Recurity Labs

Developments in Cisco IOS Forensics

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Invent & Verify

Agenda

- Why Network Equipment Forensics?
- Types of Attacks
- Types of Evidence
- Binary Evidence Analysis
- Reality Check IOS Exploitation

Why Cisco?

- This talk is Cisco centric
  - 92% market share* for routers above $1,500
  - 71% market share* enterprise switch market
- What about Juniper?
  - From both attacker and forensics point of view, Juniper routers are just FreeBSD
- What about <someCheapHomeRouter>
  - From both attacker and forensics point of view, they are just embedded Linux systems

*Source: Randomly stolen

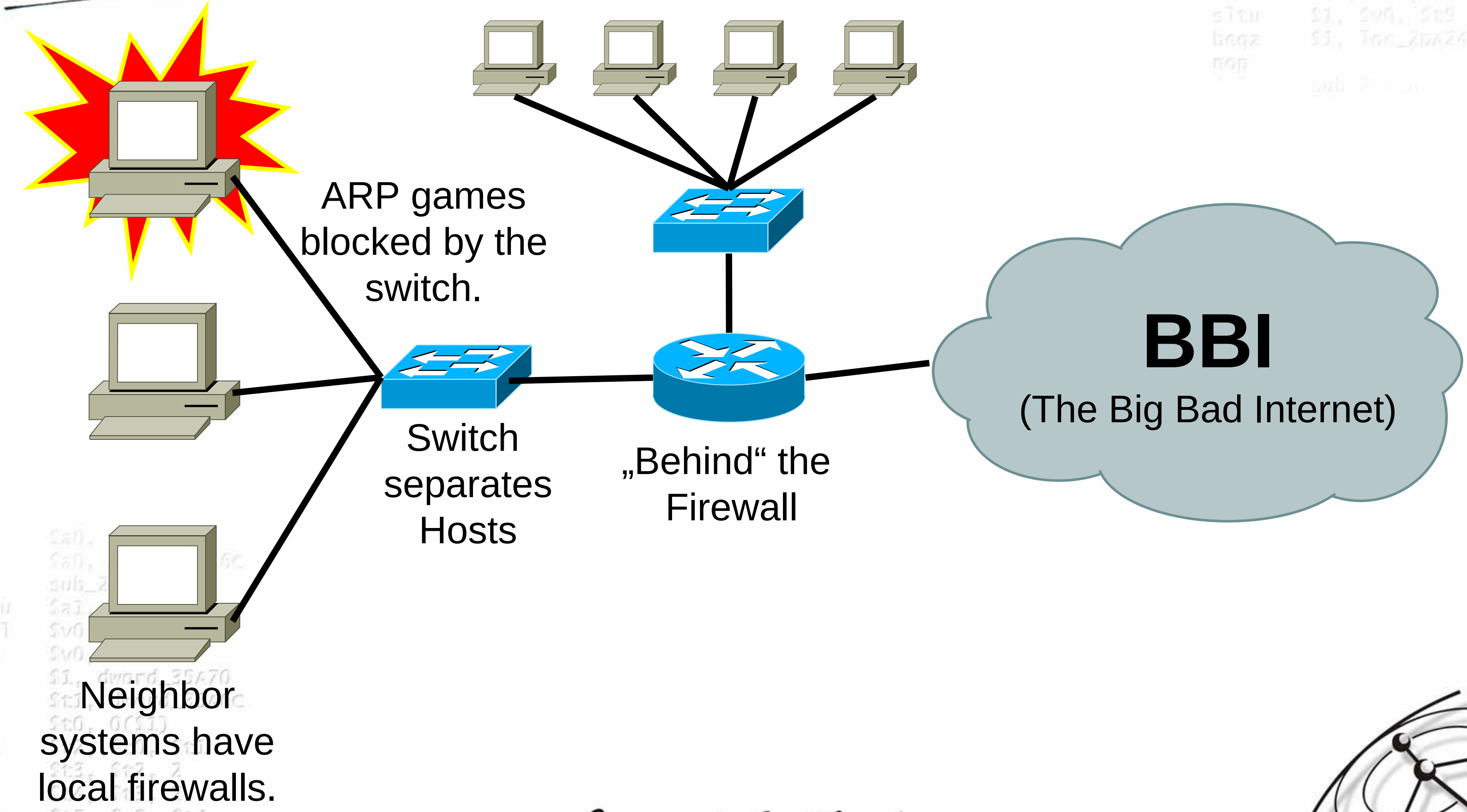
Why Network Equipment Forensics?

- By definition, the goal of computer forensics is to explain the current state of a digital artifact.
- Forensic investigations always consist of
  - Acquisition of evidence
  - Recovering information from evidence
  - Analysis of the information
- For common operating systems, the methods and tools are well established
- For network equipment, they are not

Who would hack routers?

- Compromising one machine
  ... gains you access to one machine.
- Compromising one important machine
  ... gains you access to a couple machines.
- Compromising one switch
  ... gains you access to all machines connected.
- Compromising one router
  ... gains you access to everything in the network.

Who would hack routers?



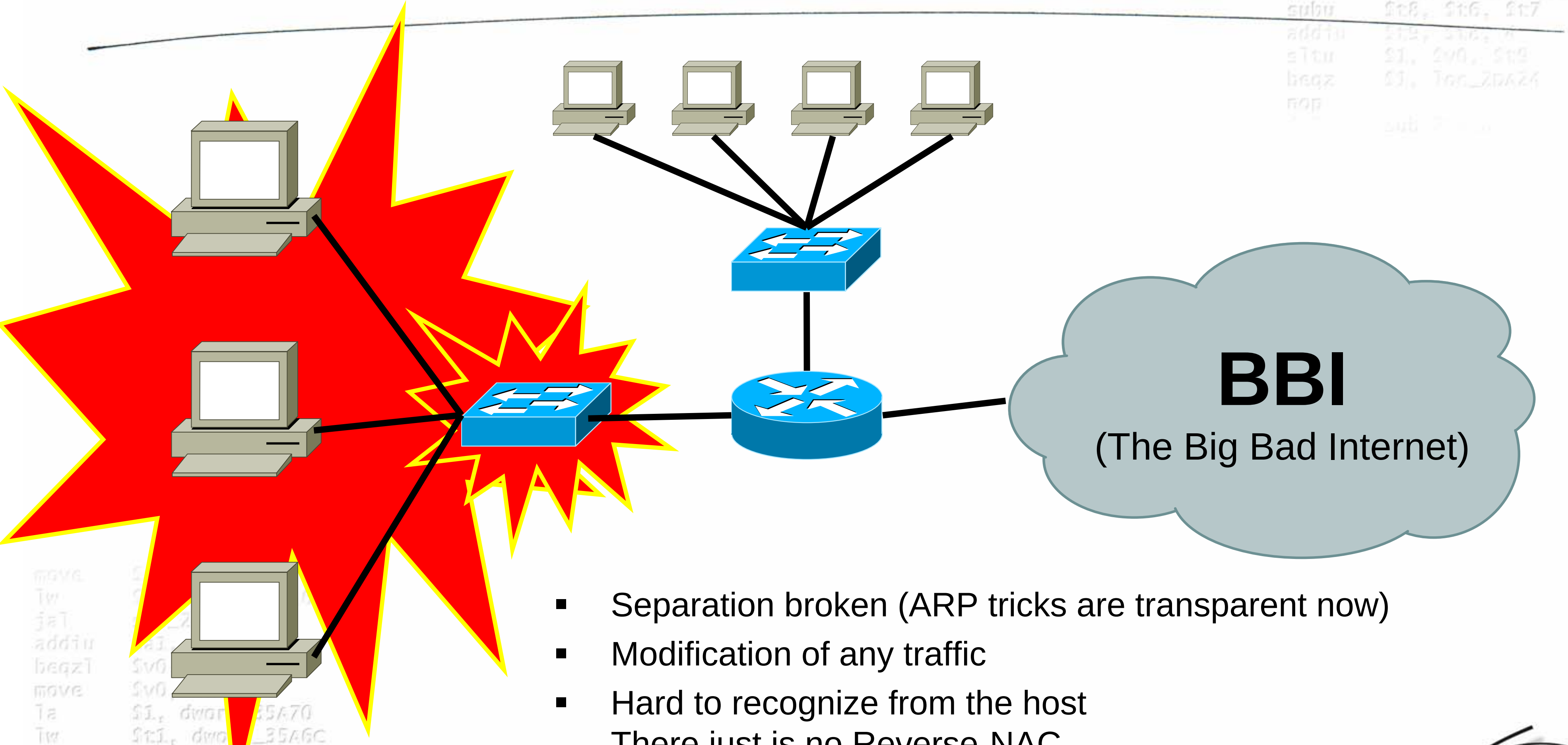
ARP games blocked by the switch.

