# Towards Automatic Inference of Kernel Object Semantics from Binary Code

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# Kernel Data Structure (or Object) Semantics

- Concerning the meaning and the behavior of kernel data structures
  - task_struct: process descriptor
  - mm_struct: memory address space descriptor

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- Concerning the meaning and the behavior of kernel data structures
  - task_struct: process descriptor
  - mm_struct: memory address space descriptor

- Useful for a number of security applications.
  - Virtual machine introspection [GR03]
  - Kernel function reverse engineering

# Why This is Challenging

## Challenges

1. Semantics concern the meaning, which is even vague for human beings.
2. Kernel tends to have a large number of kernel objects.
    - Up to tens of thousands of dynamically created kernel objects.
    - Hundreds of different semantics types.

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   - Hundreds of different semantics types.

## Current Practice

Merely relying on human beings to manually inspect kernel source code, kernel symbols, or kernel APIs to derive and annotate the semantics of the kernel objects.

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1. Recognizing and uncovering important kernel data structures with semantics, directly from binary code
2. General, working with a variety of (Linux) operating system kernels.

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2. General, working with a variety of (Linux) operating system kernels.

## Key Principle

**Data use tells data semantics**

# Key Insights

1. Starting from well-known knowledge
   - User level system call (syscall for short) specification
   - Kernel level exported API specification
2. Using execution context differencing
   - e.g., `task_struct` vs. `mm_struct`
3. Encoding the semantics using a bit-vector
   - Which syscall (e.g., `fork`, `open`, `mmap`) accessed
   - How the object was accessed:

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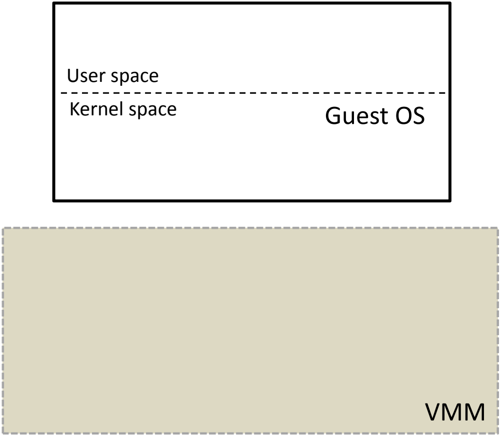
3. Encoding the semantics using a bit-vector
   - Which syscall (e.g., `fork`, `open`, `mmap`) accessed
   - How the object was accessed:
     - read
     - write
     - create
     - destroy

# How ARGOS Works



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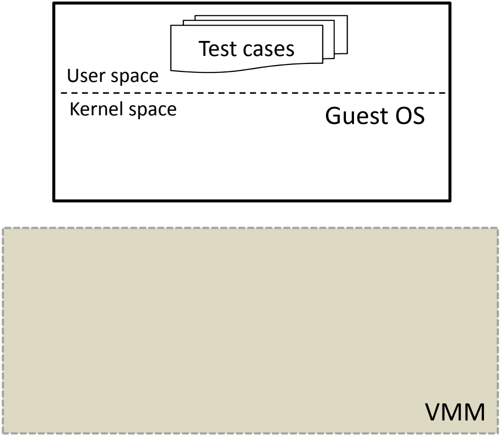

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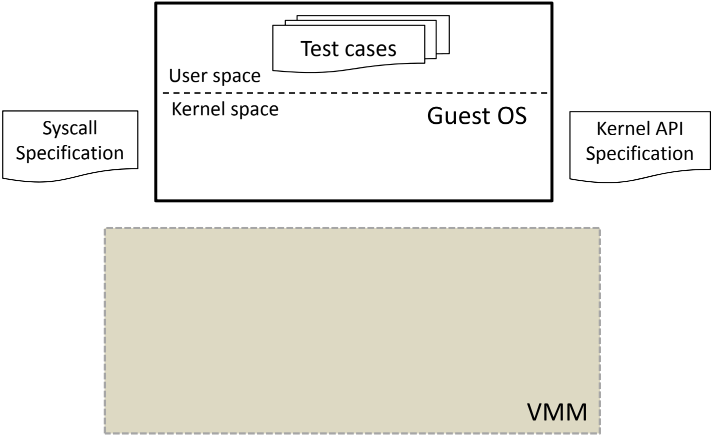

