Return to sender

Detecting kernel exploits with eBPF

Guillaume Fournier

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DATADOG

About me

Guillaume Fournier

Senior Security Engineer @Datadog
gui774ume.fournier@gmail.com

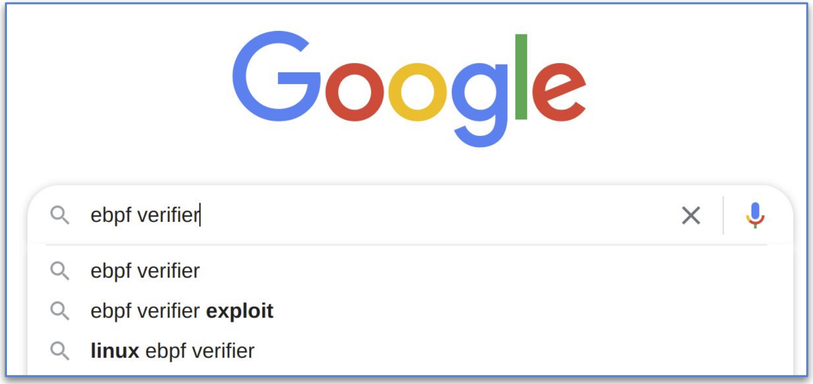
- Cloud Workload Security (CWS)
- Leverage eBPF to detect threats
- Embedded in the Datadog Agent

Agenda

- Context and threat model
- Why eBPF ?
- KRIe
  - SMEP & SMAP on a budget
  - Kernel security configuration
  - Kernel runtime alterations
  - Control flow integrity
  - Enforcement
- Performance

Context and threat model

- Critical CVEs are regularly discovered in the Linux Kernel
- Security administrators worry about:
  - Keeping up with security updates
  - Deploying security patches
  - Monitoring & protecting vulnerable hosts



Context and threat model

- Hundreds of ways to exploit the Linux kernel
- This talk targets 3 types of vulnerabilities:
  - Execution flow redirections
  - Logic bugs
  - Post compromise kernel runtime alterations

The goal is to detect (and prevent ?) these attacks with eBPF

Context and threat model

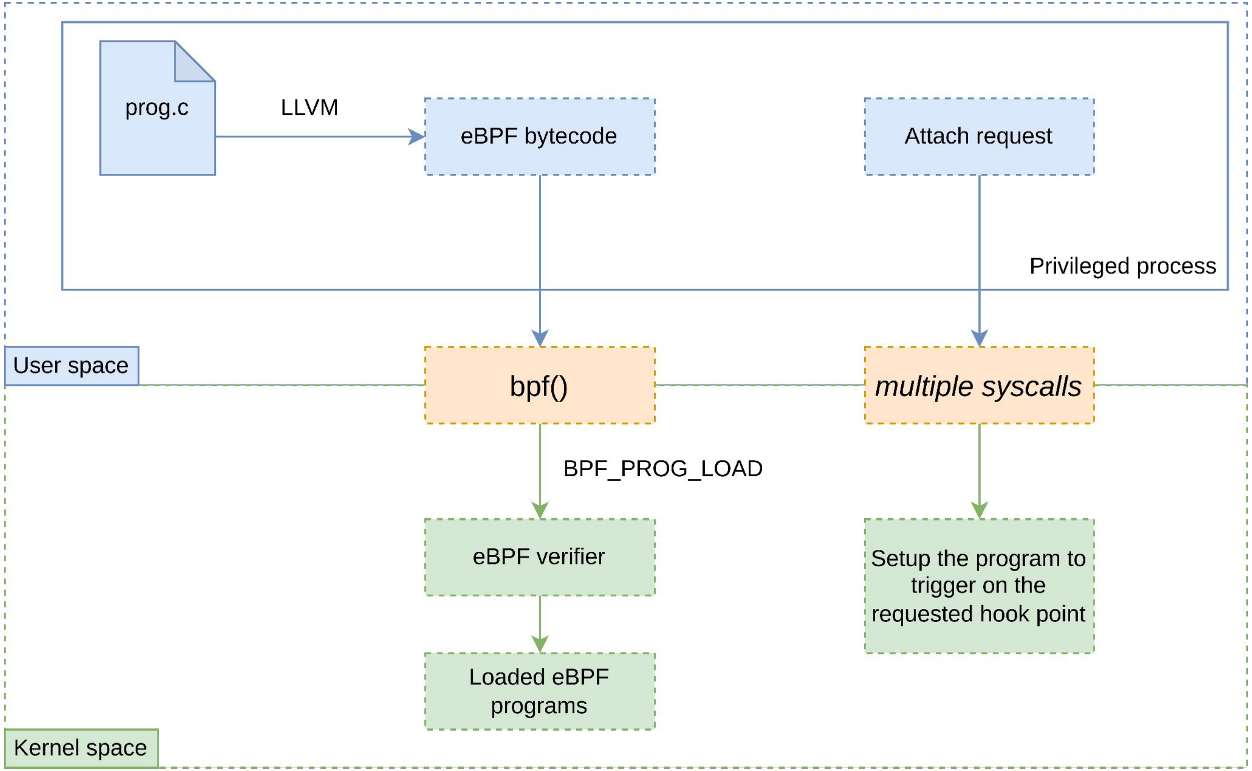
- Hundreds of ways to exploit the Linux kernel
- This talk targets 3 types of vulnerabilities:
  - Execution flow redirections
  - Logic bugs
  - Post compromise kernel runtime alterations

