Walls, Gates, and Guards

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In case you want to leave …

- **"Safe" languages, and verification and analysis tools, allow us to build software systems that are *shielded* from attack**
  - Like a walled city – can't get in
- **Programs written in "unsafe" languages are plentiful**
  - These languages are useful – like gates in a wall
  - You may not know you are using one
- **Until tools easily handle such languages we should use the abundance of computing cycles to protect systems**
  - Guards and standing armies made cities secure and functioning
- **Dynamic control-flow integrity is a promising technique to detect attacks that exploit memory errors**

Memory-safe languages

- **Automatic memory management**
- **All address arithmetic hidden from user**
  - No buffer overflows, out-of-bounds array accesses, arbitrary type conversions, …
- **Restrict memory space that can be accessed by user program**
- **Either by language design or by static code analysis**

- **Hope: a weapon against memory errors**
  - Memory error: any corruption of memory

Memory errors & vulnerabilities

Come in various forms ...

- **Allow attackers to corrupt memory in a more or less controllable way**
- **Problem: modification of arbitrary memory location**
  - Worst case: attackers gain right to execute arbitrary code
- **Exist in programs written in "unsafe" languages that do not enforce memory safety**

Safe languages

- **Just use a memory-safe language ?**

Safe languages

- **Just use a memory-safe language ?**
  - Popular memory-safe languages based on a virtual machine (VM)
  - “Language VM”, e.g., JVM
    - Provides framework for access control
    - Provides environment for multi-tier compilation (performance)

Safe languages

- **Just use a memory-safe language ?**
  - Popular memory-safe languages based on a virtual machine (VM)
  - But “language VM”
    - May be implemented in an unsafe language
    - May use or provide interface to unsafe libraries
  - Memory errors are still an issue

Attacking safe language VMs

- **Example: Java VM**
  - CVE-2013-1491
  - Target: Oracle Java SE 7 / 6 / 5
  - Memory error in OpenType fonts handling within native layer of JRE
    - Leveraged to arbitrary code execution
    - Completely bypassed state-of-the-art defenses

      (DEP & ASLR – later more)

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

Memory errors still an issue

- **Language VMs for “safe” languages implemented in “unsafe” language**
- **“Unsafe“ languages like C/C++ are still very popular**
  - Prediction: C/C++ will be with us for a long time
  - Yes, there are alternatives ..... sometimes
  - Yes, the list of alternatives is growing … for some situations
- **So we should take a look**

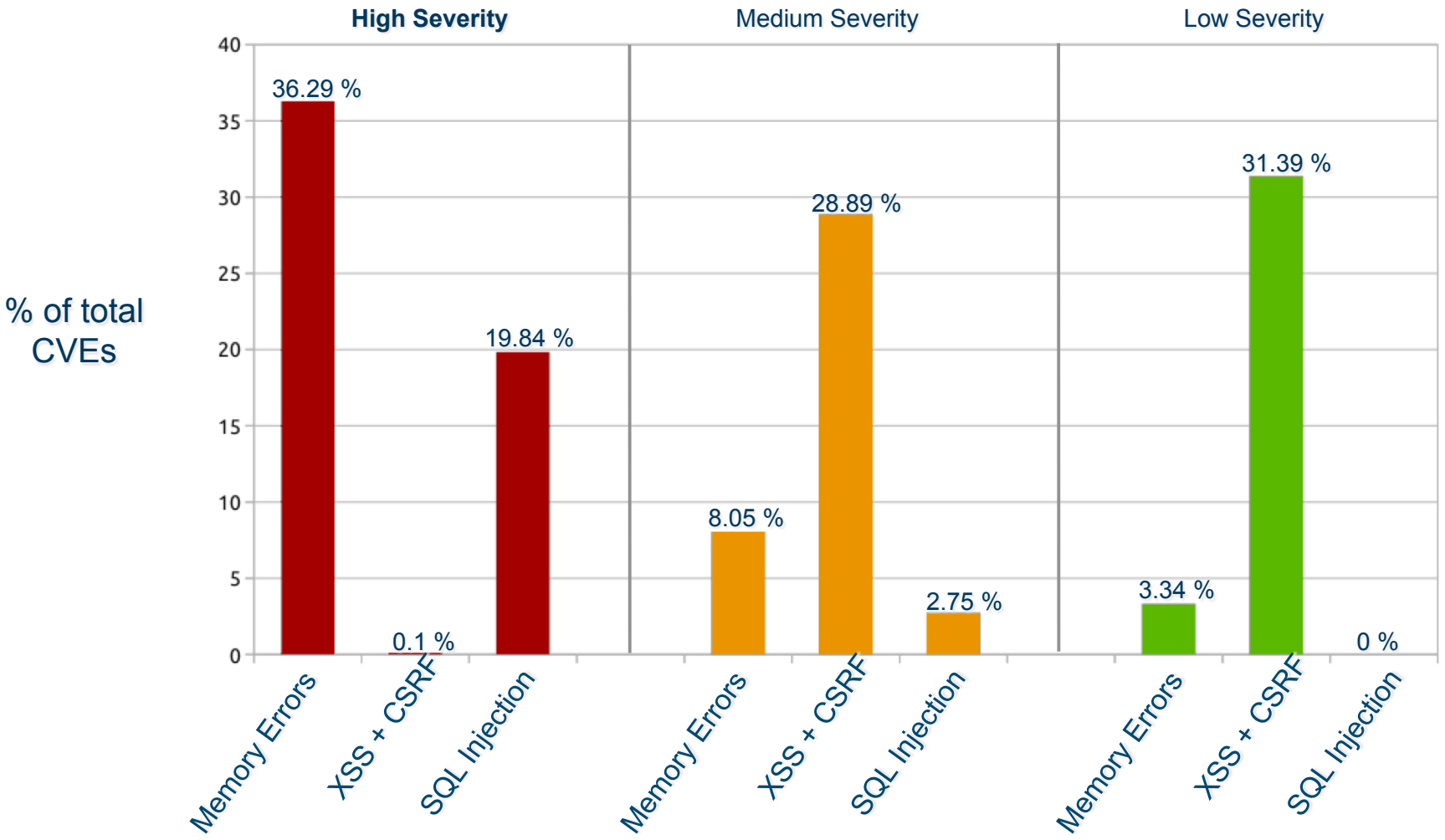
http://www.langpop.com/
http://www.tiobe.com/index.php/content/paperinfo/tpci/index.html

Memory errors

- **Old problem: modification of arbitrary memory location**

- **Memory errors can lead to serious security vulnerabilities**
  - Worst case: attackers gain arbitrary code execution capabilities

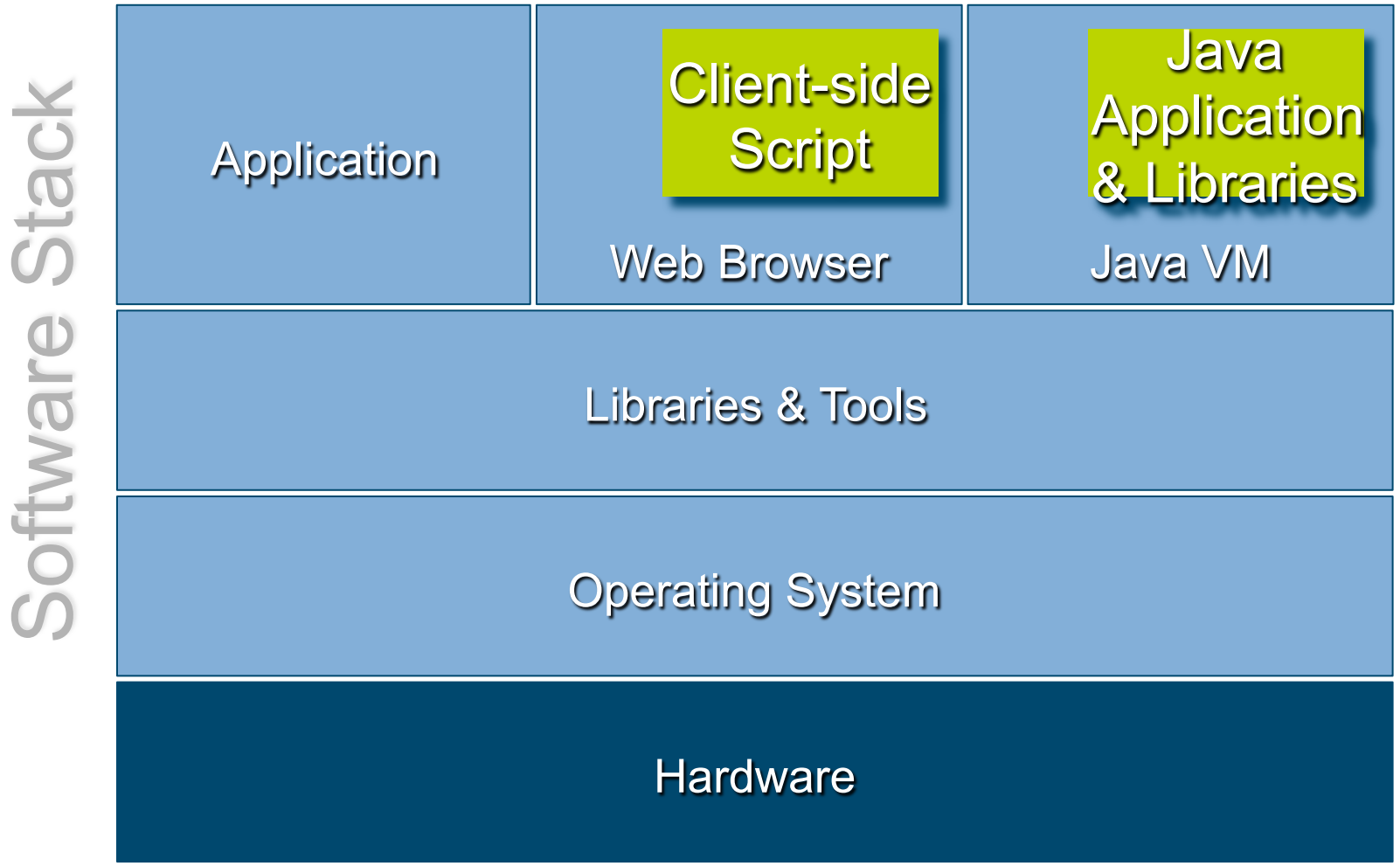
Common vulnerabilities and exposures (CVE)



https://cve.mitre.org/

Total CVEs, with „Insufficient Information“ excluded: 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

