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“An analysis of offensive capabilities of eBPF and implementation of a rootkit”

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SUMMARY

Keywords:

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ABSTRACT

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1. INTRODUCTION

1.1. Motivation

As the efforts of the computer security community grow to protect increasingly critical devices and networks from malware infections, so do the techniques used by malicious actors become more sophisticated. Following the incorporation of ever more capable firewalls and Intrusion Detection Systems (IDS), cybercriminals have in turn sought novel attack vectors and exploits in common software, taking advantage of an inevitably larger attack surface that keeps growing due to the continued incorporation of new programs and functionalities into modern computer systems.

In contrast with ransomware incidents, which remained the most significant and common cyber threat faced by organizations on 2021[1], a powerful class of malware called rootkits is found considerably more infrequently, yet it is usually associated to high-profile targeted attacks that lead to greatly impactful consequences.

A rootkit is a piece of computer software characterized for its advanced stealth capabilities. Once it is installed on a system it remains invisible to the host, usually hiding its related processes and files from the user, while at the same time performing the malicious operations for which it was designed. Common operations include storing keystrokes, sniffing network traffic, exfiltrating sensitive information from the user or the system, or actively modifying critical data at the infected device. The other characteristic functionality is that rootkits seek to achieve persistence on the infected hosts, meaning that they keep running on the system even after a system reboot, without further user interaction or the need of a new compromise. The techniques used for achieving both of these functionalities depend on the type of rootkit developed, a classification usually made depending on the level of privileges on which the rootkit operates in the system.

- **User-mode** rootkits run at the same level of privilege as common user applications. They usually work by hijacking legitimate processes on which they may inject code by preloading shared libraries, thus modifying the calls issued to user APIs, on which malicious code is placed by the rootkit. Although easier to build, these rootkits are exposed to detection by common anti-malware programs.
- **Kernel-mode** rootkits run at the same level of privilege as the operating system, thus enjoying unrestricted access to the whole computer. These rootkits usually come as kernel modules or device drivers and, once loaded, they reside in the kernel. This implies that special attention must be taken to avoid programming errors since they could potentially corrupt user or kernel memory, resulting in a fatal kernel panic and a subsequent system reboot, which goes against the original purpose of maintaining stealth.

Common techniques used for the development of their malicious activities include hooking system calls made to the kernel by user applications (on which malicious code is then injected), or modifying data structures in the kernel to change the data of user programs at runtime. Therefore, trusted programs on an infected machine can no longer be trusted to operate securely.

These rootkits are usually the most attractive (and difficult to build) option for a malicious actor, but the installation of a kernel rootkit requires of a complete previous compromise of the system, meaning that administrator or root privileges must have been already achieved by the attacker, commonly by the execution of an exploit or a local installation of a privileged user.

Historically, kernel-mode rootkits have been tightly associated with espionage activities on governments and research institutes by Advanced Persistent Threat (APT) groups[2], state-sponsored or criminal organizations specialized on long-term operations to gather intelligence and gain unauthorized persistent access to computer systems. Although rootkits' functionality is tailored for each specific attack, a common set of techniques and procedures can be identified being used by these organizations. However, during the last years, a new technology called eBPF has been found to be the heart of the latest innovation on the development of rootkits.

eBPF is a technology incorporated in the 3.18 version of the Linux kernel[3], which provides the possibility of running code in the kernel without the need of loading a kernel module. Programs are created in a restrictive version of the C language and compiled into eBPF bytecode, which is loaded into the kernel via a new `bpf()` system call. After a mandatory step of verification by the kernel in which the code is checked to be safe to run, the bytecode is compiled into native machine instructions. These programs can then get access to kernel-exclusive functionalities including network traffic filtering, system calls hooking or tracing.

Although eBPF has built an outstanding environment for the creation of networking and tracing tools, its ability to run kernel programs without the need to load a kernel module has attracted the attention of multiple APTs. On February 2022, the Chinese security team Pangu Lab reported about a NSA backdoor that remained unnoticed since 2013 that used eBPF for its networking functionality and that infected military and telecommunications systems worldwide[4]. Also on 2022, PwC reports about a China-based threat actor that has targeted telecommunications systems with a eBPF-based backdoor[5].

Moreover, there currently exists official efforts to extend the eBPF technology into Windows[6] and Android systems[7], which spreads the mentioned risks to new platforms. Therefore, we can confidently claim that there is a growing interest on researching the capabilities of eBPF in the context of offensive security, in particular given its potential on becoming a common component found of modern rootkits. This knowledge would be valuable to the computer security community, both in the context of pen-testing and for analysts which need to know about the latest trends in malware to prepare their defences.

1.2. Project objectives

The main objective of this project is to compile a comprehensive report of the capabilities in the eBPF technology that could be weaponized by a malicious actor. In particular, we will be focusing on functionalities present in the Linux platform, given the maturity of eBPF on these environments and which therefore offers a wider range of possibilities. We will be approaching this study from the perspective of a threat actor, meaning that we will develop an eBPF-based rootkit which shows these capabilities live in a current Linux system, including proof of concepts (PoC) showing an specific feature, and also by building a realistic rootkit system which weaponizes these PoCs and operates malicious activities.

Before narrowing down our objectives and selecting an specific list of rootkit capabilities to emulate using eBPF, we needed to consider previous research. The work on this matter by Jeff Dileo from NCC Group at DEFCON 27[8] is particularly relevant, setting the first basis of eBPF ability to overwrite userland data, highlighting the possibility of overwriting the memory of a running process and executing arbitrary code on it.

Subsequent talks on 2021 by Pat Hogan at DEFCON 29[9], and by Guillaume Fournier and Sylvain Afchainthe from Datadog at DEFCON 29[10], research deeper on eBPF's ability to behave like a rootkit. In particular, Hogan shows how eBPF can be used to hide the rootkit's presence from the user and to modify data at system calls, whilst Fournier and Afchainthe built the first instance of an eBPF-based backdoor with command-and-control(C2) capabilities, enabling to communicate with the malicious eBPF program by sending network packets to the compromised machine.

Taking the previous research into account, and on the basis of common functionality we described to be usually incorporated at rootkits, the objectives of our research on eBPF is set to be on the following topics:

- Analysing eBPF's possibilities when hooking system calls and kernel functions.
- Learning eBPF's potential to read/write arbitrary memory.
- Exploring networking capabilities with eBPF packet filters.

The knowledge gathered by the previous three pillars will be then used as a basis for building our rootkit. We will present attack vectors and techniques different than the ones presented in previous research, although inevitably we will also tackle common points, which will be clearly indicated and on which we will try to perform further research. In essence, our eBPF-based rootkit aims at:

- Hijacking the execution of user programs while they are running, injecting libraries and executing malicious code, without impacting their normal execution.

- Featuring a command-and-control module powered by a network backdoor, which can be operated from a remote client. This backdoor should be controlled with stealth in mind, featuring similar mechanisms to those present in rootkits found in the wild.
- Tampering with user data at system calls, resulting in running malware-like programs and for other malicious purposes.
- Achieving stealth, hiding rootkit-related files from the user.
- Achieving rootkit persistence, the rootkit should run after a complete system reboot.

The rootkit will work in a fresh-install of a Linux system with the following characteristics:

- Distribution: Ubuntu 21.04.
- Kernel version: 5.11.0-49.

1.3. Regulatory framework

1.3.1. Social and economic environment

1.3.2. Budget

1.4. Structure of the document

2. STATE OF THE ART

This chapter is dedicated to an study of the eBPF technology. Firstly, we will analyse its origins, understanding what it is and how it works, and discuss the reasons why it is a necessary component of the Linux kernel today. Afterwards, we will cover the main features of eBPF in detail. Finally, an study of the existing alternatives for developing eBPF applications will be also included.

Although during our discussion of the offensive capabilities of eBPF in section?? we will use a library that will provide us with a layer of abstraction over the underlying operations, this background is needed to understand how eBPF is embedded in the kernel and which capabilities and limits we can expect to achieve with it.

