eBPF, I thought we were friends !

Guillaume Fournier
Sylvain Afchain

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About us

- Cloud Workload Security Team
- Leverage eBPF to detect attacks at runtime
- Integrated in the Datadog Agent

Sylvain Afchain

Staff Engineer

sylvain.afchain@datadoghq.com

Sylvain Baubeau

Staff Engineer & Team lead

sylvain.baubeau@datadoghq.com

Guillaume Fournier

Security Engineer

guillaume.fournier@datadoghq.com

Agenda

- Introduction to eBPF
- Abusing eBPF to build a rootkit
  - Obfuscation
  - Persistent access
  - Command and Control
  - Data exfiltration
  - Network discovery
  - RASP evasion
- Detection and mitigation strategies

Introduction to eBPF

Introduction to eBPF

What is eBPF ?

- Extended Berkeley Packet Filter
- Sandboxed programs in the Linux kernel
- Initially designed for fast packet processing

- Use cases:
  - Kernel performance tracing
  - Network security and observability
  - Runtime security
  - etc

eBPF

cilium

Katran

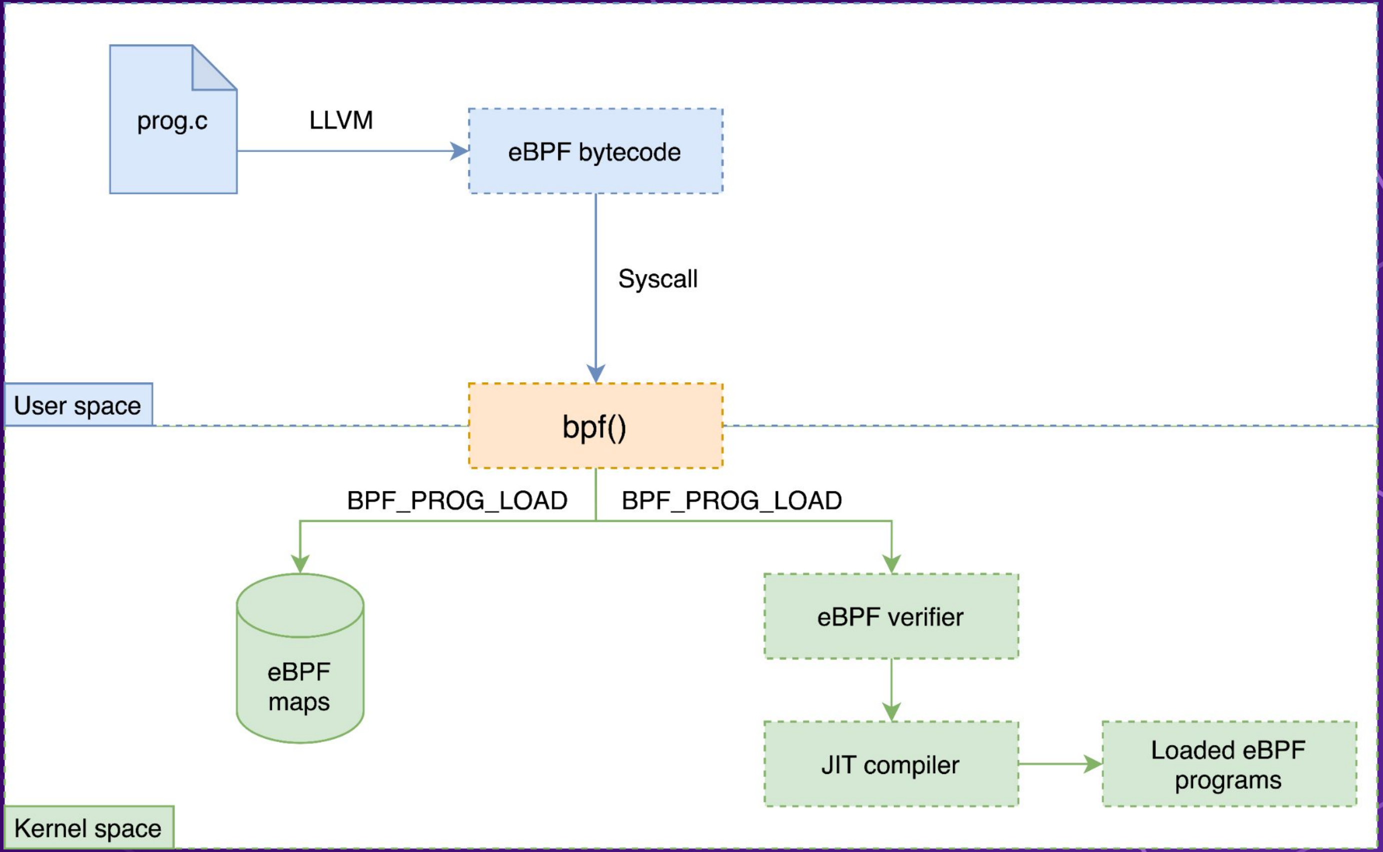
Falco

Tracee

DATADOG

Introduction to eBPF

Step 1: Loading eBPF programs



Introduction to eBPF

Step 2: Attaching eBPF programs

- Defines how a program should be triggered
- ~ 30 program types (Kernel 5.13+)
- Depends on the program type
  - BPF_PROG_TYPE_KPROBE
  - BPF_PROG_TYPE_TRACEPOINT

    “perf_event_open” syscall

  - BPF_PROG_TYPE_SCHED_CLS
  - BPF_PROG_TYPE_XDP

    Dedicated Netlink command

  - etc
- Programs of different types can share the same eBPF maps

Introduction to eBPF

eBPF internals: the verifier

The eBPF verifier ensures that eBPF programs will finish and won’t crash.

❑ Directed Acyclic Graph

❑ No unchecked dereferences

❑ No unreachable code

❑ Limited stack size (512 bytes)

❑ Program size limit (1 million on 5.2+ kernels)

❑ Bounded loops (5.2+ kernels)

❑ … and cryptic output ...

Introduction to eBPF

eBPF internals: eBPF helpers

- Context helpers
  - bpf_get_current_task
  - bpf_get_current_pid_tgid
  - bpf_ktime_get_ns
  - etc
- Map helpers
  - bpf_map_lookup_elem
  - bpf_map_delete_elem
  - etc
- Program type specific helpers
  - bpf_xdp_adjust_tail
  - bpf_csum_diff
  - bpf_l3_csum_replace
  - etc
- Memory related helpers
  - bpf_probe_read
  - bpf_probe_write_user
  - etc

… ~160 helpers (kernel 5.13+)

Abusing eBPF to build a rootkit

Abusing eBPF to build a rootkit

Why ?

- Cannot crash the host
- Minimal performance impact
- Fun technical challenge
- A growing number of vendors use eBPF
- eBPF “safety” should not blind Security Administrators

eBPF

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Abusing eBPF to build a rootkit

Goals

- Trade off between latest BPF features / availability

  => Latest Ubuntu LTS, RHEL/CentOS

- KRSI and helpers such bpf_dpath may help

Abusing eBPF to build a rootkit

Obfuscation

- Hide the rootkit process
  - eBPF programs are attached to a running process

    Our userspace rootkit has to stay resident
  - Detection through syscalls that accept pids as arguments : kill, waitpid, pidfd_open, ...
- Hide our BPF components:
  - programs
  - maps

