From Thousands of Hours to a Couple of Minutes: Towards Automating Exploit Generation for Arbitrary Types of Kernel Vulnerabilities

black hat USA 2018

AUGUST 4-9, 2018
MANDALAY BAY / LAS VEGAS

Who are We?

- Wei Wu @wu_xiao_wei
  - Visiting scholar at JD.com
    - Conducting research on software security in Enterprise Settings
  - Visiting Scholar at Penn State University
    - Vulnerability analysis
    - Memory forensics
    - Malware dissection
    - Reverse engineering
    - Symbolic execution
    - Static analysis
  - Final year PhD candidate at UCAS
    - Knowledge-driven vulnerability analysis
  - Co-founder of CTF team Never Stop Exploiting.(2015)
    - ctftime 2017 ranking 4th team in China
  - I am on market.

JD.COM

PennState

CHINESE ACADEMY OF SCIENCES

NSA Codebreaker Challenge

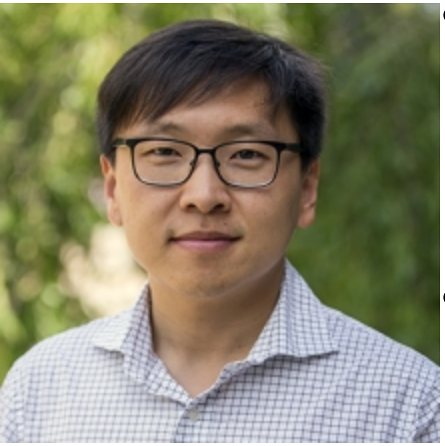
University
Carnegie Mellon University
Lafayette College
University of Hawaii
Pennsylvania State University
Georgia Institute of Technology

China

Position	Country position	Name	Points	Events
21	1	eee	365.576	16
24	2	A*0*E	332.972	6
27	3	0ops	278.460	18
30	4	Never Stop Exploiting	247.073	9
34	5	Azure Assassin Alliance	235.876	25

Who are We? (cont)

Xinyu Xing



- Visiting scholar at JD.com
  - Conducting research on software and hardware security in Enterprise Settings
- Assistant Professor at Penn State University
  - Advising PhD students and conducting many research projects on
    - Vulnerability identification
    - Vulnerability analysis
    - Exploit development facilitation
    - Memory forensics
    - Deep learning for software security
    - Binary analysis
    - …

- Jimmy Su

Head of JD security research center

- Vulnerability identification and exploitation in Enterprise Settings
- Red Team
- JD IoT device security assessments
- Risk control
- Data security
- Container security

What are We Talking about?

- Discuss the challenge of exploit development
- Introduce an automated approach to facilitate exploit development
- Demonstrate how the new technique facilitate mitigation circumvention

Background

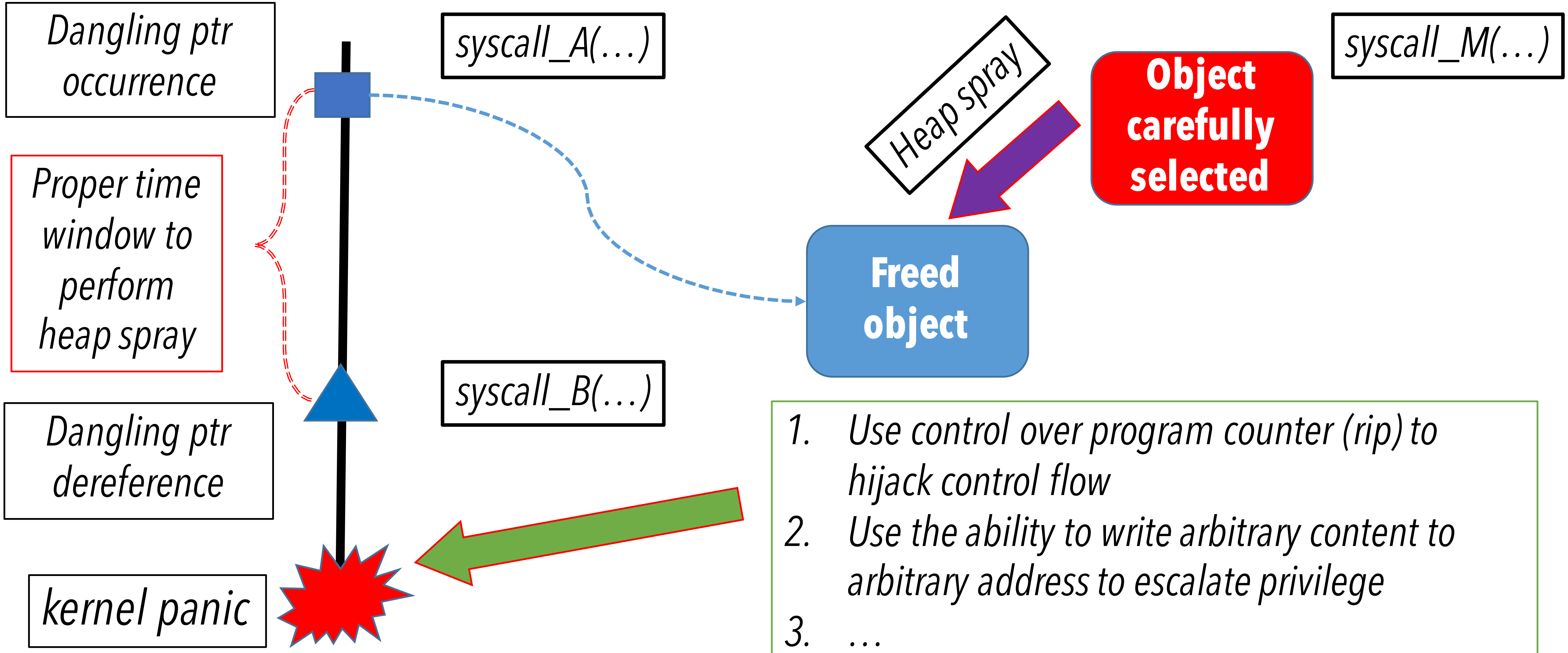
- All software contain bugs, and # of bugs grows with the increase of software complexity
  - E.g., Syzkaller/Syzbot reports 800+ Linux kernel bugs in 8 months
- Due to the lack of manpower, it is very rare that a software development team could patch all the bugs timely
  - E.g., A Linux kernel bug could be patched in a single day or more than 8 months; on average, it takes 42 days to fix one kernel bug

- The best strategy for software development team is to prioritize their remediation efforts for bug fix
  - E.g. based on its influence upon usability
  - E.g., based on its influence upon software security
  - E.g., based on the types of the bugs
  - … …

Background (cont.)

- Most common strategy is to fix a bug based on its exploitability
- To determine the exploitability of a bug, analysts generally have to write a working exploit, which needs
  1) Significant manual efforts
  2) Sufficient security expertise
  3) Extensive experience in target software

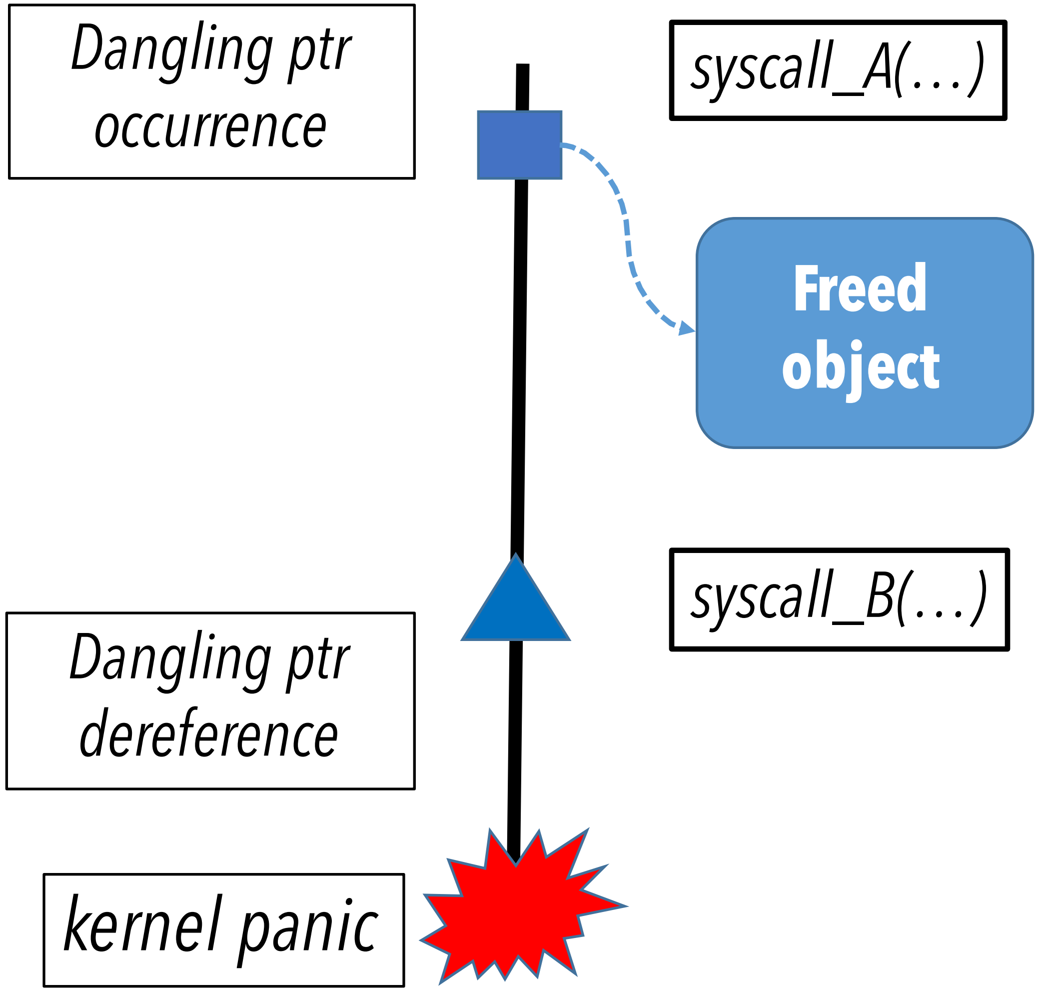
Crafting an Exploit for Kernel Use-After-Free



1. Use control over program counter (rip) to hijack control flow
2. Use the ability to write arbitrary content to arbitrary address to escalate privilege
3. …

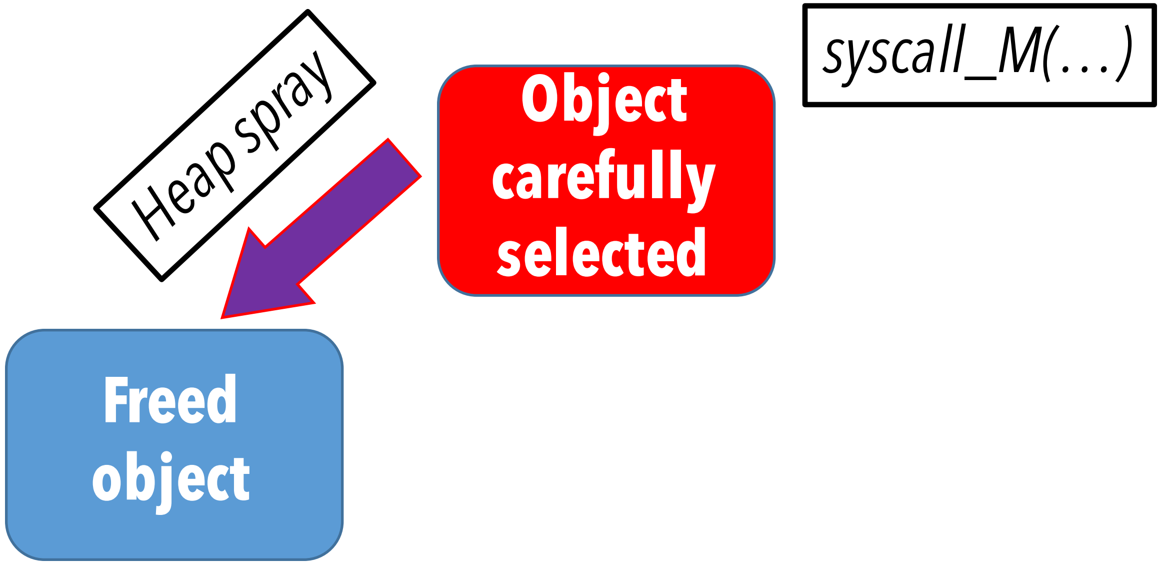
Challenge 1: Needs Intensive Manual Efforts