Modern software stack



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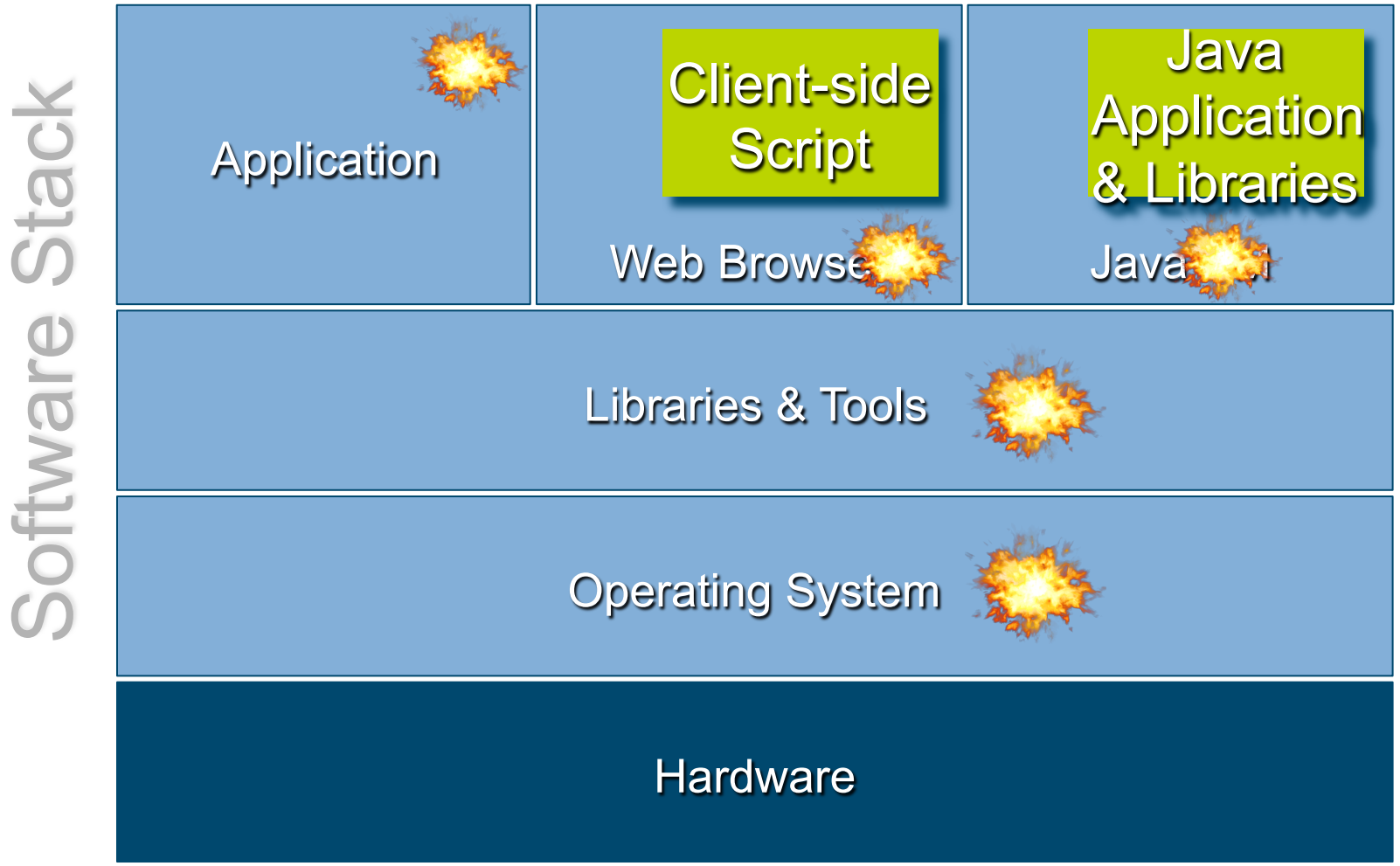
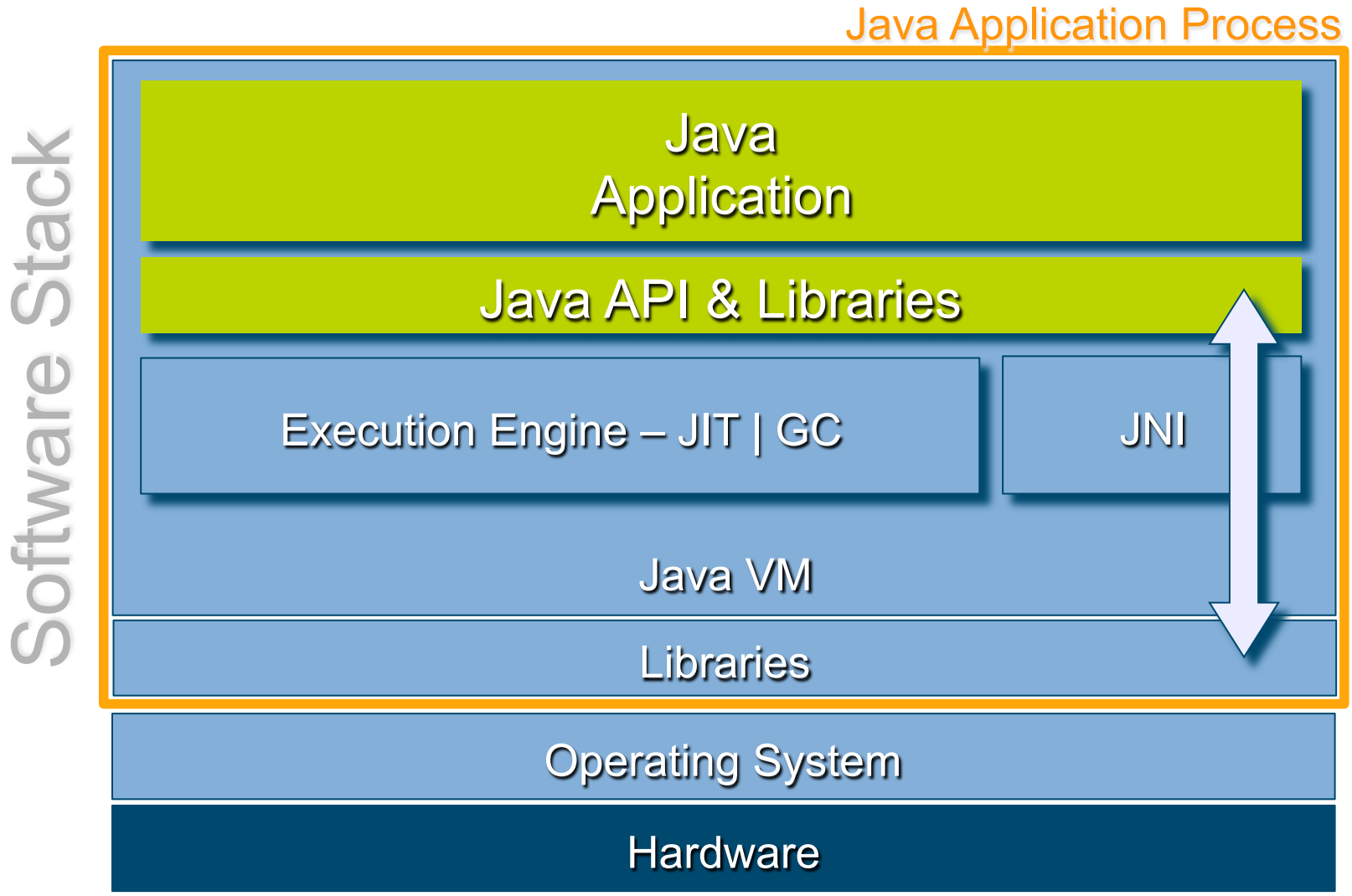


Potentially prone to memory errors & corruption

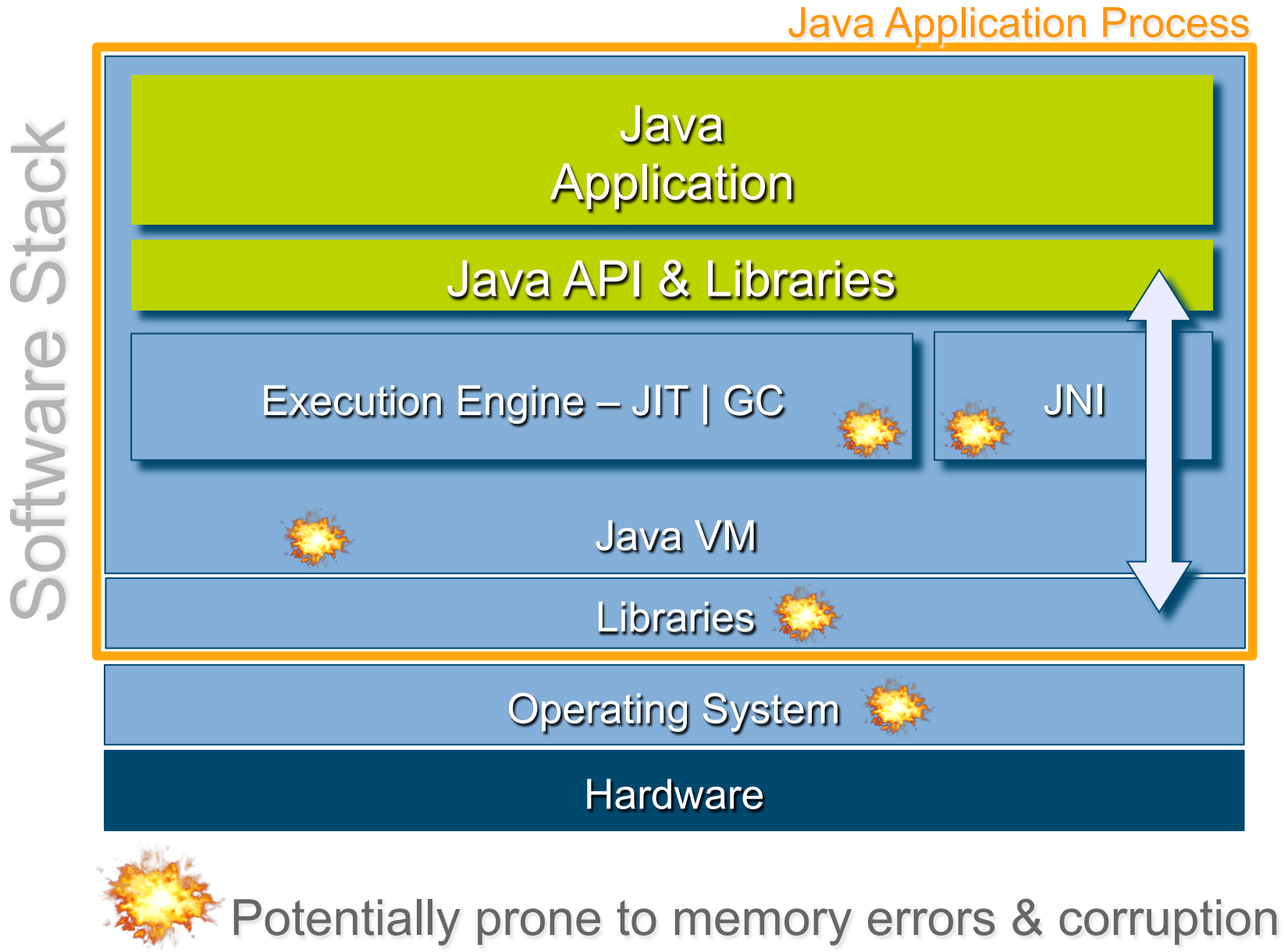
Java VM written in C/C++



Safe languages (VM based)

- **Attacker may exploit memory errors**
  - In the VM
  - In unsafe libraries used by VM or application

Java VM written in C/C++



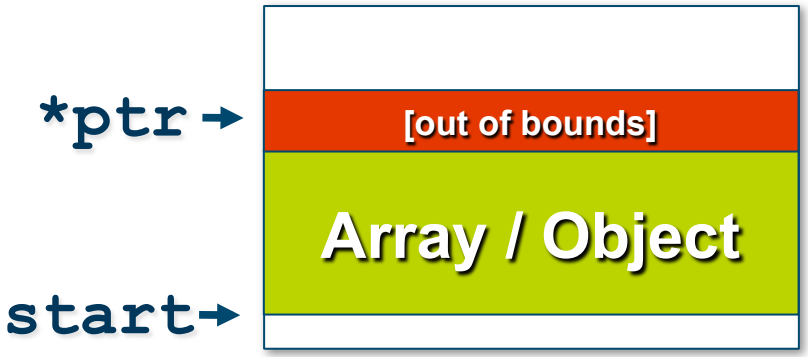
Potentially prone to memory errors & corruption

“Unsafe“ languages

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

Types of memory errors

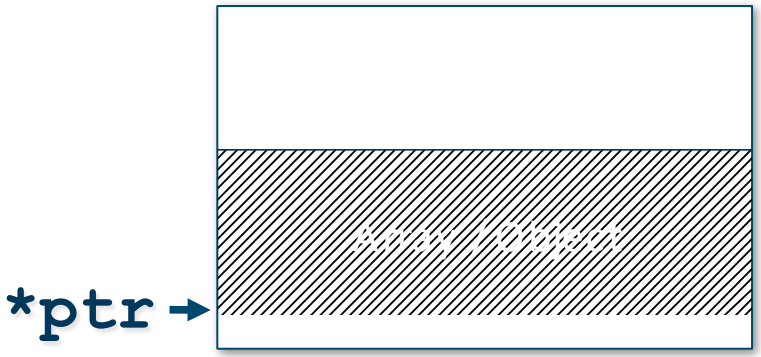
- **Spatial error**



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**
  - Function pointers, sensitive data, index values, etc.
- **Mislead information**
  - E.g., corrupt a length field
- **Construct attacker primitives**
  - Write primitive (write any value to arbitrary address)
  - Read primitive (read from any address)

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**

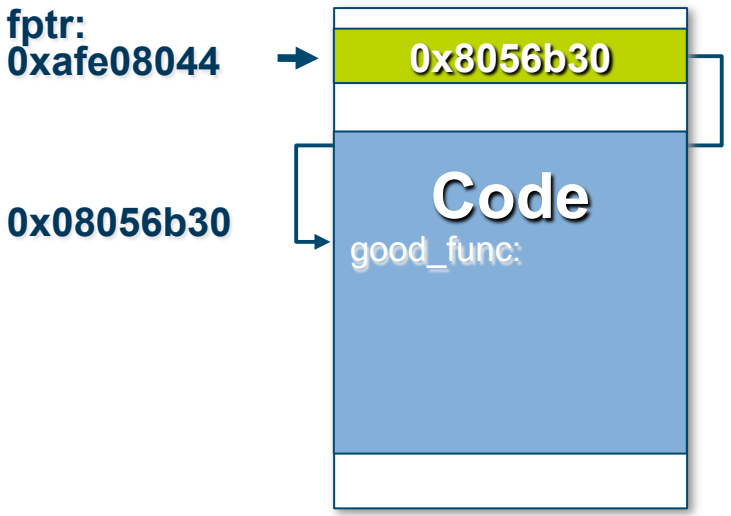
- **Hijack control-flow**
  - To attacker-supplied arbitrary machine code
  - To existing code (code-reuse attack)

