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Defeating Return-Oriented Rootkits with *"Return-less"* Kernels

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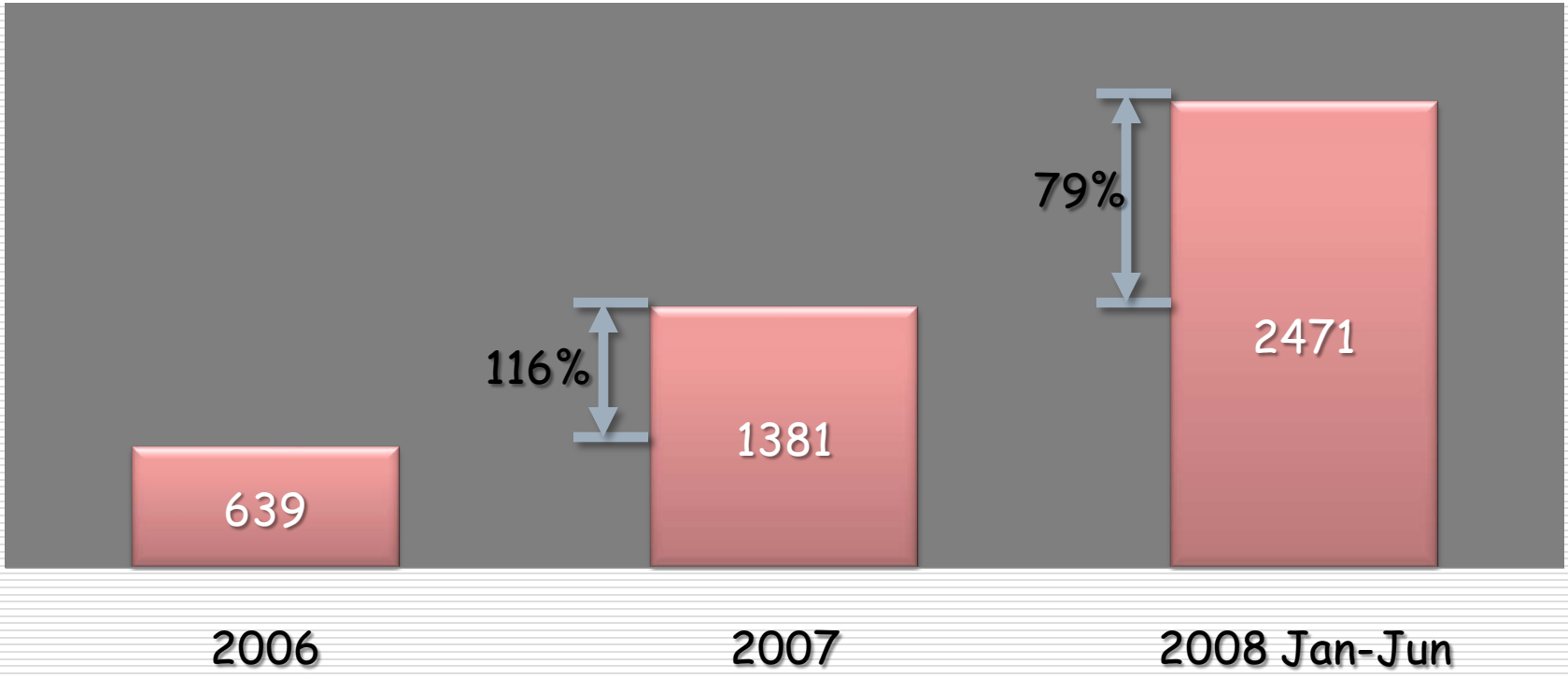
Outline

1. Motivation
2. Background: Return-Oriented Programming
3. Our Approach
4. Implementation & Evaluation
5. Conclusions

Motivation: Rootkit Threats



Source: Kaspersky Security Bulletin Malware evolution 2007 2008

Kernel Rootkits

- Rootkit goals:
  - Maintain undetectable presence
  - Keep privileges, hide malicious activities, etc.
- Need to execute code at kernel privilege