- Analyze the kernel panic
- Manually track down
    1. The site of dangling pointer occurrence and the corresponding system call
    2. The site of dangling pointer dereference and the corresponding system call



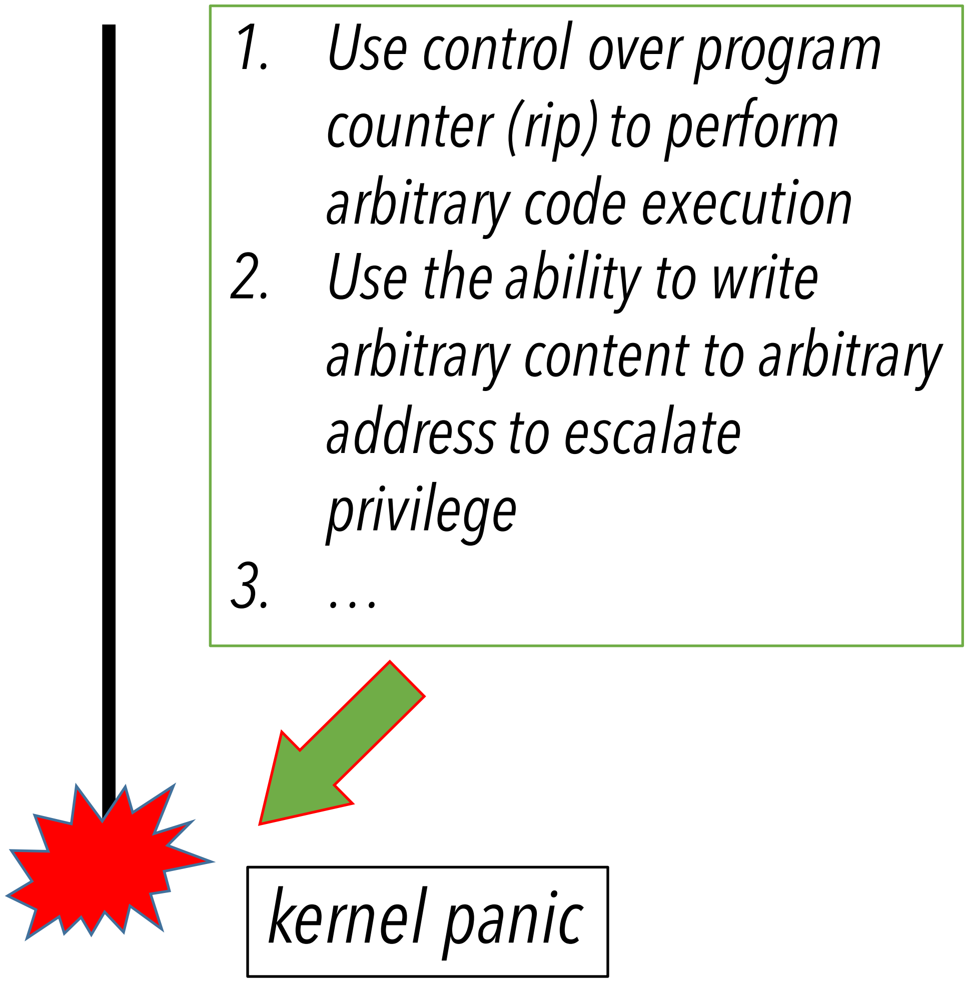
Challenge 2: Needs Extensive Expertise in Kernel

- Identify all the candidate objects that can be sprayed to the region of the freed object
- Pinpoint the proper system calls that allow an analyst to perform heap spray
- Figure out the proper arguments and context for the system call to allocate the candidate objects



Challenge 3: Needs Security Expertise

- Find proper approaches to accomplish arbitrary code execution or privilege escalation or memory leakage
  - E.g., chaining ROP
  - E.g., crafting shellcode
  - …



Some Past Research Potentially Tackling the Challenges

- Approaches for Challenge 1
  - Nothing I am aware of, but simply extending KASAN could potentially solve this problem
- Approaches for Challenge 2
  - [Blackhat07] [Blackhat15] [USENIX-SEC18]
- Approaches for Challenge 3
  - [NDSS'11] [S&P16], [S&P17]

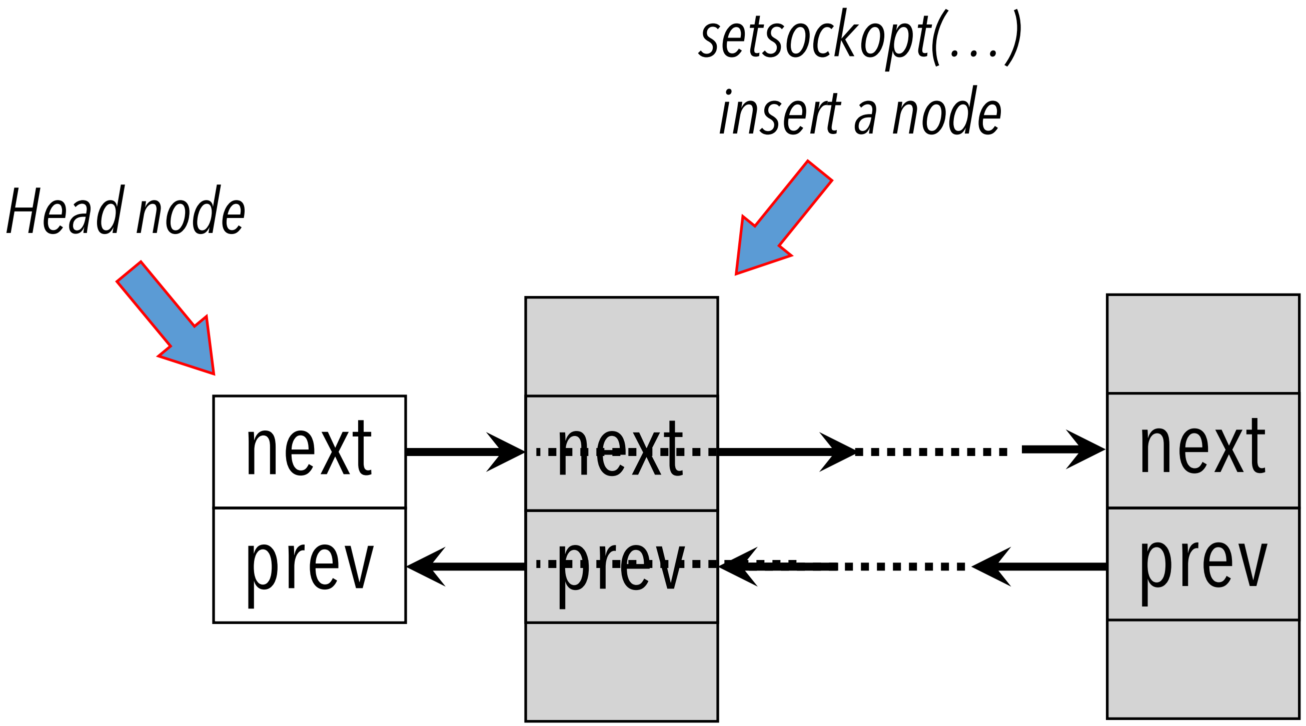
[NDSS11] Avgerinos et al., AEG: Automatic Exploit Generation.
[Blackhat 15] Xu et al., Ah! Universal android rooting is back.
[S&P16] Shoshitaishvili et al., Sok:(state of) the art of war: Offensive techniques in binary analysis.
[USENIX-SEC18] Heelan et al., Automatic Heap Layout Manipulation for Exploitation.
[S&P17] Bao et al., Your Exploit is Mine: Automatic Shellcode Transplant for Remote Exploits.
[Blackhat07] Sotirov, Heap Feng Shui in JavaScript


UNSOLVED

Roadmap

- Unsolved challenges in exploitation facilitation
- Our techniques -- FUZE
- Demonstration with real-world Linux kernel vulnerabilities
- Conclusion

A Real-World Example (CVE-2017-15649)




```
void *task1(void *unused) {
  ...
  int err = setsockopt(fd, 0x107, 18,
      ..., ...);
}

void *task2(void *unused) {
  int err = bind(fd, &addr, ...);
}

void loop_race() {
  ...
  while(1) {
    fd = socket(AF_PACKET, SOCK_RAW,
        htons(ETH_P_ALL));
    ...
    //create two racing threads
    pthread_create (&thread1, NULL,
        task1, NULL);
    pthread_create (&thread2, NULL,
        task2, NULL);

    pthread_join(thread1, NULL);
    pthread_join(thread2, NULL);

    close(fd);
  }
}
```

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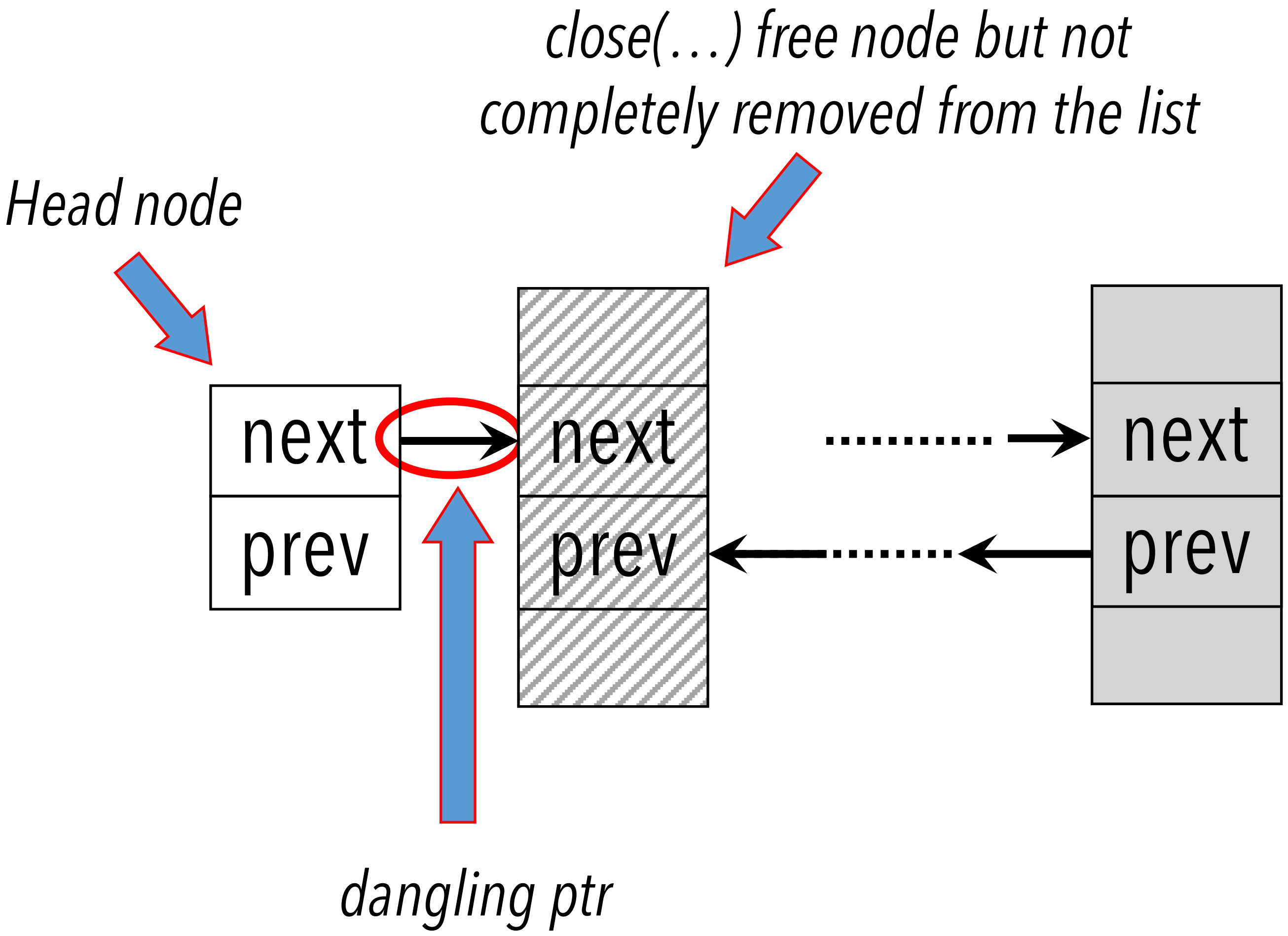


