Fighting the War in Memory

Software Vulnerabilities and Defenses Today

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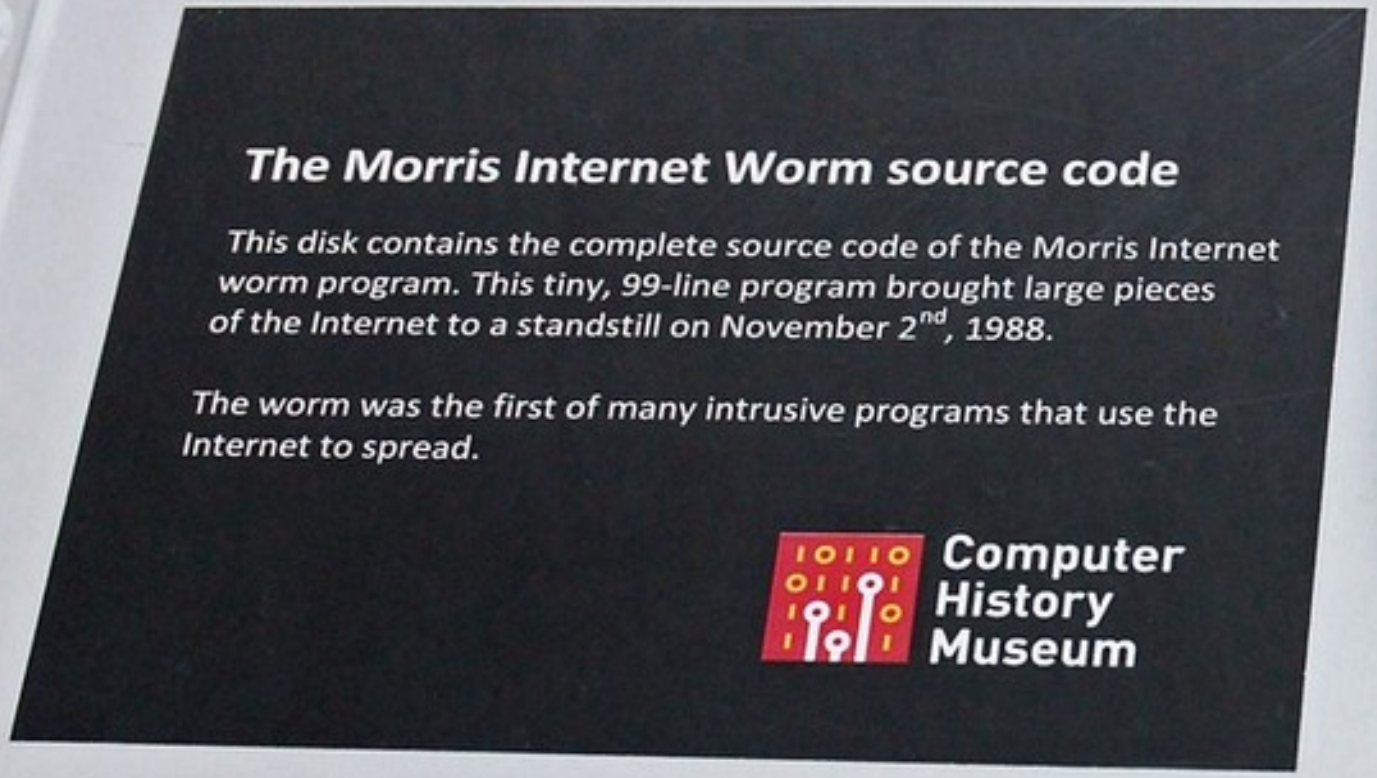
2014

ETH Zürich

LST Laboratory for Software Technology


NEVER FORGET

Morris Worm


The Morris Internet Worm source code
This disk contains the complete source code of the Morris Internet worm program. This tiny, 99-line program brought large pieces of the Internet to a standstill on November 2nd, 1988.
The worm was the first of many intrusive programs that use the Internet to spread.
Computer History Museum


Internet Worm -
Source code
X1294.96 A-D

Long ago – late 1980s

- On November 2, 1988 the Morris Worm was released
  - Mainstream media attention
  - Conviction under the Computer Fraud and Abuse Act
  - **First well-known program exploiting a buffer overflow**

http://en.wikipedia.org/wiki/Morris_worm

25 years later

Memory errors and memory corruption vulnerabilities are still an issue!

This talk is about

- Why these bugs are still a concern
- How exploits work
- Modern defenses

Motivation


LAN
DNS
127.0.0.1
192.168.1.1
Upload
Download
Used 0.0
Total 100.0 G
Used 10.0
Total 200.0 G
Connectivity
Security System
CPU 1 10%
CPU 2 8%
RAM
Total 4.0 GB
Used 2.2 GB
SWAP
Total 8.0 GB
Used 1.4 GB
Memory

Today, 2014

- Memory errors are still a problem
  - “Unsafe“ languages like C/C++ very popular
    - Prediction: C/C++ will be with us for a long time
    - Yes, there are alternatives... sometimes
  - Criminals found ways of monetization
  - Software systems are gaining complexity

http://www.langpop.com/
http://www.tiobe.com/index.php/content/paperinfo/tpci/index.html

Terminology

Exploit

"An **exploit** is a **piece of software, a chunk of data**, or a sequence of commands that **takes advantage of a bug**, glitch or vulnerability in order to..."

Zero-Day Attack

"A **zero-day** attack or threat is an attack that exploits a **previously unknown vulnerability** in a computer application, ..."

http://en.wikipedia.org/wiki/Exploit_(computer_security)
http://en.wikipedia.org/wiki/Zero-day_attack

Attacks

Runs a vulnerable web browser or PDF reader

Victim | Attacker

Runs a malicious web server serving HTML documents that trigger a memory error within the web browser

Sends a malicious PDF attachement by email

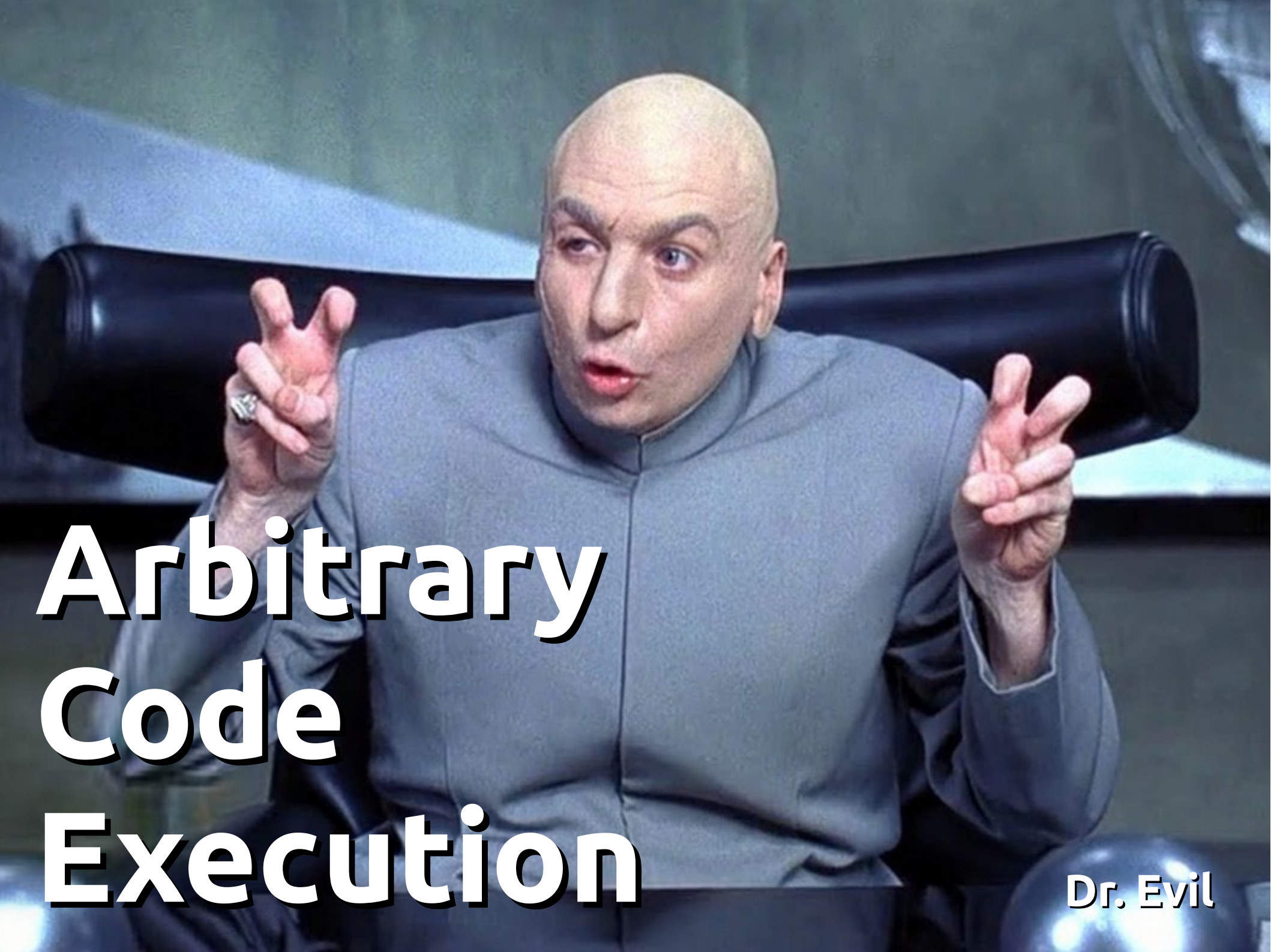
Exploits memory error within vulnerable victim software

Runs a vulnerable web server software

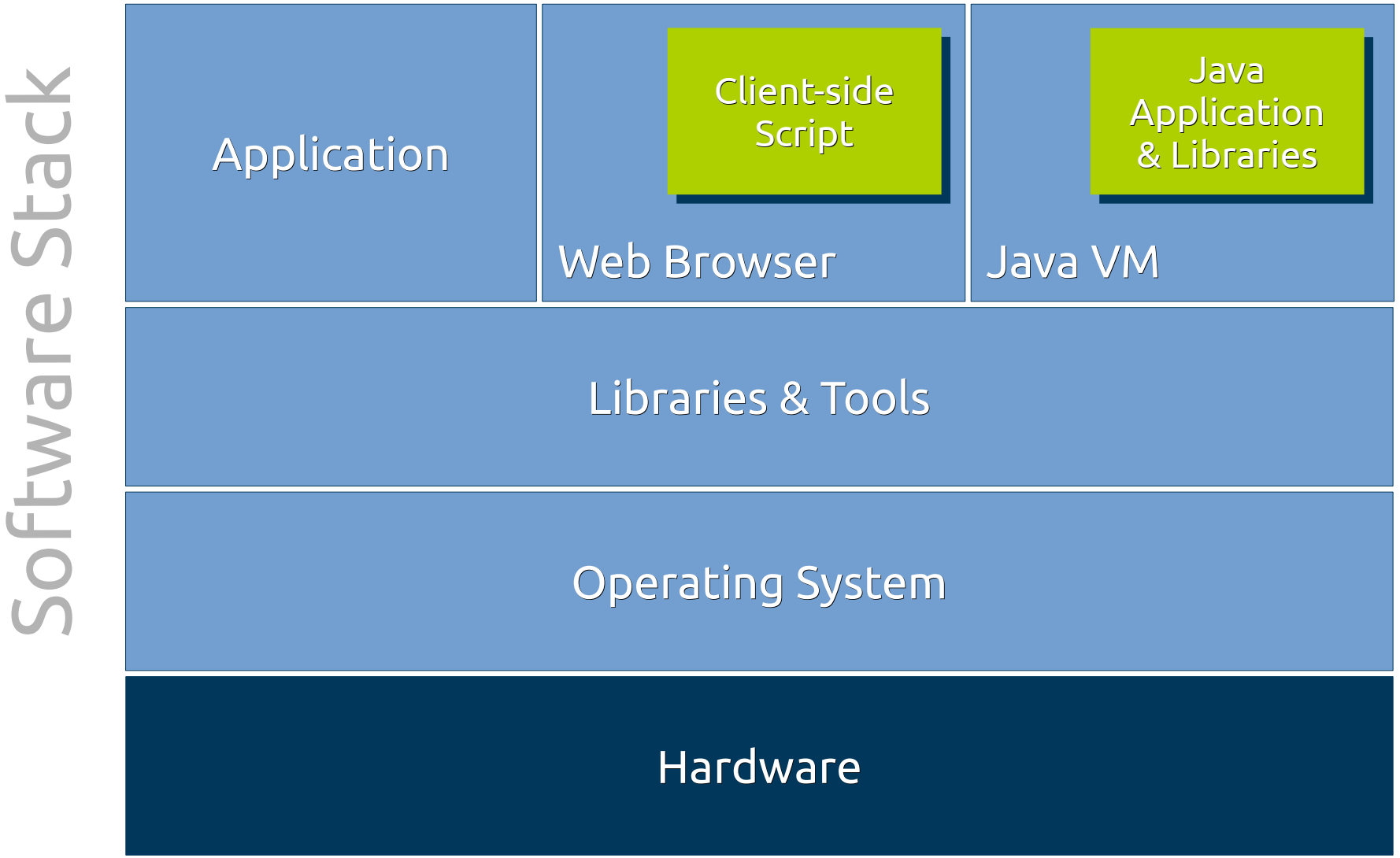
```
GET /index.html HTTP/1.1
Host: www.vulnsite.com
Keep-Alive: 300
Connection: keep-alive
Cookie: CID=r2t5uvjq43
5r4q7ib3vtdjq120f83jf8
... <binary data>
```

```
$>./exploit 192.168.1.28
```

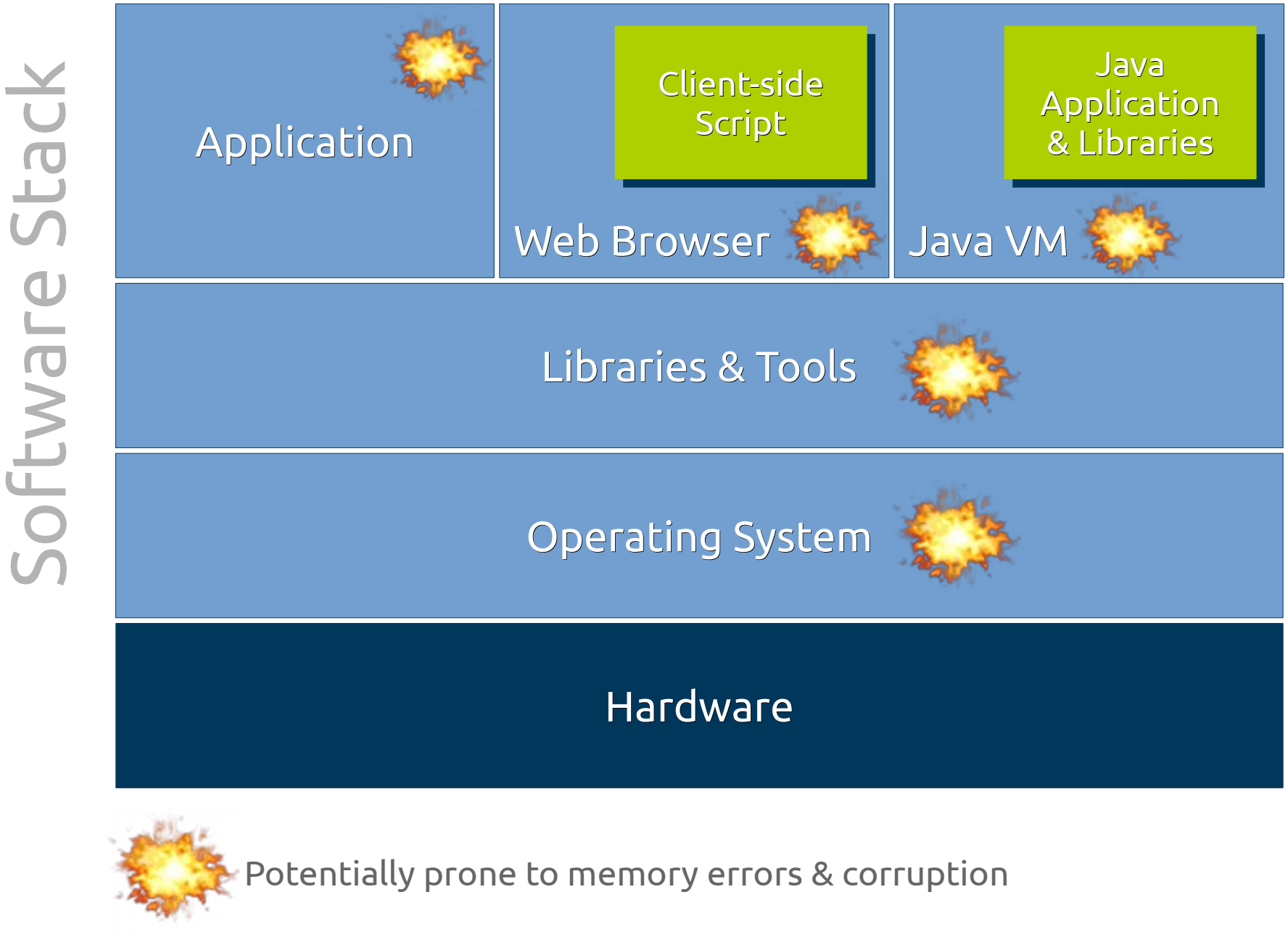
Runs an exploit that triggers a memory error within the web server software


Arbitrary
Code
Execution
Dr. Evil

Modern software stack



Modern software stack



The Internet of “Memory Unsafe“ Things









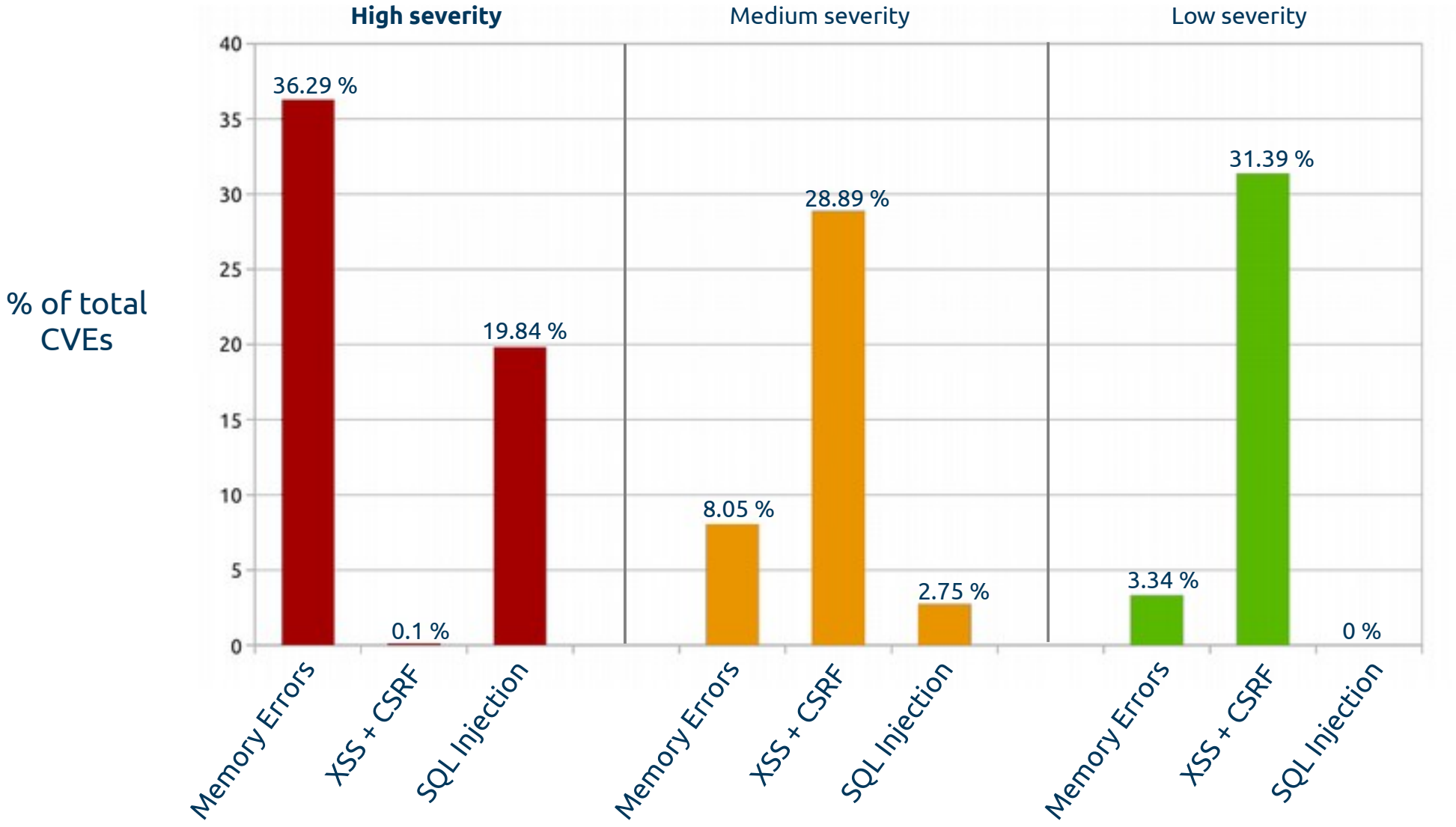








Common Vulnerabilities and Exposures



https://cve.mitre.org/

Total CVEs without "Insufficient Information" 25'298, time span: 1.1.2009 – 26.8.2014
Memory Errors: CWE-119, CWE-399 "use after free", CWE-189 in High / XSS + CSRF: CWE-79, CWE-352 / SQL Injection: CWE-89

Finding vulnerabilities

- Finding exploitable errors is not trivial
  - Static and dynamic analysis, testing, reviews

Edsger W. Dijkstra, 1969:

“Testing shows the presence,
not the absence of bugs.“

Thinking about a career change?

ADOBE READER	$5,000–$30,000
MAC OSX	$20,000–$50,000
ANDROID	$30,000–$60,000
FLASH OR JAVA BROWSER PLUG-INS	$40,000–$100,000
MICROSOFT WORD	$50,000–$100,000
WINDOWS	$60,000–$120,000
FIREFOX OR SAFARI	$60,000–$150,000
CHROME OR INTERNET EXPLORER	$80,000–$200,000
IOS	$100,000–$250,000

Chromium > Chromium Security >

Security Hall of Fame

The following bugs qualified for a Chromium Security Reward, or represent a win at our Pwnium c
our millions of users, we thank the named researchers for helping make Chromium safer.