Abusing eBPF to build a rootkit

Program obfuscation

Demo

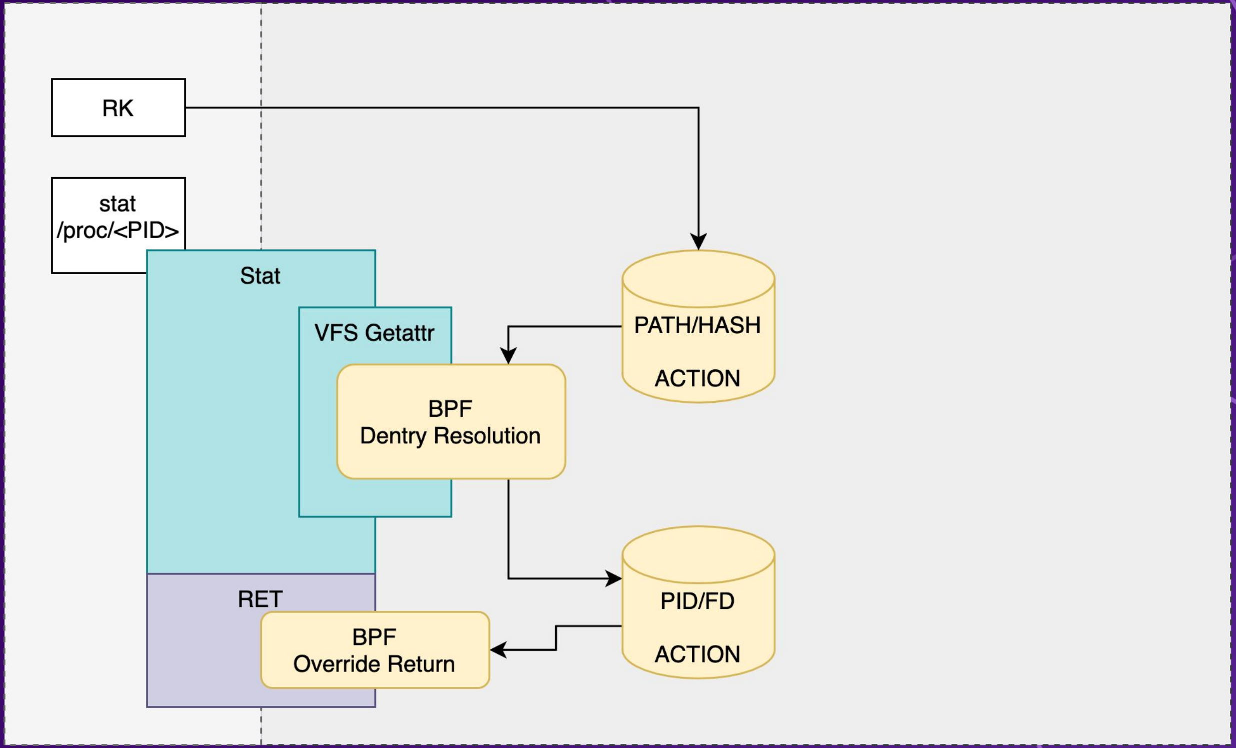
Abusing eBPF to build a rootkit

Program obfuscation - Techniques

- bpf_probe_write_user
  - Corrupt syscall output
  - Minor and major page faults
- bpf_override_return
  - Block syscall
  - Alter syscall return value
    - But syscall was really executed by the kernel !

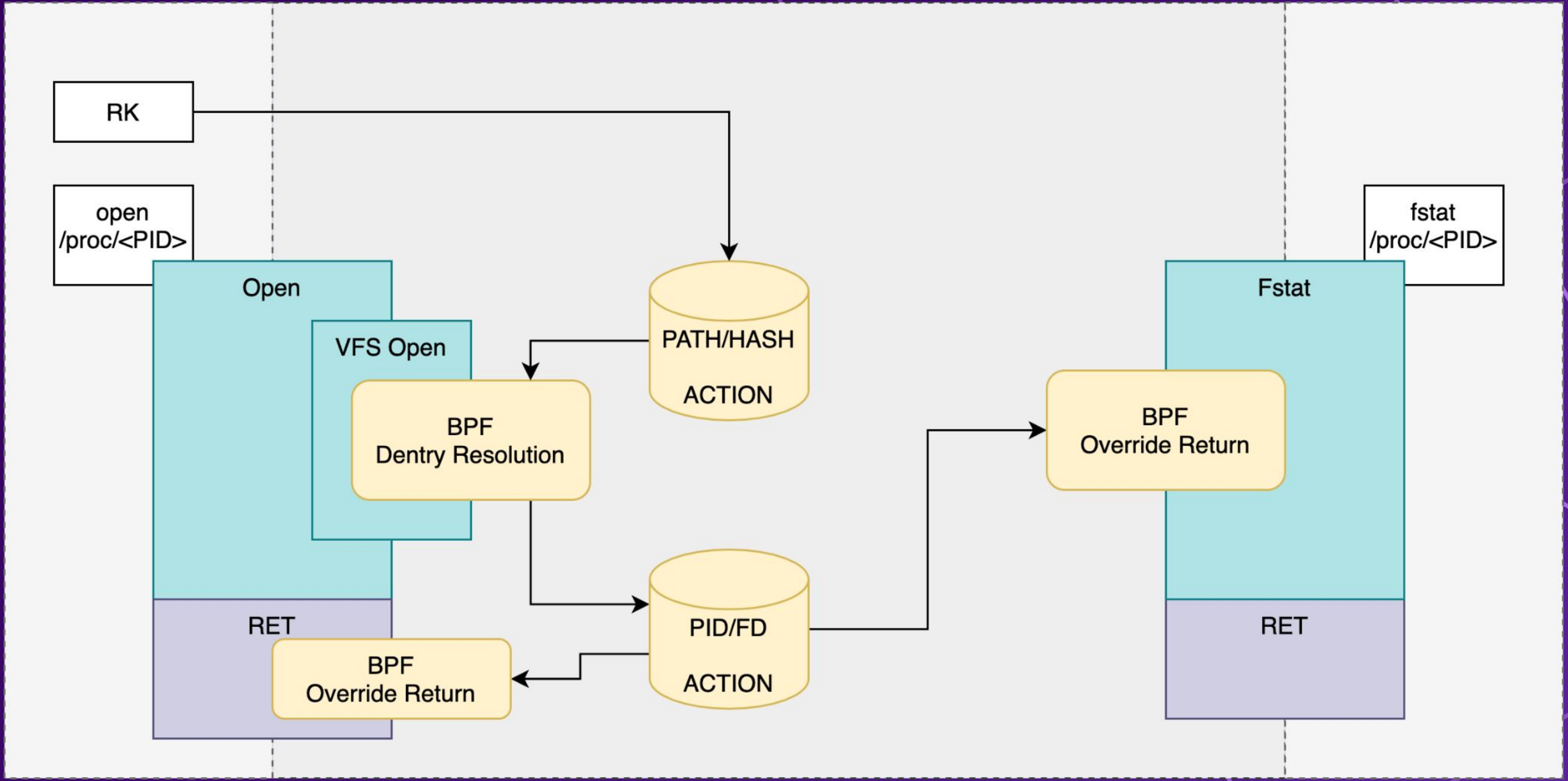
Abusing eBPF to build a rootkit

File obfuscation - stat /proc/<rootkit-pid>/cmdline (1)



Abusing eBPF to build a rootkit

Program obfuscation - stat /proc/<rootkit-pid>/exe (2)



Abusing eBPF to build a rootkit

Program obfuscation

- Block signals
  - Hook on the kill syscall entry
  - Override the return value with ESRCH

- Block kernel modules

Abusing eBPF to build a rootkit

BPF program obfuscation

Demo

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BPF program obfuscation

- bpf syscall
    - Programs:
        - BPF_PROG_GET_NEXT_ID
        - BPF_PROG_GET_FD_BY_ID
    - Maps:
        - BPF_MAP_GET_NEXT_ID
        - BPF_MAP_GET_FD_BY_ID
    - Hook on new prog / map to get the allocated ID

- Hook on read syscall and override the content

Abusing eBPF to build a rootkit

BPF program obfuscation

- bpf_probe_write_user
    - message in kernel ring buffer

      "...is installing a program with bpf_probe_write_user helper that may corrupt user memory!"
    - dmesg
    - journalctl -f
    - syscall syslog