2.1. eBPF history - Classic BPF

In this section we will detail the origins of eBPF in the Linux kernel. By offering us background into the earlier versions of the system, the goal is to acquire insight on the design decisions included in modern versions of eBPF.

2.1.1. Introduction to the BPF system

Nowadays eBPF is not officially considered to be an acronym anymore[11], but it remains largely known as "extended Berkeley Packet Filters", given its roots in the Berkeley Packet Filter (BPF) technology, now known as classic BPF.

BPF was introduced in 1992 by Steven McCanne and Van Jacobson in the paper "The BSD Packet Filter: A New Architecture for User-level Packet Capture"[12], as a new filtering technology for network packets in the BSD platform. It was first integrated in the Linux kernel on version 2.1.75[13].

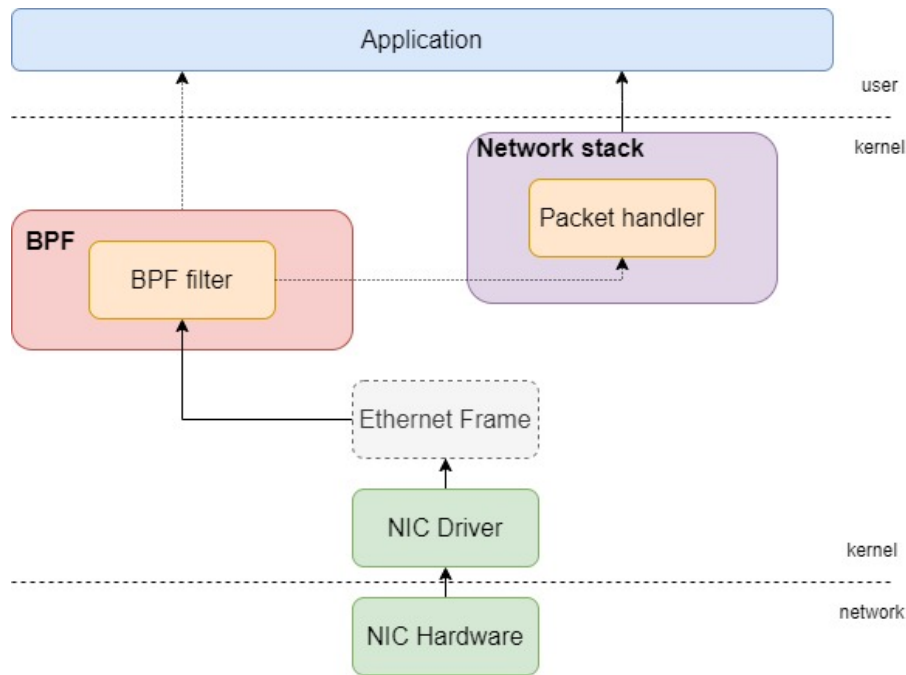


Fig. 2.1. Sketch of the functionality of classic BPF

Figure 2.1 shows how BPF was integrated in the existing network packet processing by the kernel. After receiving a packet via the Network Interface Controller (NIC) driver, it would first be analysed by BPF filters, which are programs directly developed by the user. This filter decides whether the packet is to be accepted by analysing the packet properties, such as its length or the type and values of its headers. If a packet is accepted, the filter proceeds to decide how many bytes of the original buffer are passed to the application at the user space. Otherwise, the packet is redirected to the original network stack, where it is managed as usual.

2.1.2. The BPF virtual machine

In a technical level, BPF comprises both the BPF filter programs developed by the user and the BPF module included in the kernel which allows for loading and running the BPF filters. This BPF module in the kernel works as a virtual machine[14], meaning that it parses and interprets the filter program by providing simulated components needed for its execution, turning into a software-based CPU. Because of this reason, it is usually referred as the BPF Virtual Machine (BPF VM). The BPF VM comprises the following components:

- **An accumulator register**, used to store intermediate values of operations.
- **An index register**, used to modify operand addresses, it is usually incorporated to optimize vector operations[15].
- **An scratch memory store**, a temporary storage.

- A **program counter**, used to point to the next machine instruction to execute in a filter program.

2.1.3. Analysis of a BPF filter program

As we mentioned in section 2.1.2, the components of the BPF VM are used to support running BPF filter programs. A BPF filter is implemented as a boolean function:

- If it returns *true*, the kernel copies the packet to the application.
- If it returns *false*, the packet is not accepted by the filter (and thus the network stack will be the next to operate it).

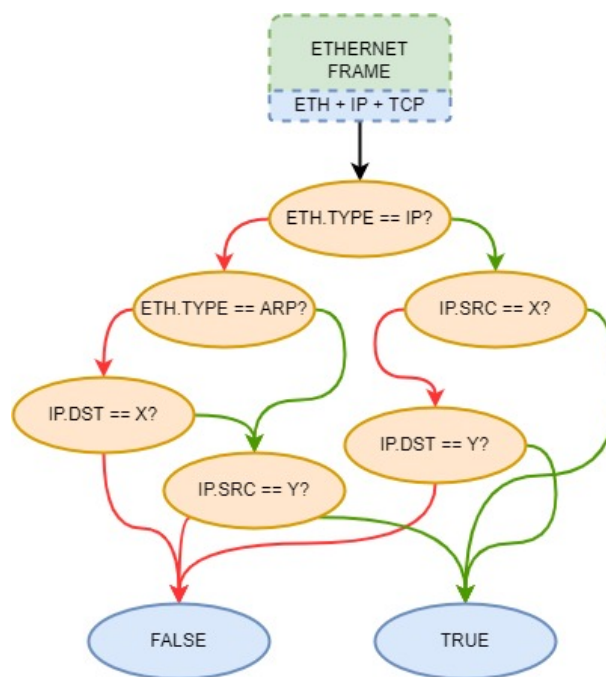


Fig. 2.2. Execution of a BPF filter.

Figure 2.2 shows an example of a BPF filter upon receiving a packet. In the figure, green lines indicate that the condition is true and red lines that it is evaluated as false. Therefore, the execution works as a control flow graph (CFG) which ends on a boolean value[16]. The figure presents an example BPF program which accepts the following frames:

- Frames with an IP packet as a payload directed from IP address X.
- Frames with an IP packet as a payload directed towards IP address Y.
- Frames belonging to the ARP protocol and from IP address Y.
- Frames not from the ARP protocol directed from IP address Y to IP address X.

2.1.4. BPF bytecode instruction format

In order to implement the CFG to be run at the BPF VM, BPF filter programs are made up of BPF bytecode, which is defined by a new BPF instruction set. Therefore, a BPF filter program is an array of BPF bytecode instructions[17].

	OPCODE	JT	JF	K
BITS	16	8	8	32

Table 2.1. Table showing BPF instruction format. It is a fixed-length 64 bit instruction, the number of bits used by each field are indicated.

Table 2.1 shows the format of a BPF bytecode instruction. As it can be observed, it is a compound of:

- An **opcode**, similar to assembly opcode, it indicates the operation to be executed.
- Field **jt** indicates the offset to the next instruction to jump in case a condition is evaluated as *true*.
- Field **jf** indicates the offset to the next instruction to jump in case a condition is evaluated as *false*.
- Field **k** is miscellaneous and its contents vary depending on the instruction opcode.

<i>opcodes</i>	<i>addr modes</i>				
ldb	[k]			[x+k]	
ldh	[k]			[x+k]	
ld	#k	#len	M[k]	[k]	[x+k]
ldx	#k	#len	M[k]	4* ([k] & 0xf)	
st	M[k]				
stx	M[k]				
jmp	L				
jeq	#k, Lt, Lf				
jgt	#k, Lt, Lf				
jge	#k, Lt, Lf				
jset	#k, Lt, Lf				
add	#k			x	
sub	#k			x	
mul	#k			x	
div	#k			x	
and	#k			x	
or	#k			x	
lsh	#k			x	
rsh	#k			x	
ret	#k			a	
tax					
txa					

Fig. 2.3. Table of supported classic BPF instructions, as shown by McCanne and Jacobson[18]

Figure 2.3 shows how BPF instructions are defined according to the BPF instruction set. As we mentioned, similarly to assembly, instructions include an opcode which indicates the operation to execute, and the multiple arguments defining the arguments of the operation. The table shows, in order by rows, the following instruction types[19]:

- Rows 1-4 are **load instructions**, copying the addressed value into the index or accumulator register.
- Rows 4-6 are **store instructions**, copying the accumulator or index register into the scratch memory store.
- Rows 7-11 are **jump instructions**, changing the program counter register. These are usually present on each node of the CFG, and evaluate whether the condition to be evaluated is true or not.
- Rows 12-19 and 21-22 are **arithmetic and miscellaneous instructions**, performing operations usually needed during the program execution.
- Row 20 is a **return instruction**, it is positioned in the final end of the CFG, and indicate whether the filter accepts the packet (returning true) or otherwise rejects it (return false).