Rootkit Examples

adore-ng

- Linux 2.4/2.6
- Kernel module
- Adds "custom" functions
- Hooks VFS

SucKIT

- Linux 2.4
- /dev/kmem
- Adds "custom" functions
- Hooks system calls

Existing Defenses

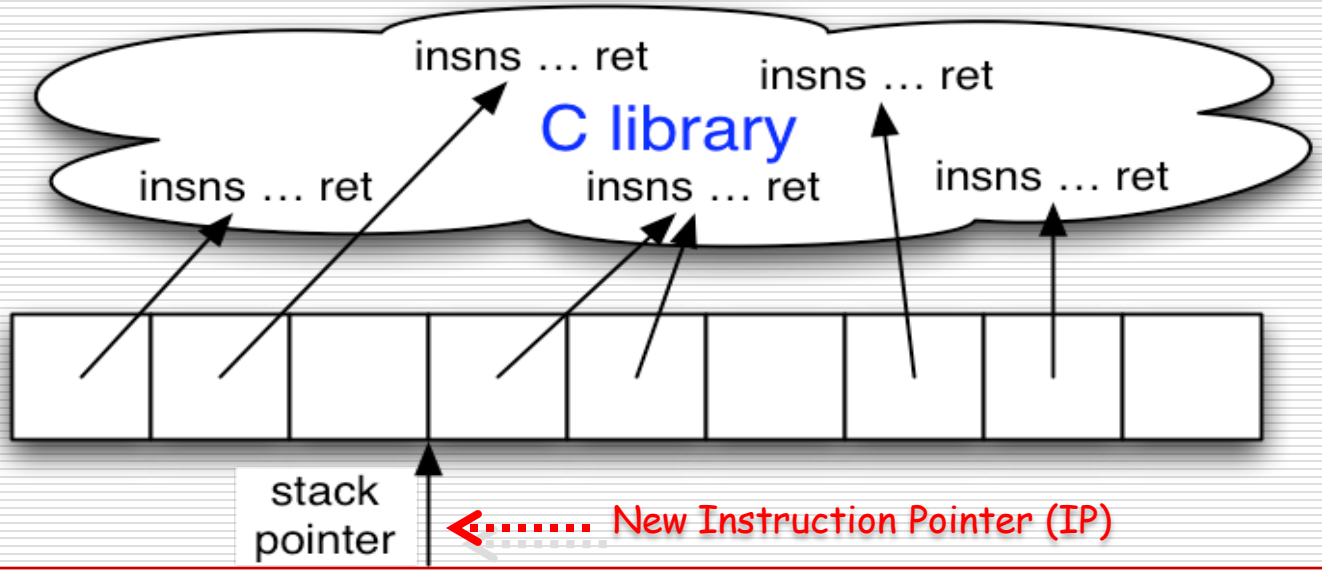
- Attestation: Is the code to be executed expected?
  - e.g., driver signing
- Kernel Code Integrity (W⊕X): Make kernel code read-only and kernel data non-executable
  - **SecVisor** [Seshadri et al., SOSP 2007], **NICKLE** [Riley et al., RAID 2008]
- Control Flow Integrity (CFI): Detect unexpected execution paths
  - **SBCFI** [Petroni et al., CCS 2007]

Arms Race

1. W⊕X prevents injected code from executing
2. Return-to-libc defeats W⊕X by returning to an existing function
   - e.g., system (char *command)
3. Return-Oriented Programming (ROP) generalizes return-to-libc by misusing legitimate code fragments or gadgets
   - [Shacham et al., CCS '07], [Buchanan et al., CCS '08], [Hund et al., USENIX Sec '09]
4. Our technique de-generalizes ROP back to return-to-libc

Return-Oriented Programming

- **Gadget**
  - A sequence of instructions ending with a ret to complete an operation
- **Stack**
  - A manipulated stack to chain gadgets together



Return-Oriented Programming

- Turing-complete: allowing for performing arbitrary computation based on gadgets
  - [Shacham et al., CCS '07], [Buchanan et al., CCS '08], [Hund et al., USENIX Sec '09]
  - Return-to-libc attacks are not Turing-complete
- Example gadgets
  - Load/store, arithmetic, logic, control flow, system calls, …

Our Defense Against ROP

- **Observation:** Each gadget ends with a ret

Can we build a kernel *without* using ret?