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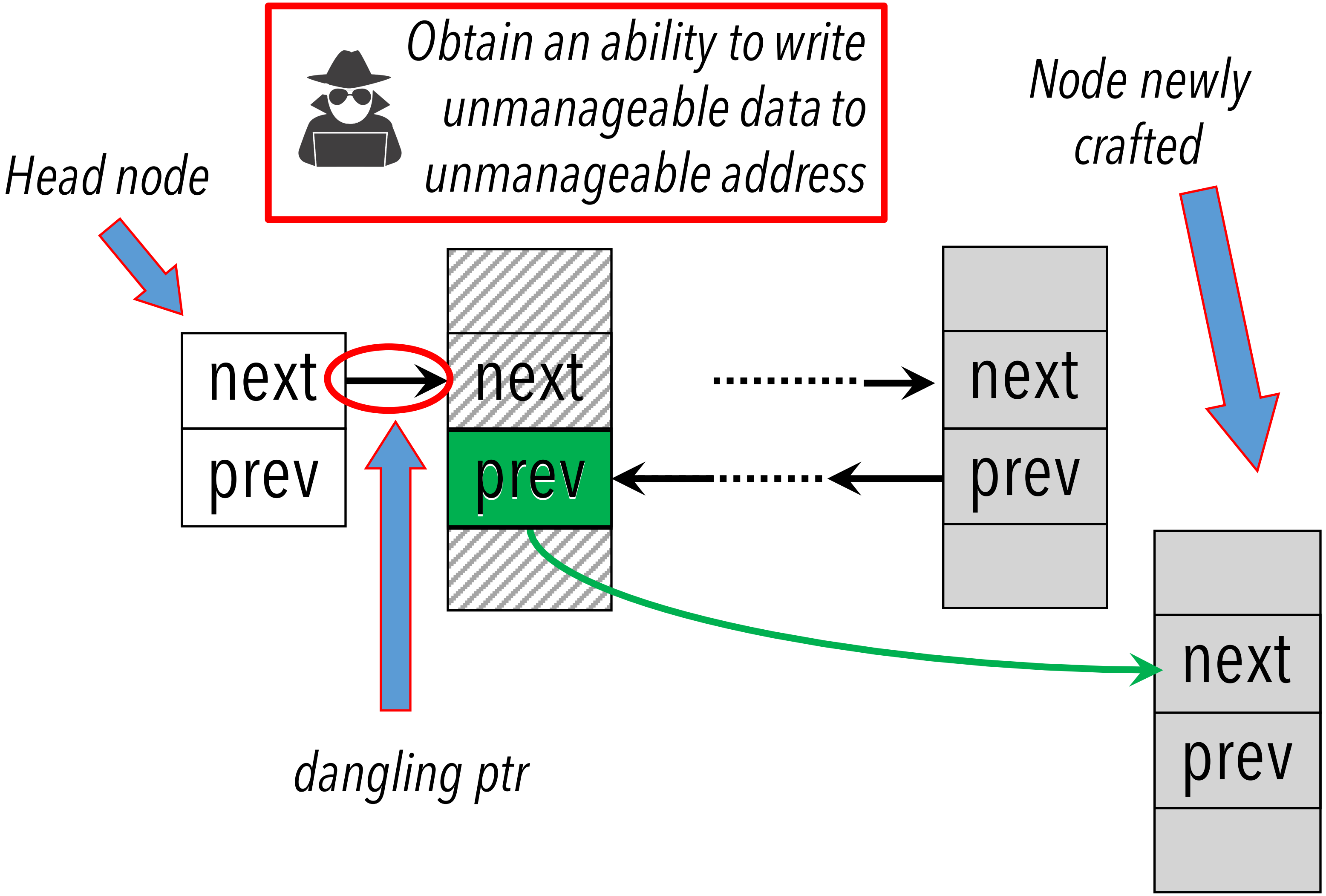
    close(fd);
  }
}
```

Challenge 4: No Primitive Needed for Exploitation




```
void *task1(void *unused) {
  ...
  int err = setsockopt(fd, 0x107, 18,
      ..., ...);
}

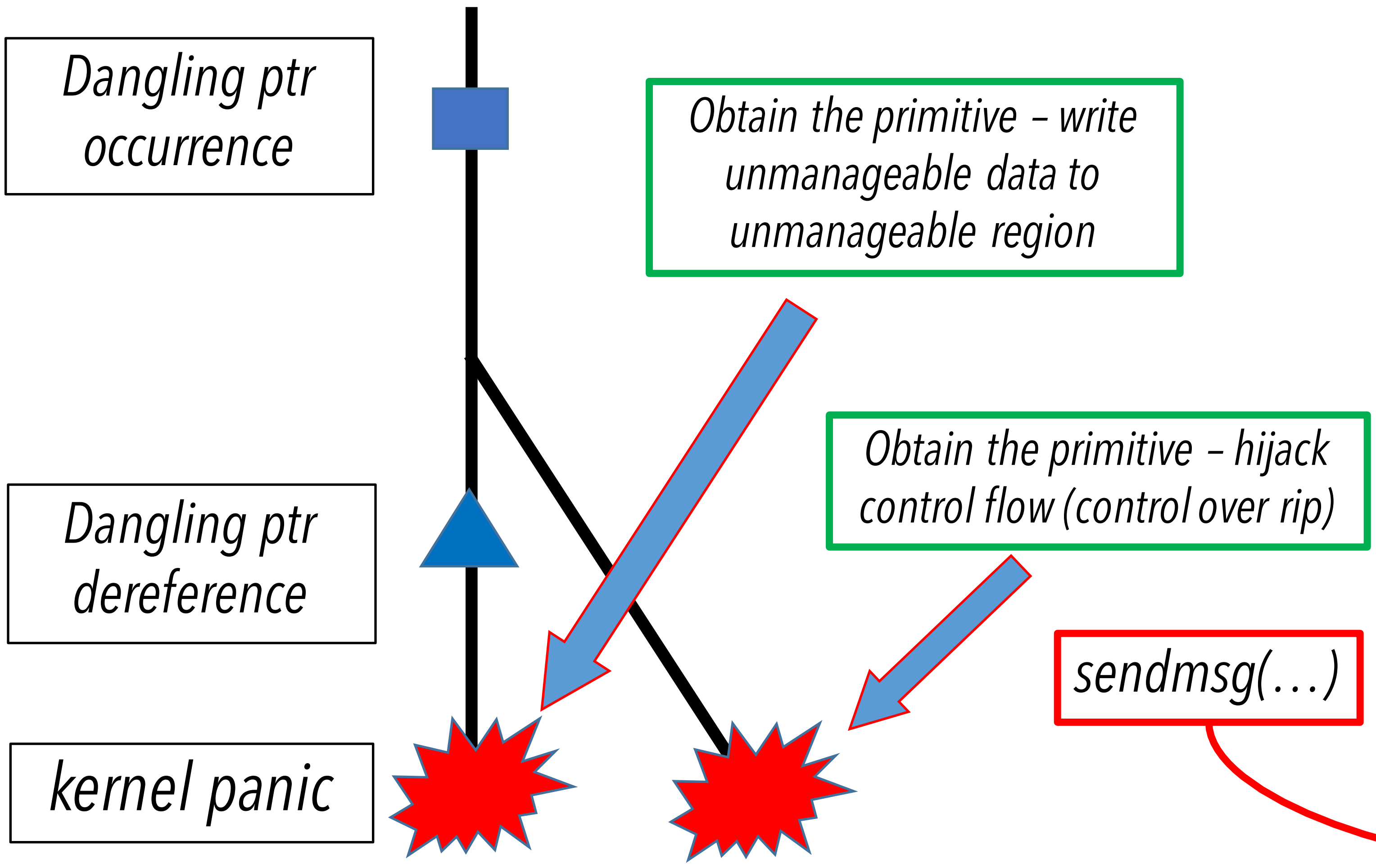
void *task2(void *unused) {
  int err = bind(fd, &addr, ...);
}

void loop_race() {
  ...
  while(1) {
    fd = socket(AF_PACKET, SOCK_RAW,
        htons(ETH_P_ALL));
    ...
    //create two racing threads
    pthread_create (&thread1, NULL,
        task1, NULL);
    pthread_create (&thread2, NULL,
        task2, NULL);

    pthread_join(thread1, NULL);
    pthread_join(thread2, NULL);

    close(fd);
  }
}
```

No Useful Primitive == Unexploitable??




```
void *task1(void *unused) {
  ...
  int err = setsockopt(fd, 0x107, 18,
      ↪ ..., ...);
}

void *task2(void *unused) {
  int err = bind(fd, &addr, ...);
}

void loop_race() {
  ...
  while(1) {
    fd = socket(AF_PACKET, SOCK_RAW,
        ↪ htons(ETH_P_ALL));
    ...
    //create two racing threads
    pthread_create (&thread1, NULL,
        ↪ task1, NULL);
    pthread_create (&thread2, NULL,
        ↪ task2, NULL);

    pthread_join(thread1, NULL);
    pthread_join(thread2, NULL);