#k	the literal value stored in k
#len	the length of the packet
M[k]	the word at offset k in the scratch memory store
[k]	the byte, halfword, or word at byte offset k in the packet
[x+k]	the byte, halfword, or word at offset $x+k$ in the packet
L	an offset from the current instruction to L
#k, Lt, Lf	the offset to Lt if the predicate is true, otherwise the offset to Lf
x	the index register
4 * ([k] & 0xf)	four times the value of the low four bits of the byte at offset k in the packet

Fig. 2.4. Table explaining the column address modes in Figure2.3, as shown by McCanne and Jacobson[19]

The column *addr modes* in figure 2.3 describes how the parameters of a BPF instruction are referenced depending on the opcode. The address modes are detailed in figure 2.4. As it can be observed, parameters may consist of immediate values, offsets to memory positions or on the packet, the index register or combinations of the previous.

2.1.5. An example of BPF filter with tcpdump

At the time, by filtering packets before they are handled by the kernel instead of using an user-level application, BPF offered a performance improvement between 10 and 150 times the state-of-the art technologies of the moment[14]. Since then, multiple popular tools began to use BPF, such as the network tracing tool *tcpdump*[20].

tcpdump is a command-line tool that enables to capture and analyse the network traffic going through the system. It works by setting filters on a network interface, so that it shows the packets that are accepted by the filter. Still today, *tcpdump* uses BPF for the filter implementation. We will now show an example of BPF code used by *tcpdump* to implement a simple filter:

```
osboxes@osboxes: ~/TFG/docs$ sudo tcpdump -d -i any port 80
(000) ldh      [14]
(001) jeq      #0x86dd      jt 2      jf 10
(002) ldb      [22]
(003) jeq      #0x84      jt 6      jf 4
(004) jeq      #0x6      jt 6      jf 5
(005) jeq      #0x11      jt 6      jf 23
(006) ldh      [56]
(007) jeq      #0x50      jt 22      jf 8
(008) ldh      [58]
(009) jeq      #0x50      jt 22      jf 23
(010) jeq      #0x800      jt 11      jf 23
(011) ldb      [25]
(012) jeq      #0x84      jt 15      jf 13
(013) jeq      #0x6      jt 15      jf 14
(014) jeq      #0x11      jt 15      jf 23
(015) ldh      [22]
(016) jset     #0x1fff      jt 23      jf 17
(017) ldxb     4*([16]&0xf)
(018) ldh      [x + 16]
(019) jeq      #0x50      jt 22      jf 20
(020) ldh      [x + 18]
(021) jeq      #0x50      jt 22      jf 23
(022) ret      #262144
(023) ret      #0
```

Fig. 2.5. BPF bytecode tcpdump needs to set a filter to display packets directed to port 80.

Figure 2.5 shows how *tcpdump* sets a filter to display traffic directed to all interfaces (*-i any*) directed to port 80. Flag *-d* instructs *tcpdump* to display BPF bytecode.

In the example, using the *jf* and *jt* fields, we can label the nodes of the CFG described by the BPF filter. Figure 2.6 describes the shortest graph path that a true comparison will need to follow to be accepted by the filter. Note how instruction 010 is checking the value 80, the one our filter is looking for in the port.

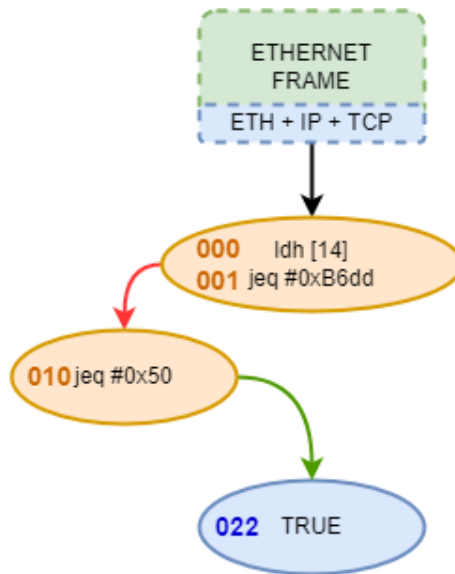


Fig. 2.6. Shortest path in the CFG described in the example of figure 2.5 that a packet needs to follow to be accepted by the BPF filter set with *tcpdump*.

2.2. Analysis of modern eBPF

This section discusses the current state of modern eBPF in the Linux kernel. By building on the previous architecture described in classic BPF, we will be able to provide a comprehensive picture of the underlying infrastructure in which eBPF relies today.

The addition of classic BPF in the Linux kernel set the foundations of eBPF, but nowadays it has already extended its presence to many other components other than traffic filtering. Similarly to how BPF filters were included in the networking module of the Linux kernel, we will now study the necessary changes made in the kernel to support these new program types. Table 2.2 shows the main updates that were incorporated and shaped modern eBPF of today.

Description	Kernel version	Year
<i>BPF</i> : First addition in the kernel	2.1.75	1997
<i>BPF+</i> : New JIT assembler	3.0	2011
<i>eBPF</i> : Added eBPF support	3.15	2014
New bpf() syscall	3.18	2014
Introduction of eBPF maps	3.19	2015
eBPF attached to kprobes	4.1	2015
Introduction of Traffic Control	4.5	2016
eBPF attached to tracepoints	4.7	2016
Introduction of XDP	4.8	2016

Table 2.2. Table showing relevant eBPF updates. Note that only those relevant for our research objectives are shown. This is a selection of the official complete table at [21].

As it can be observed in the table above, the main breakthrough happened in the 3.15 version, where Alexei Starovoitov, along with Daniel Borkmann, decided to expand the capabilities of BPF by remodelling the BPF instruction set and overall architecture[22].

Figure 2.7 offers an overview of the current eBPF architecture. During the subsequent subsections, we will proceed to explain its components in detail.