Switch separates Hosts

„Behind“ the Firewall

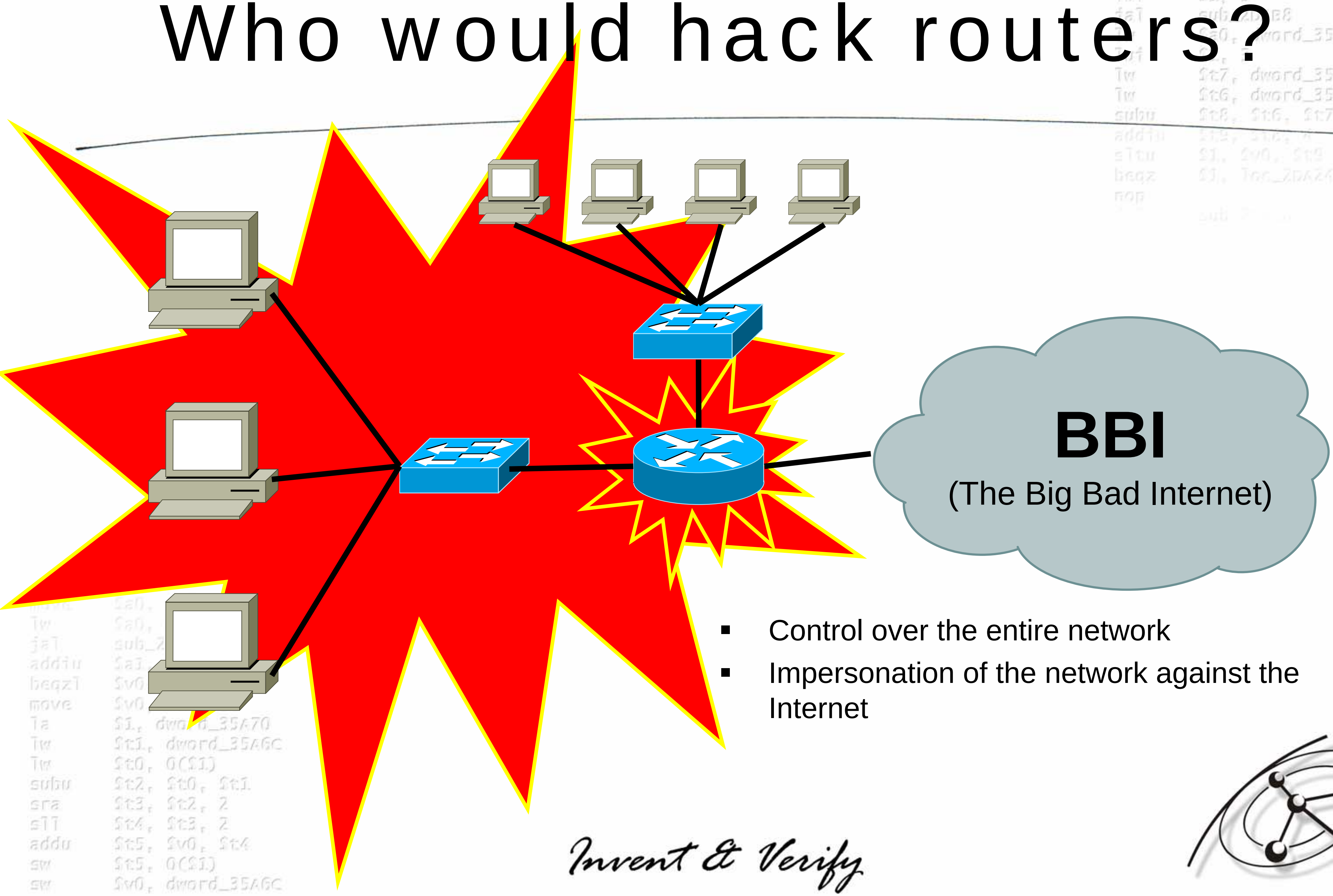
Neighbor systems have local firewalls.

Who would hack routers?



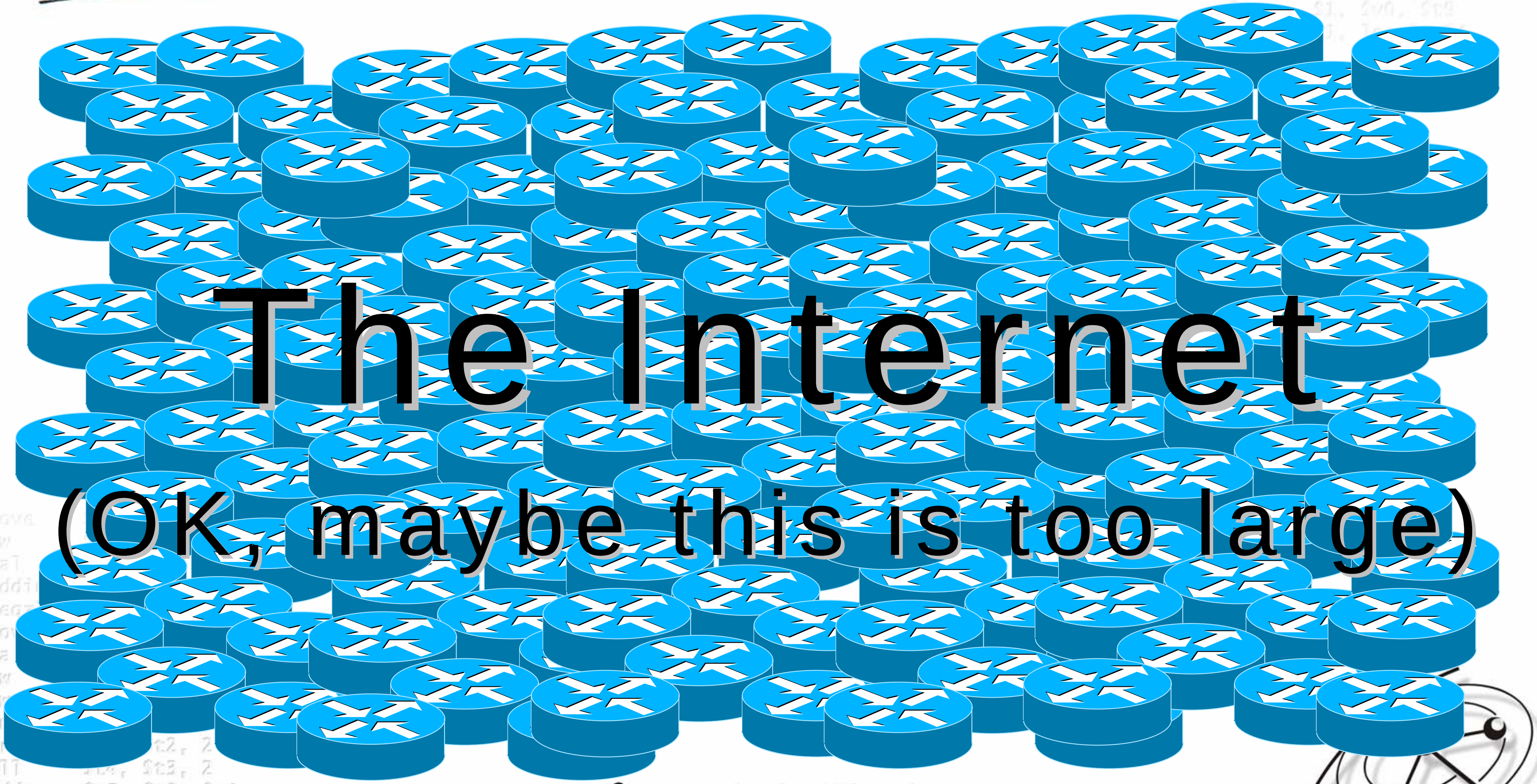
- Separation broken (ARP tricks are transparent now)
- Modification of any traffic
- Hard to recognize from the host
  There just is no Reverse-NAC.