Finding *ret*

- FreeBSD 8.0/x86-amd64:
  - 8,329 ret instr. / 675,763 total instr. = 1/81
- Additional challenge in x86: variable-length instructions
  - +10,001 additional ret opcodes
  - 18,330 ret *opcodes* / 675,763 total instr. = 1/37

Finding *ret*

- Example: *AcpiUtDeleteRwLock* (FreeBSD 8.0/x86-amd64 function)

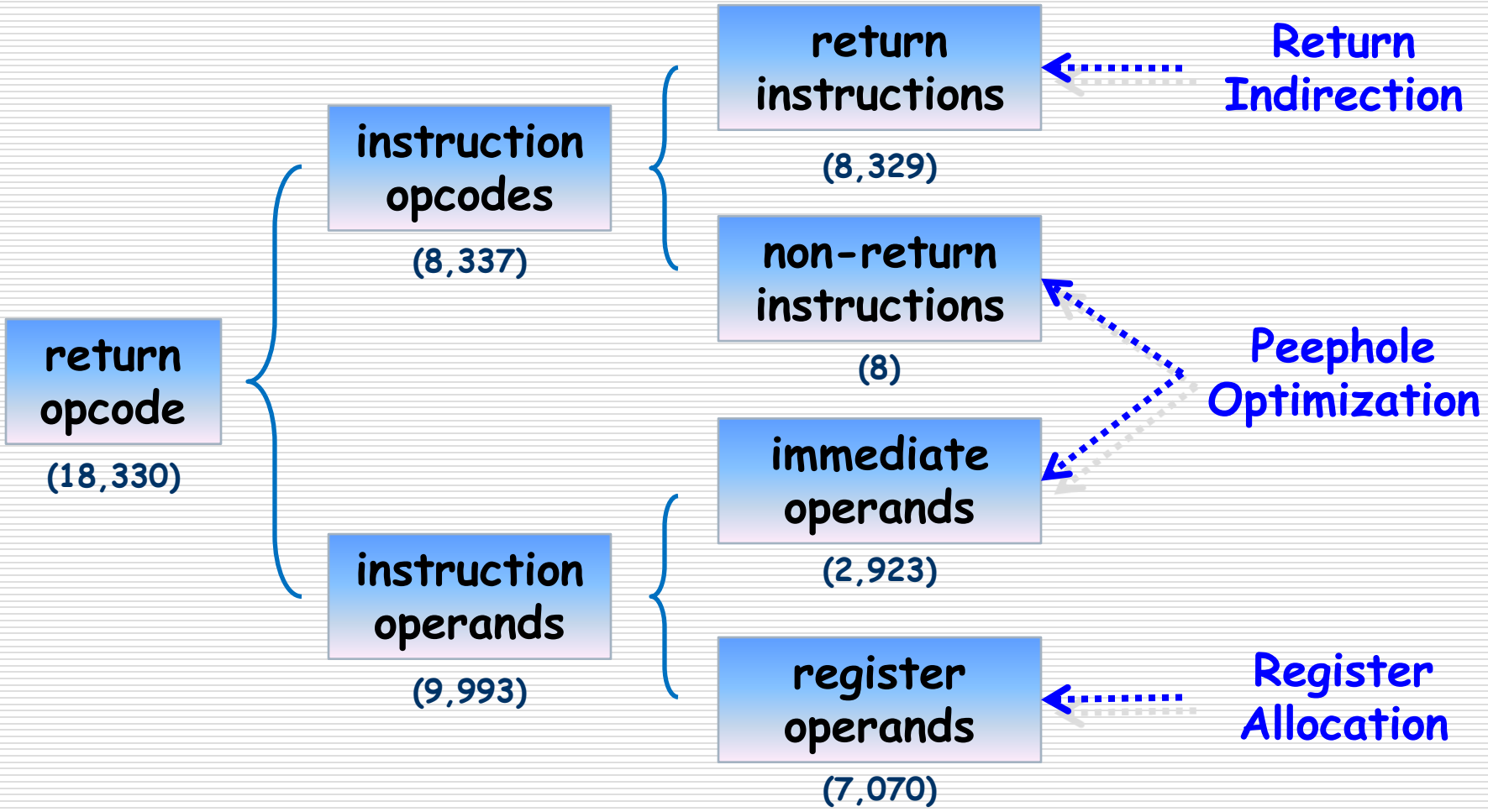
48 8b 3b	mov (%rbx), %rdi
e8 c3 e0 00 00	callq <AcpiOsDeleteMutex>