[NOTE - this list is occasionally missing a few items as it is not automatically synchronized
Please e-mail security@chromium.org if your credit is missing and we will be delighted to cc

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- $60000 to PinkiePie for bug 117620
- $40000 to PinkiePie for bug 181083 and others
- $31336 to Ralf-Philipp Weinmann for bug 227181 and others
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- $10000 to Arthur Gerkis for bug 116663
- $10000 to Sergey Glazunov for bug 143439
- $10000 to miaubiz for bug 157047
- $10000 to Atte Kettunen for bug 157048

The 2014 targets are:

Browsers:

- Google Chrome on Windows 8.1 x64: $100,000
- Microsoft Internet Explorer 11 on Windows 8.1 x64: $100,000
- Mozilla Firefox on Windows 8.1 x64: $50,000
- Apple Safari on OS X Mavericks: $65,000

Plug-ins:

- Adobe Reader running in Internet Explorer 11 on Windows 8.1 x64: $75,000
- Adobe Flash running in Internet Explorer 11 on Windows 8.1 x64: $75,000
- Oracle Java running in Internet Explorer 11 on Windows 8.1 x64 (requires click-through bypass): $30,000

"Exploit Unicorn" Grand Prize:

- SYSTEM-level code execution on Windows 8.1 x64 on Internet Explorer 11 x64 with EMET (Enhanced Mitigation Experience Toolkit) bypass: $150,000*

http://www.forbes.com/sites/andygreenberg/2012/03/23/shopping-for-zero-days-an-price-list-for-hackers-secret-software-exploits/
http://www.pwn2own.com/2014/01/pwn2own-2014-rules-unicorns/
http://www.chromium.org/Home/chromium-security/hall-of-fame

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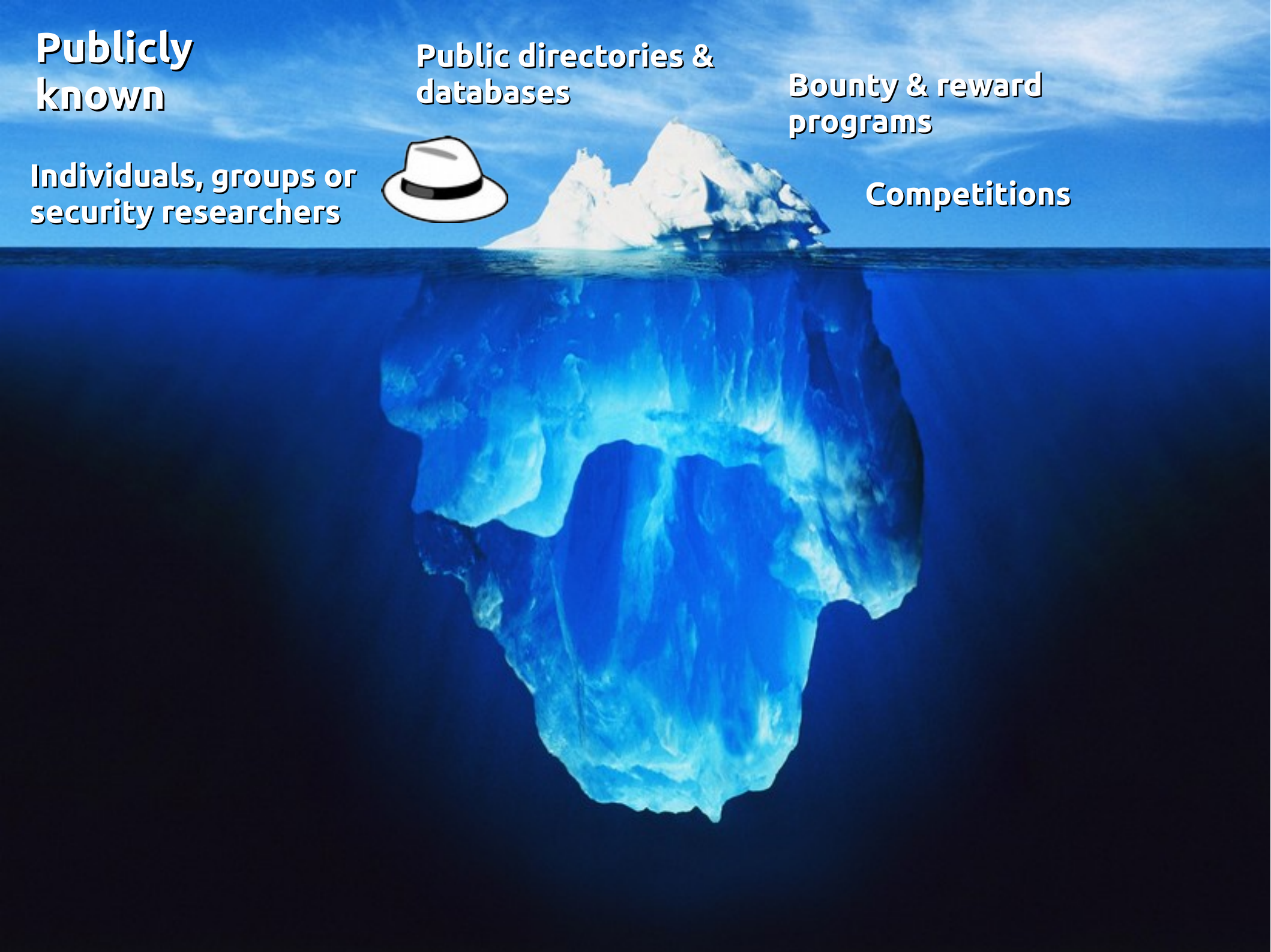
http://www.pwn2own.com/2014/01/pwn2own-2014-rules-unicorns/
http://www.chromium.org/Home/chromium-security/hall-of-fame


Publicly known
Individuals, groups or security researchers
Public directories & databases
Bounty & reward programs
Competitions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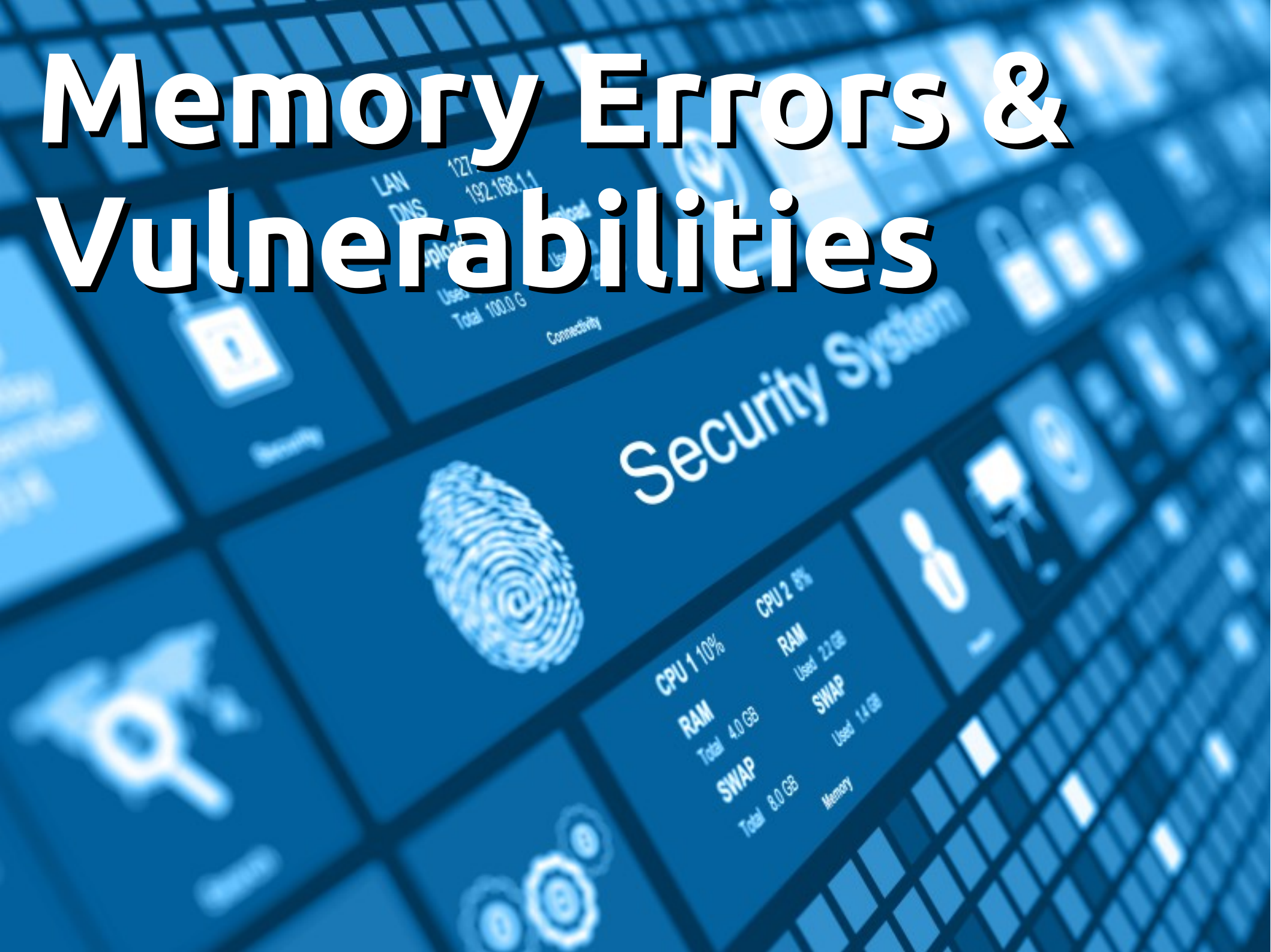
Competitions
Unknown
Specialized companies
Individuals or groups
Cybercrime
Government agencies
NATIONAL SECURITY AGENCY
UNITED STATES OF AMERICA
Industrial espionage

In the end

We have to accept the residual risk...

...but to manage the risks we have to understand the attack techniques and the effectiveness of available defenses!

Memory Errors & Vulnerabilities



Memory errors & vulnerabilities

- Come in various forms with different root causes
- Allow attackers to corrupt memory in a more or less controllable way
  - Worst case: attackers gain arbitrary code execution
- Exist in programs written in “unsafe“ languages that do not enforce memory safety

“Unsafe“ languages

- Allow low-level access to memory
  - Typed pointers & pointer arithmetic
  - No automatic bounds checking / index checking
- Weakly enforced typing
  - Cast (almost) anything to pointers
- Explicit memory management
  - Like malloc() & free() in C

“Unsafe“ languages - C

```c
#include <stdio.h>
#include <math.h>

long computation(int x, int y, int z, double f) {
 return (long)(((x*y)/z)*sin(f));
}

void main()
{
  *(int*)computation(32, 64, 2, M_PI/6) = 128;
  return;
}
```

```
shell:~$ gcc -o segfault segfault.c -lm
shell:~$ ./segfault
Segmentation fault (core dumped)
shell:~$
```

“Unsafe“ languages - C

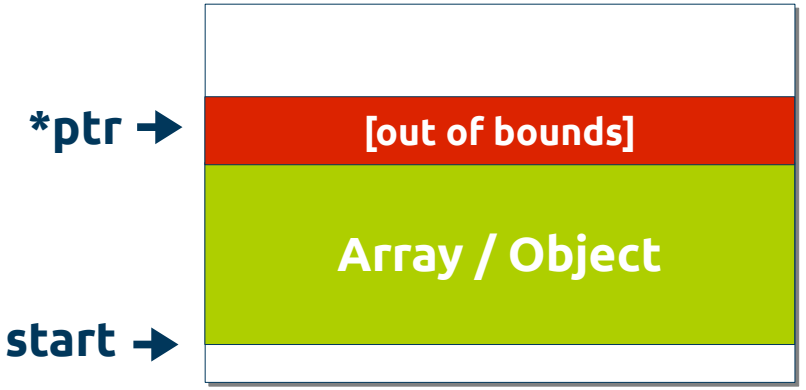
```c
#include <stdio.h>
#include <string.h>

#define STDIN 0

void vulnFunc() {
        char buf[1024];
        read(STDIN, buf, 2048);
}
```

```c
void main() {
        printf("read> ");
        vulnFunc();
        return;
}
```

```
shell:~$ gcc -o vuln vuln.c -fno-stack-protector
shell:~$ ./vuln
read> hi there!
shell:~$ ./vuln
read>
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA...
Segmentation fault (core dumped)
shell:~$
```

Types of memory errors

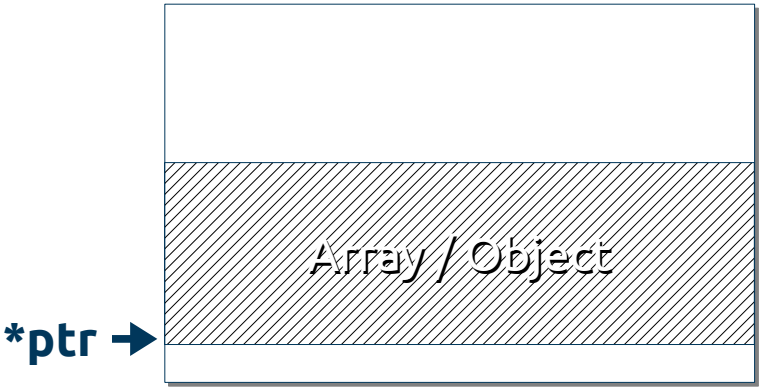
Spatial error



De-reference pointer that is out of bounds

Read or write operation

Temporal error



De-reference pointer to freed memory

Read operation

Exploiting memory errors

Spatial error

Overwrite data or pointers

Used or de-referenced later

Temporal error

Make application allocate memory in the freed area

Used as old type

Attackers use memory errors to

- Overwrite data or pointers
  - That might be used to overwrite data or pointers
  - Function pointers, sensitive data, index values, control-flow sensitive data etc.
- Leak information
  - E.g., corrupt a length field
- Construct attacker primitives
  - Write primitive (write any value to arbitrary address)
  - Read primitive (read from any address)
  - Arbitrary call primitive (call any arbitrary address)

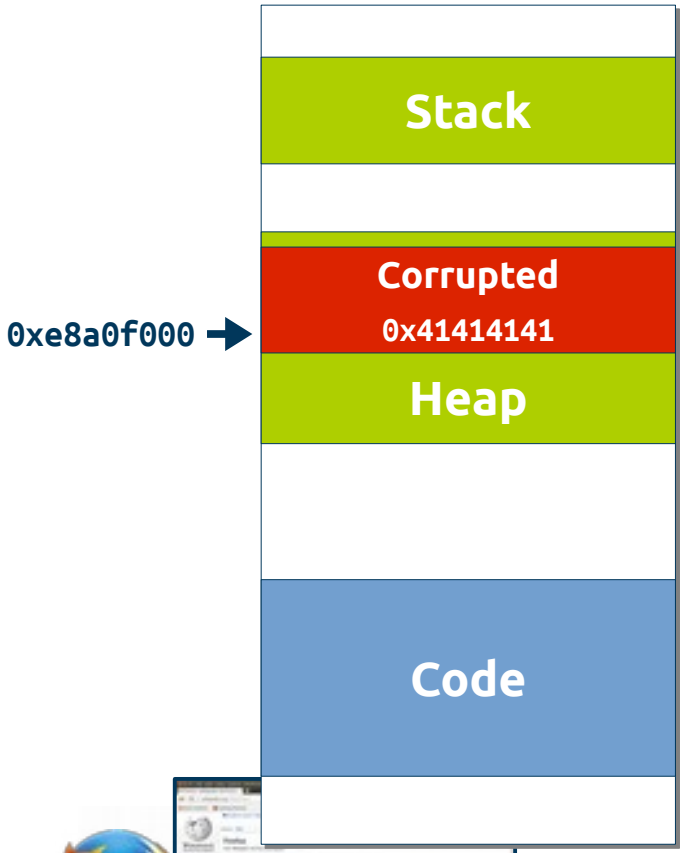
Types of bugs

- Out-of-bounds bugs / Buffer overflows
  - On stack or heap
- Dangling pointer / Use-after-free
- Integer bugs, signedness bugs
- Format string bugs
- Uninitialized memory
- NULL pointer dereference
- etc.

Memory corruption attack

Victim

Attacker




```
<html>
<head>
</head>
<body>
... <html or javascript that
triggers the memory corruption
vulnerability> ...
</body>
</html>
```

Write primitive

```
*0xe8a0f000 = 0x41414141
```

Attack types

- Code corruption attack
- Control-flow hijack attack
- Data-only attack
- Information leak

Attack model according to: “SoK: Eternal War in Memory“ Laszlo Szekeres, Mathias Payer, Tao Wei, Dawn Song
http://www.cs.berkeley.edu/~dawnsong/papers/Oakland13-SoK-CR.pdf

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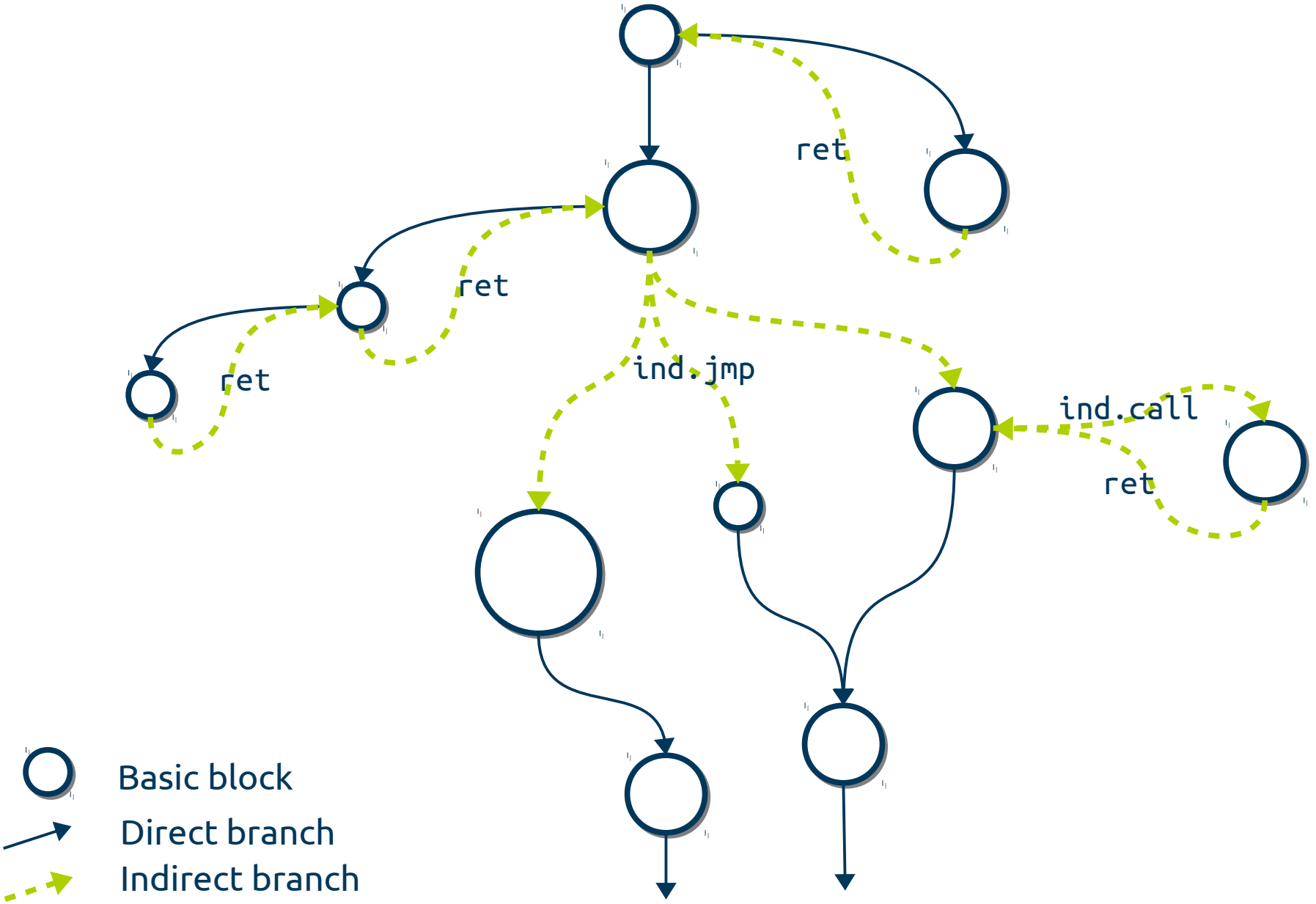
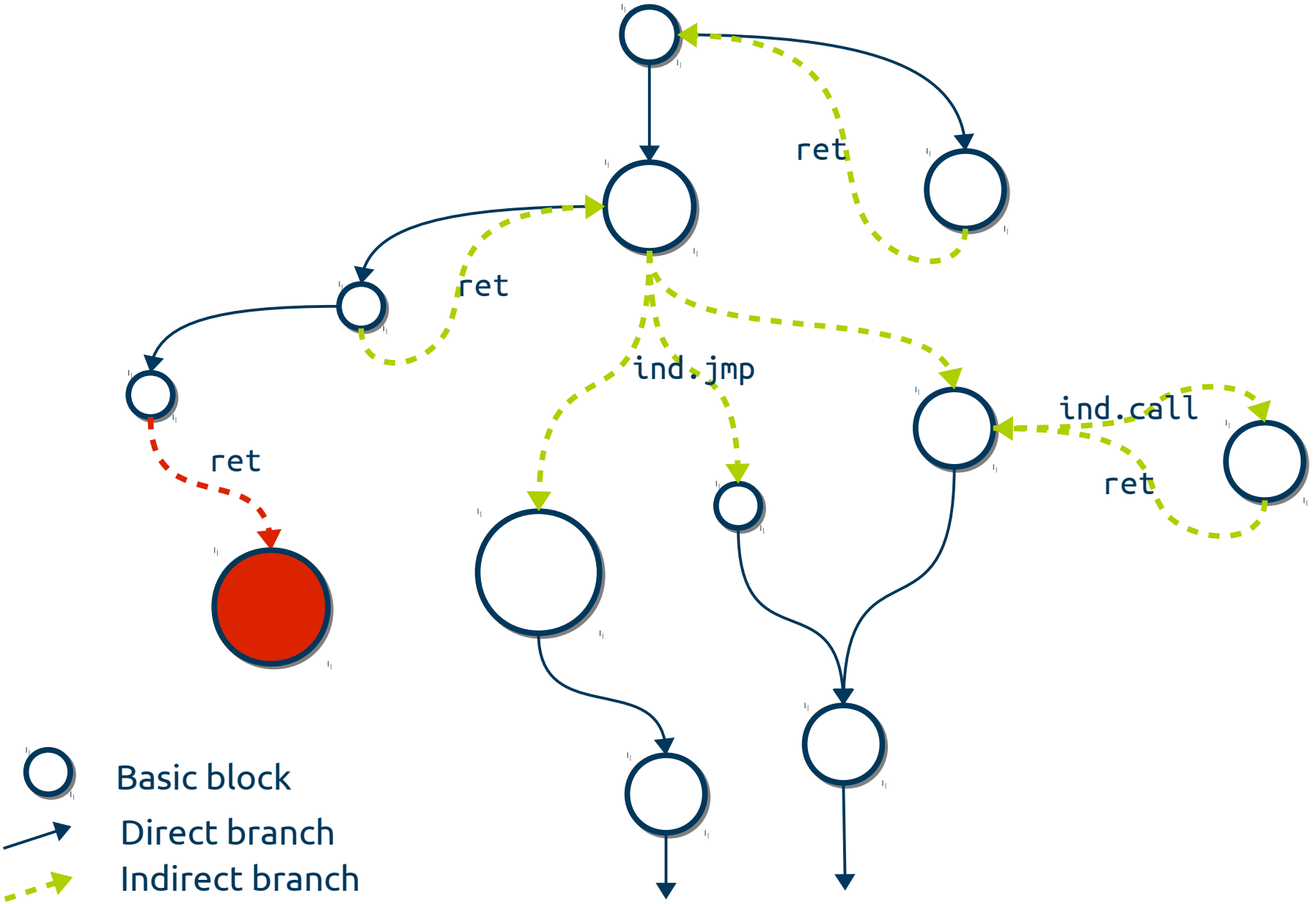
Control-flow hijack attacks