Who would hack routers?



- Control over the entire network
- Impersonation of the network against the Internet

And on a larger scale...



The Internet

(OK, maybe this is too large)

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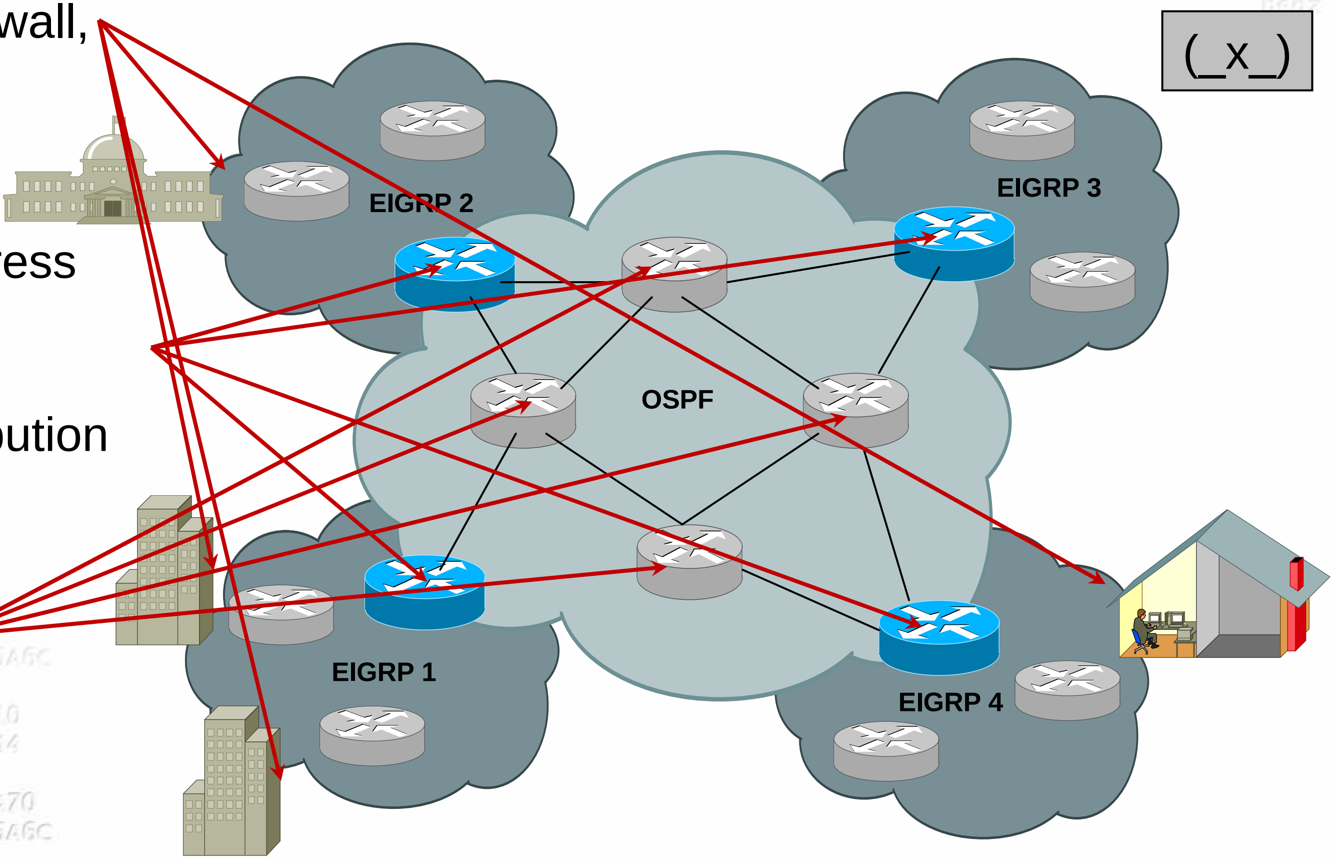
One scale down: Network Security



Network Firewall, IDS, IPS

Ingress & Egress Filtering, anti-spoofing, route redistribution

Full Trust within the autonomous system

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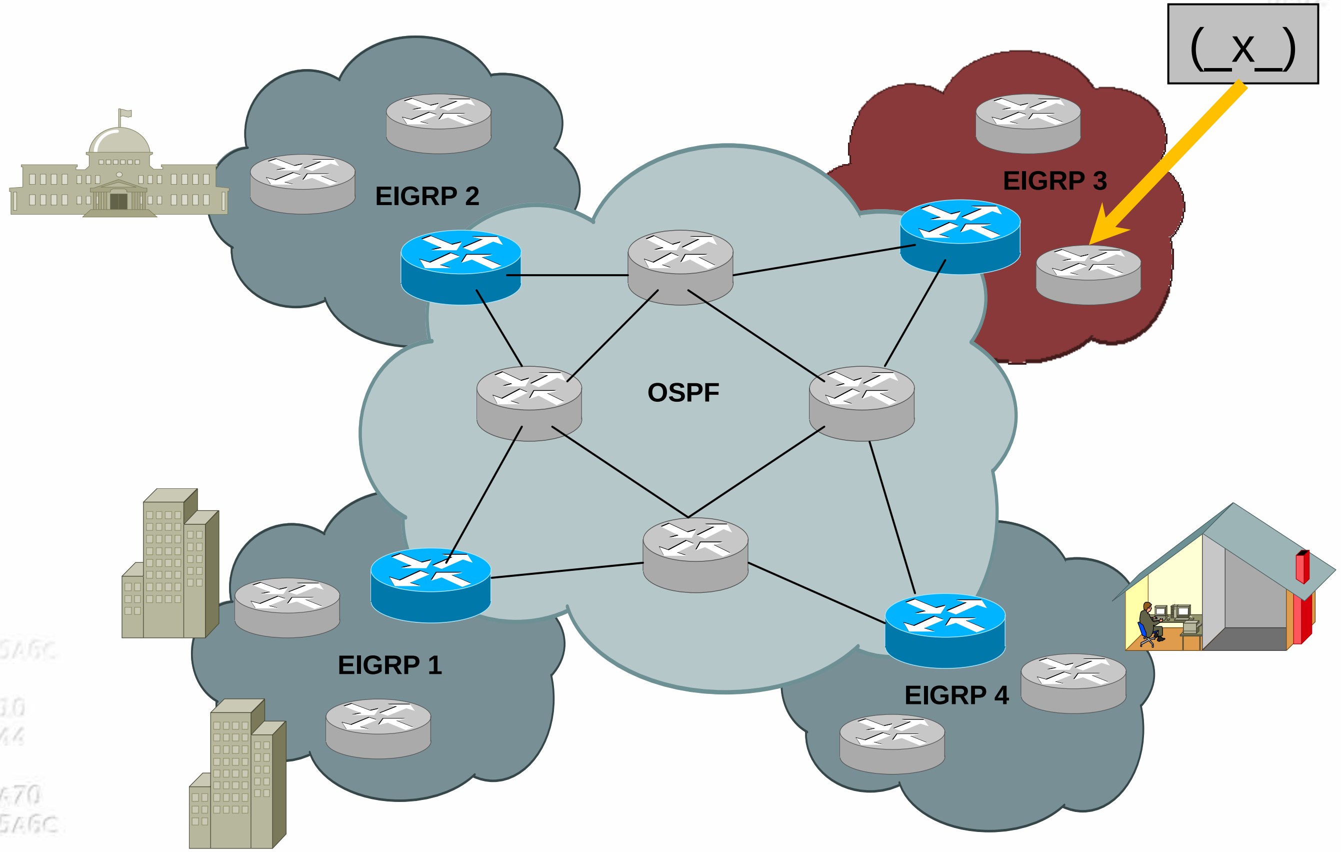
Network Security