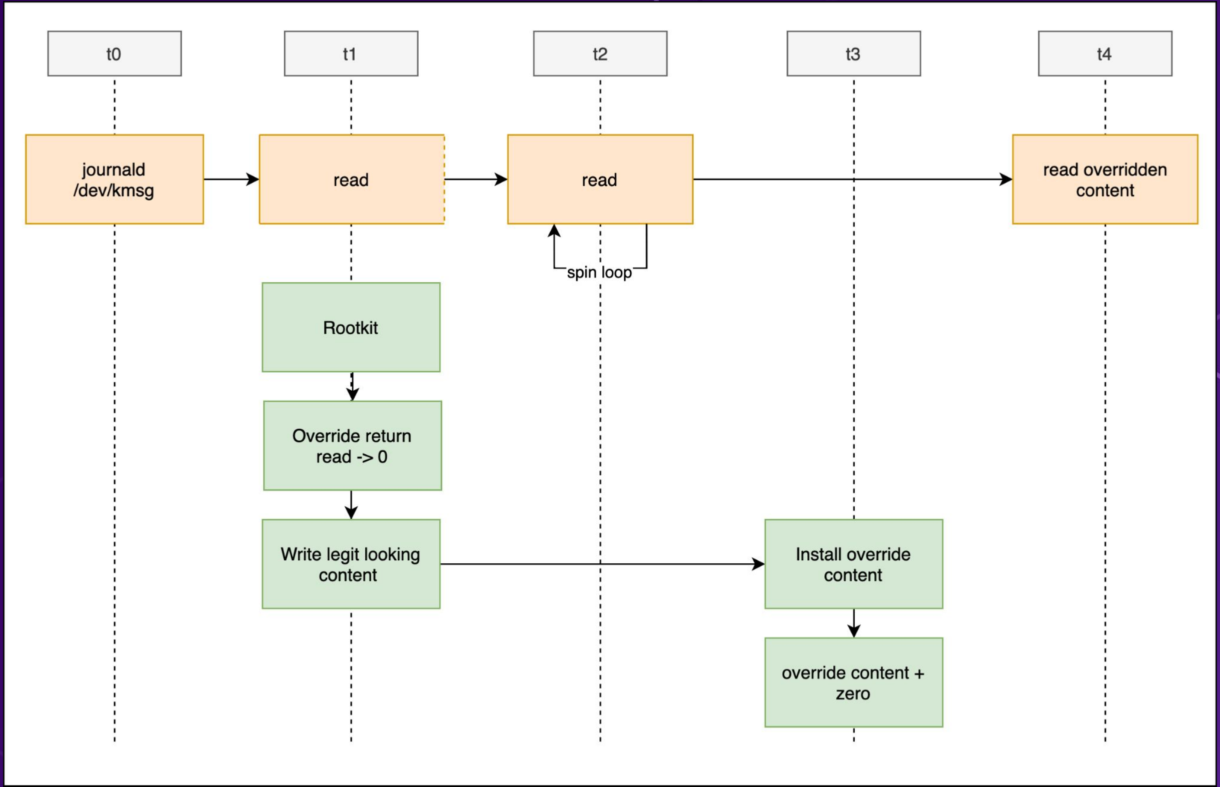
Abusing eBPF to build a rootkit

BPF program obfuscation

Demo

Abusing eBPF to build a rootkit

BPF program obfuscation



Abusing eBPF to build a rootkit

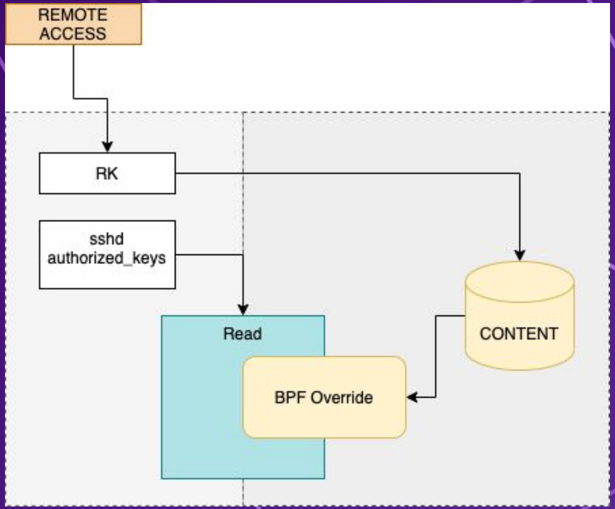
Persistent access

- Self copy
  - Generate random name
  - Copy into /etc/rcS.d
  - Hide file
- Override content of sensitive files
  - SSH authorized_keys
  - passwd
  - crontab

Abusing eBPF to build a rootkit

Persistent access - ssh/authorized_keys

- Append our ssh keys to authorized_keys files
- Only for sshd
- Available through the command and control...



Abusing eBPF to build a rootkit

Persistent access - ssh/authorized_keys

Demo

Abusing eBPF to build a rootkit

Persistent access - uprobe

- eBPF on exported user space functions
- Alter a userspace daemon to introduce a backdoor
- Compared to ptrace
    - Works on all instances of the program
    - Safer
    - Easier to write

Abusing eBPF to build a rootkit

Persistent access - postgresql

Demo

Abusing eBPF to build a rootkit

Persistent access - postgresql

```
int md5_crypt_verify( const char *role, const char *shadow_pass, const char *client_pass,
                      const char *md5_salt, int md5_salt_len, char **logdetail )
```

● md5_salt		challenge sent when user connects
shadow_pass	MD5(role + password)	stored in database
client_pass	MD5(shadow_pass + md5_salt)	sent by the client

●

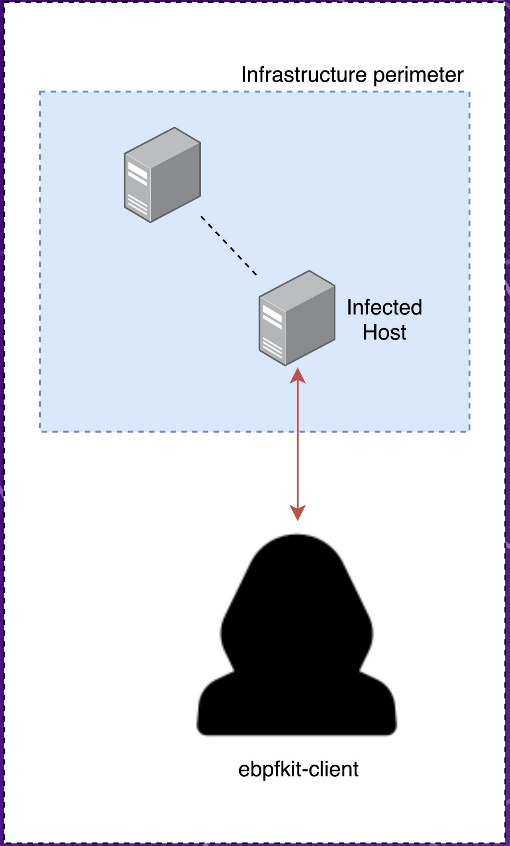
```
new_md5_hash = bpf_map_lookup_elem(&postgres_roles, &creds.role);
if (new_md5_hash == NULL) return 0;

// copy db password onto the user input
bpf_probe_write_user(shadow_pass, &new_md5_hash->md5, MD5_LEN);
```

Abusing eBPF to build a rootkit

Command and control: introduction

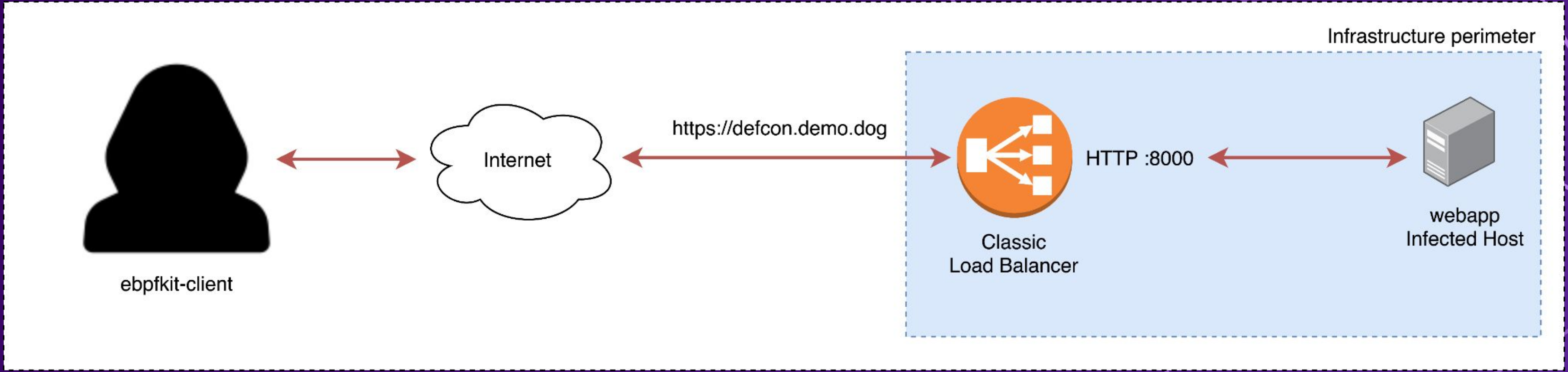
- Requirements
  - Send commands to the rootkit
  - Exfiltrate data
  - Get remote access to infected hosts
- eBPF related challenges
  - Can’t initiate a connection
  - Can’t open a port
- … but we can hijack an existing connection !