- **Corrupt code pointers**
  - Return addresses, function pointers, vtable entries, exception handlers, jmp_bufs

Control-flow hijack attacks

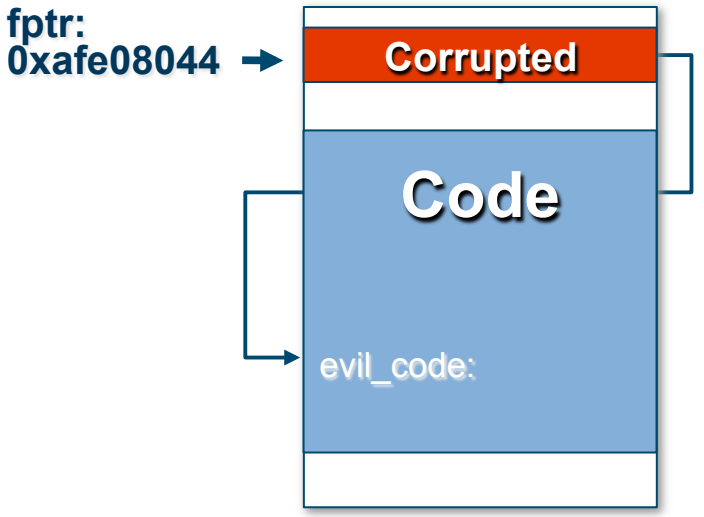
- **Most ISAs support indirect branch instructions**
  - E.g., x86 “ret“, indirect “jmp“, indirect “call“

- **fptr is a value in memory at 0xafe08044**
  - branch *fptr



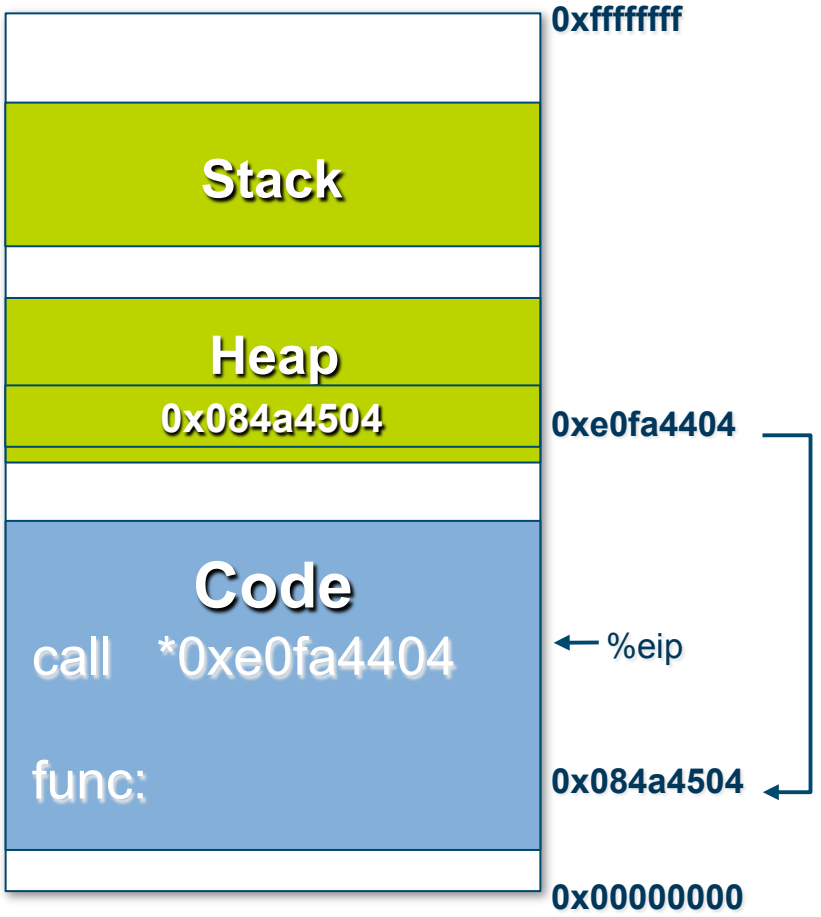
Control-flow hijack attacks

- **fptr is a value in memory at 0xafe08044**
  - branch *fptr
  - fptr was corrupted by an attacker

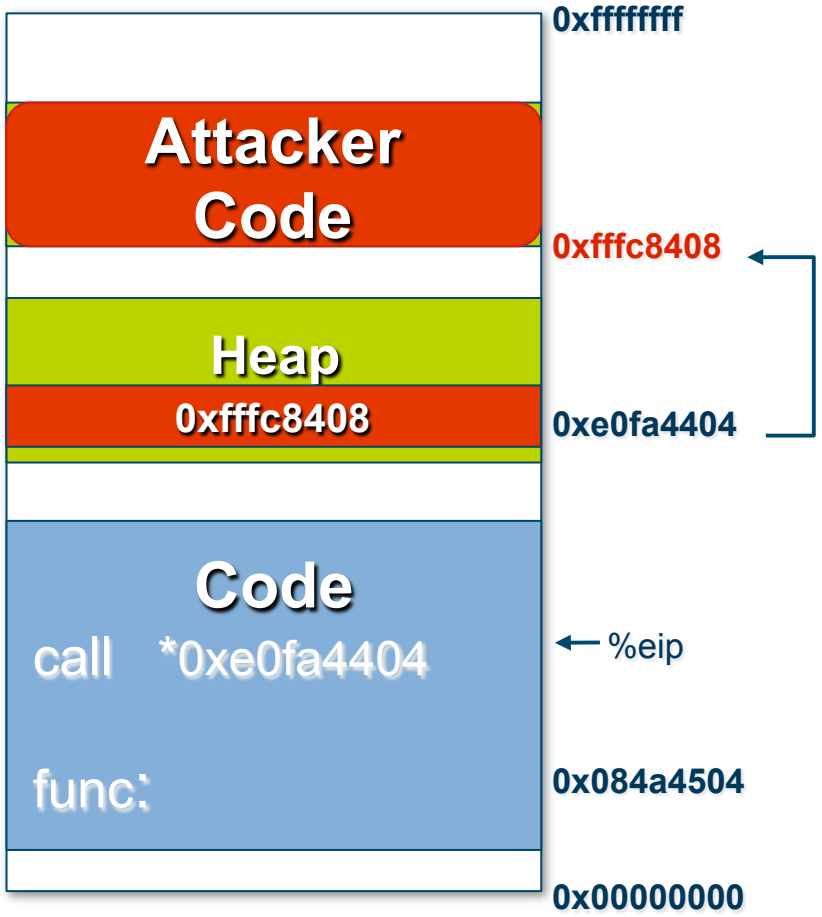


- **Attacker goal: hijack control-flow to injected machine code or to “evil functions“**

Control-flow hijack to injected code



Indirect call to func()



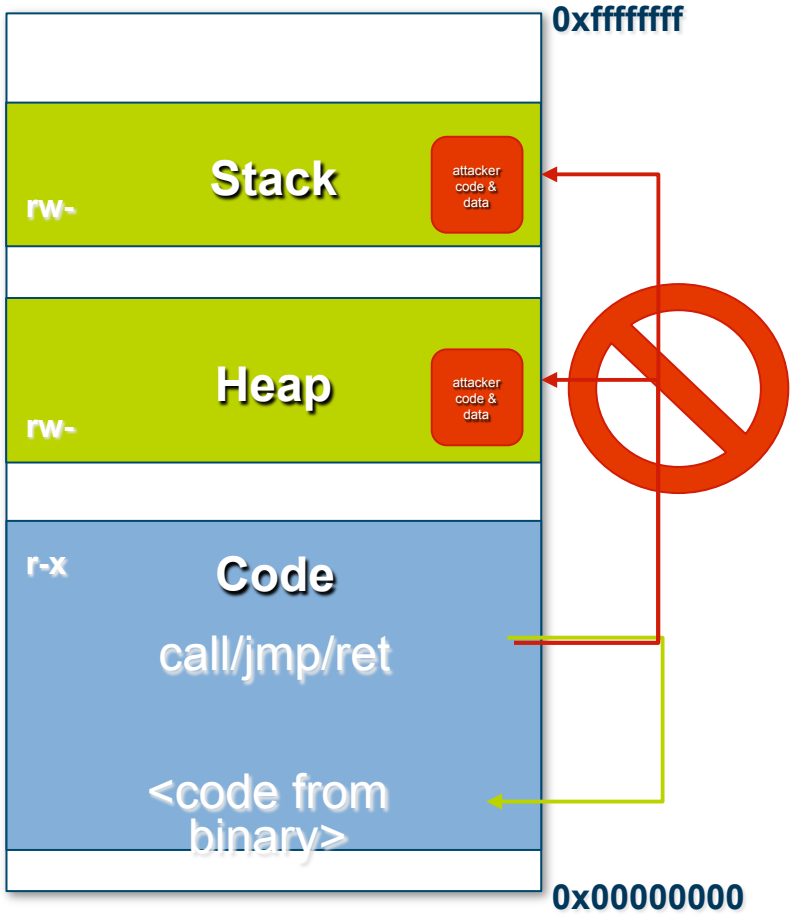
Hijacked indirect call

State of the art defenses

- **Non-executable data**
  - NX bit
- **Data Execution Prevention (DEP)**
  - OS support

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



NX / DEP

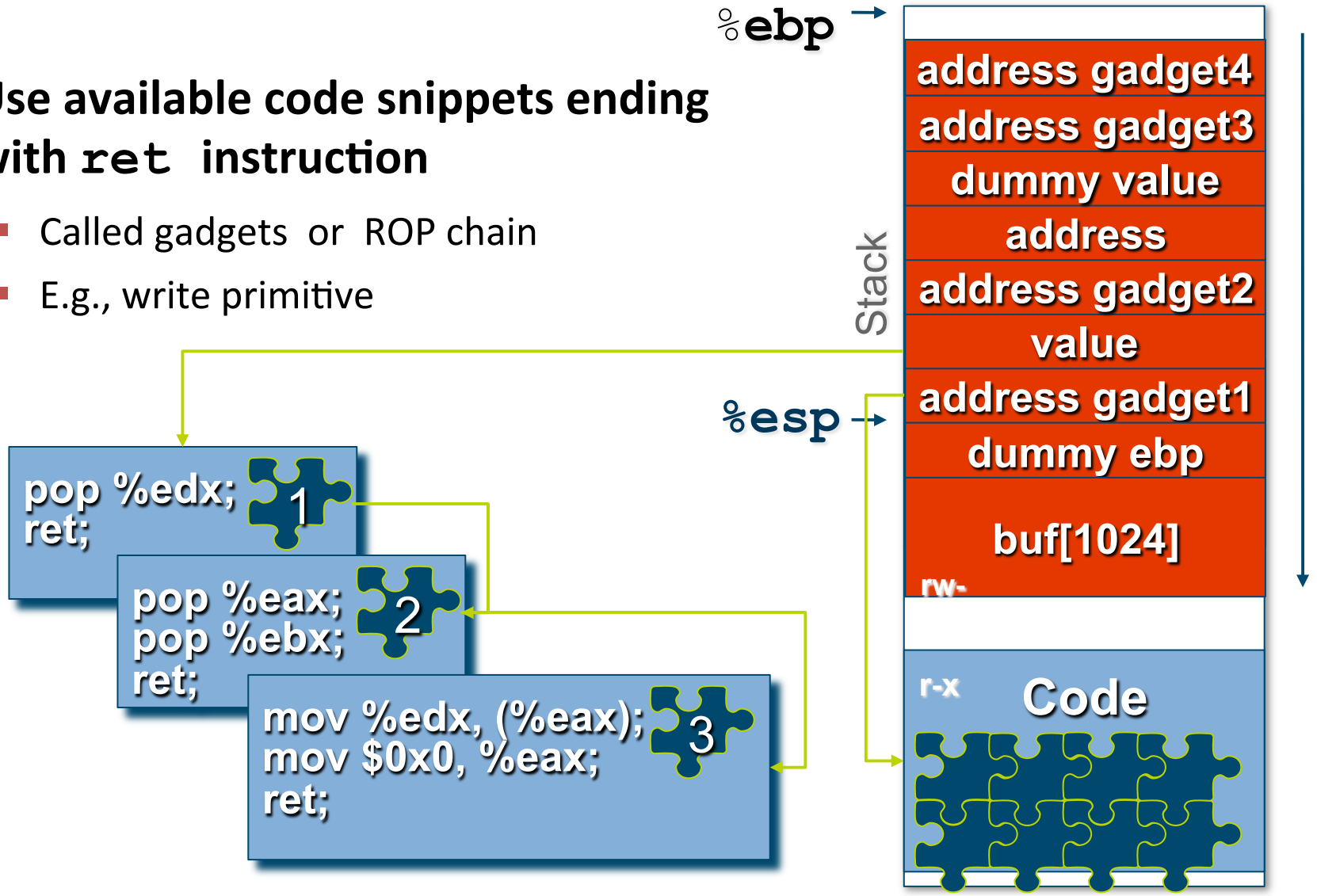
- **Binary images need to provide separate sections/segments that can be mapped exclusively as rw- OR r-x**
  - Linker support required
- **Self-modifying code not allowed**
  - Compiler support required
    - If code is generated just-in-time, explicit rwx allocation required