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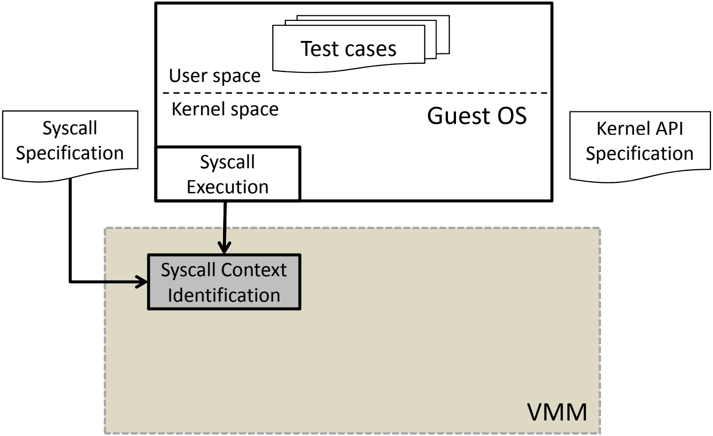

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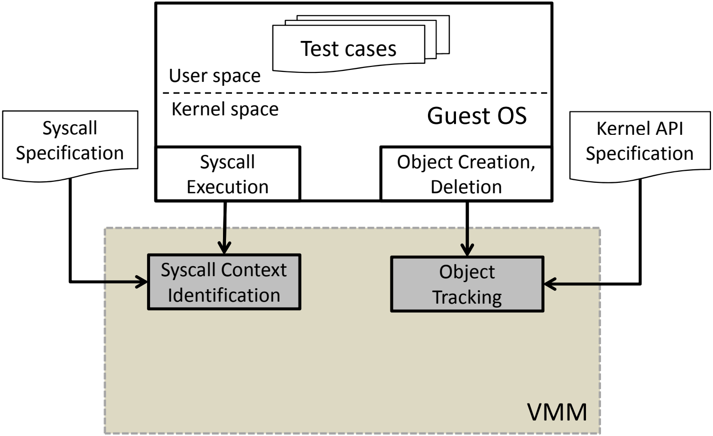

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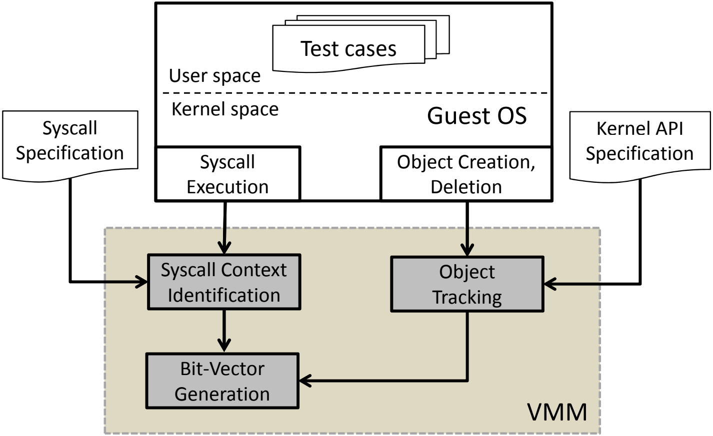

