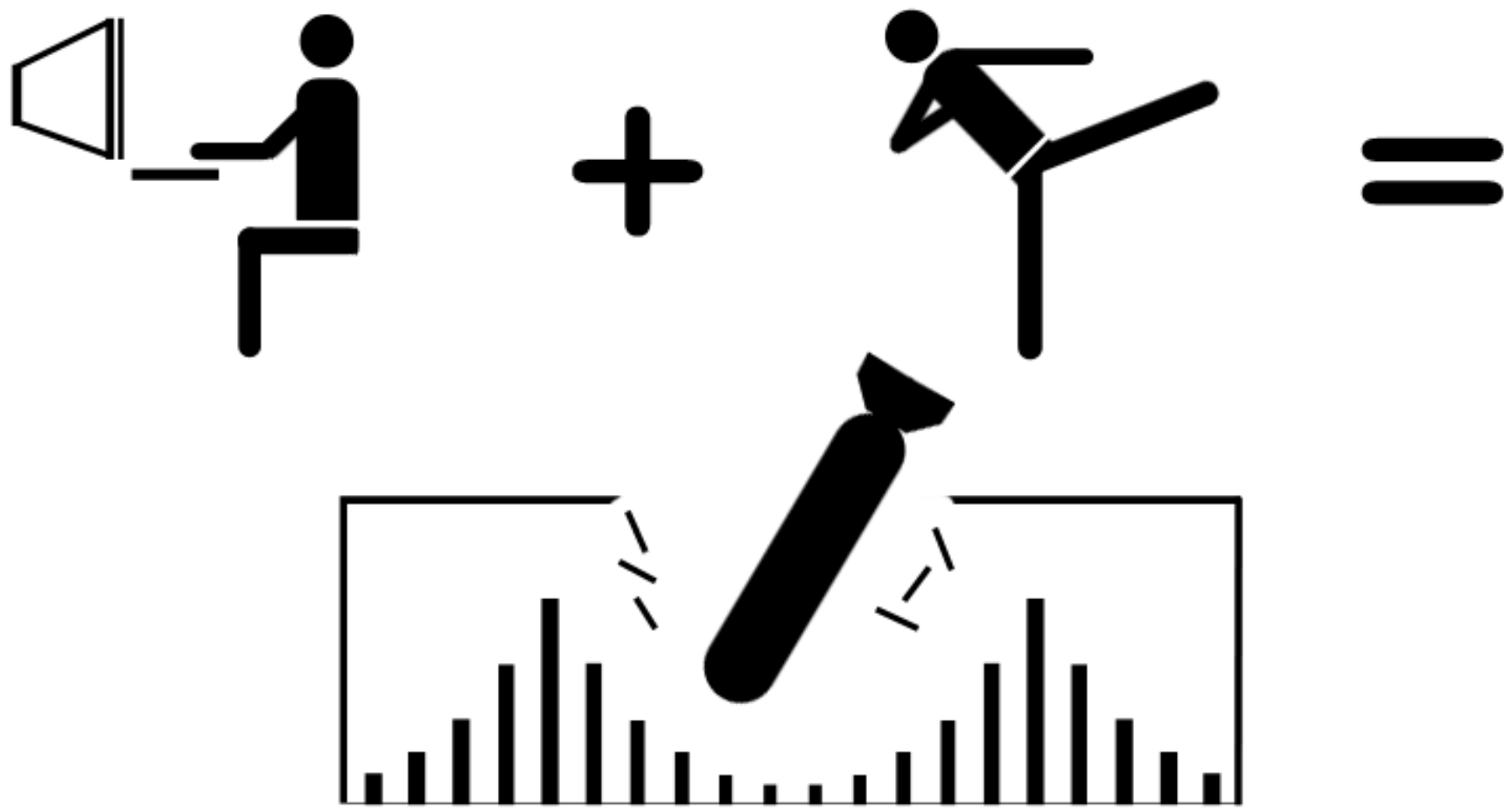


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Attacking networked embedded systems

FX of Phenoelit, Seattle 2003

Today's Session



- Design failures in embedded systems
 - Examples of design failures
 - Exploiting a design failure
- Software vulnerabilities in embedded systems
 - Examples of software vulnerabilities
 - Exploiting a software vulnerability in a common embedded system



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What's a Embedded System ?



- (Small) computer system enclosed in electronic device
- Custom operating system, designed to provide specific functionality to the device it's running on
- Operating System is often monolithic
- No or limited separation of software components and access levels inside
- No or limited ability to add third party software



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Design failures



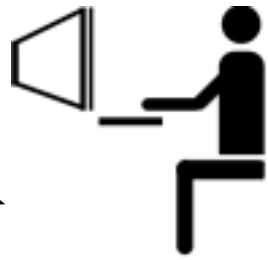
- Undocumented functionality
 - Developer backdoors
 - Auto-something features
 - Legacy functions
- Ignored standards
- Uncontrolled increase of complexity
 - New subsystems
 - Additional access methods
 - Inconsistent access restrictions



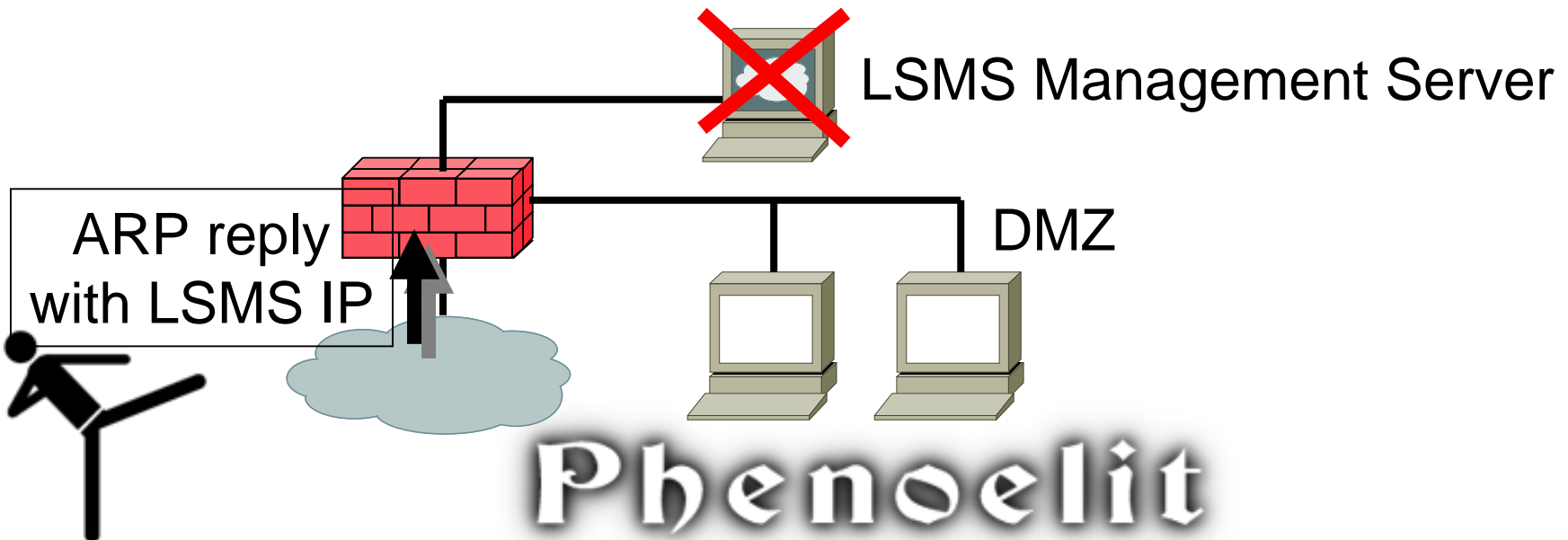
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Design failures

