be 100k hooks, so must do as quickly as possible
- Inject forkserver at program entry-point, or at user-defined point

Detect Memory Corruption

- Built-in memory debugging for better control & performance
  - Overload malloc(), free() & co
  - Utilize MMU to detect overflow/underflow bugs (like Off-by-1)
  - Use-after-free bug

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

Demos

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 & answers

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