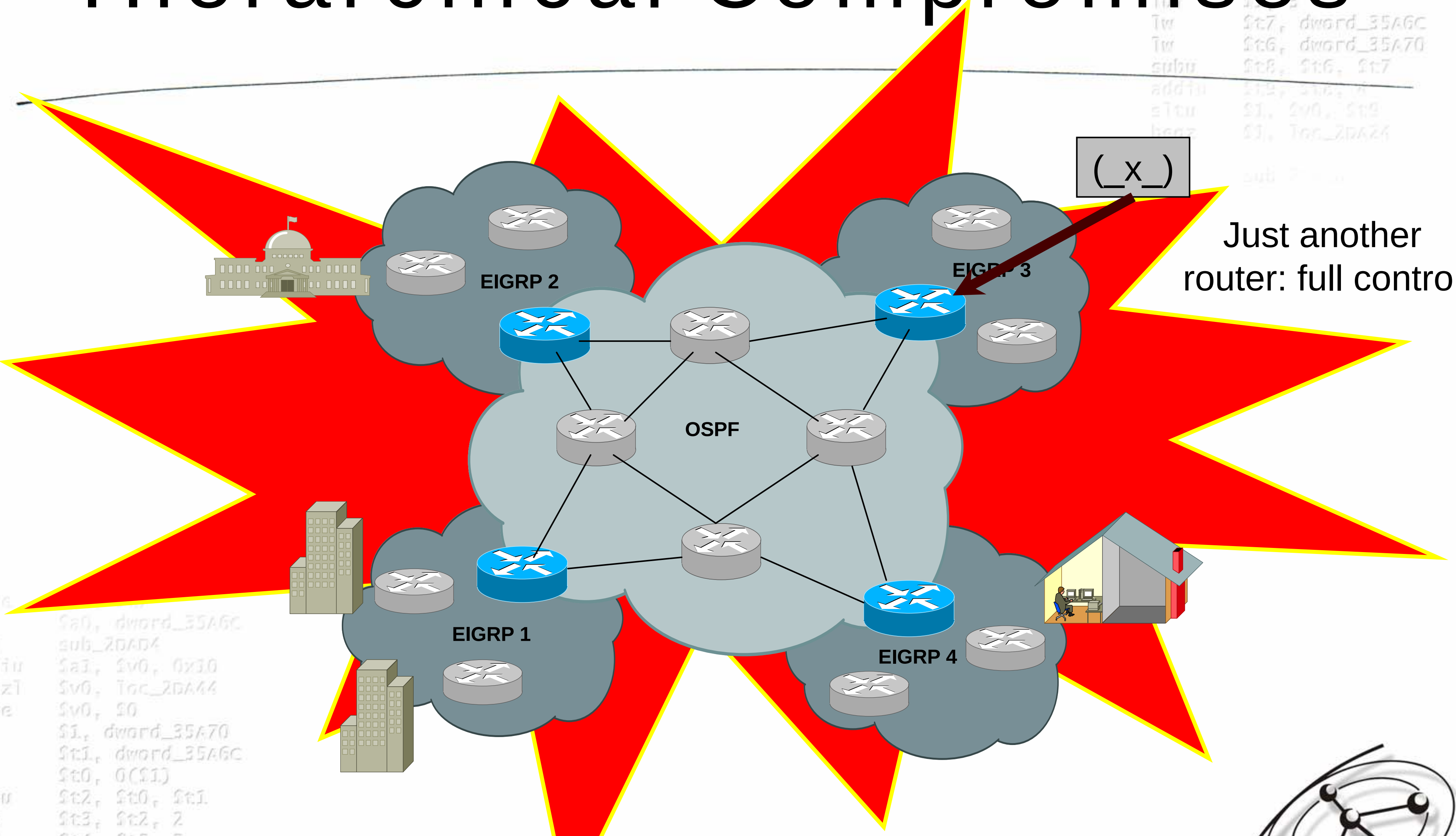
- Network security is hierarchical
  - Defending against your downstream is common
  - Defending against your upstream is rather hard
  - Defending against your peers is rare
- Control anything in the hierarchy and you control everything below

Hierarchical Compromises



Local network compromise

Hierarchical Compromises



Just another router: full control

But we got <secureProtocol>

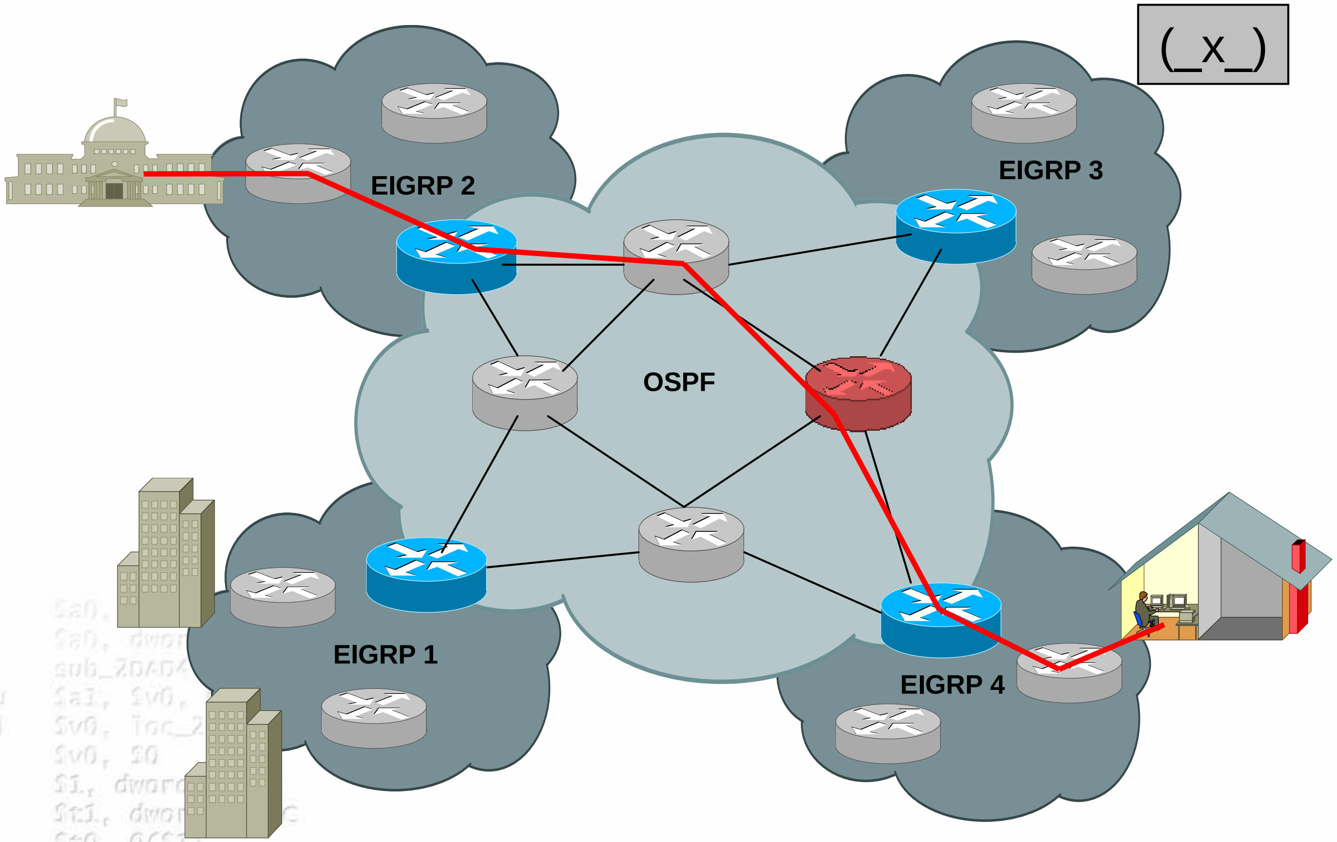
- Secure protocols can guarantee that nobody

  …modified the protocol messages

  …spoofed the communication peer

  …replayed the protocol messages
- But **if** someone did exactly that, they cannot do anything about it.
  - The choice is: Availability or Security
  - What would your boss / mom do?