- Most powerful attack
- Hijack control-flow
  - To attacker supplied arbitrary machine code
  - To existing code (code-reuse attack)
- Corrupt code pointers
  - Return addresses, function pointers, vtable entries, exception handlers, `jmp_bufs`

Normal control-flow



Hijacked control-flow

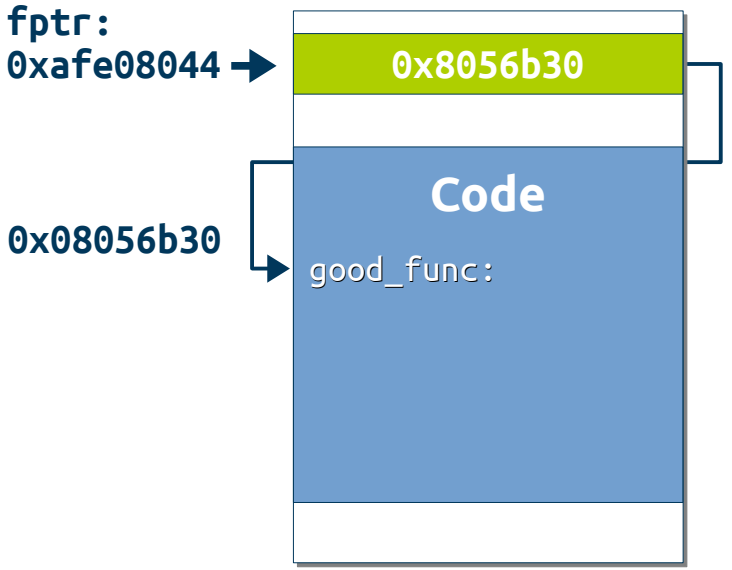


Control-flow hijack attacks

- Most ISAs support indirect branch instructions
  - E.g., x86 “`ret`“, indirect “`jmp`“, indirect “`call`“

`fptr` is a value in memory at `0xafe08044`

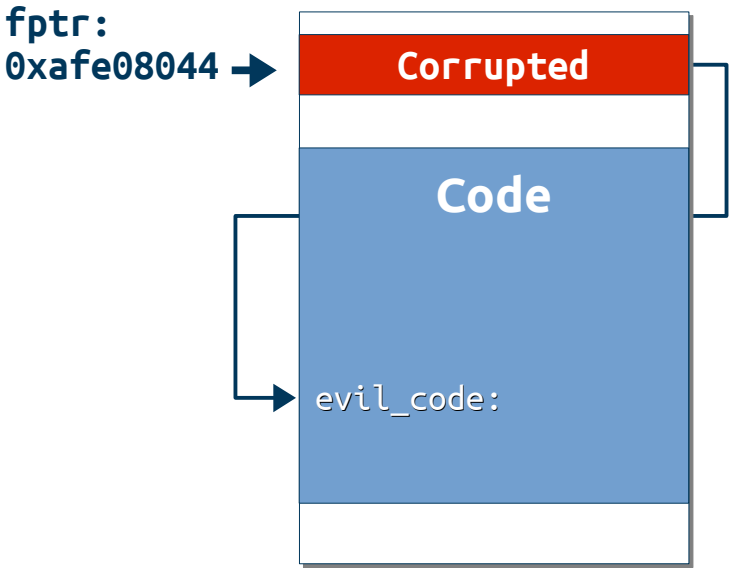
- `branch *fptr`



Control-flow hijack attacks

`fptr` is a value in memory at `0xafe08044`

- `branch *fptr`
- `fptr` was corrupted by an attacker



Attacker goal: hijack control-flow to injected machine code or to “evil functions“

Branch instructions – Intel x86

- Direct or indirect **`call`**
  - `call 804a450` or `call *0x24(%ebp)`
- Direct or indirect **`jmp`**
  - `jmp 8049e70` or `jmp *0x805a874(,%eax,4)`
  - There are also conditional jumps (direct)
- **`ret`**, Indirect by design
  - Take value on top of stack and branch to it
- **`call`** instructions push address of the next instruction onto the stack so the **`ret`** instruction can use it


Attack Techniques & Defenses
• Welcome to CityPower Grid Rerouting •
Authorised Users only!
New users MUST notify Sys/Ops.
login:
nmap -v -sS -O 10.2.2.2
Starting nmap V. 2.54BETA25
Insufficient responses for TCP sequencing (3), OS detection
accurate
Interesting ports on 10.2.2.2:
(The 1539 ports scanned but not shown below are in state:
Port State Service
22/tcp open ssh
No exact OS matches for host
Nmap run completed -- 1 IP address (1 host up) scanned
sshnuke 10.2.2.2 -rootpw="Z1ON0101"
Connecting to 10.2.2.2:ssh ... successful.
Attempting to exploit SSHv1 CRC32 ... successful.
Reseting root password to "Z1ON0101".
System open: Access Level <9>
ssh 10.2.2.2 -l root
root@10.2.2.2's password:
RIF CONTROL
ACCESS GRANTED

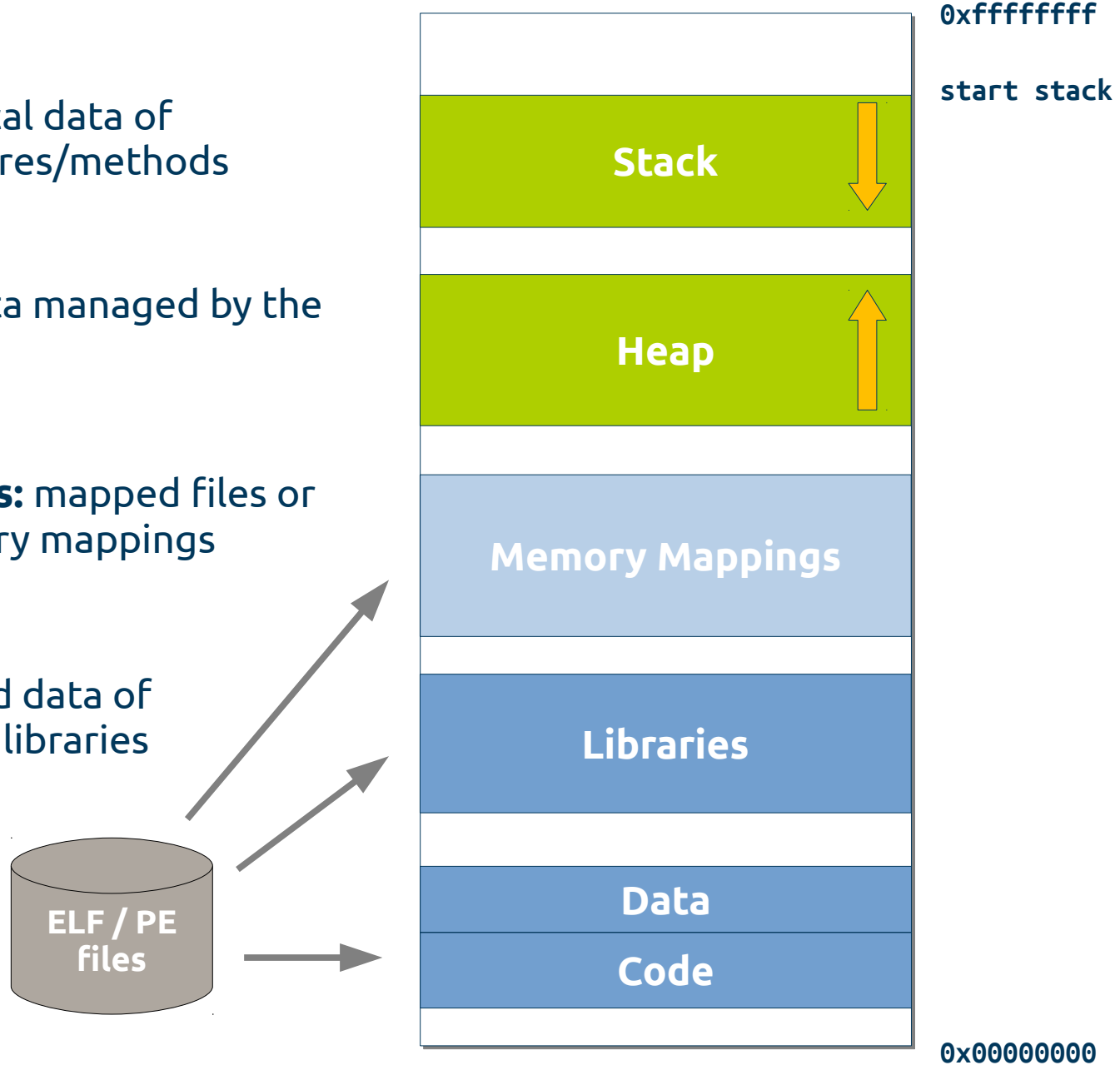
Generalized process layout – user space

Stack: contains local data of functions/procedures/methods

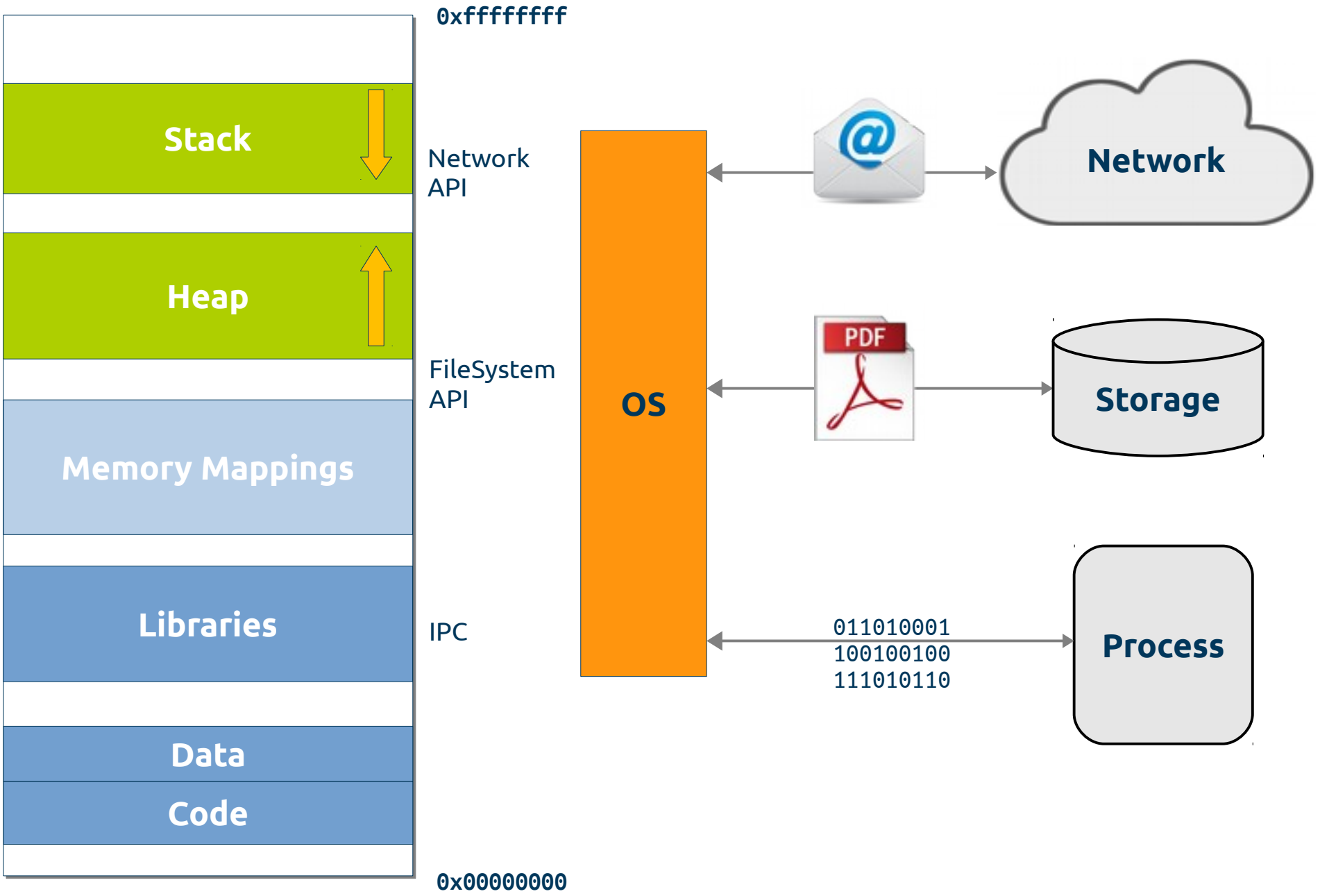
Heap: contains data managed by the heap manager

Memory Mappings: mapped files or anonymous memory mappings

Libraries: code and data of dynamically linked libraries



Attack surface



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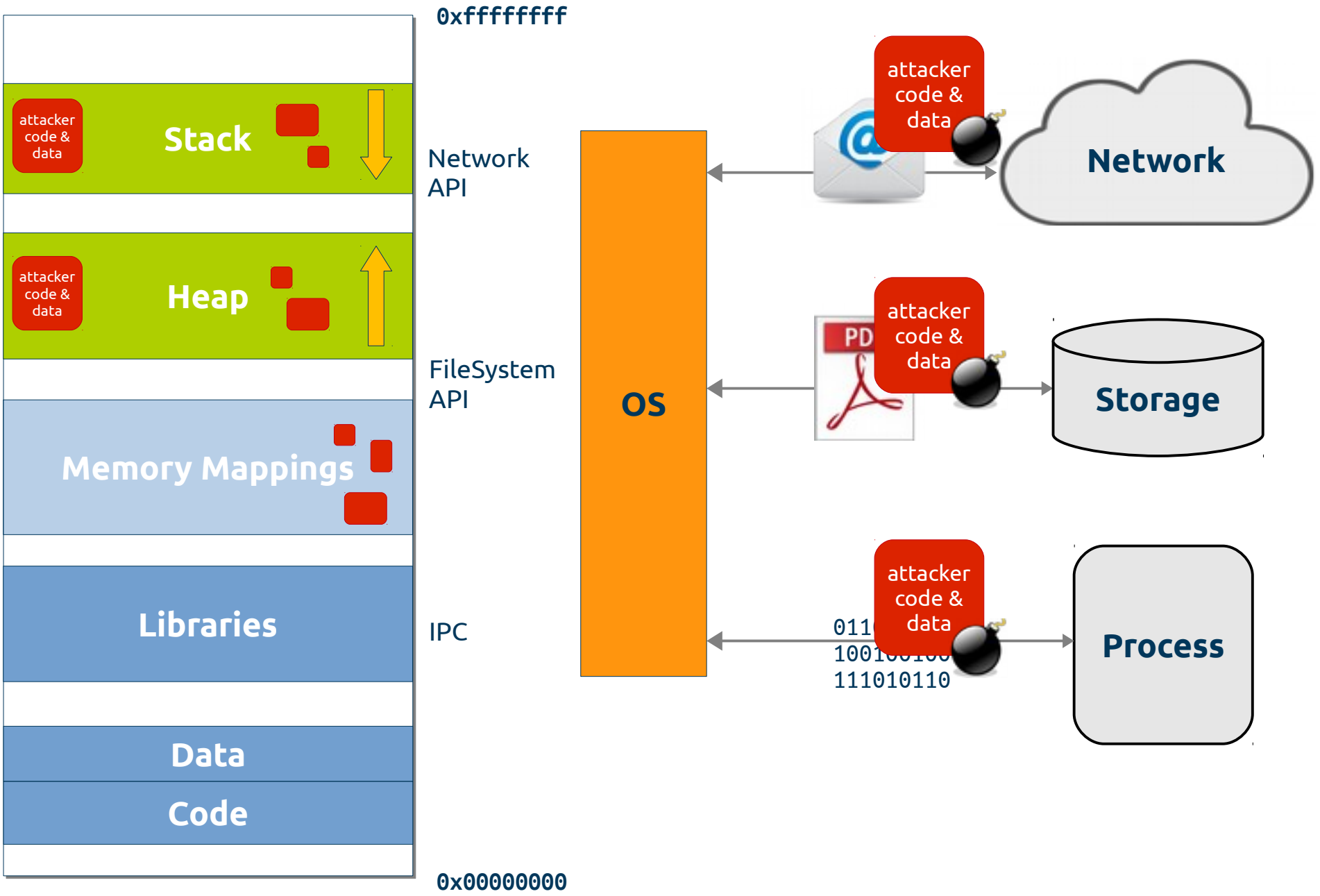
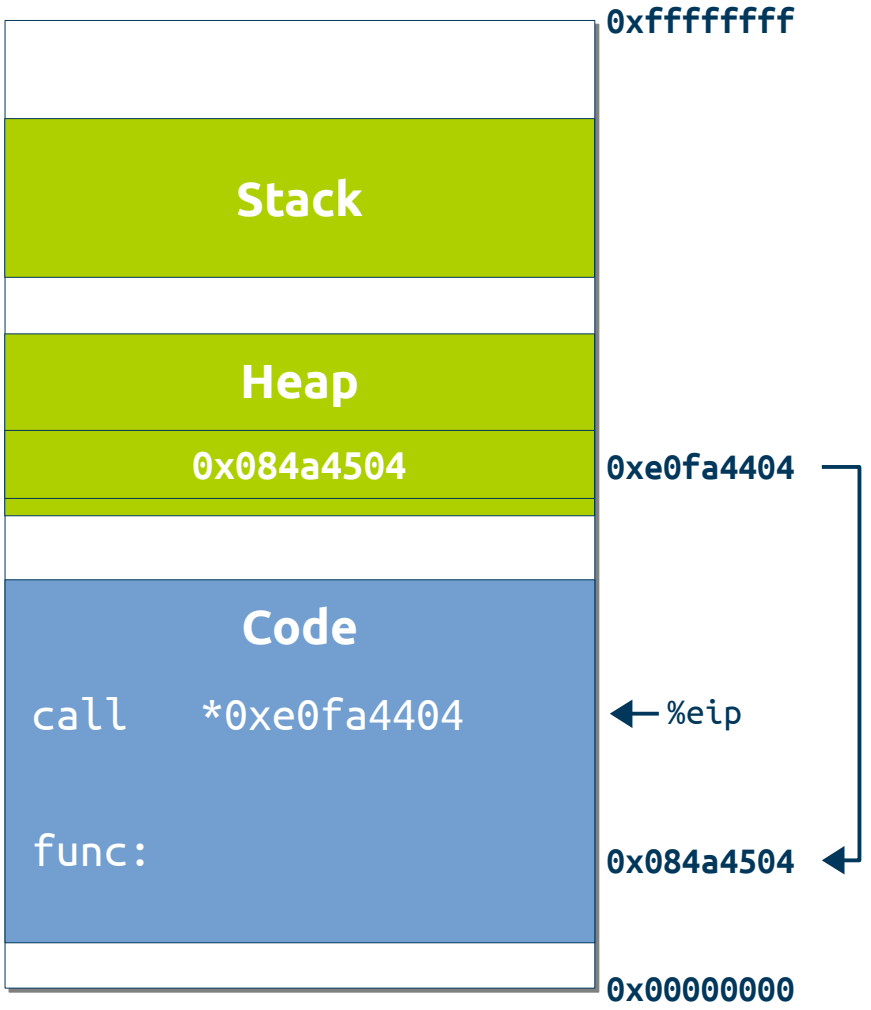
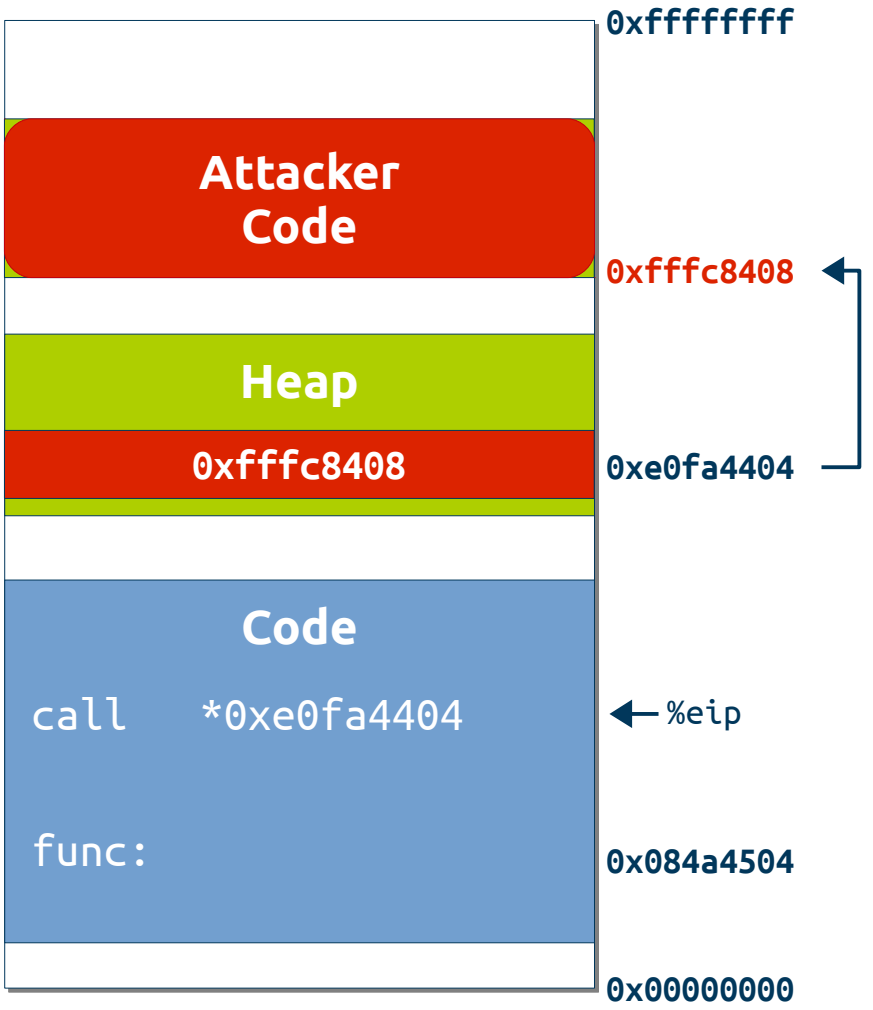


