# Expediting Exploitability Assessment through an Exploitation Facilitation Framework

Xinyu (X.Y.) Xing

JD.com


Email: xxing@ist.psu.edu

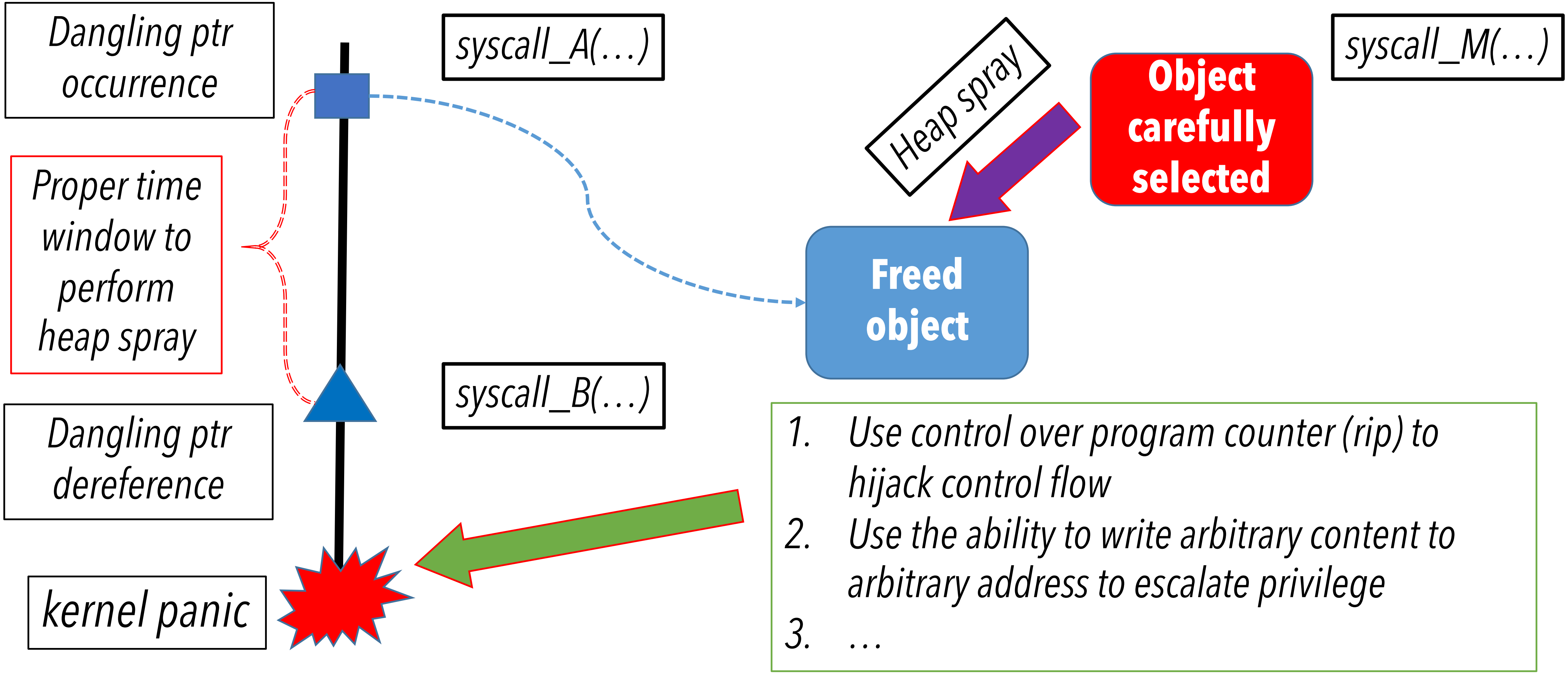
# Background

- 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





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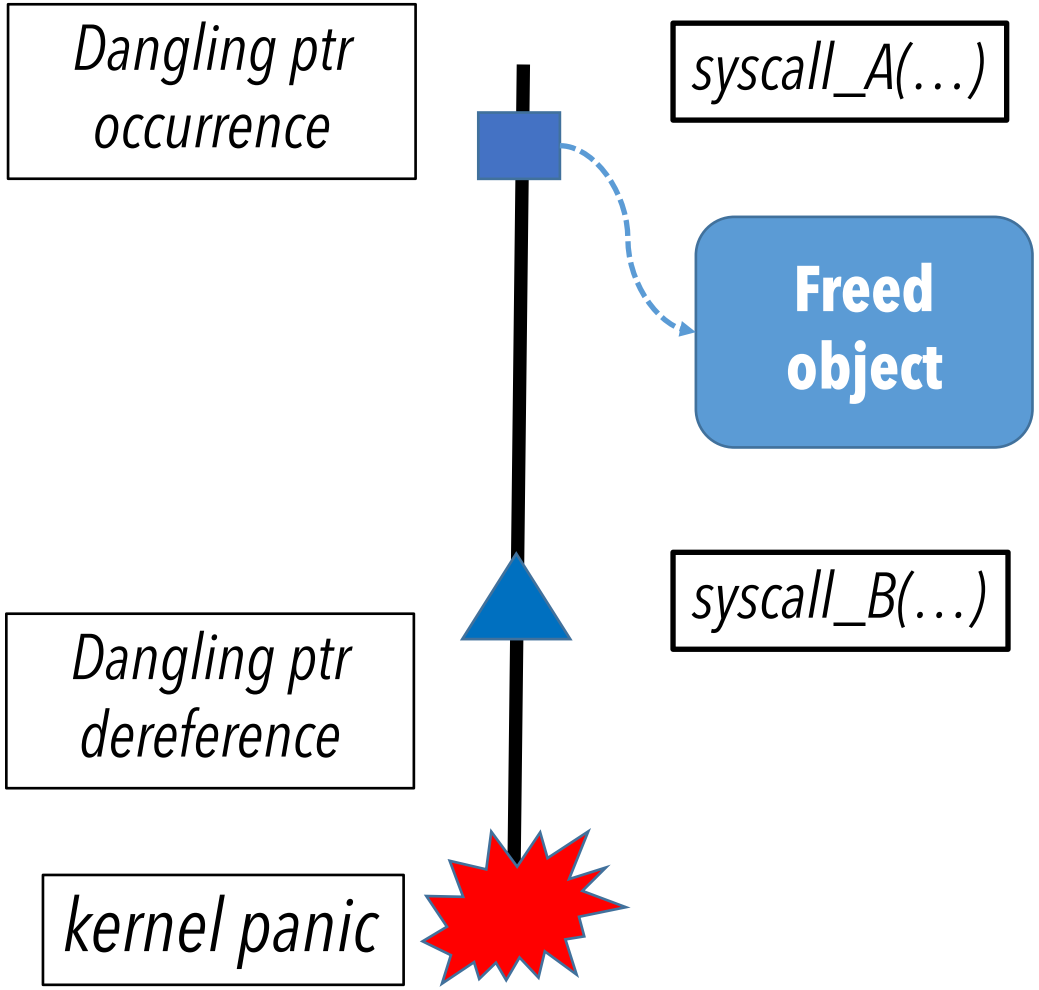
# Challenge 1: Needs Intensive Manual Efforts

- 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