But we got <secureProtocol>



If the user ***could*** control the path his communication is using, it would be called „source routing“ and there is a reason this is no longer in use *anywhere* in the Internet: The user would have power over the network.

All this is by design

- In IP networks
  - The network node makes the forwarding decisions
  - The leaf node cannot control the traffic flow

Types of Attacks against Network Equipment

- Protocol based attacks
- Functionality attacks
- Binary exploitation

Protocol attacks

- Injection of control protocol messages into the network (routing protocol attacks)
  - Attacker becomes part of the network’s internal communication
  - Attacker influences how messages are forwarded
- Typical examples include:
  - ARP poisoning
  - DNS poisoning
  - Interior routing protocol injections (OSPF, EIGRP)
  - Exterior routing subnet hijacking (BGP)

Functionality attacks

- Configuration problems
  - Weak passwords (yes, they are still big)
  - Weak SNMP communities
  - Posting your configuration on Internet forums
- Access check vulnerabilities
  - Cisco’s HTTP level 16++ vulnerability
  - SNMPv3 HMAC verification vulnerability (2008!)
    - memcmp(MyHMAC, PackHMAC, PackHMAC_len);
  - Debianized SSH keys
- Queuing bugs (Denial of Service)

Binary exploitation

- Router service vulnerabilities:
  - Phenoelit’s TFTP exploit
  - Phenoelit’s HTTP exploit
  - Andy Davis’ FTP exploit
- Router protocol vulnerabilities:
  - Phenoelit’s OSPF exploit
  - Michael Lynn’s IPv6 exploit

Detection and Monitoring

- SNMP
  - Polling mechanisms, rarely push messages (traps)
- Syslog
  - Free-form push messages
- Configuration polling
  - Polling and correlation
- Route monitoring and looking glasses
  - Real-time monitoring of route path changes
- Traffic accounting
  - Not designed for security monitoring, but can yield valuable information on who does what

Who detects what?

	SNMP	Syslog	Config polling	Route monitoring	Traffic accounting
Poisioning attacks	Yes	Yes	-	Yes	Yes
Interrior routing attacks	Yes	Yes (rare)	-	Yes	Yes
Exterrior routing attacks	Yes	Yes	-	Yes	Yes
Illegal access due to config issues	Yes	Yes	Maybe	-	-
Access check vulns	-	Yes	Maybe	-	-
Binary exploits	-	-	Maybe (if stupid)	-	-

What do binary exploits do?

- Binary modification of the runtime image
  - Patch user access credential checking (backdoor)
  - Patch logging mechanisms
  - Patch firewall functionality
- Data structure patching
  - Change access levels of VTYs (shells)
  - Bind additional VTYs (Michael Lynn’s attack)
  - Terminate processes

What do binary exploits do?

- Runtime configuration changes
    - Change the running configuration
    - Change settings of state machines (SNMP, etc.)
- Load TCL backdoors
    - Later IOS versions support TCL scripting
    - TCL scripts can bind to TCP ports
    - In some IOS versions, TCL scripts survive VTY termination

Forensics for the Binary Exploit class

What we need:

- Evidence acquisition
- Recovering of information from raw data
- Analysis of information

Plus:

- Good understanding of Cisco IOS internals

Cisco IOS Device Memory

- IOS devices start from the ROMMON
  - Loading an IOS image from Flash or network into RAM
  - The image may be self-decompressing
  - The image may contain firmware for additional hardware
- Configuration is loaded as ASCII text from NVRAM or network
  - Parsed on load
  - Mixed with image version dependent defaults of configuration settings
- Everything is kept in RAM
  - Configuration changes have immediate effect
  - Configuration is written back into NVRAM by command

Evidence Acquisition

- Common operating system:
  - Most evidence is non-volatile
  - Imaging the hard-drive is the acquisition method
  - Capturing volatile data is optional
- Cisco IOS:
  - Almost all evidence is volatile
  - What we need is memory imaging
  - On-demand or when the device restarts
    - Restarting is the **default behavior on errors**!

Non-volatile Cisco Evidence

- Flash file system
  - If the attacker modified the IOS image statically
- NVRAM
  - If the attacker modified the configuration **and** wrote it back into NVRAM
- Both cases are rare for binary exploits

Evidence Acquisition

- Using debugging features for evidence acquisition:
    - IOS can write complete core dump files
    - Dump targets: TFTP (broken), FTP, RCP, Flash
    - Complete dump
        - Includes Main Memory
        - Includes IO Memory
        - Includes PCI Memory
    - Raw dump, perfect evidence

Evidence gathering must be configured beforehand

- Core dumps are enabled by configuration
  - Configuration change has no effect on the router’s operation or performance
- Configure all IOS devices to dump core onto one or more centrally located FTP servers
  - Minimizes required monitoring of devices
  - Preserves evidence
  - Allows crash correlation between different routers
- Why wasn’t it used before?
  - Core dumps were useless, except for Cisco developers and exploit writers

What to do with the core?

- The raw memory dump data must be turned into state information
  - What was going on in the router when the memory dump was taken?
  - What processes handled what data?
  - Where did the data come from?
  - Which packet crashed the router?

Core Dump Analyzer Requirements

- Must be 100% independent
  - No Cisco code
  - No disassembly based analysis
- Must gradually recover abstraction
  - No assumptions about anything
  - Ability to cope with massively corrupted data
- Should not be exploitable itself
  - Preferably not written in C
- As you probably figured out by now, we developed such a tool:
  Cisco Incident Response (CIR)

Analyzing Cores: Inside Cisco IOS

- One large ELF binary
- Essentially a large, statically linked UNIX program
  - Loaded by ROMMON, a kind-of BIOS
- Runs directly on the router's main CPU
  - If the CPU provides privilege separation, it will not be used
    - e.g. privilege levels on PPC
  - Virtual Memory Mapping will be used, minimally