Case 1: Lucent Brick

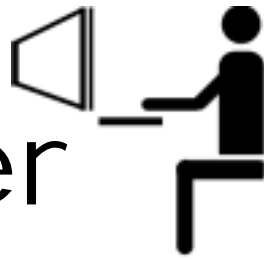


- Layer 2 Firewall running Inferno OS
- ARP cache design failures
 - ARP forwarded regardless of firewall rules
 - ARP reply poisoning of firewall
 - ARP cache does not time out



Design failures

Case 2: Ascend Router



- Undocumented discovery protocol
- Special packet format to UDP discard port
- Leaks information remotely
 - IP address/Netmask
 - MAC address
 - Name and Serial number
 - Device type
 - Features
- Can set IP address and name using SNMP write community (Default: „write“)



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Cisco IOS EIGRP



- Enhanced IGRP uses automagic neighbor discovery
- Flooding Cisco IOS with random neighbor announcements causes segment wide DoS
 - Router ARPs for the neighbor IP as long as the EIGRP timer did not expire
 - Timer value provided by attacker in packet, max over 18 hours
- IOS 11.x allows attack as unicast

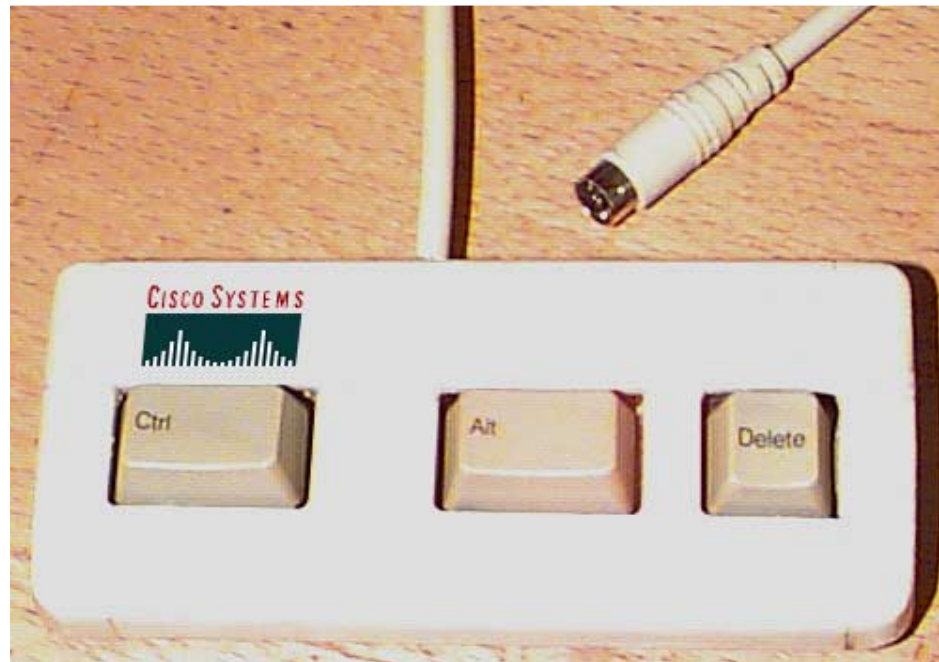


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Cisco IOS EIGRP

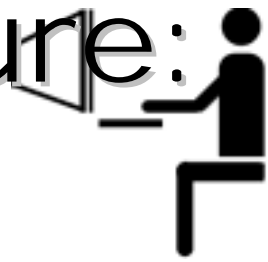


- Affected IOS versions: ALL
- Cisco's fix: none



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Exploiting a design failure: HP Printers



- Various access methods:
 - Telnet, HTTP, FTP, SNMP, PJP
- Various access restrictions
 - Admin password on HTTP and Telnet
 - IP access restriction on FTP, PJP, Telnet
 - PJP security password
- Inconsistent access restriction interworkings
 - SNMP read reveals admin password in hex at .iso.3.6.1.4.1.11.2.3.9.4.2.1.3.9.1.1.0
 - HTTP interface can be used to disable other restrictions (username: laserjet)



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HP Printers: PjL



- PjL (Port 9100) allows access to printer configuration
 - Number of copies, size, etc.
 - Locking panel
 - Input and output trays
 - Eco mode and Power save
 - I/O Buffer
- Security relies on PjL password
 - key space of 65535.
 - max. 6 hours for remote brute force



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HP Printers: PJL

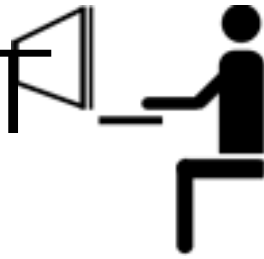


- PJL (Port 9100) allows access to printer file systems on DRAM and FLASH
 - Spool directory contains jobs
 - PCL macros on printer
- More file system content (later models)
 - Firmware
 - Web server content
 - Subsystem configuration
- Printer can be used as PJL-based file server



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Phenoelit vs. PJP: PFT

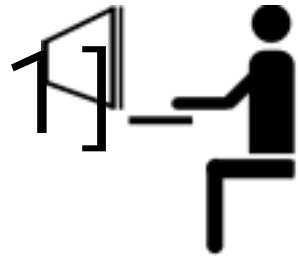


- Tool for direct PJP communication
 - Reading, modifying and writing environment variables
 - Full filesystem access
 - Changing display messages
 - PJP „security“ removal
- Available for Linux and Windows including libPJP for both platforms
- Windows GUI version „Hijetter“ by FtR
- ... and of course it's open source



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HP Printers: ChaiVM [1]



- ChaiVM is a Java Virtual Machine for embedded systems
- HP Printers 9000, 4100 and 4550 are officially supported.
- HP 8150 also runs it.
- ChaiVM on printers comes completely with web server, static files and objects.
- Everything lives on the printer's file system.



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HP Printers: ChaiVM [2]



- Chai standard loader service
 - `http://device_ip/hp/device/this.loader`
 - Loader is supposed to validate JAR signature from HP to ensure security
- HP released new EZloader
 - HP signed JAR
 - No signatures required for upload
- Adding services via printer file system access to `0:\default\csconfig`
- ~~▪ HP Java classes, documentation and tutorials available~~