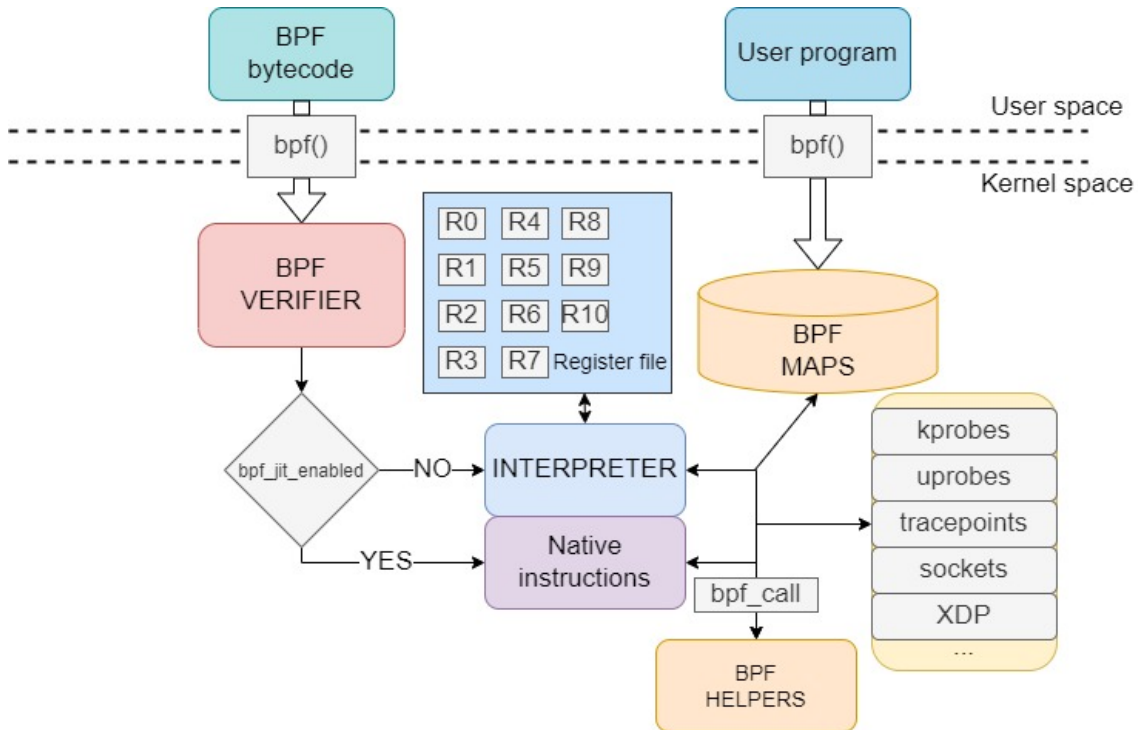


Fig. 2.7. Figure showing overall eBPF architecture in the Linux kernel and the process of loading an eBPF program. Based on[22] and [23].

2.2.1. eBPF instruction set

The eBPF update included a complete remodel of the instruction set architecture (ISA) of the BPF VM. Therefore, eBPF programs will need to follow the new architecture in order to be interpreted as valid and executed.

	IMM	OFF	SRC	DST	OPCODE
BITS	32	16	4	4	8

Table 2.3. Table showing eBPF instruction format. It is a fixed-length 64 bit instruction, the number of bits used by each field are indicated.

Table 2.3 shows the new instruction format for eBPF programs[24]. The new fields are similar to x86_64 assembly, incorporating the typically found immediate and offset fields, and source and destination registers[25]. Similarly, the instruction set is extended to be similar to the one typically found on x86_64 systems, the complete list can be consulted in the official documentation[24].

With respect to the BPF VM registers, they get extended from 32 to 64 bits of length, and the number of registers is incremented to 10, instead of the original accumulator and index registers. These registers are also adapted to be similar to those in assembly, as it is shown in table 2.4.

eBPF register	x86_64 register	Purpose
r0	rax	Return value from functions and exit value of eBPF programs
r1	rdi	Function call argument 1
r2	rsi	Function call argument 2
r3	rdx	Function call argument 3
r4	rcx	Function call argument 4
r5	r8	Function call argument 5
r6	rbx	Callee saved register, value preserved between calls
r7	r13	Callee saved register, value preserved between calls
r8	r14	Callee saved register, value preserved between calls
r9	r15	Callee saved register, value preserved between calls
r10	rbp	Frame pointer for stack, read only

Table 2.4. Table showing eBPF registers and their purpose in the BPF VM.[24][26].

2.2.2. JIT compilation

We mentioned in subsection 2.2.1 that eBPF registers and instructions describe an almost one-to-one correspondence to those in x86 assembly. This is in fact not a coincidence,

but rather it is with the purpose of improving a functionality that was included in Linux kernel 3.0, called Just-in-Time (JIT) compilation[27][28].

JIT compiling is an extra step that optimizes the execution speed of eBPF programs. It consists of translating BPF bytecode into machine-specific instructions, so that they run as fast as native code in the kernel. Machine instructions are generated during runtime, written directly into executable memory and executed there[29].

Therefore, when using JIT compiling (a setting defined by the variable *bpj_jit_enable*[30], BPF registers are translated into machine-specific registers following their one-to-one mapping and bytecode instructions are translated into machine-specific instructions[31]. There no longer exists an interpretation step by the BPF VM, since we can execute the code directly[32].

The programs developed during this project will always have JIT compiling active.

2.2.3. The eBPF verifier

We introduced in figure 2.7 the presence of the so-called eBPF verifier. Provided that we will be loading programs in the kernel from user space, these programs need to be checked for safety before being valid to be executed.

The verifier performs a series of tests which every eBPF program must pass in order to be accepted. Otherwise, user programs could leak privileged data, result in kernel memory corruption, or hang the kernel in an infinite loop, between others. Therefore, the verifier limits multiple aspects of eBPF programs so that they are restricted to the intended functionality, whilst at the same time offering a reasonable amount of freedom to the developer.

The following are the most relevant checks that the verifier performs in eBPF programs[33][34]:

- Tests for ensuring overall control flow safety:
 - No loops allowed (bounded loops accepted since kernel version 5.3[35].
 - Function call and jumps safety to known, reachable functions.
 - Sleep and blocking operations not allowed (to prevent hanging the kernel).
- Tests for individual instructions:
 - Divisions by zero and invalid shift operations.
 - Invalid stack access and invalid out-of-bound access to data structures.
 - Reads from uninitialized registers and corruption of pointers.

These checks are performed by two main algorithms:

- Build a graph representing the eBPF instructions (similar to the one shown in section 2.1.3. Check that it is in fact a direct acyclic graph (DAG), meaning that the verifier prevents loops and unreachable instructions.
- Simulate execution flow by starting on the first instruction and following each possible path, observing at each instruction the state of every register and of the stack.

2.2.4. eBPF maps

An eBPF map is a generic storage for eBPF programs used to share data between user and kernel space, to maintain persistent data between eBPF calls and to share information between multiple eBPF programs[36].

A map consists of a key + value tuple. Both fields can have an arbitrary data type, the map only needs to know the length of the key and the value field at its creation[37]. Programs can open maps by specifying their ID, and lookup or delete elements in the map by specifying its key, also insert new ones by supplying the element value and they key to store it with.

Therefore, creating a map requires a struct with the following fields:

FIELD	VALUE
type	Type of eBPF map. Described in table 2.6
key_size	Size of the data structure to use as a key
value_size	Size of the data structure to use as value field
max_entries	Maximum number of elements in the map

Table 2.5. Table showing common fields for creating an eBPF map.

TYPE	DESCRIPTION
BPF_MAP_TYPE_HASH	A hast table-like storage, elements are stored in tuples.
BPF_MAP_TYPE_ARRAY	Elements are stored in an array.
BPF_MAP_TYPE_RINGBUF	Map providing alerts from kernel to user space, covered in subsection 2.2.5
BPF_MAP_TYPE_PROG_ARRAY	Stores descriptors of eBPF programs

Table 2.6. Table showing types of eBPF maps. Only those used in our rootkit are displayed, the full list can be consulted in the man page [37]

Table ?? describes the main types of eBPF maps that are available for use. During the development of our rootkit, we will mainly focus on hash maps (BPF_MAP_TYPE_HASH), provided that they are simple to use and we do not require of any special storage for our research purposes.

2.2.5. The eBPF ring buffer

eBPF ring buffers are a special kind of eBPF maps, providing a one-way directional communication system, going from an eBPF program in the kernel to an user space program that subscribes to its events.

2.2.6. The bpf() syscall

The bpf() syscall is used to issue commands from user space to kernel space in eBPF programs. This syscall is multiplexor, meaning that it can perform a great range of actions, changing its behaviour depending on the parameters.

The main operations that can be issued are described in table ??:

COMMAND	ATTRIBUTES	DESCRIPTION
BPF_MAP_CREATE	Struct with map info as defined in table 2.5	Create a new map
BPF_MAP_LOOKUP_ELEM	Map ID, and struct with key to search in the map	Get the element on the map with an specific key
BPF_MAP_UPDATE_ELEM	Map ID, and struct with key and new value	Update the element of an specific key with a new value
BPF_MAP_DELETE_ELEM	Map ID and struct with key to search in the map	Delete the element on the map with an specific key
BPF_PROG_LOAD	Struct describing the type of eBPF program to load	Load an eBPF program in the kernel

Table 2.7. Table showing types of syscall actions. Only those relevant to our research are shown the full list and attribute details can be consulted in the man page [\[37\]](#)

With respect to the program type indicated with BPF_PROG_LOAD, this parameter indicates the type of eBPF program, setting the context in the kernel in which it will run, and to which modules it will have access to. The types of programs relevant for our research are described in table 2.8.