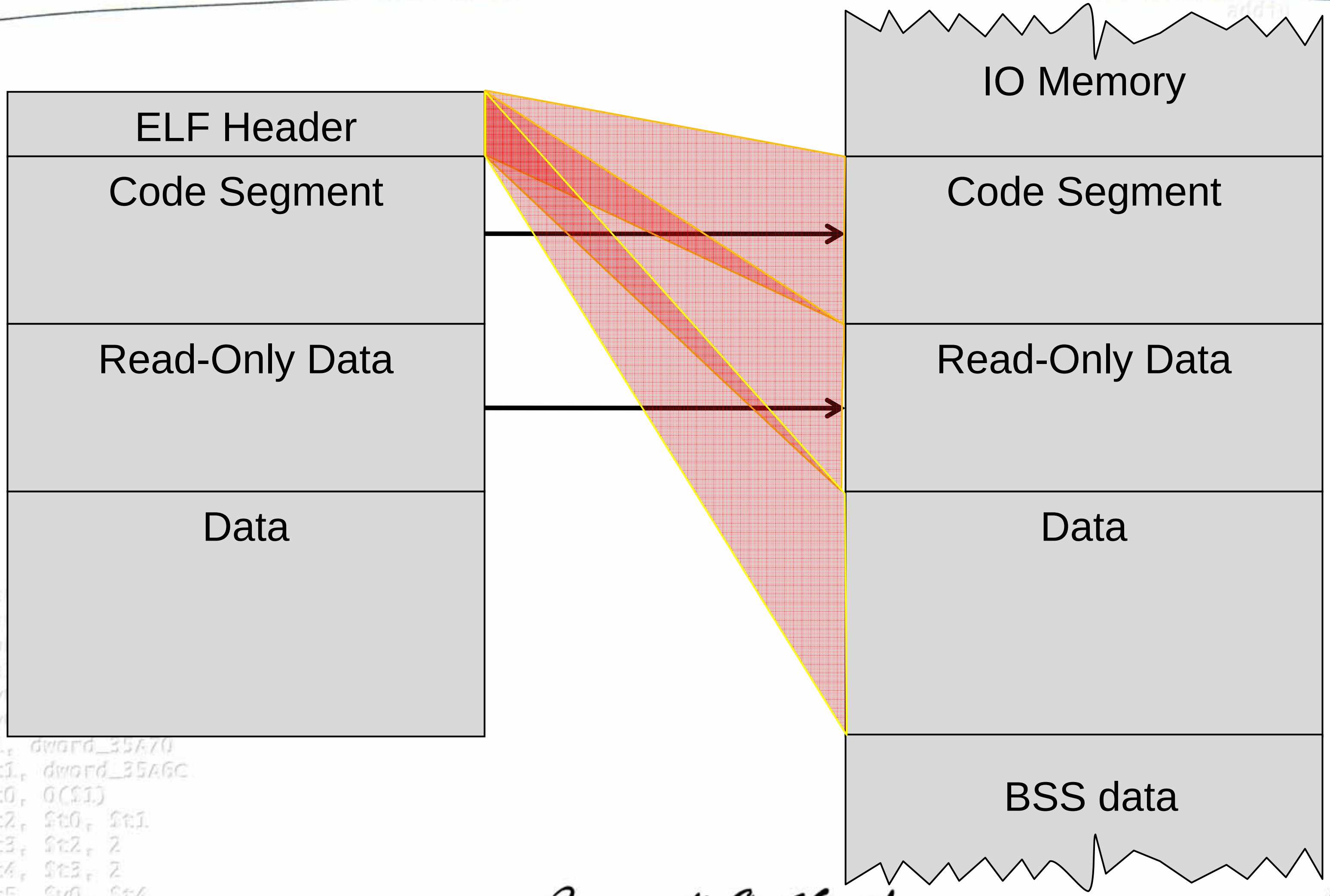
Inside Cisco IOS

- Processes are rather like threads
  - No virtual memory mapping per process
- Run-to-completion, cooperative multitasking
  - Interrupt driven handling of critical events
- System-wide global data structures
  - Common heap
  - Very little abstraction around the data structures
  - No way to force abstraction

The Image Blueprint

- The IOS image (ELF file) contains all required information about the memory mapping on the router
  - The image serves as the memory layout blueprint, to be applied to the core files
  - We wish it were as easy as it sounds
- Using a known-to-be-good image also allows verification of the code and read-only data segments
  - Now we can easily and reliably detect runtime patched images

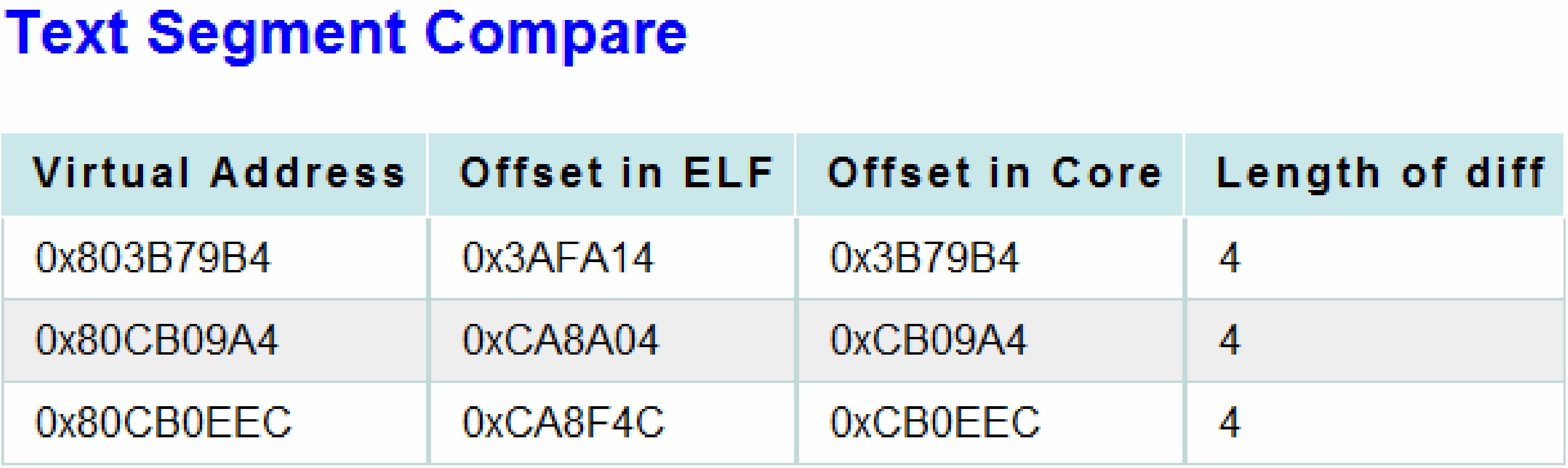
Image vs. Core



Simple Detections Work Best

Recurity Labs CIR vs. Topo‘s DIK

(at PH-Neutral 0x7d8)



Text Segment Compare

Virtual Address	Offset in ELF	Offset in Core	Length of diff
0x803B79B4	0x3AFA14	0x3B79B4	4
0x80CB09A4	0xCA8A04	0xCB09A4	4
0x80CB0EEC	0xCA8F4C	0xCB0EEC	4

CIR Online case: 120EF269A5BC2320730E60289A4B84D9047CECEE

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Heap Reconstruction

- IOS uses one large heap
- The IOS heap contains plenty of meta-data for debugging purposes
    - 40 bytes overhead per heap block in IOS up to 12.3
    - 48 bytes overhead per heap block in IOS 12.4
- Reconstructing the entire heap allows extensive integrity and validity checks
    - Exceeding by far the on-board checks IOS performs during runtime
    - Showing a number of things that would have liked to stay hidden in the shadows ☹

Heap Verification

- Full functionality of “CheckHeaps”
    - Verify the integrity of the allocated and free heap block doubly linked lists
- Find holes in addressable heap
    - Invisible to CheckHeaps
- Identify heap overflow footprints
    - Values not verified by CheckHeaps
    - Heuristics on rarely used fields
- Map heap blocks to referencing processes
- Identify formerly allocated heap blocks
    - Catches memory usage peaks from the recent past

Process List

- Extraction of the IOS Process List
  - Identify the processes’ stack block
    - Create individual, per process back-traces
    - Identify return address overwrites
  - Obtain the processes’ scheduling state
  - Obtain the processes’ CPU usage history
  - Obtain the processes’ CPU context
- Almost any post mortem analysis method known can be applied, given the two reconstructed data structures.

TCL Backdoor Detection

- We can extract any TCL script “chunk” from the memory dump
  - Currently only rare chunks
  - There is still some reversing to do
  - Potentially, a TCL decompiler will be required

Random Applications

- Find occasional CPU hogs
- Detect Heap fragmentation causes
- Determine what processes where doing
- Finding attacked processes
  - Which process had 200 packets in his hands when he died?
- Research tool
  - Pointer correlation becomes really easy
  - Essential in a shared memory environment