3b e8	cmp %eax, %ebp
c3	retq

Our Defense Against ROP

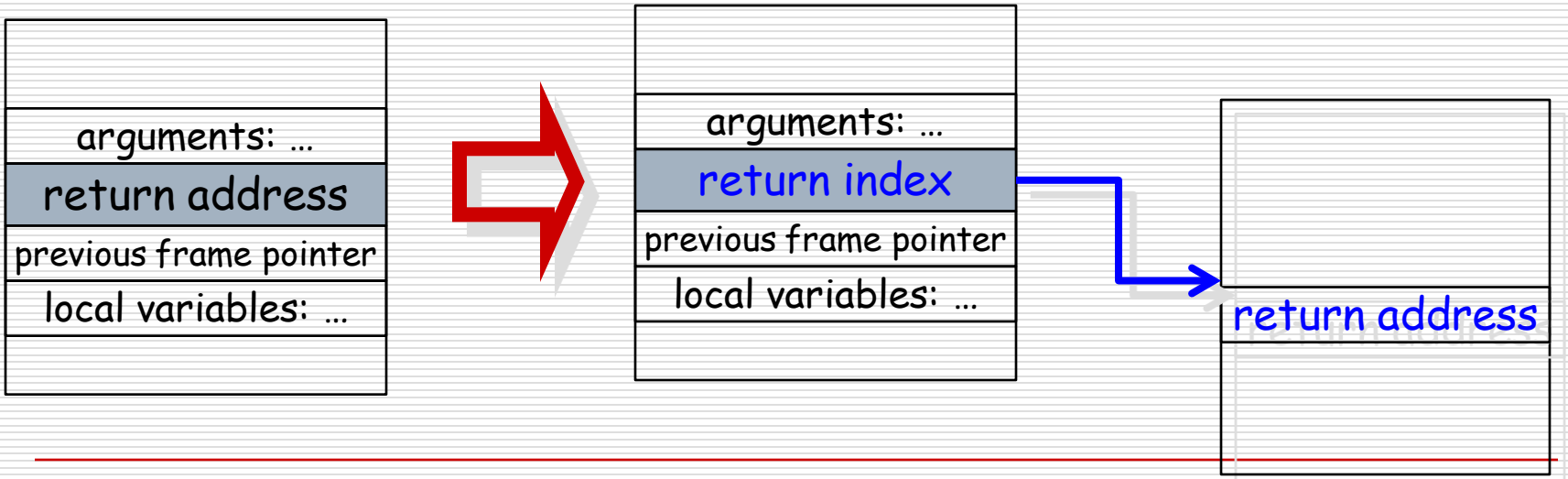
Can we build a kernel *without* return opcodes?

Our Approach



Return Indirection: Removing return instructions

- Naïve approach: ret → pop + jmp
  - This still can be used to make gadgets!
- Our approach: return address → return index
  - call dst → push $index; jmp dst
  - ret → pop %reg; jmp *RetAddrTable(%reg)



Return Indirection: Removing return instructions

- Return indirection de-generalizes ROP back to return-to-libc
- Additional control-flow integrity checks can be enforced to defeat return-to-libc
  - e.g., function type-based validation

Register Allocation

- Adjust register operands when being allocated to avoid introducing ret opcodes

- Example:

48 89 c3 mov %rax, %rbx (rbx introduces ret opcode)

49 89 c5 mov %rax, %r13 (replace rbx with r13)

Peephole Optimization

- Non-return instructions

```
0f c3 ...
movnti  mem32, reg32
```

```
89 ...
mov  mem32/64, reg32/64
```

- Immediate operands

```
cmp $0xc3, %ecx
```

```
mov $0xc4, %reg
dec  %reg
cmp %reg, %ecx
```

- Relative offset

```
e9 c3 00 00 00
jmpq 0xffffffff801a4fc9
```

```
e9 c4 00 00 00 90
jmpq 0xffffffff801a4fca
nop
```