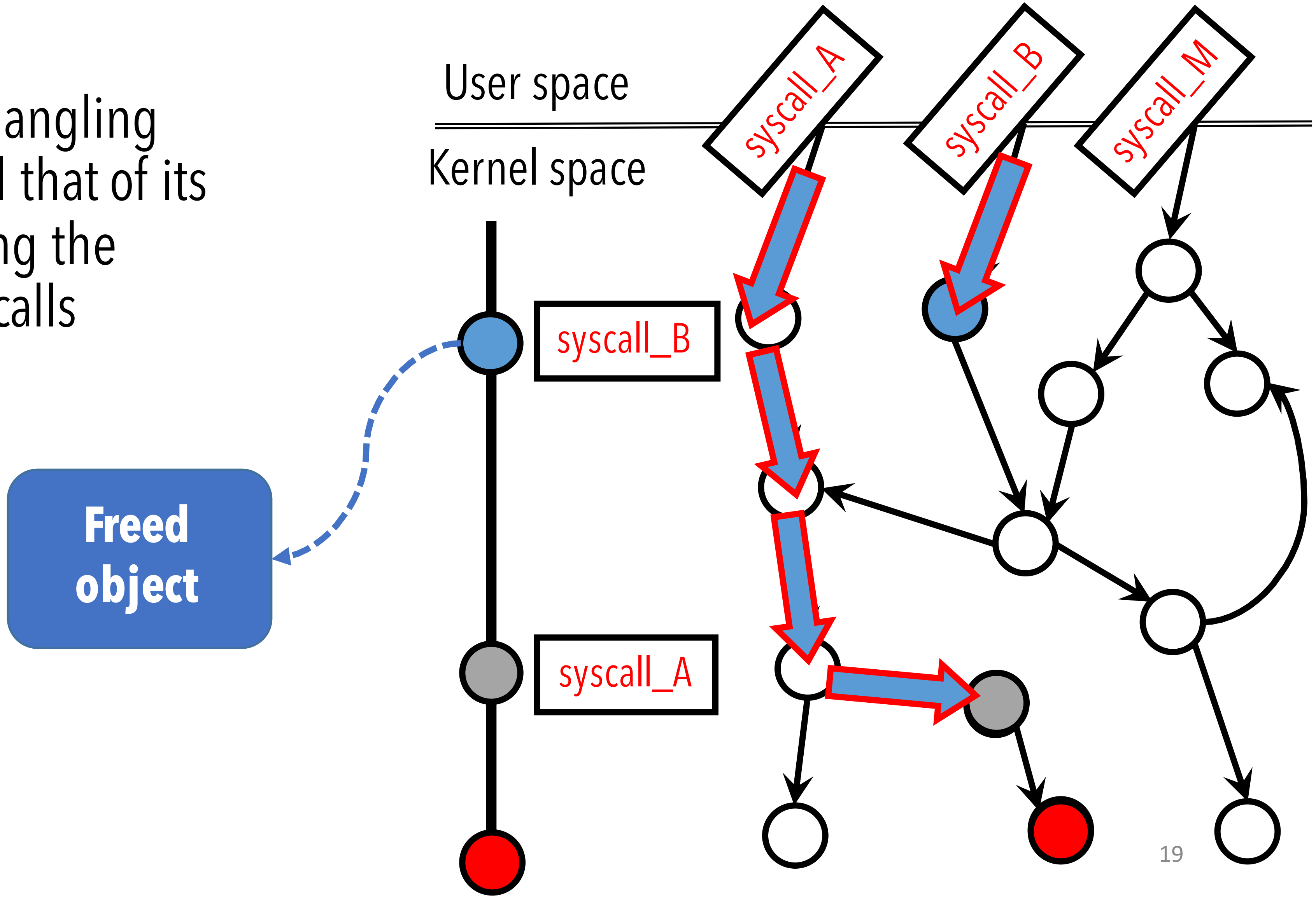
    close(fd);
  }
}
```

Roadmap

- Unsolved challenges in exploitation facilitation
- Our techniques -- FUZE
- Evaluation with real-world Linux kernel vulnerabilities
- Conclusion

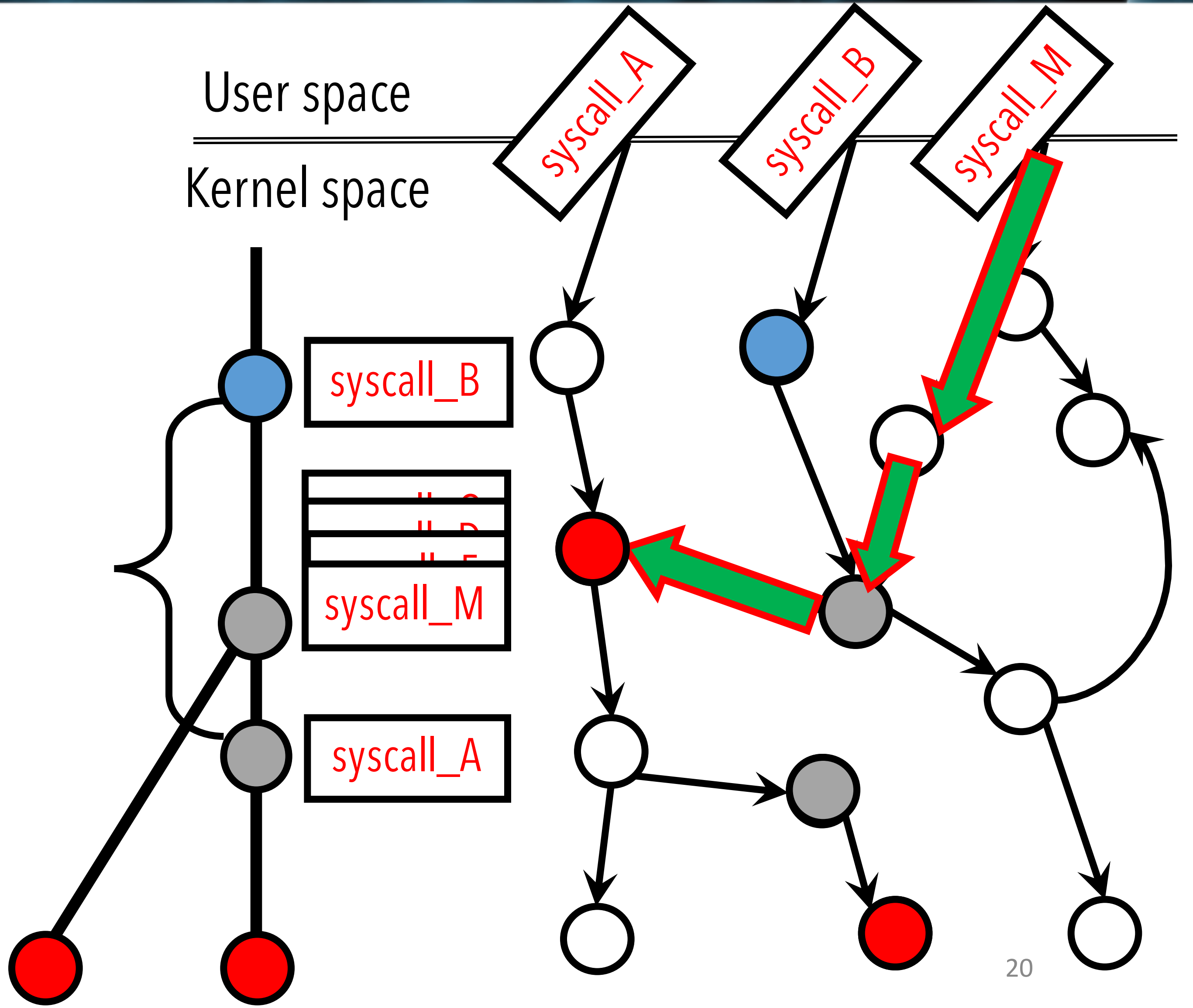
FUZE – Extracting Critical Info.

- Identifying the site of dangling pointer occurrence, and that of its dereference; pinpointing the corresponding system calls



FUZE – Performing Kernel Fuzzing

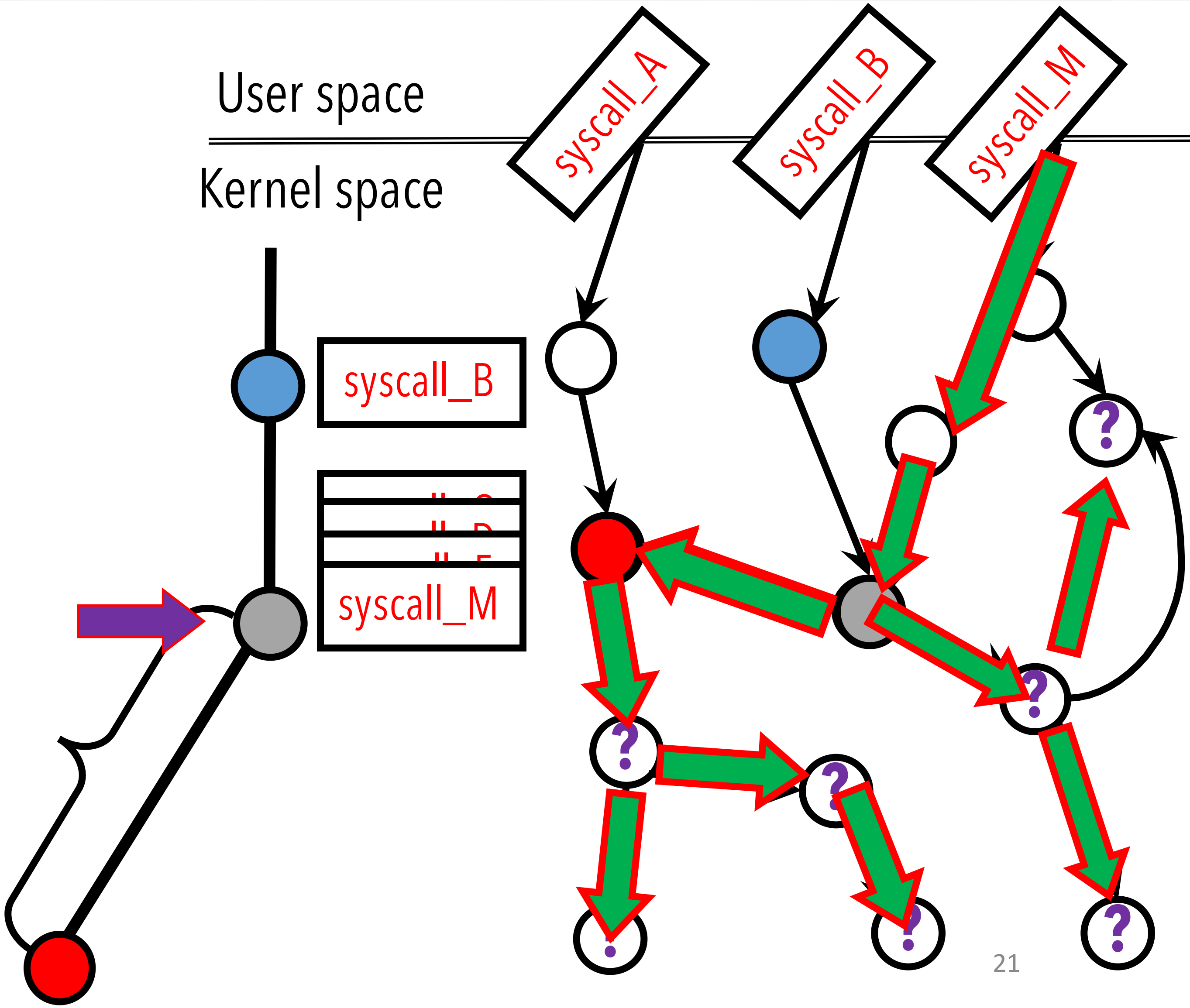
- Identifying the site of dangling pointer occurrence, and that of its dereference; pinpointing the corresponding system calls
- Performing kernel fuzzing between the two sites and exploring other panic contexts (i.e., different sites where the vulnerable object is dereferenced)



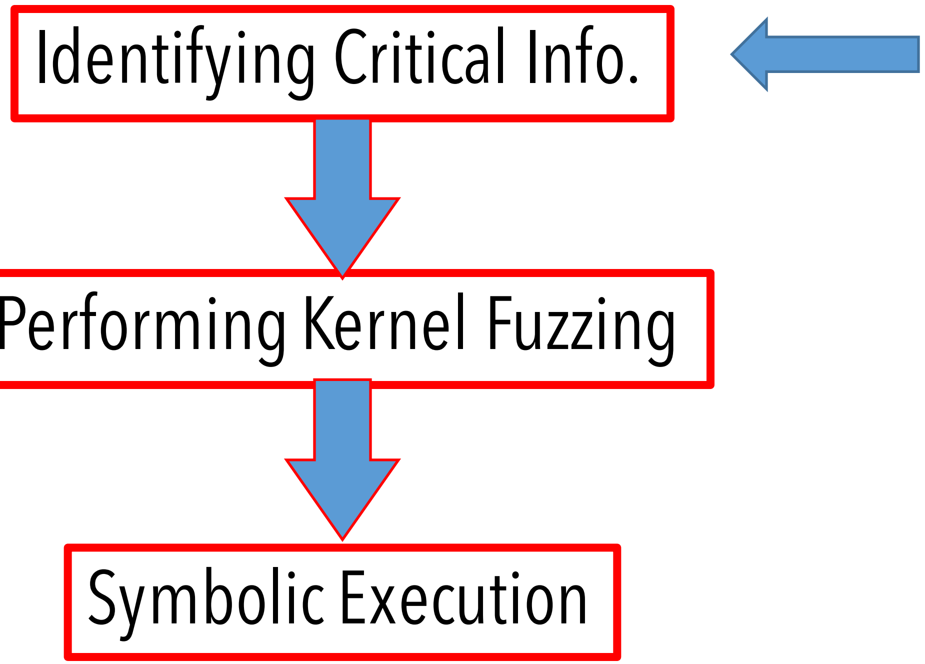
FUZE – Performing Symbolic Execution

- Identifying the site of dangling pointer occurrence, and that of its dereference; pinpointing the corresponding system calls
- Performing kernel fuzzing between the two sites and exploring other panic contexts (i.e., different sites where the vulnerable object is dereferenced)
- Symbolically execute at the sites of the dangling pointer dereference

Freed object ← Set symbolic value for each byte

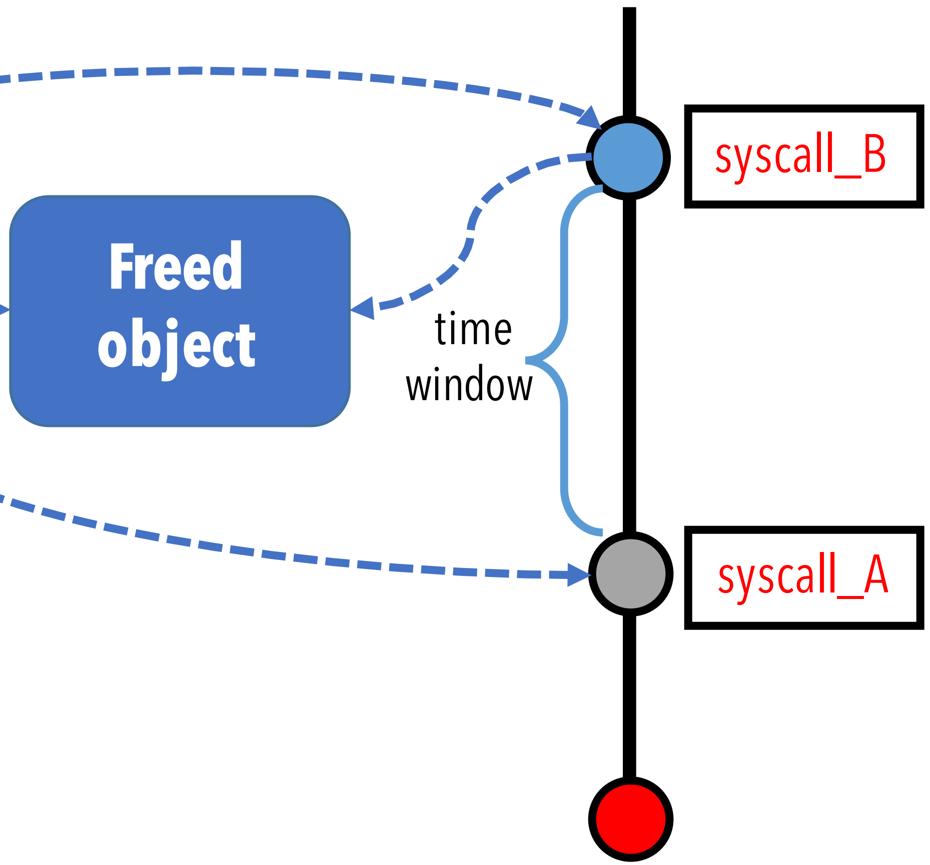


Crafting Working Exploits Step by Step



Critical Information Extraction

- Goal: identifying following critical information
  - Vulnerable object
  - Free site
  - Dereference site
  - Syscalls in PoC tied to corresponding free and dereference
  - Time window between free and dereference
- Methodology:
  - Instrument the PoC with ftrace and generate ftrace log
  - instrument kernel with KASAN
  - Combining both ftrace and KASAN log for analysis



Critical Information Extraction (cont)

- Goal: identifying following critical information
  - Vulnerable object
  - Free site
  - Dereference site
  - Syscalls in PoC tied to corresponding free and dereference
  - Time window between free and dereference
- Methodology:
  - Instrument the PoC with ftrace[1] and generate ftrace log
  - instrument kernel with KASAN[2]
  - Combining both ftrace and KASAN log for analysis

Unique ID for each syscall in PoC

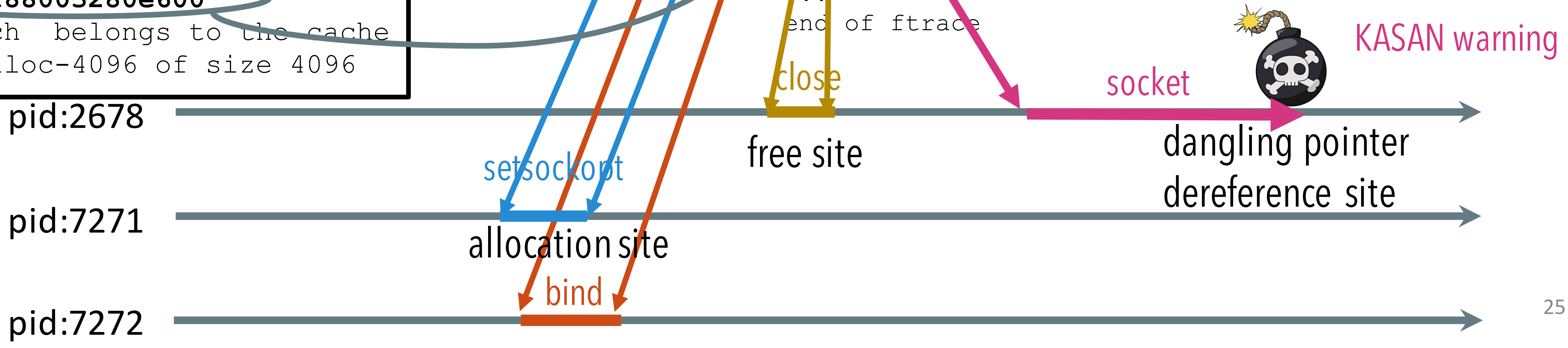
```
void *task1(void *unused) {
   ...
   write_ftrace_marker(1);
   int err = setsockopt(...);
   write_ftrace_marker(1);
}
void *task2(void *unused) {
   write_ftrace_marker(2);
   int err = bind(...);
   write_ftrace_marker(2);
}
…
void loop_race(){
   ...
}
int main(){
   ftrace_kmem_trace_enable();
   loop_race();
}
```

[1] ftrace. https://www.kernel.org/doc/Documentation/trace/ftrace.txt
[2] kasan. https://github.com/google/kasan/wiki

Critical Information Extraction (cont)

