Practical Control Flow Integrity & Randomization for Binary Executables

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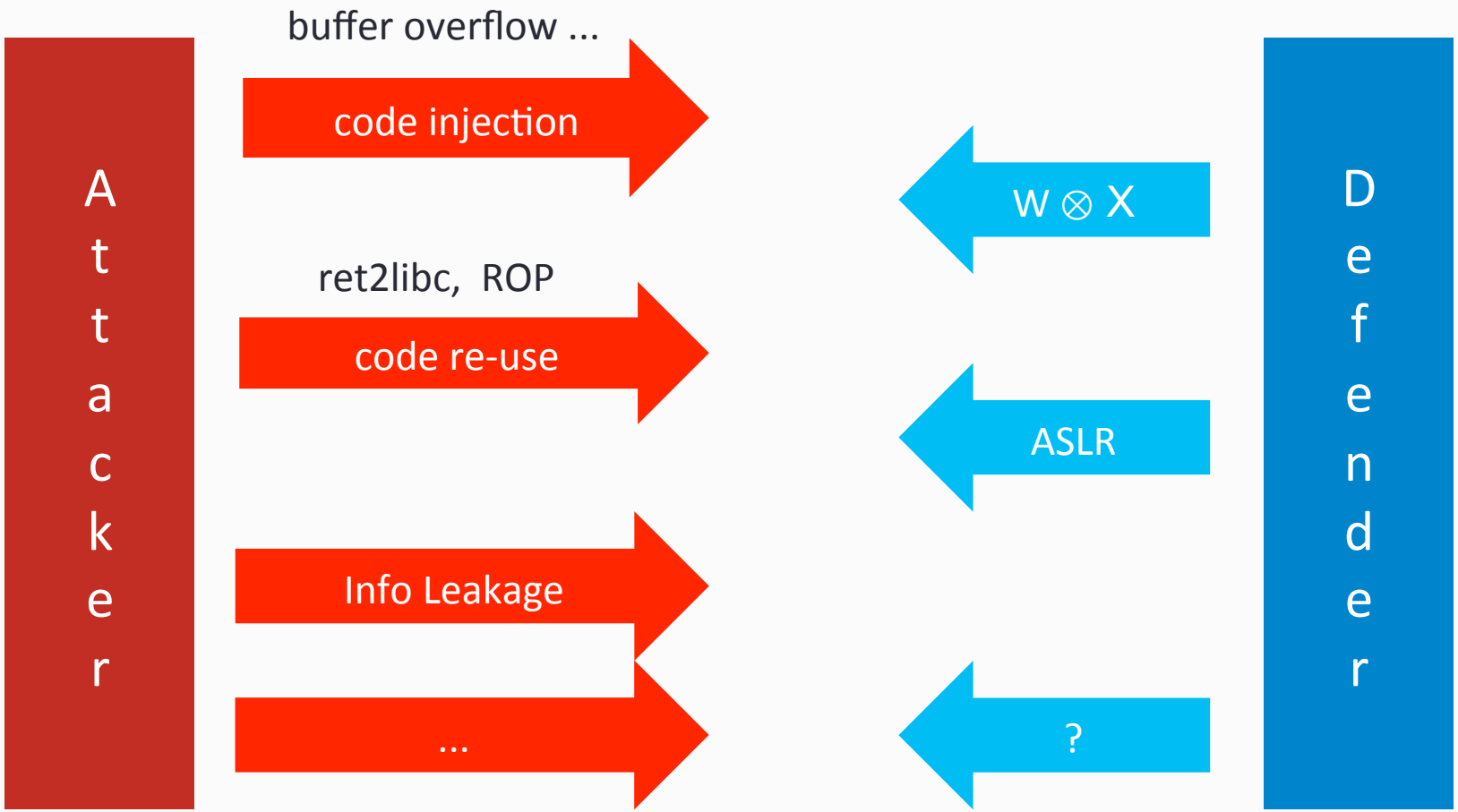
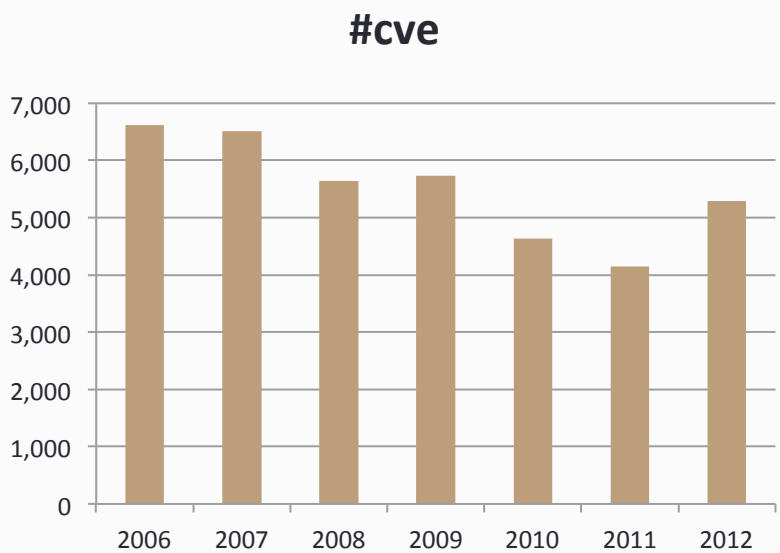
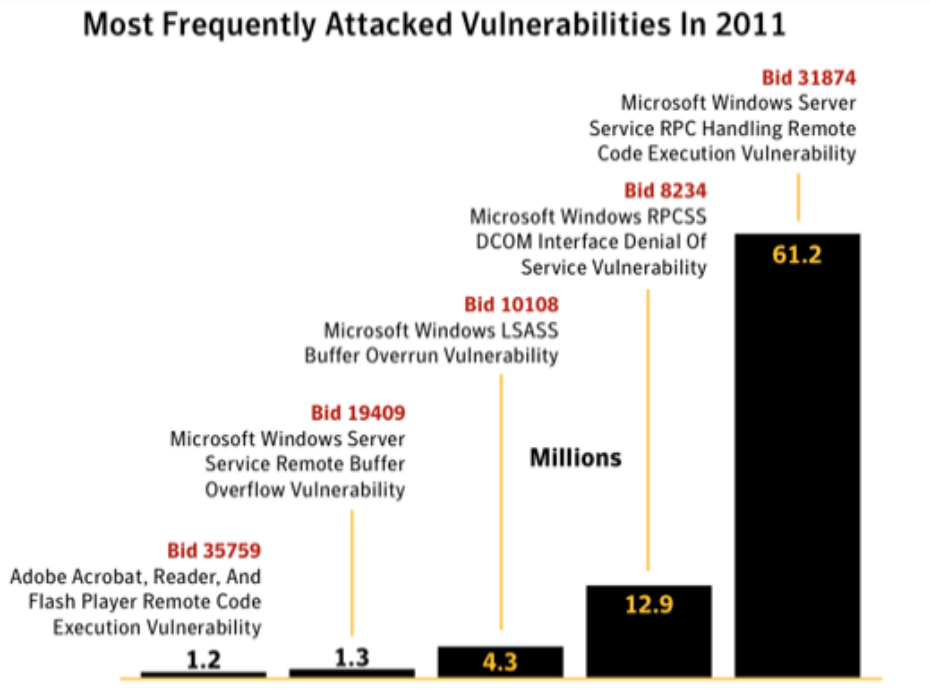
Eternal War in Memory (*Oakland'13*)



Reactive Defense is not adequate

- > 5,000 CVE vulnerabilities each year.
  - Many more are under the iceberg.
- Vulnerabilities are exploited millions of times.





Symantec Internet Security Threat Report

Proactive Defense: Control Flow Integrity

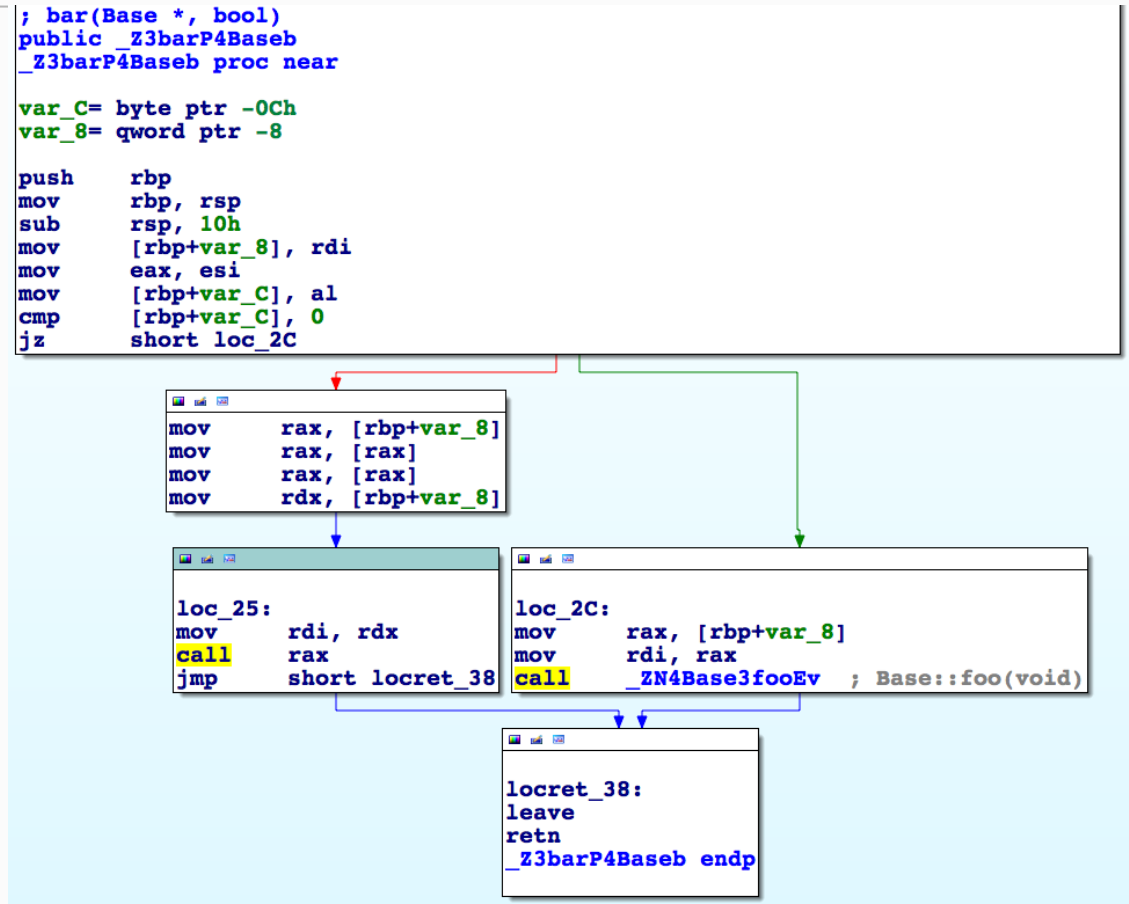
- Control Flow Integrity, CFI [CCS'05]
- Security policy
  - Each run-time control transfer must comply with programmer's compile-time intent, i.e., the control-flow graph
- A strong guarantee that can be reasoned about formally
  - ROP, JOP, UAF
- A foundation for other low-level code defenses
  - SFI, sandboxing untrusted code
- Deterministic, not probabilistic defense