Bypassing NX / DEP

- **Only use existing code**
- **Code-reuse attack**
  - ret2libc, ret2bin, ret2* attacks
  - 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

Return-oriented programming (ROP)

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



Return-oriented programming

- **Very powerful!**
  - Turing complete although not required

- **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

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 code (shellcode)
  - 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)

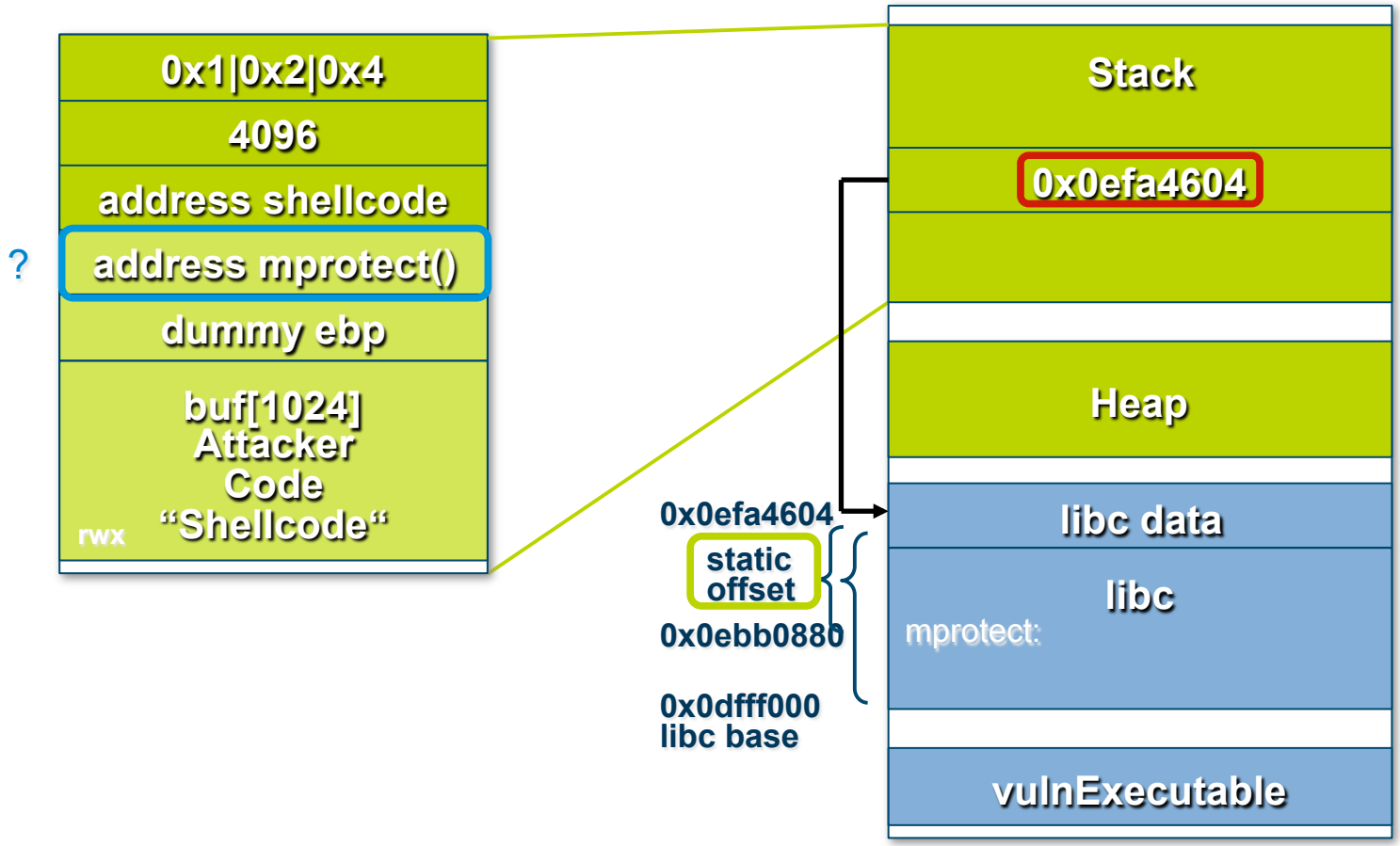
ASLR

- **Today most operating systems implement *Address Space Layout Randomization* (ASLR)**
  - What can be randomized?
    - OS: Stack, heap and memory mapping base addresses
    - OS, compiler, linker: Exectuables and libraries
      - Position-independent or relocatable code

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**

Memory leak



mprotect = leaked pointer – static offset

0x0ebb0880 = 0x0efa4604 - 0x003f3d84

Generic defense: DEP & ASLR

- **DEP: Data Execution Protection**
- **ASLR: Address Space Layout Randomization**
  - Exploitation becomes harder for all vulnerability classes & attack techniques
  - Together quite effective
    - If implemented correctly and used continuously
  - But DEP and ASLR not enough

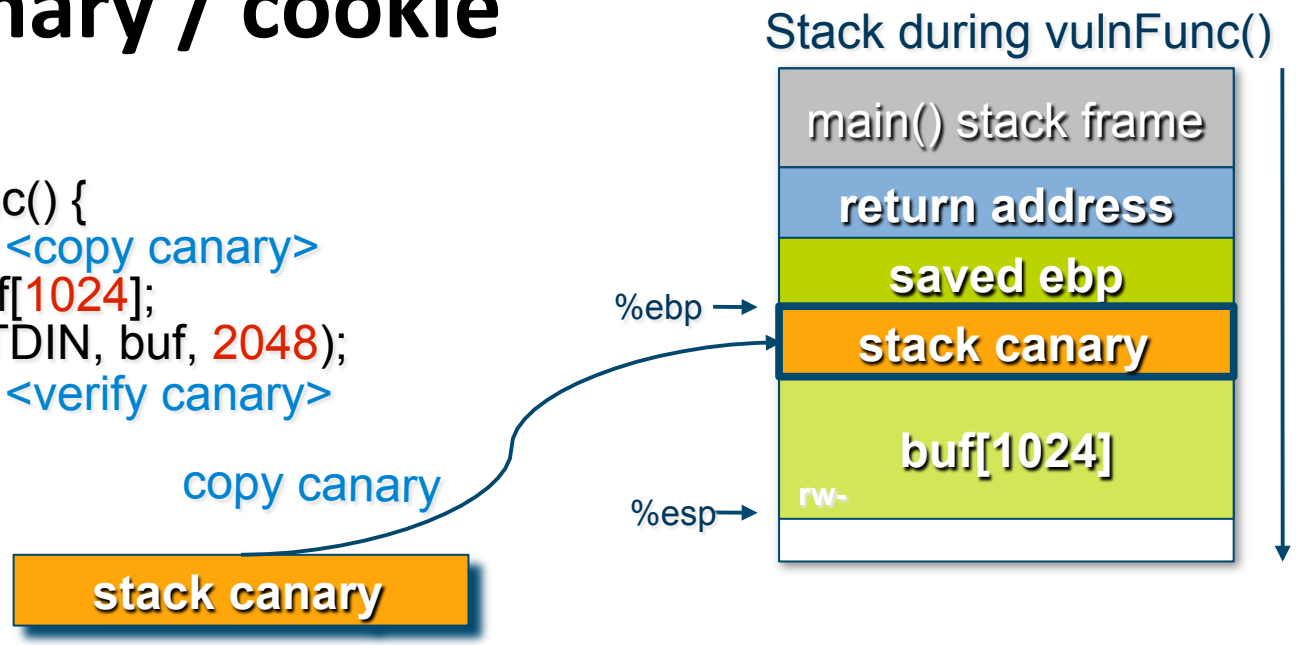
Compile-time protection

- **Usually require source code changes (annotations) and/or recompilation of the application**
  - To add run-time checks

- **Stack canaries / Cookies**
- **Pointer obfuscation**
- **/GS (buffer security check)**
- **/SAFESEH (link-time, provide list of valid handlers)**
- **SEHOP (run-time, walk down SEH chain to final handler before dispatching / integrity check)**
- **Virtual Table Verification (VTV) & vtguard**
- **Control-Flow Guard (new in Visual Studio 2015)**

Stack canary / cookie

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



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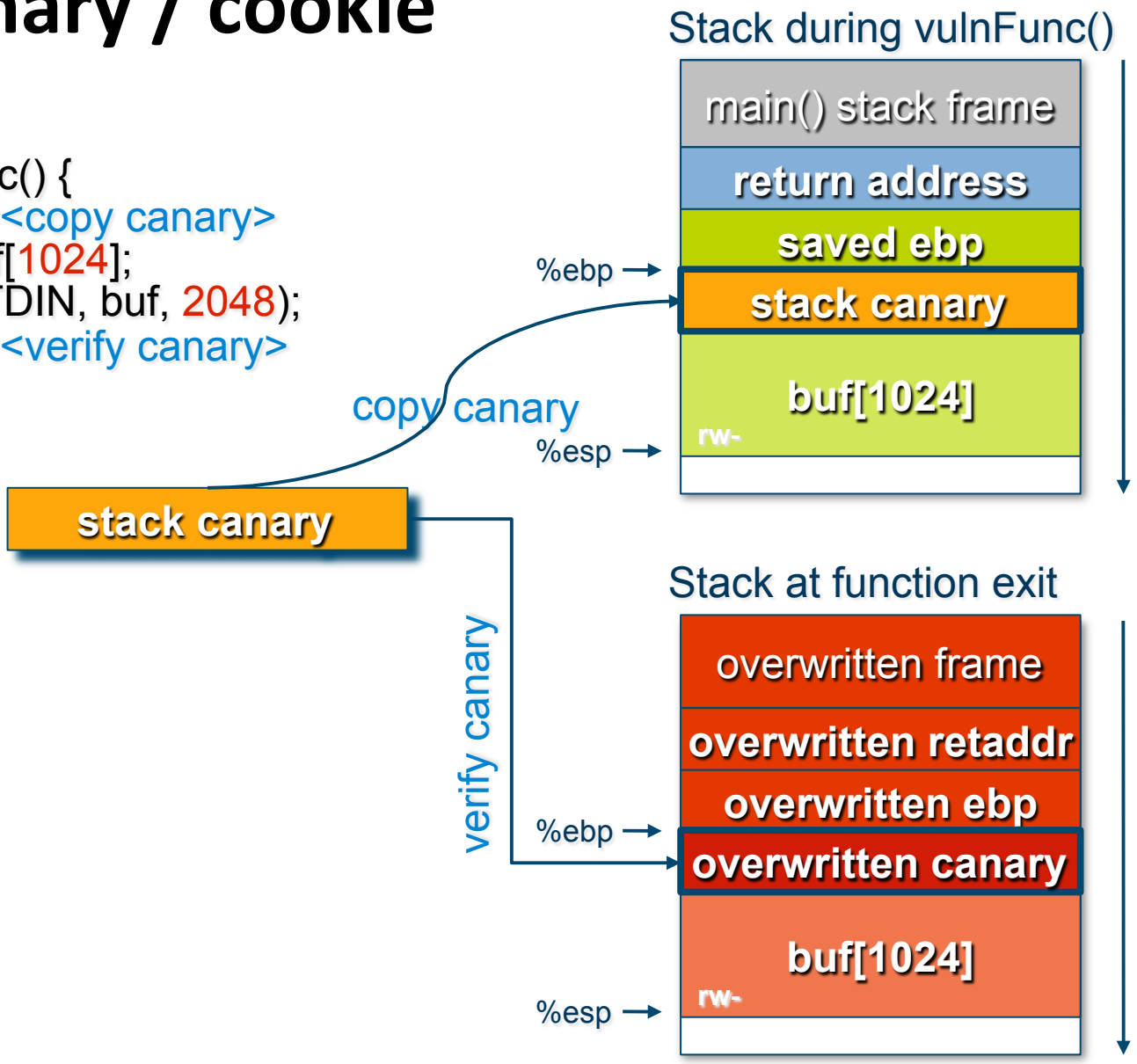


