Killing the Myth of Cisco IOS Diversity

Towards Large-Scale Exploitation of Cisco IOS

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Prior Work

FX, 2003
LYNN, 2005
UPPAL, 2007
DAVIS, 2007
MUNIZ, 2008
FX, 2009
MUNIZ AND ORTEGA, 2011

Not comprehensive, but is a good start
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MOTIVATION
Killing the Myth of Cisco IOS Diversity

Motivation

Cisco IOS is a high value target
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Cisco IOS is “undefended”
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MOTIVATION

Cisco IOS is a high value target
Cisco IOS is “undefended”
Cisco IOS is “unmonitored”
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**MOTIVATION**

Cisco IOS is a high value target
Cisco IOS is “undefended”
Cisco IOS is “unmonitored”
Cisco IOS can be exploited, just like everything else
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Motivation

But there the problem of software diversity
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But there the problem of software diversity

Approximately 300,000 unique IOS images
No reliable binary invariant
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Motivation

But there the problem of software diversity

Approximately 300,000 unique IOS images
No reliable binary invariant

The (last) major obstacle in large-scale IOS exploitation
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Reliable Shellcode

• IOS Diversity means Binary Diversity
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Reliable Shellcode

• IOS Diversity means Binary Diversity, not functional diversity
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Reliable Shellcode

• IOS Diversity means Binary Diversity, not functional diversity

• In fact, IOS is rich in Functional invariants

• For example:

```
Router>
Router>enable
Password: Password: Password: % Bad secrets
Router>
```

Functional monoculture in every box!
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Reliable Shellcode

• General strategy to overcome IOS diversity

• Use functional invariants to resolve binary targets

• For example: (see FX, 2009)
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Reliable Shellcode

• General strategy to overcome IOS diversity
  • Use functional invariants to resolve binary targets
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"Bad Secrets"

A: str

.text | .data
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Reliable Shellcode

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Reliable Shellcode

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Disassembling Shellcode #1

• **There is a catch (called the watchdog timer)**

Compute too long, and you will get caught!

Shellcode is heavily resource constrained.

Must resolve binary target using fast, (sub)linear algorithms.
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Interrupt-Hijack Shellcode

• Let’s kill 3 birds with one stone
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Interrupt-Hijack Shellcode

• Let’s kill 3 birds with one stone
  • Faster
    • Enable-bypass shellcode: 2N algorithm
    • Interrupt-hijack shellcode: twice as fast
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Interrupt-Hijack Shellcode

• Let’s kill 3 birds with one stone
  • Faster
  • Stealthier
    • Enable-bypass, vty rebind, etc requires persistent TCP connection
    • Interrupt-Hijack uses the payload of process-switched packets as a covert command and control channel
    • C&C is bidirectional thanks to IOMEM scrubber
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Interrupt-Hijack Shellcode

- Let’s kill 3 birds with one stone
  - Faster
  - Stealthier
  - More Control
    - No need to be constrained by IOS shell
    - Rootkit runs @ supervisor mode. We can even write to eeprom (See last slide)
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Interrupt-Hijack Shellcode

• 1st stage:

.text ...

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Interrupt-Hijack Shellcode

- 1\textsuperscript{st} stage: Unpack 2\textsuperscript{nd} stage

\texttt{.text} ...

$GP$

2nd-stage code
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Interrupt-Hijack Shellcode

• 1st stage: Unpack 2nd stage, hijack all int-handlers
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Interrupt-Hijack Shellcode

- 1st stage: Unpack 2nd stage, hijack all INT-handlers, compute hash on addresses of “ERET” instructions (why?)
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Interrupt-Hijack Shellcode

- 2nd-stage: Exception Hijack and IOMEM snooping

ISR #1  ISR #2  ISR #3  ...  ISR #N

2nd-stage shellcode: init

IOMEM Packet Scrubber

Load Code

Execute Code

Exfiltrate Data

2nd-stage shellcode: exit

eret

Interrupt-Hijack shellcode frees us from the tyrannies of the watchdog timer.

Perpetual, stealthy execution!

The (MIPS) ERET, or Exception-Return is an architecture invariant

ISR entry point is a binary invariant, typically found at 0x600080180, etc

Can just hijack entry point, but there is an ulterior motive

Use ERET locations in the image to fingerprint IOS version
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Int-Hijack Shellcode: Fingerprint Exfiltration

- ICMP is convenient, but any "process-switched" packet will suffice.
- C&C inside payload of "normal" traffic.
- Complex third-stage payloads can be assembled in a "protocol-spread-spectrum" manner.
- Ping, DNS, PDUs, TCP, all the same as long as it is process-switched.

Diagram:

1: Attacker sends ICMP request with magic pattern in payload.

Victim Router

RX Queue

Interrupt Hijack Shellcode

TX Queue

Attacker
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**INT-HIJACK SHELLCODE:** FINGERPRINT EXFILTRATION

- ICMP IS CONVENIENT, BUT ANY “PROCESS-SWITCHED” PACKET WILL SUCCFICE
- C&C INSIDE PAYLOAD OF “NORMAL” TRAFFIC
- COMPLEX THIRD-STAGE PAYLOADS CAN BE ASSEMBLED IN A “PROTOCOL-SPREAD-SPECTRUM” MANNER
- PING, DNS, PDUS, TCP, ALL THE SAME AS LONG AS IT IS PROCESS-SWITCHED

Runtime fingerprint gives us positive ID on the victim router's hardware platform and IOS version!
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Reliable Shellcode

- General strategy to overcome IOS diversity
  - Use functional invariants to resolve binary targets
  - IOS Diversity is (very) finite
  - How do you defeat address space randomization?
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RELIABLE SHELLCODE