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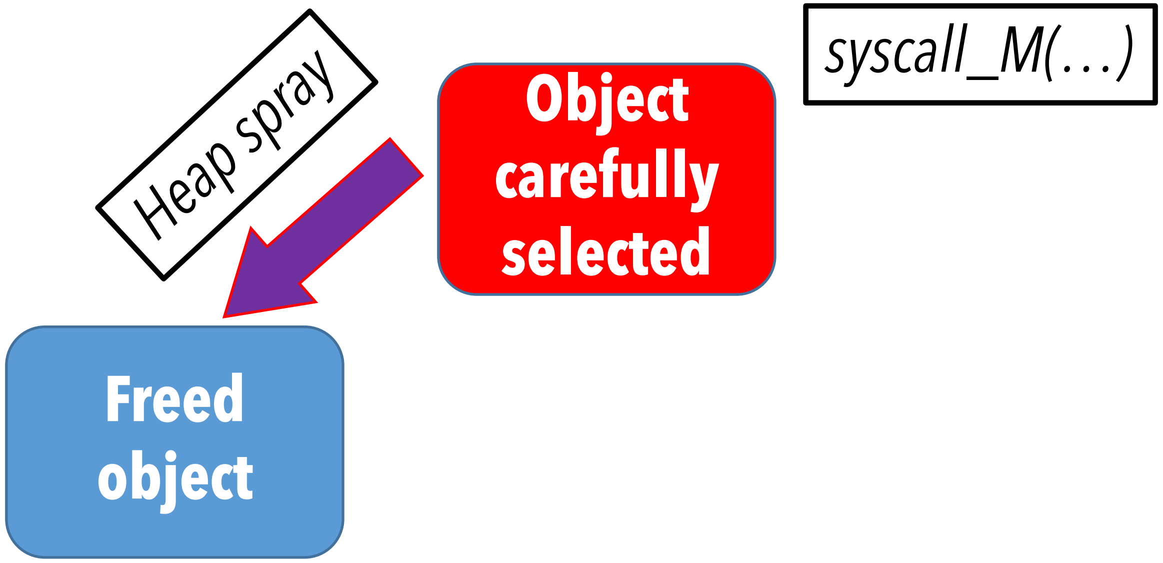
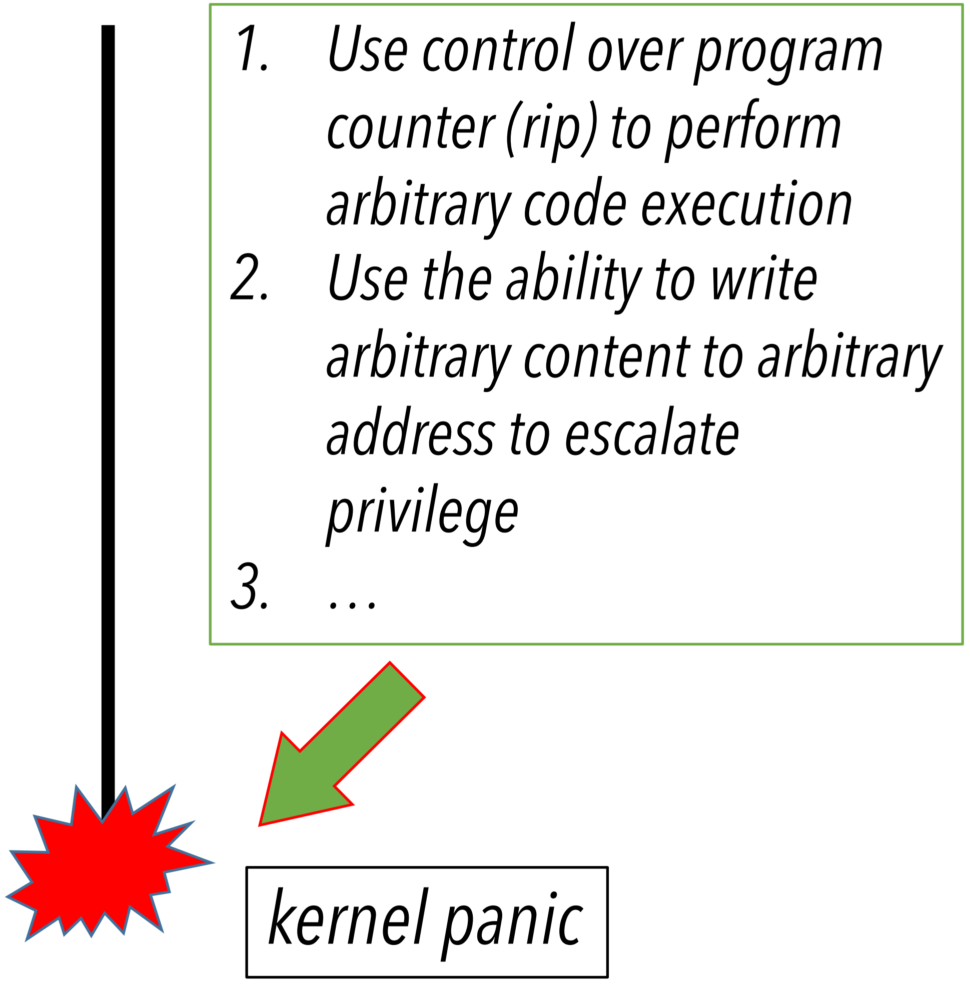
# Challenge 2: Needs Extensive Expertise in Kernel

- 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] [CCS16] [USENIX-SEC18]
- Approaches for Challenge 3
  - [NDSS'11] [S&P16], [S&P17]


[NDSS11] Avgerinos et al., AEG: Automatic Exploit Generation.