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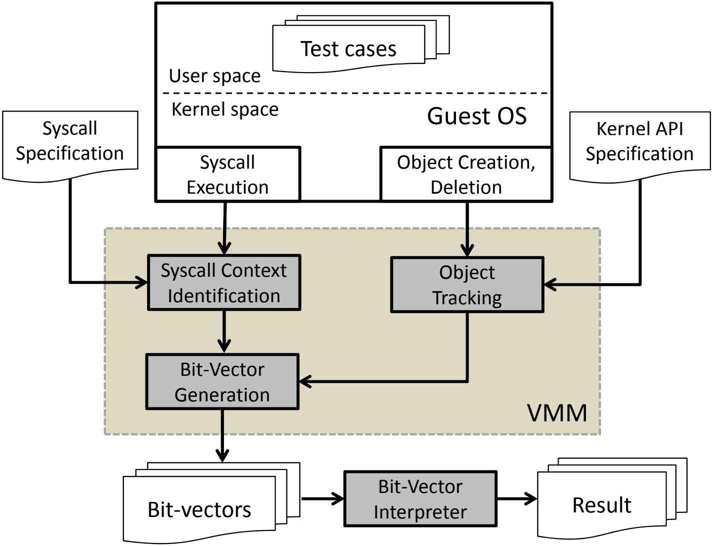
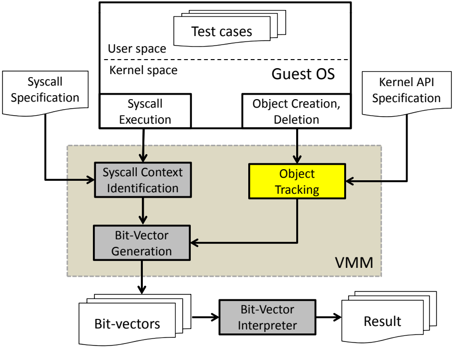


# Object Tracking



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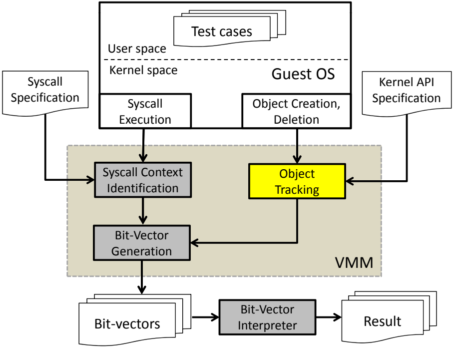


1. Tracking the object life time.
2. Assigning a static type to the dynamic object.
3. Tracking the object size.
4. Tracking object relations.

# Object Tracking: Object Life Time

An easy problem by hooking the corresponding kernel APIs

1. Creation
   - `kmem_cache_alloc`
   - `kmalloc`
   - `vmalloc`
2. Deletion
   - `kmem_cache_free`
   - `kfree`
   - `vfree`

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We will use `kmalloc/kfree` to denote these functions.

# Object Tracking: Assigning a Static Type

## The problem

- What we observe: each **dynamic** data structure (object) instance and their virtual addresses
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## Typical approaches

1. Using the call-site-chain from the top callers to `kmalloc` (e.g., $f \rightarrow g \rightarrow h \rightarrow kmalloc$)
   - May over-classify an object type
2. Using the program counter (PC) that invokes `kmalloc` (i.e., $PC_{kmalloc}$)
   - May under-classify an object type (because of wrapper)

# Object Tracking: Assigning a Static Type

## $PC_{kmalloc}$ approach

1. A single kernel object (e.g., `task_struct`) can often be allocated in different calling contexts (e.g., `vfork`, `clone`) $\rightarrow$ over-classify
2. Experimental data
   - 80.3% of the kernel objects have a direct mapping with $PC_{kmalloc}$ approach
   - 97.5% of the objects over-classified with call-chain approach

# Object Tracking: the Object Size

**The problem**

No size argument to many other kernel object allocation functions (e.g., `kmem_cache_alloc`)

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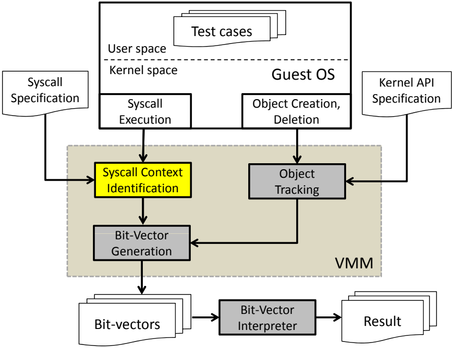
## Our observation

- Right after executing `kmalloc`, `eax` holds the base address $v$ of the allocated object
- Further access to the field of the object must start from $v$, or the propagation of $v$ (e.g., `mov eax, ebx`) (Taint Analysis)
- By observing how $v$ gets used, we infer the size

# Syscall Context Identification




## Goal

Identify the specific syscall execution context, when a kernel object got accessed.