Control-flow hijack to injected code



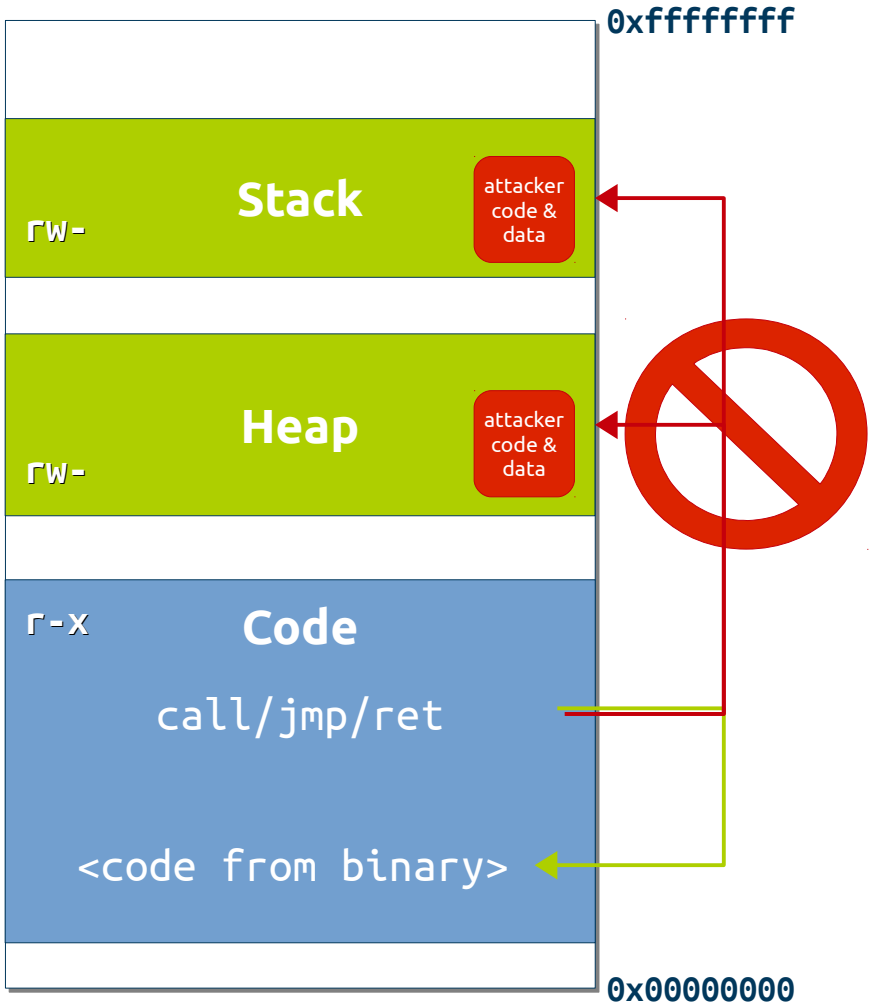
Indirect call to `func()`



Hijacked indirect `call`

Non-eXecutable data (NX)

- Make **data** regions **non-executable** (by default)
- Changing protection flags or allocating `rwx` memory still possible (on most systems)
  - Required for JITs



Non-eXecutable data (NX)

- Code regions will be non-writable
  - Else code corruption attacks possible
- Also known as
  - Data Execution Prevention (DEP) on Windows
  - NX, Non-eXecutable Memory on Linux
  - W^X, on OpenBSD
  - Implemented by hardware where available (NX-bit)

NX / DEP – implementation issues

Compatibility

- Binary images need to provide separate sections/segments that can be mapped exclusively as **rw- OR r-x**
  - Linker support required
- Self-modifying code not allowed
  - Compiler support required
  - If code is generated just-in-time, explicit **rwx** allocation required

Bypassing NX / DEP

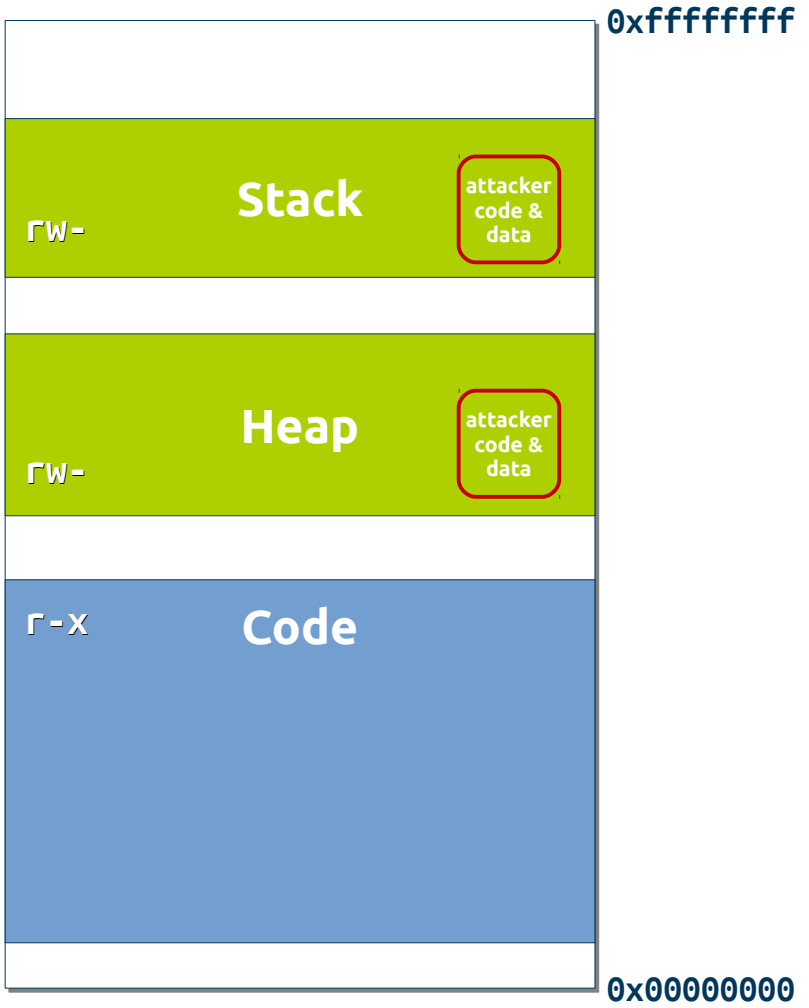
- Only use existing code

  Code-reuse attack

  - ret2libc, ret2bin, ret2*
  - Return-oriented programming (ROP)
  - Jump/Call-oriented programming

- Use code-reuse technique to **change protection flags**

  - Alllocate or make memory executable
    - mprotect/VirtualProtect
    - mmap/VirtualAlloc

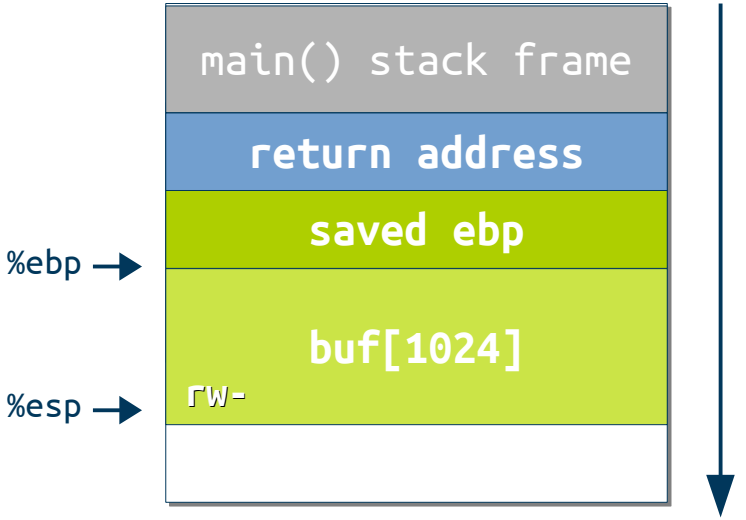


Code-reuse attack

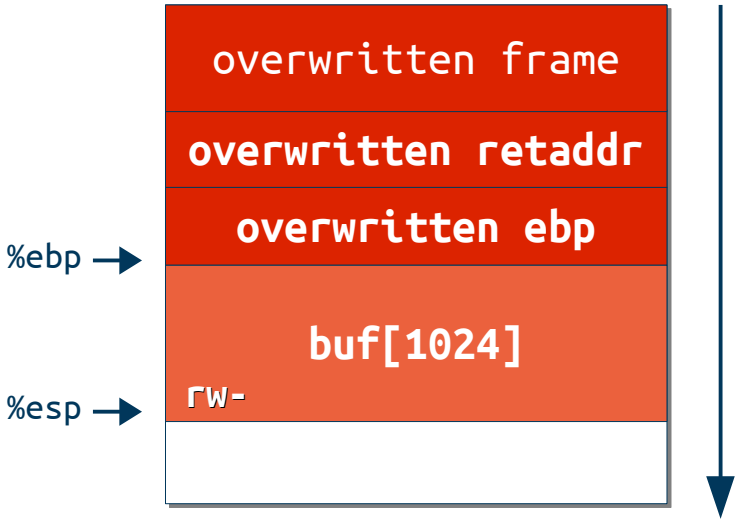
```
void vulnFunc() {
        char buf[1024];
        read(STDIN, buf, 2048);
}
```

- Stack-based buffer overflow
  - %eip and %ebp under attacker control
  - Local variables and buffers under attacker control

Stack during vulnFunc()

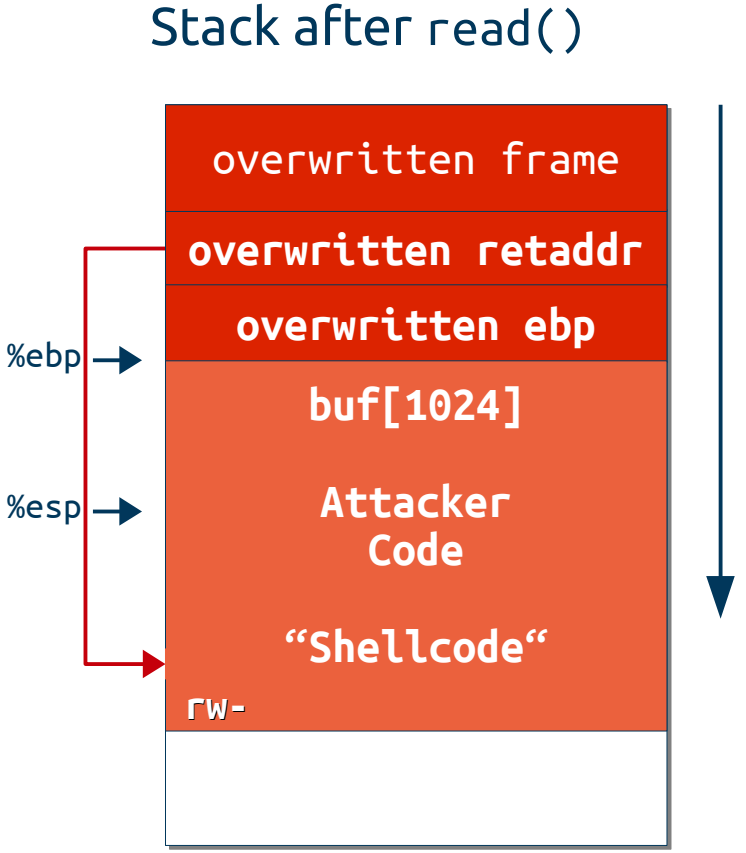


Stack after read()



Code-reuse attack

- Before NX/DEP
  - Return to attacker supplied code
    - Shellcode
- Bypass NX/DEP by using existing code
  - Executable or libraries
    E.g., mprotect()

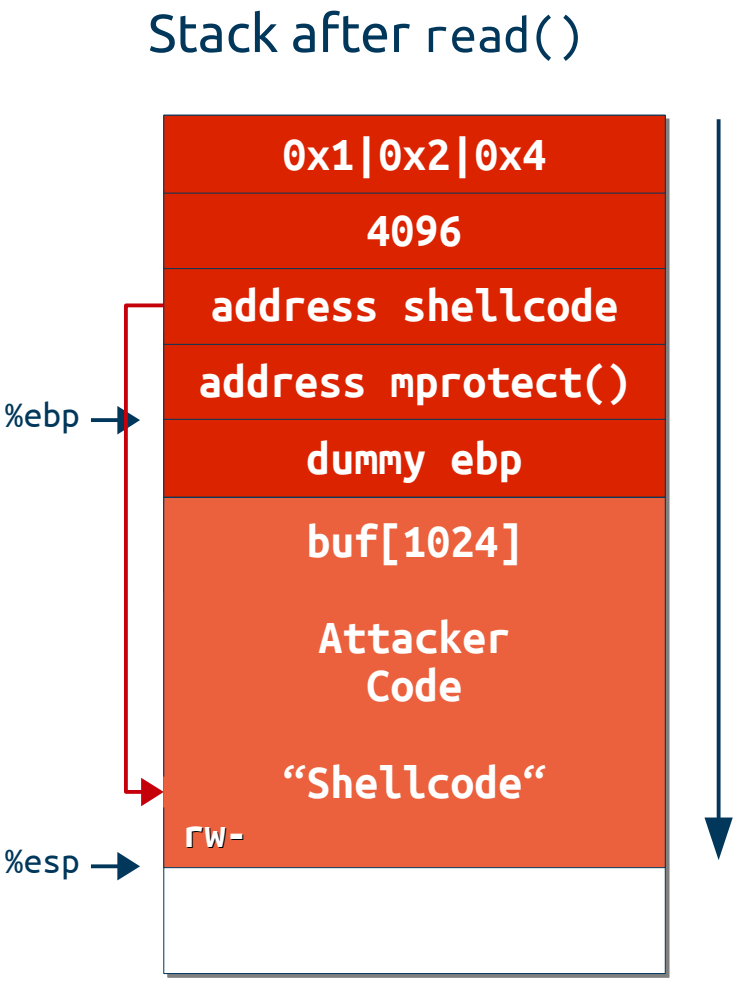


Code-reuse attack

- Let's call `mprotect()`

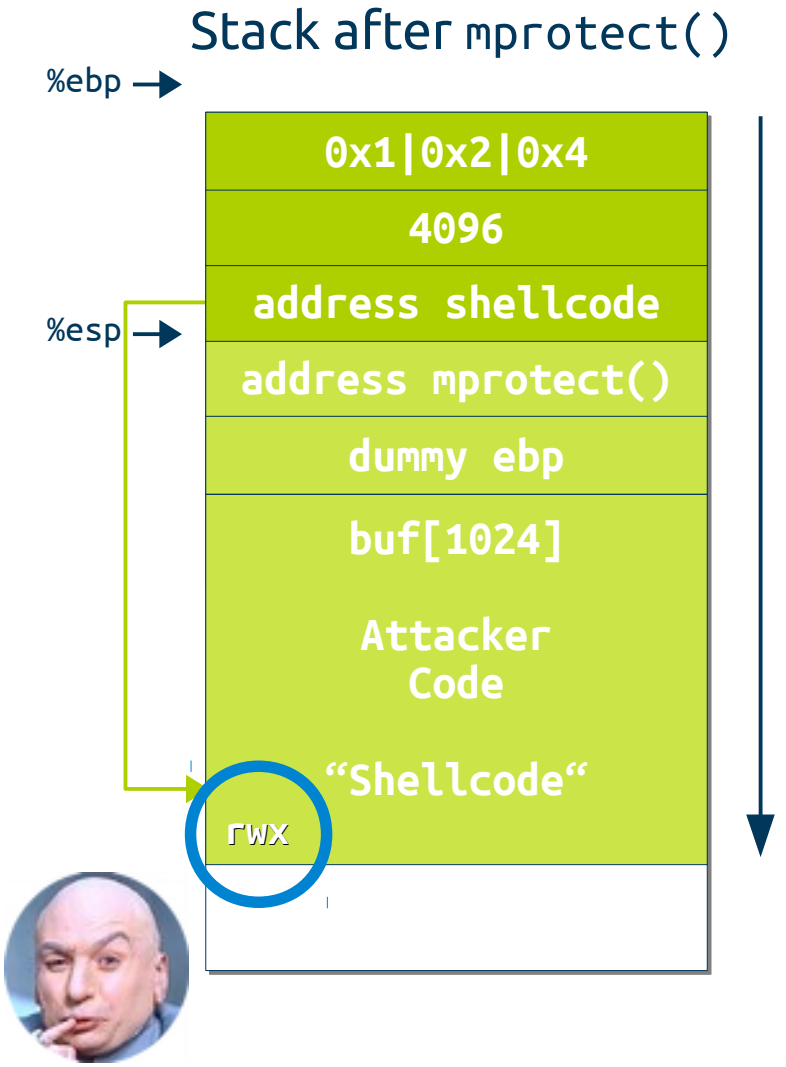
```
mprotect(address_shellcode, 4096, 0x1|0x2|0x4)
```

- `0x1|0x2|0x4` = RWX
- `mprotect()` will make the stack executable
  - And return to our shellcode



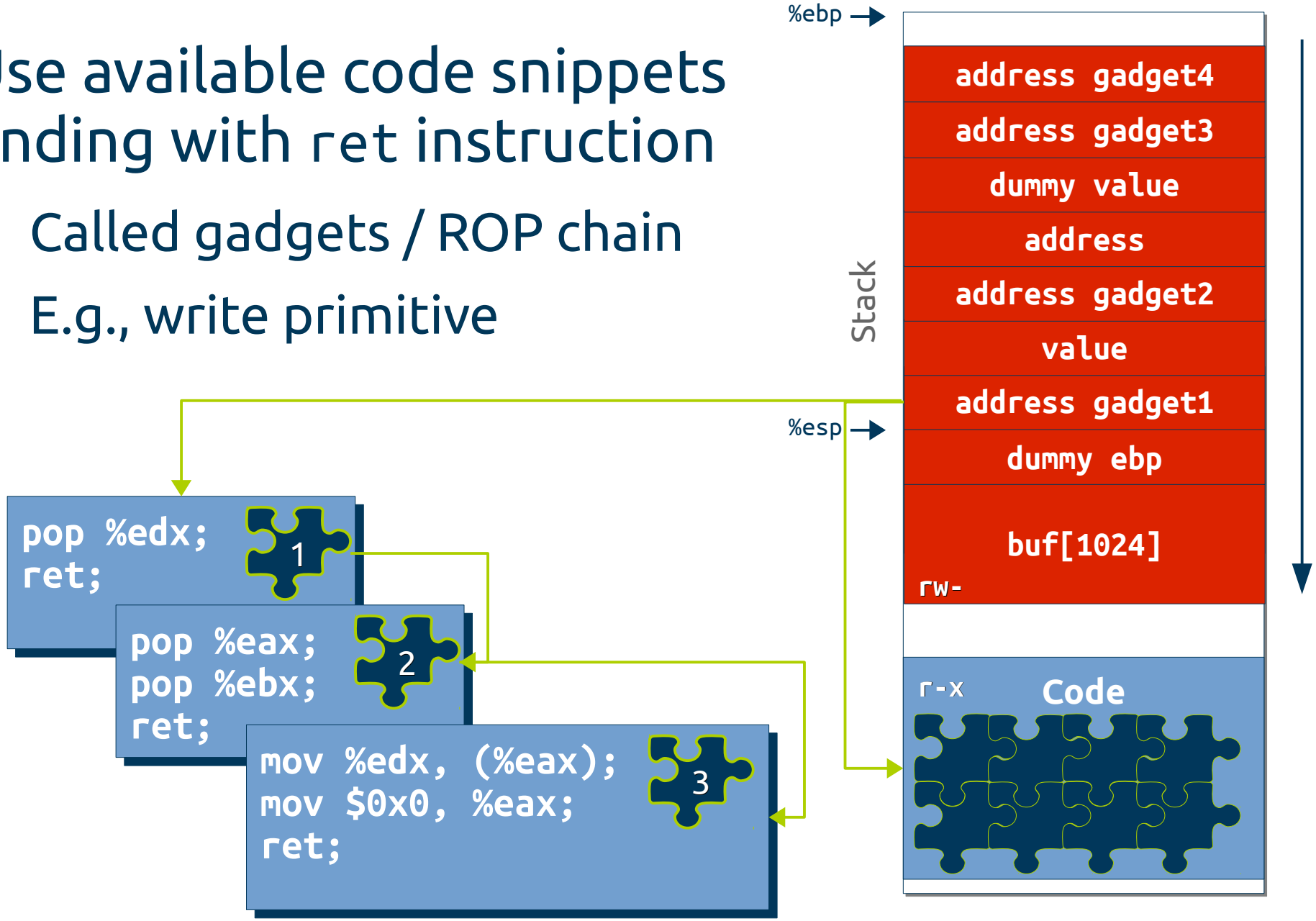
Code-reuse attack

- After `mprotect()` our stack is executable again
  - `mprotect()` will return to our shellcode
- Works well on x86 32bit but on x64 or ARM function parameters are passed over registers
  - Fill registers with parameters before invoking `mprotect()`



Return-oriented programming

- Use available code snippets ending with `ret` instruction
  - Called gadgets / ROP chain
  - E.g., write primitive



Return Oriented Programming

Return-oriented programming

- Very powerful!
  - Turing complete although not required
- Can be initiated over `call` or `jmp` as well
- Need to be in control of memory `%esp` is pointing to
  - Or make `%esp` point to area under control
- Also possible with `jmp` or `call` gadgets
  - Complicated to keep control and dispatch to the next gadget
  - Generalization: **Gadget-oriented programming**

Return-oriented programming

- Notes on calling convention
  - x86 32bit, easy, arguments passed over stack
    - If stack attacker controlled
  - x86 64bit & ARM, arguments passed in registers
    - More general purpose registers
    - Calling functions more laborious
    - Copy arguments from attacker data to registers
      - ARM has interesting „pop“ into multiple registers feature

Addresses in memory

- To hijack control-flow or to corrupt memory an attacker **needs to know where things are in memory**
  - Addresses of **data** or **pointers** to corrupt
  - Addresses of injected **shellcode/payload**
  - Addresses of **gadgets**

- Sometimes it's enough to know the rough location but **most of the time** attackers need the **exact location**
  - Corrupting only least significant bytes i.e. an offset might work in some special cases (but not in general)

Addresses in memory

Once upon a time...