Control-Flow Graph

```
class Base{
public:
        virtual void vfoo();
                void  foo();
};

class Derived: public Base{
public:
        virtual void vfoo();
                void  foo();
};

void bar(Base* b, bool virt)
{
        if(virt)
                b->vfoo();
        else
                b->foo();
}
```

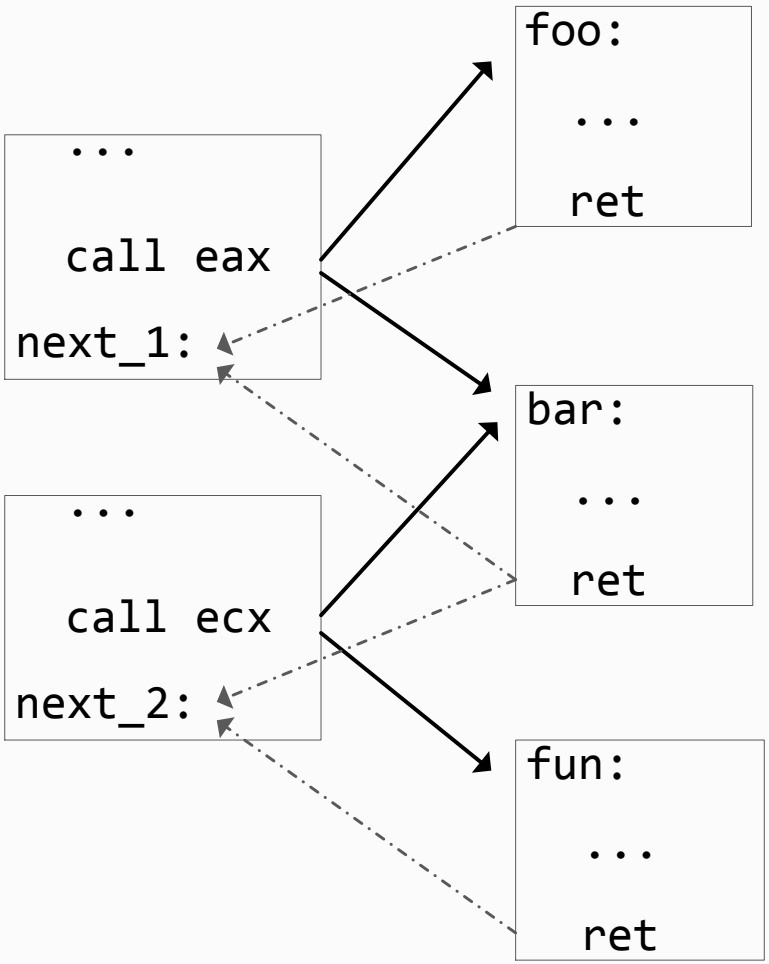


- conditional jump (jz …): target relative address
- direct jump/call: target relative or absolute address
- indirect jump/call: target? (read or computed from memory)
- return: target return address on the stack

Scope of Control-Flow Integrity Protection

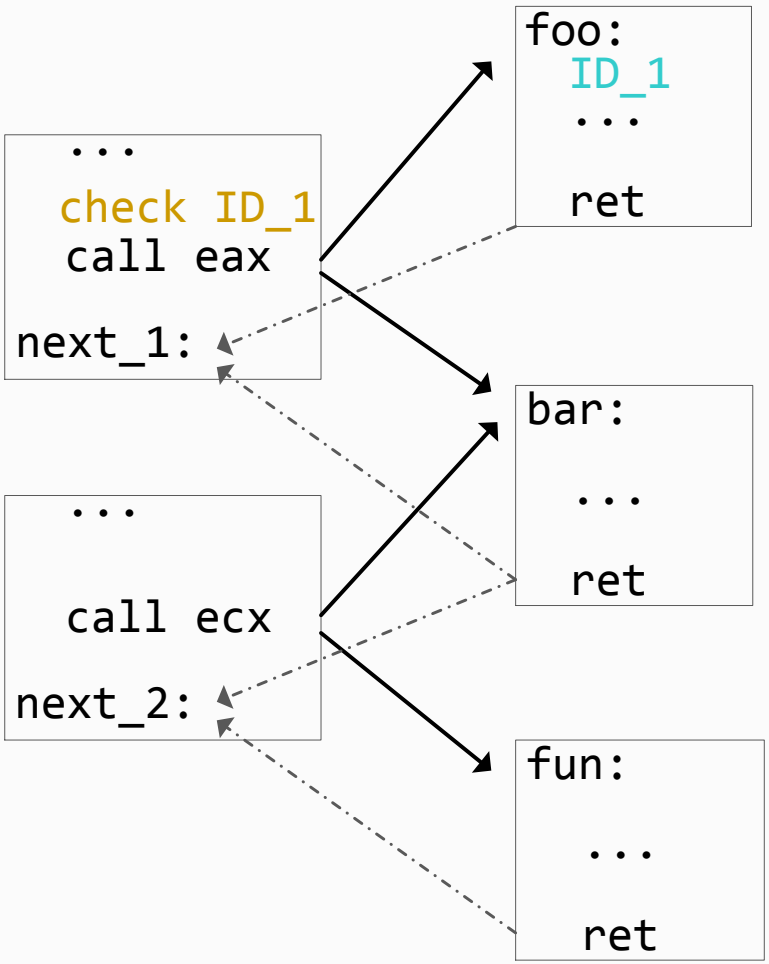
Control Transfer Method	Transfer Targets	Integrity Protection
Exceptions	Exception handlers	SafeSEH, SEHOP
Direct CALL/JMP, Conditional jump (JZ...)	Hard-coded function pointers (embedded in the code)	W⊗X
Indirect CALL/JMP	In-memory function pointers	**CFI**
RET instructions	On-stack return addresses	/GS, shadow stack, **CFI**

Control Flow Integrity (CCS'05)



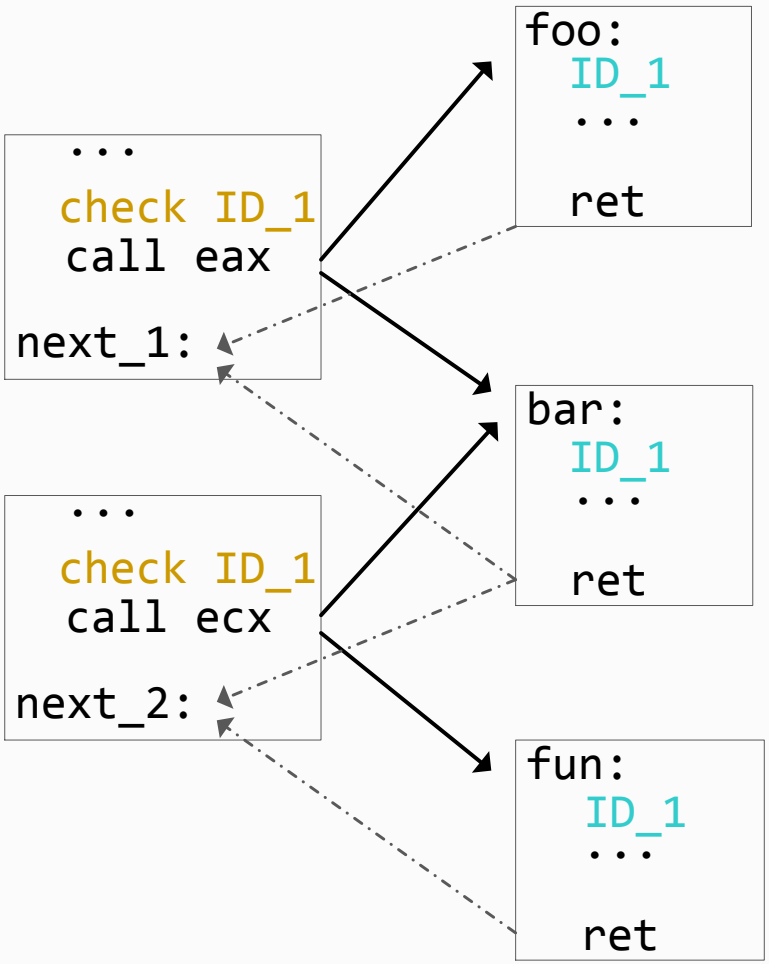
- build Control Flow Graph
  - source code/debug info
  - all modules

Control Flow Integrity (CCS'05)