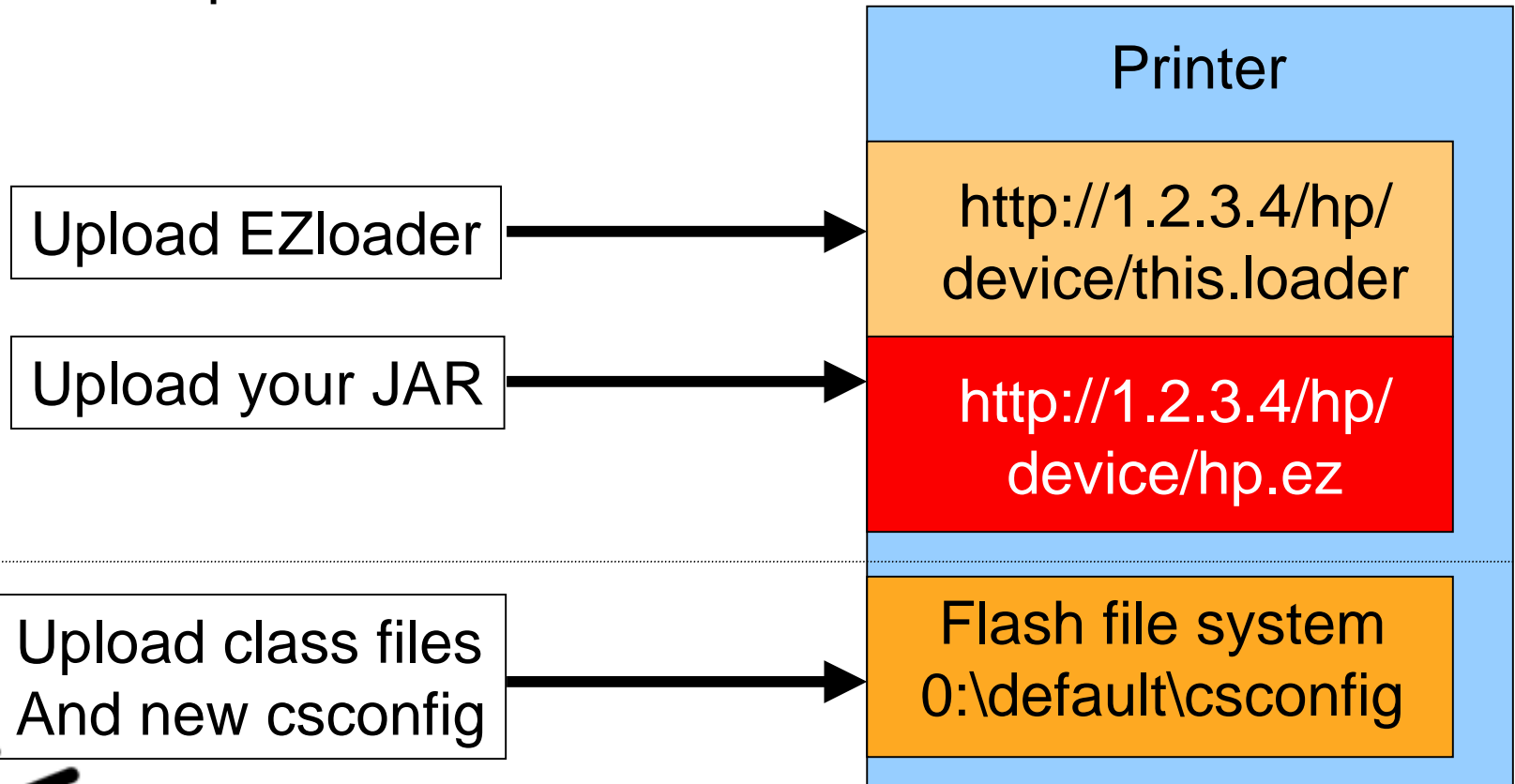


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HP Printers: ChaiVM [3]



- Getting code on the printer

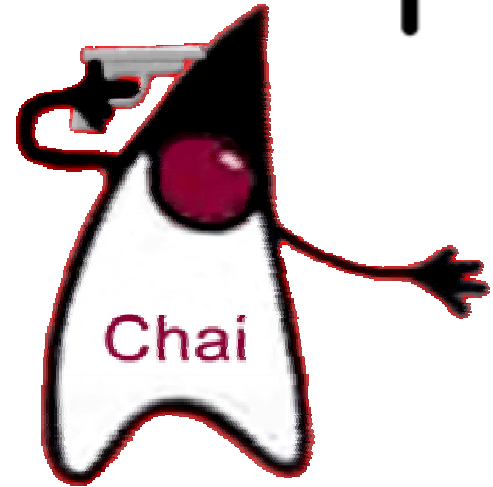


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HP Printers: ChaiVM [4]



- ChaiVM is quite instable
 - Too many threads kill printer
 - Connect() to unreachable hosts or closed port kills VM
 - Doesn't always throw an Exception
 - Huge differences between simulation environment and real-world printers
 - Unavailability of all instances of a service kills VM
- To reset printer use SNMP set:
.iso.3.6.1.2.1.43.5.1.1.3.1 = 4



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HP Printers: Things you can do...



- Phenoelit ChaiPortScan
 - Web based port scanner daemon for HP Printers with fixed firmware
- Phenoelit ChaiCrack
 - Web based crypt() cracking tool for HP Printers
- Backdoor servers
 - Binding and listening is allowed
 - Chai services have access to authentication



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HP Printers: ChaiVM [5]



- ChaiServices are fully trusted between each other
- ChaiAPNP service supports Service Location Protocol (SLP)
 - **find other devices and services**
- Notifier service can notify you by HTTP or Email of „interesting events“
- ChaiOpenView enables ChaiVM configuration via SNMP
- ChaiMail service is „designed to work across firewalls“.
 - **Issue commands to your Chai service via Email!**



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HP Printers

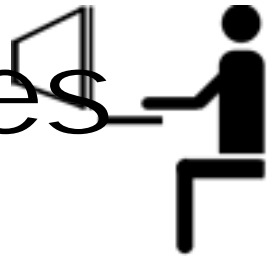


Tools and source available at
<http://www.phenoelit.de/hp/>



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Software Vulnerabilities



- Classic mistakes are also made on embedded systems
 - Input validation
 - Format strings
 - Buffer overflows
 - Cross Site Scripting
- Most embedded HTTP daemons vulnerable
- Limited resources lead to removal of sanity checks



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Buffer overflows



- Xedia Router
(now Lucent Access Point)
 - long URL in HTTP GET request crashes router
- Brother Network Printer (NC-3100h)
 - Password variable in HTTP GET request with 136 chars crashes printer
- HP ProCurve Switch
 - SNMP set with 85 chars in
.iso.3.6.1.4.1.11.2.36.1.1.2.1.0 crashes switch
- SEH IC-9 Pocket Print Server
 - Password variable in HTTP GET request with 300 chars crashes device



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Common misconceptions



- Embedded systems are harder to exploit than multipurpose OS's
- You have to reverse engineer the firmware or OS to write an exploit
- You need to know how the sys-calls and lib functions work to write an exploit
- The worst thing that can happen is a device crash or reboot



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Proving it wrong: A Cisco IOS Exploit

