Parallax: Implicit Code Integrity Verification Using Return-Oriented Programming

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Introduction

Code Integrity Self-Verification on a Hostile Host

- Delay tampering/reversing of software by verifying code integrity
- Application-level: No hardware/kernel support or verification servers
- Prevent malware reversing, cracking, protect critical systems, . . .

Introduction

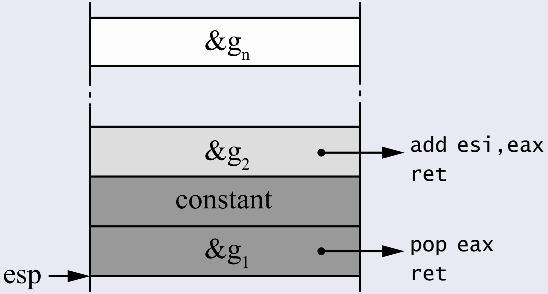
Code Integrity Self-Verification on a Hostile Host

- Existing work uses checksums → broken by Würster et al.
- Oblivious Hashing works, but checks only deterministic program states
- *Parallax* verifies deterministic and non-deterministic paths

Introduction

Return-Oriented Programming

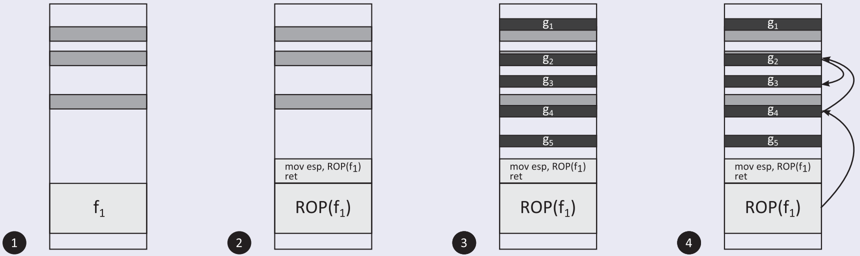
- *Parallax* is based on Return-Oriented Programming (ROP)
- Originally used in exploits to circumvent W⊕X
- Craft ROP programs on stack by chaining returns to *gadgets*



Parallax Overview

Protecting Code

- *Parallax* intentionally creates gadgets to overlap with *protected code*
- One or more code regions are translated into ROP *verification code*
- Verification code uses the gadgets in the protected code
- Tampering breaks gadgets → verification fails, implicit detection
- Gadgets can be "unaligned" relative to original instruction stream!
- *Parallax* can be implemented entirely at the binary level



Parallax Example

Ptrace detector

```
n+38 <cleanup_and_exit>:
n+38: 55                       push ebp
n+39: 89 e5                    mov  ebp,esp
n+3b: 83 ec 18                 sub  esp,24
n+3e: 89 04 24                 mov  [esp],eax
n+41: e8 d5 fe ff ff           call exit@plt

n+46 <check_ptrace>:
n+46: 55                       push ebp
n+47: 89 e5                    mov  ebp,esp
n+49: 83 ec 18                 sub  esp,24
n+4c: c7 44 24 0c 00 00 00 00  mov  [esp+0xc],0
n+54: c7 44 24 08 00 00 00 00  mov  [esp+0x8],0
n+5c: c7 44 24 04 00 00 00 00  mov  [esp+0x4],0
n+64: c7 04 24 00 00 00 00     mov  [esp],0
n+6b: e8 cb fe ff ff           call ptrace@plt
n+70: 85 c0                    test eax,eax
n+72: 79 07                    jns  n+7b
n+74: b8 01 00 00 00           mov  eax,1
n+79: eb bd                    jmp  n+38
n+7b: b8 00 00 00 00           mov  eax,0
n+80: c9                       leave
n+81: c3                       ret
```

Parallax Example

Ptrace detector

```
n+38 <cleanup_and_exit>:
n+38: 55                          push ebp
n+39: 89 e5                       mov  ebp,esp
n+3b: 83 ec 18                    sub  esp,24
n+3e: 89 04 24                    mov  [esp],eax
n+41: e8 d5 fe ff ff              call exit@plt

n+46 <check_ptrace>:
n+46: 55                          push ebp
n+47: 89 e5                       mov  ebp,esp
n+49: 83 ec 18                    sub  esp,24
n+4c: c7 44 24 0c 00 00 00 00     mov  [esp+0xc],0
n+54: c7 44 24 08 00 00 00 00     mov  [esp+0x8],0
n+5c: c7 44 24 04 00 00 00 00     mov  [esp+0x4],0
n+64: c7 04 24 00 00 00 00        mov  [esp],0
n+6b: e8 cb fe f
n+70: 85 c0
n+72: 79 07
n+74: b8 01 00 00
n+79: eb bd                       jmp  n+38
n+7b: b8 00 00 00 00              mov  eax,0
n+80: c9                          leave
n+81: c3                          ret
```

```
(gdb) set *(unsigned char*)0x08048479=0x90
(gdb) set *(unsigned char*)0x0804847a=0x90
```

