KEPLER: Facilitating Control-flow Hijacking Primitive Evaluation for Linux Kernel Vulnerabilities

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Background

- OS kernels are written in low-level languages C/C++
  - Linux: C
  - Windows: C and C++
- OS kernels are prone to memory corruption bugs
  - Out of Bounds Access, Use-After-Free, data race and even type confusion (in C++ components)
- Bugs in OS kernel are plenty and many of them are exploitable
- Exploit Mitigation: make exploit harder with ignorable cost
  - The cost to prove exploitability is increasing
- Exploitability: a predicate related to each bug
- A concrete "kernel exploit" could serve as a proof of exploitability

Background (cont.)

- Automatic exploit generation systems: capable of generating concrete exploits
- Automatic exploit generation systems in two steps:
  1. Identifying exploit primitives
  2. Evaluating exploit primitives
- Exploit primitive:
  - A machine state which empowers an attacker to craft an exploit (a.k.a. programming weird machine)
    - Data flow: Writing 8 bytes anywhere, write 1 byte to adjacent heap chunk etc.
    - Control flow: Control-flow hijacking
- Control-flow hijacking primitive is one of the most popular exploit primitives.

Crafting a control-flow hijacking kernel exploit

1 Adjusting syscall parameters and memory layout

2 Getting a control-flow hijacking primitive

3 Executing exploitation payload

- Step 1. Adjusting parameters of system calls and memory layout
  - [USENIX-SEC18][CCS 16]
- Step 2. Getting a control-flow hijacking primitive
  - [P0 blog][POC16]
- Step 3. Payload execution
  - [USENIX-SEC 14]

[USENIX-SEC14] Vasileios et al., ret2dir: Rethinking Kernel Isolation
[CCS 16] Xu et al., From Collision To Exploitation: Unleashing Use-After-Free Vulnerabilities in Linux Kernel.
[USENIX-SEC18] Heelan et al., Automatic Heap Layout Manipulation for Exploitation.
[P0 blog] Andrey Konovalov. Exploiting the Linux kernel via packet sockets.
[POC2016] Dong-hoon you. New reliable android kernel root exploitation techniques.

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Key Step: from control-flow hijack to ROP payload execution

Getting a control-flow hijacking primitive

Kernel State S

```
gdb> info registers
  rsp: x rip: 0x41424344
  …
gdb> x/10gx $rsp
X     : ???????? ????????
X+8   : ???????? ????????
```

How to bootstrap a ROP attack? (e.g. Transition S -> S')

Executing exploitation payload (e.g. through ROP)

Kernel State S'

```
gdb> info registers
  rsp: x' rip: 0x51525354
  …
gdb> x/10gx $rsp
X'     : 41414141 41414141
X'+8   : 41414141 41414141
```

Semantic of an example ROP payload

commit_creds(prepare_kernel_cred(0))

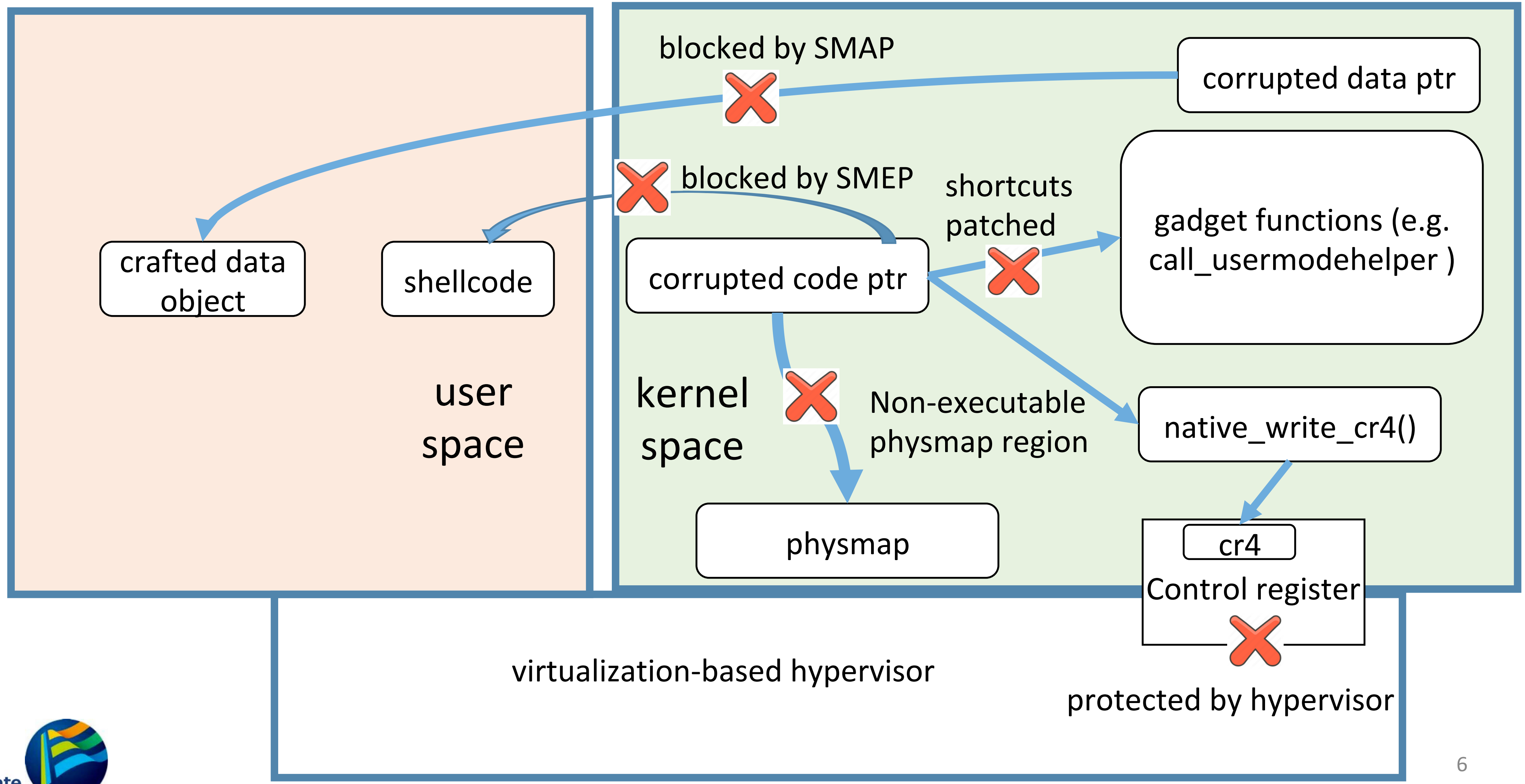
...