- Addresses were more or less predictable
- Executables and libraries were prelinked to certain addresses
- Stack and Heap base addresses were fixed
  - With differences at runtime for specific locations due to the dynamic behaviour of the process

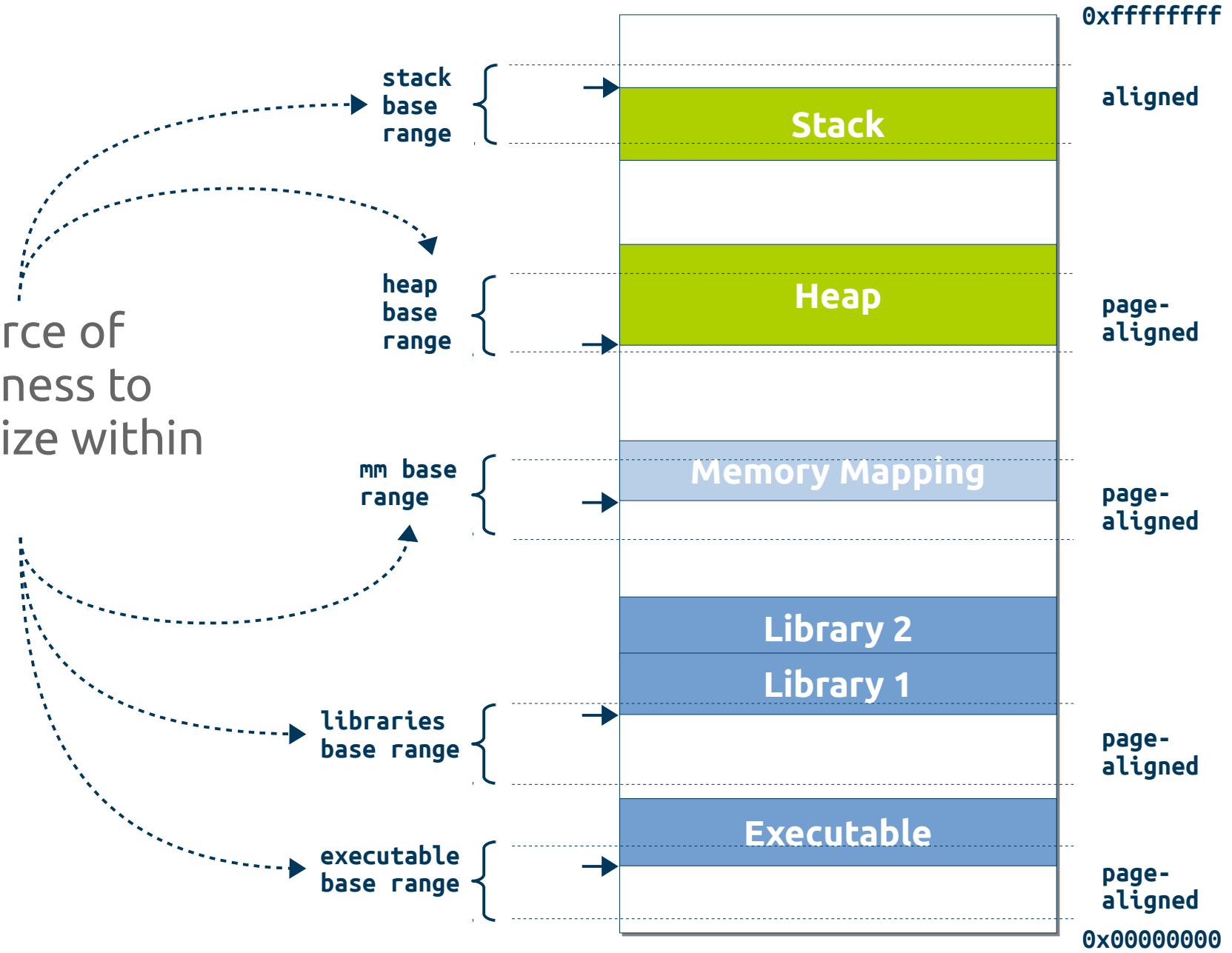
ASLR

Today most Operating Systems implement **Address Space Layout Randomization**

- Randomize memory layout of processes to make address prediction or guessing hard
- What can be randomized?
  - OS: Stack, heap and memory mapping base addresses
  - OS, compiler, linker: Exectuables and libraries
    - Position-indipendent or relocatable code

Randomization of layout

Use source of randomness to randomize within ranges



ASLR – implementation issues

Compatibility

- In general: Usage of fixed addresses not allowed
  - Hardcoded addresses

- Code should be position-indipendent or relocatable
  - Linux/ELF:
    - PIC & PIE supported, libraries all PIC, executables sometimes still prelinked
  - Windows/PE:
    - No PIC support! But libraries/executables relocatable!

  - x86 32bit PIE/PIC slower, no IP relative data addressing
  - Relocated PE images not sharable between processes

ASLR – effectiveness

- Enough entropy?
  - Base range size
  - Alignment constraints
  - Address width (64bit is better than 32bit)
- Randomization strategy
  - Per process, system-wide per boot
- Source of randomness

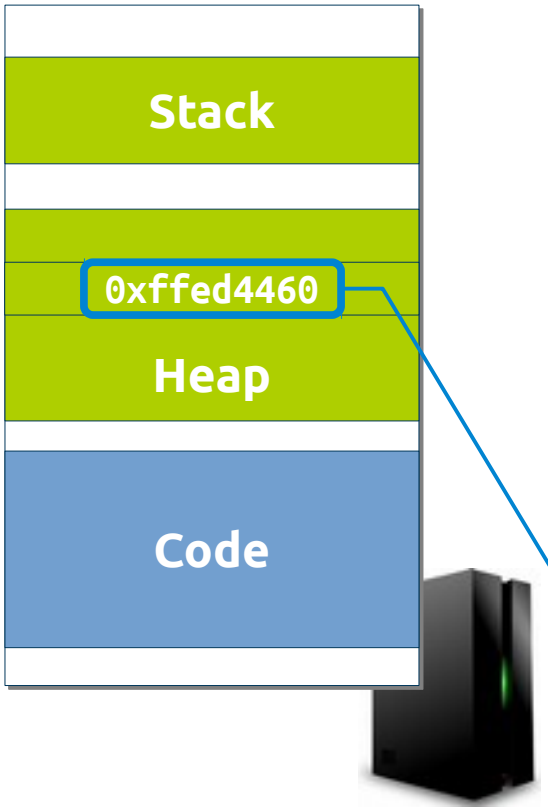
ASLR – all or nothing

- ASLR only effective without exceptions
- One library/executable without ASLR might already compromise security
  - One datastructure without ASLR as well

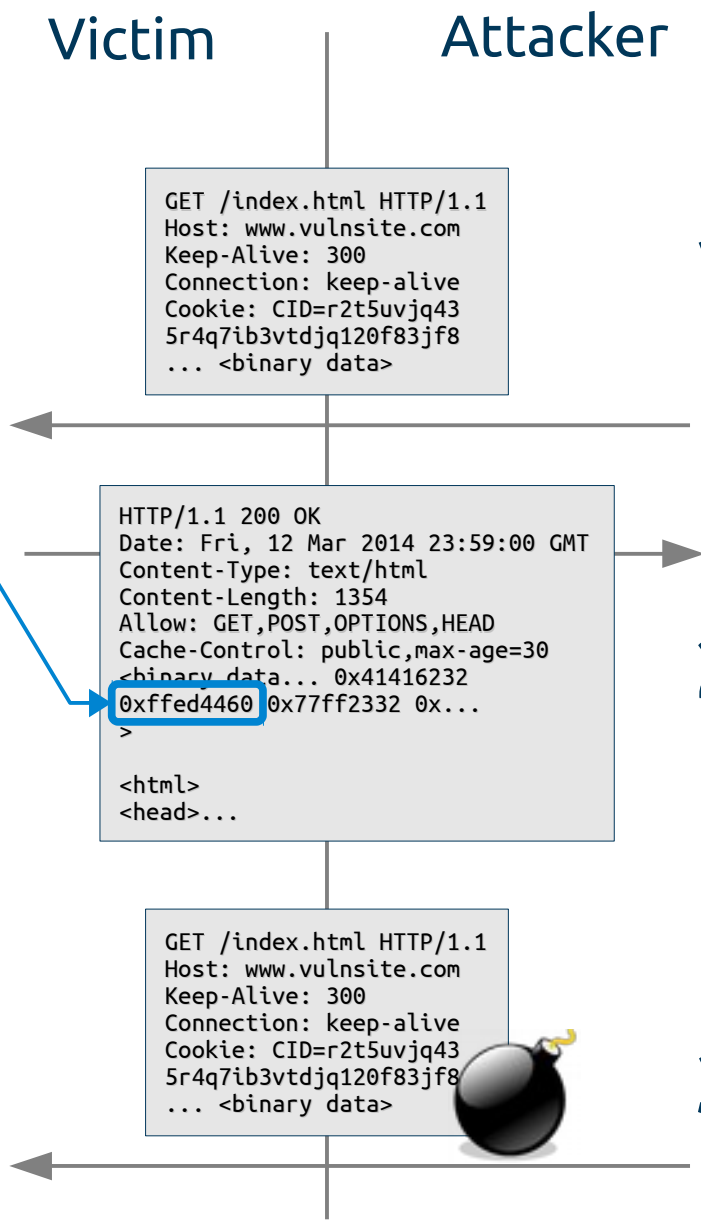
Bypassing ASLR

- Low entropy
  - Brute-force addresses (multiple attempts required)
- Memory leaks (information disclosure)
  - Leak addresses to derive base addresses
    - E.g., run-time address pointing into a library
  - Construct and enforce a leak by memory corruption
- Application and vulnerability specific attacks
  - Force predictable memory state
    - Heap-spraying
  - Pointer inference
    - Use a side-channel
  - Avoid using exact addresses
    - Only corrupt least significant bytes i.e. offsets

Memory leak



Runs web server software with memory leak and exploitable memory corruption vulnerability

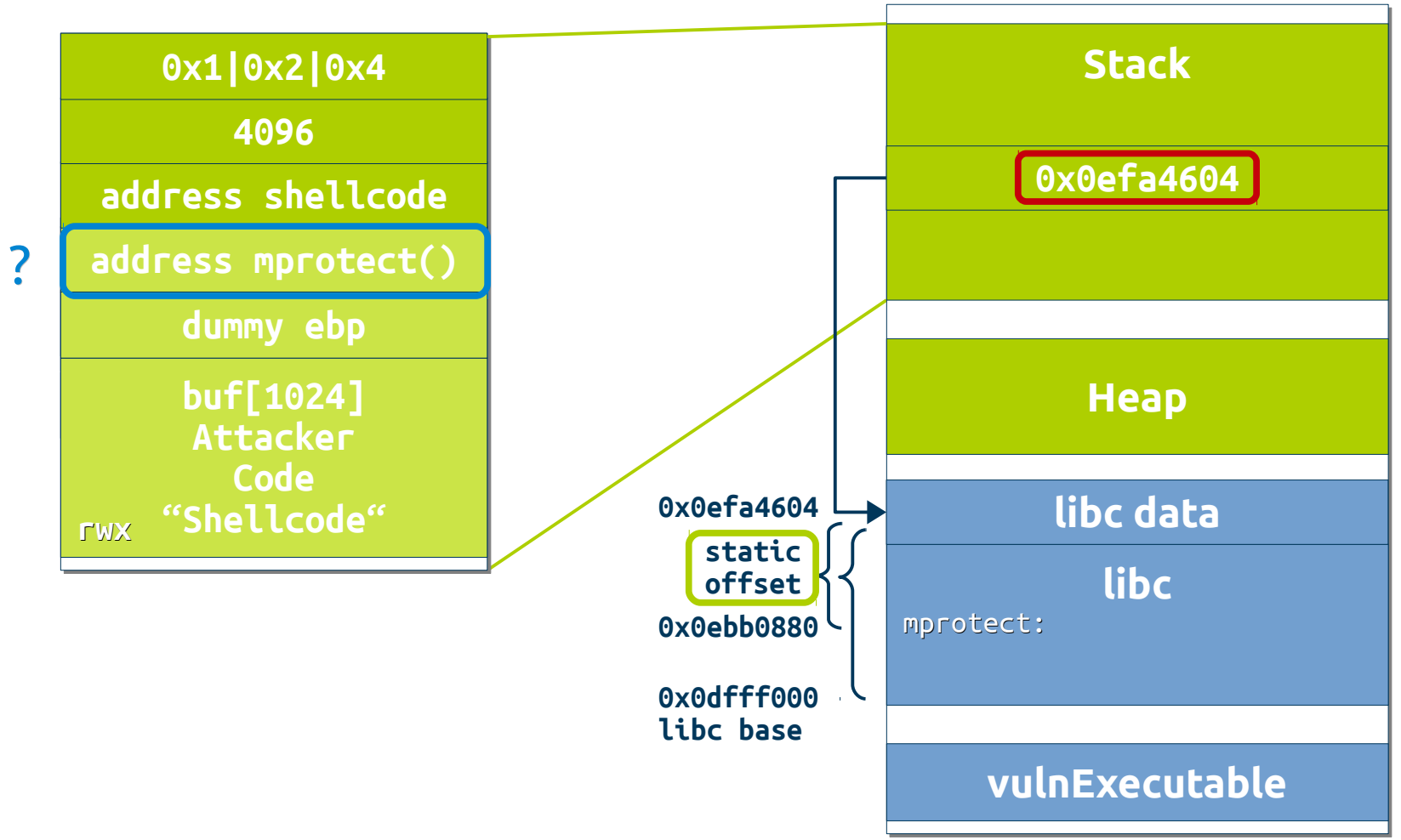


1 Trigger memory leak

2 Parse response for leaked memory and **construct exploit**

3 Exploit memory error with tailored exploit

Memory leak



mprotect = leaked pointer – static offset

0x0ebb0880 = 0x0efa4604 - 0x003f3d84

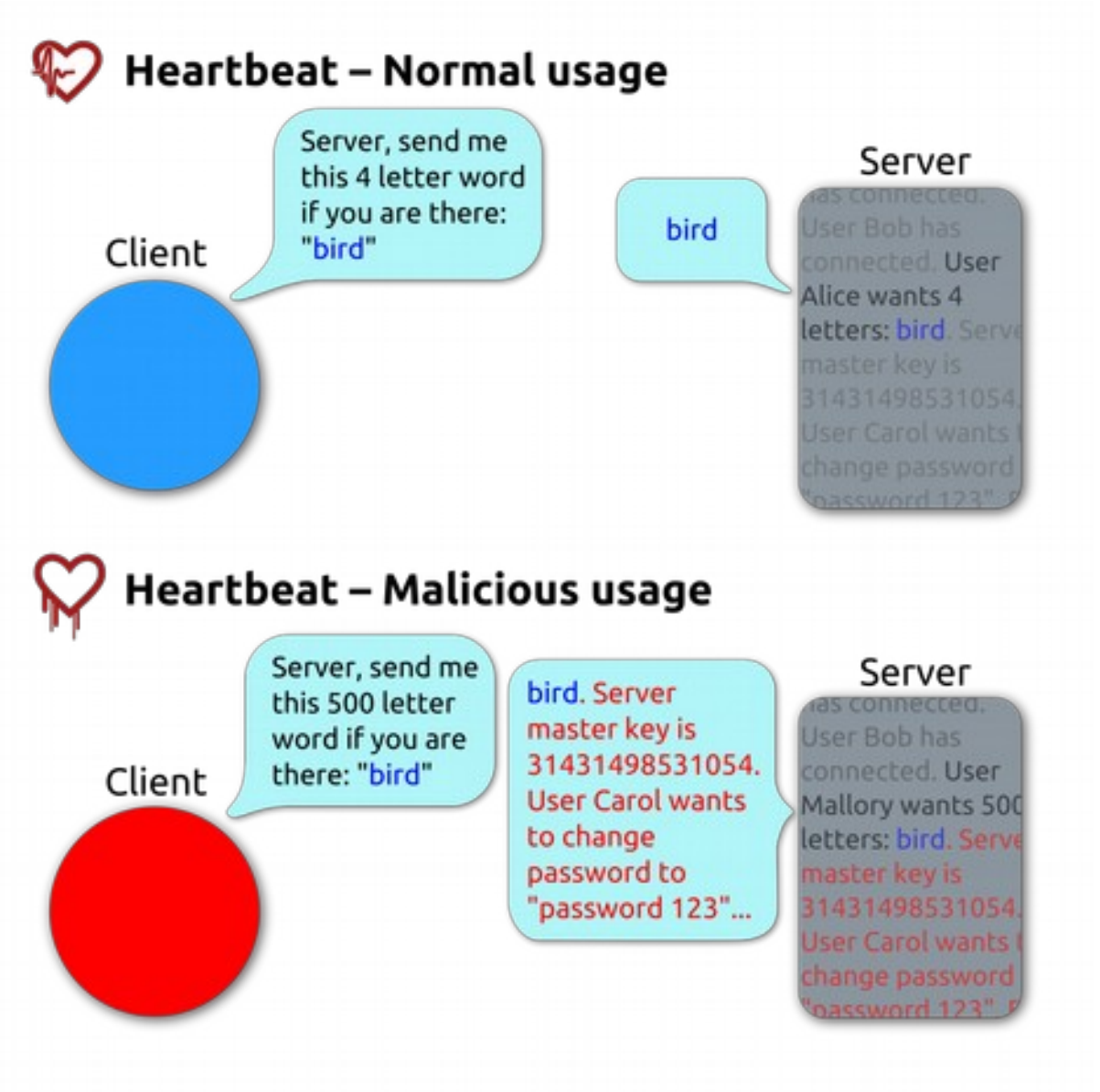
Memory leak – format string bug

```c
#include <stdio.h>
#include <string.h>

#define STDIN 0

void memLeak() {
        char buf[256];
        scanf("%s", buf);
        printf(buf);
}
```

```c
void main() {
        printf("echo> ");
        memLeak();
        printf("\n");
        return;
}
```

```
shell:~$ gcc -o memleak memleak.c
memleak.c: In function ‘memLeak’:
memleak.c:9:2: warning: format not a string literal and no format arguments [-Wformat-
security]
shell:~$ ./memleak
echo> hi
hi
shell:~$ ./memleak
echo> %llx,%llx,%llx,%llx,%llx,%llx,%llx,%llx
1,7fabf517cac0,a,ffffffff,0,6c6c252c786c6c25,252c786c6c252c78,786c6c252c786c6c
shell:~$
```

Heartbleed – CVE-2014-0160 - OpenSSL



http://en.wikipedia.org/wiki/Heartbleed
Simplified Heartbleed explanation by FenixFeather licensed under CC

DEP & ASLR

DEP & ASLR are generic defenses

- Exploitation becomes harder for all vulnerability classes & attack techniques
- Together quite effective
  - If implemented correctly and used continuously
- Injecting code and corrupting pointers with exact addresses is in general desirable for attackers

DEP & ASLR

- But DEP & ASLR are not enough
- A determined attacker will use code-reuse techniques and memory leaks to bypass DEP & ASLR
  - And application specific bypasses/properties

Additional protections

- Raise vulnerability discovery and exploit development costs with additional protections
  - The more line of defenses, the better!
  - Implement protections against **specific** vulnerability classes and exploitation techniques