```
BUG: KASAN: use-after-free
in dev_add_pack+0x304/0x310
Write of size 8 at addr
ffff88003280ee70
by task poc/2678
Call Trace:
    ...
Allocated by task 7271:
    ...(allocation trace)
Freed by task 2678:
    ...(free trace)
The buggy address belongs
to the object at
ffff88003280e600
which  belongs to the cache
kmalloc-4096 of size 4096
```

```
...
poc-7271 : tracing_mark_write: executing syscall: setsockopt
poc-7272 : tracing_mark_write: executing syscall: bind
poc-7271 : kmalloc: call_site=... ptr=ffff88003280e600
bytes_req=2176 bytes_alloc=4352 gfp_flags=GFP_KERNEL
...
poc-7271 : tracing_mark_write: finished syscall: setsockopt
...
poc-7272 : tracing_mark_write: finished syscall: bind
...
poc-2678 : tracing_mark_write: executing syscall: close
poc-2678 : kfree: call_site=... ptr=ffff88003280e600
...
poc-2678 : tracing_mark_write: finished syscall: close
poc-2678 : tracing_mark_write: executing syscall: socket
...
end of ftrace
```



Critical Information Extraction (cont)

```
void *task1(void *unused) {
  ...
  int err = setsockopt(fd,
0x107, 18, ..., ...);
}
void *task2(void *unused) {
  int err = bind(fd, &addr,
...);
}
```

```
void loop_race() {
   ...
   while(1) {
     fd = socket(AF_PACKET, SOCK_RAW,
htons(ETH_P_ALL));
     ...
     pthread_create (&thread1, NULL, task1, NULL);
     pthread_create (&thread2, NULL, task2, NULL);
     pthread_join(thread1, NULL);
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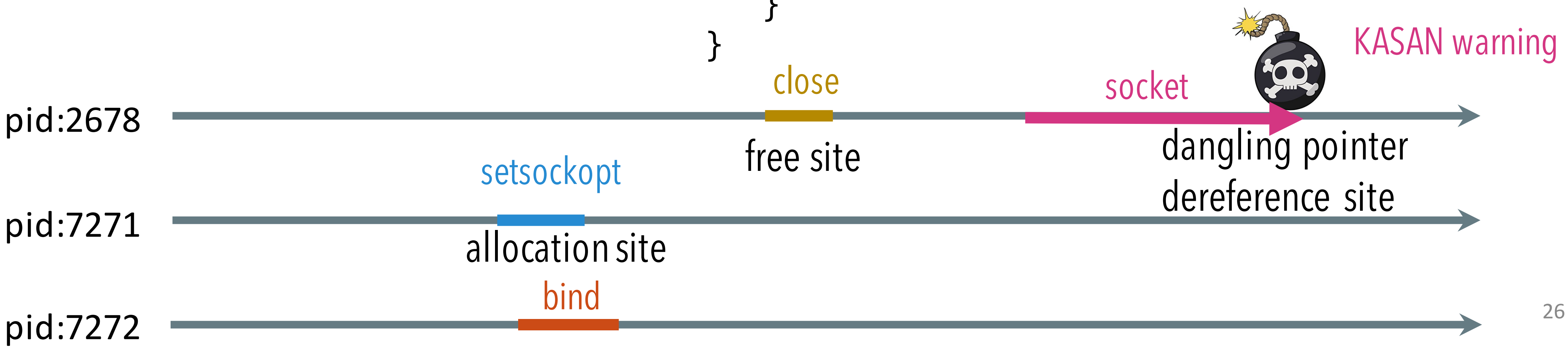
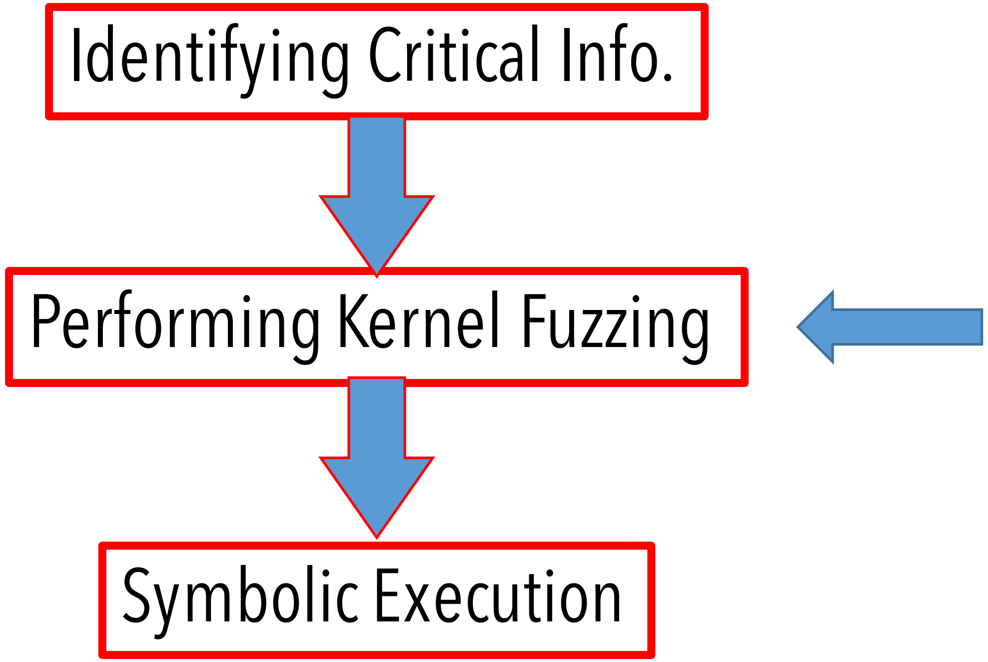
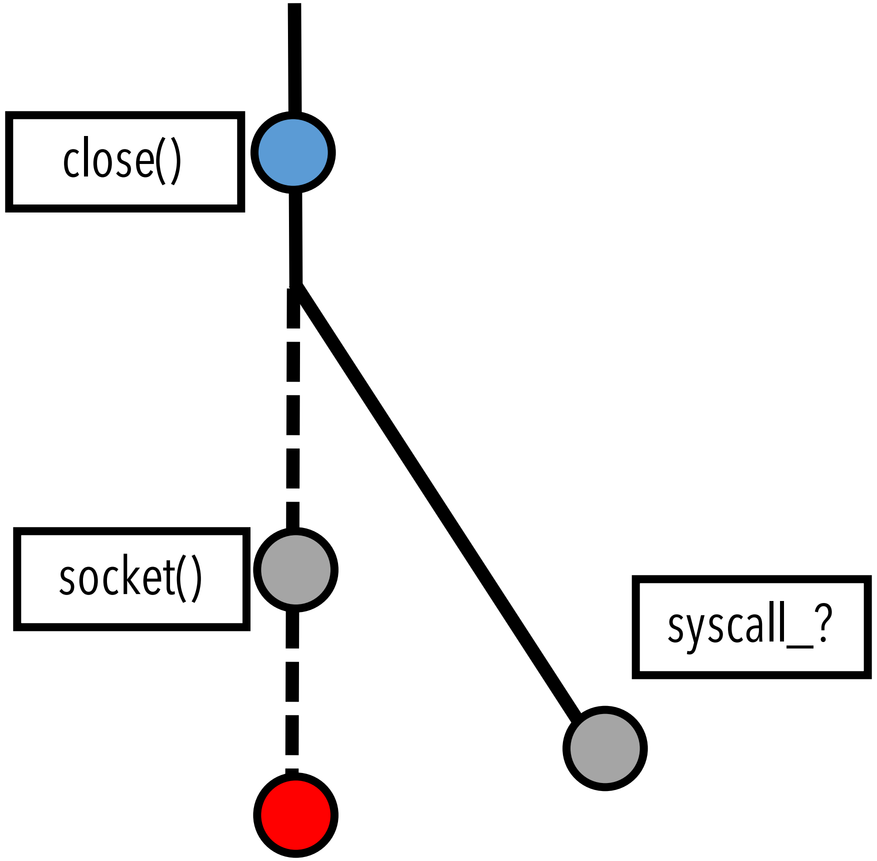
     close(fd);
   }
}
```



Crafting Working Exploits Step by Step



Kernel Fuzzing

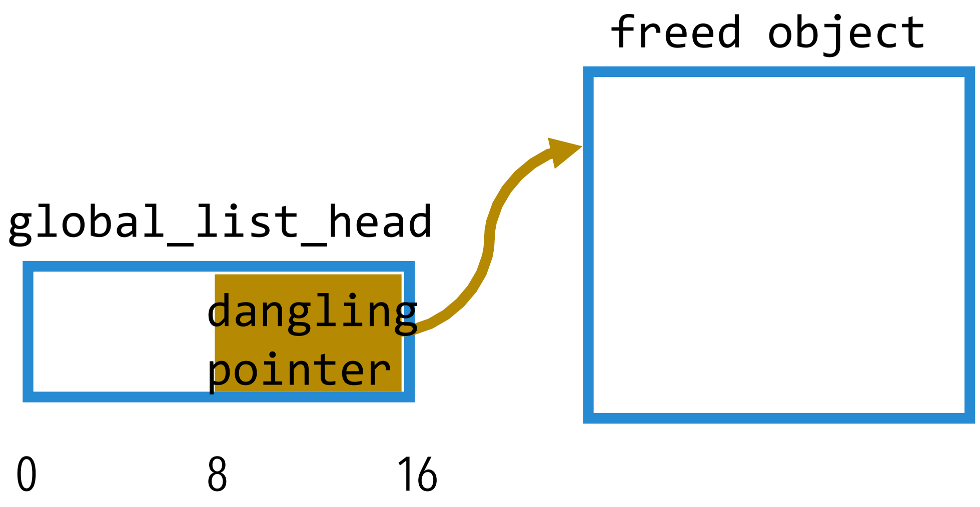



