Enforcing Kernel Security Invariants with Data Flow Integrity

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Kernel Memory Corruption Vulnerability

- Kernel is important
  - The de-facto trusted computing base (TCB)
  - Foundation of upper level security mechanisms (e.g., app sandbox)
- Kernel vulnerabilities are not rare
  - Written in C
  - Emphasize on performance

Privilege escalation attacks

- One of the most powerful attacks
- Most popular attack against kernel
- Hard to prevent
  - Chrome sandbox bypass
  - iOS jailbreak
  - Android rooting

Challenge 1: many ways to exploit

```
1  static int acl_permission_check
2      (struct inode *inode, int mask)
3  {
4    unsigned int mode = inode->i_mode
5
6    if (likely(uid_eq(current_fsuid(), inode->i_uid)))
7      mode >>= 6;
8    else if (in_group_p(inode->i_gid))
9      mode >>= 3;
10
11   if ((mask & ~mode &
12       (MAY_READ | MAY_WRITE | MAY_EXEC)) == 0)
13     return 0;
14   return -EACCES;
15 }
```

Code Injection Attack

Disable the check

Control-flow hijacking

Bypass the check

Data-oriented attacks

Manipulate the check

Challenge 2: performance

- Protecting all data is not practical
  - Secure Virtual Architecture (SVA) [SOSP'07]
    - Enforces kernel-wide memory safety
    - Performance overhead: 5.34x ~ 13.10x (LMBench)

Our approach

- Only protects a subset of data that is large enough to enforce **access control invariants** [NTIS AD-758 206]
  - Complete mediation
    - **Control-data** → Code Pointer Integrity [OSDI'14]
  - Tamper proof
    - **Non-control-data** used in **security checks** → this work
  - Correctness

Step 1: discover all related data

- Observation: OS kernels have well defined error code for **security checks** (when they fail)
  - POSIX: EPERM, EACCESS, etc.
  - Windows: ERROR_ACCESS_DENIED, etc.
- Solution: leverage this implicit semantic to automatically infer **security checks**
- Benefits
  - **Soundness**: capable of detecting all security related data (as long as there is no semantic errors)
  - **Automated**: no manual annotation required

A simple example

Step 1: collect return values

```
1  static int acl_permission_check
2      (struct inode *inode, int mask)
3  {
4    unsigned int mode = inode->i_mode;
5
6    if (likely(uid_eq(current_fsuid(), inode->i_uid)))
7      mode >>= 6;
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11   if ((mask & ~mode &
12        (MAY_READ | MAY_WRITE | MAY_EXEC)) == 0)
13     return 0;
14   return -EACCES;
15 }
```

A simple example

Step 2: collect conditional branches

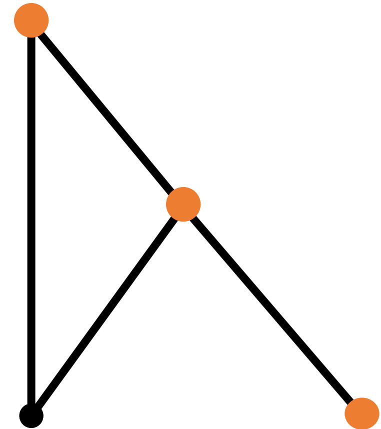
```
1  static int acl_permission_check
2      (struct inode *inode, int mask)
3  {
4    unsigned int mode = inode->i_mode;
5
6    if (likely(uid_eq(current_fsuid(), inode->i_uid)))
7      mode >>= 6;
8    else if (in_group_p(inode->i_gid))
9      mode >>= 3;
10
11   if ((mask & ~mode &
12        (MAY_READ | MAY_WRITE | MAY_EXEC)) == 0)
13     return 0;
14   return -EACCES;
15 }
```

A simple example

Step 2: collect conditional branches

Collect Dominators

```
if (condition1 || condition2)
    return 0;
else
    return -EACCESS;
```