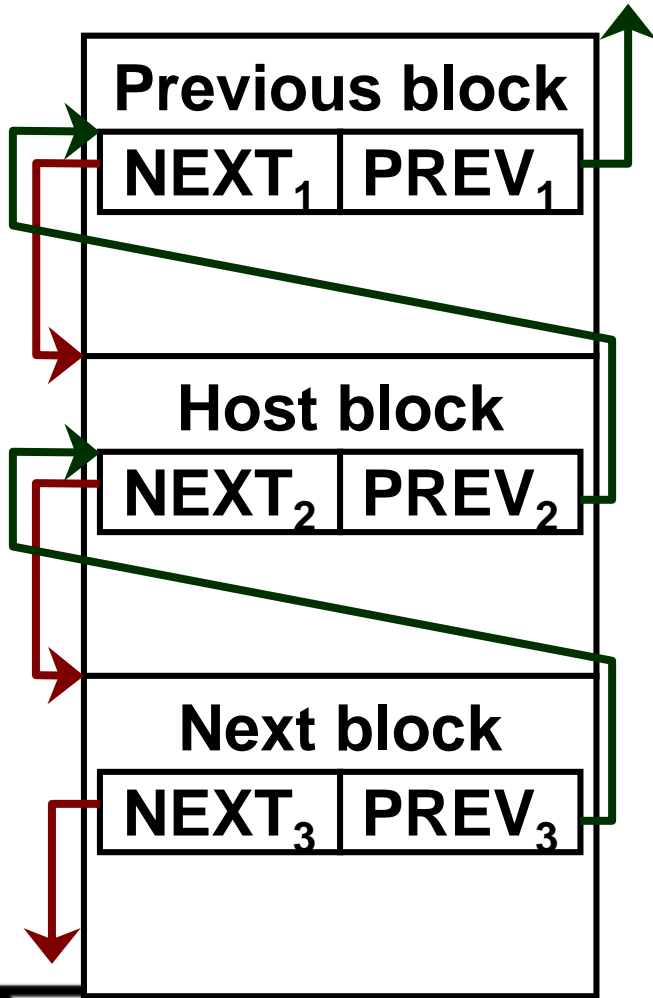


- Exploiting an overflow condition in Cisco Systems IOS to take over the Router.
- The process you crash is tightly integrated into the OS, so you probably crash the whole OS as well
- According to Cisco, memory corruption is the most common bug in IOS. So it's probably a heap overflow.
- Vulnerability for research:
Buffer overflow in IOS (11.1.x – 11.3.x)
TFTP server for long file names



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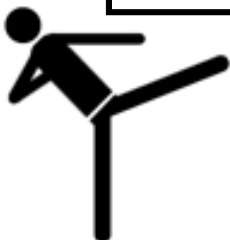
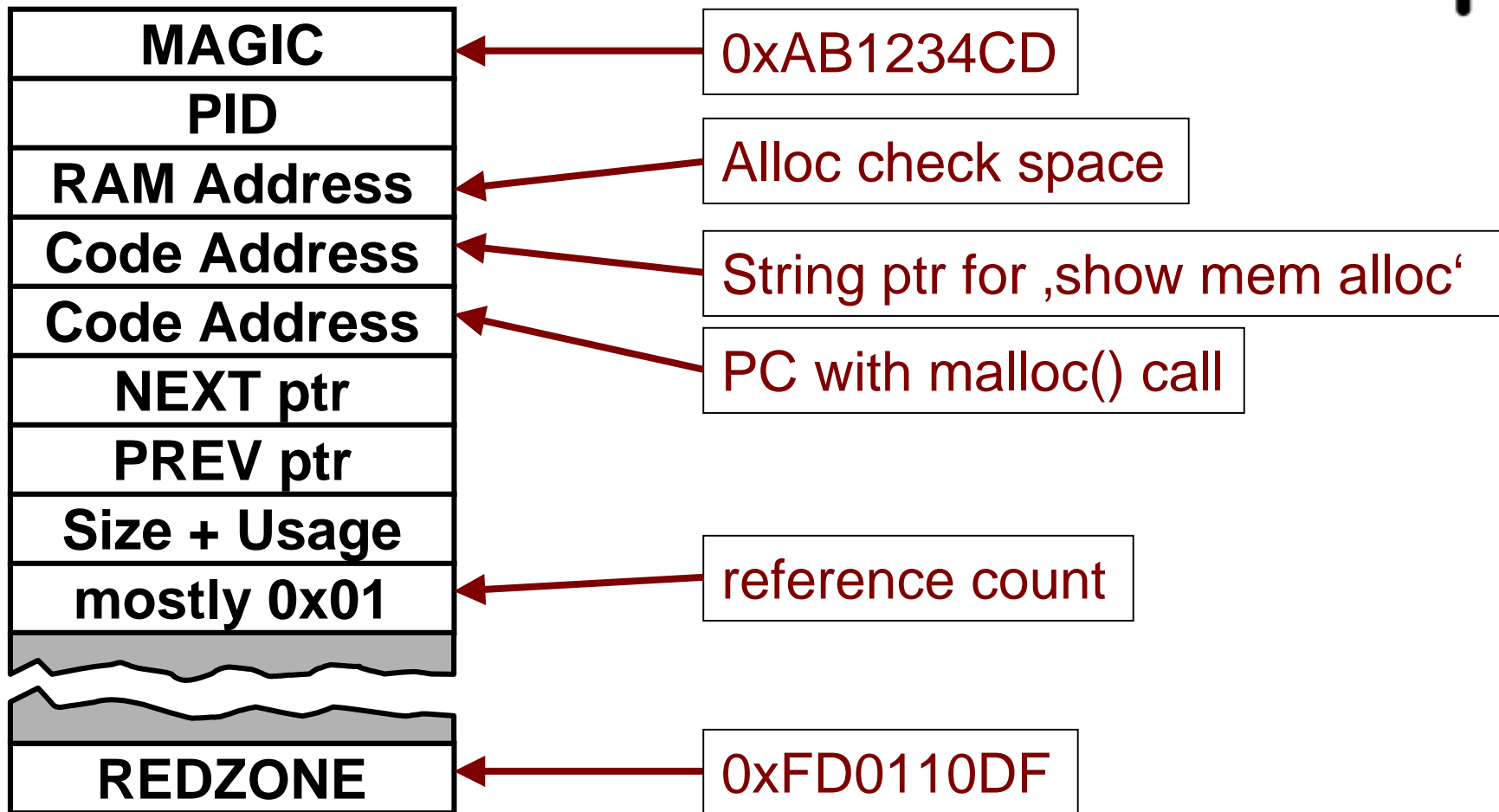
Heap Layout



- Two different memory areas: main and IO memory
- Double linked pointer list of memory blocks
 - Same size in IO
 - Various sizes in main
- Probably based off a tree structure
- A single block is part of multiple linked lists

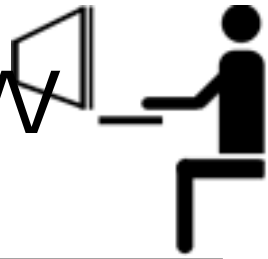
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Block layout