Parallax Example

Ptrace detector

```
n+32 <cleanup_and_exit>:                                  (relocated)
n+32: 55                          push ebp
n+33: 89 e5                       mov  ebp,esp
n+35: 83 ec 18                    sub  esp,24
n+38: 89 04 24                    mov  [esp],eax
n+3b: e8 d5 fe ff ff              call exit@plt

n+46 <check_ptrace>:
n+46: 55                          push ebp
n+47: 89 e5                       mov  ebp,esp
n+49: 83 ec 18                    sub  esp,24
n+4c: c7 44 24 0c 00 00 00 00     mov  [esp+0xc],0
n+54: c7 44 24 08 00 00 00 00     mov  [esp+0x8],0
n+5c: c7 44 24 04 00 00 00 00     mov  [esp+0x4],0
n+64: c7 04 24 00 00 00 00        mov  [esp],0
n+6b: e8 cb fe ff ff              call ptrace@plt      (existing far ret)
n+70: 85 c0                       test eax,eax
n+72: 79 07                       jns  n+7b
n+74: b8 c3 00 00 00              mov  eax,0xc3        (modify exit arg)
n+79: eb c3                       jmp  n+32            (modify target)
n+7b: b8 00 00 00 00              mov  eax,0
n+80: c9                          leave
n+81: c3                          ret
```

Protected Code

Binary Rewriting Rules

- *Parallax* uses existing gadgets, plus binary rewriting as needed
- Several binary rewriting rules in current prototype:
  - Modify immediate operands, and split instruction to compensate
  - Rearrange code/data to encode (partial) gadgets in offsets
  - Use `add` for memory operations if `mov` cannot be encoded
  - Use `retf` (far return) if a `ret` cannot be encoded
  - Insert spurious instructions to encode missing gadget prefixes/suffixes

Verification Code

Function-Level Verification

- Select function(s) to use as verification code at binary or source level
- Use modified ROPC compiler to generate verification function
- Verification function uses gadgets used to protect code

Dynamically Generated Function Chains

- Function chains live in data memory $\rightarrow$ can be generated dynamically
- Enables encryption, self-modification, random selection from equivalent gadgets

Instruction-Level Verification

- Experiments with fine-grained verification code $\rightarrow$ high overhead due to setup/teardown ($2\times$ compared to function-level)

Attack Resistance

Code Restoration Attacks (restore modified code after execution)

- Main threat to any tamperproofing scheme (not applicable in cracking)
- *Parallax* complicates this by choosing verification code that runs often
- Verification code is decoupled from protected code → hard to pinpoint

Verification code replacement

- Adversary must craft equivalent code → ROP code hard to reverse
- Dynamically generated/self-modifying verification code even stronger

Verification code modification

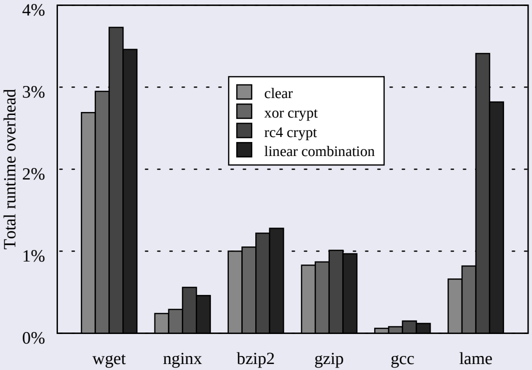
- Again, adversary must reverse ROP code first
- Verification code is data → protectable with (network of) checksums

Evaluation

Coverage and Performance

- *Parallax* protects up to 90% of code bytes with gadget length ≤ 6, not using spurious instructions (not simultaneously, as rules may conflict)
- Performance overhead $< 4\%$ if verification code outside critical path

Runtime Overhead (Function-Level Verification)



Discussion

Dynamic Circumvention

- *Parallax* protects code against explicit modification
- Cannot detect dynamic non-explicit code patching (Pin, DynamoRIO)
- *Parallax* can instead protect specialized detection code for this

Control-Flow Integrity

- Use of ROP requires special consideration when combined with Control-Flow Integrity (CFI)

Protection Coverage (vs Oblivious Hashing)

- *Parallax* protects input-/environment-based code that OH cannot
  - Arguably, such code is the most interesting to attackers
- In contrast to OH, *Parallax* requires no offline testing to compute valid states $\rightarrow$ can protect even untested/unexplored code

Conclusion

Summary

- *Parallax* enables tamperproofing on deterministic *and* non-deterministic paths, without susceptibility to the attack of Würster et al.
- Up to 90% of code bytes can be protected with gadget length ≤ 6
- Wisely chosen verification code keeps runtime overhead under 4%
- Performance overhead is in verification code only, isolated from protected code
- Verification code resides in data memory $\rightarrow$ traditional tamperproofing techniques re-enabled for multi-layered protection