(fixing context and safely return to userspace)

...

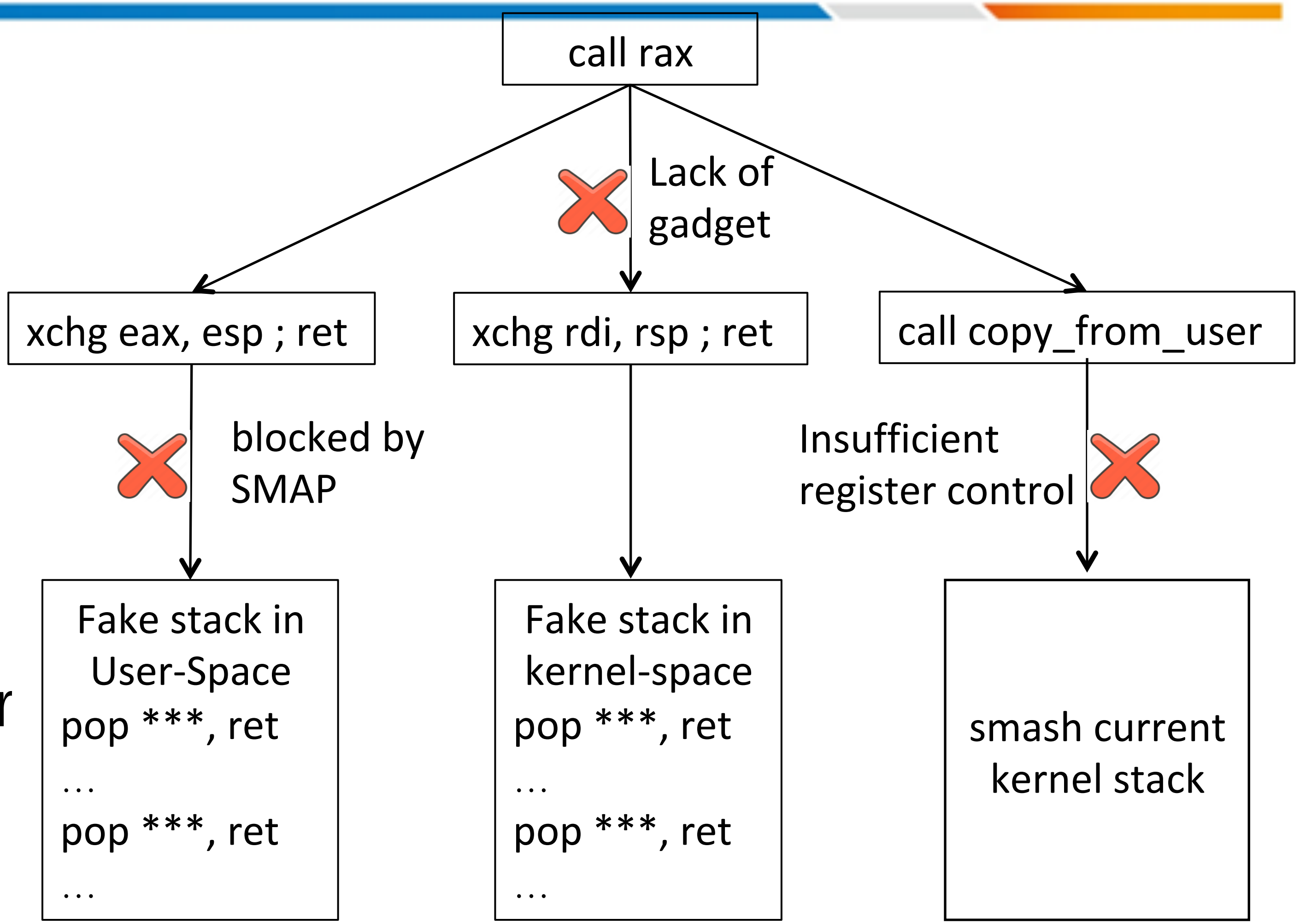
execve("/bin/sh",NULL,NULL)