Abusing eBPF to build a rootkit

Command and control: introduction

- Setup
  - Simple webapp with AWS Classic Load Balancer
  - TLS resolution at the Load Balancer level
- Goal: Implement C&C by hijacking the network traffic to the webapp



Abusing eBPF to build a rootkit

Command and control: choosing a program type

BPF_PROG_TYPE_XDP	BPF_PROG_TYPE_SCHED_CLS
❑ Deep Packet Inspection	❑ Deep Packet Inspection
❑ Ingress only	❑ Egress and Ingress
❑ Can be offloaded to the NIC / driver	❑ Attached to a network interface
❑ Can drop, allow, modify and retransmit packets	❑ Can drop, allow and modify packets
❑ Usually used for DDOS mitigation	❑ Often used to monitor & secure network access at the container / pod level on k8s

Abusing eBPF to build a rootkit

Command and control: choosing a program type

BPF_PROG_TYPE_XDP

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❑ Ingress only

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❑ Can **drop**, allow, **modify** and retransmit packets

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Network packets can be hidden from the Kernel entirely !

BPF_PROG_TYPE_SCHED_CLS

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Abusing eBPF to build a rootkit

Command and control: choosing a program type

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BPF_PROG_TYPE_SCHED_CLS

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- ❑ **Egress** and Ingress
- ❑ Attached to a network interface
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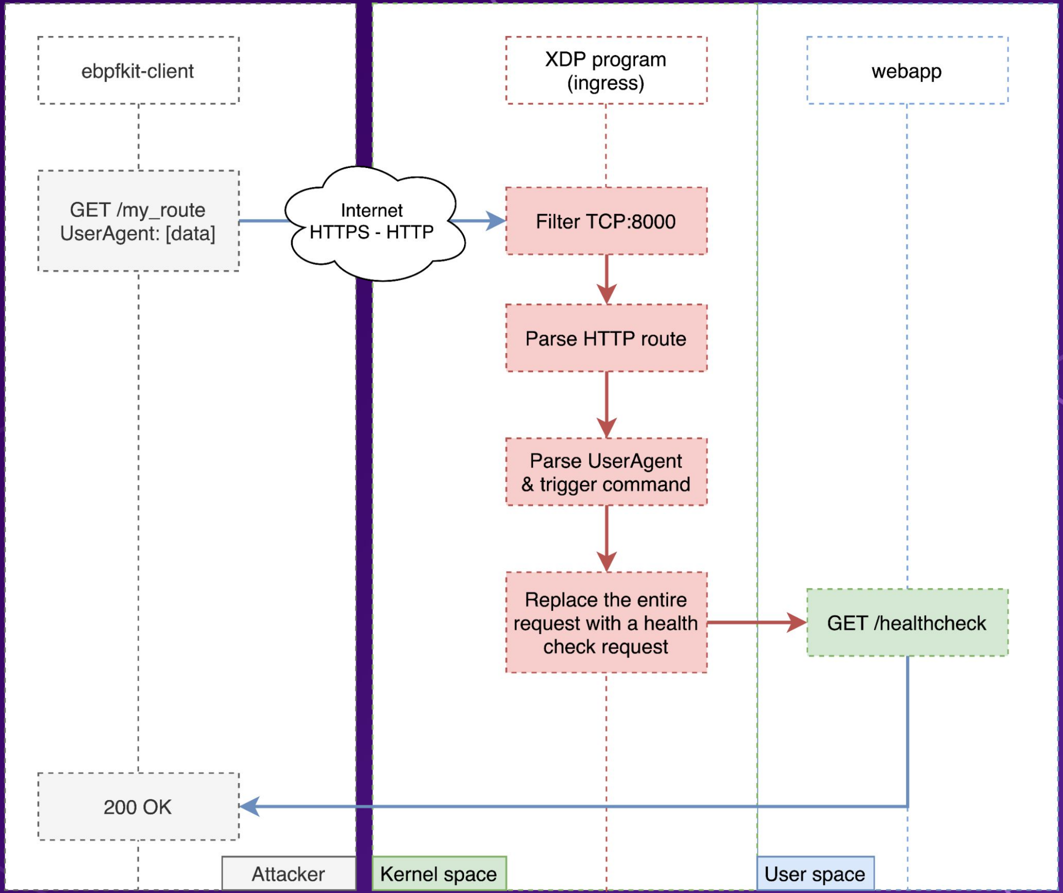
Data can be exfiltrated with an eBPF TC classifier !

Abusing eBPF to build a rootkit

Command and control: hijacking HTTP requests



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Command and control: hijacking HTTP requests

Demo

Sending Postgres credentials over C&C

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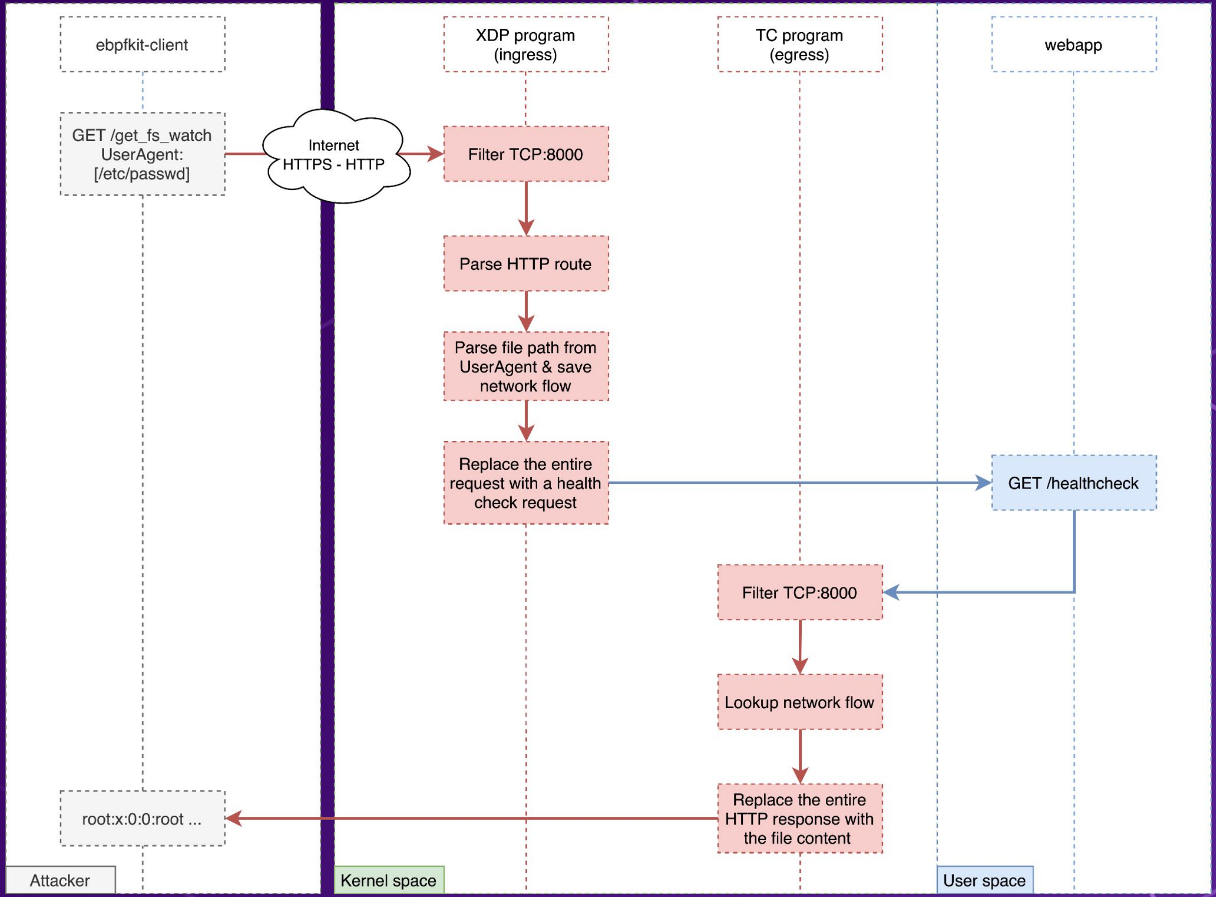
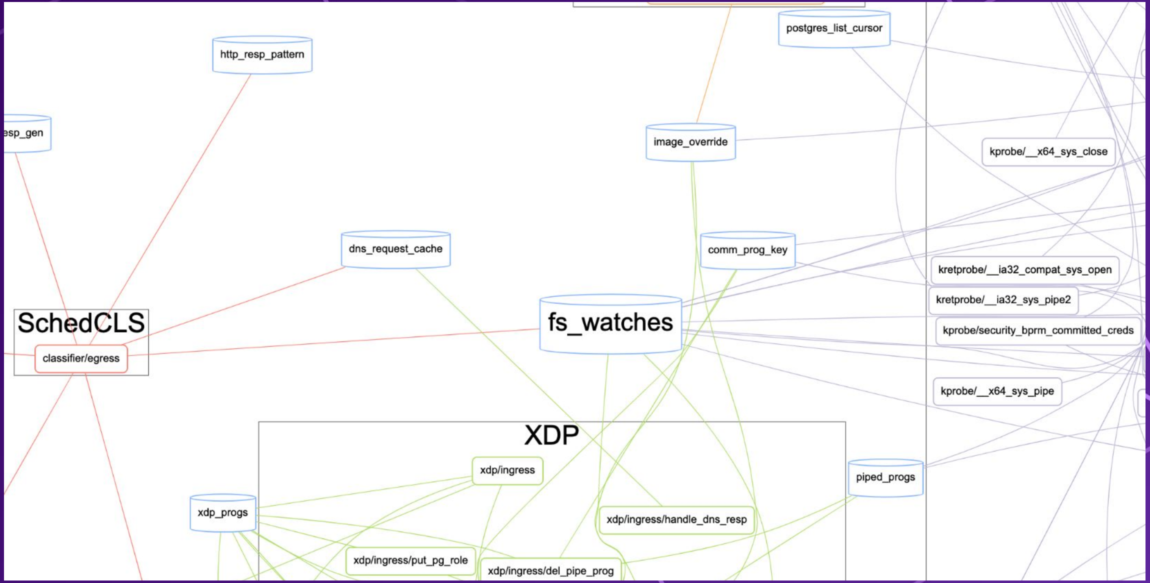
Data exfiltration