Stack canary / cookie

- **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

- **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

More defenses

- **DEP and ASLR based on memory model**
  - Prevent/complicate attacker access to memory
- **Programs execute instructions**
  - More involved than use of memory

- **Goal: protect program *execution***

Attacker model

- **Let's assume a powerful attacker**
  - Can arbitrarily corrupt data and pointers
  - Can read entire address space of a process
  - Only restriction on attacker:
    - No data execution and no code corruption (NX/DEP/W^X)

Question

- **Can we still prevent arbitrary code execution and code-reuse attacks?**

Observations

- **Attacker needs to hijack control-flow**
  - To injected or existing code

- **VM/runtime system must ensure that control-flow stays on the intended legitimate path**
  - As allowed by compiler resp. control-flow graph (CFG)

Control-flow integrity (CFI)

- **Construct a control-flow graph (CFG)**
  - Should be as strict as possible

- **Ensure that control-flow stays within CFG**

Control-flow integrity (CFI)

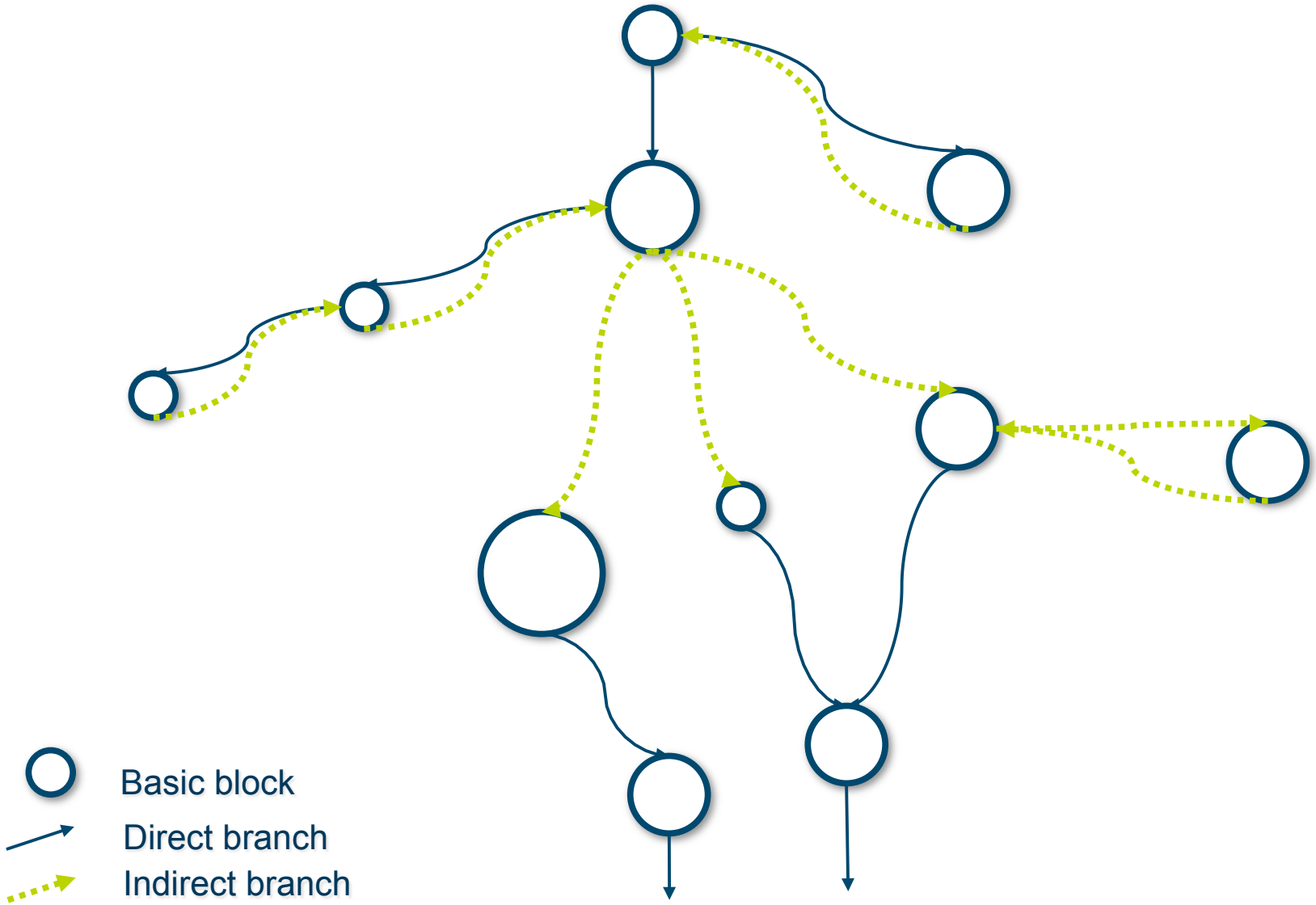
- **Original publication in 2005**
  - "Control-Flow Integrity – Principles, Implementations, and Applications"
  - M. Abadi, M. Budiu, U. Erlingsson, J. Ligatti
  - CCS'05 (ACM Trans. on Information and System Security (TISSEC) 13(1) Oct 2009)

- **Many CFI implementations were proposed during recent years**
  - Compiler-based
  - Binary-only (static rewriting)

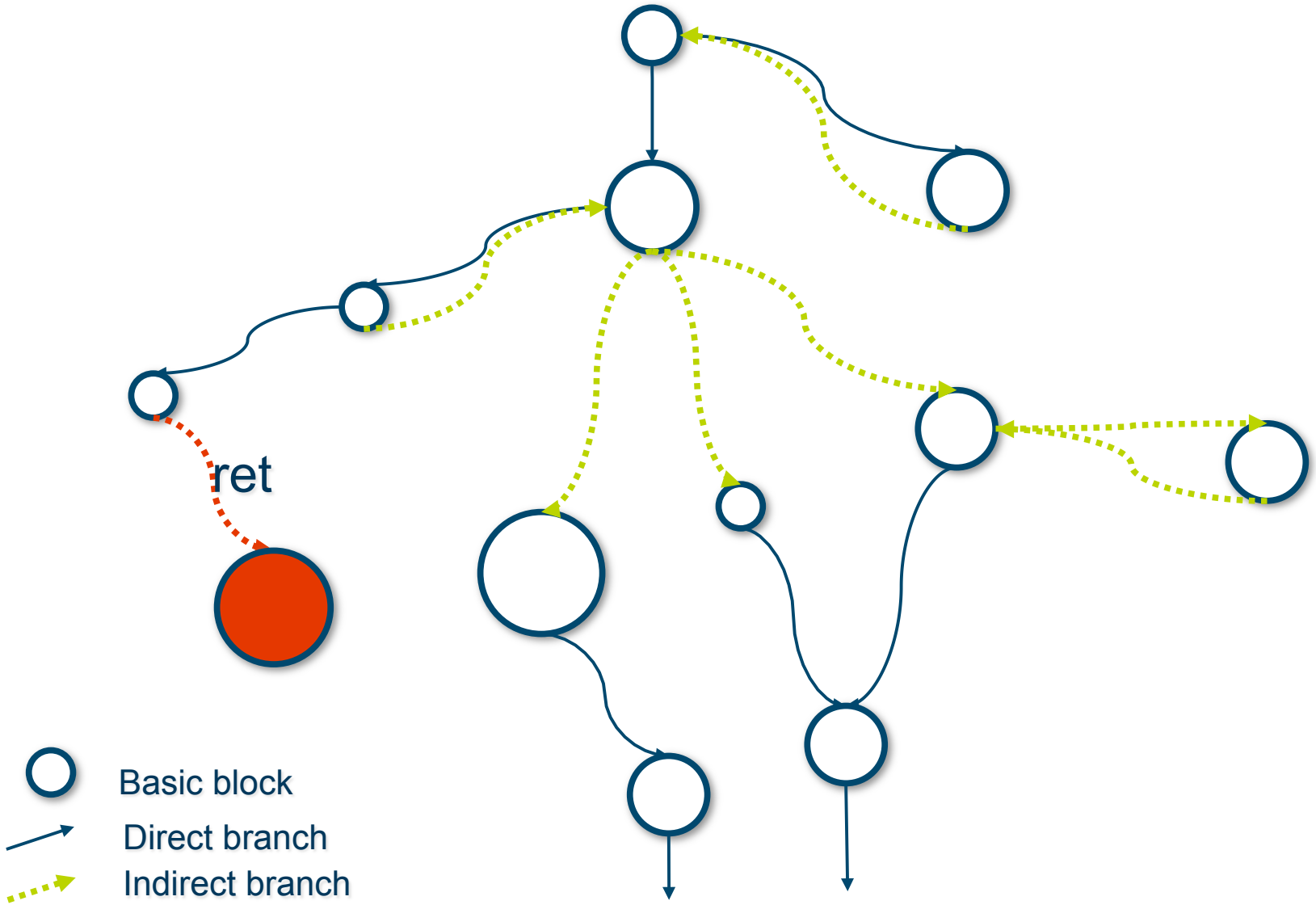
Control-flow integrity (CFI)

- **Construct a control-flow graph (CFG)**
  - Should be as strict as possible
- **Ensure that control-flow stays within CFG**
- **If no path within the CFG can be misused by an attacker then the CFI policy can be considered secure**

Control-Flow Integrity (CFI)



Hijacked control-flow



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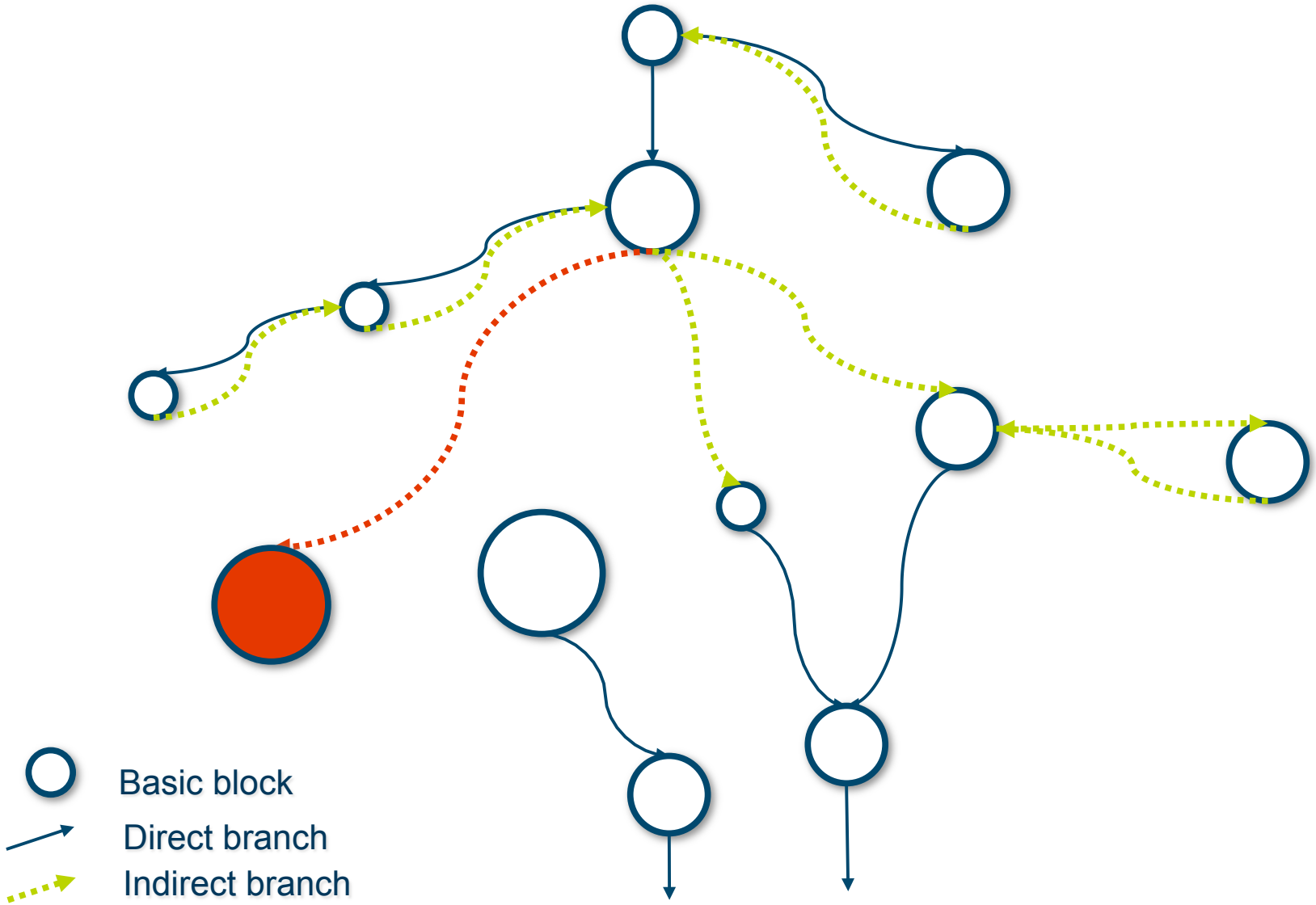