Challenge 1. kernel exploit mitigations



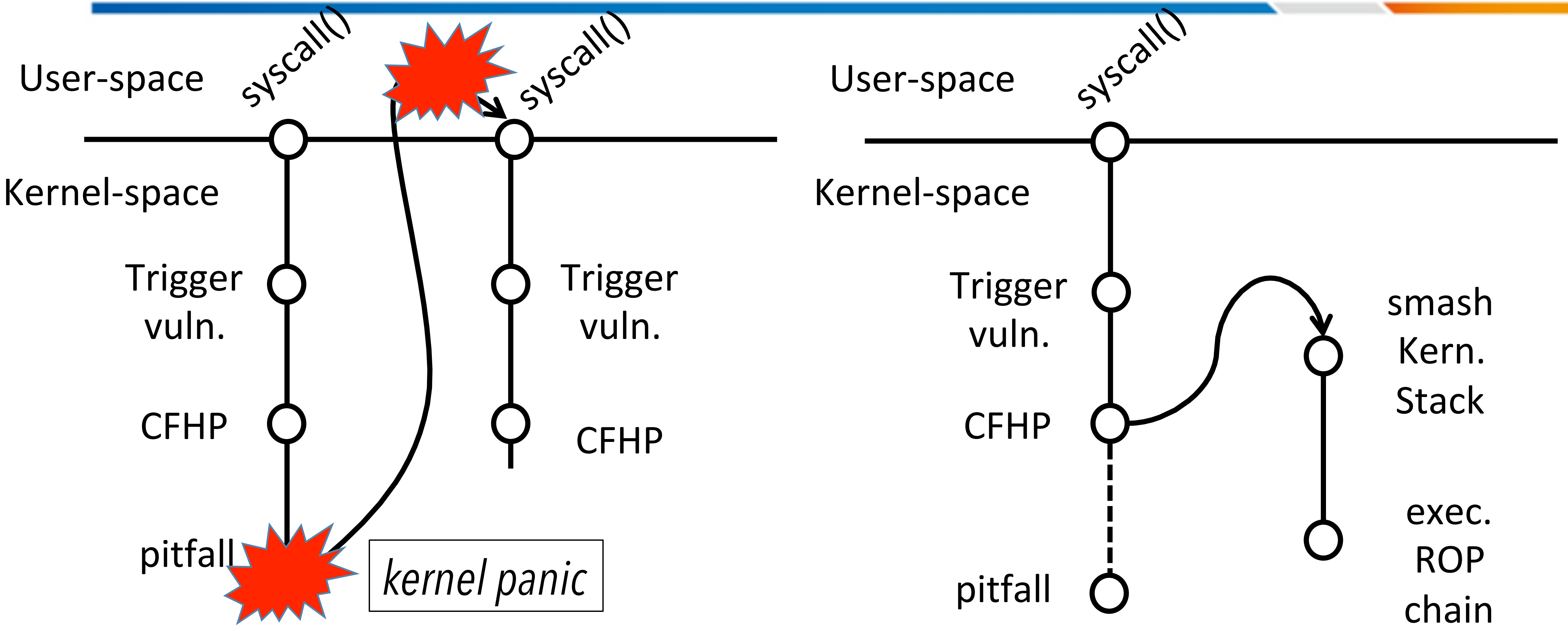
Challenge 2. ill-suited exploit primitive

- Lack of stack pivoting gadget in Linux kernel
  - traditional stack pivoting gadget blocked by SMAP because it accesses user-space memory
  - Intra-kernel stack pivoting gadget sometimes does not exist.
- Insufficient control over registers for invoking kernel functions



copy_from_user(dst, src, size)