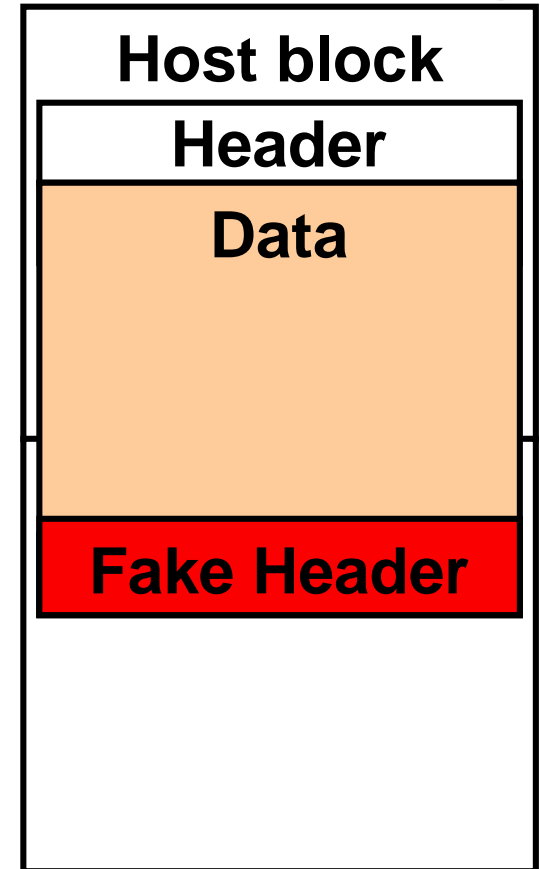


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Theory of the overflow

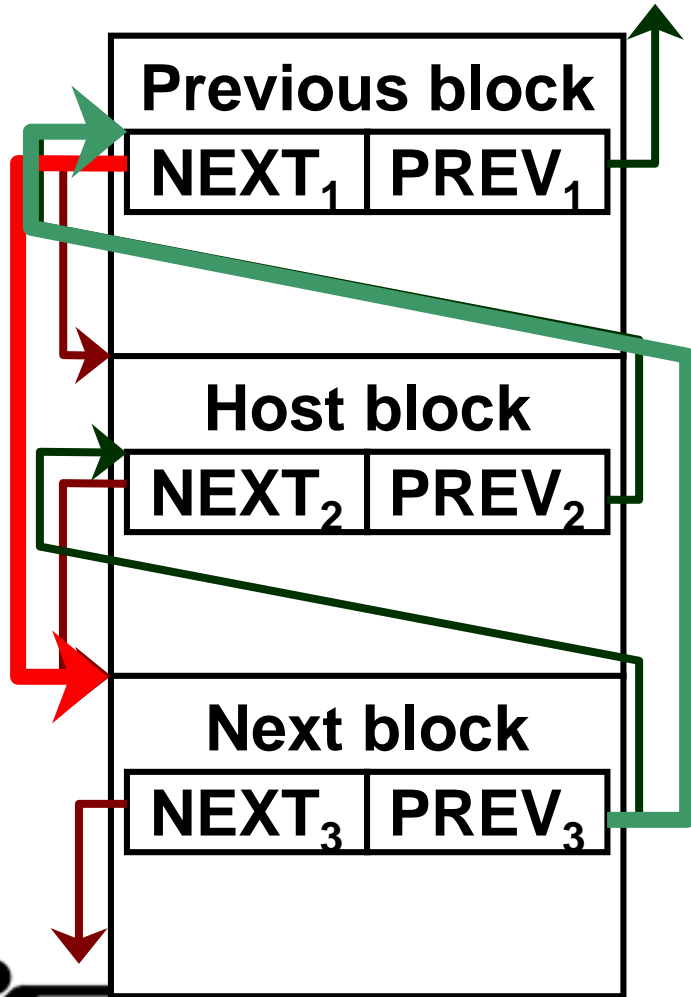
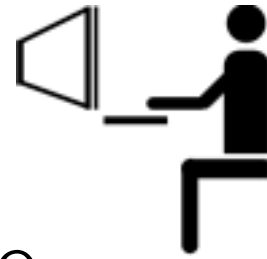


- Filling the „host block“
- Overwriting the following block header – hereby creating a „fake block“
- Let IOS memory management use the fake block information
- Desired result:
Writing to arbitrary memory locations



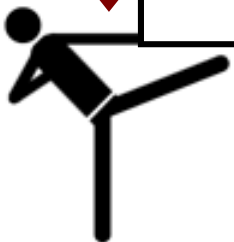
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A free() on IOS

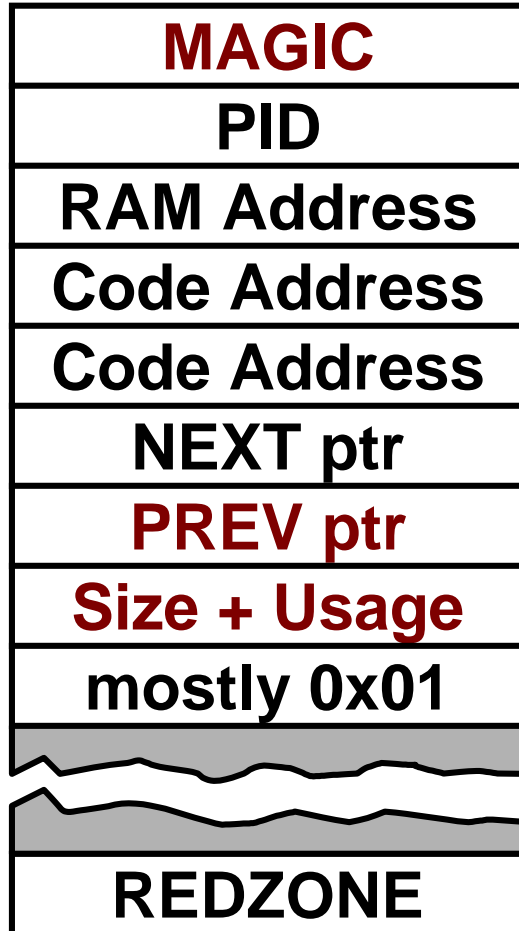


- Remember: Double linked pointer list of memory blocks
- Upon free(), an element of the list is removed
- Pointer exchange operation, much like on Linux or Windows

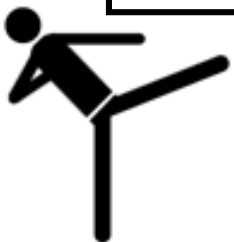
```
Host->prev=next2;  
(Host->next2)+prevofs=prev2;  
delete(Host_block);
```



The requirements

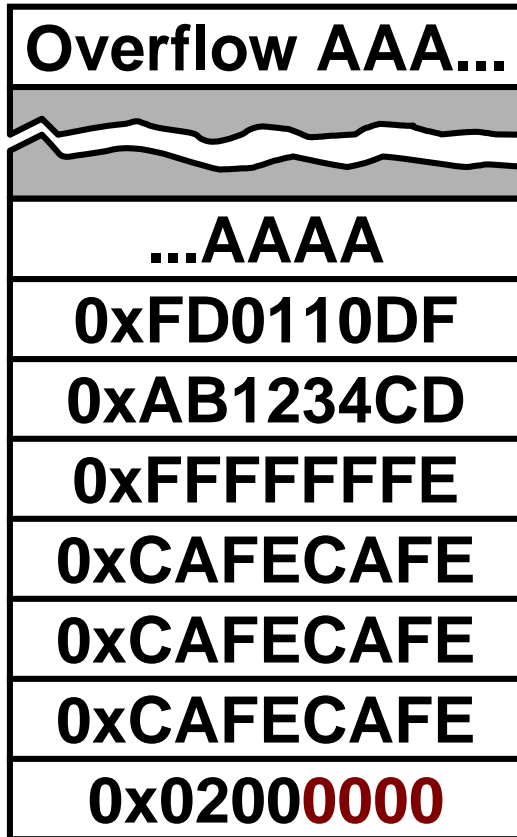
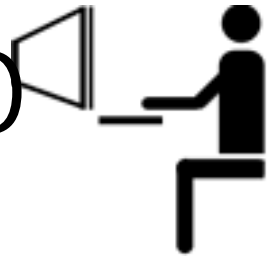


- Required:
 - MAGIC, RED ZONE
 - PREV PTR
 - Size
- Unchecked:
 - Wasted pointers
 - NEXT PTR
- „Check heaps“ process validates MAGIC and REDZONE
- Performing an overflow up to the NEXT ptr is possible.