Additional protections

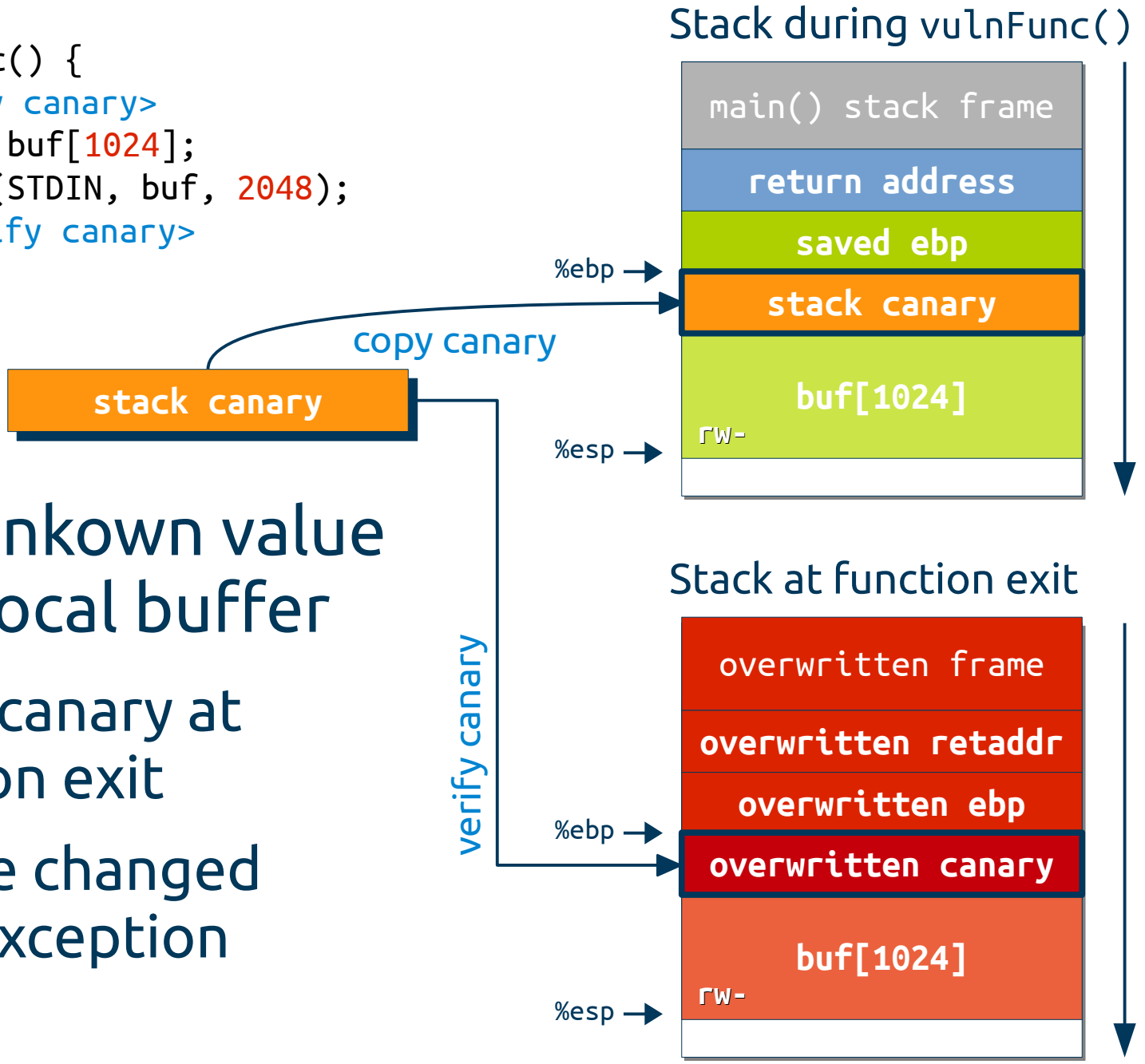
- Usually require source code changes (annotations) and/or recompilation of the application
  - To add run-time checks
- Implement safe datastructures and operations
  - E.g., heap manager, SEH, vtable

Additional protections

- **Stack canaries / Cookies**
  - Detects buffer overflows on stack
- Heap protections
  - Protects heap management data and operations
- Pointer obfuscation
- GOT protection (BIND_NOW & RELRO)
  - Relocate at load-time and mark GOT read-only
- /GS (more than just cookies)
- /SAFESEH (link-time, provide list of valid handlers)
- SEHOP (run-time, registry, might cause compatibility issues, walk down SEH chain to final handler before dispatching / integrity check)
- Virtual Table Verification (VTV) & vtguard

Stack canary / cookie

```
void vulnFunc() {
        <copy canary>
        char buf[1024];
        read(STDIN, buf, 2048);
        <verify canary>
}
```



- Put an unkown value before local buffer
  - Verify canary at function exit
  - If value changed raise exception

Stack canary / cookie

- Detects linear buffer overflows on stack
  - At function exit
- Corruption of local stack not detected
  - Only if canary / cookie value is overwritten
- Incurs runtime overhead
- Effectiveness relies on secret
  - Leaking, predicting, guessing or brute-forcing might work in special cases

DEP & ASLR Adoption

Windows

	Windows XP	Vista	Windows 7	Windows 8
DEP	> SP2 Opt-in	(Opt-in 32bit)	(Opt-in 32bit)	(Opt-in 32bit)
ASLR		Opt-in *	Opt-in *	Opt-in + Enforced by EXE + HE for 64bit + Full

* Opt-in for all images (/DYNAMICBASE)
  - Gaps might still exist, **not full ASLR** (E.g., VirtualAlloc or MapViewOfFile)
  - No difference between 32bit and 64bit ASLR

- Different ways to opt-in to ASLR and DEP
  - Linker flag, process creation attribute, SetProcessMitigationPolicy API, „MitigationOptions“ (Image File Execution Options), boot.ini switch

- **DEP is mandatory on 64-bit Windows**, on 32-bit Windows:
  - From Vista on, /NXCOMPAT linker switch sufficient
  - “Always On“ can be configured system-wide (incl. exceptions list)
  - DEP opt-out for Windows Server (>2003)

Windows ASLR

- Introduced with Vista
- Windows 7 + Vista
  - Gaps in ASLR might still exist
  - Heaps and stacks randomized
  - PEB/TEB randomized (limited entropy)
  - VirtualAlloc and MapViewOfFile **not** randomized
  - Non-ASLR images (without /DYNAMICBASE)
  - Predictable memory regions (E.g., VirtualAlloc(), SharedUserData)
- Windows 8
  - Processes can force ASLR for non-ASLR images
  - All bottom-up/top-down allocations randomized (opt-in, /DYNAMICBASE)
  - More entropy for PEB/TEB

Windows 8 ASLR

- High entropy for 64-bit (8TB addr. Space)
  - High entropy bottom-up
    - stacks, heaps, mapped files, VirtualAlloc, etc.
    - Breaks spraying techniques
  - High entropy top-down
    - PEBs, TEBs, MEM_TOP_DOWN
  - High entropy image randomization
    - /HIGHENTROPYVA (EXE)

Windows 8 / 8.1

- Further improvements
  - Sophisticated attacks still possible
  - Code-reuse & info leaks
  - Pwn2own 2014

"Writing exploits for Windows 8 will be very costly"

- 64bit, >IE10, VS 2012 + enable mitigations

Windows 8 / 8.1

- Built with enhanced /GS (v3, VS 2010)
  - Array index range checks (compiler-inserted)
- Sealed optimization
  - Eliminates indirect calls through vtable
  - Direct call faster and reduces attack surface
- vTable guard (class annotation required)
  - Random value “vtguard“ at end of vtable
  - Verified before vtable gets used
  - IE10 uses it for a handful key classes

Windows 8 / 8.1

- ASLR improvements
- Windows heap improvements
  - Encounters specific exploitation techniques
    - LFH & integrity checks
  - Guard pages
    - Allocates guard pages between heap memory
  - Allocation order randomization (LFH, <16KB)
- Kernel improvements
  - DEP, ASLR, Kernel pool integrity checks
  - NULL dereference protection

Windows 7

- Ok, thanks, but I really just have 7...

- 64bit: DEP enforced
  - 32bit: Opt-in
- Enforce ASLR with EMET
  - And enable additonal EMET hardening
- Use newest client software
  - Ideally, just one... and harden configuration

- And the usual: keep everything up-to-date!

Ubuntu Linux

	10.04	12.04	14.04
NX/DEP	(32bit, non-PAE: emulated)	(32bit, non-PAE: emulated)	(32bit, non-PAE: emulated)
ASLR	Full *	Full *	Full *

* Stack, libraries/mmap, brk, exec, vdso
  - System-wide `/proc/sys/kernel/randomize_va_space`
- Executables: ASLR only for PIE (position-indipendent executable)
  - On x86 this results in 5-10% performance loss
    - Therefore not all executables are compiled as PIE
  - On x86 64bit: PIE comes without penalties
    - But still not all executables are PIEs
- Shared libraries: use position-indipendent code by default
- NX/DEP requires PAE, otherwise emulated

https://wiki.ubuntu.com/Security/Features
http://en.wikipedia.org/wiki/Physical_Address_Extension

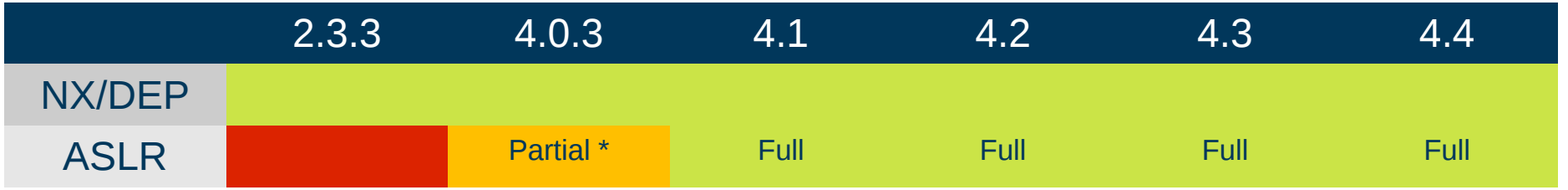
iOS

	iOS 5	iOS 6	iOS 7	iOS 8
NX/DEP	++	++	++	++
ASLR				

- ASLR introduced with iOS 4.3 in 2010
- For full ASLR, executables need to be PIE
  - Since 2011 default in XCode
  - Else (at least in iOS 4), exec, stack, linker are at fixed addresses
- Mandatory Code Signing
  - Application has to be signed (checked at execution time)
- Code Signing Enforcement (++)
  - Executed code has to be signed (checked at runtime)
  - No new executable code can be generated, mprotect(addr,len,PROT_EXEC)
  - Mapped code is not mutable (W^X enforcement)

"iOS Security" - Apple
Apple iOS 4 Security Evaluation – Dino A. Dai Zovi, Trail of Bits LLC

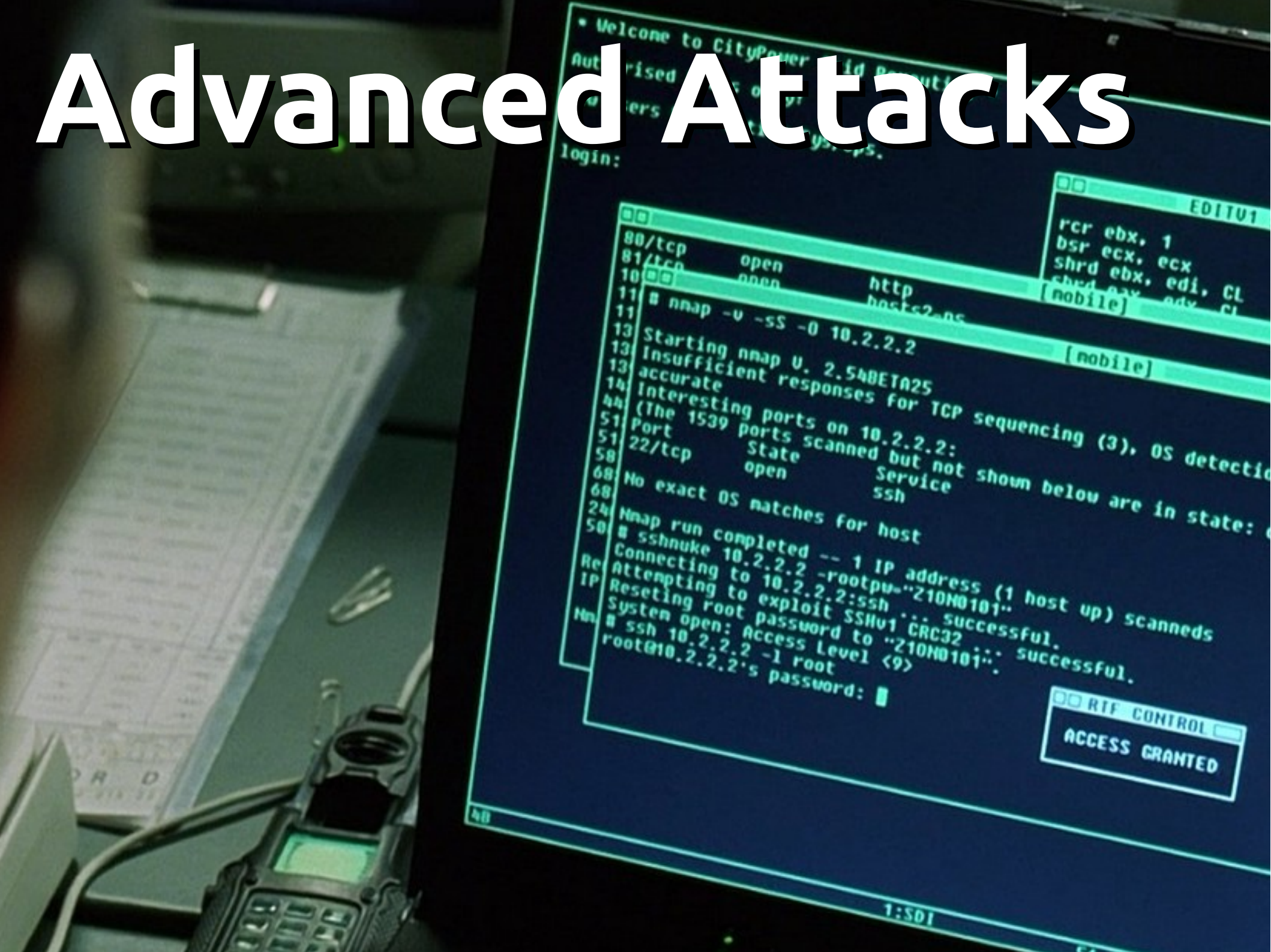
Android



* Stack and libraries/mmap
i.e. no ASLR for executable, heap/brk, linker

- NX/DEP introduced with 2.3 (Gingerbread)
- Partial ASLR introduced with 4.0
  - Full ASLR and PIE support since 4.1
    - Stack, libraries/mmap, executable, heap/brk, linker

https://www.duosecurity.com/blog/exploit-mitigations-in-android-jelly-bean-4-1
https://www.duosecurity.com/blog/a-look-at-aslr-in-android-ice-cream-sandwich-4-0


Advanced Attacks
login:
80/tcp open http
nmap -v -sS -O 10.2.2.2
Starting nmap V. 2.54BETA25
Insufficient responses for TCP sequencing (3), OS detectio
accurate
Interesting ports on 10.2.2.2:
(The 1539 ports scanned but not shown below are in state:
Port State Service
22/tcp open ssh
No exact OS matches for host
Nmap run completed -- 1 IP address (1 host up) scanneds
sshnuke 10.2.2.2 -rootpw="Z1ON0101"
Connecting to 10.2.2.2:ssh ... successful.
Attempting to exploit SSHv1 CRC32 ... successful.
Reseting root password to "Z1ON0101".
System open: Access Level <9>
ssh 10.2.2.2 -l root
root@10.2.2.2's password:
RIF CONTROL
ACCESS GRANTED

Application specific attacks

- **Today, attacks are much more application and vulnerability specific!**
  - No universal exploitation techniques
    - Attackers focus on promising applications
  - ASLR bypass depends on situation
    - Or uses information leaks
  - DEP bypassed by code-reuse techniques
    - ROP chain depends on available gadgets

Heap-spraying

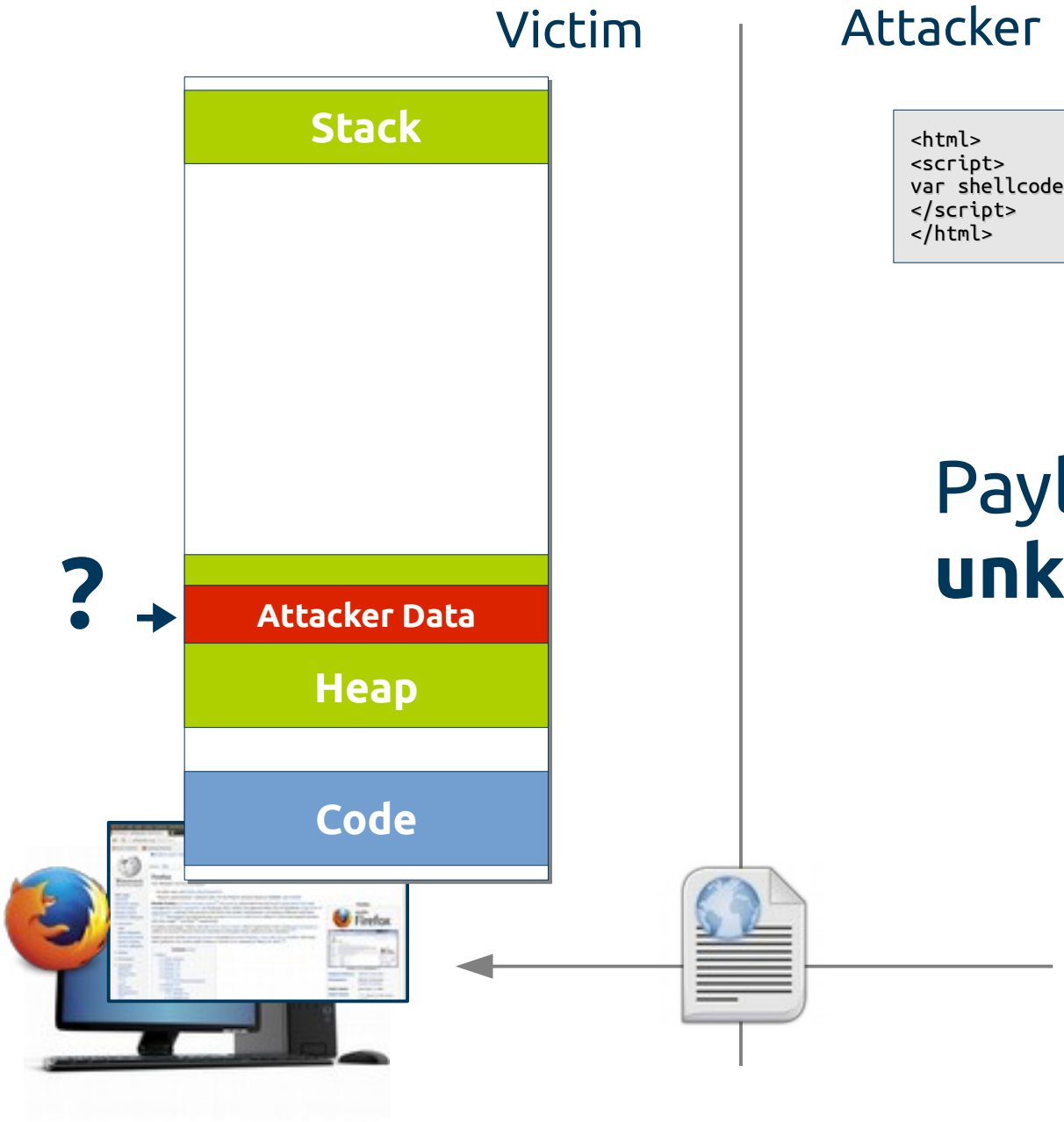
- Payload delivery technique
  - Shellcode and/or ROP chain
- Attacker goal: deliver data to predictable address on heap
- First documented usage in 2001
  - Widespread use in browser exploits since 2005

https://www.corelan.be/index.php/2011/12/31/exploit-writing-tutorial-part-11-heap-spraying-demystified/
http://en.wikipedia.org/wiki/Heap_spraying

Heap-spraying

- Only possible if attacker has (partial) control over heap allocations
  - Data and layout (indirectly)
- Popular in applications with client-side scripting support
  - E.g., Browsers, Flash, PDF Reader
- OS, heap implementation and application specific

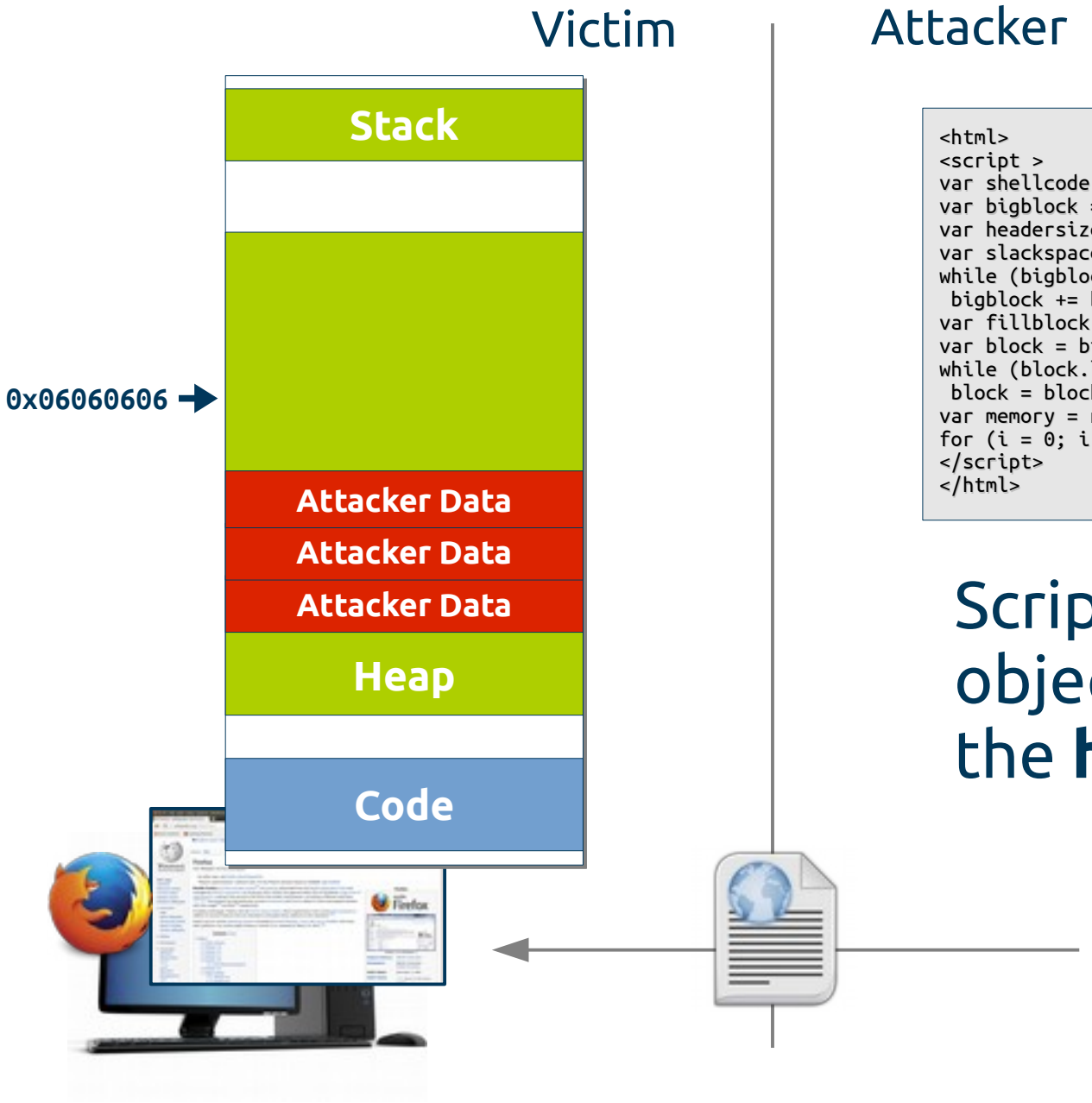
Heap-spraying




```
<html>
<script>
var shellcode = unescape('%u\4141%u\4141');
</script>
</html>
```