## Challenges

1. Context switches
2. Interrupts (bottom half, top half)

# Syscall Context Identification

## Observations

1. Tracking `sysenter/int 0x80/sysexit/iret`, and the `eax`
2. Context switches lead to kernel stack (`esp`) exchange
3. Interrupt handler
   - Top half execution (of an interrupt handler) can be identified by `iret`
   - Bottom half execution also has (`esp`) exchange

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2. Context switches lead to kernel stack (`esp`) exchange
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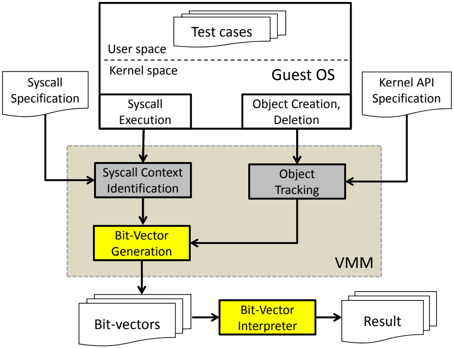
   - Top half execution (of an interrupt handler) can be identified by `iret`
   - Bottom half execution also has (`esp`) exchange

By tracking the `sysenter/int 0x80/sysexit/iret` instructions, as well as kernel `esp`, we can uniquely identify kernel syscall context [FL12, FL13]

# Bit-Vector Generation and Interpretation



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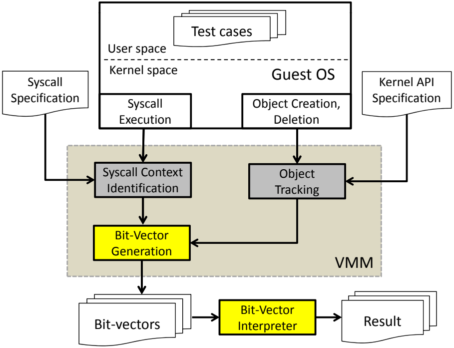


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Associate the kernel object semantics with the captured execution context

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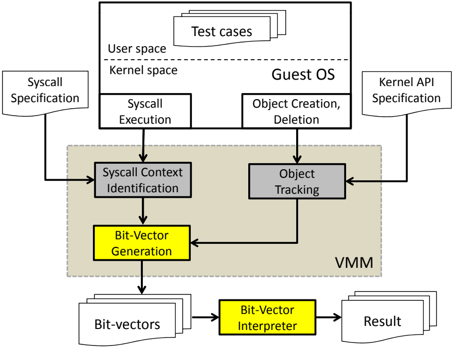



## Goal

Associate the kernel object semantics with the captured execution context

## Challenges

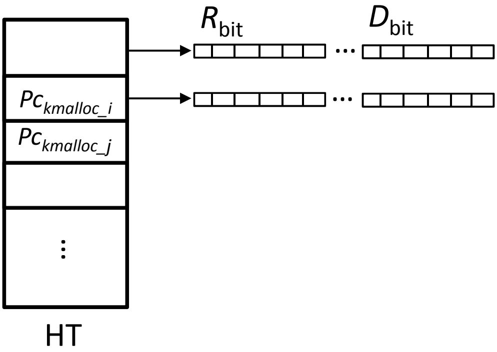
1. How to represent such information (Bit-Vector).
2. How to interpret it (Bit-Vector Interpreter).

# Bit-Vector Generation

## What information does the Bit-Vector contain

- Each object is associated with one bit-vector of length 4*N where N is the number of syscall.
- For each syscall, four bits are presented
  - *C-bit*: whether this syscall created the object;
  - *R-bit*: whether this syscall read the object;
  - *W-bit*: whether this syscall wrote the object ;
  - *D-bit*: whether this syscall destroyed the object.

# Bit-Vector Generation - All Involved Data Structures



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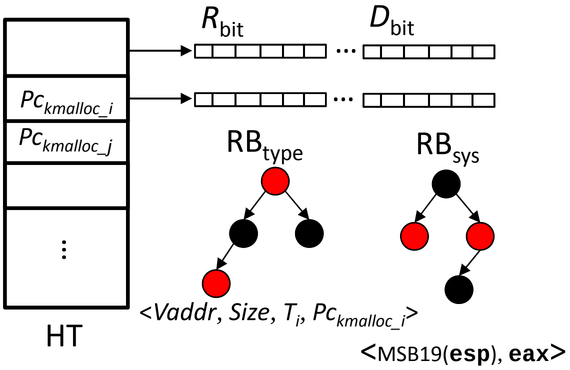


e.g., `mov %ecx, (%ebx)` → resolve the vaddr of `ebx`, locate the syscall context by using kernel `esp`.