Abusing eBPF to build a rootkit

Data exfiltration

- Multiple program types can share data through eBPF maps
- Anything accessible to an eBPF program can be exfiltrated:
  - File content
  - Environment variables
  - Database dumps
  - In-memory data
  - etc



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Data exfiltration

Demo

Exfiltration over HTTPS

Postgres credentials & /etc/passwd

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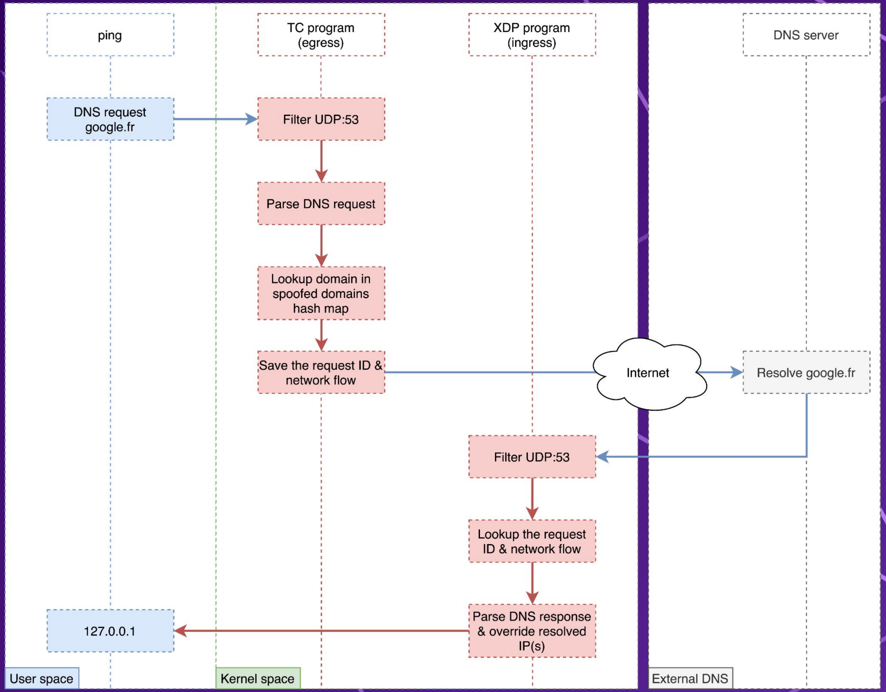
DNS spoofing

The same technique applies to any unencrypted network protocol ...



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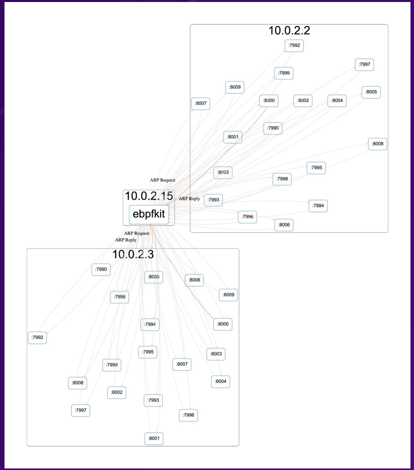
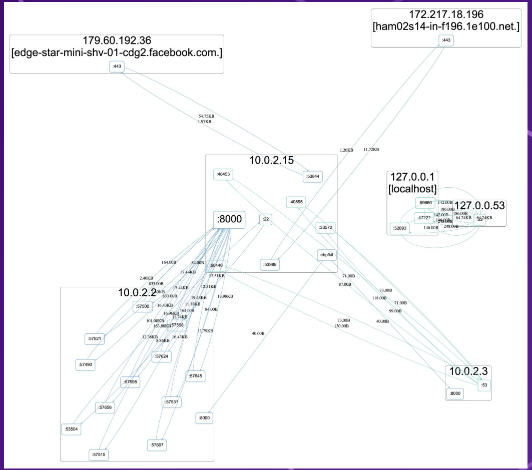
Abusing eBPF to build a rootkit

Network discovery

- Discover machines and services on the network
- 2 methods
- Activated through Command and Control



Active network discovery



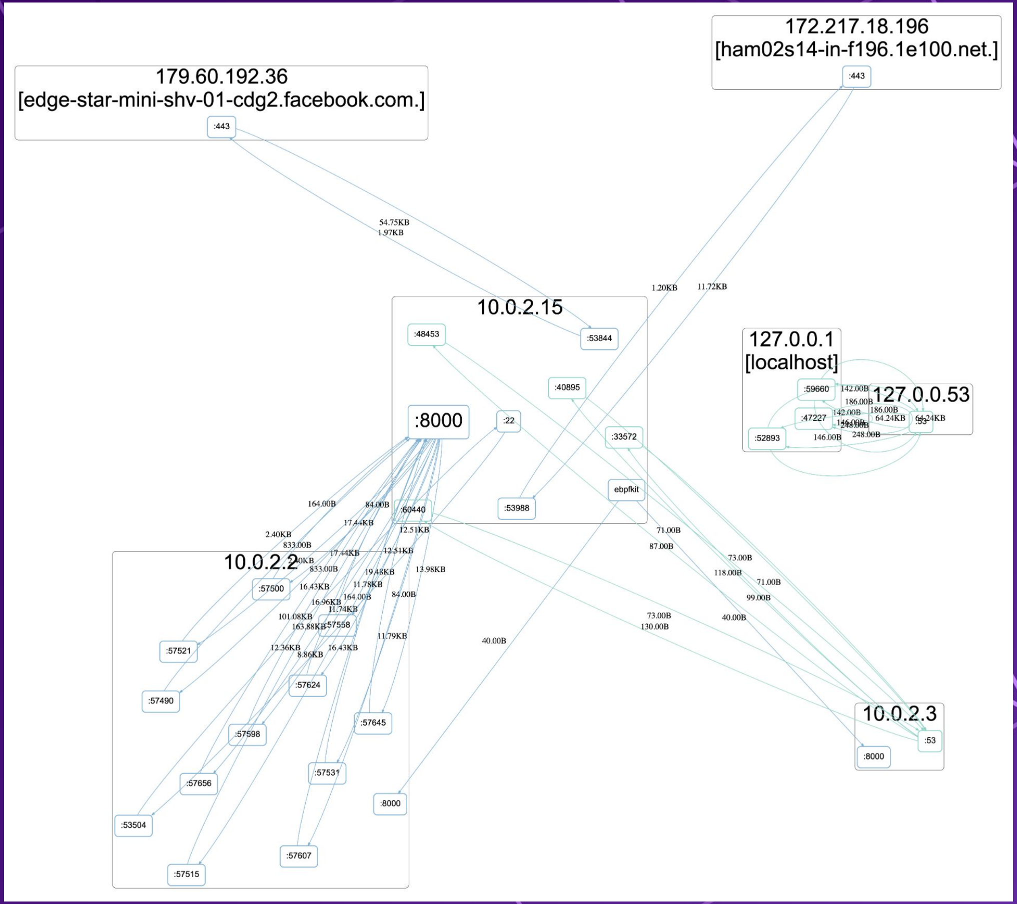
Passive network discovery

Abusing eBPF to build a rootkit

Network discovery: passive method

- Listen for egress and ingress traffic
- TC & XDP
- Discover existing network connections
- TCP & UDP traffic (IPv4)
- No traffic is generated