Challenge 3. exploit path pitfall

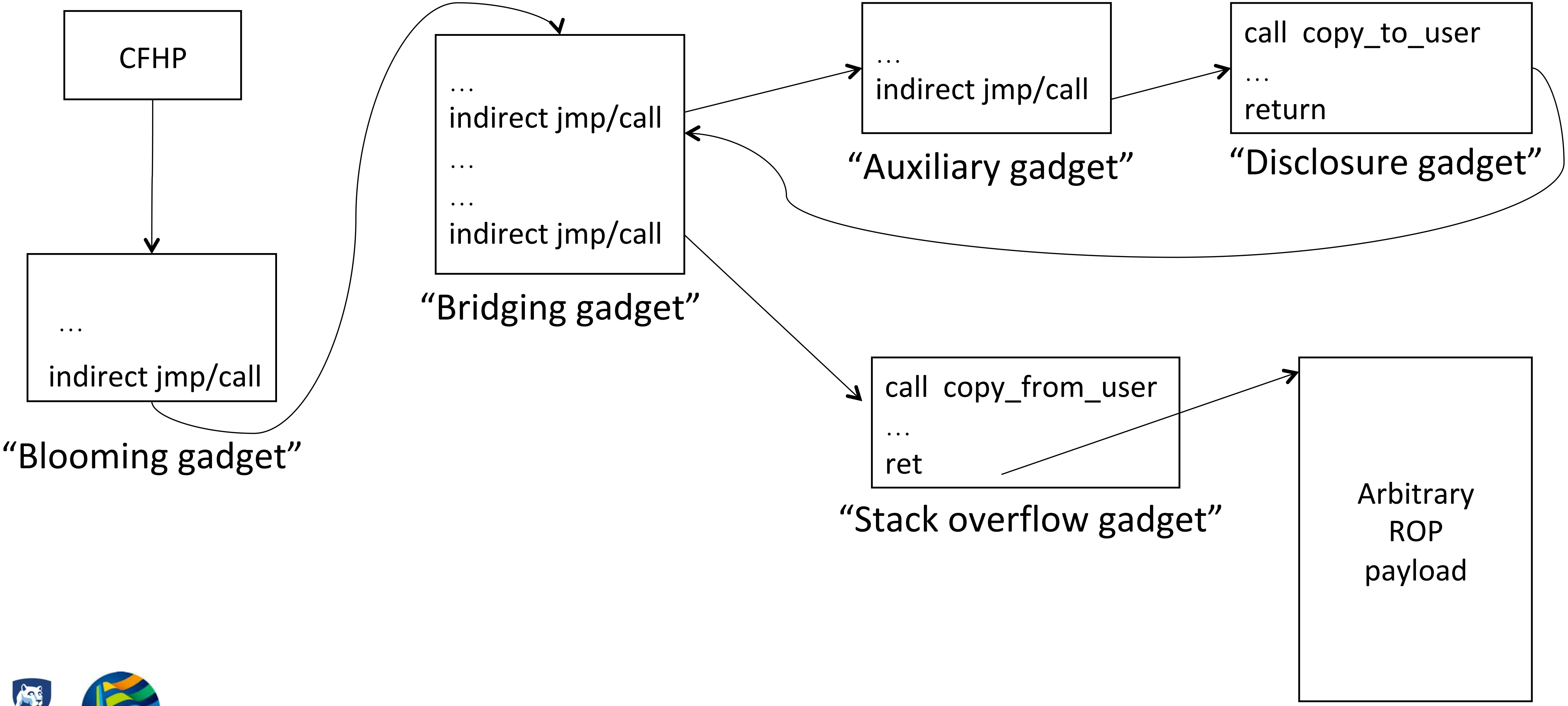


Our Solution: “single-shot” exploitation

Roadmap

- Challenges
- Our Technique
- Evaluation with real-world Linux kernel vulnerabilities
- Conclusion

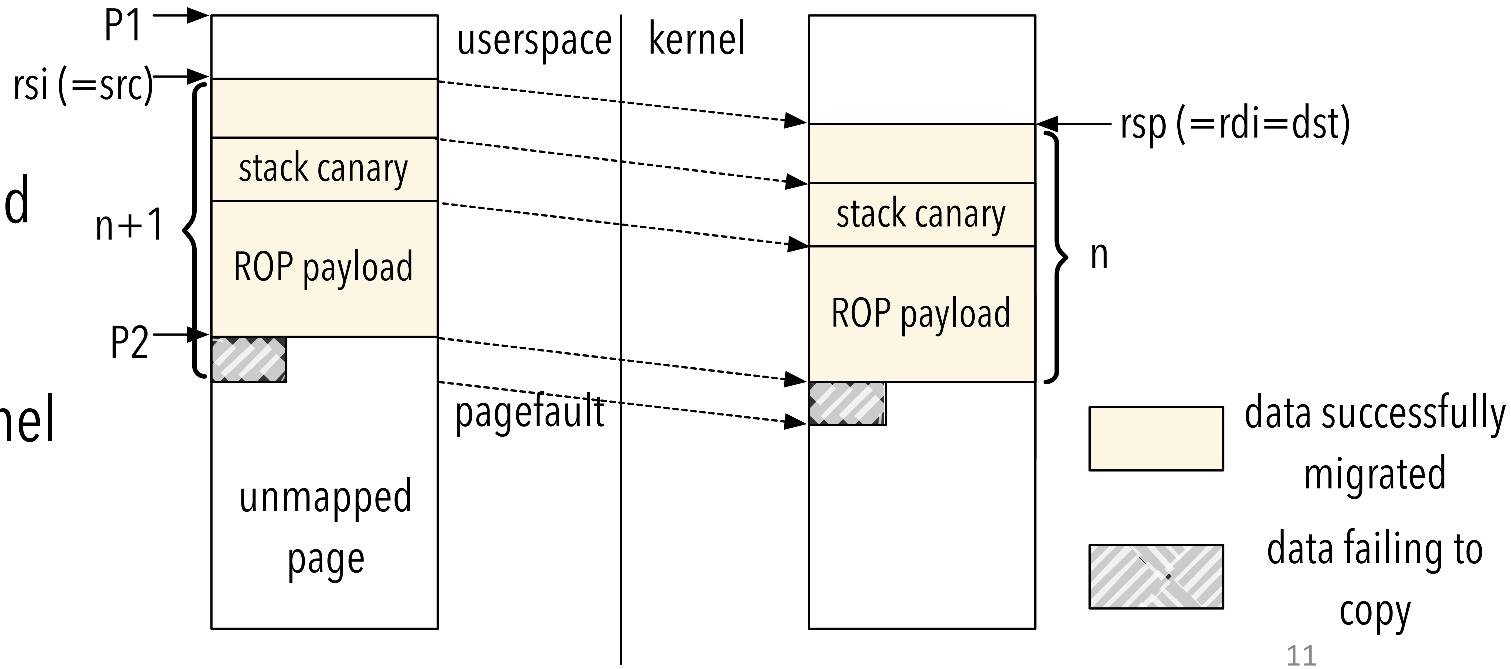
Overview of "single-shot" Exploitation



Stack smashing gadget

- copy_from_user(dst, src, size)
  - Data channel between user-space and kernel-space
  - Destination is kernel stack for 91% invocations of copy_from_user() in Linux kernel 4.15.
- Short return
  - Check for non-zero return value and returns -EFAULT
  - Short return path exists for more than 99% invocations in Linux kernel 4.15