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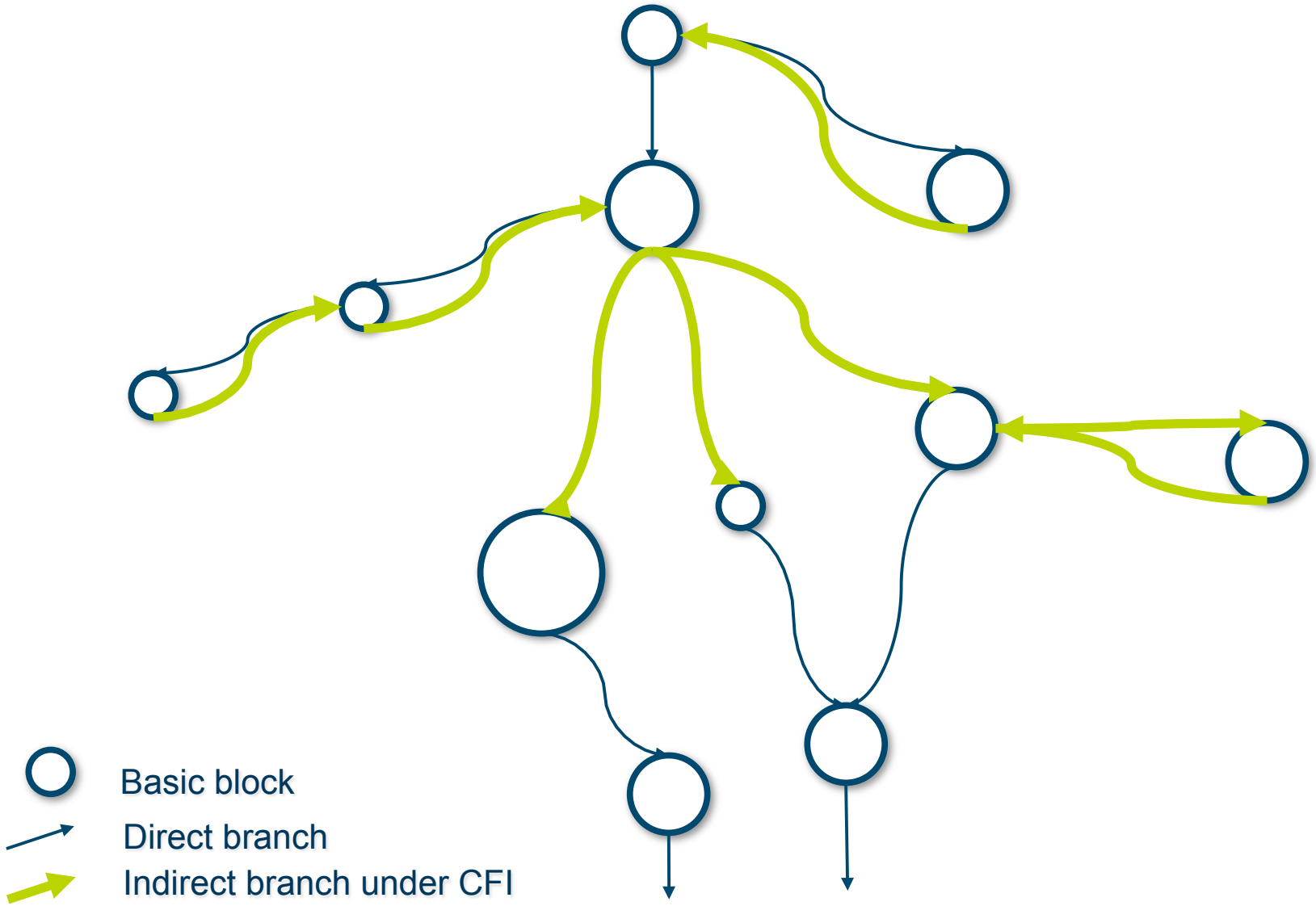

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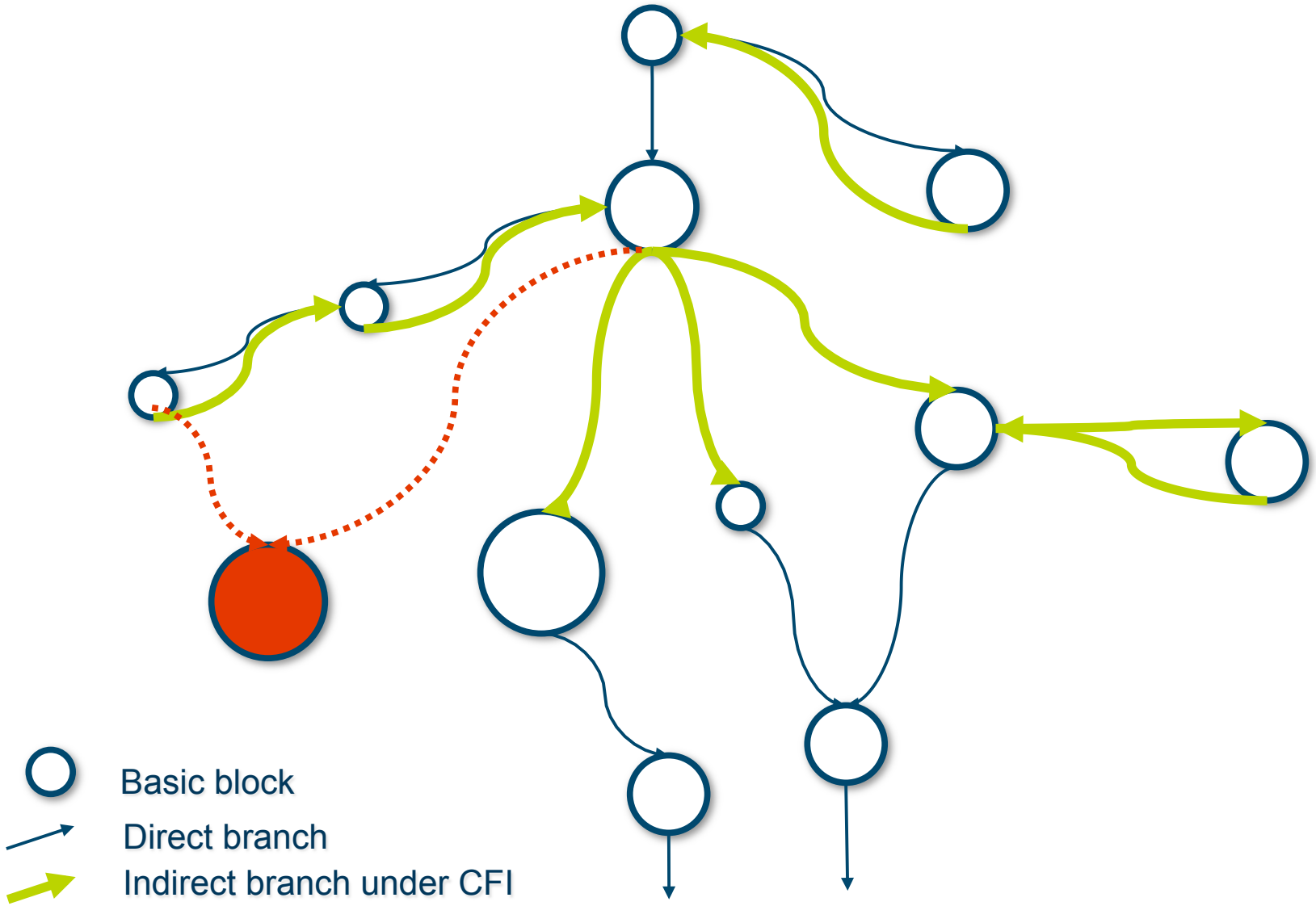

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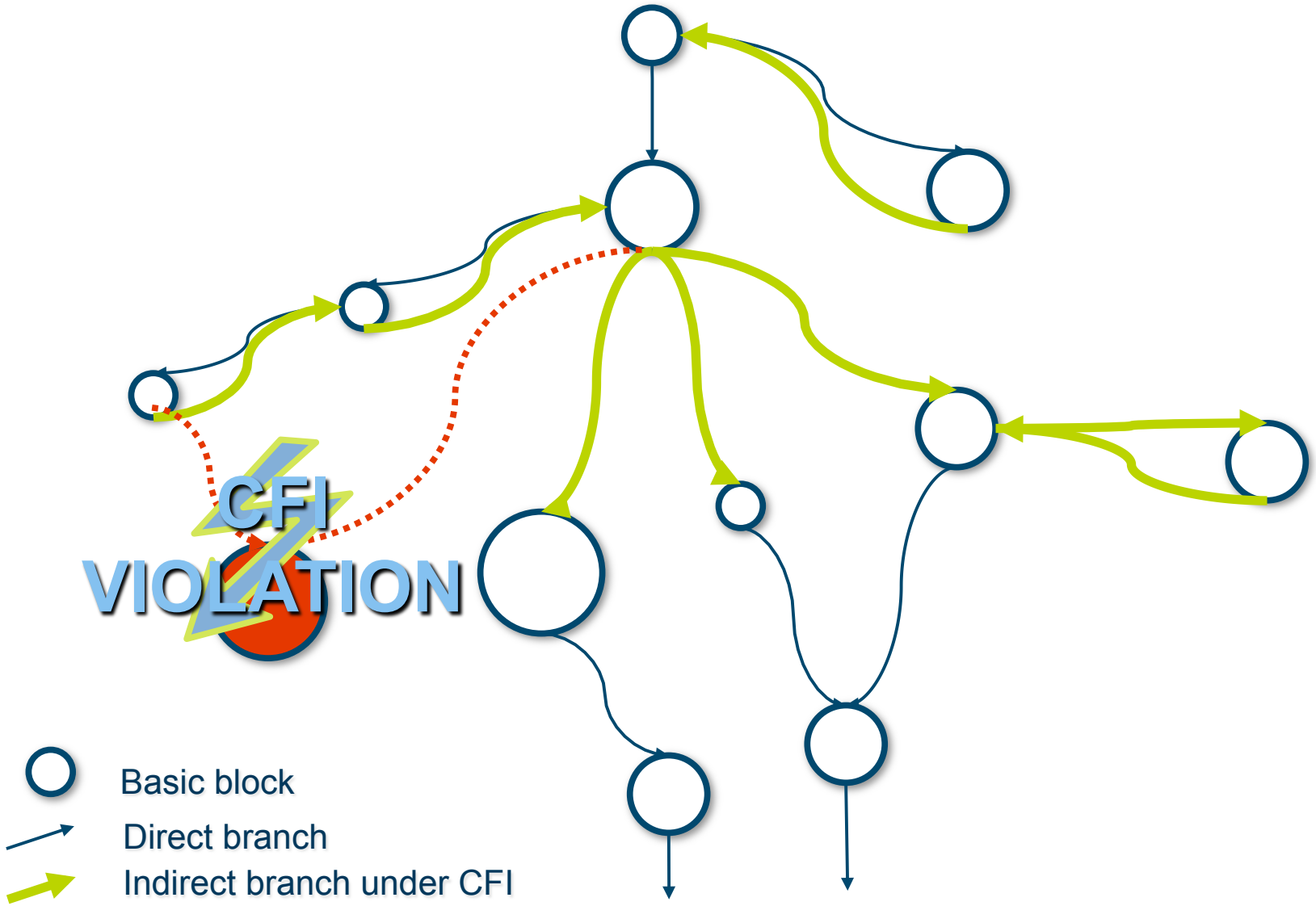


Control-flow integrity (CFI)

- **Drawbacks of proposed solutions**
  - Too permissive CFG due to over-approximation
  - Need to recompile
  - No support for shared libraries

- **Most solutions shown to be ineffective**
  - “Hardened” exploits still worked under CFI