# Bit-Vector Interpreter

## How to interpret Bit-Vector

- Bit-Vector can be viewed as:
  - What are these syscalls that have contributed to the meaning of the object.
  - How these syscalls contributed (recorded in our *R*, *W*, *C*, *D*-bits).

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## Current Design

- Deriving the rules based on the general syscall and kernel knowledge.
  - e.g., `task_struct` must be created by `fork`-family syscall, and accessed by `getpid` syscall.

# Experiment Setup

## Experiment Environment

- Guest OS
  - `Linux-2.6.32` with `debian-6.0`
  - `Linux-3.2.58` with `debian-7`
- Host OS: `ubuntu-12.04` with `3.5.0-51-generic`.

## System Input

1. Syscall Specification
2. Kernel API Specification
3. Test Suites:
   - Linux Kernel Test Suite: `ltp-20140115`
   - User Level: `spec2006`, `lmbench-2alpha8`

# Rules to Infer the Semantics

| Rule Num | Detailed Rules | Data Structure |
|---|---|---|
| I | sys_clone[*C*] ∩ sys_getpid[*R*] | task_struct, pid |
| II | ((sys_clone[*C*] - sys_vfork[*C*]) ∩ sys_brk[*RW*]) ∩ sys_munmap[*D*] | vm_area_struct |
| III | ((sys_clone[*C*] - sys_vfork[*C*]) ∩ sys_brk[*RW*]) - sys_munmap[*D*] | mm_struct |
| IV | sys_open[*C*] ∩ sys_lseek[*W*] ∩ sys_dup[*R*] | file |
| V | sys_clone[*C*] - sys_clone[*C*](CLONE_FS) | fs_struct |
| VI | sys_clone[*C*] - sys_clone[*C*](CLONE_FILES) | files_struct |
| VII | sys_mount[*C*] ∩ sys_umount[*D*] | vfs_mount |
| VIII | sys_socketcall[*C*](SYS_SOCKET) ∩ sys_socketcall[*W*] (SYS_SETSOCKOPT) | sock |
| IX | sys_clone[*C*] - sys_clone[*C*](CLONE_SIGHAND) | sighand_struct |
| X | sys_capget[*R*] ∩ sys_capset[*W*] | credential |

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# Statistics of the Bit-Vector

| Rule Num | Kernel Version | Symbol Name | Traced Size | Statistics of the R/W Bit Vector | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | P | F | M | T | G | S | N | I | D | O |
| I | 2.6.32 | pid | 44 | 25 | 16 | 4 | 0 | 3 | 0 | 1 | 3 | 1 | 0 |
| | | task_struct | 1072 | 47 | 48 | 5 | 0 | 12 | 0 | 1 | 1 | 2 | 0 |
| | 3.2.58 | pid | 64 | 28 | 24 | 3 | 0 | 3 | 0 | 1 | 3 | 1 | 0 |
| | | task_struct | 1072 | 73 | 109 | 13 | 6 | 19 | 1 | 2 | 7 | 2 | 0 |
| II | 2.6.32 | vm_area_struct | 88 | 4 | 17 | 12 | 0 | 3 | 0 | 0 | 1 | 1 | 0 |
| | 3.2.58 | vm_area_struct | 88 | 3 | 5 | 12 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| III | 2.6.32 | mm_struct | 420 | 15 | 6 | 5 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| | 3.2.58 | mm_struct | 448 | 15 | 9 | 6 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| IV | 2.6.32 | file | 128 | 41 | 93 | 12 | 0 | 10 | 0 | 1 | 7 | 2 | 0 |
| | 3.2.58 | file | 160 | 35 | 97 | 12 | 0 | 11 | 0 | 1 | 7 | 2 | 0 |
| V | 2.6.32 | fs_struct | 32 | 4 | 50 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| | 3.2.58 | fs_struct | 64 | 4 | 51 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| VI | 2.6.32 | files_struct | 224 | 11 | 73 | 3 | 0 | 4 | 0 | 1 | 6 | 1 | 0 |
| | 3.2.58 | files_struct | 256 | 39 | 84 | 5 | 0 | 6 | 0 | 1 | 6 | 1 | 0 |
| VII | 2.6.32 | vfs_mount | 128 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| | 3.2.58 | vfs_mount | 160 | 3 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| VII | 2.6.32 | sock | 1216 | 19 | 55 | 8 | 0 | 9 | 1 | 6 | 6 | 2 | 0 |
| | 3.2.58 | sock | 1248 | 28 | 74 | 7 | 0 | 9 | 1 | 1 | 6 | 2 | 0 |
| IX | 2.6.32 | sighand_struct | 1288 | 15 | 5 | 0 | 0 | 12 | 0 | 1 | 1 | 1 | 0 |
| | 3.2.58 | sighand_struct | 1312 | 15 | 7 | 0 | 0 | 12 | 0 | 1 | 1 | 1 | 0 |
| X | 2.6.32 | cred | 128 | 51 | 72 | 8 | 3 | 3 | 1 | 2 | 4 | 2 | 0 |
| | 3.2.58 | cred | 128 | 53 | 75 | 7 | 3 | 2 | 1 | 2 | 4 | 2 | 0 |