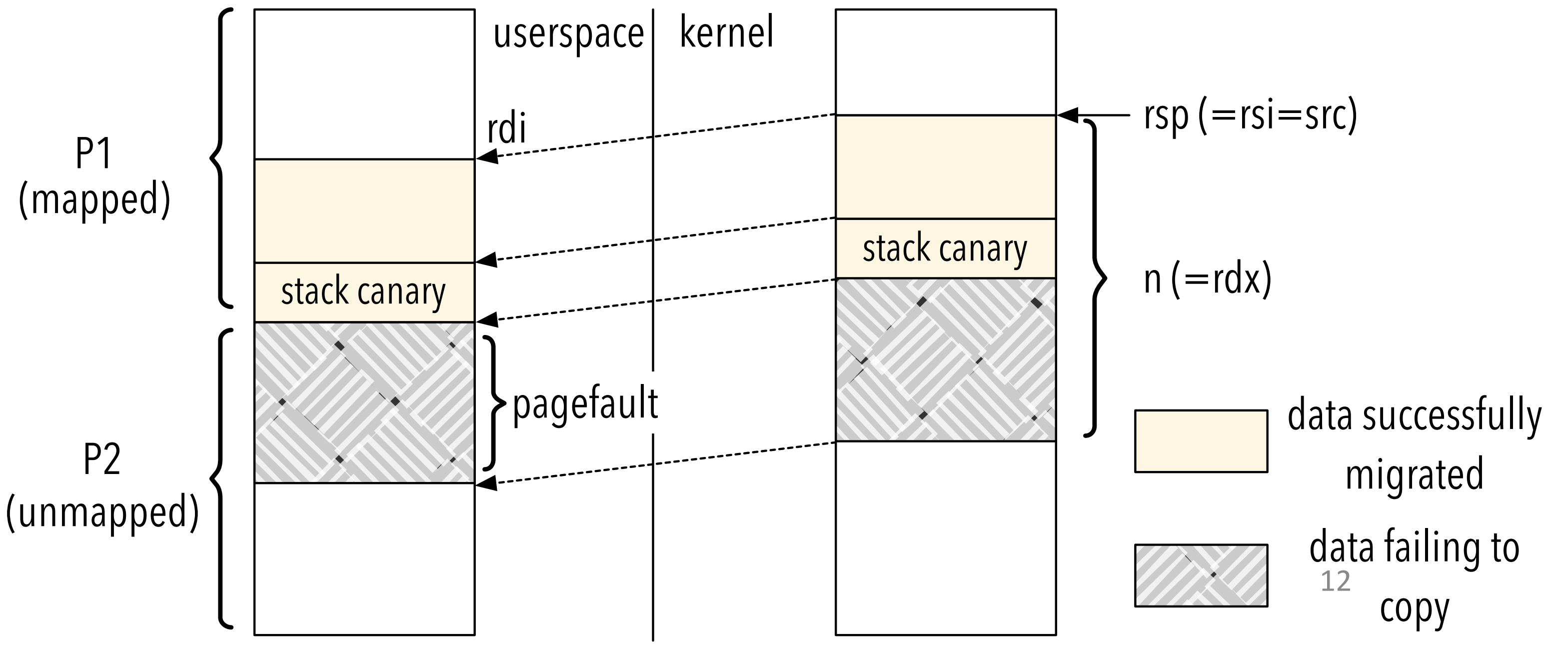
```
static long bsg_ioctl(struct file *file, unsigned int cmd,
unsigned long arg){
    struct sg_io_v4 hdr; // destination is local variable
    ...
    if (copy_from_user(&hdr, uarg, sizeof(hdr))) {
        return -EFAULT; // short return
    }
```



Bypassing stack canary: stack disclosure gadget

- copy_to_user(to, from, n)
  - Copying kernel data to user-space
  - Src is usually kernel stack (82% in 4.15)
  - Short return path exists
- Problem:
  - Caller of copy_to_user also protected by stack canary

```
SYSCALL_DEFINE2(gettimeofday, struct timeval *, tv, struct timezone *, tz){
    struct timeval ktv;
    …
    if(copy_to_user(tv, &ktv, sizeof(ktv))) {
        return -EFAULT;
    }
    …
```



Bypassing stack canary (cont.)

- Auxiliary function gadget
  - Protected by stack canary
  - controllable indirect call
- Leaking stack canary by combination of
  - Auxiliary function, and
  - Canary disclosure gadget

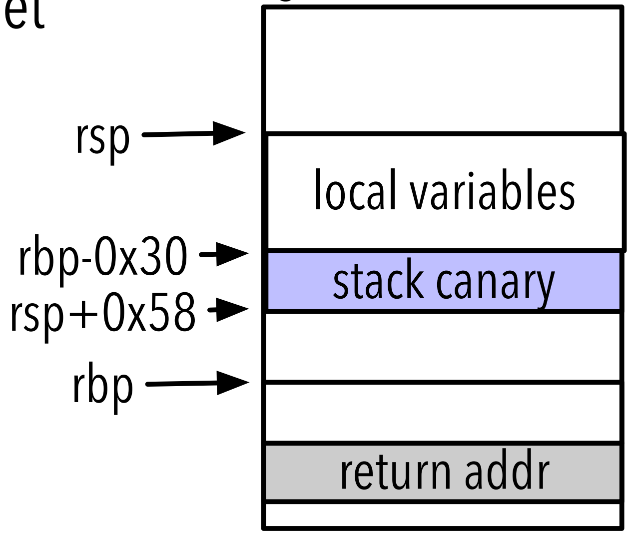
Auxiliary function gadget

```
push    rbp
mov     rbp, rsp
push    r12
...
sub     rsp, 58h
mov     rax, gs:qword_28
mov     [rbp-30h], rdi
mov     rax, [rdi]
call    rax
...
```