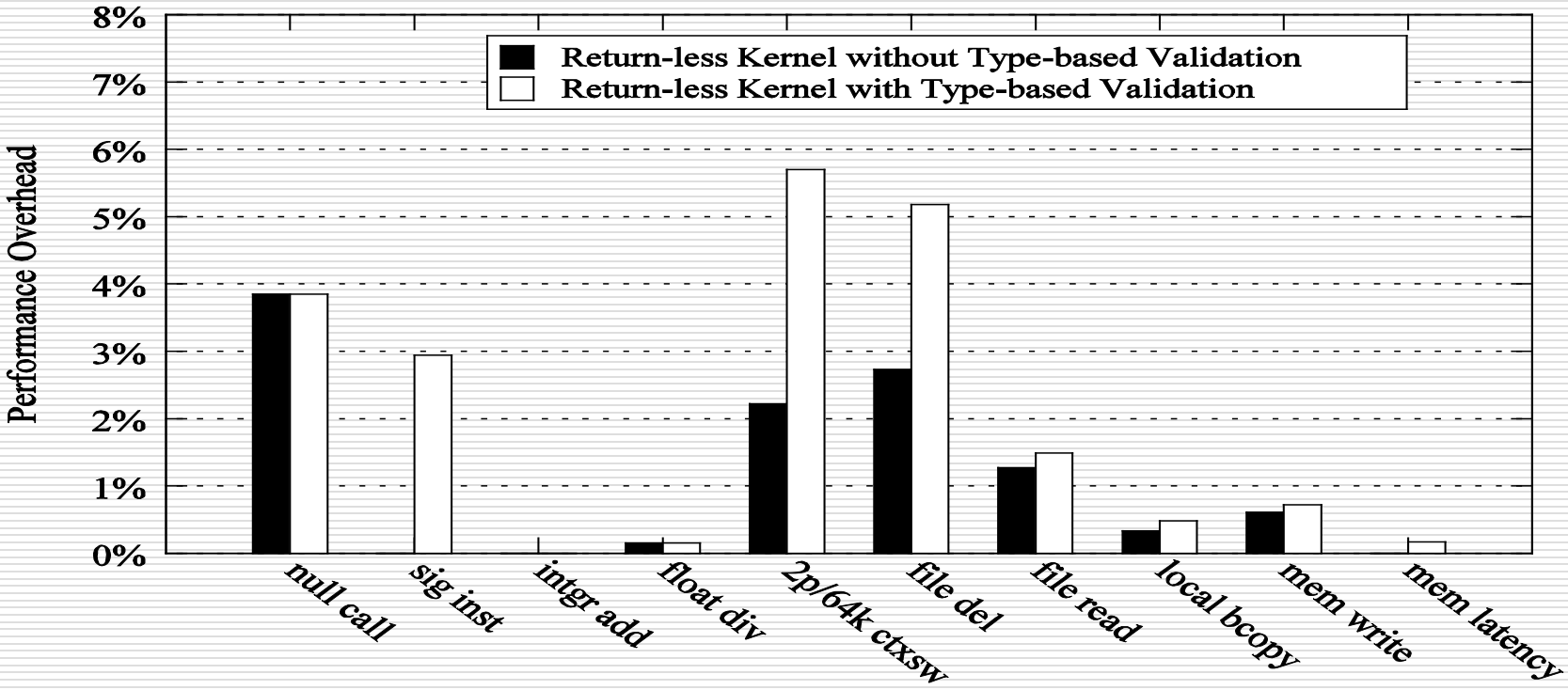
Implementation & Evaluation

- Our prototype, based on LLVM, is used to compile a FreeBSD 8.0 kernel
  - FreeBSD OS image file size increased by 9.4%
    - 4,370,704 bytes ➔ 4, 782,952 bytes
  - Instruction count increased by 10.9%
    - 675,763 ➔ 749,227

No return opcodes!

Implementation & Evaluation

- LMbench microbenchmark



Limitations

- Kernel source code access
- Return-oriented attacks → return-to-libc
- Jump-oriented programming?

Related Work

- Return-Oriented Rootkit Detection
  - e.g **DROP** [Chen et al., ICISS '09], **DynIMA** [Davi et al., STC '09]…
- Kernel Rootkit Prevention
  - e.g **SecVisor** [Seshadri et al., SOSP '07], **Lares** [Payne et al., Oakland '08], **NICKLE** [Riley et al., RAID '08]…

Conclusions

- Compiler-based approach to defeat ROP
  - Return indirection
  - Peephole optimization
  - Register allocation
- Result: Return-less Kernel
  - No ret opcode ➔ no return-oriented gadgets

Thank you!

Return Opcodes

- x86 has four ret opcodes
  - c2, c3, ca, cb
  - All handled

CFI vs. Return-less Kernels

- Major CFI approaches:
  - Control transfer instruction instrumentation
  - Data Flow Integrity
  - Memory-safe programming languages
  - Software bounds checking
- Challenging to apply in kernel space

- Return-less approach complements CFI