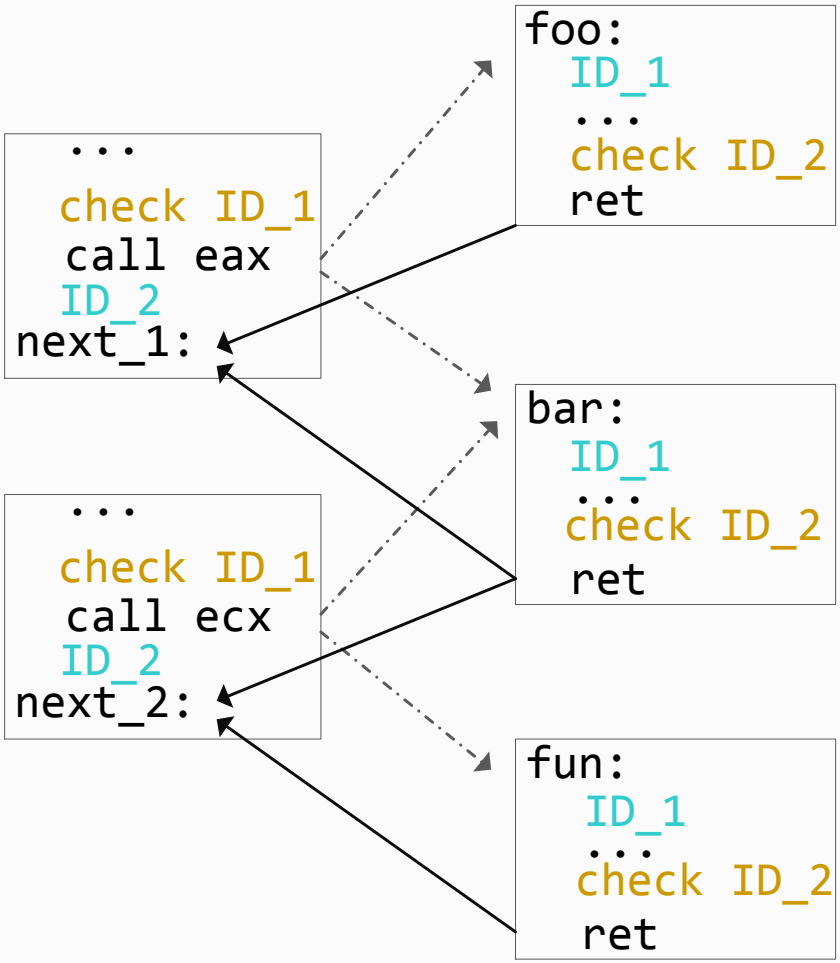
- build Control Flow Graph
- binary rewriting
  - instrument IDs before transfer targets
  - validate IDs before control transferring

Control Flow Integrity (CCS'05)



- build Control Flow Graph
- binary rewriting
- diversity of IDs

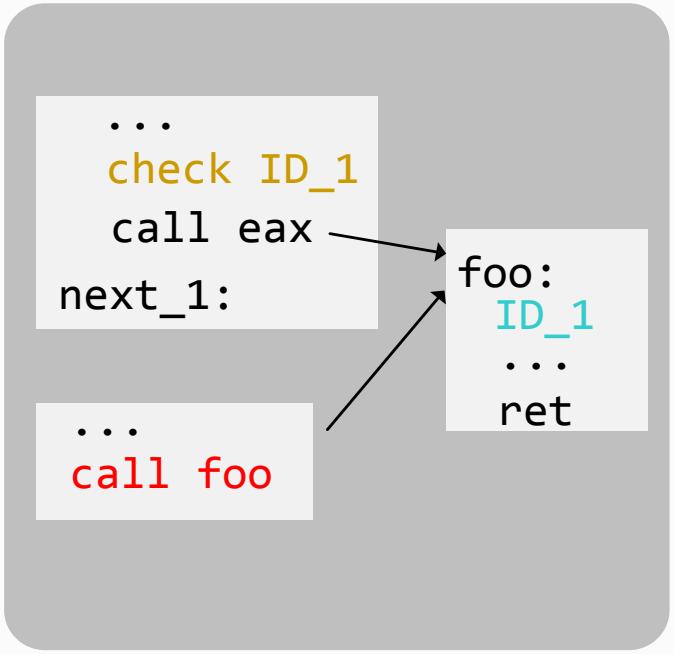
Control Flow Integrity (CCS'05)



- build Control Flow Graph
- binary rewriting
- diversity of IDs
- all indirect transfers
  - indirect call
  - indirect jmp
  - ret

Challenges faced by CFI

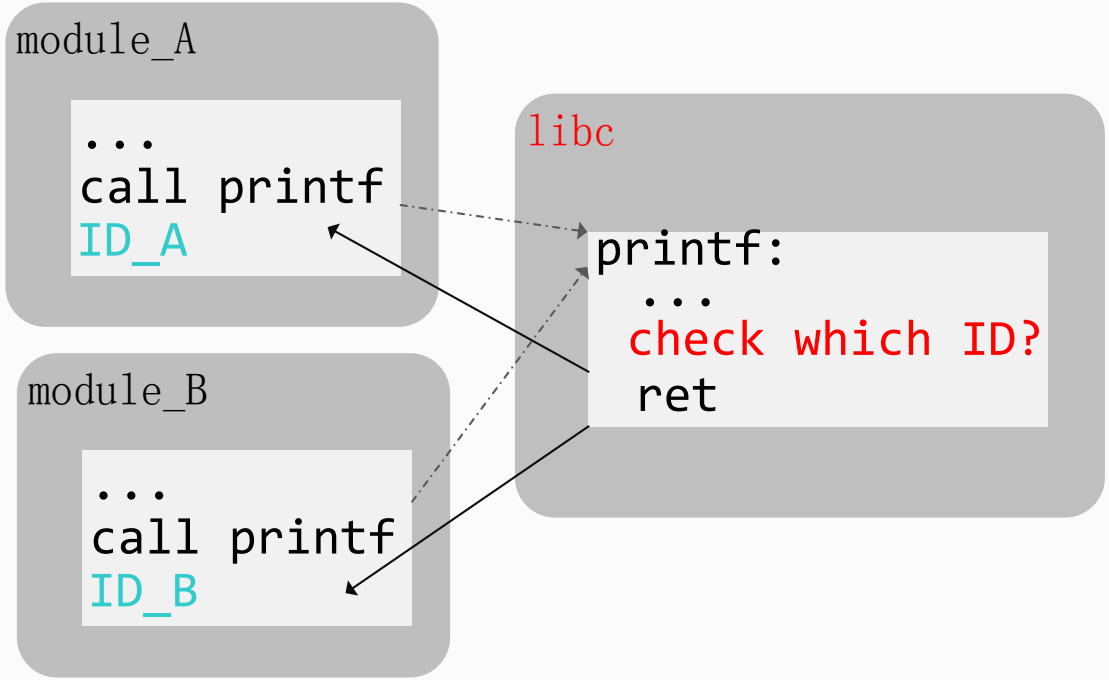
- performance overhead: average 15%, max 46%



- ID is embedded in a slow *prefetchnta* instruction
  - executed each time the transfer target is reached
- introduce overhead even if *foo* is called/jumped to directly
  - ✓ most calls/jumps are direct

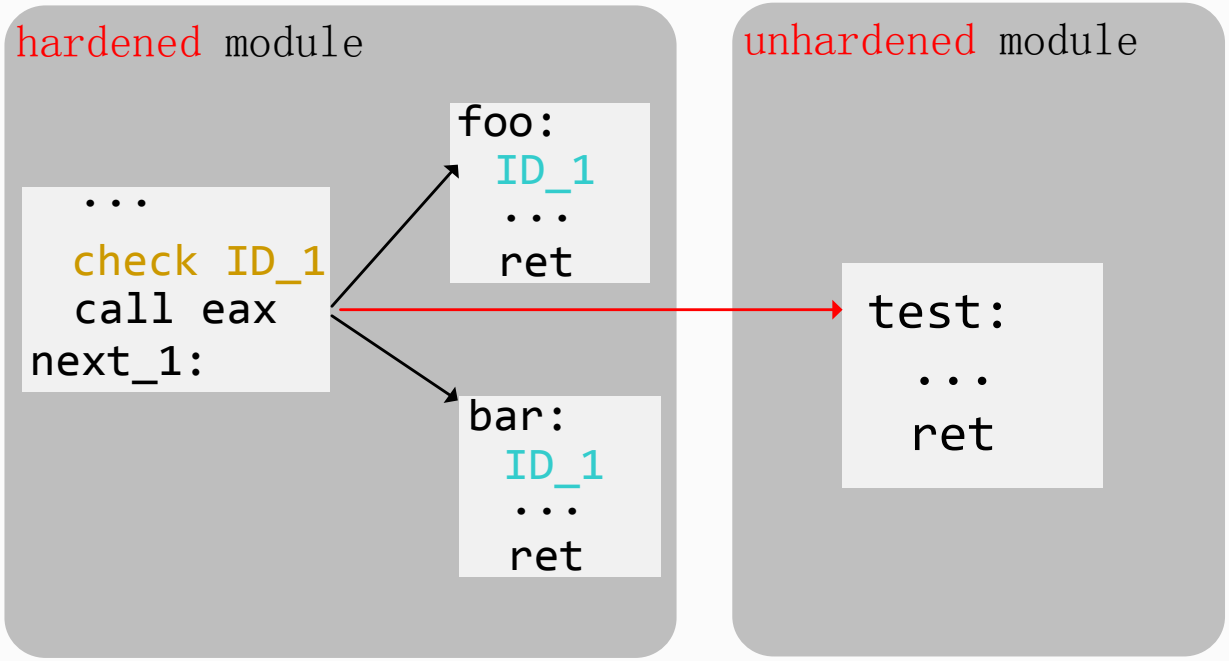
Challenges faced by CFI

- performance overhead
- modularity support
  - A single module cannot be hardened independently



Challenges faced by CFI

- performance overhead
- modularity support
- backward compatibility



Challenges faced by CFI

- performance overhead
- modularity support
- backward compatibility
- source code/debug info dependency
  - to build Control Flow Graph

Motivation

- A light-weight CFI solution with a strong protection
  - performance overhead ✓ ✓ ✓
  - modularity support ✓ ✓ ✓
  - backward compatibility ✓ ✓ ✓
  - source code independent ✓ ✓ ✓

Assumption

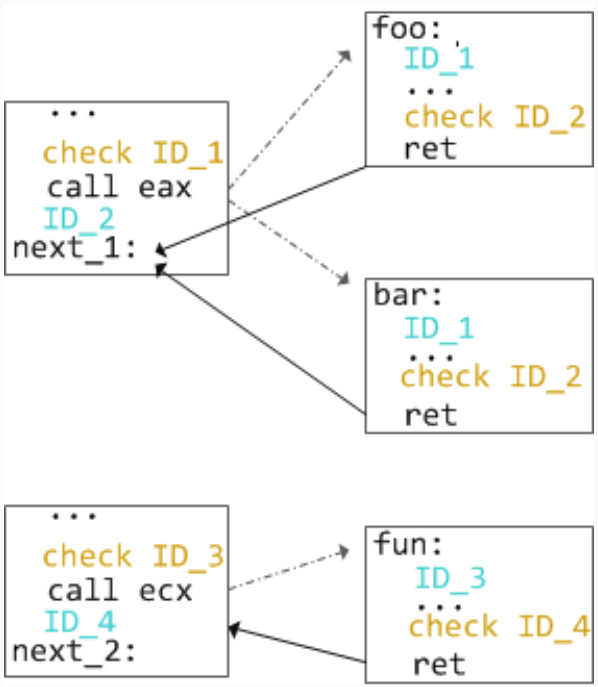
- ASLR and W⊗X (e.g. DEP) are deployed
- NO self-modifying code or dynamically generated code.
- Limited information disclosure vulnerabilities
  - e.g., cannot read entire memory regions