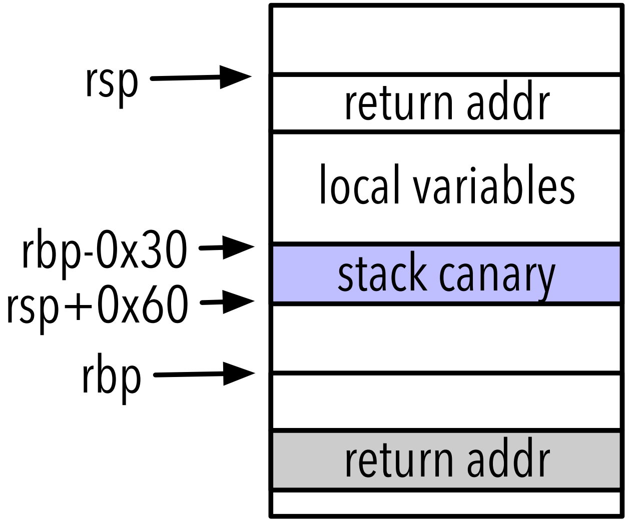
Canary disclosure gadget

```
lea     rsi, [rbp-60h]
call    _copy_to_user
test    rax, rax
jnz     fail
...
fail:
mov     rbx, FFFFFFF2h
jmp     exit
...
exit:
  mov     rcx,
[rbp-30h]
  xor     rcx,
gs:qword_28
  jnz     panic
  add     rsp, 60h
  pop     rbx
  ...
  ret
```

stack right before "**call rax**"



stack right after "**call rax**"



Enhancing register control: blooming gadget

- Linux kernel code have features of object-oriented programming
  - "self" passed as first parameter
- Blooming gadget:
  - Given register rdi is under control
  - A family of kernel functions containing an indirect call
    - target is controllable
    - three parameters of the indirect call are controllable

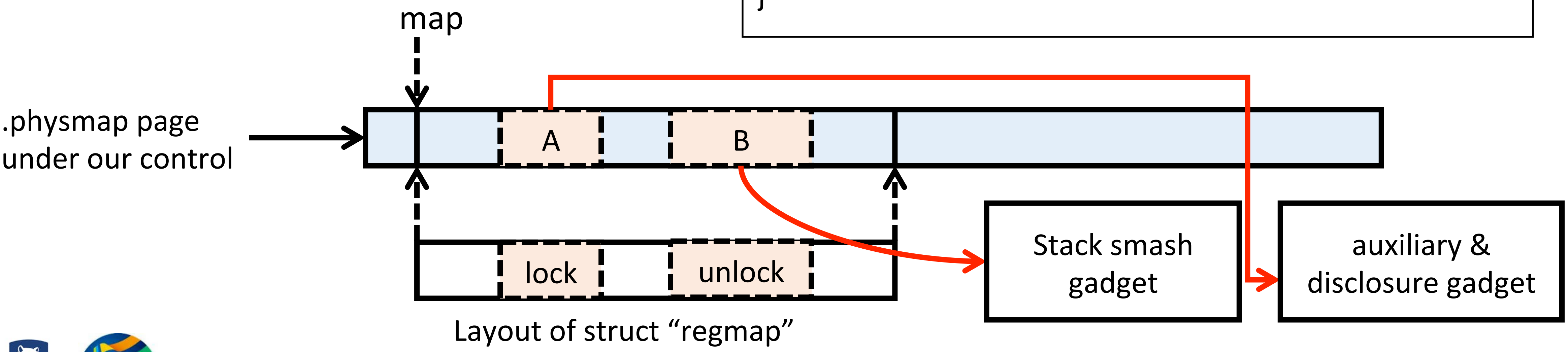
```
static void aliasing_gtt_unbind_vma(struct i915_vma *vma) {
    ...
    vma->vm->clear_range(vma->vm, vma>node.start, vma->size);
...
}
```

```
push rbp
push rbx
mov rbx,rdi
mov rax,QWORD PTR [rdi+0xa8]
mov rbp,QWORD PTR [rax+0x330]
mov rax,QWORD PTR [rdi+0xf8]
...
mov rdi,QWORD PTR [rbp+0x3f28]
mov rdx,QWORD PTR [rbx+0xd0]
mov rsi,QWORD PTR [rbx+0x8]
pop rbx
pop rbp
mov rax,QWORD PTR [rdi+0x468]
jmp rax
```