[CCS16] Xu et al., Unleashing Use-After-Free Vulnerabilities in Linux Kernel.
[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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# Roadmap

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


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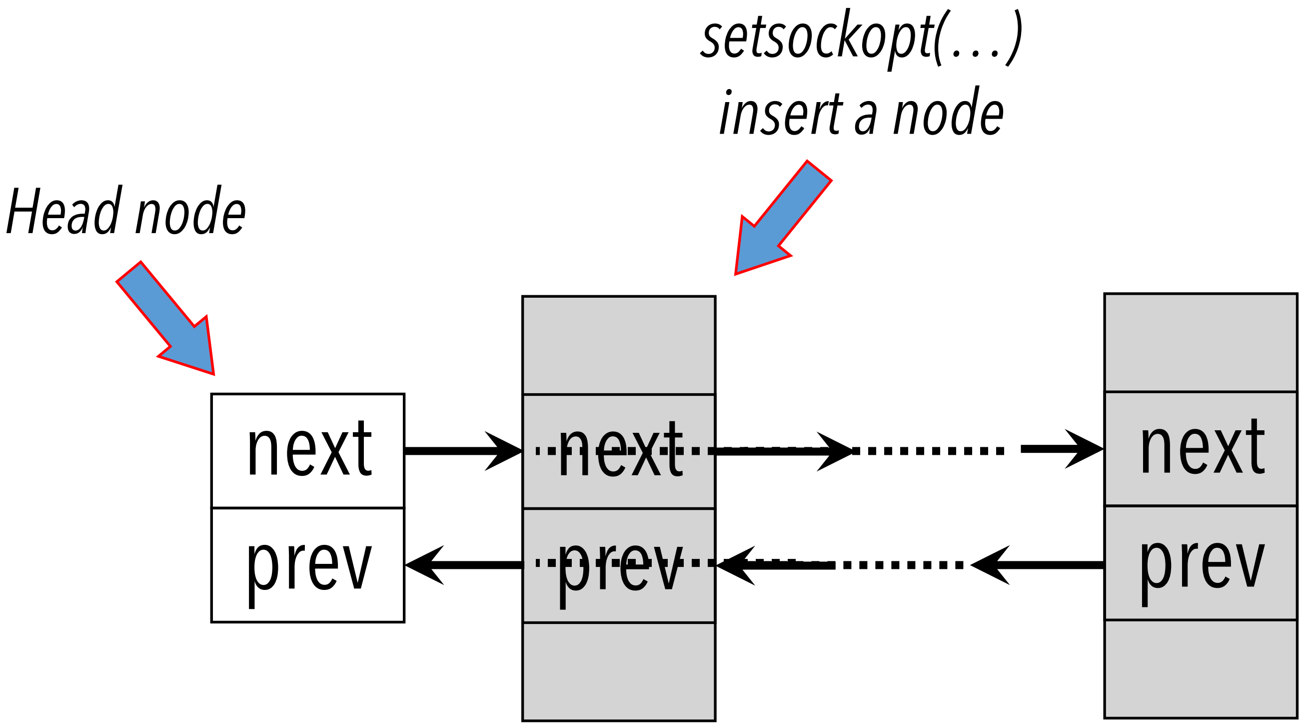
# A Real-World Example (CVE 2017-15649)




```c