- Doesn’t work for services which the host is not communicating with



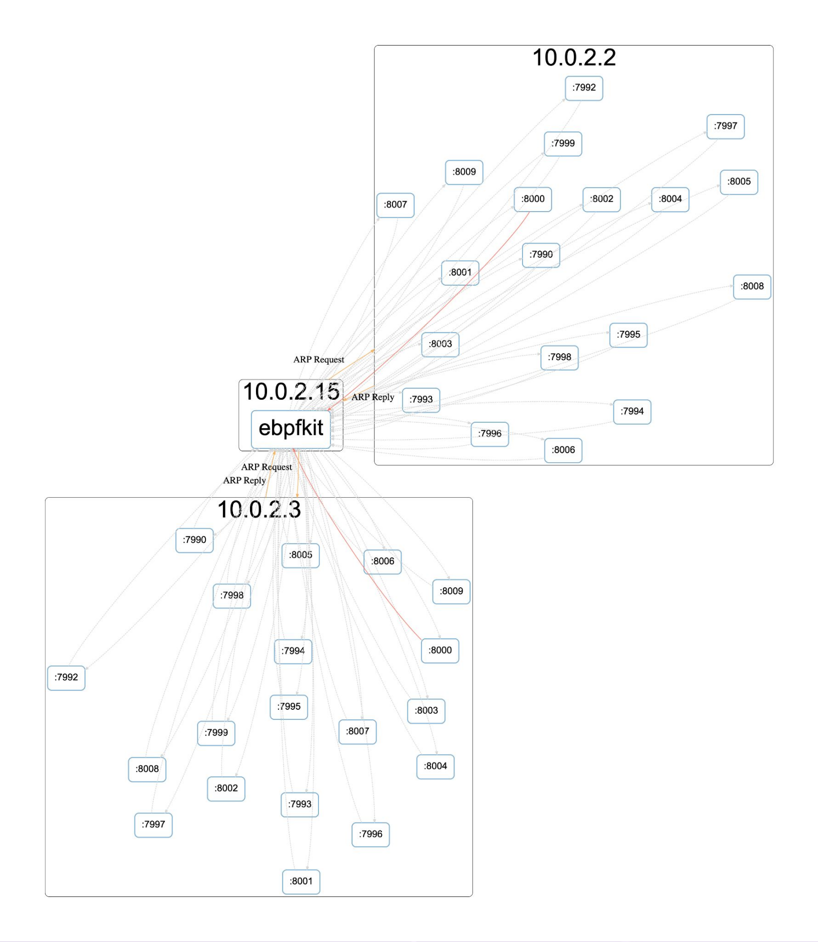
Passive network discovery

Abusing eBPF to build a rootkit

Network discovery: active method

- ARP scanner & SYN scanner
- XDP only
- Discover hosts and services which the host doesn’t necessarily talk to

⇒ XDP can’t generate packets, so we had to figure out how to make hundreds of SYN requests ...



Active network discovery

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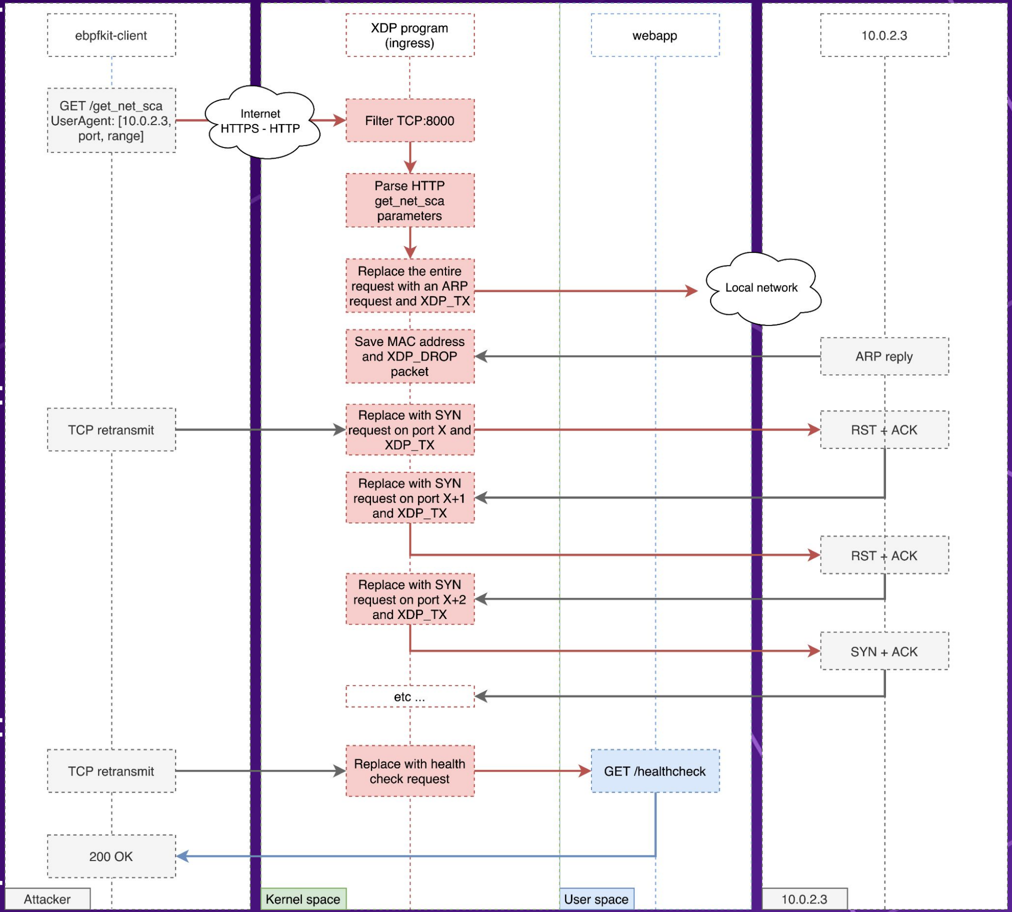
Network discovery: active method

ARP request

SYN scan

Client answer


ebpfkit-client
XDP program (ingress)
webapp
10.0.2.3
GET /get_net_sca UserAgent: [10.0.2.3, port, range]
Internet HTTPS - HTTP
Filter TCP:8000
Parse HTTP get_net_sca parameters
Replace the entire request with an ARP request and XDP_TX
Local network
Save MAC address and XDP_DROP packet
ARP reply
TCP retransmit
Replace with SYN request on port X and XDP_TX
RST + ACK
Replace with SYN request on port X+1 and XDP_TX
RST + ACK
Replace with SYN request on port X+2 and XDP_TX
SYN + ACK
etc ...
TCP retransmit
Replace with health check request
GET /healthcheck
200 OK
Attacker
Kernel space
User space
10.0.2.3

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Abusing eBPF to build a rootkit