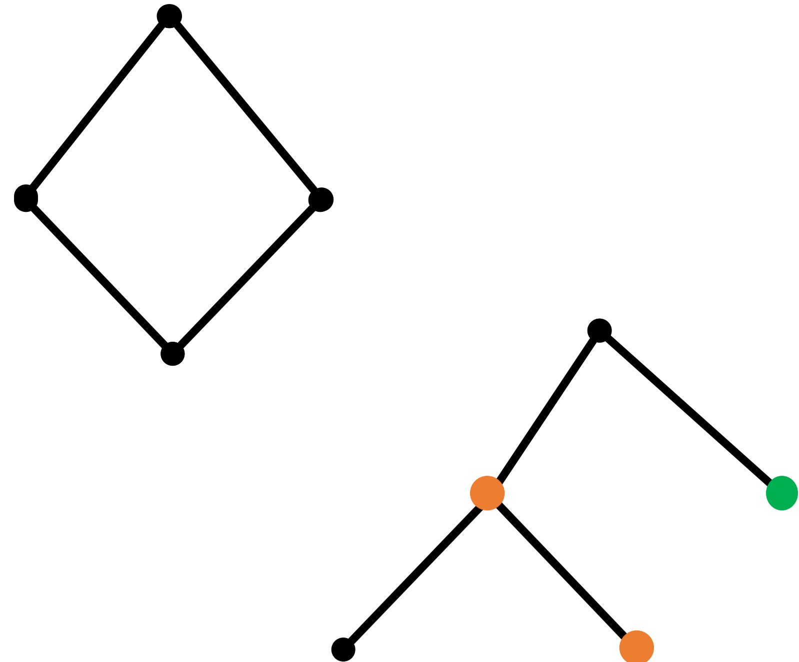
A simple example

Step 2: collect conditional branches

Avoid Explosion

```
if (uid_eq)
    mode >> 6;
else
    mode >> 3;

if (condition)
    return -EINVAL;
```



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A simple example

Step 3: collect dependencies

```
1  static int acl_permission_check
2      (struct inode *inode, int mask)
3  {
4    unsigned int mode = inode->i_mode;
5
6    if (likely(uid_eq(current_fsuid(), inode->i_uid)))
7      mode >>= 6;
8    else if (in_group_p(inode->i_gid))
9      mode >>= 3;
10
11   if ((mask & ~mode &
12        (MAY_READ | MAY_WRITE | MAY_EXEC)) == 0)
13     return 0;
14   return -EACCES;
15 }
```

Be complete

- Collects data- and control-dependencies **transitively**
- Collects sensitive pointers **recursively**

Step 2: protect the integrity of data

- Data-flow integrity [OSDI'06]
  - Runtime data-flow should not deviate from static data-flow graph (similar to control-flow integrity)
    - For example, string should not flow to return address or uid
  - How
    - Check the last writer at every memory read
  - Challenge
    - Performance! (104%)

How to reduce performance overhead

- Observation 1: reads are more frequent than writes
  - **Check write instead of read**
- Observation 2: most writes are not relevant
  - **Use isolation instead of inlined checks**
- Observation 3: most relevant write are safe
  - **Use static analysis to verify**

Write Integrity Test [S&P'08]

Two-layered protection

- Layer one: data-flow isolation
  - Prevents unrelated writes from tampering sensitive data
  - Mechanisms: segment (x86-32), WP flag (x86-64), access domain (ARM32), **virtual address space**, virtualization, TrustZone, etc.
- Layer two: WIT
  - Prevents related but unrestricted writes from tampering sensitive data

Additional building blocks

- Shadow objects
  - Lacks fine-grained isolation mechanisms
  - Sensitive data is mixed with non-sensitive data
- Safe stack
  - Certain critical data is no visible at language level, e.g., return address, register spills
  - Access pattern of stack is different
  - Safety is easier to verify