• General strategy to overcome IOS diversity

  • Use functional invariants to resolve binary targets

  • IOS Diversity is (very) finite

    • How do you defeat ASR if there are ONLY 300,000 possible permutations?
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Reliable Shellcode

• General strategy to overcome IOS diversity
  • Use functional invariants to resolve binary targets
  • IOS Diversity is (very) finite
    • How do you defeat ASR if there are ONLY 300,000 possible permutations?
    • Build a lookup table!
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Generalized reliable exploitation of IOS (in 4 simple steps)

1.a: exploit vulnerability, load and run 1st stage eret-hijack rootkit (~400 bytes, pic, will run anywhere)
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1.b: 1st stage code locates/hijacks all eret instructions, exfiltrate hash (fingerprint) of eret-addrs back to attacker (via ICMP, etc)
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Generalized reliable exploitation of IOS (in 4 simple steps)

1.a: Exploit vulnerability, load and run 1st stage eret-hijack rootkit (~400 bytes, PIC, will run anywhere)

1.b: 1st stage code locates/hijacks all eret instructions, exfiltrate hash (fingerprint) of eret-addrs back to attacker (via ICMP, etc)

2.a: Attacker consults offline IOS fingerprint database, makes positive ID (hardware platform, IOS version)

Phase 2.a ID Victim Router

Attacker

Victim IOS Device

IOS Database
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Generalized reliable exploitation of IOS (in 4 simple steps)

1.a: EXPLOIT VULNERABILITY, LOAD AND RUN 1ST STAGE ERET-HIJACK ROOTKIT (~400 BYTES, PIC, WILL RUN ANYWHERE)

1.b: 2ST STAGE CODE LOCATES/HIJACKS ALL ERET INSTRUCTIONS, EXFILTRATE HASH (FINGERPRINT) OF ERET-ADDRS BACK TO Attacker (VIA ICMP, etc)

2.a: Attacker consults offline IOS fingerprint database, makes positive ID (hardware platform, IOS version)

2.b: Construct version dependent 3RD stage payload. Upload using 2ND stage C&C (again, using ICMP, etc)… WIN!
3rd Stage Payloads!

- More demos
- Third-stage payloads to:
  - Disable IOS integrity verification command “show sum”
  - Disable password authentication
  - Remote bricking of router motherboard
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SACRIFICE
TO THE
DEMO
GODS

Remotely brickling router using 3rd-stage payload over ICMP!

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What’s Next (Offensive)?

• More comprehensive fingerprint database
  • ~3,000 images in the fingerprint DB. Roughly 1% coverage.
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- EEPROM resident malware
  - Current Rootkit will not survive IOS update
  - Better to live in EEPROM
    - Line cards
    - Network modules
    - Motherboard EEPROM
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What’s Next (Offensive)?

• More comprehensive fingerprint database
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• EEPROM resident malware
  • Current Rootkit will not survive IOS update
  • Better to live in EEPROM
    • Line cards
    • Network modules
    • Motherboard EEPROM

• Lawful Intercept Hijacking, routing shenanigans, be creative!
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What’s Next (Defensive)?

• Software Symbiotes
  • Generic Host-based Defense for Embedded Devices.
  • “Defending Legacy Embedded Systems with Software Symbiotes”
• To Appear in RAID 2011. Look out!
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What’s Next (Defensive)?

- Cisco IOS Rootkit Detectors
  - Runs on Real Cisco Iron
  - Deployed in real networks
  - Will catch real IOS malware

CONTROL-FLOW INTERCEPST

SYMBIOTE & PAYLOAD
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What’s Next (Defensive)?

- Cisco IOS Rootkit Detectors
  - Runs on Real Cisco Iron
  - Deployed in real networks
  - Will catch real IOS malware

- A friendly shootout to test our defenses? :-)

- Please contact us!

CONTROL-FLOW INTERCEPTS

SYMBIOTE & PAYLOAD

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In the City of New York
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ANSWERS!

• FEEL FREE TO CONTACT US
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• PLEASE CHECKOUT OUR PUBLICATIONS AND ONGOING RESEARCH
  • HTTP://IDS.CS.COLUMBIA.EDU

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BACKUP SLIDES
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Disassembling Shellcode #1

• Originally presented by Felix Linder

Somewhere in every IOS image...

FLAG = passwordisright()

IF (FLAG!=0){
    ROOTME()
}
ELSE {
    printf("bad secrets -("n")
}
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Disassembling Shellcode #1

- Originally presented by Felix Linder

somewhere in every IOS image...

```assembly
FLAG = 1

IF (flag!=0){
    rootme()
}
ELSE {
    printf("bad secrets -("
}
```

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Comparison of potential fingerprint features

- Fairly random, can be used to fingerprint IOS
- A single feature fingerprint
- One firmware, one address
- Potential for collision higher than the next option

Distribution of "Bad Secrets" string x-ref in IOS (32-bit memory space)
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Comparison of Potential Fingerprint Features

- Concentrated in a predictable range in IOS memory
- Yet diverse enough to uniquely identify unknown firmware version
- Also needed in 2nd stage rootkit, kill 2 birds with one stone
- In our opinion, a pretty good target, but there are many others.
- Multi-vector feature. Each image contains approximately 6-30 ERET instructions.
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The basic idea

- Reduce (binary) diverse target to a (functional) monoculture
- Take advantage of offline processing
  - Use a two-phase attack
  - Build a database of device fingerprints
- Macro-ize 3rd stage payloads, generate device specific payloads on the fly
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For example

Dotplot of two minor revisions of 12.4 IOS images for the same hardware

IOS 12.4-23b vs 12.4-12
Cisco 7200 / NPE-200