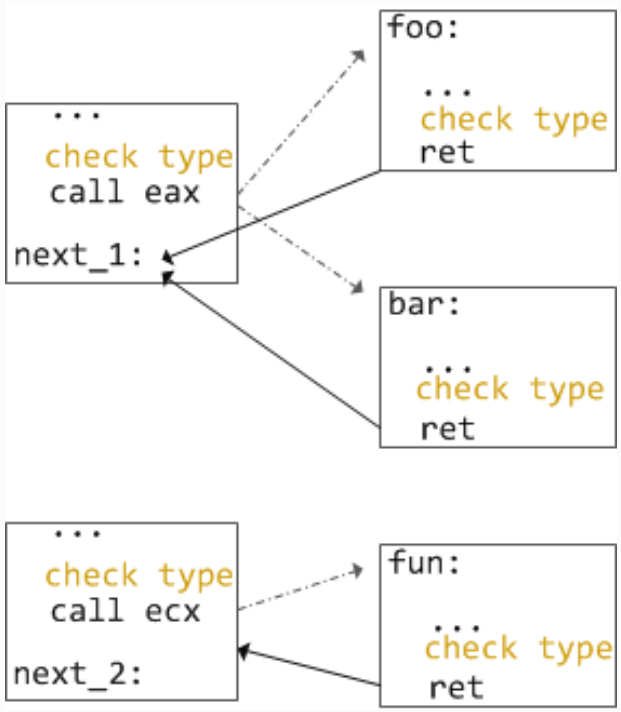
Outline

- Motivation
- Intuition & Design
- Implementation
- Security Enhancement
- Evaluation
- Conclusion

Intuition

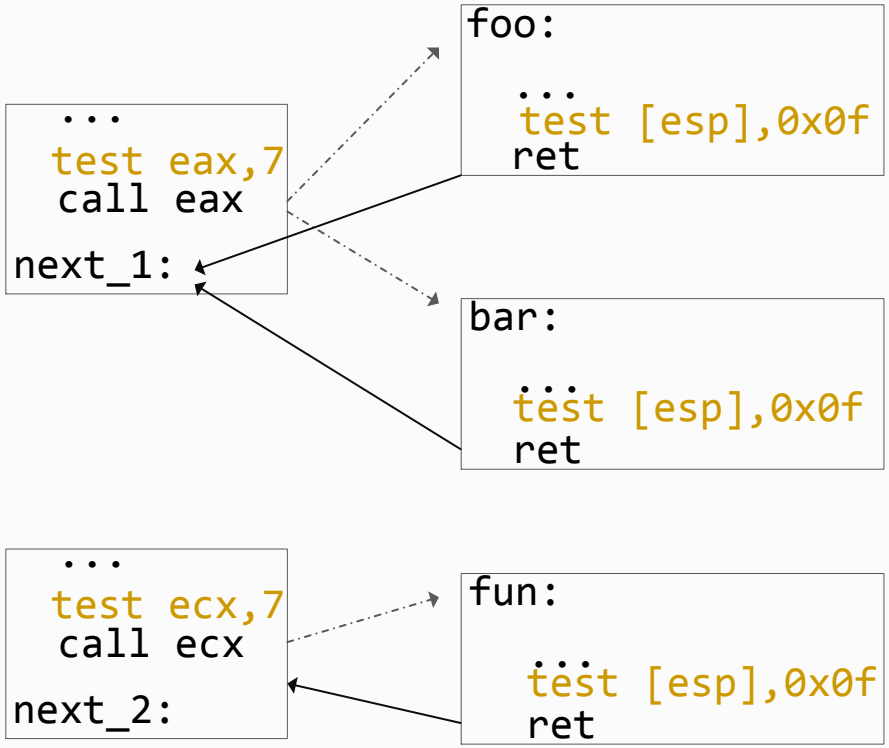
- Checking transfer targets' kind, rather than IDs
  - indirect call/jmp can only transfer to function-pointer stubs
  - returns can only transfer to return-address stubs





Intuition: efficient check

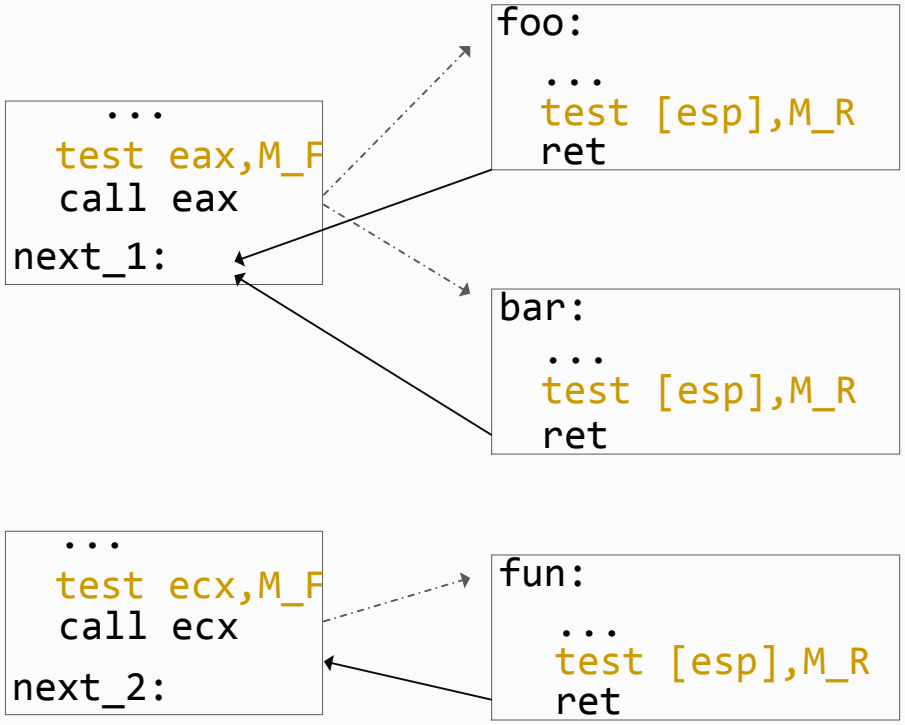
- memory alignment
  - function pointer stubs are 8-bytes aligned
  - return address stubs are 16-bytes aligned



- fast bit testing
  - performance overhead ✓
- No IDs
  - performance overhead ✓ ✓
- only check type
  - modularity support ✓ ✓ ✓

Intuition: security

- Transfer targets must be within memory region Springboard
  - 27th bit is 0



M_F = 0x8000007

M_R = 0x800000f

- Policy: all indirect transfer targets must be aligned stubs in Springboard.

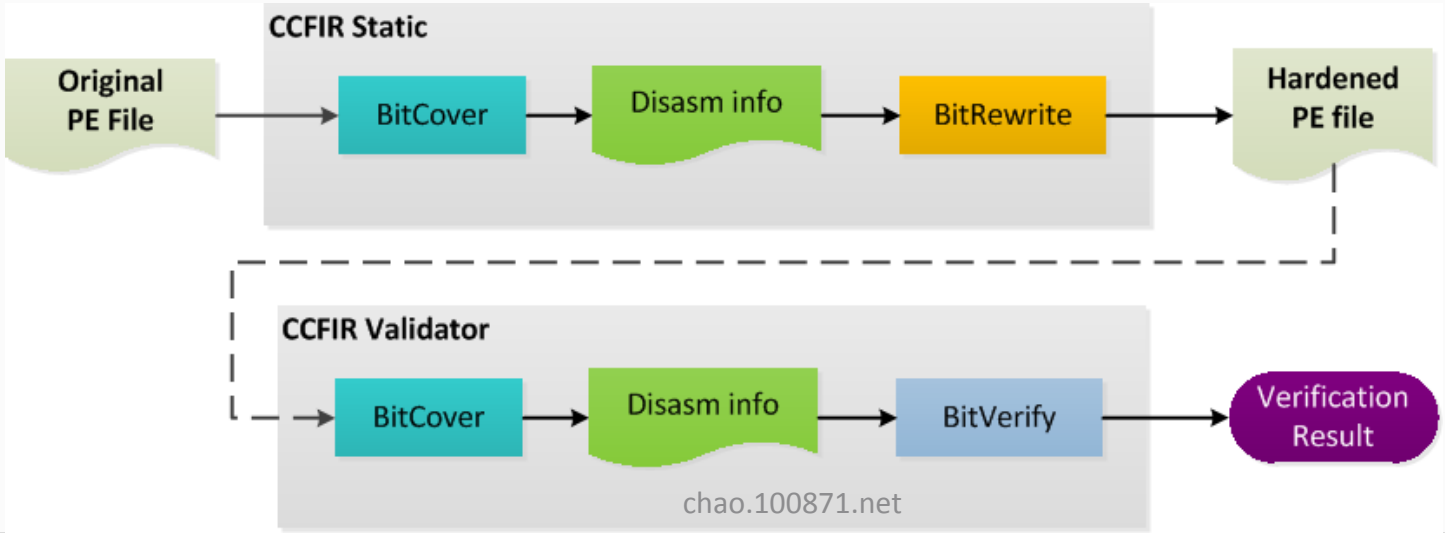
Design: Memory layout with Springboard

Executable ?	Bits				Meaning
	27	26	3	2-0	
No	*	*	*	***	Non-executable section
Yes	1	*	*	***	Normal code section
Yes	0	*	*	!000	Invalid entry in Springboard
Yes	0	*	1	000	fp-stub entry in Springboard
Yes	0	1	0	000	Sensitive ret-stub entry in Springboard
Yes	0	0	0	000	Normal ret-stub entry in Springboard

- Springboard vs. normal code section (27th bit)
- Entries in the Springboard are all aligned. (0-2 bits)
- Three kinds of stubs in Springboard
  - fp-stub entries vs. ret-stub entries (3rd bit)
  - sensitive vs. normal ret-stub (26th bit)
    - normal ret-stubs cannot return into the middle of sensitive functions
- One or two fast bit testing instructions are sufficient

Architecture of our solution: CCFIR

- Find out all indirect transfer instructions and their targets
  - BitCover: disassemble target binary
- Redirect transfer targets to aligned stubs in Springboard
- Validate transfer targets
  - BitRewrite: binary rewriting
- Verify the hardened binary
  - BitVerify