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Taking the first: 2500

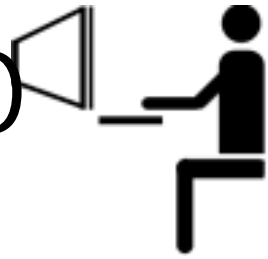


- Cisco 2500 allows anyone to write to the NVRAM memory area
- Since NEXT ptr is not checked, we can put 0x02000000 (NVRAM) in there
- The 0x00 bytes don't get written because we are doing a string overflow here
- The pointer exchange leads to a write to NVRAM and invalidates it (checksum error)



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Taking the first: 2500



- NVRAM gets invalidated by exploit
- Device reboots after discovering issue in memory management („Check heaps“ process)
- Boot without valid config leads to BOOTP request and TFTP config retrieval
- Result: **Attacker provides config**



Getting around PREV



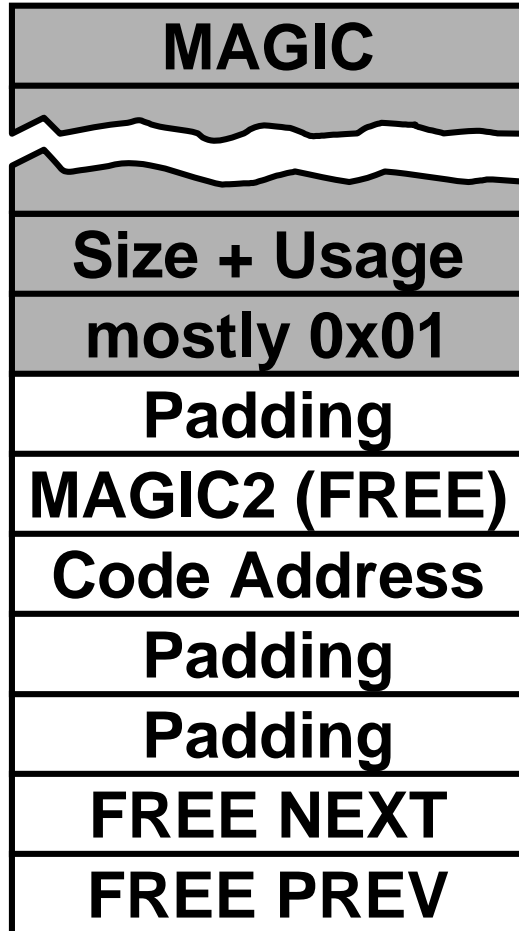
- PREV ptr is checked while the previous block is inspected before the free()
- Test seems to be:

```
if (next_block->prev!=this_block+20)
    abort();
```
- Perform uncontrolled overflow to cause device reboot
 - Proves the device is vulnerable
 - Puts memory in a predictable state
 - Crash information can be obtained from network or syslog host if logged (contains PREV ptr address)

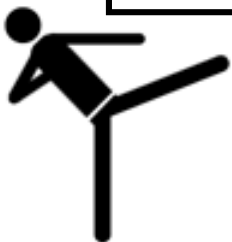


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Free memory blocks

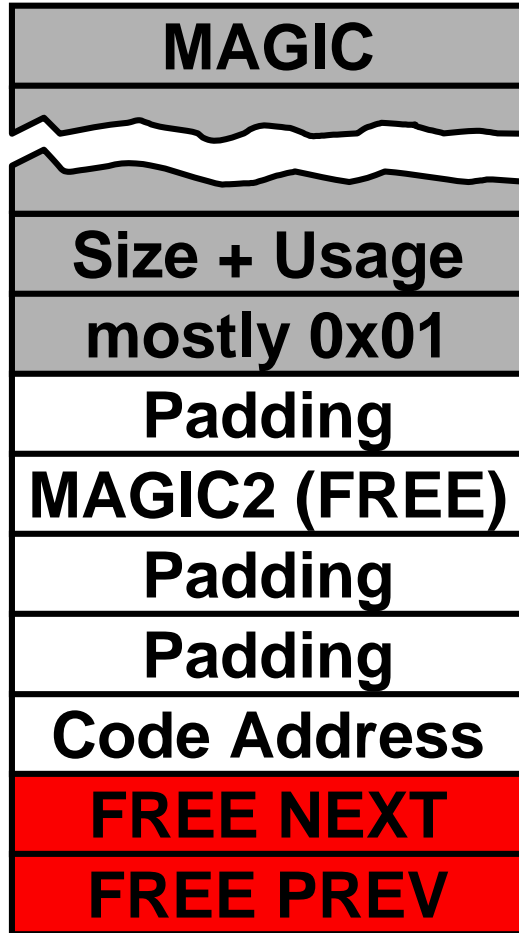
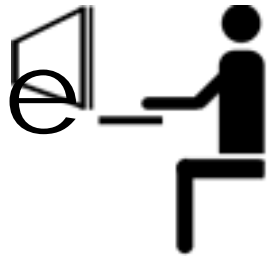


- Free memory blocks carry additional management information
- Information is probably used to build linked list of free memory blocks
- Functionality of FREE NEXT and FREE PREV comparable to NEXT and PREV



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Arbitrary Memory write



- FREE NEXT and FREE PREV are not checked
- Pointer exchange takes place
- Using 0x7FFFFFFF in the size field, we can mark the fake block „free“
- Both pointers have to point to writeable memory

```
*free_prev=*free_next;  
*(free_next+20)=*free_prev;
```



Places for pointers



- ‚show mem proc alloc‘ shows a „Process Array“
- Array contains addresses of process information records indexed by PID
- Process information record’s second field is current stack pointer
- All of these are static addresses per IOS image



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Taking the Processor

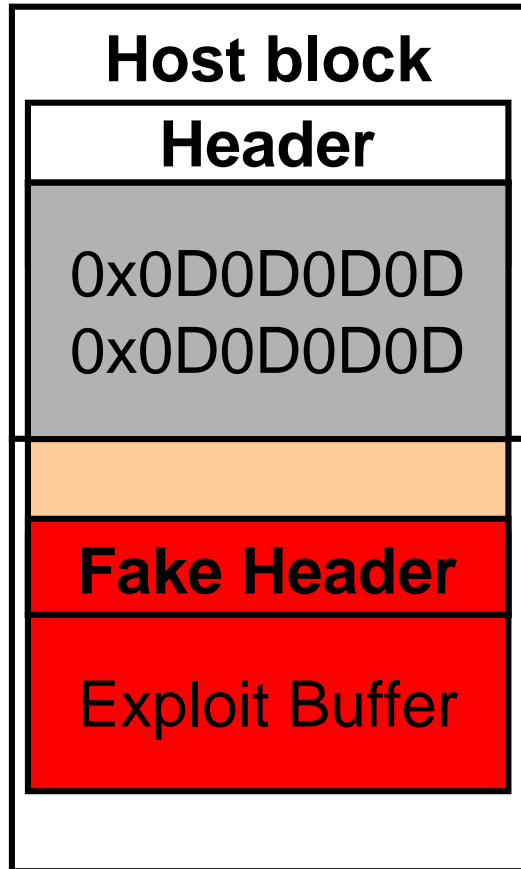


- The stack of any IOS process is writable by any code running on the system
- We can overwrite
 - Frame pointer
 - Return address
 - Process Array entry
 - Process Record stack entry
 - Process Record SP entry



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The Buffer



- A free() on IOS actually clears the memory (overwrites it with 0x0D)
- Buffer after fake block is considered already clean and can be used for exploitation
- Position of the buffer relative to PREV ptr is static per platform/IOS



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The shell code - V1



- Example based on Cisco 1600
- Motorola 68360 QUICC CPU
- Memory protection is set in the registers at 0x0FF01000
- Disabling memory protection for NVRAM address by modifying the second bit of the appropriate QUICC BaseRegister (See MC68360UM, Page 6-70)
- Write invalid value to NVRAM
- Device reboots and asks for config