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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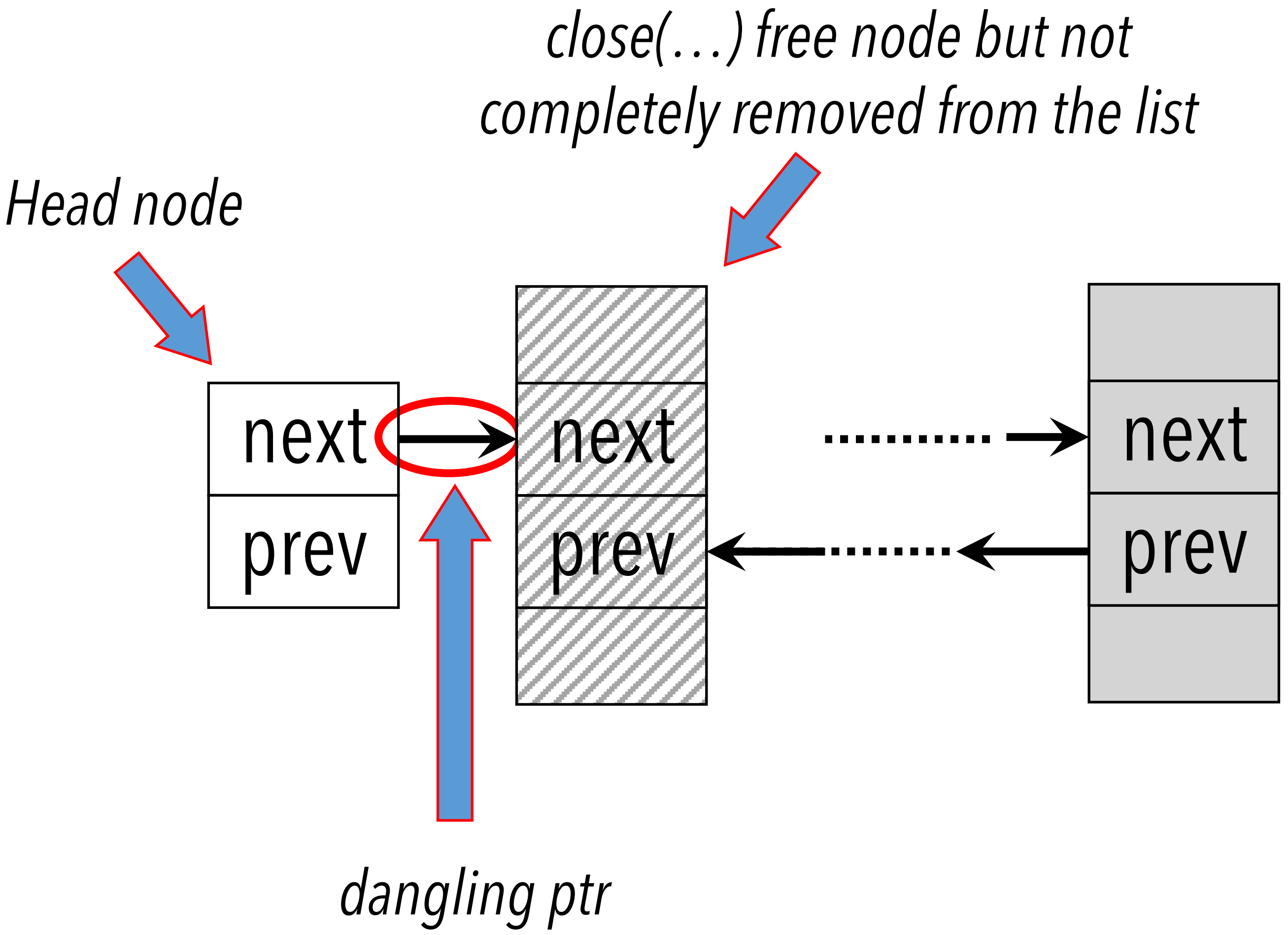


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    close(fd);
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}
```


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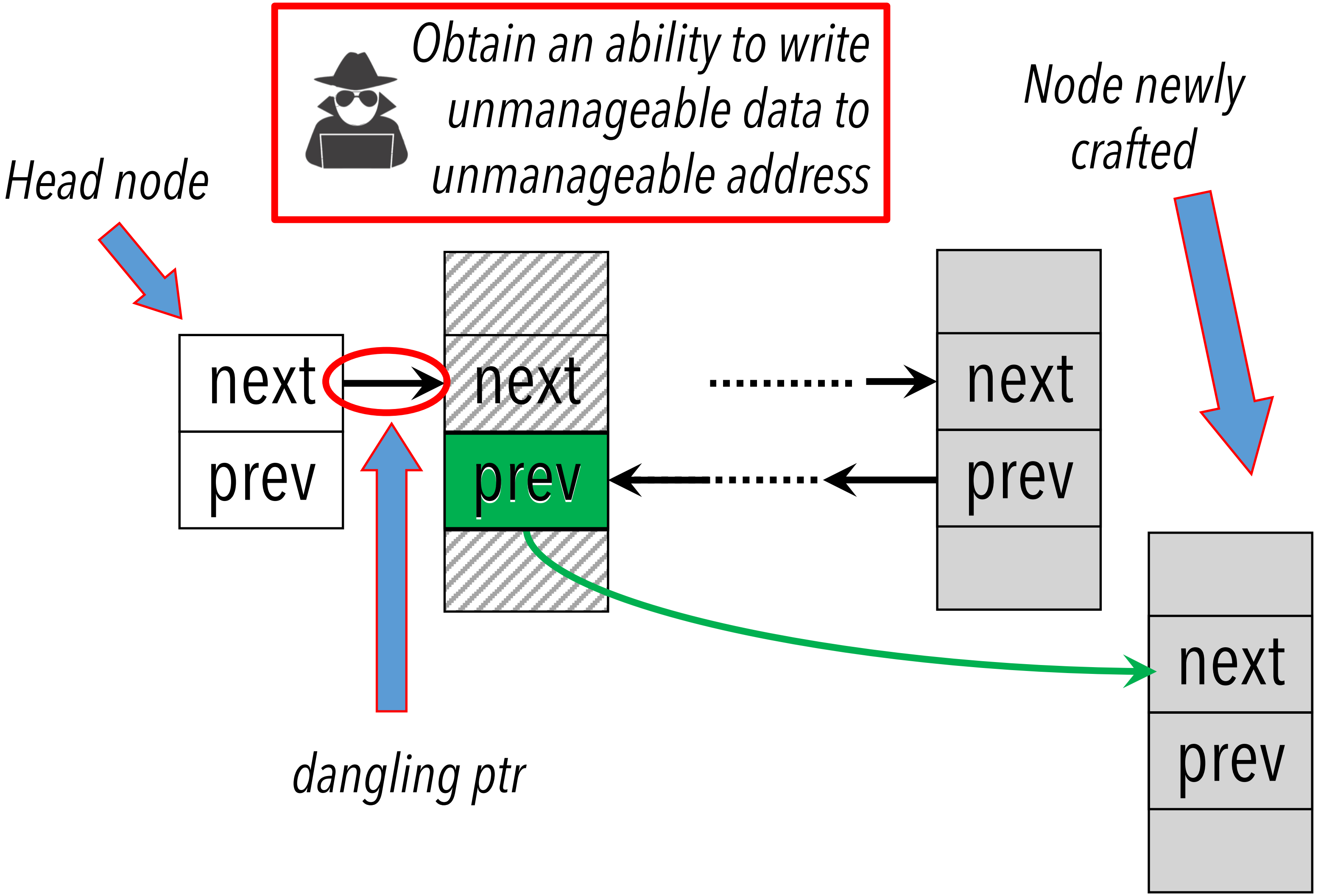
# Challenge 4: No Primitive Needed for Exploitation

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    pthread_join(thread1, NULL);