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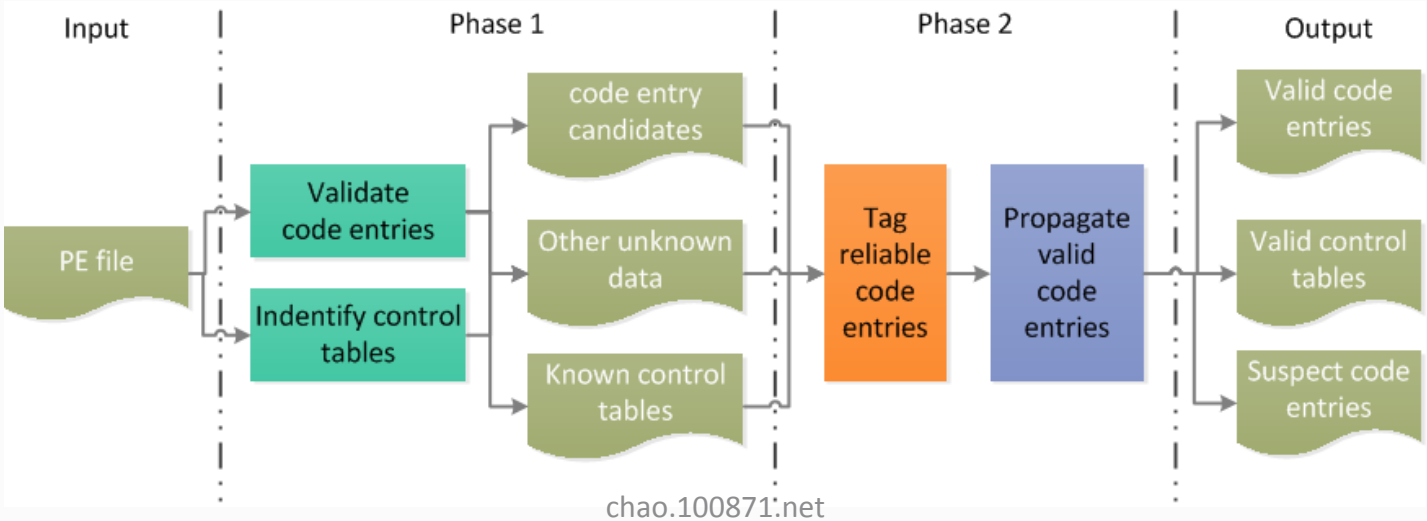
BitCover: disassembling

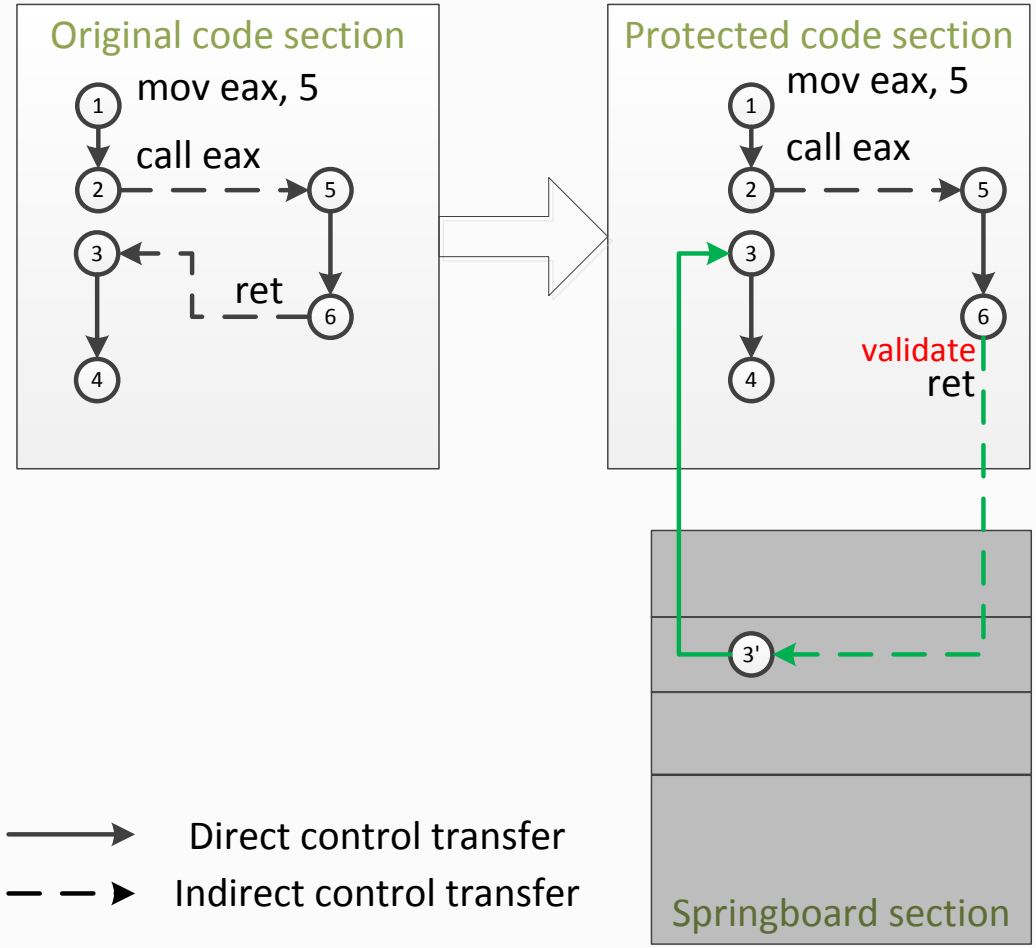
- performance overhead ✓ ✓
- modularity support ✓ ✓ ✓
- backward compatibility
- source code independent ✓ ✓ ✓

- Target: ***normal*** binaries generated by modern compilers
  - Support ASLR
    - On Windows, it implies the executable contains relocation information
    - We can identify all legal function pointers (indirect call/jmps' targets)
- Automatically disassemble most of ***normal*** binaries
  - Based on well-defined rules
  - More accurate than IDA Pro, especially designed for binary rewriting



BitRewrite: binary rewriting

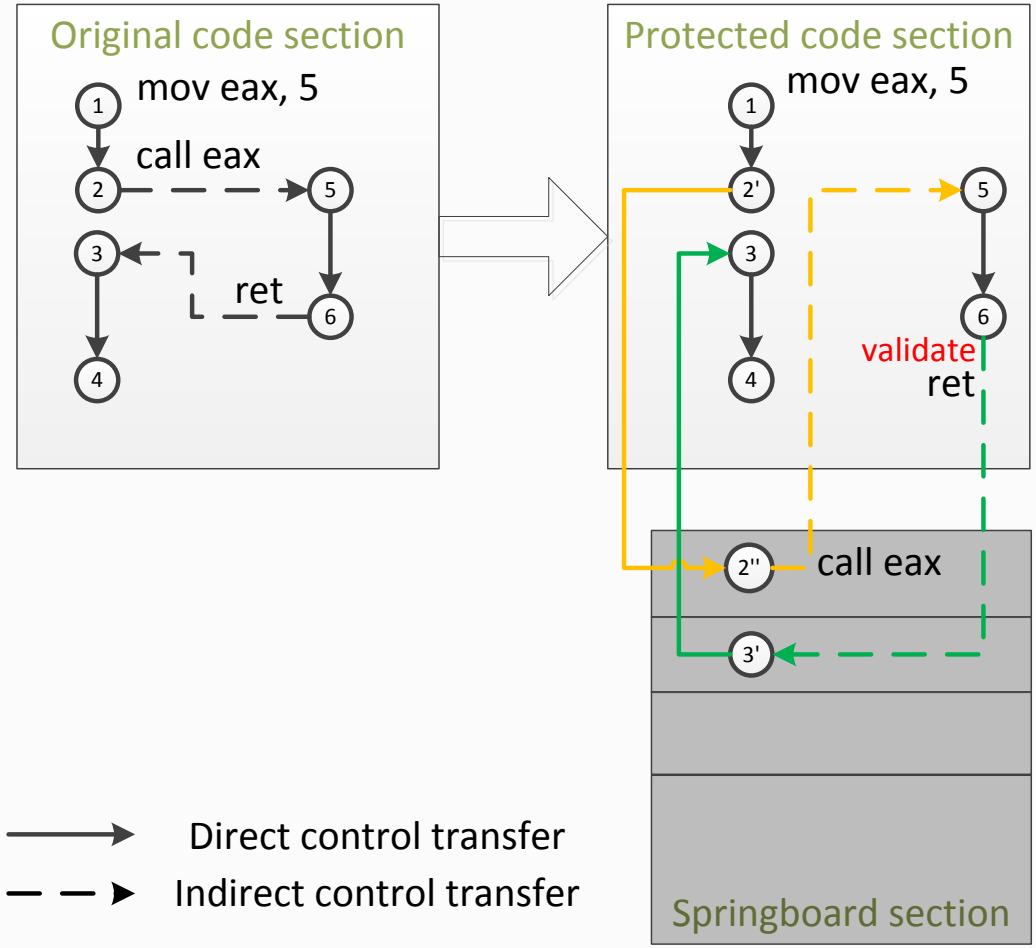
- Policy: all indirect transfers are enforced to aligned stubs in Springboard.