Network discovery: active method

Demo

Active network discovery

Abusing eBPF to build a rootkit

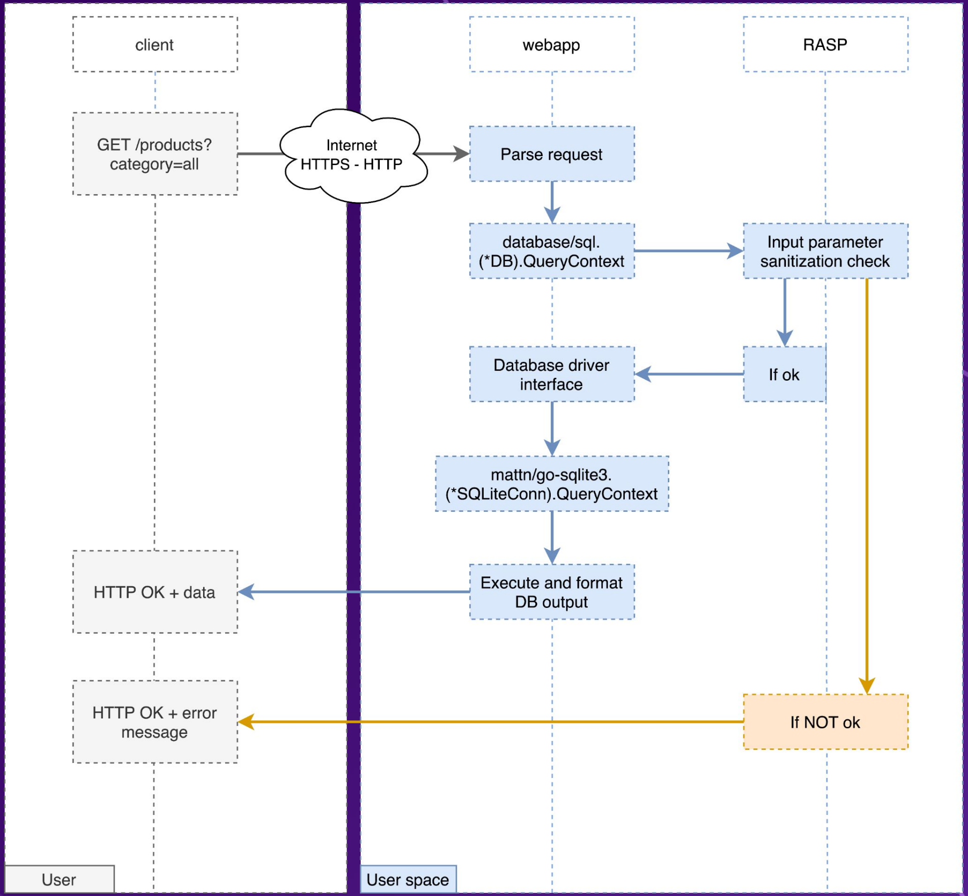
RASP evasion

- Runtime Application Self-Protection (RASP)
- Advanced input monitoring tool
- Textbook example: SQL injection
  - Hook HTTP server library functions
  - Hook SQL library functions
  - Check if user controlled parameters are properly sanitized before executing a query

A RASP relies on the assumption that the application runtime has not been compromised

Abusing eBPF to build a rootkit

RASP evasion: SQL injection with a golang application



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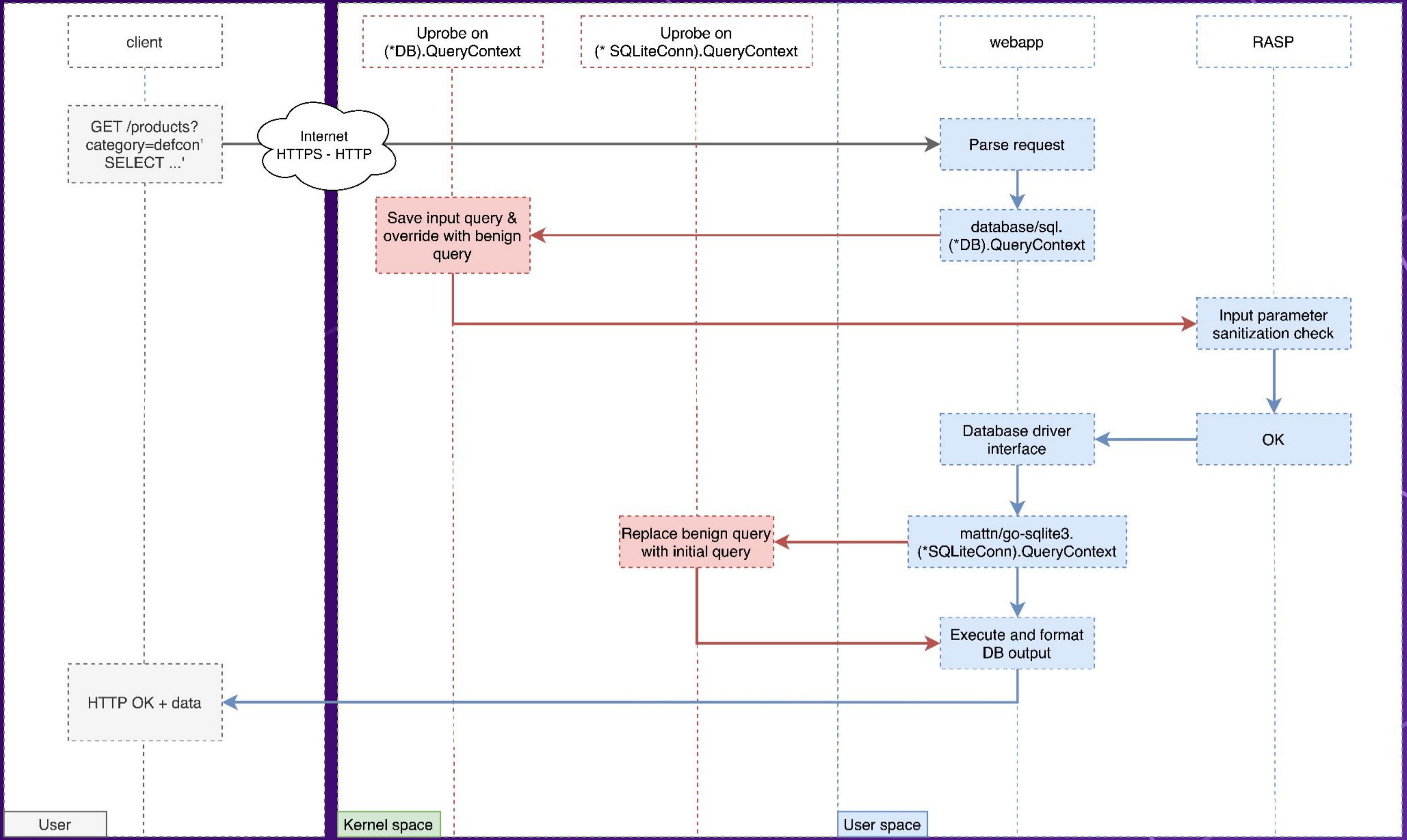
Abusing eBPF to build a rootkit

RASP evasion: SQL injection with a golang application



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Abusing eBPF to build a rootkit