~~The goal is to detect (and prevent ?) these attacks~~ with eBPF

Make attackers' lives a living hell

What is eBPF ?

- Run sandboxed programs in the Linux kernel



Why eBPF ?

- Relatively wide kernel support (4.1 +) depending on eBPF features
- System safety and stability insurances
- Rich feature set with easy to use introspection capabilities
- Some write access and enforcement capabilities

Why ~~eBPF~~ ?

Why is this a terrible idea ?

- Detecting post compromise activity is fighting a lost battle
- There are dozens of ways to disable an eBPF program
- eBPF can have a significant in kernel performance impact

So what's the point ?

- Script kiddies and OOTB rootkits
- Make it harder to exploit a flaw
- Detecting & blocking pre-compromise is ***sometimes*** possible

Kernel Runtime Integrity with eBPF (KRIe)

- Open source project
- No ARM support (yet)
- Compatible with at least kernels 4.15+ to now
- First version released today !

https://github.com/Gui774ume/krie

KRIe: SMEP & SMAP on a budget

Scenario 1: the attacker controls the address of the next instruction executed by the kernel

- Textbook use case for Return Object Programming (ROP) attacks
- Privilege escalation attacks

KRIe: SMEP & SMAP on a budget

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Kernel Executable code		User space memory	
Addresses	Bytecode	Addresses	Bytecode

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[@stack_pivot]	xchg esp, eax ; ret		

Attacker jumps to

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[@stack_pivot]	xchg esp, eax ; ret	[@rop_chain] [@rop_chain+8] [@rop_chain+16]	@gadget_1 0x42 @kernel_func

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[@stack_pivot]	xchg esp, eax ; ret	[@rop_chain] [@rop_chain+8] [@rop_chain+16]	@gadget_1 0x42 @kernel_func
[@kernel_func]	push %rbp		

Attacker jumps to

Stack pivot

Execute a kernel function with attacker controlled parameters

KRIe: SMEP & SMAP on a budget

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[@kernel_func]	push %rbp		

Attacker jumps to

Stack pivot

Not possible with SMAP

KRIe: SMEP & SMAP on a budget

- SMEP would have prevented the CPU from executing code in user space executable memory
- Our example ROP chain will eventually call:

```
commit_creds(prepare_kernel_cred(0))
```

What can we do for machines without SMEP / SMAP ?

KRIe: SMEP & SMAP on a budget

- ➔ Place a `BPF_PROG_TYPE_KPROBE` on "`prepare_kernel_cred`" and check if the Stack pointer / Frame pointer / Instruction pointer registers point to user space memory

Demo

(Ubuntu Bionic 18.04 - Kernel 4.15.0-189-generic - SMAP disabled)

KRIe: SMEP & SMAP on a budget

- On a budget because:
  - Need to hook “all the functions called by exploits”
  - Blocking mode only works on 5.3+ kernels
  - An attacker will try to prevent our kprobe from firing …

KRIe: SMEP & SMAP on a budget

- So … how can one disable a kprobe ?
  - `echo 0 > /sys/kernel/debug/kprobes/enabled`
  - `sysctl kernel.ftrace_enabled=0`
  - By killing the user space process that loaded the kprobe