Bridging gadget

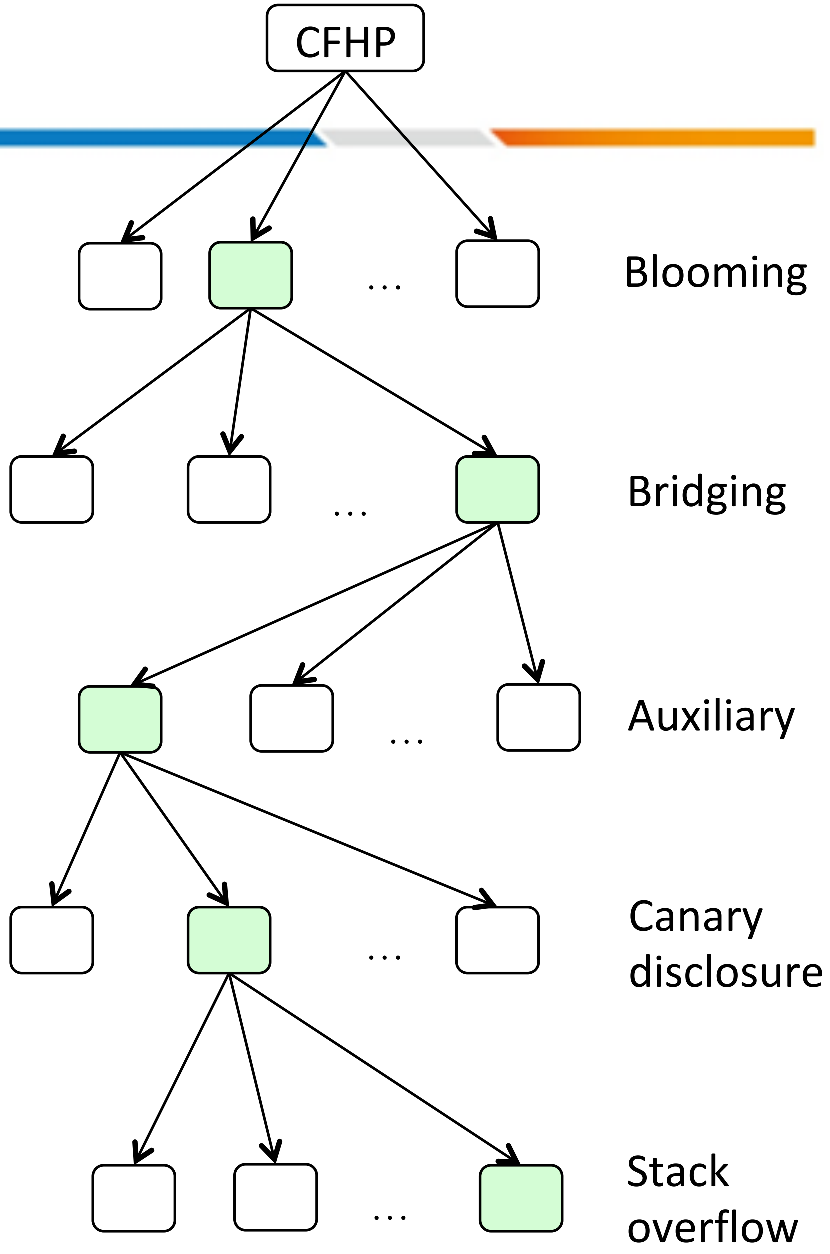
- Bridging gadget
  - Containing multiple controllable indirect calls
- Spawning two CFHPs and combining canary leak and stack smash into a single shot.

```
void regcache_mark_dirty(struct regmap *map){
  map->lock(map->lock_arg);// the 1st control-flow hijack
  map->cache_dirty=true;
  map->no_sync_defaults=true;
  map->unlock(map->lock_arg);// the 2nd control-flow hijack
}
```



Implementation

- Collecting candidate gadgets with static analysis
  - Built on IDA-Pro SDK 6.95
- Taking Exploit chain identification as a tree search problem
  - 28 workers to search different sub-trees concurrently
- Stitching gadgets with symbolic execution
  - Built on angr
  - Initialization: QEMU snapshot
  - Pruning: checking constraints satisfiability at key locations
  - State explosion mitigations:
    - Giving up after 20 steps for each stage
    - Entering a loop for less than 5 times.



Evaluation

- Test Cases:
  - 16 CVEs + 3 CTF challenges
- Comparing with previous exploit generation/hardening techniques
  - FUZE: relying on an exploit technique named "CR4 hijacking"
    - Not bypassing VMM-based hypervisor
    - Not bypassing exploitation pitfalls
  - Q : relying on stack-pivoting gadget which is not available in the kernel binary image

ID	Vulnerability type	Public exploit	Q	FUZE	KEPLER
CVE-2017-16995	OOB readwrite	✓†	✗	✗	✓
CVE-2017-15649	use-after-free	✓	✗	✓	✓
CVE-2017-10661	use-after-free	✗	✗	✗	✓
CVE-2017-8890	use-after-free	✗	✗	✗	✓
CVE-2017-8824	use-after-free	✓	✗	✓	✓
CVE-2017-7308	heap overflow	✓	✗	✗	✓
CVE-2017-7184	heap overflow	✓	✗	✗	✓
CVE-2017-6074	double-free	✓	✗	✗	✓
CVE-2017-5123	OOB write	✓†	✗	✗	✓
CVE-2017-2636	double-free	✗	✗	✗	✓
CVE-2016-10150	use-after-free	✗	✗	✗	✓
CVE-2016-8655	use-after-free	✓†	✗	✓†	✓
CVE-2016-6187	heap overflow	✗	✗	✗	✓
CVE-2016-4557	use-after-free	✗	✗	✗	✓
CVE-2017-17053	use-after-free	✗	✗	✗	✗
CVE-2016-9793	integer overflow	✗	✗	✗	✗
TCTF-credjar	use-after-free	✓†	✗	✗	✓
0CTF-knote	uninitialized use	✗	✗	✗	✓
CSAW-stringIPC	OOB read&write	✓†	✗	✗	✓

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Evaluation (cont.)

- Finding exploit chain in 50 wall clock minutes
- Generating tens of thousands of exploit chains
- Hard to defeat because the gadget could not be easily removed.

ID	Vulnerability type	G1	G2	G3	G4	First chain (min)	Total time (hour)	Total # of exploitation chains
CVE-2017-16995	OOB readwrite	41	114	27	201	45	37	29788
CVE-2017-15649	use-after-free	29	79	25	280	16	28	60207
CVE-2017-10661	use-after-free	28	78	30	301	17	25	49070
CVE-2017-8890	use-after-free	21	88	23	304	17	18	50471
CVE-2017-8824	use-after-free	63	101	35	306	50	70	164898
CVE-2017-7308	heap overflow	31	91	30	241	14	47	110176
CVE-2017-7184	heap overflow	31	95	31	254	24	37	93752
CVE-2017-6074	double-free	18	79	31	308	16	15	31436
CVE-2017-5123	OOB write	40	86	27	311	14	39	113466
CVE-2017-2636	double-free	18	89	29	289	29	19	26372
CVE-2016-10150	use-after-free	34	84	25	293	52	34	88499
CVE-2016-8655	use-after-free	18	109	32	260	15	17	47413
CVE-2016-6187	heap overflow	22	85	32	301	17	21	51954
CVE-2016-4557	use-after-free	21	80	21	295	16	37	40889
CVE-2017-17053	use-after-free	-	-	-	-	-	-	-
CVE-2016-9793	integer overflow	-	-	-	-	-	-	-
TCTF-credjar	use-after-free	35	89	25	292	25	14	82913
0CTF-knote	uninitialized use	21	89	33	318	17	36	40923
CSAW-stringIPC	OOB read&write	35	88	25	289	17	33	84414