- Validate ret's target.
  - ret-stub in Springboard

BitRewrite: binary rewriting

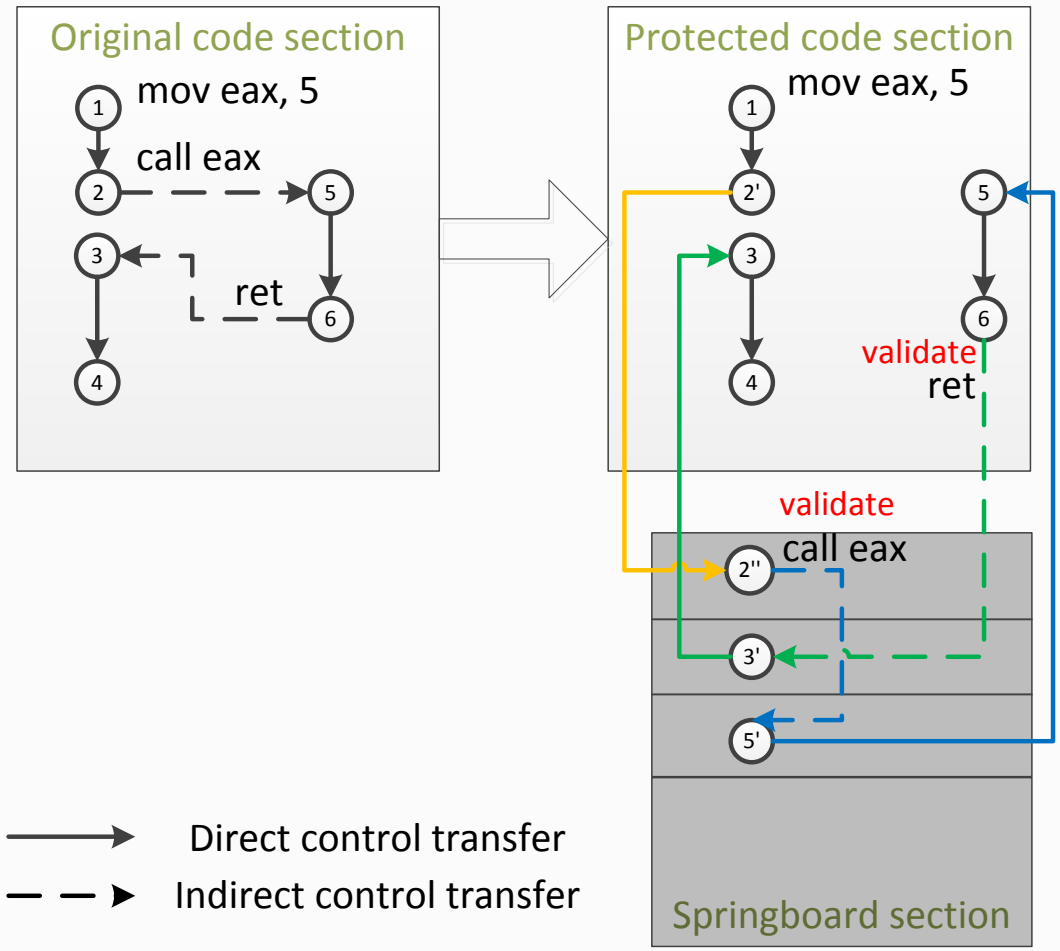
- Policy: all indirect transfers are enforced to aligned stubs in Springboard.



- Validate ret's target.
  - ret-stub in Springboard
- Redirect ret's target.
  - move call to Springboard

BitRewrite: binary rewriting

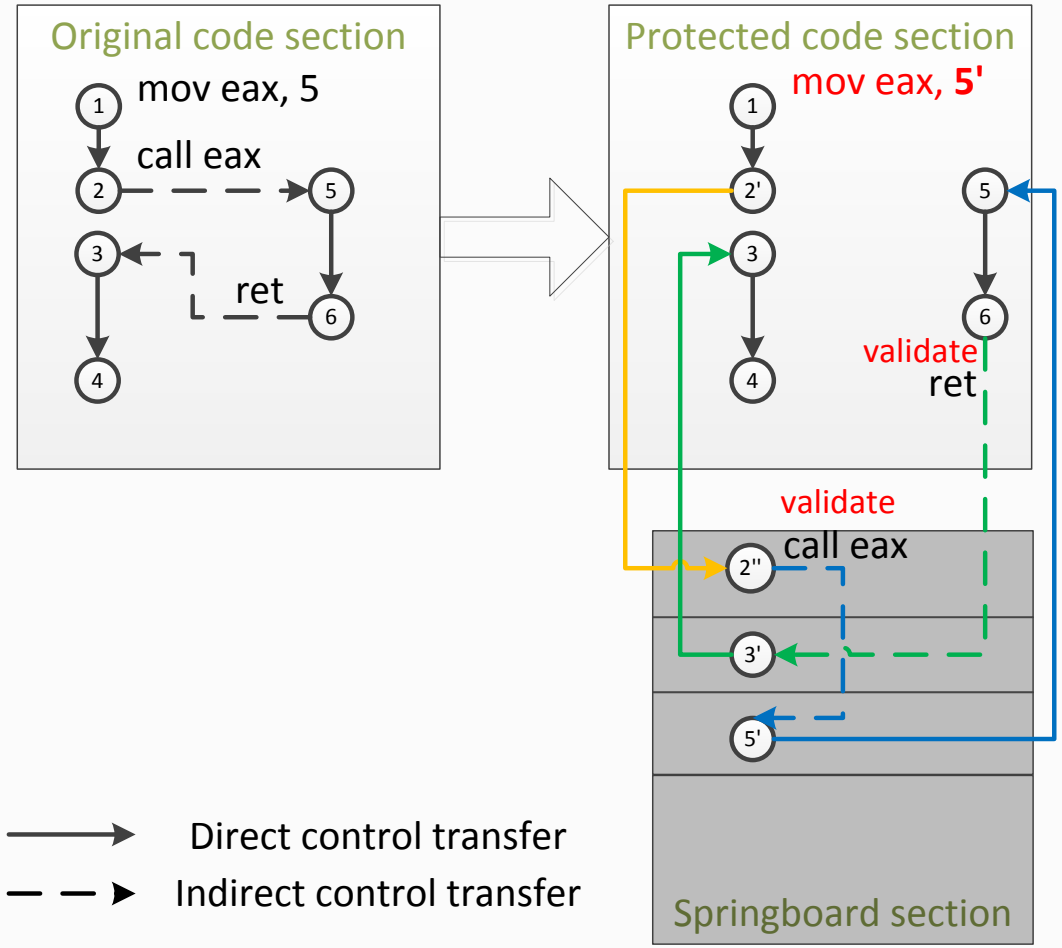
- Policy: all indirect transfers are enforced to aligned stubs in Springboard.



- Validate ret's target.
  - ret-stub in Springboard
- Redirect ret's target.
  - move call to Springboard
- Validate call's target.
  - fp-stub in Springboard

BitRewrite: binary rewriting

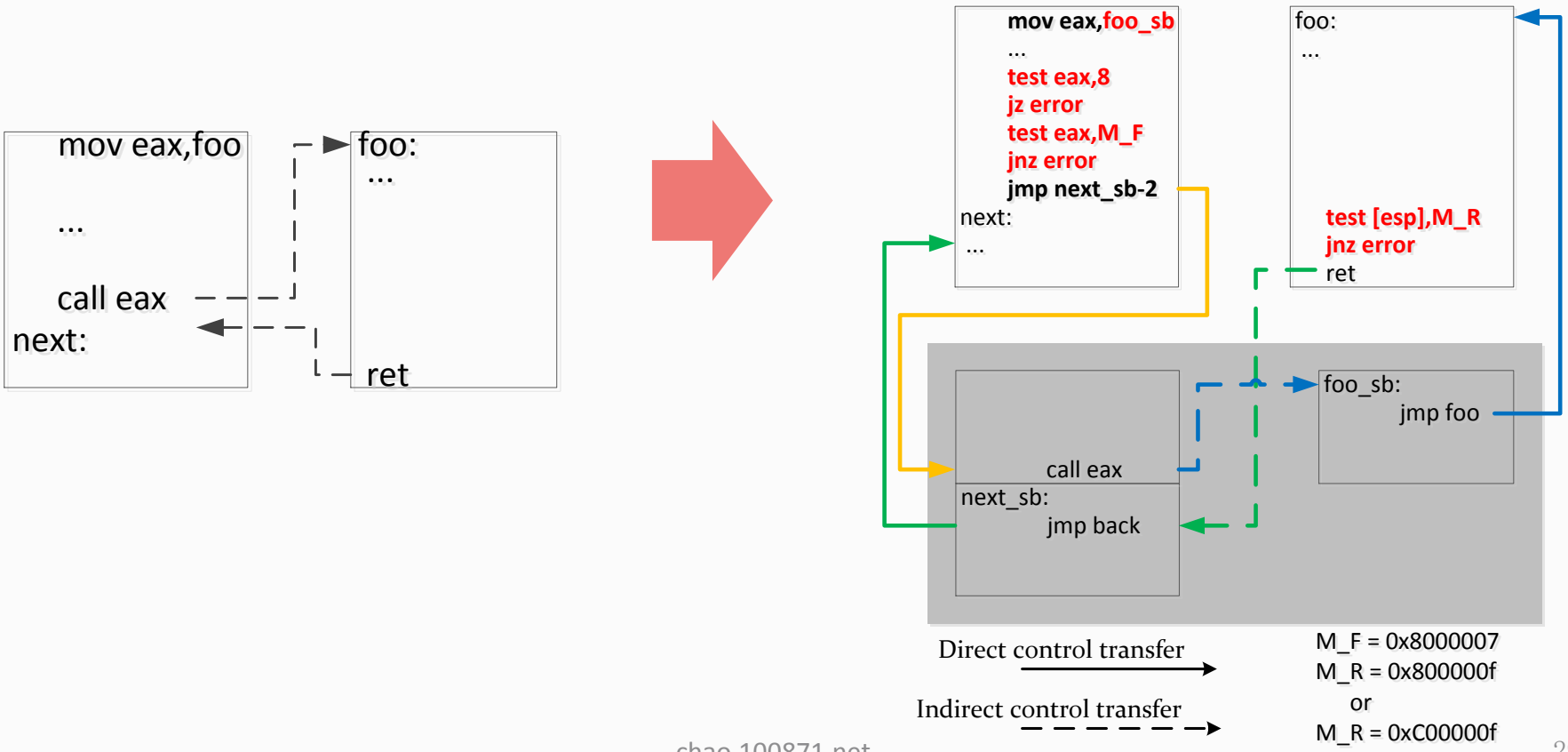
- Policy: all indirect transfers are enforced to aligned stubs in Springboard.