Payload address
unknown

Heap-spraying



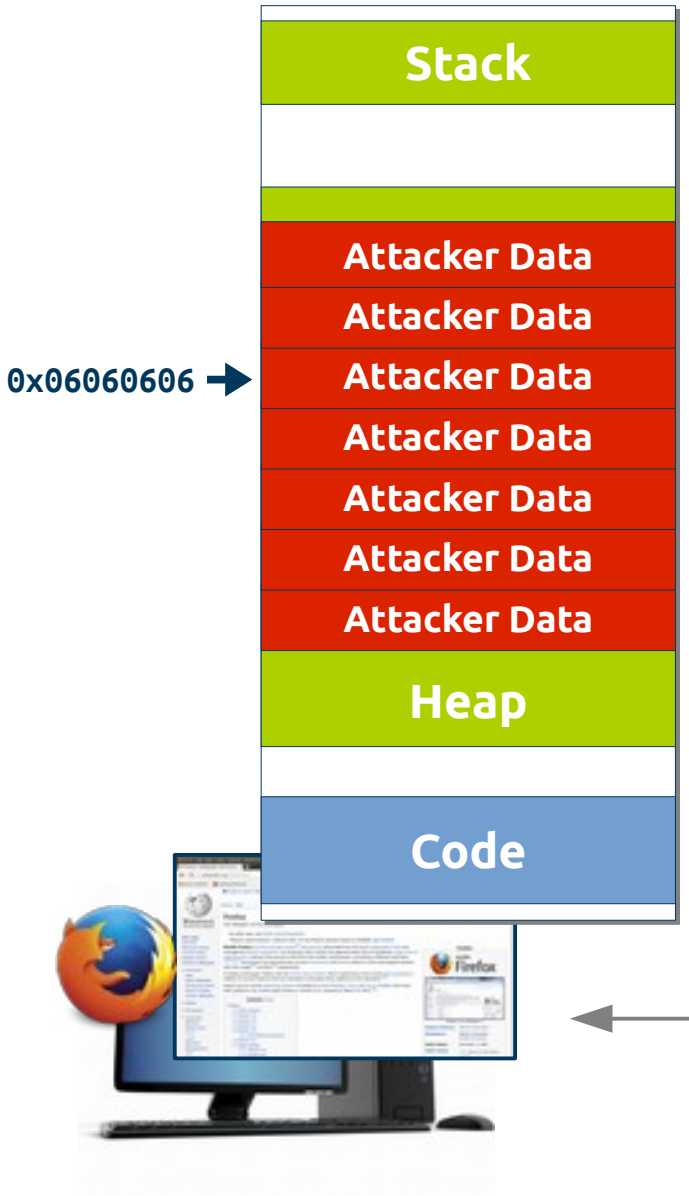

```
<html>
<script >
var shellcode = unescape('%u\4141%u\4141');
var bigblock = unescape('%u\9090%u\9090');
var headersize = 20;
var slackspace = headersize + shellcode.length;
while (bigblock.length < slackspace)
 bigblock += bigblock;
var fillblock = bigblock.substring(0,slackspace);
var block = bigblock.substring(0,bigblock.length - slackspace);
while (block.length + slackspace < 0x40000)
 block = block + block + fillblock;
var memory = new Array();
for (i = 0; i < 500; i++){ memory[i] = block + shellcode }
</script>
</html>
```

Script **sprays** objects/data **to** the **heap!**

Heap-spraying

Victim

Attacker




```
<html>
<script >
var shellcode = unescape('%u\4141%u\4141');
var bigblock = unescape('%u\9090%u\9090');
var headersize = 20;
var slackspace = headersize + shellcode.length;
while (bigblock.length < slackspace)
 bigblock += bigblock;
var fillblock = bigblock.substring(0,slackspace);
var block = bigblock.substring(0,bigblock.length - slackspace);
while (block.length + slackspace < 0x40000)
 block = block + block + fillblock;
var memory = new Array();
for (i = 0; i < 500; i++){ memory[i] = block + shellcode }
</script>
</html>
```

Payload is at **known address** now!

Heap-spraying

- Use control over heap to spray the heap with data (payload)
  - After spraying the data is found at a deterministic address
- Sprayed data can be anything
  - E.g., JS objects/strings, images

https://www.corelan.be/index.php/2011/12/31/exploit-writing-tutorial-part-11-heap-spraying-demystified/
http://en.wikipedia.org/wiki/Heap_spraying

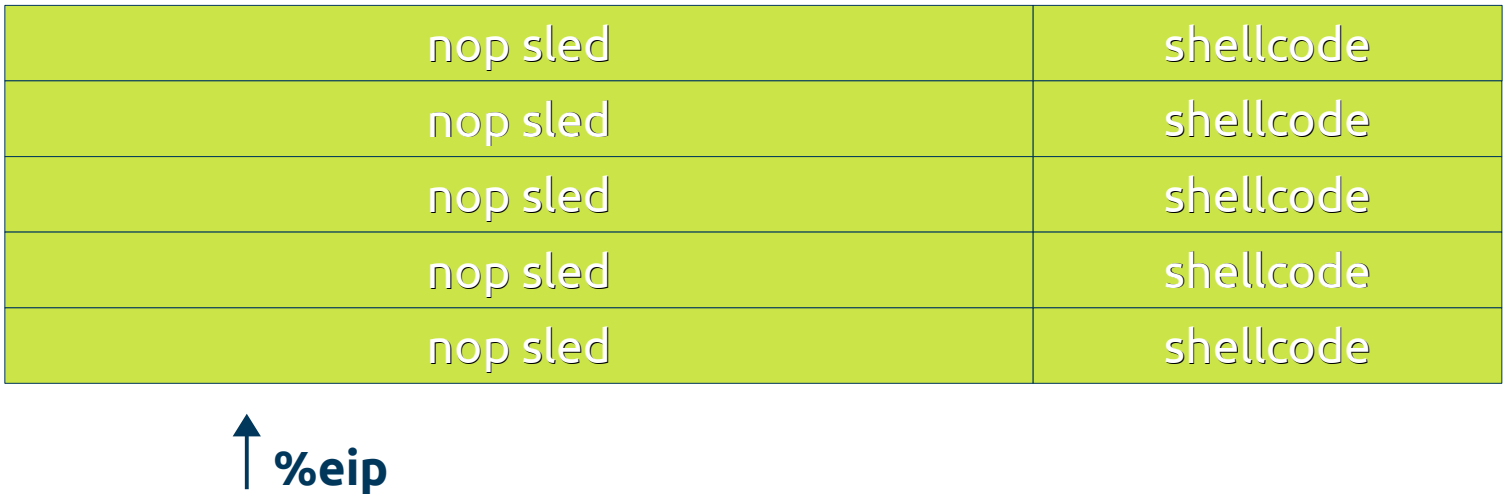
Heap-spraying

- Note: not feasible for effective ASLR bypass!
  - Entire address space too large to spray
    - Especially for 64bit address space
  - Heap base address range has to be non-randomized
    - E.g., VirtualAlloc no ASLR up to Windows 7
- If effective ASLR in place heap-spraying can still be useful
  - Spray heap and corrupt heap relative offset

http://recxltd.blogspot.ch/2011/12/curious-case-of-virtualalloc-aslr-and.html
http://ifsec.blogspot.ch/2013/11/exploiting-internet-explorer-11-64-bit.html

Heap-spraying

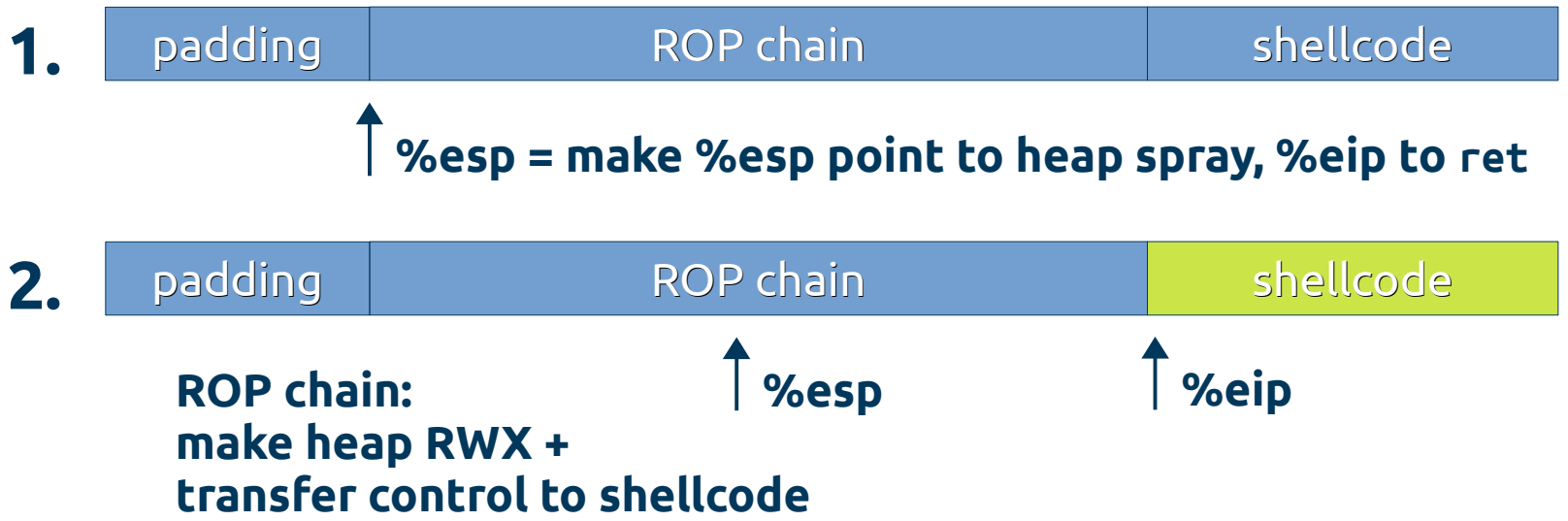
- Without DEP: heap is executable

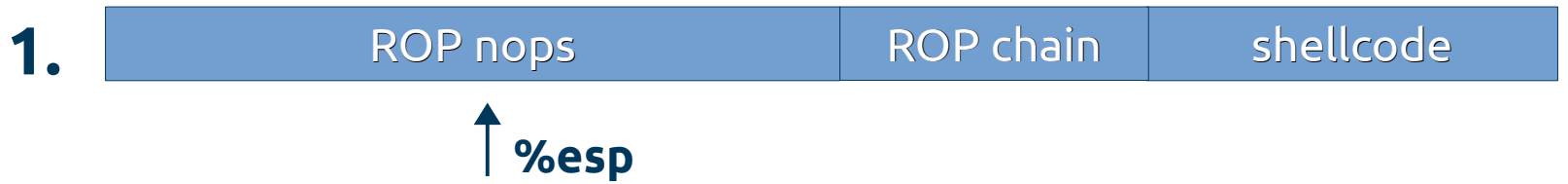


https://www.corelan.be/index.php/2011/12/31/exploit-writing-tutorial-part-11-heap-spraying-demystified/
http://en.wikipedia.org/wiki/Heap_spraying

Heap-spraying

- With DEP (exact spray desirable)





https://www.corelan.be/index.php/2011/12/31/exploit-writing-tutorial-part-11-heap-spraying-demystified/
http://en.wikipedia.org/wiki/Heap_spraying

Heap-spraying countermeasures

- Heap-spray detection inside browsers
  - Detect suspicious allocations
    - Patterns, valid instructions, large static blocks
  - Nozzle (>IE9) and BuBBle (>Firefox 9)
- Pre-allocation of popular regions
  - EMET or HeapLocker , e.g., 0x0c0c0c0c
- Monitor memory usage and limit amount of memory per process / script

https://www.corelan.be/index.php/2011/12/31/exploit-writing-tutorial-part-11-heap-spraying-demystified/

Heap-spraying variations

- Randomize bytes in spray
- Don't use strings
  - DEPS: „DOM Element Property Spray“
  - DOM object properties = payload
- HTML5 spraying
  - Uses canvas objects for payload and web workers for speed up

https://www.corelan.be/index.php/2013/02/19/deps-precise-heap-spray-on-firefox-and-ie10/
http://exploiting.wordpress.com/2012/10/03/html5-heap-spray-eusecwest-2012/

Enforcing information leaks

- To bypass ASLR attackers can “construct“ memory leaks
  - Corrupt length field of a object and read object data, e.g., JS string
  - Length field corruption has to be feasible without bypassing ASLR
    - Use heap-spraying for reliability

Pointer inference

- Recover addresses of internal objects without explicit memory leaks
  - Only by „interacting“
  - Like a side-channel attack
- E.g., over ActionScript Dictionaries as described by Dion Blazakis
  - Associative map data sctructure
  - Keys can be integers, strings, other objects
  - Hashtable uses values or references
  - By placing ordered values into the data structure and iterating through it bits of the object's address are disclosed

JITs

- JIT: Just-In-Time
  - Refers to execution engines / compilers
  - Native just-in-time code generation
  - E.g., javascript engines in browsers, Java VMs, .NET CLR, ActionScript, other language runtimes
  - JIT types: Method & Tracing JITs
  - Front-end, syntax parser, produces IR
  - Back-end, generates native code out of IR

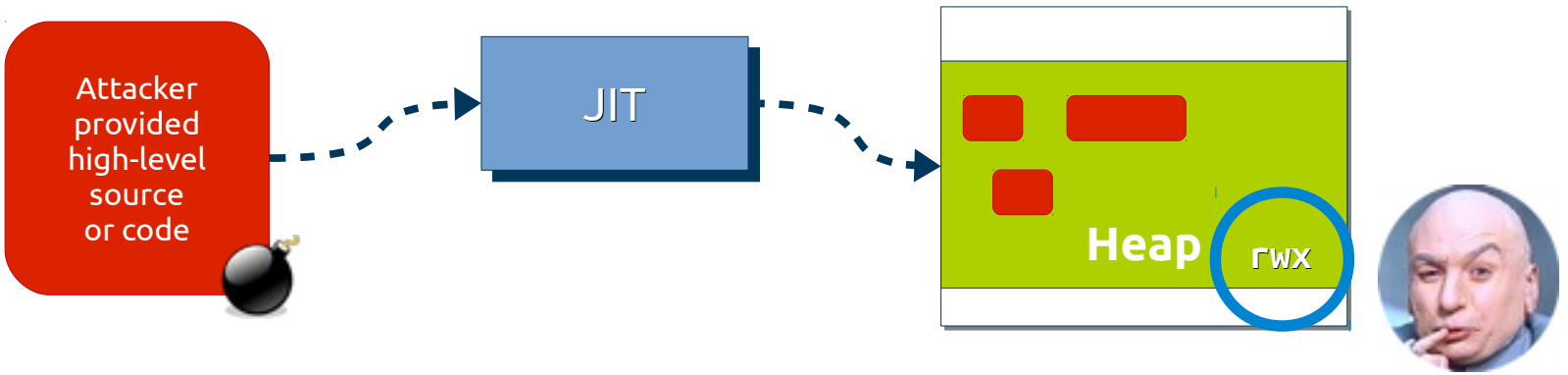
JITs

- JIT vulnerabilities
  - Incorrect code generation
    - Like having a bug in generated native code
  - Logic errors (in generated code)
  - Information leaks
  - Diversion of control-flow

- JITs are sources of vulnerabilities and means of exploitation

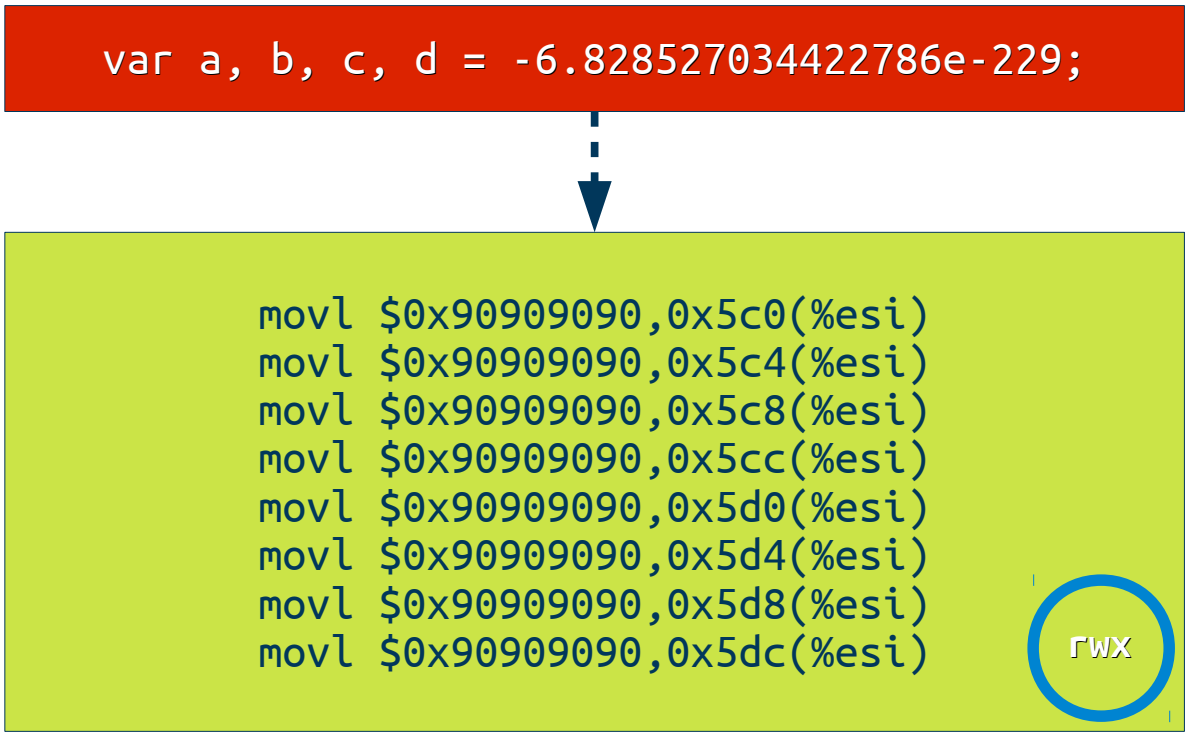
JIT-spraying

- Remember DEP?
  - Makes machine-code injection difficult
- But wait... JITs generate code!
  - They need RWX memory (code cache)
  - Native code is generated out of untrusted attacker supplied higher-level source or code, e.g., javascript or Java bytecode



JIT-spraying

- Generate predictable byte sequences in generated native code
  - Example from “Attacking Clientside JIT C ompilers“



Floating point value uses 64bit in 32bit x86, will be represented as 0x9090909090909090

0x90 is opcode for nop

x86 has variable instructions length, jump into valid instructions possible

JIT-spraying

- If JIT memory locations are predictable
  - Spraying or non-randomized allocations
  - Information leaks
- Attackers might inject code into executable memory and divert execution to it
  - Or spray gadgets throughout JIT memory

JIT hardening

- Randomization / full ASLR
- Page permissions
  - RW for generation, RX for execution
- Guard pages
  - Prevent overflows from RW to RWX pages
  - Overwrite generated native code and trigger execution
- Constant folding / blinding
- Allocation size restrictions for native code
- Random NOP insertion, random code base offsets

Attacking safe language VMs

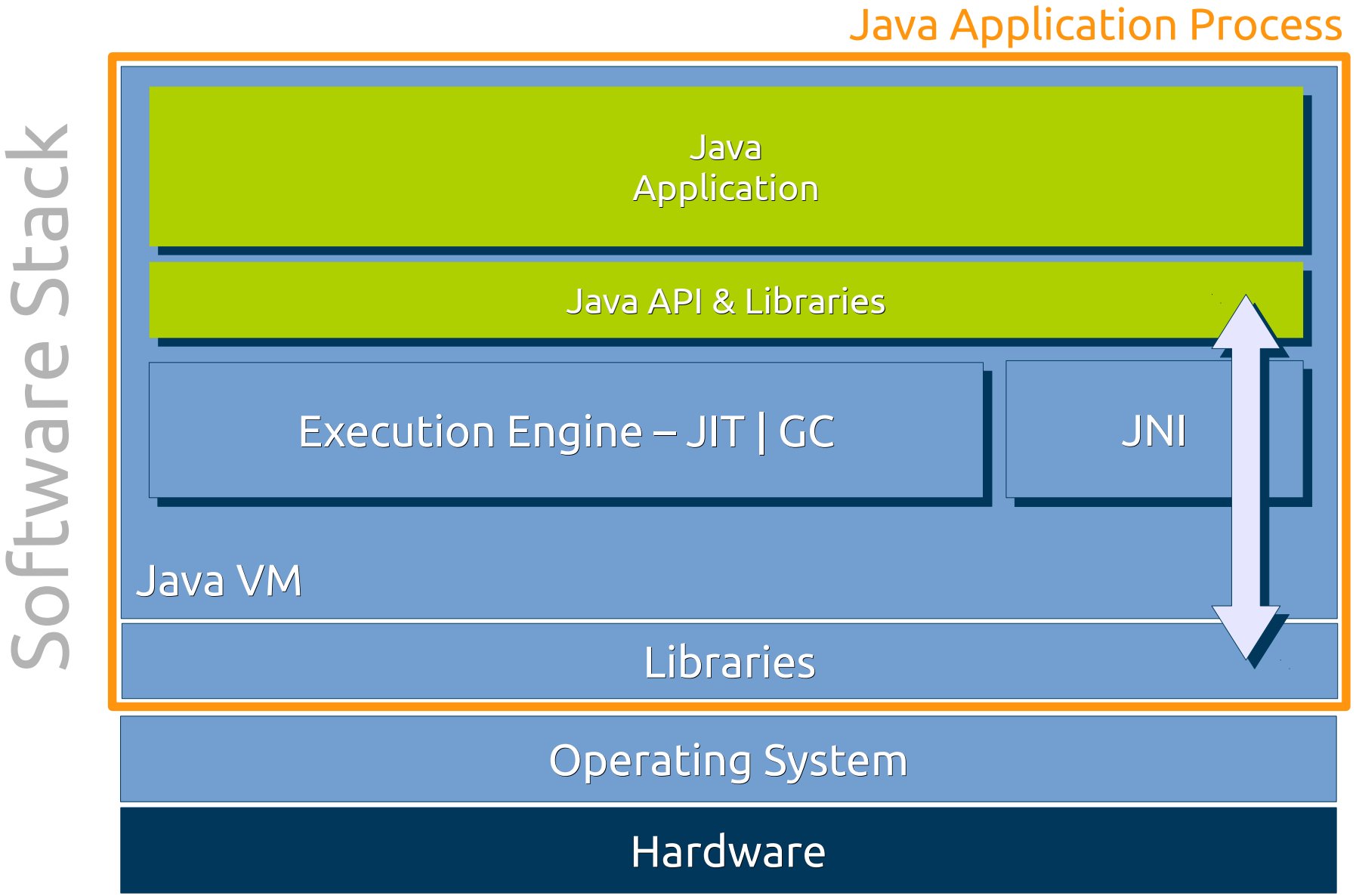
- Just use a type & memory safe language ?