PROGRAM TYPE	DESCRIPTION
BPF_PROG_TYPE_KPROBE	Program to instrument code to an attached kprobe
BPF_PROG_TYPE_UPROBE	Program to instrument code to an attached uprobe
BPF_PROG_TYPE_TRACEPOINT	Program to instrument code to a syscall tracepoint
BPF_PROG_TYPE_XDP	Program to filter, redirect and monitor network events from the Xpress Data Path
BPF_PROG_TYPE_SCHED_CLS	Program to filter, redirect and monitor events using the Traffic Control classifier

Table 2.8. Table showing types of eBPF programs. Only those relevant to our research are shown. The full list and attribute details can be consulted in the man page [37].

In section ??, we will proceed to analyse in detail the different program types and what capabilities they offer.

2.2.7. eBPF helpers

Our last component to cover of the eBPF architecture are the eBPF helpers. Since eBPF programs have limited accessibility to kernel functions (which kernel modules commonly have free access to), the eBPF system offers a set of limited functions called helpers[38], which are used by eBPF programs to perform certain actions and interact with the context on which they are run. The list of helpers a program can call varies between eBPF program types, since different programs run in different contexts.

It is important to highlight that, just like commands issued via the bpf() syscall can only be issued from the user space, eBPF helpers correspond to the kernel-side of eBPF program exclusively. Note that we will also find a symmetric correspondence to those functions of the bpf() syscall related to map operations (since these are accessible both from user and kernel space).

Table 2.9 lists the most relevant general-purpose eBPF helpers we will use during the development of our project. We will later detail those helpers exclusive to an specific eBPF program type in the sections on which they are studied.

eBPF helper	DESCRIPTION
bpf_map_lookup_elem()	Query an element with a certain key in a map
bpf_map_delete_elem()	Delete an element with a certain key in a map
bpf_map_update_elem()	Update the value of the element with a certain key in a map
bpf_probe_read_user()	Attempt to safely read data at an specific user address into a buffer
bpf_probe_read_kernel()	Attempt to safely read data at an specific kernel address into a buffer
bpf_trace_printk()	Similarly to printk() in kernel modules, writes buffer in syskerneldebugtracingtrace_pipe
bpf_get_current_pid_tgid()	Get the process process id (PID) and thread group id (TGID)
bpf_get_current_comm()	Get the name of the executable
bpf_probe_write_user()	Attempt to write data at a user memory address
bpf_override_return()	Override return value of a probed function
bpf_ringbuf_submit()	Submit data to an specific eBPF ring buffer, and notify to subscribers
bpf_tail_call()	Jump to another eBPF program preserving the current stack

Table 2.9. Table showing common eBPF helpers. Only those relevant to our research are shown. Those helpers exclusive to an specific program type are not listed. The full list and attribute details can be consulted in the man page [38].

2.3. eBPF program types

In the previous subsection 2.2.6 we introduced the new types of eBPF programs that are supported and that we will be developing for our offensive analysis. In this section, we will analyse in greater detail how eBPF is integrated in the Linux kernel in order to support these new functionalities.

2.3.1. XDP

eXpress Data Path (XDP) programs are a novel type of eBPF program that allows for the lowest-latency traffic filtering and monitoring in the whole Linux kernel. In order to load an XDP program, a bpf() syscall with the command BPF_PROG_LOAD and the program type BPF_PROG_TYPE_XDP must be issued.

These programs are directly attached to the Network Interface Controller (NIC) driver, and thus they can process the packet before any other module[39].

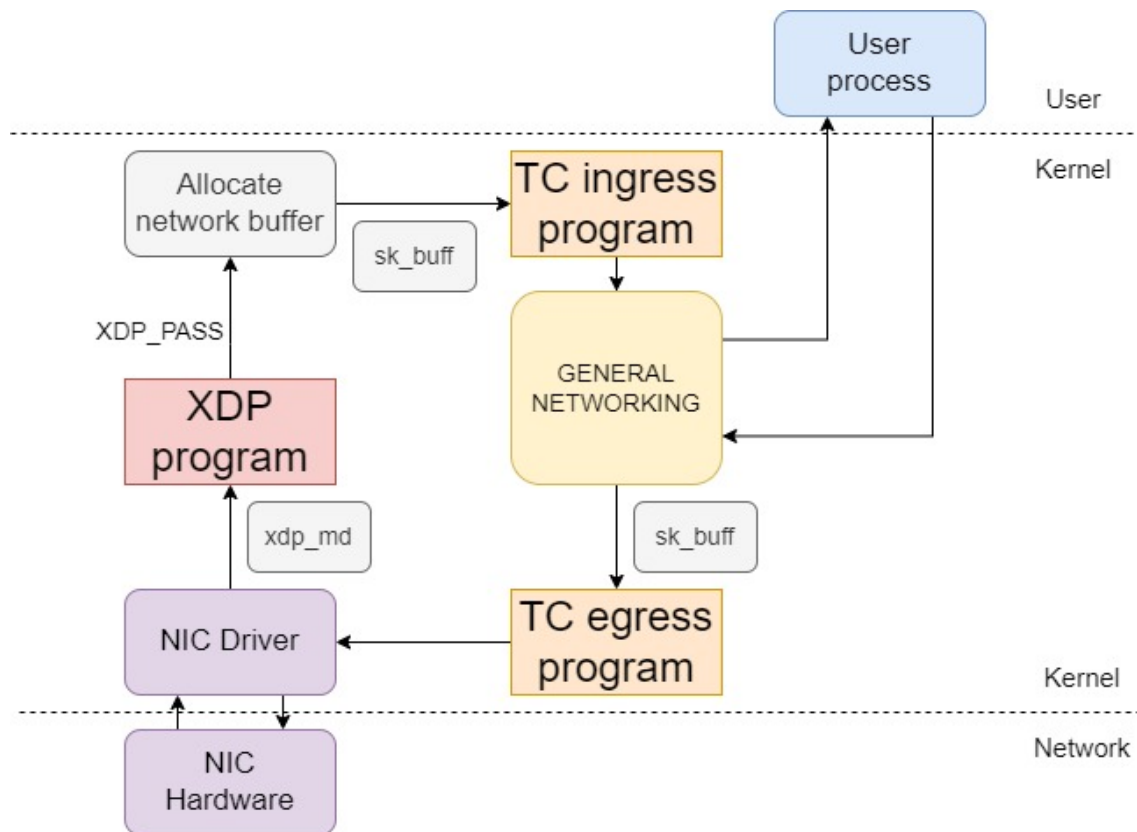


Fig. 2.8. Figure showing how the eBPF XDP and TC modules are integrated in the network processing in the Linux kernel.

Figure 2.8 shows how XDP is integrated in the network processing of the Linux kernel. After receiving a raw packet (in the figure, *xdp_md*, which consists on the raw bytes plus some very basic metadata about the packet) from the incoming traffic, XDP program can perform the following actions[40]:

- Analyse the data between the packet buffer bounds.
- Modify the packet contents, and modify the packet length.
- Decide between one of the actions displayed in table 2.10.

ACTION	DESCRIPTION
XDP_PASS	Let packet proceed with operated modifications on it.
XDP_TX	Return the packet at the same NIC it was received from. Packet modifications are kept.
XDP_DROP	Drops the packet completely, kernel networking will not be notified.

Table 2.10. Table showing XDP relevant return values.

Some of the XDP-exclusive eBPF helpers we will be discussing in later sections are shown in table 2.11.

eBPF helper	DESCRIPTION
<code>bpf_xdp_adjust_head()</code>	Enlarges or reduces the extension of a packet, by moving the address of its first byte.
<code>bpf_xdp_adjust_tail()</code>	Enlarges or reduces the extension of a packet, by moving the address of its last byte.

Table 2.11. Table showing relevant XDP-exclusive eBPF helpers.