KRIe: SMEP & SMAP on a budget

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➔ Let’s booby trap everything 🎉

KRIe: Kernel security configuration

1) `echo 0 > /sys/kernel/debug/kprobes/enabled`

- Global switch that disarms all kprobes on a machine
- The ROP chain can be updated to call

```
write_enabled_file_bool(NULL, "0", 1, NULL)
```

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→ Let's put a kprobe on it 🎉

KRIe: Kernel security configuration

1) `echo 0 > /sys/kernel/debug/kprobes/enabled`

- Even when enabled, a kprobe can *still* be bypassed:

@write_enabled_file_bool - **No kprobe**	@write_enabled_file_bool - **With a kprobe**
0x0: **nop dword ptr [...]** 0x5: push %rbp 0x6: mov %rsp,%rbp 0x9: push %r14 0xb: push %r13 0xd: push %r12 …	0x0: **callq 0xffffffff81a01cf0** 0x5: push %rbp 0x6: mov %rsp,%rbp 0x9: push %r14 0xb: push %r13 0xd: push %r12 …

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Jump here with the ROP chain

KRIe: Kernel security configuration

1) `echo 0 > /sys/kernel/debug/kprobes/enabled`

➔ Booby trap the function at random offsets 🎉

@write_enabled_file_bool - **No kprobe**	@write_enabled_file_bool - **With kprobe(s)**

`0x0: nop dword ptr [...]`
`0x5: push %rbp`
`0x6: mov %rsp,%rbp`
`0x9: push %r14`
`0xb: push %r13`
`0xd: push %r12`
…
	`0x0: callq 0xffffffff81a01cf0`
	`0x5: push %rbp`
	`0x6: callq 0xffffffff81a01cf0`
	`0xb: push %r13`
	`0xd: callq 0xffffffff81a01cf0`
	…

KRIe: Kernel security configuration

1) `echo 0 > /sys/kernel/debug/kprobes/enabled`

- “`write_enabled_file_bool`” writes 0 or 1 to a global variable called “`kprobes_all_disarmed`”
- An attacker could try to write 1 to it directly

KRIe: Kernel security configuration

1) `echo 0 > /sys/kernel/debug/kprobes/enabled`

- "`write_enabled_file_bool`" writes 0 or 1 to a global variable called "`kprobes_all_disarmed`"
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➔ We can use a `BPF_PROG_TYPE_PERF_EVENT` program to periodically check the values of all sensitive kernel parameters 🎉

KRIe: Kernel security configuration

2) `sysctl kernel.ftrace_enabled=0`

- There is an eBPF program type dedicated to monitoring and enforcing `sysctl` commands :

  `BPF_PROG_TYPE_CGROUP_SYSCTL` (kernels 5.2+)

- (Almost) all sysctl parameters are checked by KRIe's periodical check

KRIe: Kernel runtime alterations

Scenario 2: the attacker is root on the machine and wants to persist its access by modifying the kernel runtime

- Insert a rogue kernel module
- Hook syscalls to hide their tracks
  - Using kprobes
  - By hooking the syscall table directly
- BPF filters are used to silently capture network traffic
- eBPF programs can also be used to implement rootkits

KRIe: Kernel runtime alterations

Scenario 2: the attacker is root on the machine and wants to persist its access by modifying the kernel runtime

→ KRIe monitors:

- All bpf() operations and insertion of BPF filters
- Kernel module load / deletion events
- K(ret)probe registration / deletion / enable / disable / disarm events
- Ptrace events
- Sysctl commands
- Execution of hooked syscalls

… and more to come !

KRIe: Kernel runtime alterations

- ➔ All syscall tables are checked periodically with the `BPF_PROG_TYPE_PERF_EVENT` program trick
- ➔ KRIe is also able to detect and report when a process executes a hooked syscall