  But language VM

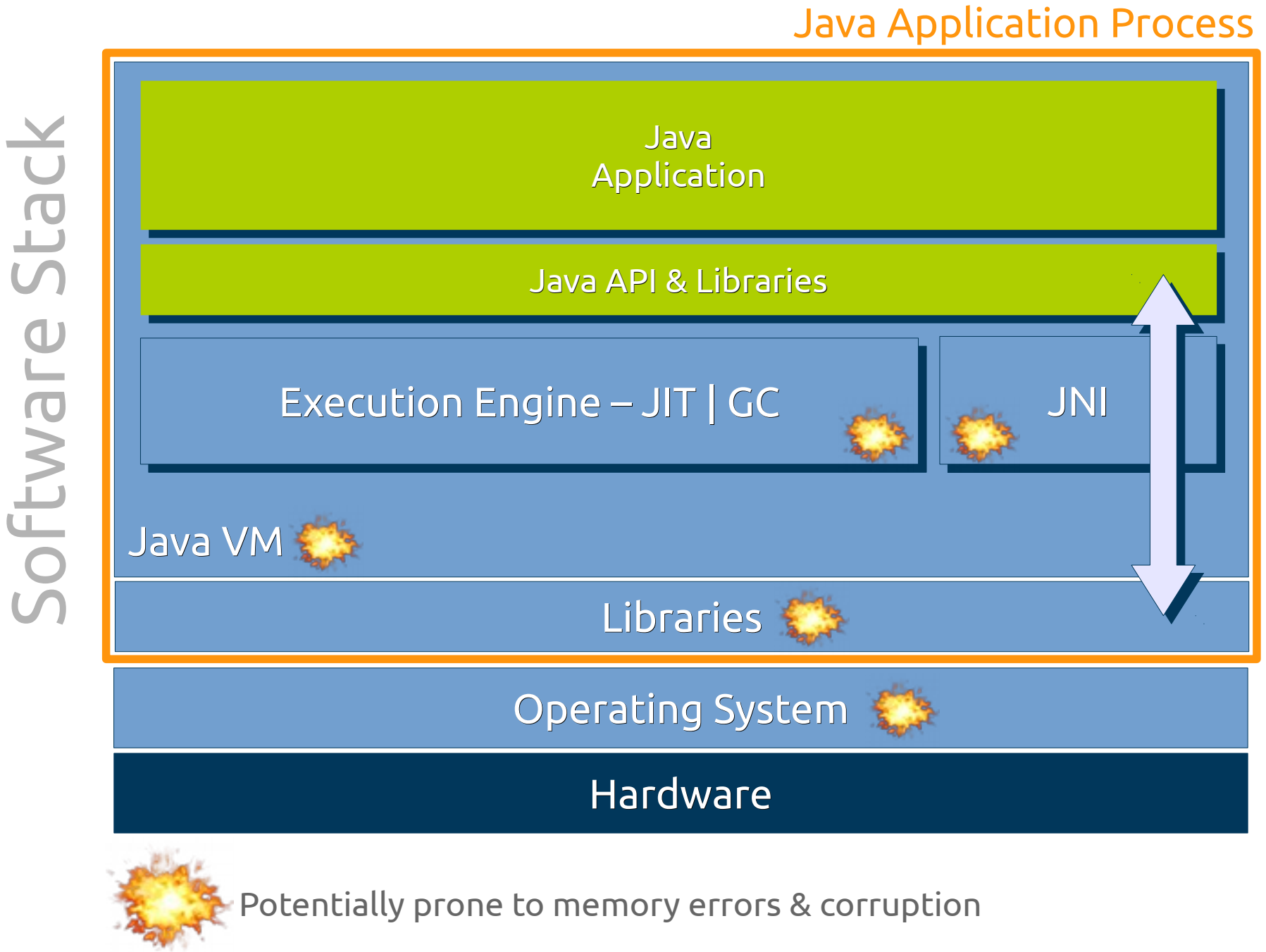
  - May be implemented in an unsafe language
  - May use or provide interfaces to unsafe libraries

  Exploit memory errors in the VM or in unsafe libraries used by the VM or the application

Java VM written in C/C++



Java VM written in C/C++



Attacking safe language VMs

E.g., Java VM

- CVE-2013-1491
- Affected Oracle Java SE 7 / 6 / 5
- Memory error in OpenType Fonts handling within native layer of JRE
  - Leveraged to arbitrary code excecution
  - Completely bypassed DEP & ASLR

Demonstrated at Pwn2Own at CanSecWest 2013 by Joshua Drake (on Windows 8 + Java SE 7 Update 17)
http://www.accuvant.com/blog/pwn2own-2013-java-7-se-memory-corruption
https://media.blackhat.com/bh-ad-11/Drake/bh-ad-11-Drake-Exploiting_Java_Memory_Corruption-WP.pdf

Attacking Java VM

Attack surface

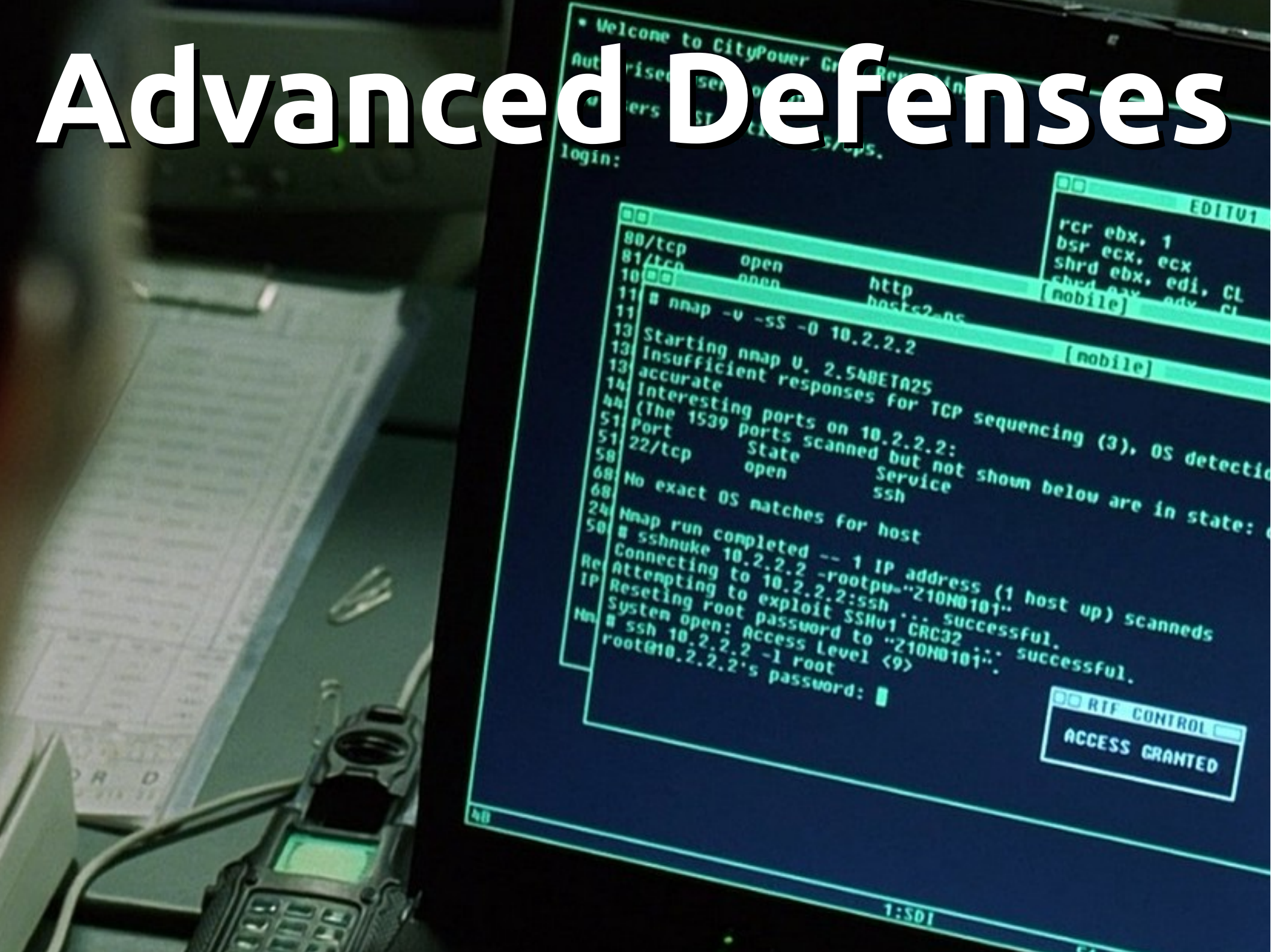
- Any Java application relying on native code
- Untrusted Java Applet (over the web)
  - Java Applet under attacker control
  - Sandboxed, but a lot of native code reachable
    - Image, sound, data processing

Demonstrated at Pwn2Own at CanSecWest 2013 by Joshua Drake (on Windows 8 + Java SE 7 Update 17)
http://www.accuvant.com/blog/pwn2own-2013-java-7-se-memory-corruption
https://media.blackhat.com/bh-ad-11/Drake/bh-ad-11-Drake-Exploiting_Java_Memory_Corruption-WP.pdf

Oracle JRE 6 / 7 / 8

- JRE 6
  - Only used /GS and /SafeSEH (stack protections)
  - No DEP or ASLR
    - DEP could be enforced
    - But msvcr71.dll allowed easy bypass (no ASLR)
      - Shipped with all releases of JRE 6
- JRE 7 & 8
  - Many improvements
  - DEP & ASLR enabled

https://media.blackhat.com/bh-ad-11/Drake/bh-ad-11-Drake-Exploiting_Java_Memory_Corruption-WP.pdf


Advanced Defenses
login:
80/tcp open
81/tcp open
nmap -v -sS -O 10.2.2.2
Starting nmap V. 2.54BETA25
Insufficient responses for TCP sequencing (3), OS detectio
accurate
Interesting ports on 10.2.2.2:
(The 1539 ports scanned but not shown below are in state:
Port State Service
22/tcp open ssh
No exact OS matches for host
Nmap run completed -- 1 IP address (1 host up) scanneds
sshnuke 10.2.2.2 -rootpw="Z1ON0101"
Connecting to 10.2.2.2:ssh ... successful.
Attempting to exploit SSHv1 CRC32 ... successful.
Reseting root password to "Z1ON0101".
System open: Access Level <9>
ssh 10.2.2.2 -l root
root@10.2.2.2's password:
ACCESS GRANTED
1:SDI

Additional hardening

- A lot of additional hardening techniques
  - EMET on Windows
  - PaX/grsecurity patches on Linux
  - Hardened configurations
  - And many additional tools and techniques

Enhanced Mitigation Experience Toolkit

- EMET 5.0, released 31.7.2014
  - 3.x 2012, 4.x 2013
- **Hardening Toolkit**
  - Set of protections against exploitation techniques
  - Works on binaries, configurable per process
  - Interesting for legacy software
- Supports enterprise deployment
  - Built-in Group Policy and
    System Center Configuration Manager support

http://technet.microsoft.com/en-us/security/jj653751

EMET 5.0

- Application compatibility risk
  - Testing required before production rollout
- Some features also exist without EMET
  - But can be activated for older Windows versions
- “EMET User's Guide“ not that detailed
- Supports Windows Vista SP2, Windows 7 SP1, Windows 8/8.1 and Server 2003/2008/2012

http://technet.microsoft.com/en-us/security/jj653751

EMET 5.0

- SEHOP - run-time validation of SEH chain
- DEP enforcement (without flag)
- Heapspray pre-allocation
- ASLR enforcement (without flag)
  - < Windows 8 (native ASLR)
- EAF – Export Address Table Access Filtering
- EAF+
  - Stack register boundary check, stack/frame pointer mismatch
  - Detects memory read accesses to certain tables/headers

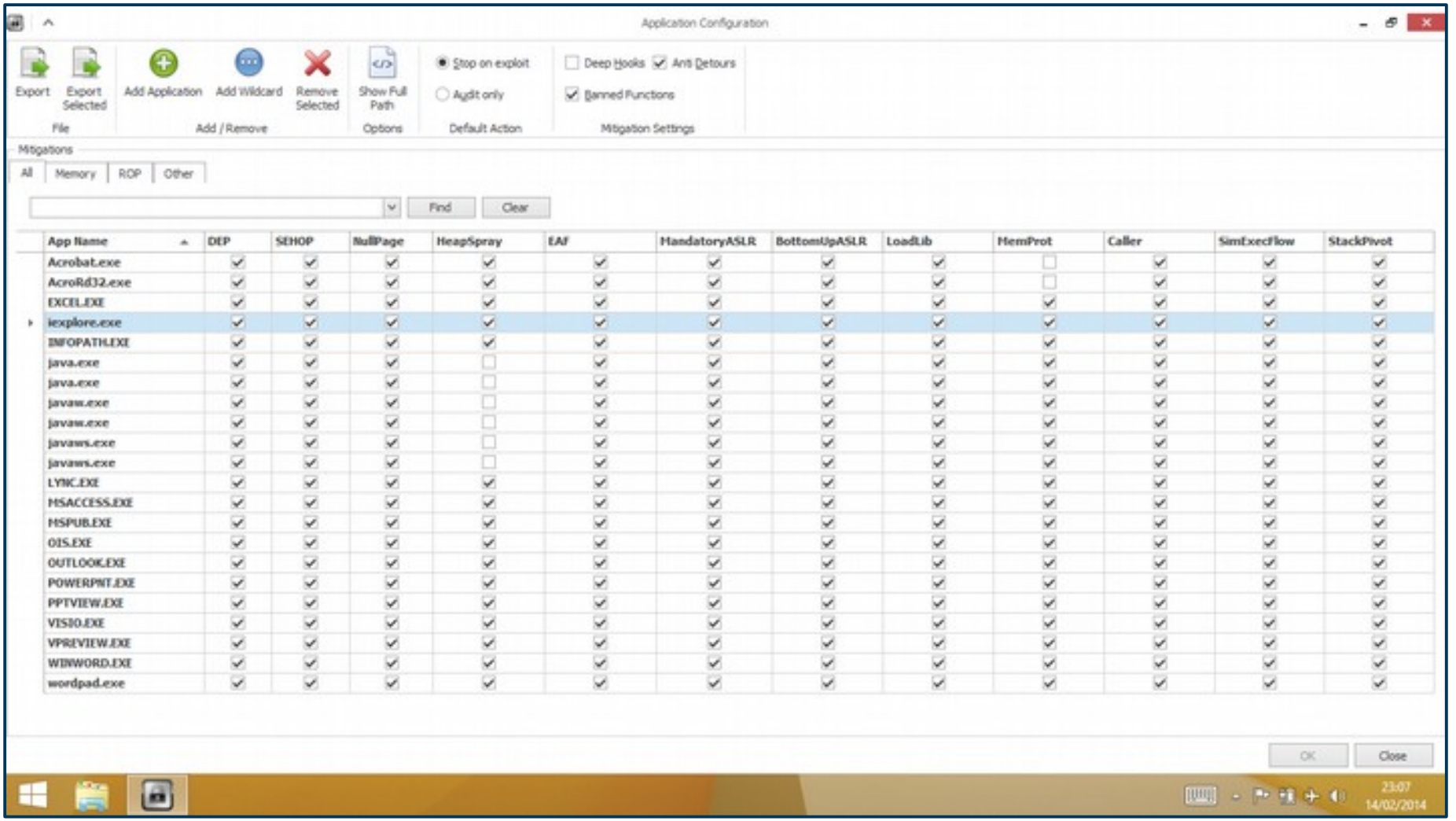
EMET 5.0

- Bottom-up randomization
  - Randomizes (8 bits entropy) base address of bottom-up allocations (heaps, stacks, other memory allocations)
- ROP mitigations (all for 32bit and **some for 64bit**)
  - Load library checks (LoadLibrary API, UNC paths -> network)
  - Memory protection check, disallows making stack executable
  - Caller checks for critical functions
    - Check if transfer originated from call instruction
  - Simulate execution flow
    - Check after a critical function if ROP chain is executed
  - Stack pivot
    - Check if stack has been pivoted

EMET 5.0

- Attack Surface Reduction
  - DLL blacklist per application (and Security Zone)
  - E.g., disable Java plugin within IE in Internet Zone
- Advanced Mitigations for ROP
  - Deep hooks (protect critical APIs on all levels)
  - Anti detours
  - Banned functions (ntdll!LdrHotPatchRoutine)

EMET 5.0


Application Configuration
Export
Export Selected
File
Add Application
Add Wildcard
Remove Selected
Add / Remove
Show Full Path
Options
Stop on exploit
Audit only
Default Action
Deep Hooks
Anti Detours
Banned Functions
Mitigation Settings
Mitigations
All
Memory
ROP
Other
Find
Clear
App Name
DEP
SEHOP
NullPage
HeapSpray
EAF
MandatoryASLR
BottomUpASLR
LoadLib
MemProt
Caller
SimExecFlow
StackPivot
Acrobat.exe
AcroRd32.exe
EXCEL.EXE
iexplore.exe
INFOPATH.EXE
java.exe
java.exe
javaw.exe
javaw.exe
javaws.exe
javaws.exe
LYNC.EXE
MSACCESS.EXE
MSPUB.EXE
OIS.EXE
OUTLOOK.EXE
POWERPNT.EXE
PPTVIEW.EXE
VISIO.EXE
VPREVIEW.EXE
WINWORD.EXE
wordpad.exe
OK
Close
23:07
14/02/2014

EMET 5.0

Incompatible mitigations

Product	EMET 4.1 Update 1	EMET 5.0
7-Zip Console/GUI/File Manager	EAF	EAF
Adobe Acrobat	Not applicable	EAF+ (AcroRd32.dll)
Adobe Reader	Not applicable	EAF+ (AcroRd32.dll)
Certain AMD/ATI video drivers	System ASLR=AlwaysOn	System ASLR=AlwaysOn
DropBox	EAF	EAF
Google Chrome	SEHOP*	SEHOP*
Google Talk	DEP, SEHOP*	DEP, SEHOP*
Immidio Flex+	Not applicable	EAF
Microsoft Office Web Components (OWC)	System DEP=AlwaysOn	System DEP=AlwaysOn
Microsoft Word	Headspray	Not applicable
Oracle Java	Heapspray	Heapspray
Skype	EAF	EAF
SolarWinds Syslogd Manager	EAF	EAF
VLC Player 2.1.3+	SimExecFlow	Not applicable
Windows Media Player	MandatoryASLR, EAF, SEHOP*	MandatoryASLR, EAF, SEHOP*
Windows Photo Gallery	Caller	Caller

* Only in Windows Vista and earlier versions

http://support.microsoft.com/kb/2909257/en-us

EMET 4.1 bypass

- From the “Executive Summary“

  “We were able to bypass EMET’s protections in example code and with a real world browser exploit.“

- No ROP protections for 64 bit processes
- EMET raises the costs for exploit development
  - But no magic bullet

“Bypassing EMET 4.1“ Jared DeMott, Security Researcher, Bromium

Linux - PaX

- Better ASLR implementation
- Additional kernel protections
- No RWX pages (basically W^X)
- Random padding between thread stacks
- Hardened BPF JIT in kernel
- Exploit bruteforce protection
  - Restrict forks on network services

https://www.grsecurity.net/features.php

Linux - Ubuntu

- Long list of security features
  - Run-time and compile-time hardening
- Also support for MAC (instead of DAC)
  - Implemented as LSM:
    AppArmor, SELinux, SMACK
- SECCOMP: syscall filtering

https://wiki.ubuntu.com/Security/Features

Sandboxing

- Any mean of isolation & reducing privileges
  - Goal: restrict potentially malicious code
    - Not trusted or not trustworthy
  - Can be implemented on any layer
    - Can come with virtualization/emulation
  - App sandbox on iOS / Android
  - A virtual machine
  - Browser process sandbox

Conclusion


LAN
DNS
127.0.0.1
192.168.1.1
Upload
Download
Used 0.0
Total 100.0 G
Connectivity
Security System
CPU 1 10%
CPU 2 8%
RAM
Total 4.0 GB
Used 2.2 GB
SWAP
Total 8.0 GB
Used 1.4 GB
Memory

Conclusion

- Memory errors are still an issue
- Attacks and defenses gain complexity
- In the end... there is still a residual risk

Conclusion

- There are a lot of hardening technologies
  - That just have to be used
  - Proper risk assessment and technical understanding is key
- There is a lot of vendor awareness
  - Consequently, products are getting more secure
- New effective technologies are on the rise...

Thanks!

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