RASP evasion: SQL injection with a golang application

Demo

Bypass SQL injection protection

Detection and mitigation

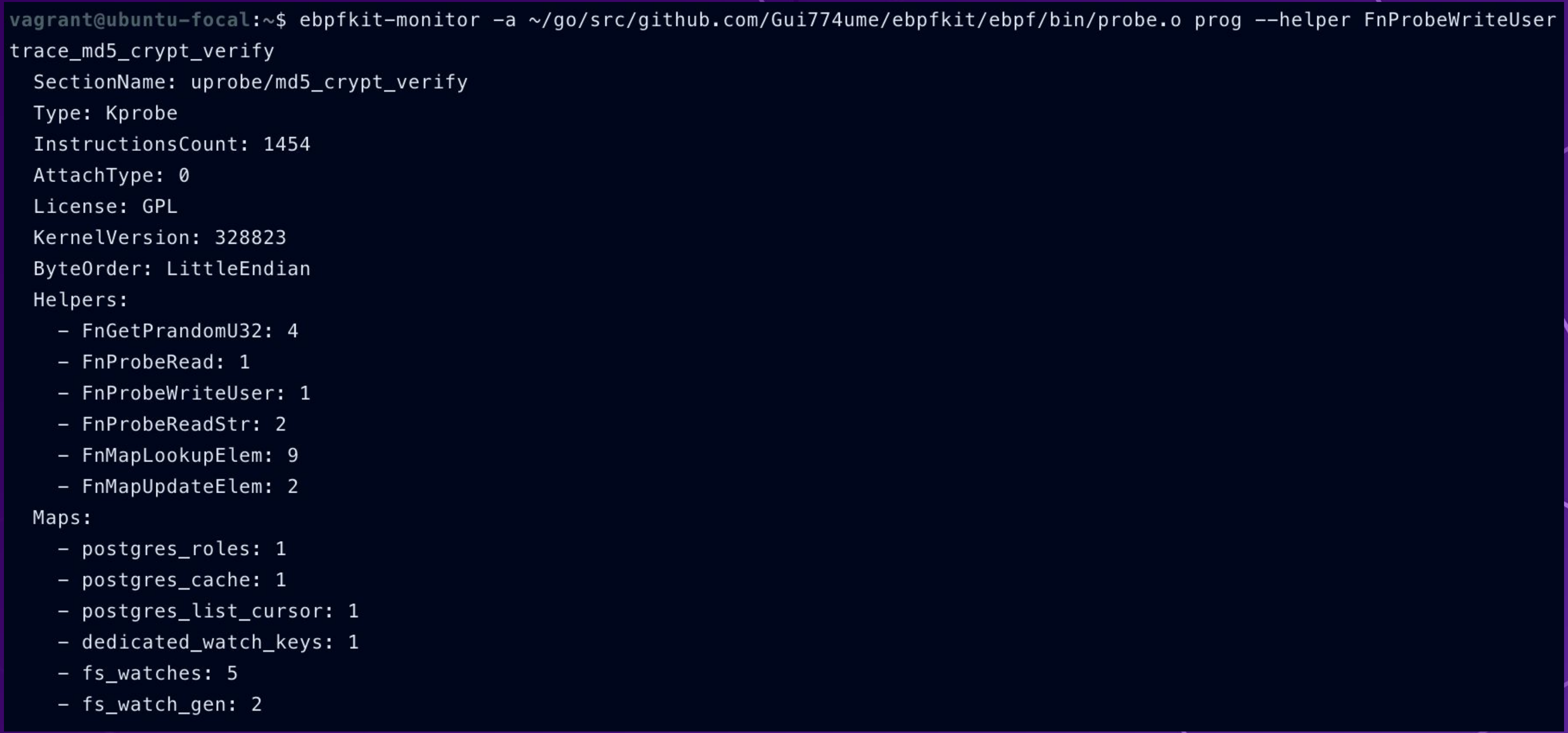
Detection and mitigation

Step 1: assessing an eBPF based third party vendor

- Audit & assessment
  - Ask to see the code ! (GPL)
  - Look for sensitive eBPF patterns:
    - program types
    - eBPF helpers
    - cross program types communication
- Useful tool: “ebpfkit-monitor”
  - parses ELF files and extract eBPF related information
  - https://github.com/Gui774ume/ebpfkit-monitor

Detection and mitigation

Step 1: assessing an eBPF based third party vendor

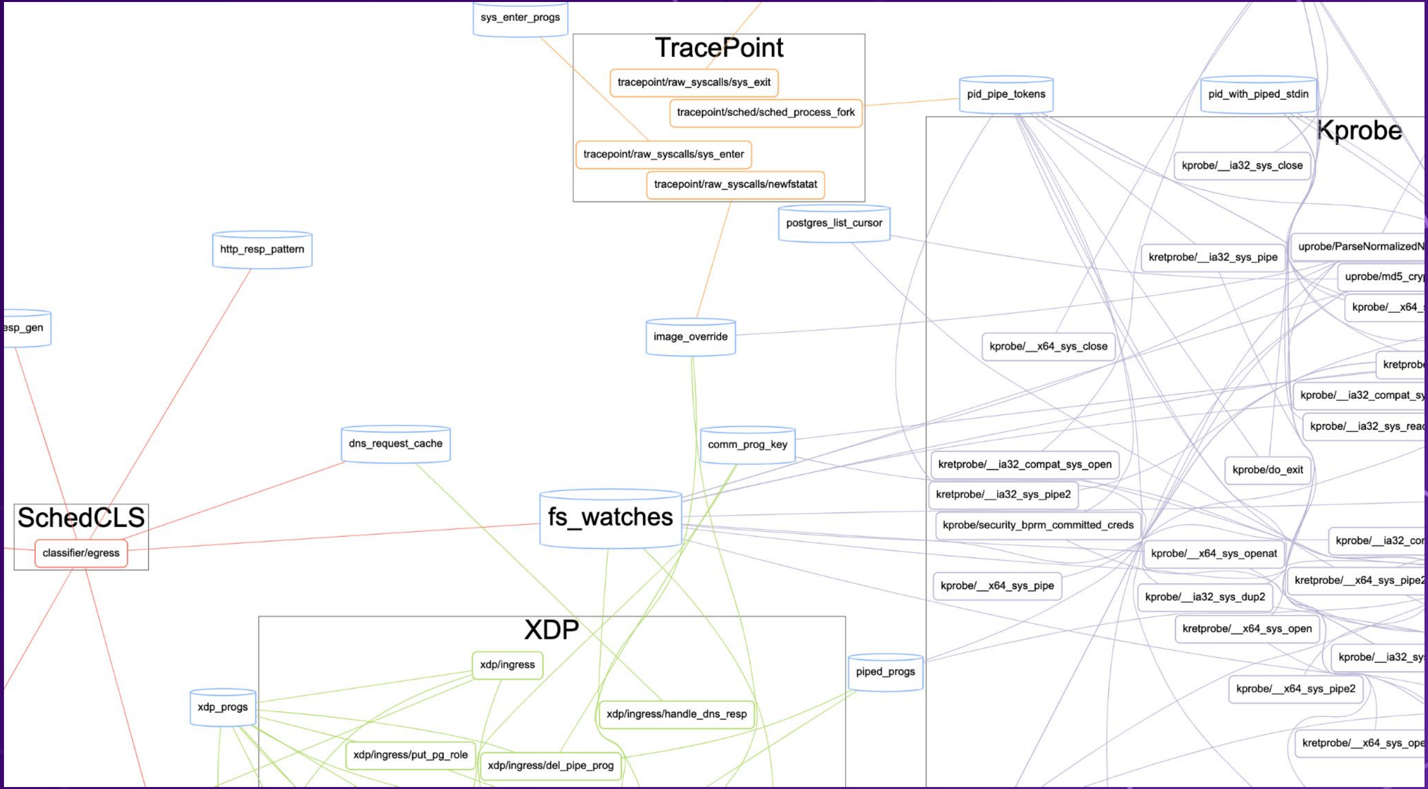


```
vagrant@ubuntu-focal:~$ ebpfkit-monitor -a ~/go/src/github.com/Gui774ume/ebpfkit/ebpf/bin/probe.o prog --helper FnProbeWriteUser
trace_md5_crypt_verify
  SectionName: uprobe/md5_crypt_verify
  Type: Kprobe
  InstructionsCount: 1454
  AttachType: 0
  License: GPL
  KernelVersion: 328823
  ByteOrder: LittleEndian
  Helpers:
    - FnGetPrandomU32: 4
    - FnProbeRead: 1
    - FnProbeWriteUser: 1
    - FnProbeReadStr: 2
    - FnMapLookupElem: 9
    - FnMapUpdateElem: 2
  Maps:
    - postgres_roles: 1
    - postgres_cache: 1
    - postgres_list_cursor: 1
    - dedicated_watch_keys: 1
    - fs_watches: 5
    - fs_watch_gen: 2
```

“ebpfkit-monitor” can list eBPF programs with sensitive eBPF helpers

Detection and mitigation

Step 1: assessing an eBPF based third party vendor



“ebpfkit-monitor” shows suspicious cross program types communications

Detection and mitigation

Step 2: runtime mitigation

- Monitor accesses to the “bpf” syscall
  - Keep an audit trail
  - “ebpfkit-monitor” can help !
- Protect accesses to the “bpf” syscall:
  - Block bpf syscalls from unknown processes
  - Reject programs with sensitive eBPF helpers or patterns
  - Sign your eBPF programs (https://lwn.net/Articles/853489)
  - “ebpfkit-monitor” can help !
- Prevent unencrypted network communications even within your internal network

Detection and mitigation

Step 3: Detection & Investigation

- It is technically possible to write a perfect eBPF rootkit *
- But:
  - look for actions that a rootkit would have to block / lie about to protect itself
  - (if you can) load a kernel module to list eBPF programs
  - (if you can) load eBPF programs to detect abnormal kernel behaviors
  - monitor network traffic anomalies at the infrastructure level
- Disclaimer: our rootkit is far from perfect !

* with enough time, motivation, insanity, and absolute hatred for life.

Thanks !

“ebpfkit” source code: *https://github.com/Gui774ume/ebpfkit*

“ebpfkit-monitor” source code: *https://github.com/Gui774ume/ebpfkit-monitor*

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