Demo

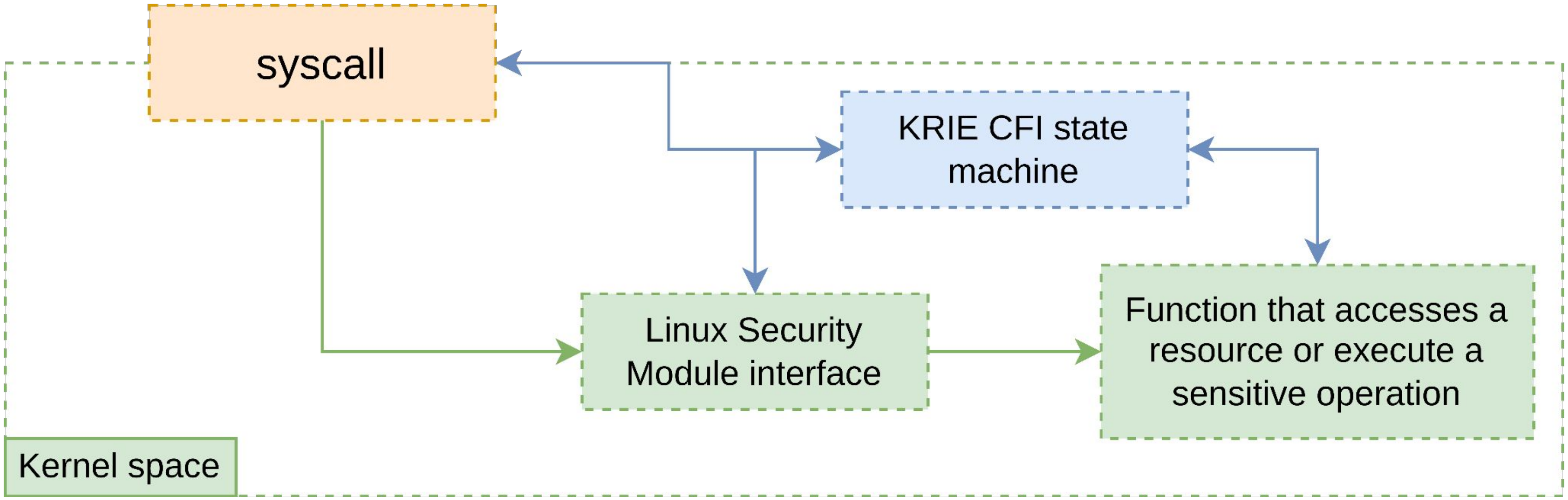
(Ubuntu Jammy 22.04 - Kernel 5.15.0-43-generic)

KRIe: Control flow Integrity (CFI)

- Locks down the execution flows in the kernel by controlling call sites at runtime
- Usually added at compile time or implemented in hardware
- CFI is a great way to prevent ROP attacks
- These features aren’t always available; specifically the hardware ones

KRIe: Control flow Integrity (CFI)

- KRIe locks down jumps between control points
- Both hook points and parameters are checked



KRIe: Control flow Integrity (CFI)

The goal:

- Catch malicious calls to sensitive functions (via ROP)
- Detect logic bugs, specifically for access rights

But:

- Tedious process
- Hook points limitations

KRIe: Enforcement

- KRIe enables blocking features when available:
  - `bpf_override_return` helper (4.16+)
  - `BPF_PROG_TYPE_CGROUP_SYSCTL` programs (5.2+)
  - `bpf_send_signal` helper (5.3+)
  - LSM programs (5.7+)
- Every detection is configurable:
  - Log
  - Block
  - Kill
  - Paranoid

Performance

- Linux kernel compilation time

	User space CPU time		Kernel space CPU time		Total elapsed time
Without KRIe	4,320s	88%	568s	12%	5:53.14
With KRIe (all features)	4,517s	68%	2,097s	32%	8:15.76
	+4.5%		**+270%**		**+40%**
With KRIe (syscall hook check disabled on syscall entry)	4,380s	88%	585s	12%	5:58.36
	+1%		**+3%**		**+1%**

(Benchmark run on a 5.15.0 kernel, 11th Gen Intel(R) Core(TM) i9-11950H @ 2.60GHz, 32GB of RAM, average on 10 iterations)