- Validate ret's target.
  - ret-stub in Springboard
- Redirect ret's target.
  - move call to Springboard
- Validate call's target.
  - fp-stub in Springboard
- Redirect call's target.
  - rewrite function pointers

BitRewrite: In a nutshell

- redirect function pointers and return addresses
  - rewrite function pointers in memory
  - move call instructions to springboard
- validate transfer targets with bit testing instructions



BitRewrite: Optimizations

- performance overhead ✓ ✓ ✓
- modularity support ✓ ✓ ✓
- backward compatibility
- source code independent ✓ ✓ ✓

- With the support of W⊗X, we can skip redirecting or validating
  - directly used function pointers
    - call foo
  - directly used imported functions
    - call [imp_foo]
  - switch statements and jump table
    - jmp jump_table[eax*4]

BitRewrite: backward compatibility

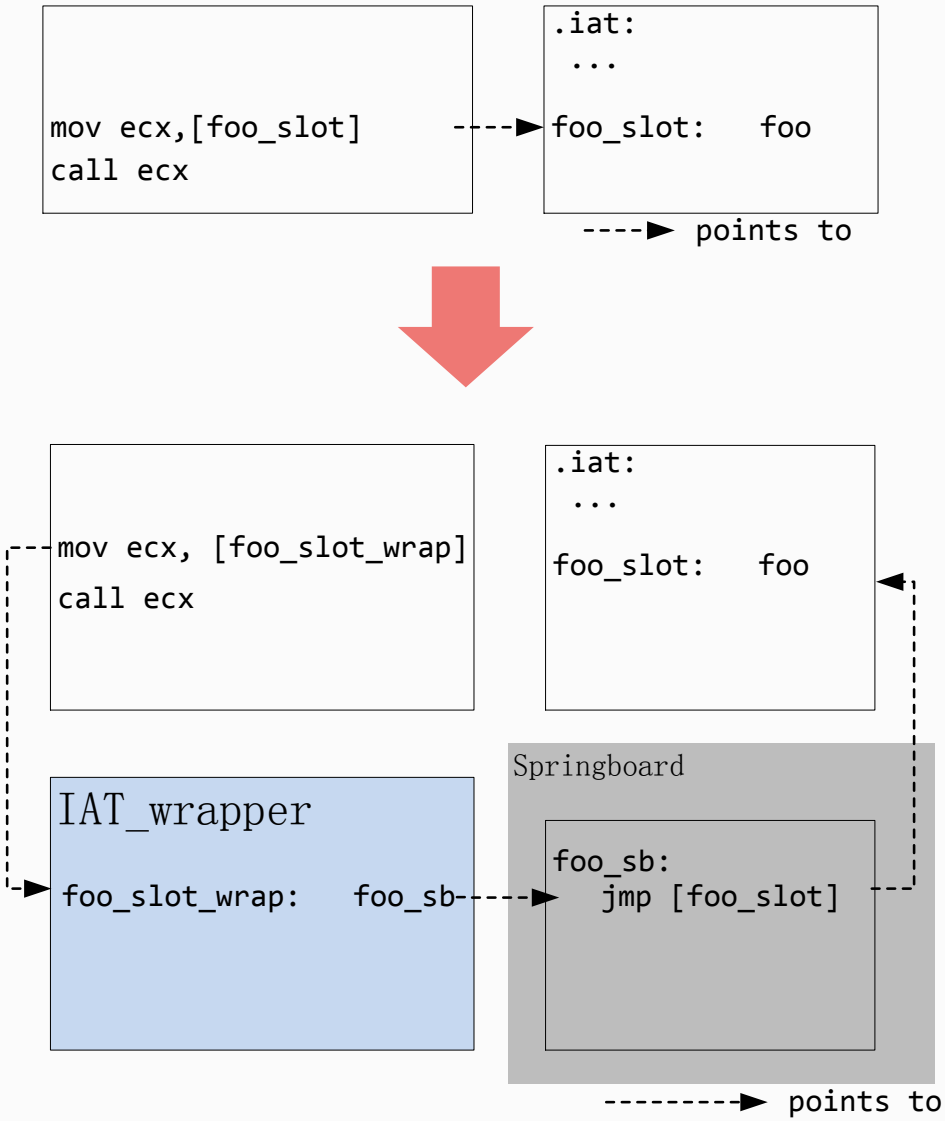
- performance overhead ✓ ✓ ✓
- modularity support ✓ ✓ ✓
- backward compatibility ✓ ✓ ✓
- source code independent ✓ ✓ ✓

- With a full deployment (i.e., all modules hardened),
  - backward compatibility issues no longer existed.

- With incremental deployment, such issues occur when
  - CALL/JMP to functions in unhardened modules
  - RET to return addresses in unhardened modules

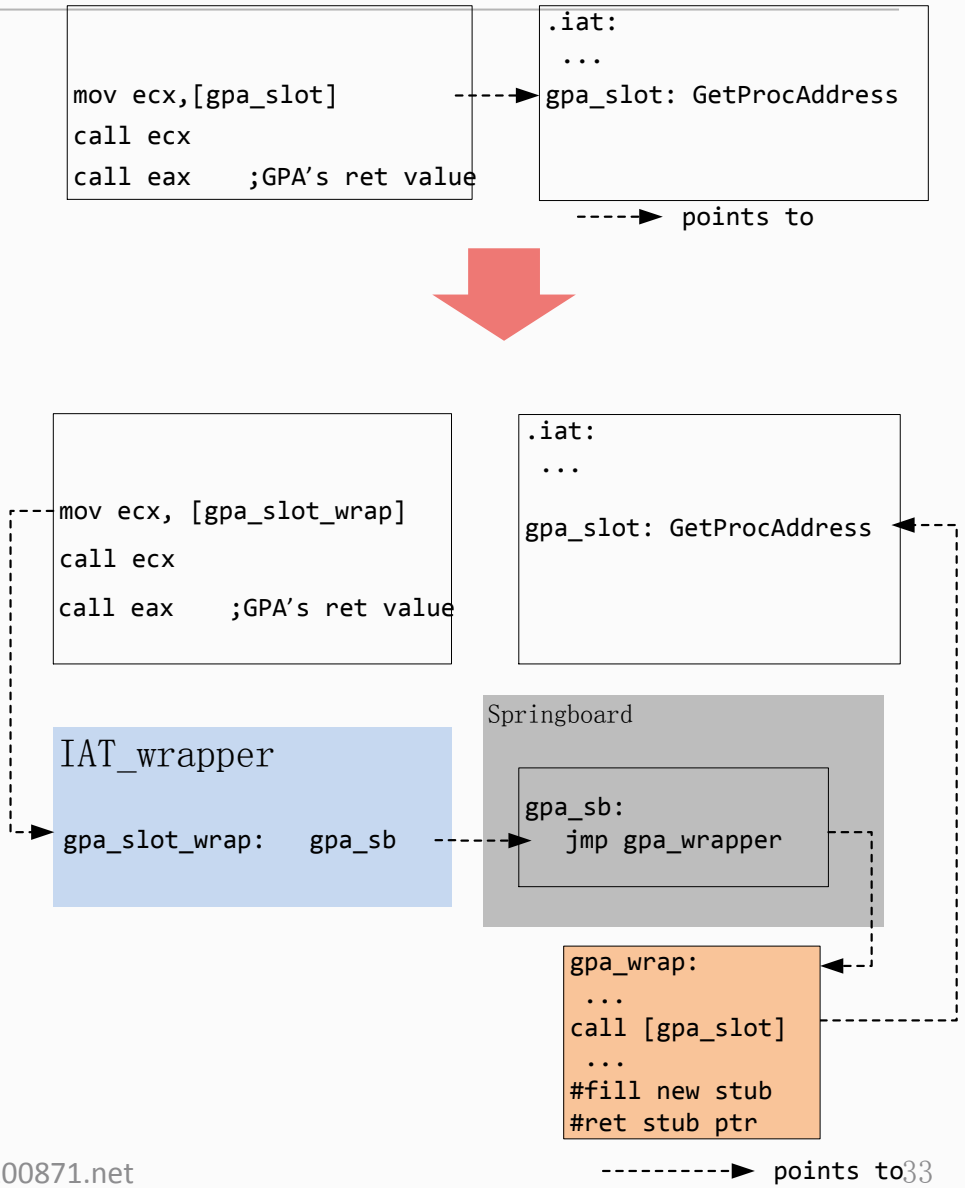
case 1: Imported functions

- Challenge
  - Import Address Table (IAT)
  - load-time resolving
    - the loader will update IAT
    - we cannot statically rewrite IAT entries (function pointers)
- Solution
  - Replace IAT with a wrapper table



case 2: Functions resolved by GetProcAddress

- Challenge
  - GetProcAddress() returns a non-redirected function pointer.
  - The instrumented security check will fail
- Solution
  - wrapper for GetProcAddress
  - redirect return value at runtime



BitVerify: Offline Verification

- whether a given binary conforms to security rules?
  - 27th bit of executable section except Springboard should be 1
  - Code stubs in Springboard are all aligned
  - Function pointers are redirected
  - Call instruction has been redirected
  - Check code has been correctly inserted
  - ...

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Policy 1: Restrain sensitive functions

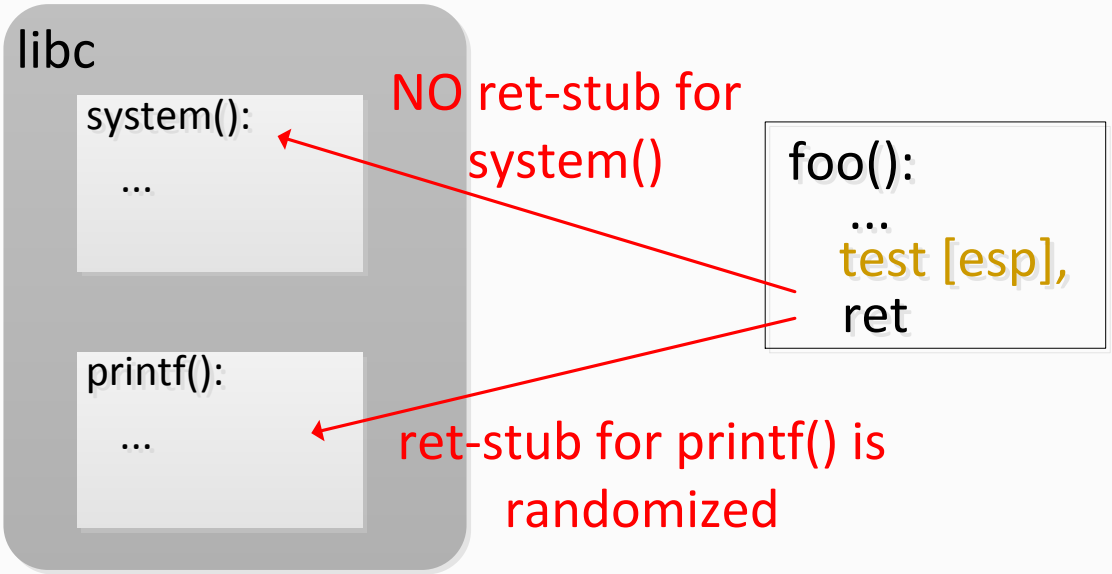
- Sensitive functions
  - system(), execv(), VirtualProtect(), VirtualAlloc(), ...
- Policy:
  - Sensitive functions should be used via direct calls.
    - i.e., their addresses are never taken except hard−coded in instructions
- Benefit:
  - NO fp-stubs for sensitive functions in the Springboard
  - Attackers cannot indirectly call/jump to these functions.