Prototype

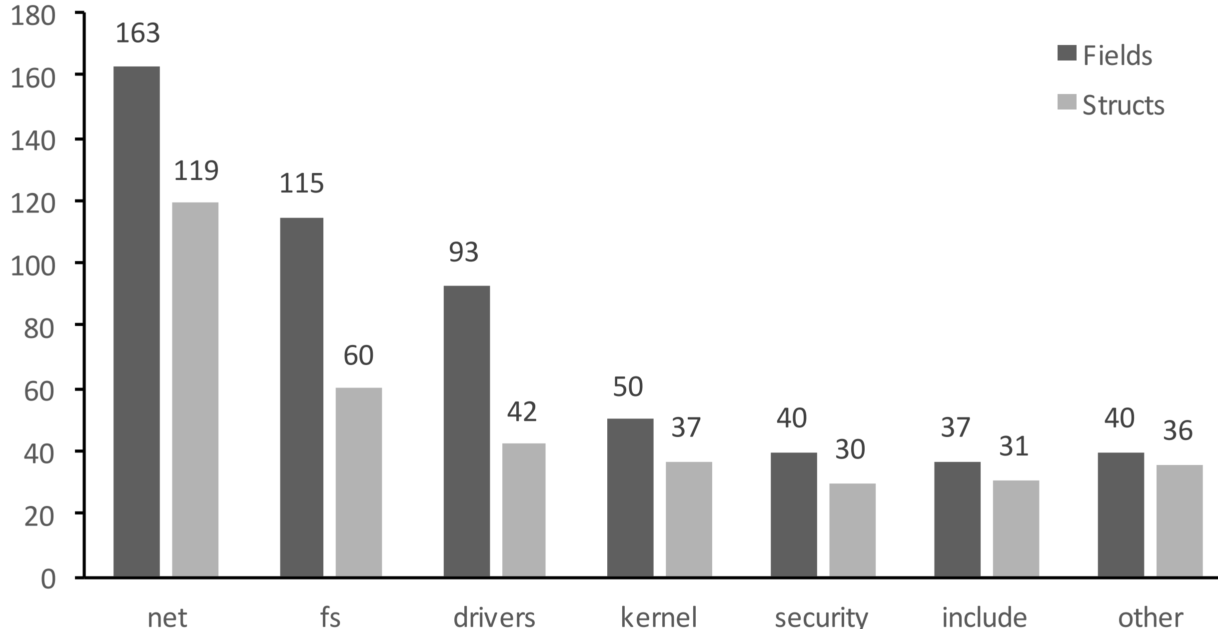
- ARM64 Android
  - For its practical importance and long updating cycle
  - Enough entropy for stack randomization
- Data-flow isolation
  - Heap: virtual address space based, uses ASID to reduce overhead
  - Stack: randomization based
- Shadow objects
  - Modified the SLUB allocator

Implementation

- Kernel
  - Nexus 9 lollipop-release + LLVMLinux patches
  - Our modifications: 1900 LoC
- Static Analysis
  - Framework: KINT [OSDI'12]
  - Point-to analysis: J. Chen's field-sens [GitHub]
    - Context sensitive from KOP [CCS'09]
  - Safe stack: CPI [OSDI'14]
  - Our analysis + modifications: 4400 LoC
  - Instrumentation: 500 LoC

How many sensitive data structures

- Control data: 3699 fields (783 structs), 1490 global objects
- Non-control data: **1731** fields (**855** structs), **279** global objects
  - False positives: 491 fields (221 structs) / 61 fields (25 structs)



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How secure is our approach

- Inference
    - Sound → no false negatives
    - Catch: no semantic errors
- Data-flow (point-to) analysis
    - Sound but not complete → over permissive
    - Improve the accuracy with context and field sensitivity
- Against existing attacks
    - All prevented

Performance impact

- Write operations
  - 26645 (4.30%) allowed, 2 checked
- Context switch
  - 1700 cycles
- Benchmarks
  - LMBench (syscalls): 1.42x ~ 3.13x (0% for null syscall)
  - Android benchmarks: 7% ~ 15%

Conclusion

- Data-oriented attacks are very practical, especially in kernel
- Leveraging implicit semantics to avoid annotation
- Combining program analysis with system design is a great way to build **principled** and **practical** security solution

Thank you!

Q & A