2.3.2. Traffic Control

Traffic Control (TC) programs are also indicated for networking instrumentation. Similarly to XDP, their module is positioned before entering the overall network processing of the kernel. However, as it can be observed in figure 2.8, they differ in some aspects:

- TC programs receive a network buffer with metadata (in the figure, *sk_buff*) about the packet in it. This renders TC programs less ideal than XDP for performing large packet modifications (like new headers), but at the same time the additional metadata fields make it easier to locate and modify specific packet fields[41].
- TC programs can be attached to the *ingress* or *egress* points, meaning that an eBPF program can operate not only over incoming traffic, but also over the outgoing packets.

With respect to how TC programs operate, the Traffic Control system in Linux is greatly complex and would require a complete section by itself. In fact, it was already a complete system before the appearance of eBPF. Full documentation can be found at [42]. For this document, we will explain the overall process needed to load a TC program[43]:

1. The TC program defines a so-called queuing discipline (qdisc), a packet scheduler that issues packets in a First-In-First-Out (FIFO) order as soon as they are received. This qdisc will be attached to an specific network interface (e.g.: wlan0).
2. Our TC eBPF program is attached to the qdisc. It will work as a filter, being run for every of the packets dispatched by the qdisc.

Similarly to XDP, the TC eBPF programs can decide an action to be executed on a packet by specifying a return value. These actions are almost analogous to the ones in XDP, as it can be observed in table 2.12.

ACTION	DESCRIPTION
TC_ACT_OK	Let packet proceed with operated modifications on it.
TC_ACT_RECLASSIFY	Return the packet to the back of the qdisc scheduling queue.
TC_ACT_SHOT	Drops the packet completely, kernel networking will not be notified.

Table 2.12. Table showing TC relevant return values. Full list can be consulted at [44].

Finally, as in XDP, there exists a list of useful BPF helpers that will be relevant for the creation of our rootkit. They are shown in table 2.13.

eBPF helper	DESCRIPTION
bpf_l3_csum_replace()	Recomputes the network layer 3 (e.g.: IP) checksum of the packet.
bpf_l4_csum_replace()	Recomputes the network layer 4 (e.g: TCP) checksum of the packet.
bpf_skb_store_bytes()	Write a data buffer into the packet.
bpf_skb_pull_data()	Reads a sequence of packet bytes into a buffer.
bpf_skb_change_head()	(Only) enlarges the extension of a packet, by moving the address of its first byte.
bpf_skb_change_tail()	Enlarges or reduces the extension of a packet, by moving the address of its last byte.

Table 2.13. Table showing relevant TC-exclusive eBPF helpers.

2.3.3. Tracepoints

Tracepoints are a technology in the Linux kernel that allows to hook functions in the kernel, connecting a 'probe': a function that is executed every time the hooked function is called[45]. These tracepoints are set statically during kernel development, meaning that for a function to be hooked, it needs to have been previously marked with a tracepoint statement indicating its traceability. At the same time, this limits the number of tracepoints available.

The list of tracepoint events available depends on the kernel version and can be visited under the directory `/sys/kernel/debug/tracing/events`.

It is particularly relevant for our later research that most of the system calls incorporate a tracepoint, both when they are called (*enter* tracepoint) and when they are exited (*exit* tracepoints). This means that, for a system call `sys_open`, both the tracepoint `sys_enter_open` and `sys_exit_open` are available.

Also, note that the probe functions that are called when hitting a tracepoint receive some parameters related to the context on which the tracepoint is located. In the case of syscalls, these include the parameters with which the syscall was called (only for *enter* syscalls, *exit* ones will only have access to the return value). The exact parameters and their format which a probe function receives can be visited in the file `/sys/kernel/debug/tracing/events/<subsystem>/<tracepoint>/format`. In the previous example with `sys_enter_open`, this is `/sys/kernel/debug/tracing/events/syscalls/sys_enter_open/format`.

In eBPF, a program can issue a `bpf()` syscall with the command `BPF_PROG_LOAD` and the program type `BPF_PROG_TYPE_TRACEPOINT`, specifying which is the function with the tracepoint to attach to and an arbitrary function probe to call when it is hit. This function probe is defined by the user in the eBPF program submitted to the kernel.

2.3.4. Kprobes

Kprobes are another tracing technology of the Linux kernel whose functionality has been become available to eBPF programs. Similarly to tracepoints, kprobes enable to hook functions in the kernel, with the only difference that it is dynamically attached to any arbitrary function, rather than to a set of predefined positions[46]. It does not require that kernel developers specifically mark a function to be probed, but rather kprobes can be attached to any instruction, with a short list of blacklisted exceptions.

As it happened with tracepoints, the probe functions have access to the parameters of the original hooked function. Also, the kernel maintains a list of kernel symbols (addresses) which are relevant for tracing and that offer us insight into which functions we can probe. It can be visited under the file `/proc/kallsyms`, which exports symbols of kernel functions and loaded kernel modules[47].

Also similarly, since tracepoints could be found in their *enter* and *exit* variations, kprobes have their counterpart, name kretprobes, which call the hooked probe once a return instruction is reached after the hooked symbol. This means that a kretprobe hooked to a kernel function will call the probe function once it exits.

In eBPF, a program can issue a `bpf()` syscall with the command `BPF_PROG_LOAD` and the program type `BPF_PROG_TYPE_KPROBE`, specifying which is the function with the kprobe to attach to and an arbitrary function probe to call when it is hit. This function probe is defined by the user in the eBPF program submitted to the kernel.

2.3.5. Up probes

Up probes is the last of the main tracing technologies which has been become accessible to eBPF programs. They are the counterparts of Kprobes, allowing for tracing the execution of an specific instruction in the user space, instead of in the kernel. When the execution flow reaches a hooked instruction, a probe function is run.

For setting an uprobe on an specific instruction of a program, we need to know three components:

- The name of the program.
- The address of the function where the instruction is contained.
- The offset at which the specific instruction is placed from the start of the function.

Similarly to kprobes, uprobes have access to the parameters received by the hooked function. Also, the complementary uretprobes also exist, running the probe function once the hooked function returns.

In eBPF, programs can issue a `bpf()` syscall with the command `BPF_PROG_LOAD` and the program type `BPF_PROG_TYPE_UPROBE`, specifying the function with the uprobe to attach to and an arbitrary function probe to call when it is hit. This function probe is also defined by the user in the eBPF program submitted to the kernel.

2.4. Developing eBPF programs

In section 2.2, we discussed the overall architecture of the eBPF system which is now an integral part of the Linux kernel. We also studied the process which a piece of eBPF bytecode follows in order to be accepted in the kernel. However, for an eBPF developer, programming bytecode and working with `bpf()` calls natively is not an easy task, therefore an additional layer of abstraction was needed.

Nowadays, there exist multiple popular alternatives for writing and running eBPF programs. We will overview which they are and proceed to analyse in further detail the option that we will use for the development of our rootkit.

2.4.1. BCC

BPF Compiler Collection (BCC) is one of the first and well-known toolkits for eBPF programming available[48]. It allows to include eBPF code into user programs. These programs are developed in python, and the eBPF code is embedded as a plain string. An example of a BCC program is included in

Although BCC offers a wide range of tools to easy the development of eBPF programs, we found it not to be the most appropriate for our large-scale eBPF project. This was in particular due to the feature of eBPF programs being stored as a python string, which leads to difficult scalability, poor development experience given that programming errors are detected at runtime (once the python program issues the compilation of the string), and simply better features from competing libraries.

2.4.2. Bpftool

bpftool is not a development framework like BCC, but one of the most relevant tools for eBPF program development. Some of its functionalities include:

- Loading eBPF programs.
- List running eBPF programs.
- Dumping bytecode from live eBPF programs.
- Extract program statistics and data from programs.
- List and operate over eBPF maps.

Although we will not be covering bpftool during our overview on the constructed eBPF toolkit, it was used extensively during the development and became a key tool for debugging eBPF programs, particularly to peek data at eBPF maps during runtime.

2.4.3. Libbpf

libbpf[49] is a library for loading and interacting with eBPF programs, which is currently maintained in the Linux kernel source tree[50]. It is one of the most popular frameworks to develop eBPF applications, both because it makes eBPF programming similar to common kernel development and because it aims at reducing kernel-version dependencies, thus increasing programs portability between systems[51]. During our research, however, we will not make use of this functionalities given that a portable program is not in our research goals.