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The shell code - V1



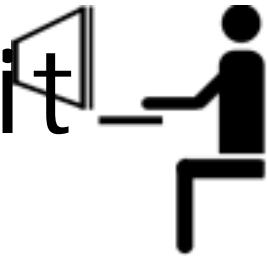
- Simple code to invalidate NVRAM
(Sorry, we are not @home on 68k)
- Dummy move operation to d1, data part of OP code is overwritten on free()
- ADDA trick used to circumvent 0x00 bytes in code

```
\x22\x7C\x0F\xF0\x10\xC2      move.l #0xFF010C2,%a1
\xE2\xD1                        lsr    (%a1)
\x22\x7C\x0D\xFF\xFF\xFF      move.l #0xDFFFFFFF,%a1
\xD2\xFC\x02\xD1              adda.w #0x02D1,%a1
\x22\x3C\x01\x01\x01\x01      move.l #0x01010101,%d1
\x22\xBC\xCA\xFE\xBA\xBE      move.l #0xCAFEBABE,(%a1)
```

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The Cisco 1600 Exploit

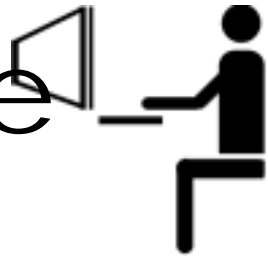


- Overflow once to get predictable memory layout
- Overflow buffer with
 - Fake block and correct PREV ptr
 - Size of 0x7FFFFFFF
 - FREE NEXT points to code buffer
 - FREE PREV points to return address of process „Load Meter“ in stack
 - Code to unprotect memory and write into NVRAM



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The remote shell code

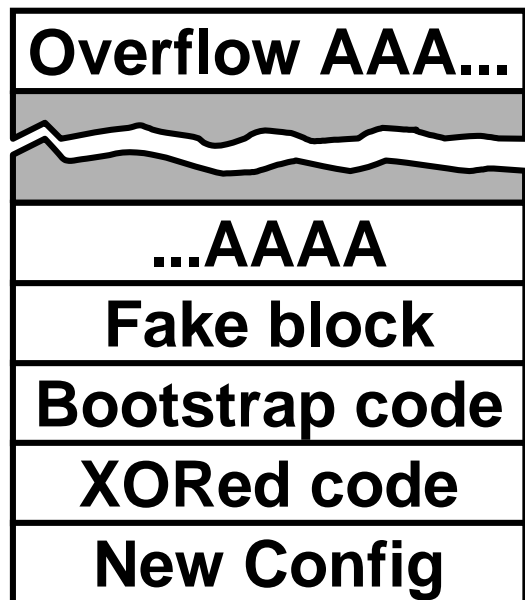
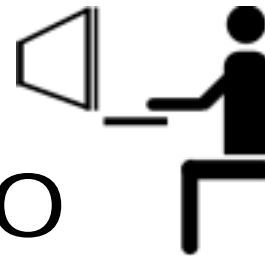


- Append new minimum config to the overflow
- Disable interrupts
- Unprotect NVRAM
- Calculate values for NVRAM header
 - Length
 - Checksum
- Write new header and config into NVRAM (**slowly!**)
- Perform clean hard reset



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The IOS Exploit Phenoelit Ultima Ratio



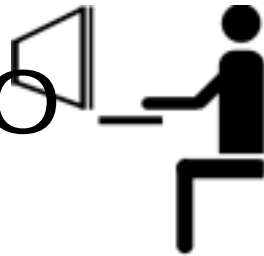
- Code size including fake block: 282 bytes
- New config can be specified in command line
- Adjustments available from command line
- Full source code available



<http://www.phenoelit.de/ultimaratio/>

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Phenoelit Ultima Ratio



```
"\xFD\x01\x10\xDF" // RED
"\xAB\x12\x34\xCD" // MAGIC
"\xFF\xFF\xFF\xFF" // PID
"\x80\x81\x82\x83" // AL chk
"\x08\x0C\xBB\x76" // NAME
"\x80\x8a\x8b\x8c" // Al PC
"\x02\x0F\x2A\x04" // NEXT
"\x02\x0F\x16\x94" // PREV
"\x7F\xFF\xFF\xFF" // SIZE
"\x01\x01\x01\x01" // ref cnt
"\xA0\xA0\xA0\xA0" // De Al
"\xDE\xAD\xBE\xEF" // MAGIC2
"\x81\x82\x83\x84" // De PC
"\xFE\xFE\x0B\xAD" // CCC greets
"\xFE\xFE\xBA\xBE" // CCC greets
"\x02\x0F\x2A\x24" // Fnext
"\x02\x05\x7E\xCC" // Fprev
```

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OoopSPF

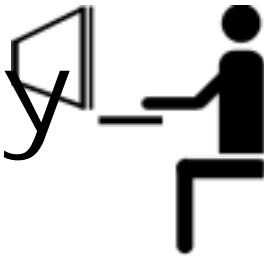


- Cisco IOS 11.2, 11.3, 12.0 crash with more than 255 OSPF neighbors
- Cisco Bug ID: **CSCdp58462**
- Overwrites memory structures – but different:
 - Overflow is not single packet
 - Overflow is in IO memory buffers
 - Overflow is not at the end of memory block chain



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OoopSPF Exploitability

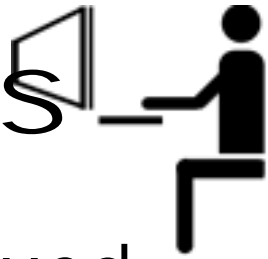


- Creation of a list entry depends on the source address of the IP OSPF HELLO packet
 - Source IP address has to be expected on this interface (network statement)
 - Netmask smaller than 0xFFFFFFFF00 required (more than 255 neighbors)
- List entry is the OSPF header Router ID
 - Not checked against the source network
 - No plausibility checks at all



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IO memory and buffers



- IOS uses dynamically scaled lists of fixed size buffers for packet forwarding and other traffic related operations
- **Public buffer pools**
(small, middle, big, very big, hug)
- **Private interface pools**
(size depends on MTU)
- Allocation/Deallocation depends on thresholds (perm, min, max, free)

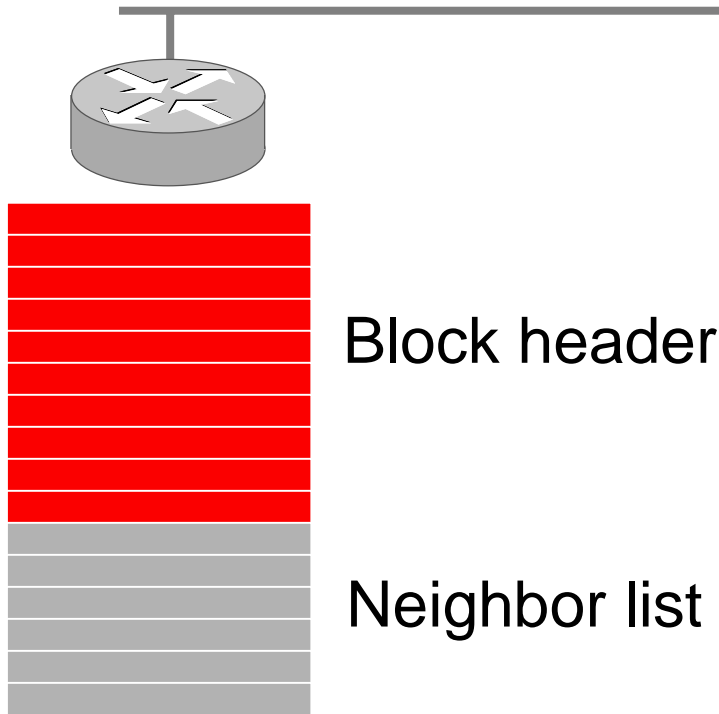


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OoopSPF Exploit



Hey Cisco, piece this together for me!