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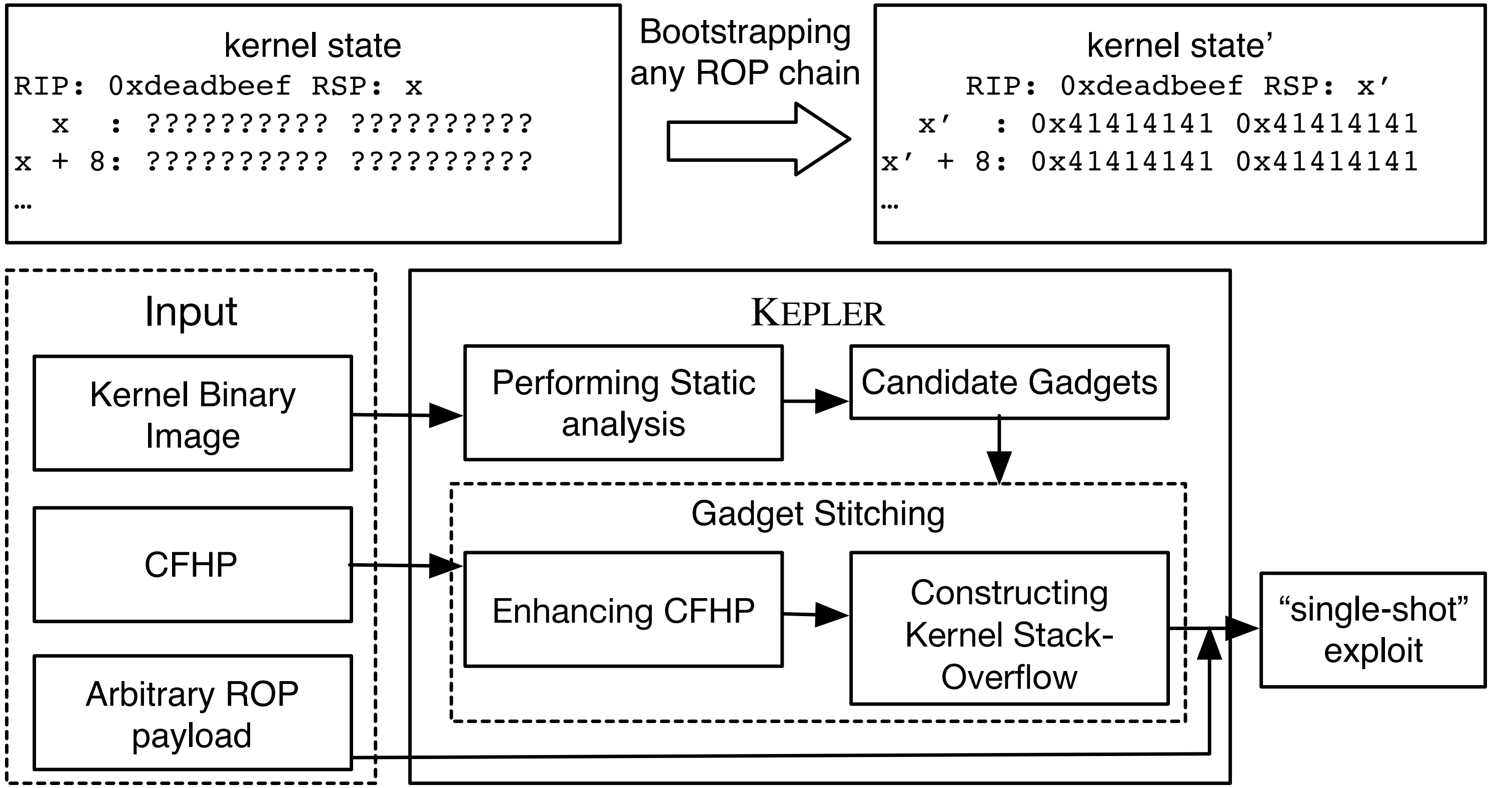
Conclusions

- New technique: Single-shot exploitation is an effective kernel exploitation technique
  - Reduction: From "ROP is Turing Complete" to "control-flow hijacking is Turing Complete"
- New tool: Kepler is able to convert Linux kernel ROP bootstrapping task into a bounded tree-search problem and facilitate evaluation of control-flow hijacking primitive
  - Source: https://github.com/ww9210/ kepler-cfhp
- Suggestion: Kernel CFI should be deployed because other mitigations hardly stop exploitation

Thank you.


kernel state
RIP: 0xdeadbeef RSP: x
x : ?????????? ??????????
x + 8: ?????????? ??????????
…
Bootstrapping any ROP chain
kernel state'
RIP: 0xdeadbeef RSP: x'
x' : 0x41414141 0x41414141
x' + 8: 0x41414141 0x41414141
…
Input
Kernel Binary Image
CFHP
Arbitrary ROP payload
KEPLER
Performing Static analysis
Candidate Gadgets
Gadget Stitching
Enhancing CFHP
Constructing Kernel Stack-Overflow
"single-shot" exploit