As we discussed in section 2.2, eBPF programs are composed of both the eBPF code in the kernel and a user space program that can interact with it. With libbpf, the eBPF kernel program is developed in C (a real program, not a string later compiled as with BCC), while user programs are usually developed in C, Rust or GO. For our project, we will use the C version of libbpf, so both the user and kernel side of our toolkit will be developed in this language.

When using libbpf with the C language, both the user-side and kernel eBPF program are compiled together using the Clang/LLVM compiler, translating C instructions into eBPF bytecode. As a clarification, Clang is the front-end of the compiler, translating C instructions into an intermediate form understandable by LLVM, whilst LLVM is the back-end compiling the intermediate code into eBPF bytecode. As it can be observed in figure 2.9, the result of the compilation is a single program, comprising the user-side which will launch a user process, the eBPF bytecode to be run in the kernel, and other structures libbpf generates about eBPF maps and other meta data. This program is encapsulated as an ELF file (a common executable format).

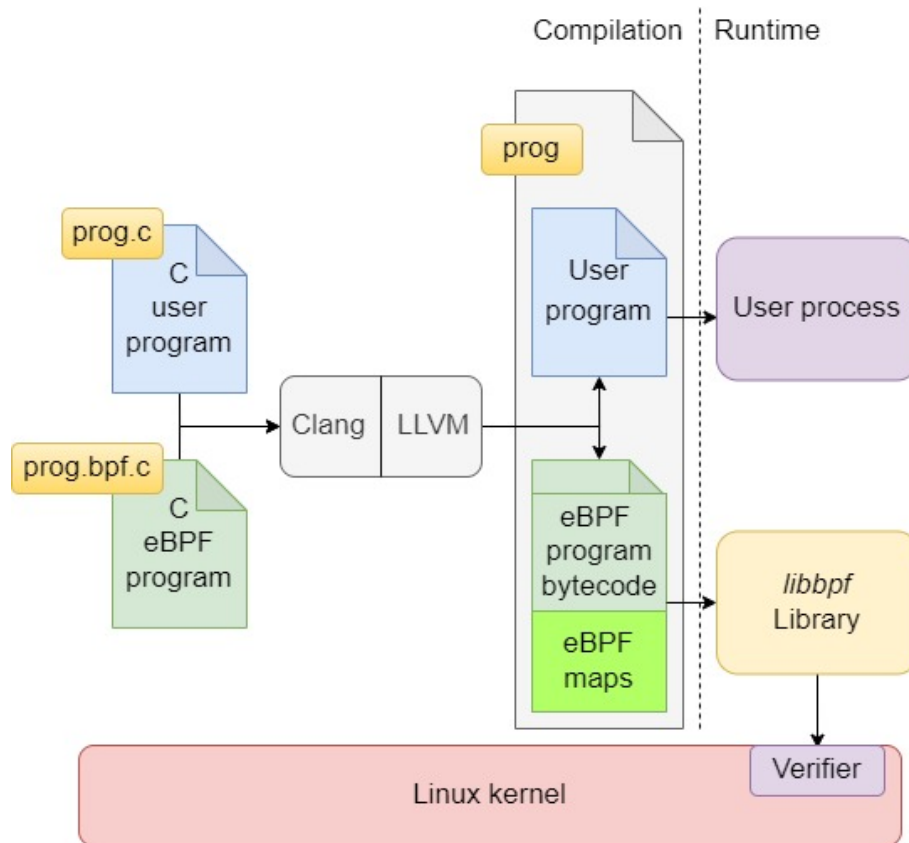


Fig. 2.9. Sketch of the compilation and loading process of a program developed with libbpf.

Finally, we will overview one of the main functionalities of libbpf to simplify eBPF programming, namely the BPF skeleton. This is auto-generated code by libbpf whose aim is to simplify working with eBPF from the user-side program. As a summary, it parses the eBPF programs developed (which may be using different technologies such as XDP, kprobes, TC...) and the eBPF maps used, and as a result offers a simple set of functions for dealing with these programs from the user program. In particular, it allows for loading and unloading an specific eBPF program from user space at runtime.

Table 2.14 describes the API offered by the BPF skeleton. Note that <name> is substituted by the name of the program being compiled.

Function name	Description
<name>__open()	Parse the eBPF programs and maps.
<name>__load()	Load the eBPF map in the kernel after its validation, create the maps. However the programs are not active yet.
<name>__attach()	Activate the eBPF programs, attaching them to their corresponding parts in the kernel (e.g. kprobes to kernel functions).
<name>__destroy()	Detach and unload the eBPF programs from the kernel.

Table 2.14. Table showing BPF skeleton functions.

Note that the BPF skeleton also offers further granularity at the time of dealing with programs, so that individual programs can be loaded or attached instead of all simultaneously. This is the approach we will generally use in the development of our rootkit, as it will be explained in section ??.

3. ANALYSIS OF OFFENSIVE CAPABILITIES

In the previous chapter, we detailed which functionalities eBPF offers and studied its underlying architecture. As with every technology, a prior deep understanding is fundamental for discussing its security implications.

Therefore, given the previous background, this chapter is dedicated to an analysis in detail of the security implications of a malicious use of eBPF. For this, we will firstly explore the security features incorporated in the eBPF system. Then, we will identify the fundamental pillars onto which malware can build their functionality. As we mentioned during the project goals, these main topics of research will be the following:

- Analysing eBPF's possibilities when hooking system calls and kernel functions.
- Learning eBPF's potential to read/write arbitrary memory.
- Exploring networking capabilities with eBPF packet filters.

Finally, we will study in detail some of the malicious applications that previous researchers have proposed to take advantage of these capabilities of eBPF. In the next chapter, we will proceed to elaborate on these ideas, find new purposes and design our own rootkit.

3.1. Security features in eBPF

As we shown in section 2.2, eBPF has been an active part of the Linux kernel from its 3.18 version. However, as with many other components of the kernel, its availability to the user depends on the parameters with which the kernel has been compiled. Specifically, eBPF is only available to kernels compiled with the flags specified in table 3.1.

Flag	Value	Description
CONFIG_BPF	y	Basic BPF compilation (mandatory)
CONFIG_BPF_SYSCALL	m	
CONFIG_NET_ACT_BPF	m	Traffic Control functionality
CONFIG_NET_CLS_BPF	y	
CONFIG_BPF_JIT	y	Enable JIT compilation
CONFIG_HAVE_BPF_JIT	y	
CONFIG_BPF_EVENTS	y	Enable kprobes, uprobes and tracepoints
CONFIG_KPROBE_EVENTS	y	
CONFIG_UPROBE_EVENTS	y	
CONFIG_TRACING	y	
CONFIG_XDP_SOCKETS	y	Enable XDP

Table 3.1. Kernel compilation flags for eBPF.

The above table is based on BCC’s documentation^{3.1}, but the full list of eBPF-related flags can be extracted in a live system via bpftool, as detailed in Annex 6. Nowadays, all mainstream Linux distributions include kernels with full support for eBPF.

3.1.1. Access control

It must be noted that, similarly to kernel modules, loading an eBPF program requires privileged access in the system. In old kernel versions, this means either an user having full root permissions, or having the Linux capability^[52] CAP_SYS_ADMIN. Therefore, there existed two main options:

- **Privileged users** can load any kind of eBPF program and use any functionality.
- **Unprivileged users** can only load and attach eBPF programs of type BPF_PROG_TYPE_SOCKET_FILTER, offering the very limited functionality of filtering packets received on a socket.

More recently, in an effort to further granulate the permissions needed for loading, attaching and running eBPF programs, CAP_SYS_ADMIN has been substituted by more specific capabilities^{[54][55]}. The current system is therefore described in table 3.2.