```
poc_wrapper(){
 /* PoC wrapping function */
    ...
    socket();//dereference site
    while(true){ // Race condition
        ...
        threadA(...);
        threadB(...);
        ...
        close(); //free site
        /* instrumented statements */
        if (!ioctl(...)) // interact with
a kernel module
            return;
    }
}
poc_wrapper();
fuzzing();
```

Kernel Module for Dangling Pointer Identification

- Identifying dangling pointer through the global variable pertaining to vulnerable object
  - Setting breakpoint at syscall tied to the dangling pointer dereference
  - Executing PoC program and triggering the vulnerability
  - Debugging the kernel step by step and recording dataflow (all registers)
  - Tracking down global variable (or current task_struct) through backward dataflow analysis
  - Recording the base address the global variable (or current task_struct) and the offset corresponding to the freed object

```
mov rdx, ds: global_list_head
...
mov rax, qword ptr[rdx+8]
mov rdi, qword ptr[rax+16] : dangl. deref.
```



Kernel Module for Dangling Pointer Identification (cont)

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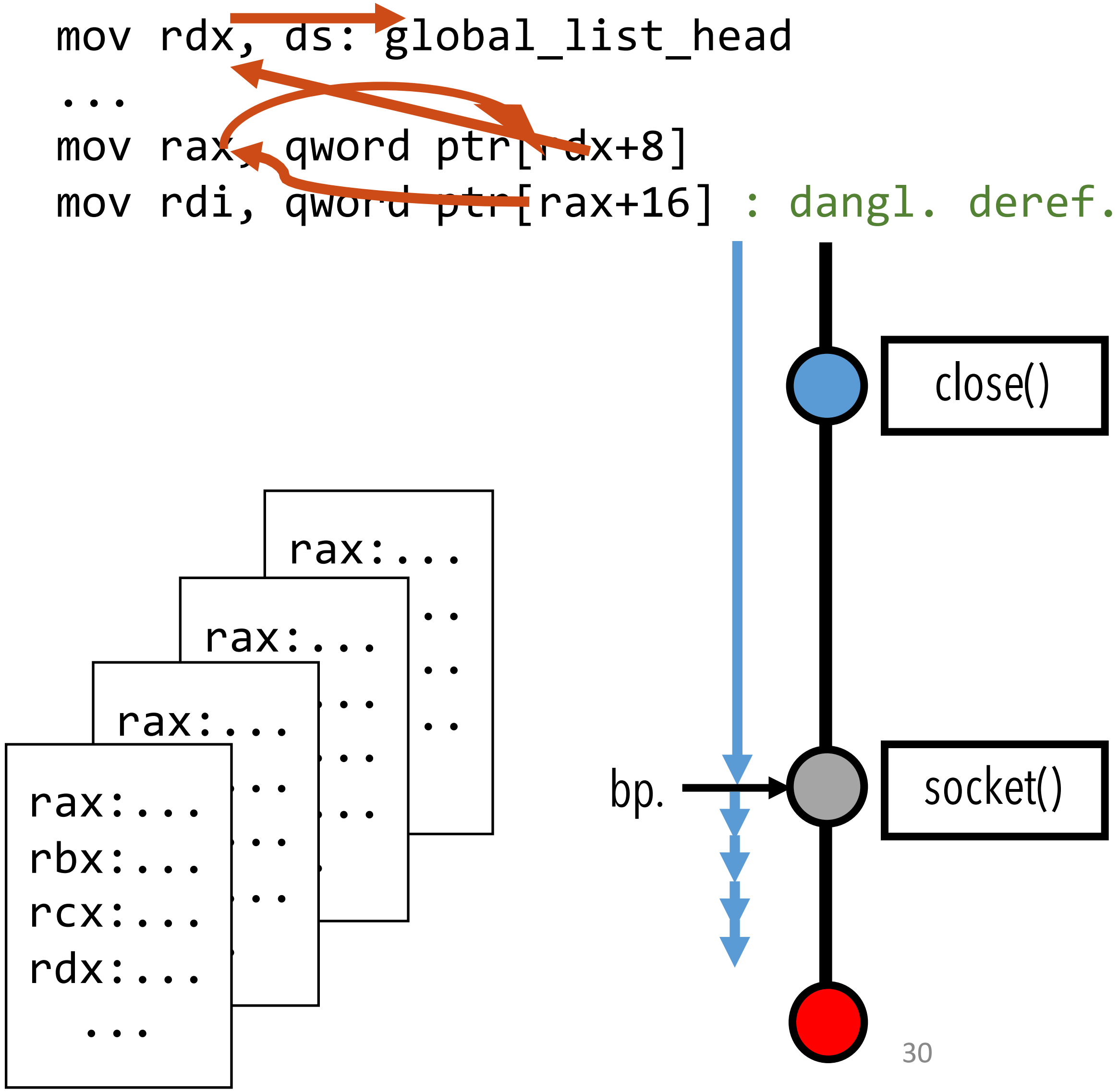


Kernel Fuzzing(cont)

- Reusing syzkaller[1] to performing kernel fuzzing after a dangling pointer is identified
  - generate syz-executor which invoke poc_wrapper first
- enable syscalls that potentially dereference the vulnerable object
  - "enable_syscalls"
- transfer variables that appears in the PoC into the interface
  - e.g. file descriptors

```
poc_wrapper();
fuzzing();
```

[1] syzkaller – kernel fuzzer. https://github.com/google/syzkaller

Crafting Working Exploits Step by Step

Identifying Critical Info.

↓

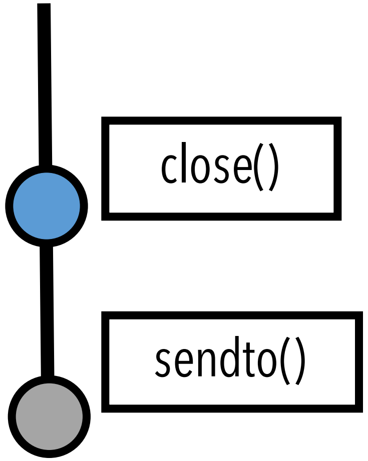
Performing Kernel Fuzzing

↓

Symbolic Execution ←

Symbolic Execution

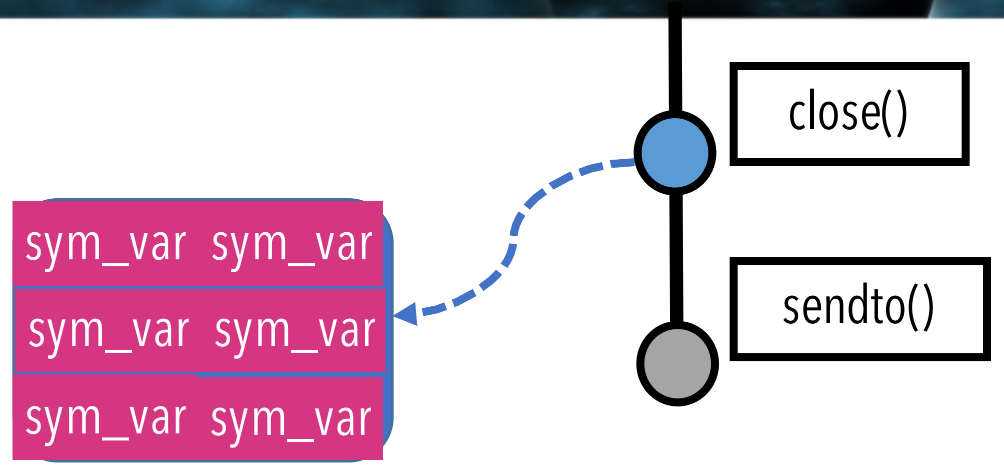
- Symbolic execution for kernel is challenging.
  - How to model and emulate interrupts?
  - How to handling multi-threading?
  - How to emulate hardware device?
- Our goal: use symbolic execution for identifying exploitable primitives
- We can opt-in angr[1] for kernel symbolic execution from a concrete state 
  - single thread
  - no interrupt
  - no context switching



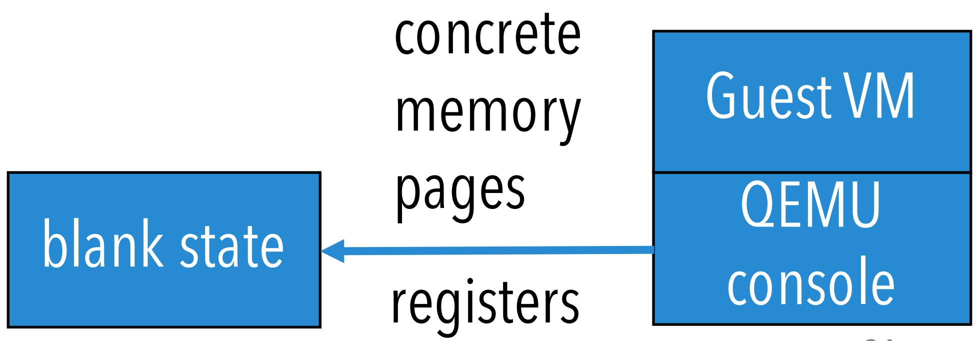
[1] angr. http://angr.io/

Symbolic Execution

- Symbolic Execution initialization
  - Setting conditional breakpoint at the dangling pointer dereference site
  - Running the PoC program to reach the dangling pointer dereference site
  - Migrating the memory/register state to a blank state
  - Setting freed object memory region as symbolic
  - Starting symbolic execution!
- Challenges:
  - How to handle state(path) explosion
  - How to determine exploitable primitive
  - How to handle symbolic read/write




```
for i in range(uaf_object_size):
    sym_var = state.se.BVS("uaf_byte"+str(i), 8)
    state.memory.store(uaf_object_base+i,sym_var)
```



State(Path) Explosion

Memory consumption ≈ number_of_states * size_of_each_state

- Our design already mitigates state explosion by starting from the first dereference site
  - no syscall issues
  - no user input issues
- However, if a byte from the freed object is used in a branch condition, path explosion occurs.
- Workarounds:
  - limiting the time of entering a loop.
  - limiting the total length of a path.
  - copying concrete memory page on demand
  - writing kernel function summary.
    - e.g. mutex_lock

```
    mov edx, dword ptr[freed obj]
loop:
    ...
    inc ecx
    cmp ecx, edx
    jne loop (0xffffffff81abcdef)
    ...
```

active states: loop, loop, loop, loop, loop, loop, ...