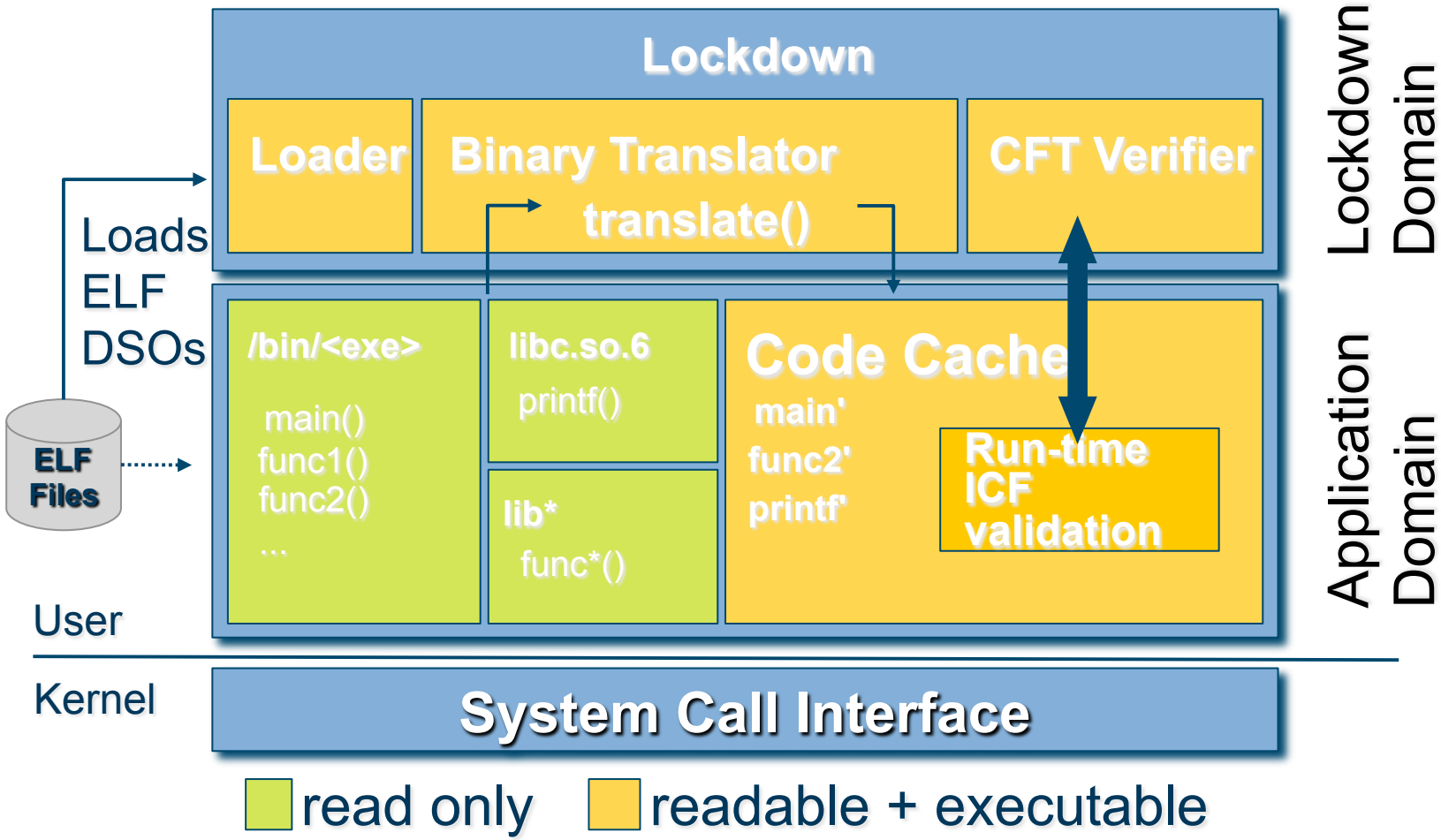
Control-flow integrity (CFI)

- **Static CFI not enough: Dynamic approach necessary**
  - Dynamic CFI

Lockdown – dynamic CFI

- **Enforces a strict CFI policy for binaries**
- **Supports shared libraries & dynamic loading**
- **Constructs and enforces CFG at runtime**
  - Using static and dynamic information

Lockdown – dynamic CFI



CFT: Control-Flow Transfer, ICF: Indirect Control-Flow,
ELF: Executable and Linkable Format, DSO: Dynamic Shared Object

Lockdown – design

- **Dynamic binary translation to instrument code with additional CFT checks**
  - Basically a user-space VM
  - Ensures no untranslated code is ever executed
- **A trusted loader loads ELF dynamic shared objects (DSOs) and provides symbol information for CFG construction**

Mathias Payer, Tobias Hartmann, Thomas R. Gross: „Safe Loading - A Foundation for Secure Execution of Untrusted Programs“ IEEE Symposium on Security and Privacy 2012: 18-32

Lockdown – design

- **Separation of domains achieved by**
  - Separate memory areas
  - Randomization of locations
  - Trampolines
  - Information leak prevention
- **Stronger guarantees achieved by marking Lockdown areas as read-only during code-cache execution**

Lockdown – attacker model

- **Like in general CFI Attacker Model**
  - Can arbitrarily corrupt data and pointers in application domain
  - Can read entire address space of application domain
  - Only restriction on attacker
    - No data execution and no code corruption (NX/DEP/W^X)

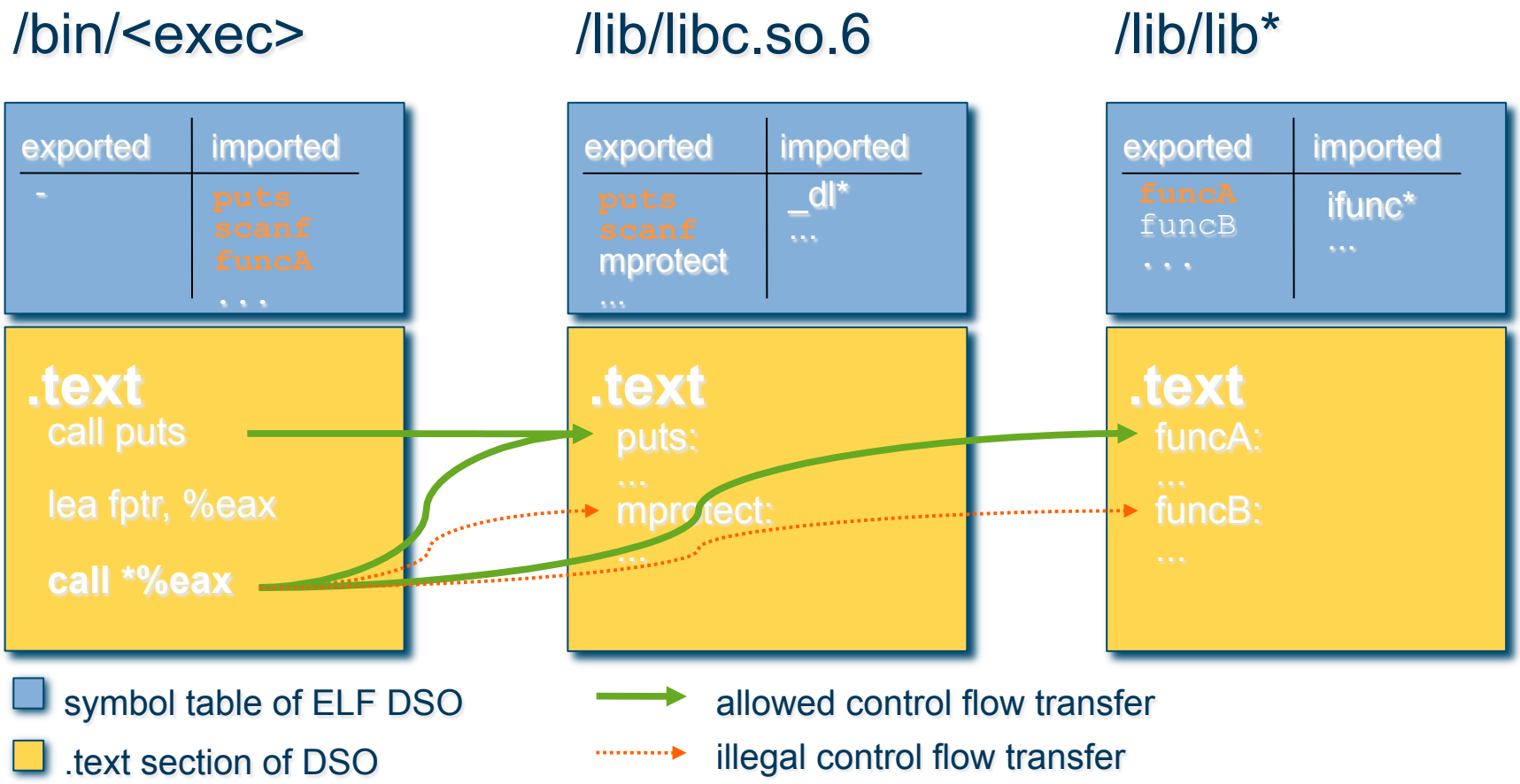
Lockdown – High-Level CFI policy

- **`call` policy**
  - Allow calls to imported & exported symbols
  - Allow calls to local symbols

- **`jmp` policy**
  - Allow local jumps within symbol boundaries
  - Allow jumps to local symbols

- **`ret` policy**
  - Shadow stack (allows reauthentication)

Lockdown – CFI policy for calls

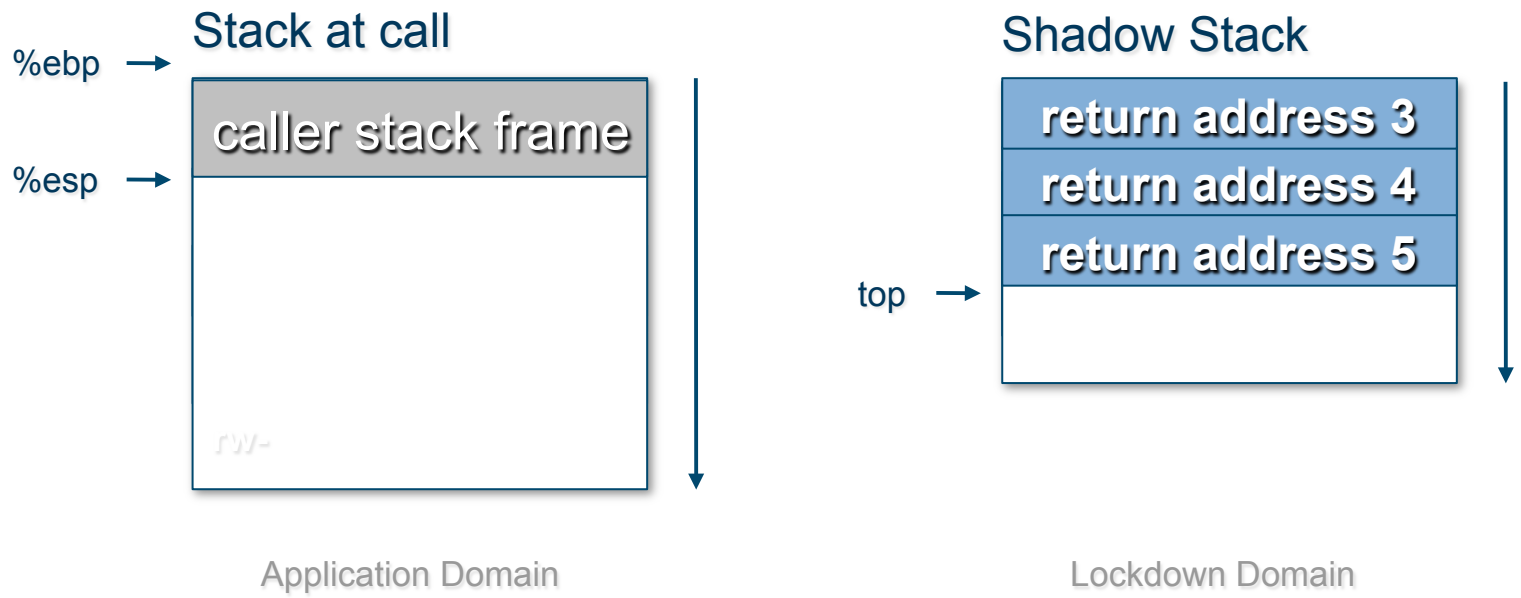


Lockdown – CFI policy for returns

- **Instrument `calls` and `returns`**
  - Return address pushed to a shadow stack
  - Upon return: return address is compared to value on shadow stack
    - Resynchronization possible
  - If values don't match raise exception

Lockdown – CFI policy for returns

- **call instrumented such that**
  - Return address is pushed onto the shadow stack and the application stack
  - Control-flow is transferred to callee