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    close(fd);
  }
}
```
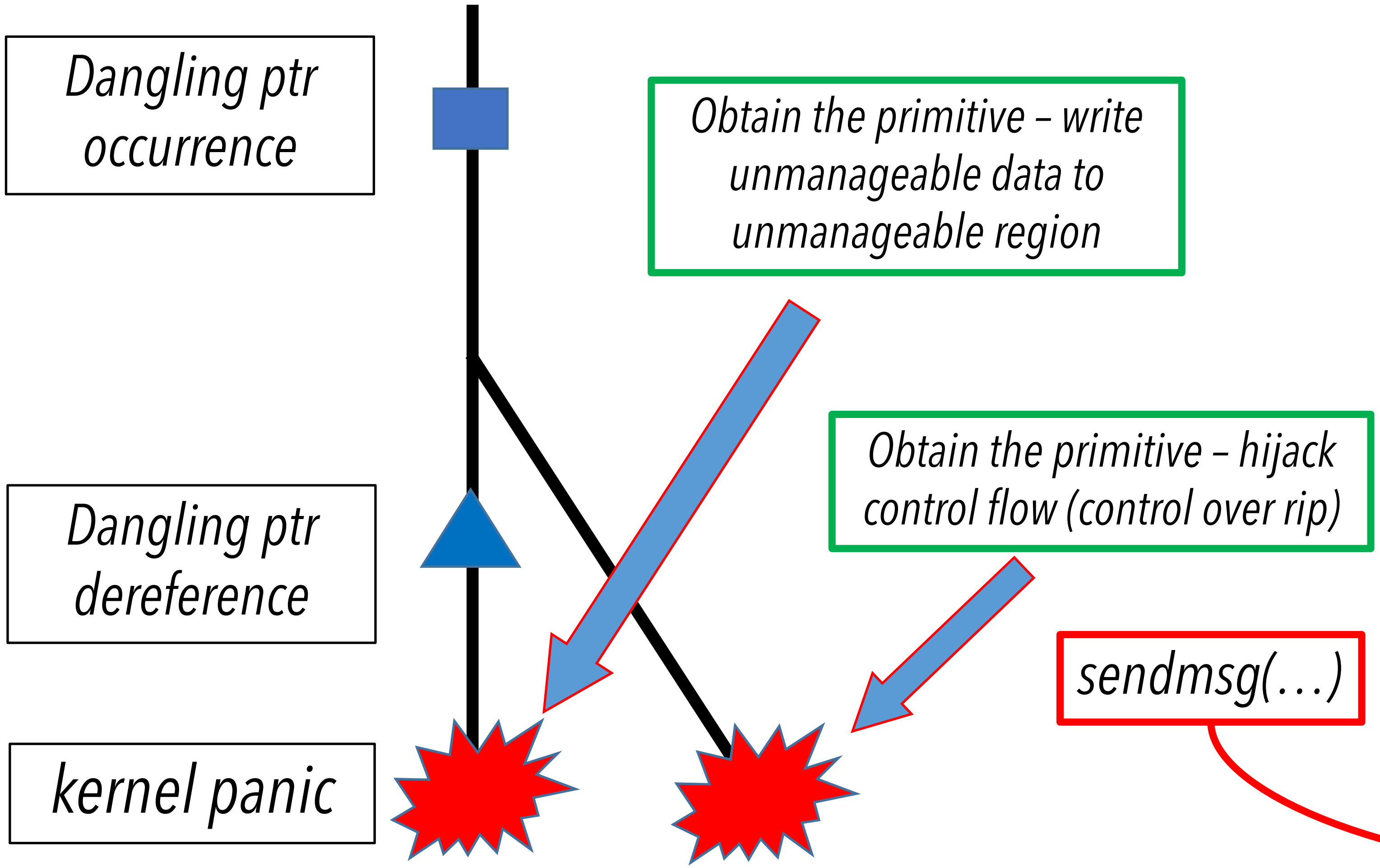

# No Useful Primitive == Unexploitable??

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# Roadmap

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- Our techniques -- FUZE
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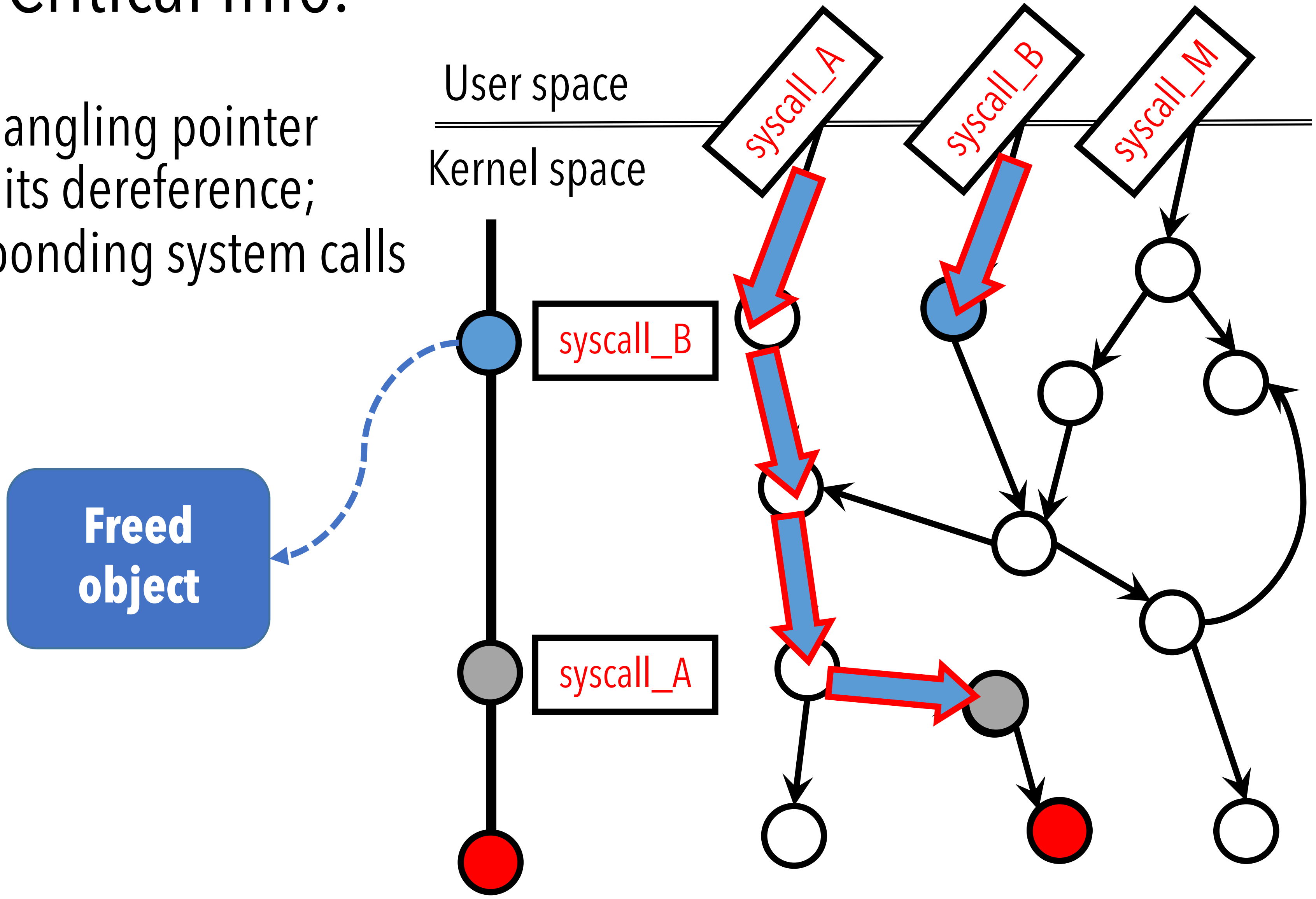