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| | 3.2.58 | cred | 128 | 53 | 75 | 7 | 3 | 2 | 1 | 2 | 4 | 2 | 0 |

# The Syscall Classification

| Syscall Type | Short Name | #Syscalls Linux-2.6.32 | #Syscalls Linux-3.2.58 |
|---|---|---|---|
| Process | P | 90 | 92 |
| File | F | 152 | 156 |
| Memory | M | 19 | 21 |
| Time | T | 13 | 13 |
| Signal | G | 25 | 25 |
| Security | S | 3 | 3 |
| Network | N | 2 | 4 |
| IPC | I | 7 | 7 |
| Module | D | 4 | 4 |
| Other | O | 3 | 3 |
| Total | - | 317 | 328 |

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# Application: Inference of Kernel Internal Functions

| Type | Version | Creation Function | | Deletion Function | |
|---|---|---|---|---|---|
| | | PC | Symbol | PC | Symbol |
| pid | 2.6.32 | c10414d0 | alloc_pid | c10413de | put_pid |
| | 3.2.58 | c104bb02 | alloc_pid | c104b969 | put_pid |
| task_struct | 2.6.32 | c102daaf | copy_process | c102da55 | free_task |
| | 3.2.58 | c103719d | copy_process | c10368a7 | free_task |
| vm_area_struct | 2.6.32 | c102d730 | dup_mm | c109d387 | remove_vma |
| | 3.2.58 | c1036d97 | dup_mm | c10b13d7 | remove_vma |
| mm_struct | 2.6.32 | c102d730 | dup_mm | c102d3dc | __mmdrop |
| | 3.2.58 | c1036d97 | dup_mm | c1036a58 | __mmdrop |
| file | 2.6.32 | c10b230d | get_empty_filp | c10b2030 | file_free_rcu |
| | 3.2.58 | c10cee78 | get_empty_filp | c10ceba0 | file_free_rcu |
| fs_struct | 2.6.32 | c10cac50 | copy_fs_struct | c10cae5b | free_fs_struct |
| | 3.2.58 | c10eaac4 | copy_fs_struct | c10eaa55 | free_fs_struct |
| files_struct | 2.6.32 | c10c1839 | dup_fd | c1030a32 | put_files_struct |
| | 3.2.58 | c10df2ab | dup_fd | c103b16d | put_files_struct |
| vfs_mount | 2.6.32 | c10c3a35 | alloc_vfsmnt | c10c30ba | free_vfsmnt |
| | 3.2.58 | c10dfd23 | alloc_vfsmnt | c10dfe36 | free_vfsmnt |
| sighand_struct | 2.6.32 | c102daaf | copy_process | c102d148 | __cleanup_sighand |
| | 3.2.58 | c103719d | copy_process | c103717b | __cleanup_sighand |
| sock | 2.6.32 | c11cd7a5 | sk_prot_alloc | c11cc884 | __sk_free |
| | 3.2.58 | c12146e5 | sk_prot_alloc | c1214d46 | __sk_free |
| cred | 2.6.32 | c1047923 | prepare_creds | c1047d00 | put_cred_rcu |
| | 3.2.58 | c10525fe | prepare_creds | c105239b | put_cred_rcu |