Lockdown – CFI policy for returns

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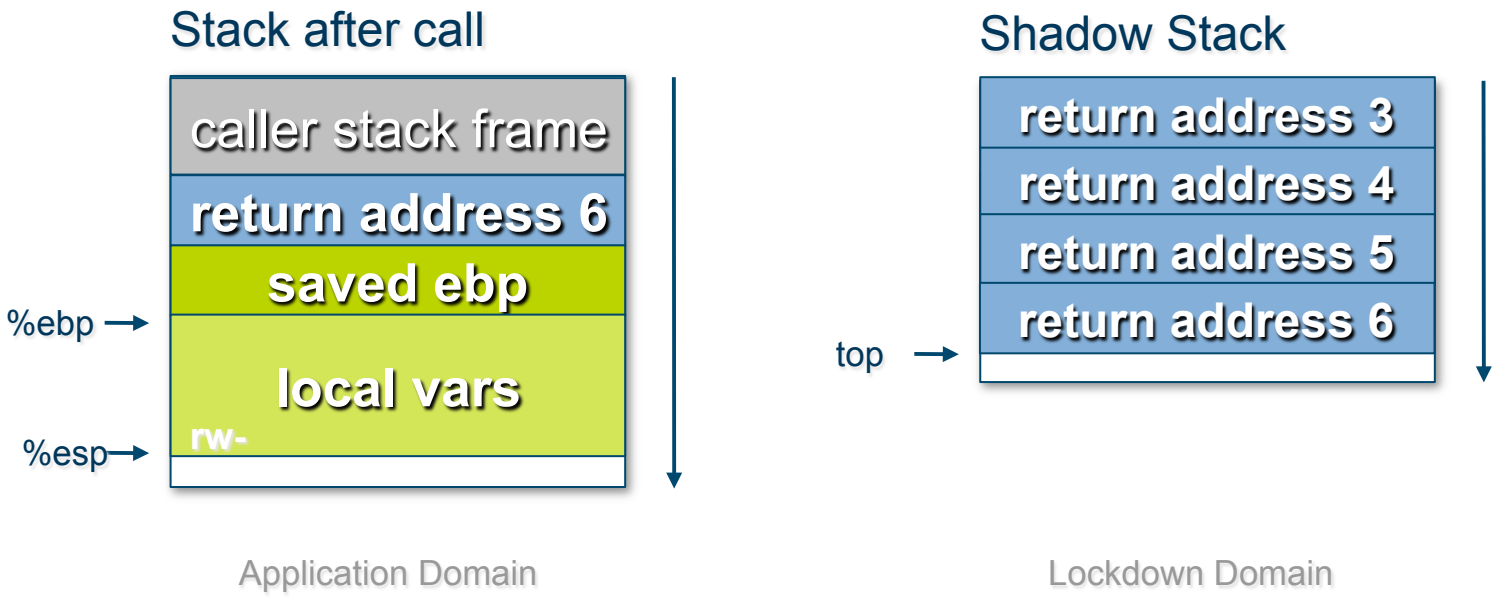
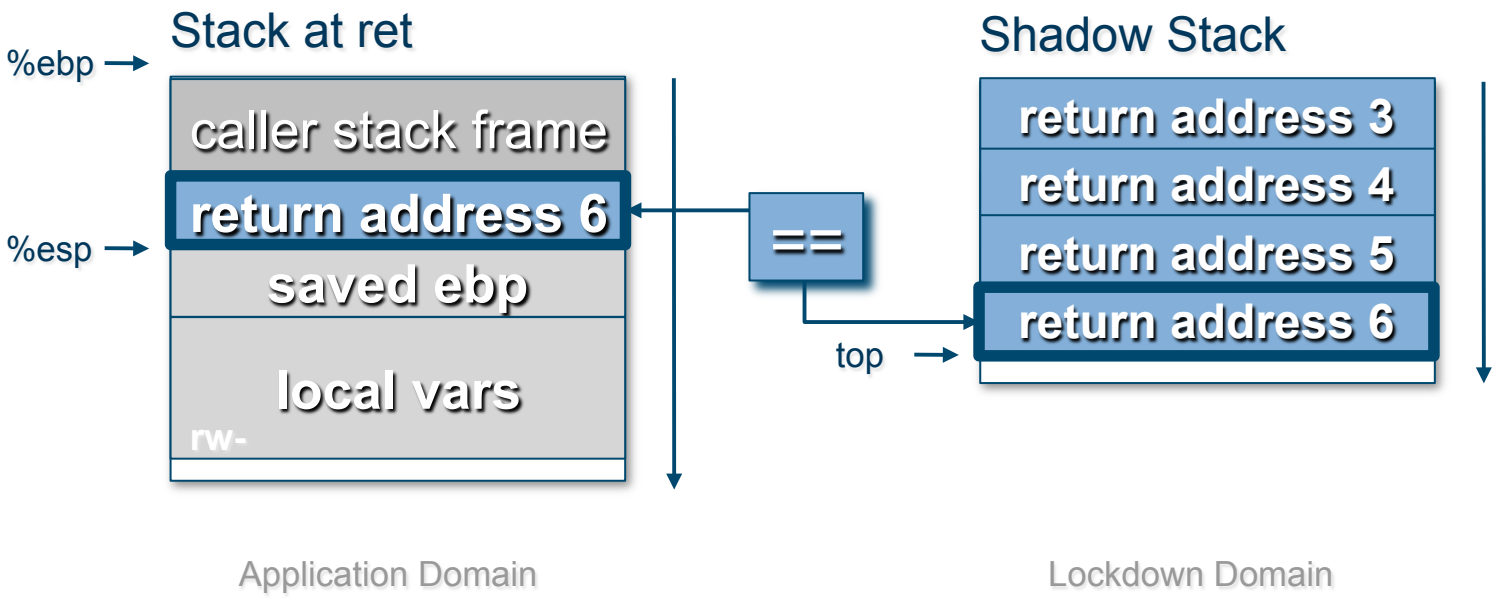


Lockdown – CFI policy for returns

- **`ret` instrumented such that**
  - Return address on the application stack is compared to value on shadow stack
  - If values differ, try to resynchronize else raise exception



Lockdown – challenges

- **Detection of callbacks & function pointers**
  - No information regarding types at runtime
  - If stripped, no extended symbol information
    - Coarser-grained CFG
- **Control-flow transfers do not always adhere to the rules presented**
- **Overhead of CFT checks**

Lockdown – implementation

- **Heuristics for function pointer detection**
  - E.g., "`leal imm32(%ebx), %e*x`"
  - E.g., relocation entries like R_386_RELATIVE
- **Special handling of control-flow specifics**
  - E.g., PLT inlining
  - E.g., whitelisting of runtime support CFT
- **Several inlined performance optimizations**

Preliminary performance evaluation

- **SPEC CPU2006**
- **29 programs**
- **Total 27 benchmarks**
  - 2 benchmarks missing
  - Tool chain problems

Lockdown – good and bad performance

Benchmark	BT overhead	Lockdown overhead
400.perlbench	108.85%	148.16%
401.bzip2	6.65%	6.79%
403.gcc	41.67%	52.22%
433.milc	4.05%	7.92%
444.namd	1.73%	2.08%

Intel Core i7 CPU 920@2.67 GHz with 12GiB Ubuntu Linux 12.04.4 LTS 32-bit x86 / gcc 4.6.3

- **Avg overhead Lockdown: 19.09%**
  - Overhead binary translation alone: 14.64
- **Most benchmarks overhead below 20%**
  - Only 5 benchmarks over 45%

Lockdown – security evaluation

- **Unfortunately most static CFI solutions were shown to be ineffective**

- **(D)AIR bad in measuring CFI security effectiveness**
  - LibreOffice has 56'417'429 bytes of executable memory
  - 99% (D)AIR allows 1% of the bytes as attacker targets
    - 564'174 potential targets
  - Attacker normally just needs a handful of gadgets to mount a successful code-reuse attack

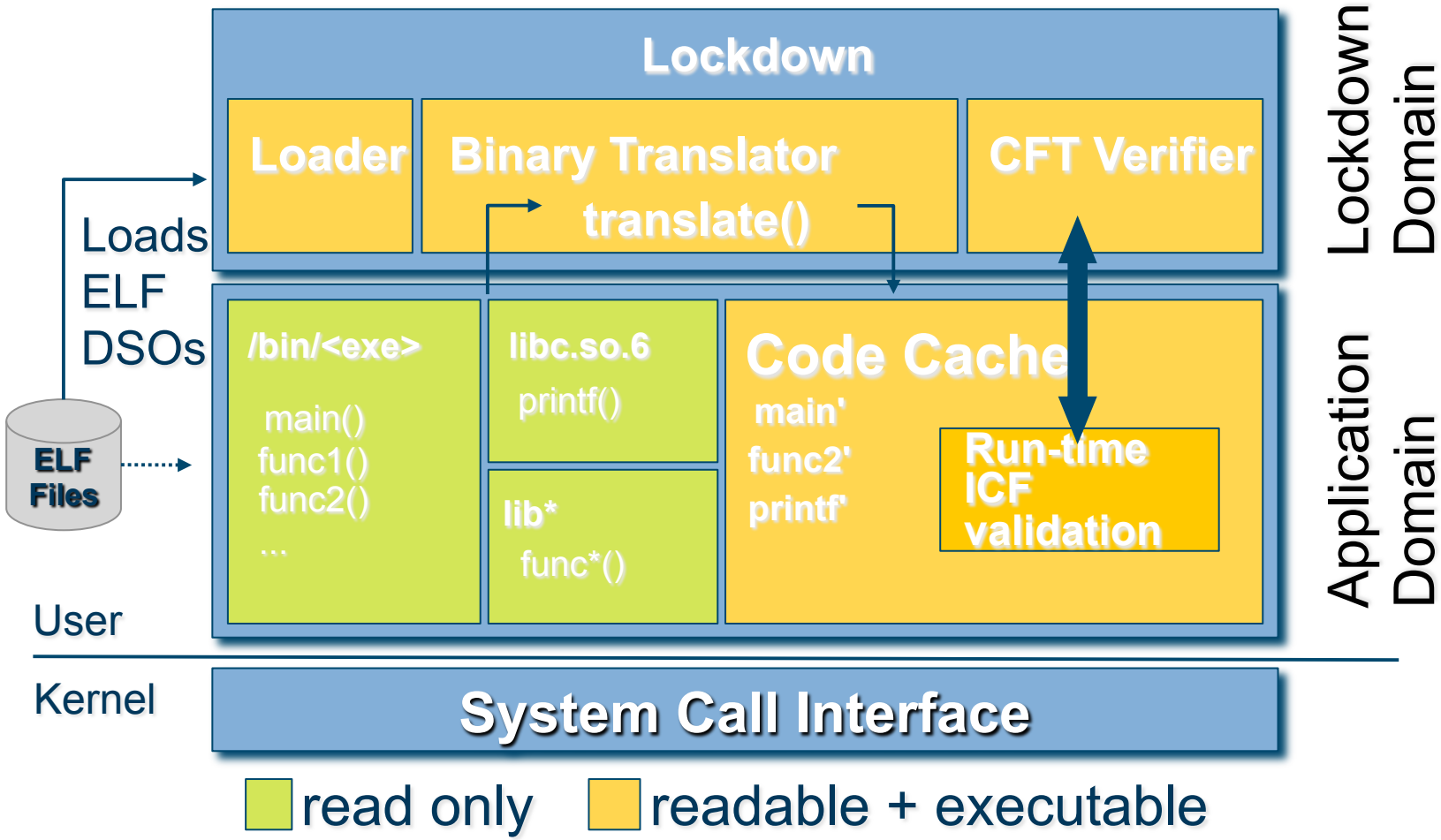
Dynamic CFI

- **Key idea: use binary translator to rewrite program on the fly**
  - Practical solution
- **Works for arbitrary x86 binaries**
  - No source code needed
- **Binary translator adds overhead**
  - Less than 15% for many programs

Dynamic CFI

- **Key idea: use binary translator to rewrite program on the fly**
  - Practical solution
- **Works for arbitrary x86 binaries**
  - No source code needed
- **Binary translator adds overhead**
  - Less than 15% for many programs
- **Binary translator with dynamic CFI guards against (some) attacks**
  - No complete protection

Lockdown – dynamic CFI



CFT: Control-Flow Transfer, ICF: Indirect Control-Flow,
ELF: Executable and Linkable Format, DSO: Dynamic Shared Object

Thanks to

- **Antonio Barresi**
  - Now at xorlab
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  - Now at xorlab
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  - Now at Purdue

Concluding remarks

- **Control-flow integrity protects program execution paths**
  - Static CFI elegant but not practical
- **Dynamic CFI offers chance to block wide avenue**
  - More work needed
  - Implementation
  - Evaluation models
- **Spend cycles on guarding execution of programs**
  - No (user) program should run on bare hardware
  - A layer of indirection adds overhead – but protects

Thank you for your attention