Thanks

- Powerful defensive tools can be implemented with eBPF
- eBPF is not really the ideal technology to detect kernel exploits
- KRIe is realistically a last resort, not a bulletproof strategy

https://github.com/Gui774ume/krie

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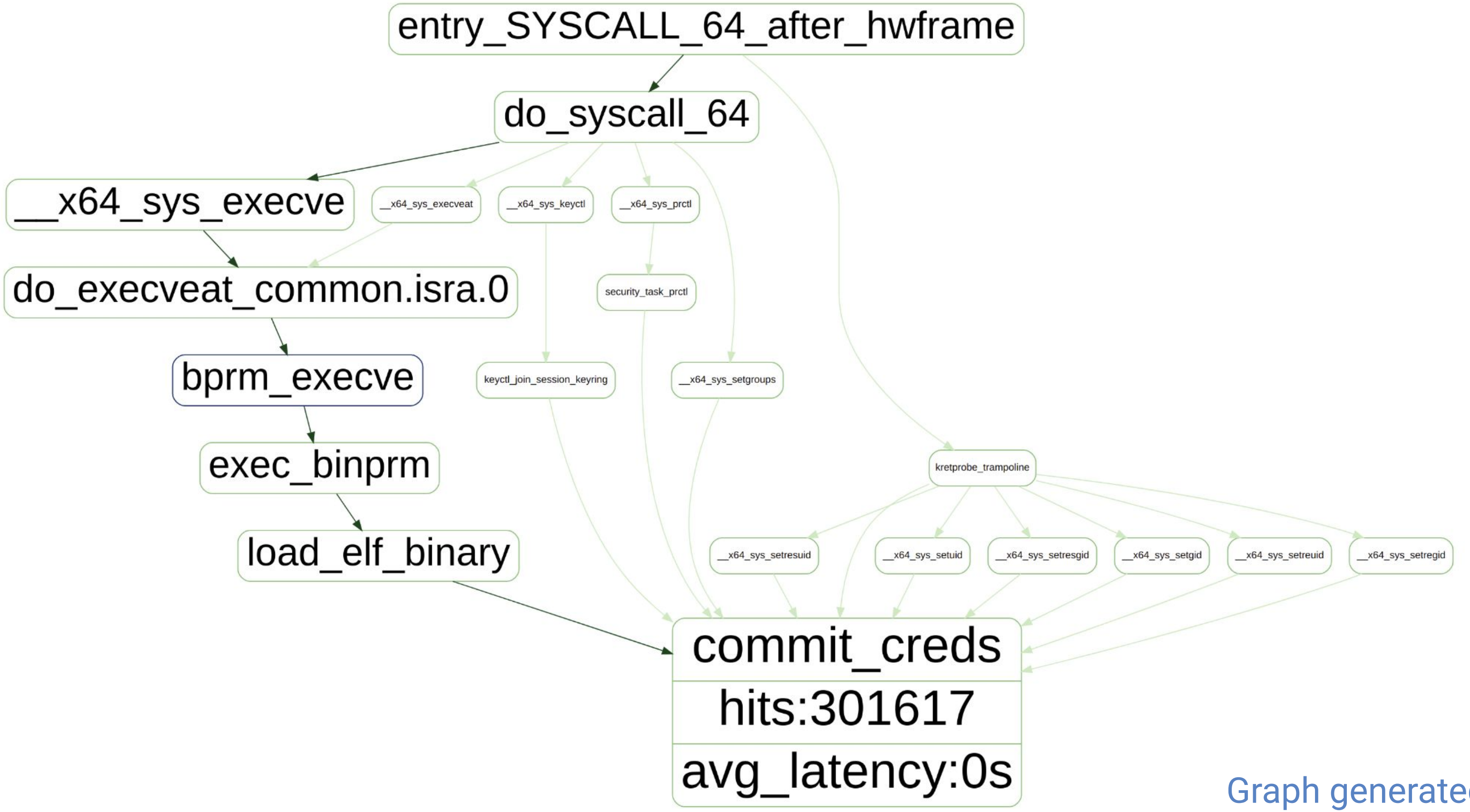
KRIe: Control flow Integrity (CFI)



Graph generated with utrace:
https://github.com/Gui774ume/utrace

Kernel stack traces to `commit_creds`

KRIe: real world rootkits

- Syscall hooking method:
  - croemheld/lkm-rootkit
  - QuokkaLight/rkduck
  - m0nad/Diamorphine
  - Eterna1/puszek-rootkit
  - reveng007/reveng_rtkit
- Kprobe / Ftrace hooking method:
  - h3xduck/Umbra
- eBPF / BPF filters methods:
  - Gui774ume/ebpfkit
  - pathtofile/bad-bpf
  - h3xduck/TripleCross

… and many others !