IOS Packet Forwarding Memory

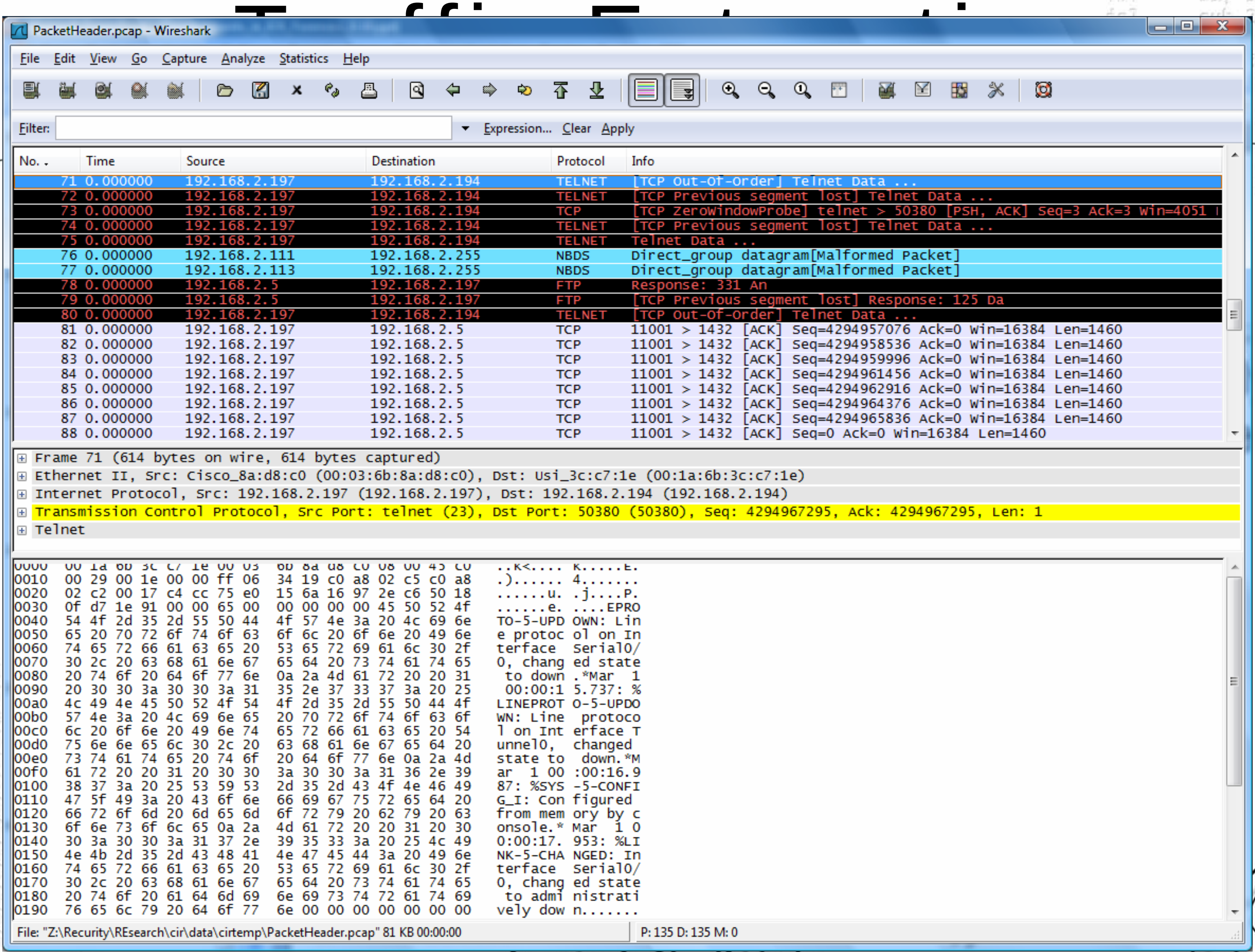
- IOS performs routing either as:
  - Process switching
  - Fast switching
  - Particle systems
  - Hardware accelerated switching
- Except hardware switching, all use IO memory
  - IO memory is written as separate code dump
  - By default, about 6% of the router's memory is dedicated as IO memory
    - In real world installations, it is common to increase the percentage to speed up forwarding
- Hardware switched packets use PCI memory
  - PCI memory is written as separate core dump

IO Memory Buffers

- Routing (switching) **ring buffers** are grouped by packet size
  - Small
  - Medium
  - Big
  - Huge
- Interfaces have their own buffers for locally handled traffic
- IOS tries really hard to not copy packets around in memory
- New traffic does not automatically erase older traffic in a linear way

Traffic Extraction

- CIR dumps packets that were process switched by the router from IO memory into a PCAP file
  - Traffic addressed to and from the router itself
  - Traffic that was process switching inspected
    - Access List matching
    - QoS routed traffic
- CIR could dump packets that were forwarded through the router too
  - Reconstruction of packet fragments possible
  - Currently not in focus, but can be done if desired


PacketHeader.pcap - Wireshark
File Edit View Go Capture Analyze Statistics Help
Filter:
Expression... Clear Apply

```
No. .  Time      Source          Destination     Protocol Info
   71 0.000000  192.168.2.197   192.168.2.194   TELNET   [TCP Out-Of-Order] Telnet Data ...
   72 0.000000  192.168.2.197   192.168.2.194   TELNET   [TCP Previous segment lost] Telnet Data ...
   73 0.000000  192.168.2.197   192.168.2.194   TCP      [TCP ZeroWindowProbe] telnet > 50380 [PSH, ACK] Seq=3 Ack=3 Win=4051 I
   74 0.000000  192.168.2.197   192.168.2.194   TELNET   [TCP Previous segment lost] Telnet Data ...
   75 0.000000  192.168.2.197   192.168.2.194   TELNET   Telnet Data ...
   76 0.000000  192.168.2.111   192.168.2.255   NBDS     Direct_group datagram[Malformed Packet]
   77 0.000000  192.168.2.113   192.168.2.255   NBDS     Direct_group datagram[Malformed Packet]
   78 0.000000  192.168.2.5     192.168.2.197   FTP      Response: 331 An
   79 0.000000  192.168.2.5     192.168.2.197   FTP      [TCP Previous segment lost] Response: 125 Da
   80 0.000000  192.168.2.197   192.168.2.194   TELNET   [TCP Out-Of-Order] Telnet Data ...
   81 0.000000  192.168.2.197   192.168.2.5     TCP      11001 > 1432 [ACK] Seq=4294957076 Ack=0 Win=16384 Len=1460
   82 0.000000  192.168.2.197   192.168.2.5     TCP      11001 > 1432 [ACK] Seq=4294958536 Ack=0 Win=16384 Len=1460
   83 0.000000  192.168.2.197   192.168.2.5     TCP      11001 > 1432 [ACK] Seq=4294959996 Ack=0 Win=16384 Len=1460
   84 0.000000  192.168.2.197   192.168.2.5     TCP      11001 > 1432 [ACK] Seq=4294961456 Ack=0 Win=16384 Len=1460
   85 0.000000  192.168.2.197   192.168.2.5     TCP      11001 > 1432 [ACK] Seq=4294962916 Ack=0 Win=16384 Len=1460
   86 0.000000  192.168.2.197   192.168.2.5     TCP      11001 > 1432 [ACK] Seq=4294964376 Ack=0 Win=16384 Len=1460
   87 0.000000  192.168.2.197   192.168.2.5     TCP      11001 > 1432 [ACK] Seq=4294965836 Ack=0 Win=16384 Len=1460
   88 0.000000  192.168.2.197   192.168.2.5     TCP      11001 > 1432 [ACK] Seq=0 Ack=0 Win=16384 Len=1460
```

```
⊞ Frame 71 (614 bytes on wire, 614 bytes captured)
⊞ Ethernet II, Src: Cisco_8a:d8:c0 (00:03:6b:8a:d8:c0), Dst: Usi_3c:c7:1e (00:1a:6b:3c:c7:1e)
⊞ Internet Protocol, Src: 192.168.2.197 (192.168.2.197), Dst: 192.168.2.194 (192.168.2.194)
⊞ Transmission Control Protocol, Src Port: telnet (23), Dst Port: 50380 (50380), Seq: 4294967295, Ack: 4294967295, Len: 1
⊞ Telnet
```

```
0000  00 1a 6b 3c c7 1e 00 03  6b 8a d8 c0 08 00 45 c0   ..k<.... k.....E.
0010  00 29 00 1e 00 00 ff 06  34 19 c0 a8 02 c5 c0 a8   .)...... 4.......
0020  02 c2 00 17 c4 cc 75 e0  15 6a 16 97 2e c6 50 18   ......u. .j....P.
0030  0f d7 1e 91 00 00 65 00  00 00 00 00 45 50 52 4f   ......e. ....EPRO
0040  54 4f 2d 35 2d 55 50 44  4f 57 4e 3a 20 4c 69 6e   TO-5-UPD OWN: Lin
0050  65 20 70 72 6f 74 6f 63  6f 6c 20 6f 6e 20 49 6e   e protoc ol on In
0060  74 65 72 66 61 63 65 20  53 65 72 69 61 6c 30 2f   terface  Serial0/
0070  30 2c 20 63 68 61 6e 67  65 64 20 73 74 61 74 65   0, chang ed state
0080  20 74 6f 20 64 6f 77 6e  0a 2a 4d 61 72 20 20 31    to down .*Mar  1
0090  20 30 30 3a 30 30 3a 31  35 2e 37 33 37 3a 20 25    00:00:1 5.737: %
00a0  4c 49 4e 45 50 52 4f 54  4f 2d 35 2d 55 50 44 4f   LINEPROT O-5-UPDO
00b0  57 4e 3a 20 4c 69 6e 65  20 70 72 6f 74 6f 63 6f   WN: Line  protoco
00c0  6c 20 6f 6e 20 49 6e 74  65 72 66 61 63 65 20 54   l on Int erface T
00d0  75 6e 6e 65 6c 30 2c 20  63 68 61 6e 67 65 64 20   unnel0,  changed
00e0  73 74 61 74 65 20 74 6f  20 64 6f 77 6e 0a 2a 4d   state to  down.*M
00f0  61 72 20 20 31 20 30 30  3a 30 30 3a 31 36 2e 39   ar  1 00 :00:16.9
0100  38 37 3a 20 25 53 59 53  2d 35 2d 43 4f 4e 46 49   87: %SYS -5-CONFI
0110  47 5f 49 3a 20 43 6f 6e  66 69 67 75 72 65 64 20   G_I: Con figured
0120  66 72 6f 6d 20 6d 65 6d  6f 72 79 20 62 79 20 63   from mem ory by c
0130  6f 6e 73 6f 6c 65 0a 2a  4d 61 72 20 20 31 20 30   onsole.* Mar  1 0
0140  30 3a 30 30 3a 31 37 2e  39 35 33 3a 20 25 4c 49   0:00:17. 953: %LI
0150  4e 4b 2d 35 2d 43 48 41  4e 47 45 44 3a 20 49 6e   NK-5-CHA NGED: In
0160  74 65 72 66 61 63 65 20  53 65 72 69 61 6c 30 2f   terface  Serial0/
0170  30 2c 20 63 68 61 6e 67  65 64 20 73 74 61 74 65   0, chang ed state
0180  20 74 6f 20 61 64 6d 69  6e 69 73 74 72 61 74 69    to admi nistrati
0190  76 65 6c 79 20 64 6f 77  6e 00 00 00 00 00 00 00   vely dow n.......
```