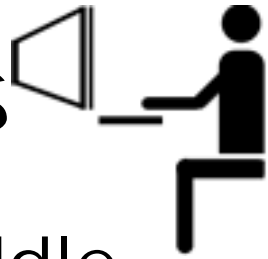


- Every packet can deliver 4 bytes to the buffer
- Overflow happens bottom to top (copy action)
- 256 IP addresses gives a buffer of 1024 bytes
- Larger buffers possible

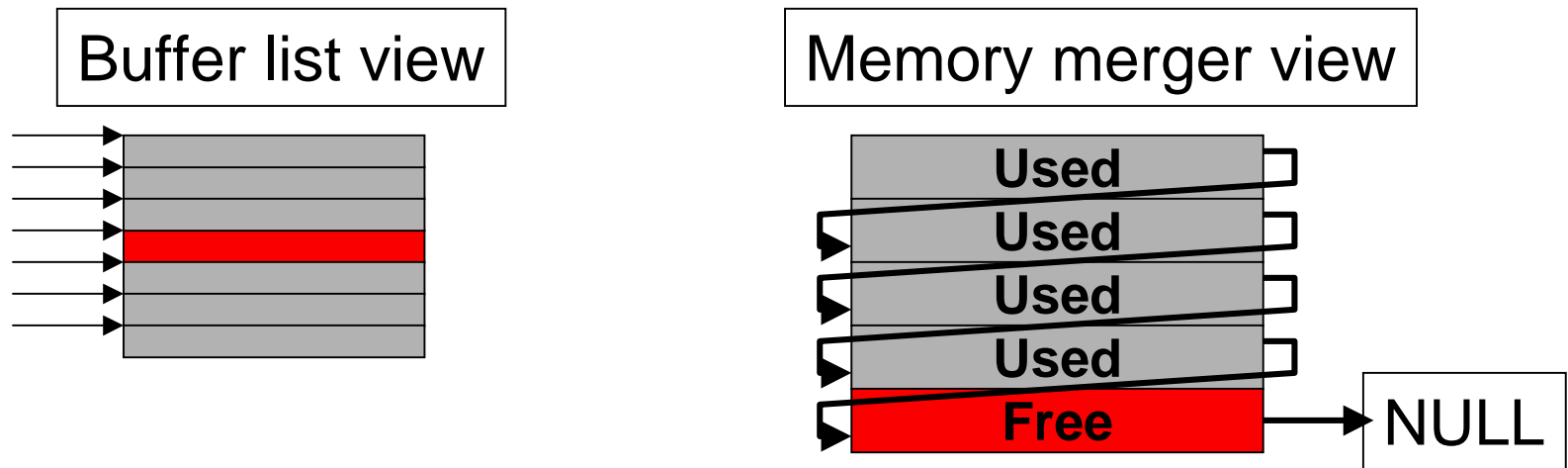


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Memory Mgmt Tricks

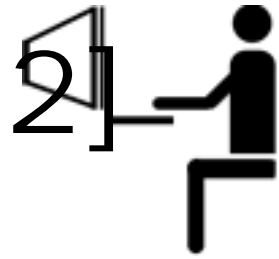


- Overflowed block header is in the middle of a memory block chain
- Free() exploit depends on memory being coalesced
- Solution: make a free used block ; -)



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Memory Mgmt Tricks [2]



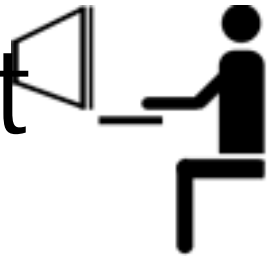
- Requires
 - Correct PREV Pointer
 - Correct Size up to the end of the memory pool
- System stays stable after successful overflow – *exploit dormant*

Address	Bytes	Prev.	Next	Ref	PrevF	NextF	Alloc PC	What
....								
E2F5F8	1680	E2EF3C	E2FCB4	1			3172EF0	*Packet Data*
E2FCB4	1680	E2F5F8	E30370	1			3172EF0	*Packet Data*
E30370	1680	E2FCB4	E30A2C	1			3172EF0	*Packet Data*
E30A2C	260	E30370	E30B5C	1			3172EF0	*Packet Data*
E30B5C	1897592	E30A2C	0	0	0	E30B80	808A8B8C	[PHENOELIT]

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Activating the Exploit

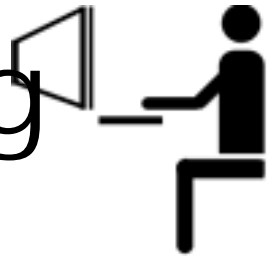


- The box has to need more small (or medium) buffers than set as „permanent“
 - Heavy traffic load
 - Complex routing updates
- After „trimming“ the buffers (deallocation), the box comes back with a new config
- Alternative (social engineering):
buffers small permanent 0



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A minimum IOS config



```
ena p c
in e0
  ip ad 62.1.2.3 255.255.255.0
ip route 0.0.0.0 0.0.0.0 62.1.2.1
li v 0 4
  pas c
  logi
```



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Work to do

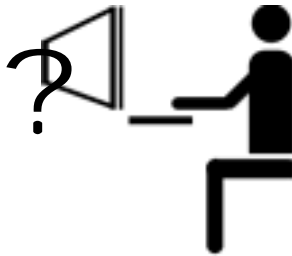


- PREV ptr addresses and all the other guesswork
 - Mapping commonly used addresses
 - Stabilizing the PREV ptr address
 - Produce „stable“ exploits ; -)
- NVRAM and Config
 - Writing to FLASH instead of NVRAM
 - Anti-Forensics shell codes
 - Real time config modification code



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IOS Exploit - so what?



- Most IOS heap overflows seem to be exploitable
 - Protocol based exploitation
 - Debug based exploitation
 - Network infrastructure still mostly unprotected
- NVRAM still contains former config after local network exploitation
 - Password decryption
 - Network structure and routing protocol authentication disclosed



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How to protect



- Do not rely on one type of device for protection
- Consider all your networked equipment vulnerable to the fullest extent
- Employ all possible protection mechanisms a device provides
- Do not ignore equipment because it is small, simple, or has not been exploited in the past.
- Plan your device management as you plan root logins to UNIX systems



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How to protect - HP

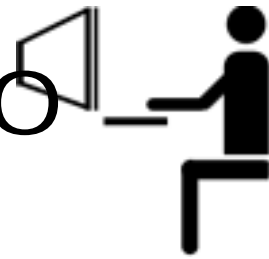


- Assign passwords
 - Admin password
 - SNMP *read and write* community
 - PJP protection (gives you time)
- Allow access to port 9100 on printer only from print servers
- Remove this.loader from the printer (edit /default/csconfig and restart)
- Consider putting your printers behind an IP filter device



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How to protect - Cisco



- Have no overflows in IOS
- Keep your IOS up to date
- Do not run unneeded services (TFTP)
- Tell your IDS about it. Signature:
\xFD\x01\x10\xDF\xAB\x12\x34\xCD
- **debug sanity** might stop less experienced attackers
- The hard way: **config-register 0x00**
- Perform logging on a separate segment
- Protect your syslog host



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Thanks and Greetings go to ...

Jeff, Ping, Gaus, Halvar, Johnny Cyberpunk, WarLord,
Skyper, Gamma, Svoern, Scusi, Pandzilla, Dizzy
and of course #phenoelit !

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