Policy 2: Load-time Randomization

- Policy:
  - The order of all stubs in the Springboard are randomized at load-time.
- Benefit:
  - cannot guess one stub's address even if another address is leaked in the Springboard.
  - A stronger randomization than ASLR.
- It provides an extra layer of protection from the previous CFI-style checking.

Brief Security Analysis

- return-to-libc



(info leakage is needed)

- jump-to-libc
  - similar to return-to-libc
  - gadgets must start from fp-stubs in the Springboard
- ROP
  - Valid gadgets must start from ret-stubs in the Springboard
  - Few valid ROP gadgets
    - much longer, hard to chain.

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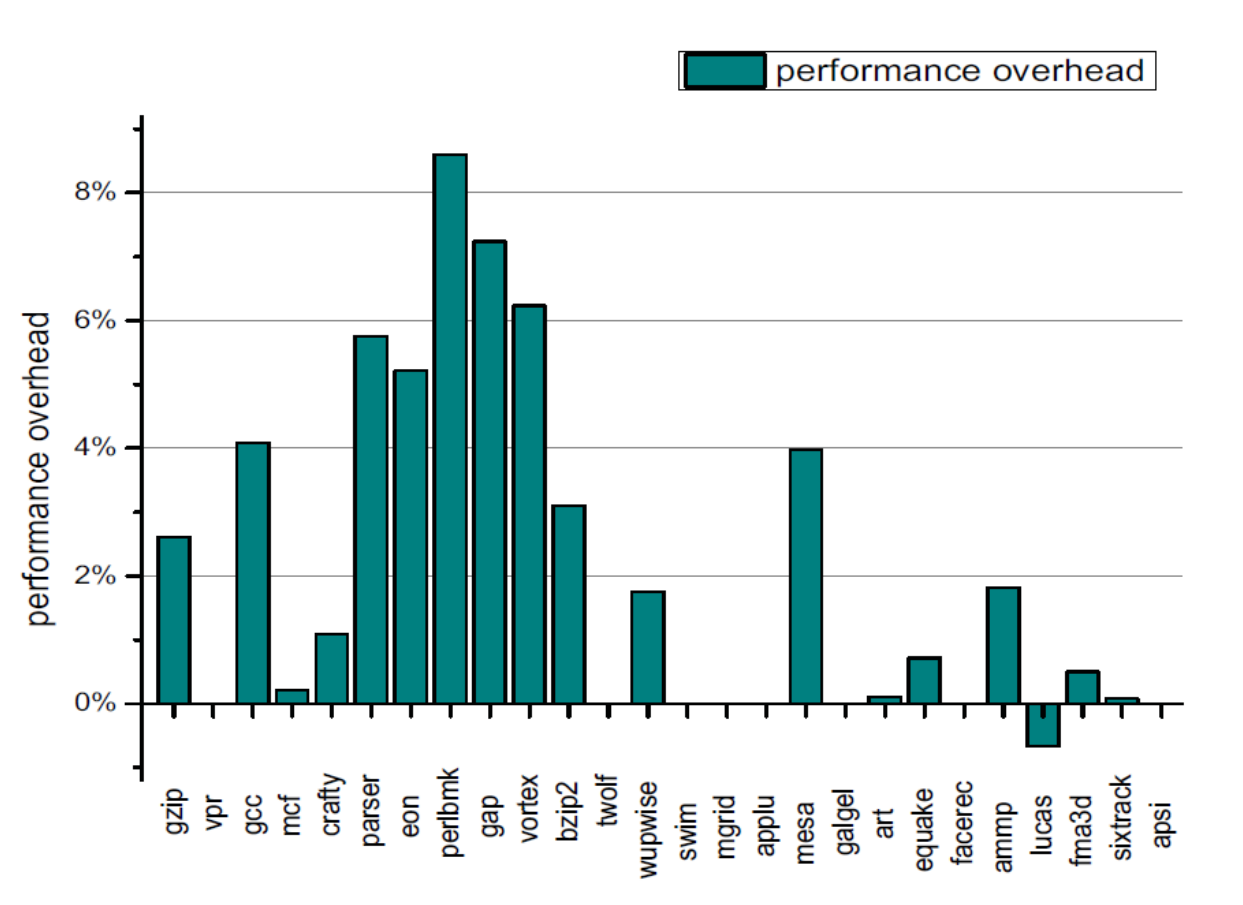
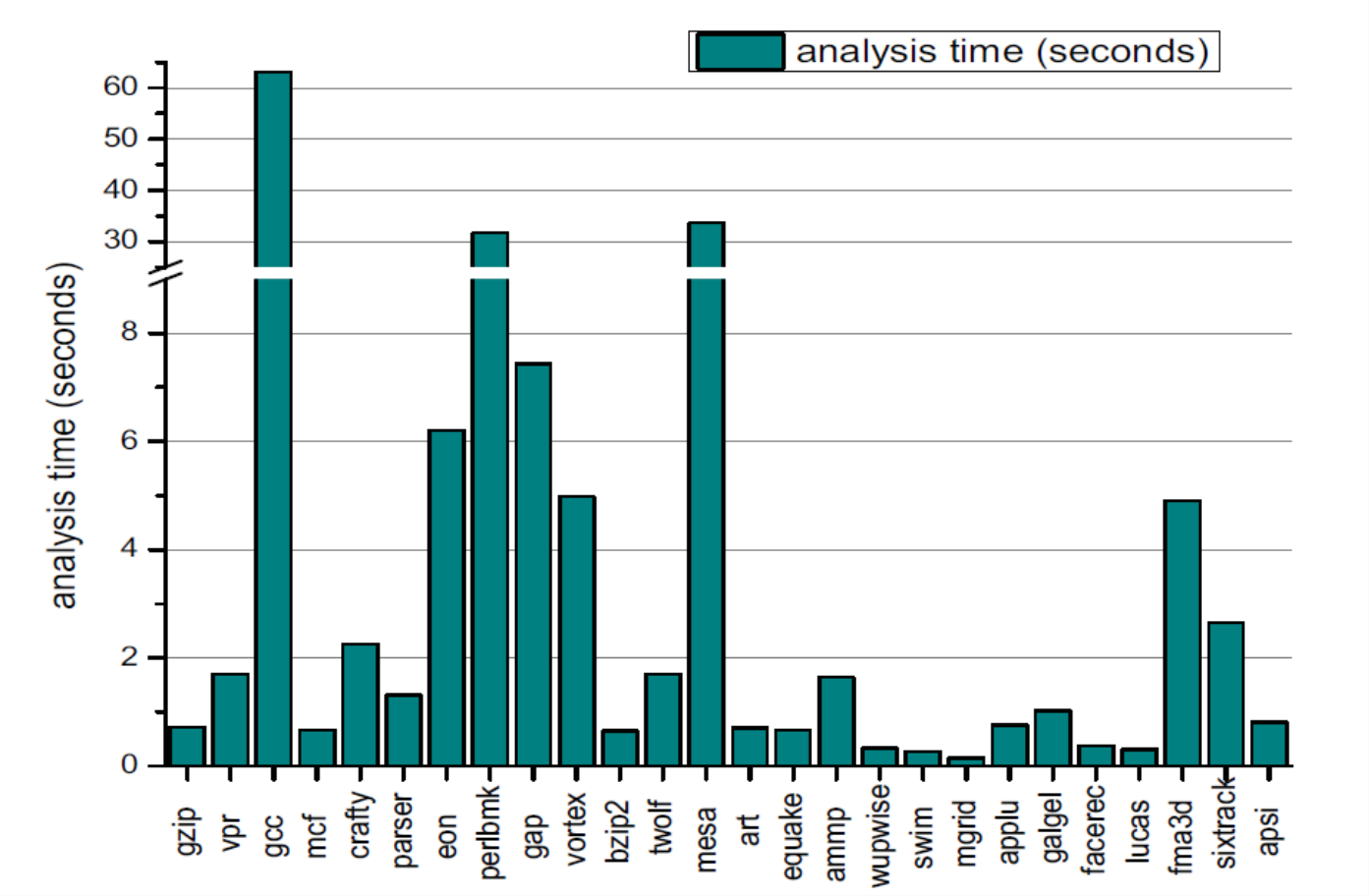
Runtime Overhead

- SPECint2000, average 3.6%, max 8.6%
- SPECfp2000, average 0.59%, max 3.98%



Static Analysis Time

- SPECint2000 & SPECfp2000, 10s seconds



ROP Elimination

- Mona is used to count ROP gadgets
- Valid gadgets must start from ret-stubs in Springboard

SPECfp2000 App	original #gadgets	new #gadgets	valid #gadgets
wupwise	255	0	0
swim	116	134	0
mgrid	161	166	0
applu	182	172	0
mesa	21696	0	0
galgel	1515	952	0
art	1874	0	0
equake	1710	0	0
facerec	826	775	0

ROP gadgets count (part)

Real World Exploits Protection

ID	App	Vul Type	Vul Module	Protected
CVE-2011-0065	**FF 3**	Use After Free	xul.dll	yes
CVE-2010-0249	**IE 6**	Use After Free	mshtml.dll	yes
CVE-2010-3962	**IE 6**	Use After Free	mshtml.dll	yes
CVE-2011-1260	**IE 6**	Mem. Corrupt	mshtml.dll	yes
CVE-2005-1790	**IE 6**	Mem. Corrupt	mshtml.dll	yes
CVE-2008-0348	coolplayer	Stack Overflow	core exe	yes
CVE-2010-5081	RM-MP3	Stack Overflow	core exe	yes
OSVDB-83362	urlhunter	Stack Overflow	core exe	yes
CVE-2007-1195	XM ftp	Format String	core exe	yes
OSVDB-82798	ComSndFTP	Format String	core exe	yes

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Conclusion

- Performance and compatibility issues limit the adoption of Control Flow Integrity.
- CCFIR is a lightweight CFI solution providing a strong guarantee, can block control-flow hijacks like ROP and ret2libc.
- CCFIR overcomes the performance and compatibility issues, and make it a practical solution.

Thanks!