File: "Z:\Recurity\REsearch\cir\data\cirtemp\PacketHeader.pcap" 81 KB 00:00:00 P: 135 D: 135 M: 0

What about crashinfo?

- Later IOS versions write a text file called “crashinfo” to the flash file system when the router crashes
  - Crashinfo contains fairly little information
  - Contents depend on what IOS thought was the cause of the crash
- We found exploitation cases where the router failed to write core dumps, but did write crashinfo
  - Crashinfo correlation to core dumps will likely become an analysis method in future versions of CIR

State of CIR

- Development of Version 1.0 completed
- Online Service at http://cir.recurity-labs.com
    - Available since February 2008
- Free rootkit detection version available
- Professional version available

- There is a large list of things we want in version 1.1 – feel free to add stuff ☺

Challenges with IOS

- The challenge with IOS is the combinatory explosion of platform, IOS version and additional hardware
- Every IOS image is compiled individually
- Over 100.000 IOS images currently used in the wild (production networks)
  - Around 15.000 officially supported by Cisco
  - Cisco IOS is rarely updated and cannot be patched
- This is a great headache for IOS forensics, but also for IOS exploit writers

Reality Check IOS Exploits

- The entire code is in the image
- Remotely, you have a 1-in-100.000 chance to guess the IOS image (conservative estimate)
- Any exception causes the router to restart
  - This is inherent to a monolithic firmware design, as it looses integrity entirely with a single error
- Stacks are heap blocks
  - Always at different memory addresses
  - Addresses vary even within the same image

Reality Check IOS Exploits

- So far, all IOS exploits *published* use **fixed** addresses that depend on the **exact** IOS image being known before the attack
  - IOS’s address diversity is a similar “protection” to the Source Port Randomization patch you applied to your DNS servers recently
  - We perform our own research in this area, to make CIR ready for the next generation exploits
- It will most certainly not stay this way!

Let the arms race begin!

Next Attack	Detection
Rootkit code patching core dump writing	GDB debug protocol memory acquisition
GDB debugger stub patching	ROMMON privilege mode memory acquisition
Data segement only backdooring	Data structure validation
Compiled configuration patching	Configuration de-compilation

Once we get all those Cisco IOS platforms covered, we do pretty good in terms of detection mechanisms. But getting there is **a lot** of work!

Want to learn more?

- We are constantly writing about Cisco IOS related information in the **“IOS Crash Analysis and Rootkit Wiki”**
- CIR Online is available (registration free)

http://cir.recurity-labs.com/

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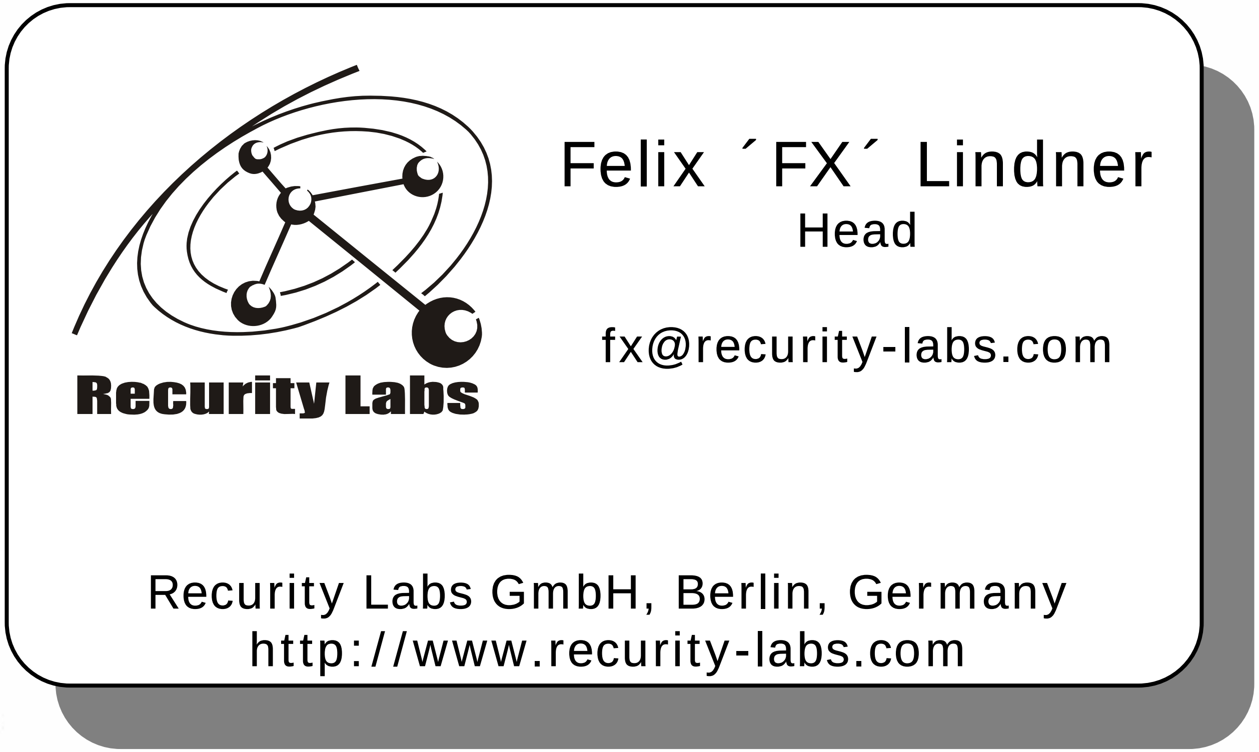

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