# FUZE – Extracting Critical Info.

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





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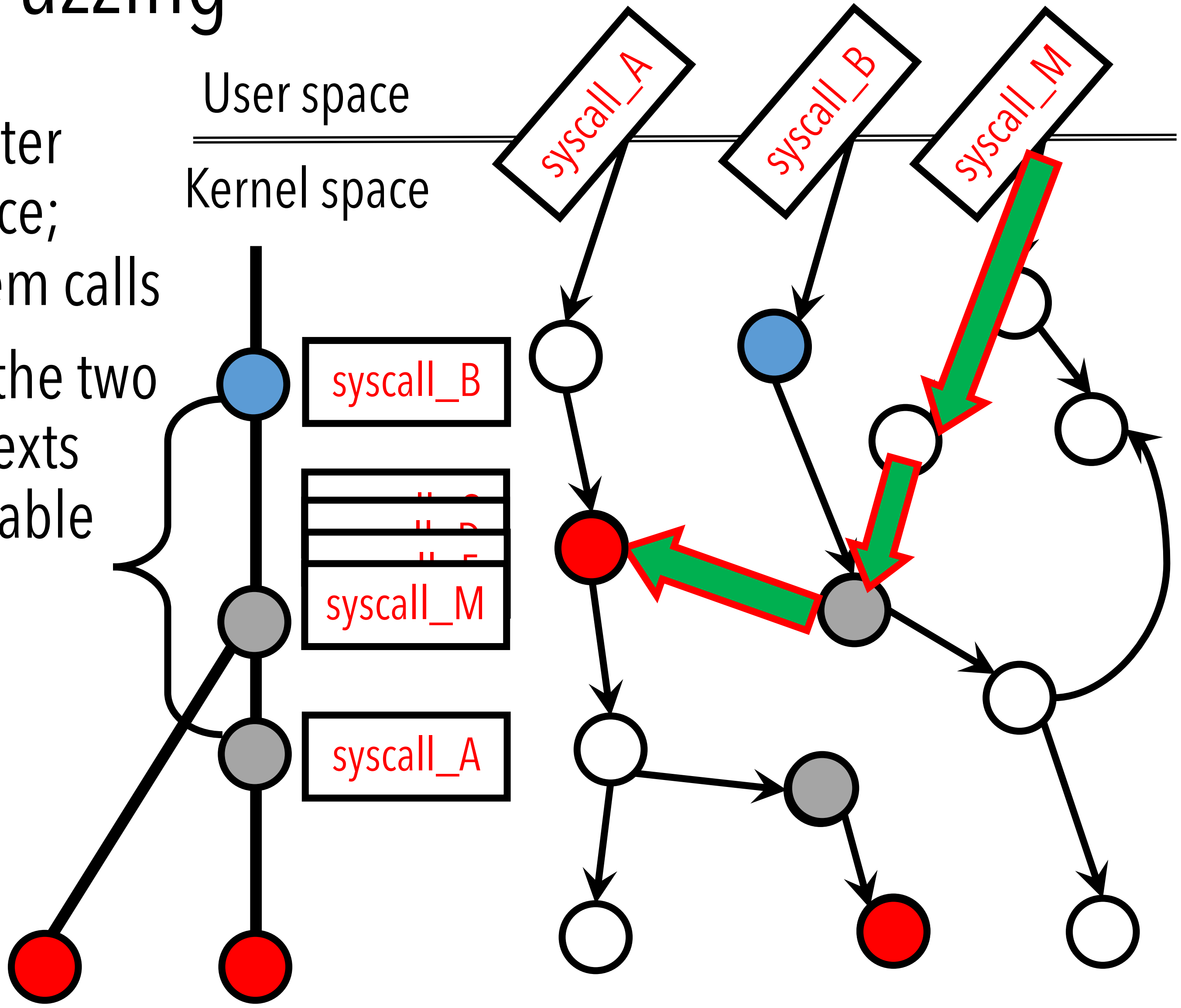
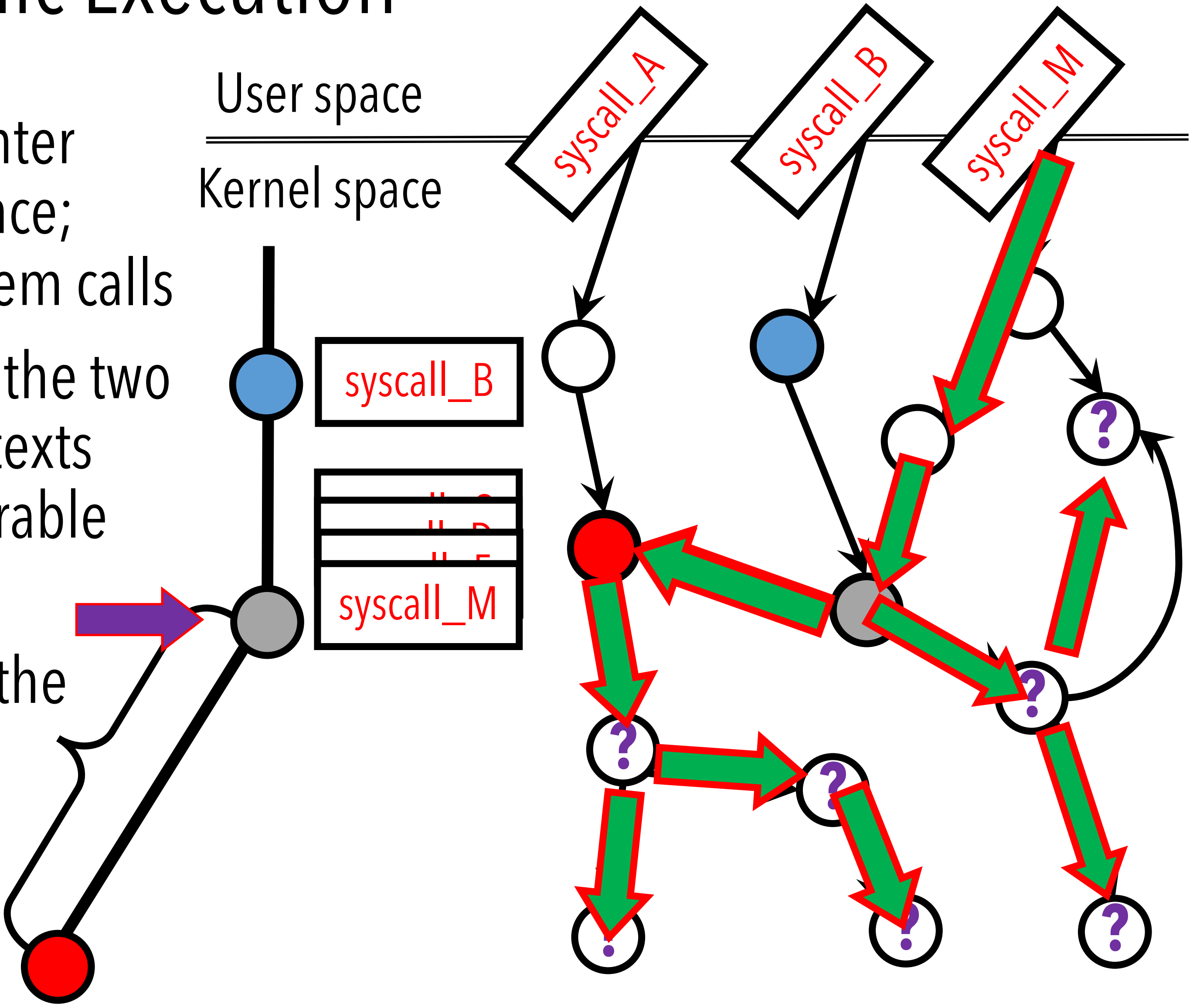
# FUZE – Performing Kernel Fuzzing

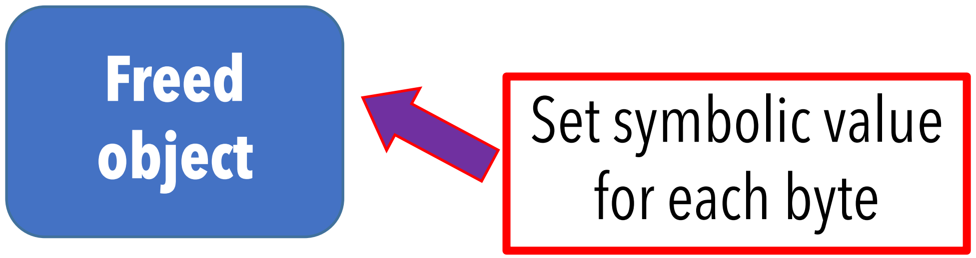
- Identifying the site of dangling pointer occurrence, and that of its dereference; pinpointing the corresponding system calls
- Performing kernel fuzzing between the two sites and exploring other panic contexts (i.e., different sites where the vulnerable object is dereferenced)



# FUZE – Performing Symbolic Execution

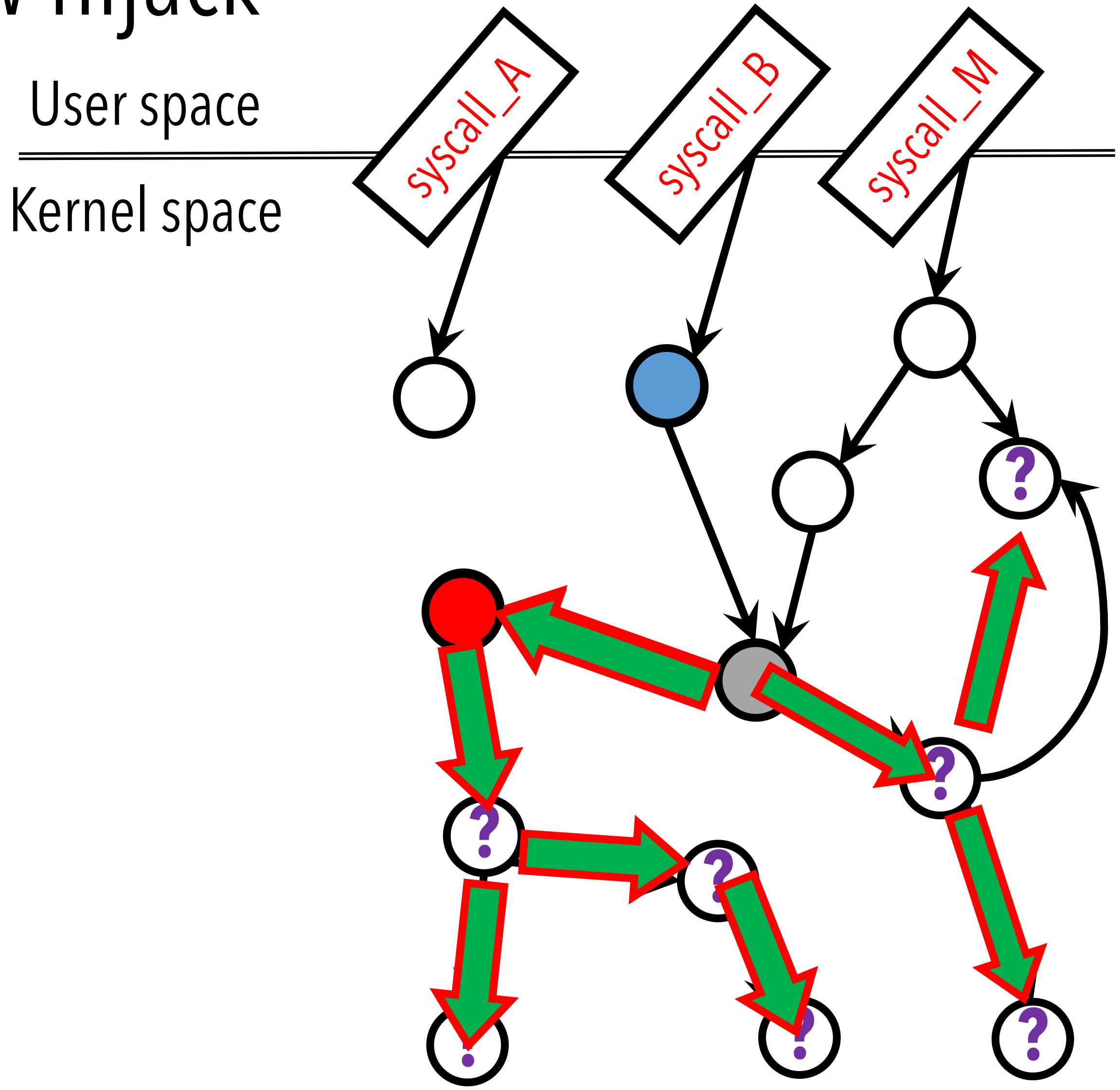
- Identifying the site of dangling pointer occurrence, and that of its dereference; pinpointing the corresponding system calls
- Performing kernel fuzzing between the two sites and exploring other panic contexts (i.e., different sites where the vulnerable object is dereferenced)