```
for state in simgr.active:
    if detect_loop(state, 5):
        simgr.remove(state)

for state in simgr.active:
    if len(state.history) > 200:
        simgr.remove(state)
```

Useful primitive identification

- Unconstrained state
  - state with symbolic Instruction pointer
  - symbolic callback
- double free
  - e.g. `mov rdi, uaf_obj; call kfree`
- memory leak
  - invocation of copy_to_user with src point to a freed object
  - syscall return value

Code fragment related to an exploit primitive of CVE-2017-15649

```
if (ptype->id_match)
    return ptype->id_match(ptype, skb->sk)
```

Code fragment related to an exploit primitive of CVE-2017-17053

```
...
kfree(ldt); // ldt is already freed
```

Code fragment related to an exploit primitive of CVE-2017-8824

```
case 127...191:
    return ccid_hc_rx_getsockopt(dp->dccps_hc_rx_ccid, sk, optname, len, (u32 __user *)optval, optlen)
```

Useful primitive identification(cont)

- write-what-where
  - mov qword ptr [rdi], rsi

rdi (destination)	rsi (source)	primitive
symbolic	symbolic	arbitrary write (qword shoot)
symbolic	concrete	write fixed value to arbitrary address
free chunk	any	write to freed object
x(concrete)	x(concrete)	self-reference structure
metadata of freed chunk	any	meta-data corruption
…	…	…

From Primitive to Exploitation

- When you found a cute exploitation technique, why not make it reusable?
- Each technique can be implemented as state plugins to angr.
- Exploit technique database
  - Control flow hijack attacks:
    - pivot-to-user
    - turn-off-smap and ret-to-user
    - set_rw() page permission modification
    - …
  - Double free attacks
    - auxiliary victim object
    - loops in free pointer linked list
  - memory leak attacks
    - leak sensitive information (e.g. credentials)
  - write-what-where attacks
    - heap metadata corruption
    - function-pointer-hijack
    - vdso-hijack
    - credential modification
    - …

From Primitive to Exploitation: SMEP bypass

- Solution: ROP
  - stack pivot to userspace [1]

```
If simgr.unconstrained:
    for ucstate in simgr.unconstrained:
        try_pivot_and_rop_chain(ucstate)
```

control flow hijack primitive

```
mov rax, qword ptr[evil_ptr]
call rax
```

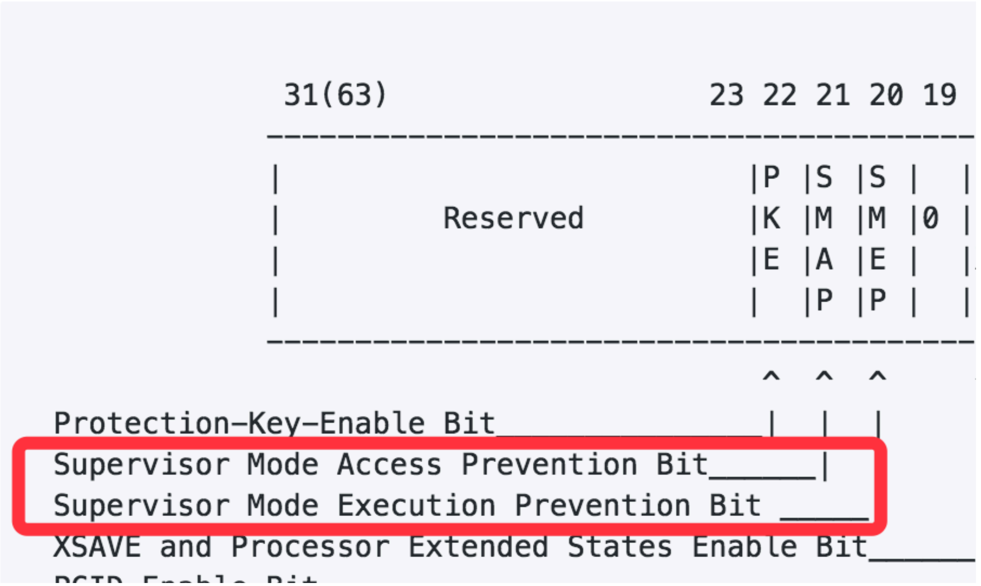
stack pivot gadget

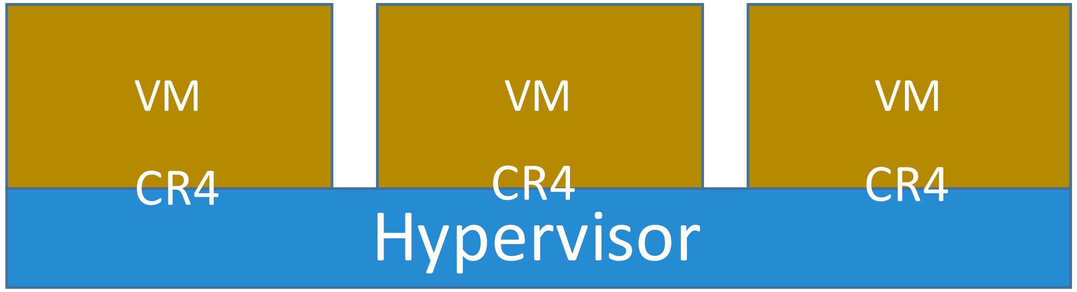
```
xchg eax, esp; ret
```

[1] Linux Kernel ROP – Ropping your way to # (Part 2)
https://www.trustwave.com/Resources/SpiderLabs-Blog/Linux-Kernel-ROP---Ropping-your-way-to---(Part-2)

From Primitive to Exploitation: SMAP bypass

- Solution: using two control flow hijack primitives to clear SMAP bit (21th) in CR4 and land in shellcode
  - 1st --- > mov cr4, rdi ; ret
  - 2nd --- > shellcode
- limitation
  - can not bypass hypervisor that protects control registers
- Universal Solution: kernel space ROP
  - bypass all mainstream mitigations.





Extra Symbolization

- Goal: enhance the ability to find useful primitives
- Observation: we can use a ROP/JOP gadget to control an extra register and explore more state space
- Approach:
  - forking states with additional symbolic register upon symbolic states
  - We may explore more states by adding extra symbolic registers

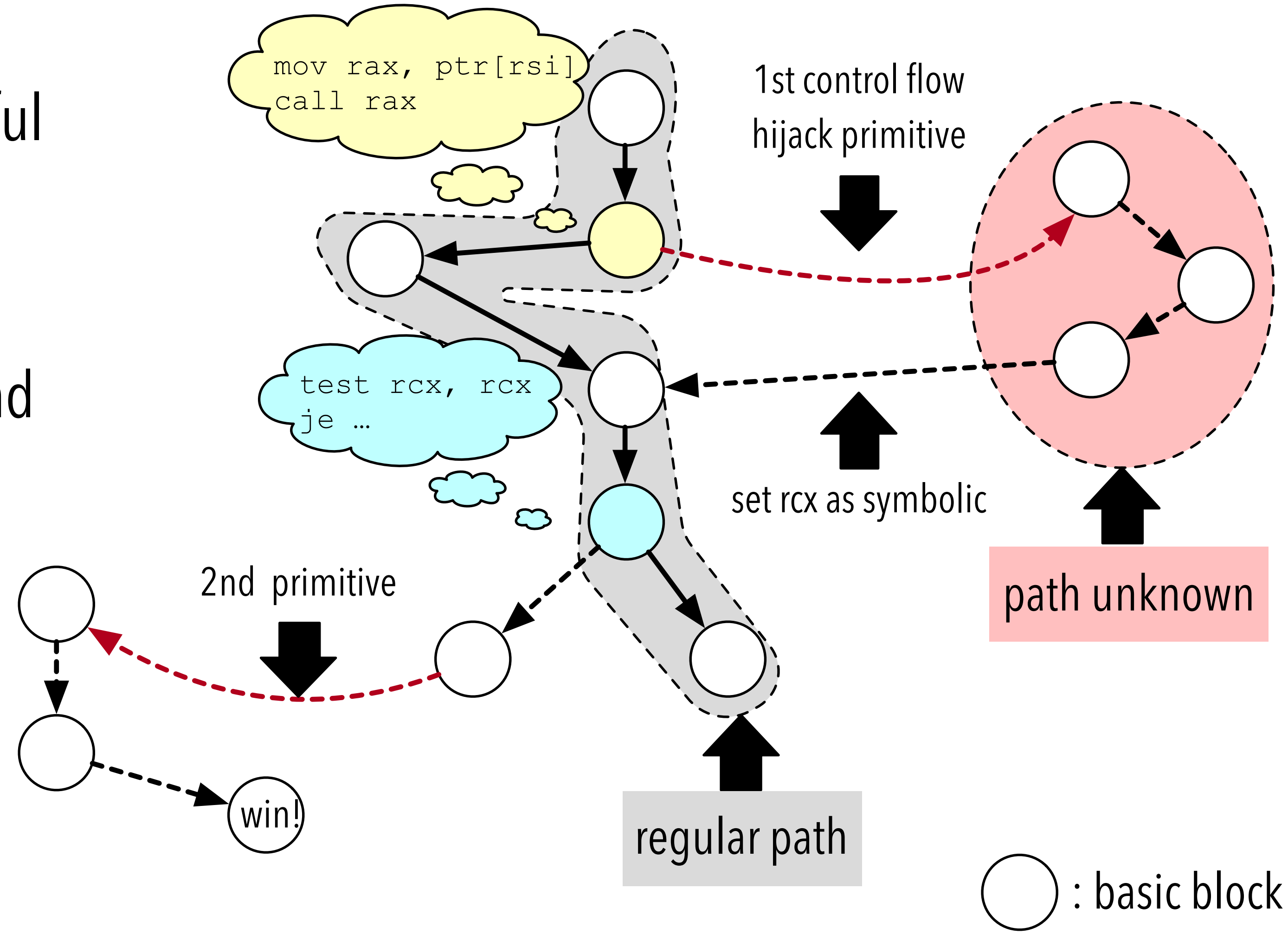


Figure: Identifying two control flow hijack primitive for CVE-2017-15649

From Primitive to Exploitation: post-exploit fix

- Sometimes we get control flow hijack primitive in interrupt context.
  - avoiding double fault: keep writing to your ROP payload page to keep it mapped in

- Some syscall (e.g. execve) checks current execution context (e.g. via reading preempt_count) and decides to panic upon unmatched context.

`BUG_ON(in_interrupt());` →

```
------------[ cut here ]------------
kernel BUG at linux/mm/vmalloc.c:1394!
```

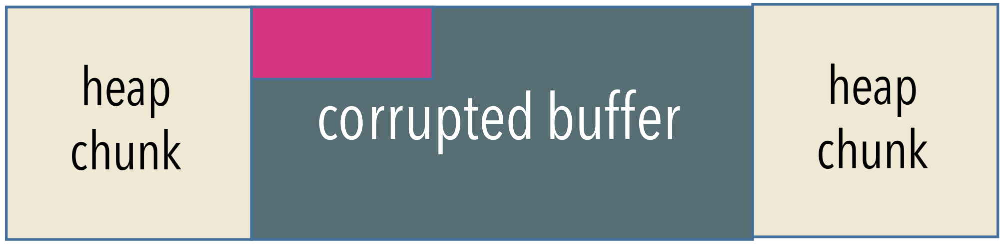
- Solution: fixing preempt_count before invoking `execve(“/bin/sh”, NULL, NULL)`

Symbolic Read/Write