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| task_struct | 2.6.32 | c102daaf | copy_process | c102da55 | free_task |
| | 3.2.58 | c103719d | copy_process | c10368a7 | free_task |
| vm_area_struct | 2.6.32 | c102d730 | dup_mm | c109d387 | remove_vma |
| | 3.2.58 | c1036d97 | dup_mm | c10b13d7 | remove_vma |
| mm_struct | 2.6.32 | c102d730 | dup_mm | c102d3dc | __mmdrop |
| | 3.2.58 | c1036d97 | dup_mm | c1036a58 | __mmdrop |
| file | 2.6.32 | c10b230d | get_empty_filp | c10b2030 | file_free_rcu |
| | 3.2.58 | c10cee78 | get_empty_filp | c10ceba0 | file_free_rcu |
| fs_struct | 2.6.32 | c10cac50 | copy_fs_struct | c10cae5b | free_fs_struct |
| | 3.2.58 | c10eaac4 | copy_fs_struct | c10eaa55 | free_fs_struct |
| files_struct | 2.6.32 | c10c1839 | dup_fd | c1030a32 | put_files_struct |
| | 3.2.58 | c10df2ab | dup_fd | c103b16d | put_files_struct |
| vfs_mount | 2.6.32 | c10c3a35 | alloc_vfsmnt | c10c30ba | free_vfsmnt |
| | 3.2.58 | c10dfd23 | alloc_vfsmnt | c10dfe36 | free_vfsmnt |
| sighand_struct | 2.6.32 | c102daaf | copy_process | c102d148 | __cleanup_sighand |
| | 3.2.58 | c103719d | copy_process | c103717b | __cleanup_sighand |
| sock | 2.6.32 | c11cd7a5 | sk_prot_alloc | c11cc884 | __sk_free |
| | 3.2.58 | c12146e5 | sk_prot_alloc | c1214d46 | __sk_free |
| cred | 2.6.32 | c1047923 | prepare_creds | c1047d00 | put_cred_rcu |
| | 3.2.58 | c10525fe | prepare_creds | c105239b | put_cred_rcu |

# Limitation and Future Work

1. Only semantics, no syntax (the layout, field)
2. Unable to track the inlined `kmalloc` execution
3. Only demonstrated our techniques for Linux Kernel
4. ...

# Related Work on Data Structure Analysis

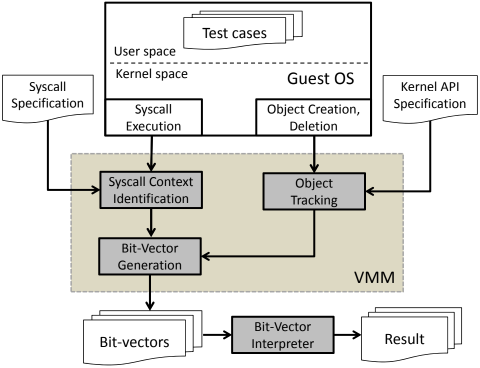
## Static Analysis

1. **Aggregate structure identification (ASI)** [RFT99]
2. **Value set analysis (VSA)** [BR04, RB08]
3. TIE [LAB11]

## Dynamic Analysis

1. **Protocol Reverse Engineering**: Polyglot [CS07], AutoFormat [LJXZ08], ANP [WMKK08], Tupni [CPC+08], ReFromat [WJC+09], Dispatcher [CPKS09]
2. **Data Structure Reverse Engineering**: Rewards [LZX10], Howard [SSB11], PointerScope [ZPL+12], Laika [CSXK08]

# Summary: ARGOS




1. The first system to infer kernel object semantics
2. Starting from syscall and kernel API knowledge
3. Tracking the instruction execution and using bit-vector
4. Evaluated w/ Linux kernel

# Thank you

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