- Symbolically execute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



# Useful Primitives for Control flow hijack

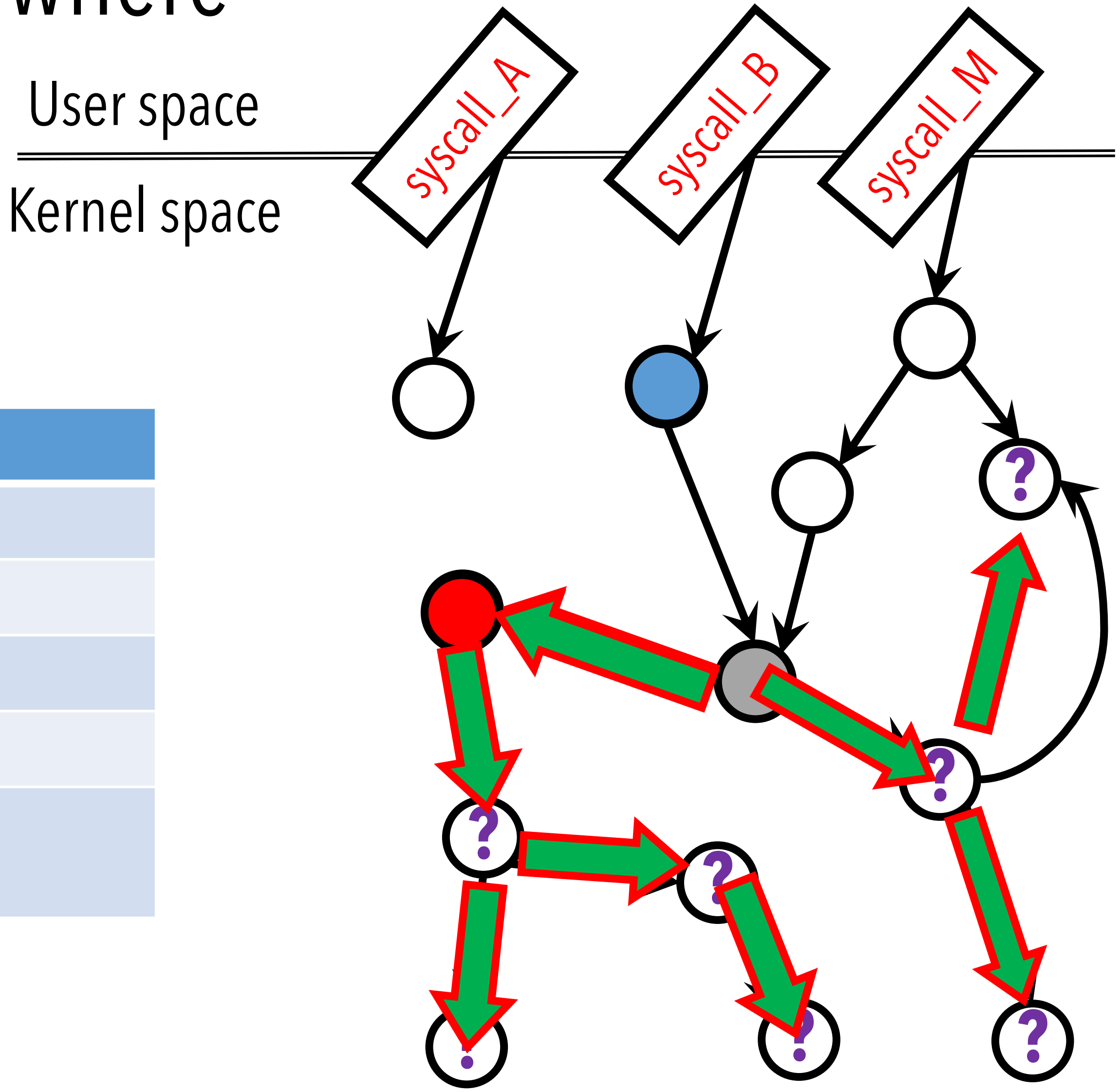
- Control flow hijack primitive
  - call rax where rax = sym. val.
- Double Free
- Memory leak
  - e.g. invocation of copy_to_user(…) with src point to a freed object
- linked list corruption



# Useful Primitives for Write-what-where

- E.g., mov qword ptr [rdi], rsi

| rdi (dst) | rsi (src) | 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 |





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# Useful Primitives != Ability to Perform Exploitation

SMEP

SMAP

Hypervisor

CFI

KASLR

KPTI

heap metadata hardening

read-only credentials

read-only vdso

read-only vsyscall



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# Exploitable Machine States

- A machine state with the ability to bypass SMEP
  - Control over rip which could redirect execution to pivot gadget -- xchg eax, esp
  - E.g., mov rax, qword ptr[evil_ptr]; call rax
- A machine state with the ability to bypass SMAP/SMEP
  - Control over rip which could redirect execution to native_write_cr4(...)
  - Also, control over rdi, rsi and rax


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# Evaluation

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


Email: xxing@ist.psu.edu

# Evaluation (cont.)

- 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 performing 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 |
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| 2014-2851 | 1 | 0 | 1 | 0 |
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| Overall | 5 | 2 | 19 | 5 |


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# 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

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# 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…


Email: xxing@ist.psu.edu