```
t0
  mov rdi, QWORD PTR [corrupted_buffer]
t1
  mov rax, QWORD PTR [rdi]
t2
```

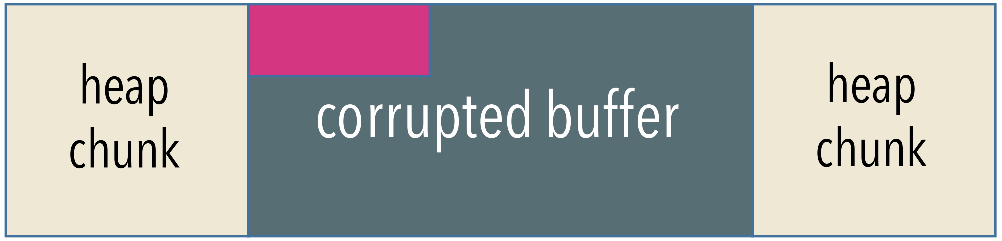
t0

rdi: symbolic_qword



t1

rdi: ??? rax: ???

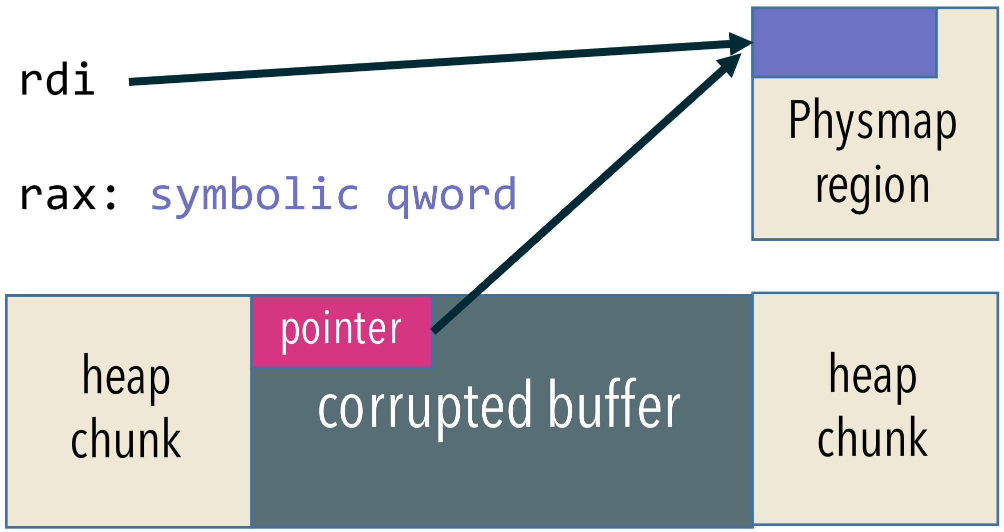


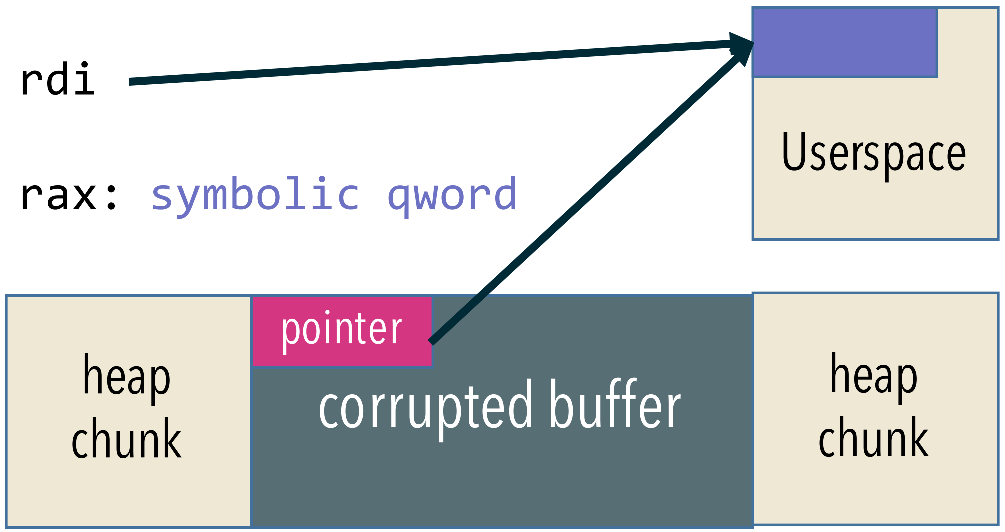
t2

Symbolic read/write concretization strategy

- Concretize the symbolic address to pointing a region under our control
  - no SMAP: entire userspace
  - with SMAP but no KASLR: physmap region
  - with SMAP and KASLR: … need a leak first

```
mov rdi, QWORD PTR [corrupted_buffer]
mov rax, QWORD PTR [rdi]
```





Roadmap

- Unsolved challenges in exploitation facilitation
- Our techniques -- FUZE
- Demonstration with real-world Linux kernel vulnerabilities
- Conclusion

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Case Study

#BHUSA

- 15 real-world UAF kernel vulnerabilities
- Only 5 vulnerabilities have demonstrated their exploitability against SMEP
- Only 2 vulnerabilities have demonstrated their exploitability against SMAP

*: discovered new dereference by fuzzing

CVE-ID	# of public exploits		# of generated exploits	
	SMEP	SMAP	SMEP	SMAP
2017-17053	0	0	1	0
2017-15649*	0	0	3	2
2017-15265	0	0	0	0
2017-10661*	0	0	2	0
2017-8890	1	0	1	0
2017-8824*	0	0	2	2
2017-7374	0	0	0	0
2016-10150	0	0	1	0
2016-8655	1	1	1	1
2016-7117	0	0	0	0
2016-4557*	1	1	4	0
2016-0728*	1	0	3	0
2015-3636	0	0	0	0
2014-2851*	1	0	1	0
2013-7446	0	0	0	0
overall	5	2	19	5

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Case Study (cont)

#BHUSA

- FUZE helps track down useful primitives, giving us the power to
  - Demonstrate exploitability against SMEP for 10 vulnerabilities
  - Demonstrate exploitability against SMAP for 2 more vulnerabilities
  - Diversify the approaches to perform kernel exploitation
    - 5 vs 19 (SMEP)
    - 2 vs 5 (SMAP)

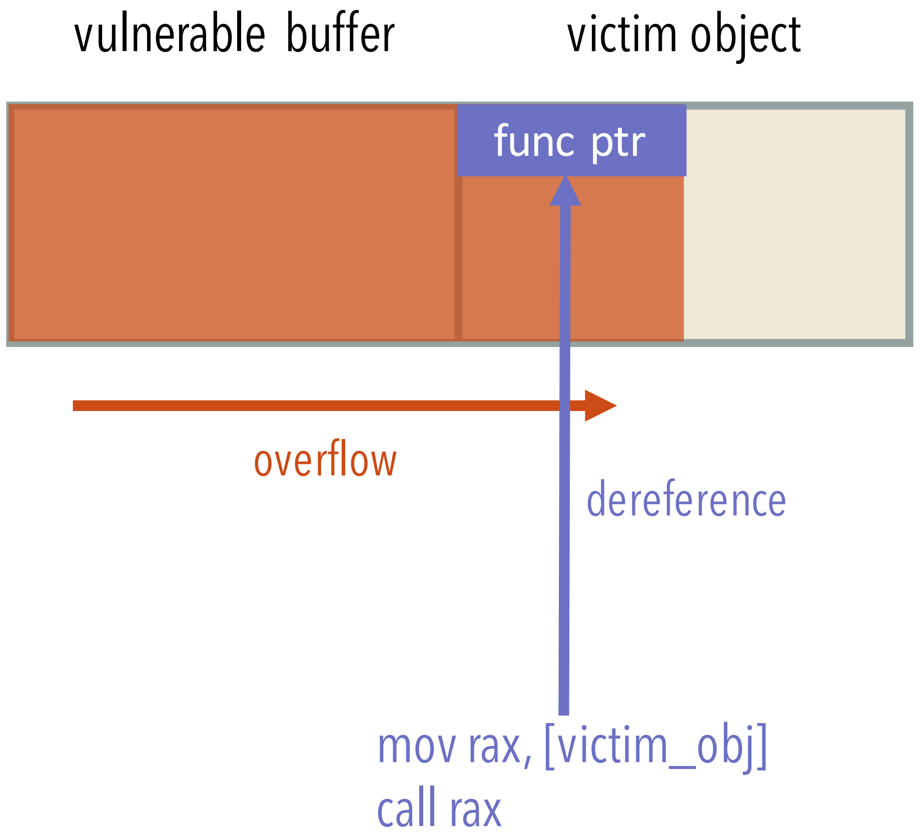
CVE-ID	# of public exploits		# of generated exploits	
	SMEP	SMAP	SMEP	SMAP
2017-17053	0	0	1	0
2017-15649	0	0	3	2
2017-15265	0	0	0	0
2017-10661	0	0	2	0
2017-8890	1	0	1	0
2017-8824	0	0	2	2
2017-7374	0	0	0	0
2016-10150	0	0	1	0
2016-8655	1	1	1	1
2016-7117	0	0	0	0
2016-4557	1	1	4	0
2016-0728	1	0	3	0
2015-3636	0	0	0	0
2014-2851	1	0	1	0
2013-7446	0	0	0	0
overall	5	2	19	5

Discussion on Failure Cases

- Dangling pointer occurrence and its dereference tie to the same system call
- FUZE works for 64-bit OS but some vulnerabilities demonstrate its exploitability only for 32-bit OS
  - E.g., CVE-2015-3636
- Perhaps unexploitable!?
  - CVE-2017-7374 ← null pointer dereference
  - E.g., CVE-2013-7446, CVE-2017-15265 and CVE-2016-7117

What about heap overflow

- Heap overflow is similar to use-after-free:
  - a victim object can be controlled by attacker by:
    - heap spray (use-after-free)
    - overflow (or memory overlap incurred by corrupted heap metadata)
- Heap overflow exploitation in three steps:
  1) Understanding the heap overflow
     off-by-one? arbitrary length? content controllable?
  2) Find a suitable victim object and place it after the vulnerable buffer
     automated heap layout[1]
  3) Dereference the victim object for exploit primitives



[1] Heelan et al. Automatic Heap Layout Manipulation for Exploitation. USENIX Security 2018.

Roadmap

- Unsolved challenges in exploitation facilitation
- Our techniques -- FUZE
- Evaluation with real-world Linux kernel vulnerabilities
- Conclusion

Conclusion

- Primitive identification and security mitigation circumvention can greatly influence exploitability
- Existing exploitation research fails to provide facilitation to tackle these two challenges
- Fuzzing + symbolic execution has a great potential toward tackling these challenges
- Research on exploit automation is just the beginning of the GAME! Still many more challenges waiting for us to tackle…

Usage Scenarios

- Bug prioritization
  - Focus limited resources to fix bugs with working exploits
- APT detection
  - Use generated exploits to generate fingerprints for APT detection
- Exploit generation for Red Team
  - Supply Red Team with a lot of new exploits

Q&A

- Acknowledgement:
  - Yueqi Chen
  - Jun Xu
  - Xiaorui Gong
  - Wei Zou

JD.COM

PennState

- Exploits and source code available at:
  - https://github.com/ww9210/Linux_kernel_exploits
- Contact: wuwei@iie.ac.cn

JD.COM Introduction

236.5 million

Largest retailer in China, online or offline shoppers

$37.5bn

Third largest internet company in the world by revenue in 2016

First e-commerce company to use commercial drone delivery

Massive Scale

700 Million

June Sales Event **Items** Sold

Massive Scale

236.5M

active customer accounts

120K

active third-party vendors on JD platform

120K

full-time employees

1.59B

full-time orders fulfilled in 2016