Capabilities	eBPF functionality
No capabilities	Load and attach BPF_PROG_TYPE_SOCKET_FILTER, load BPF_PROG_TYPE_CGROUP_SKB programs.
CAP_BPF	Load (but not attach) any type of program, create most types of eBPF map and access them if their id is known
CAP_NET_ADMIN	Attach networking programs (Traffic Control, XDP, ...)
CAP_PERFMON	Attaching kprobes, uprobes and tracepoints. Read access to kernel memory.
CAP_SYS_ADMIN	Privileged eBPF. Includes iterating over eBPF maps, and CAP_BPF, CAP_NET_ADMIN, CAP_PERFMON functionalities.

Table 3.2. Capabilities needed for eBPF.

Therefore, eBPF network programs usually require both CAP_BPF and CAP_NET_ADMIN, whilst tracing programs require CAP_BPF and CAP_PERFMON. CAP_SYS_ADMIN still remains as the (non-preferred) capability to assign to eBPF programs with complete access in the system.

Although for a long time there have existed efforts towards enhancing unprivileged eBPF, it remains a worrying feature[56]. The main issue is that the verifier must be prepared to detect any attempt to extract kernel memory access or user memory modification by unprivileged eBPF programs, which is a complex task. In fact, there have existed numerous security vulnerabilities which allow for privilege escalation using eBPF, that is, execution of privileged eBPF programs by exploiting vulnerabilities in unprivileged eBPF[57].

This influx of security vulnerabilities leads to the recent inclusion of an attribute into the kernel which allows for setting whether unprivileged eBPF is allowed in the system or not. This parameter is named *kernel.unprivileged_bpf_disabled*, its values can be seen in table 3.3.

Value	Meaning
0	Unprivileged eBPF is enabled.
1	Unprivileged eBPF is disabled. A system reboot is needed to enable it after changing this value.
2	Unprivileged eBPF is disabled. A system reboot is not needed to enable it after changing this value.

Table 3.3. Values for unprivileged eBPF kernel parameter.

Nowadays, most Linux distributions have set value 1 to this parameter, therefore disallowing unprivileged eBPF completely. These include Ubuntu[58], Suse Linux[59] or Red Hat Linux[60], between others.

3.1.2. eBPF maps security

In table 3.2, we observed that only programs with `CAP_SYS_ADMIN` are allowed to iterate over eBPF maps. The reason why this is restricted to privileged programs is because it is functionality that is a potential security vulnerability, which we will now proceed to analyse.

In subsection 2.2.4 we mentioned that eBPF maps are opened by specifying an ID (which works similarly to the typical file descriptors), while in table 2.6 we showed that, for performing operations over eBPF maps using the `bpf()` syscall, the map ID must be specified too.

Map IDs are known by a program after creating the eBPF map, however, a program can also explore all the available maps in the system by using the `BPF_MAP_GET_NEXT_ID` operation in the `bpf()` syscall, which allows for iterating through a complete hidden list of all the maps created. This means that privileged programs can find and have read and write access to any eBPF map used by any program in the system.

Therefore, a malicious privileged eBPF program can access and modify other programs' maps, which can lead to:

- Modify data used for the program operation. This is the case for maps which mainly store data structures, such as `BPF_MAP_TYPE_HASH`.
- Modify the program control flow, altering the instructions executed by an eBPF program. This can be achieved if a program is using the `bpf_tail_call()` helper (introduced in table 2.9) which is taking data from a map storing eBPF programs (`BPF_MAP_TYPE_PROG_ARRAY`, introduced in table 2.6).

3.2. Abusing tracing programs

eBPF tracing programs (kprobes, uprobes and tracepoints) are hooked to specific points in the kernel or in the user space, and call probe functions once the flow of execution reaches the instruction to which they are attached. This section details the main security concerns regarding this type of programs.

3.2.1. Access to function arguments

As we saw in section 2.3, tracing programs receive as a parameter those arguments with which the hooked function originally was called. These parameters are read-only and thus, in principle, they cannot be modified inside the tracing program (we will show this is not entirely true in section 3.3). The next code snippets show the format in which parameters are received when using `libbpf` (Note that `libbpf` also includes some macros that offer an alternative format, but the parameters are the same).

CODE 3.1. Probe function for a kprobe on the kernel function `vfs_write`.

```
1 SEC("kprobe/vfs_write")
2 int kprobe_vfs_write(struct pt_regs* ctx){
```

CODE 3.2. Probe function for an uprobe, `execute_command` is defined from user space.

```
1 SEC("uprobe/execute_command")
2 int uprobe_execute_command(struct pt_regs *ctx){
```

CODE 3.3. Probe function for a tracepoint on the start of the syscall `sys_read`.

```
1 SEC("tp/syscalls/sys_enter_read")
2 int tp_sys_enter_read(struct sys_read_enter_ctx *ctx) {
```

In code snippets 3.1 and 3.2 we can identify that the parameters are passed to kprobe and uprobe programs as a pointer to a *struct pt_regs**. This struct contains as many attributes as registers exist in the system architecture, in our case `x86_64`. Therefore, on each probe function, we will receive the state of the registers at the original hooked function. This explains the format of the *struct pt_regs*, shown in code snippet 3.4:

CODE 3.4. Format of *struct pt_regs*.

```
1 struct pt_regs {
2     long unsigned int r15;
3     long unsigned int r14;
4     long unsigned int r13;
5     long unsigned int r12;
6     long unsigned int bp;
7     long unsigned int bx;
8     long unsigned int r11;
9     long unsigned int r10;
10    long unsigned int r9;
11    long unsigned int r8;
12    long unsigned int ax;
13    long unsigned int cx;
14    long unsigned int dx;
15    long unsigned int si;
16    long unsigned int di;
17    long unsigned int orig_ax;
18    long unsigned int ip;
19    long unsigned int cs;
20    long unsigned int flags;
21    long unsigned int sp;
22    long unsigned int ss;
23 };
```

By observing the value of the registers, we are able to extract the parameters of the original hooked function. This can be done by using the System V AMD64 ABI[61], the

calling convention used in Linux. Depending on whether we are in the kernel or in user space, the registers used to store the values of the function arguments are different. Table 3.4 summarizes these two interfaces.

User interface		Kernel interface	
Register	Purpose	Register	Purpose
rdi	1st argument	rdi	1st argument
rsi	2nd argument	rsi	2nd argument
rdx	3rd argument	rdx	3rd argument
rcx	4th argument	r10	4th argument
r8	5th argument	r8	5th argument
r9	6th argument	r9	6th argument
rax	Return value	rax	Return value

Table 3.4. Argument passing convention of registers for function calls in user and kernel space respectively.

In the case of tracepoints, we can see in code snippet 3.3 that it receives a *struct sys_read_enter_ctx**. This struct must be manually defined, as explained in 2.3.3, by looking at the file */sys/kernel/debug/tracing/events/syscalls/sys_enter_read/format*. Code snippet 3.6 shows the format of the struct.

CODE 3.5. Format for parameters in *sys_enter_read* specified at the format file.

```

1 field:unsigned short common_type; offset:0; size:2; signed:0;
2 field:unsigned char common_flags; offset:2; size:1; signed:0;
3 field:unsigned char common_preempt_count; offset:3; size:1; signed
  :0;
4 field:int common_pid; offset:4; size:4; signed:1;
5 field:int __syscall_nr; offset:8; size:4; signed:1;
6 field:unsigned int fd; offset:16; size:8; signed:0;
7 field:char * buf; offset:24; size:8; signed:0;
8 field:size_t count; offset:32; size:8; signed:0;
```

CODE 3.6. Format of custom struct *sys_read_enter_ctx*.

```

1 struct sys_read_enter_ctx {
2     unsigned long long pt_regs;
3     int __syscall_nr;
4     unsigned int padding;
5     unsigned long fd;
6     char* buf;
7     size_t count;
8 };
```

As we can observe, we are given a set of attributes which include the parameters

with which the syscall was called. Moreover, we can still obtain an address pointing to another *struct pt_regs*, as in kprobes and uprobes, by combining the first four fields and considering it as a 32-bit long address. This means we will still be able to extract the value of the rest of the registers too.

It must be noted that, in syscalls, in addition to use the kernel parameter passing convention specified in table 3.4, the number specifying the syscall must be passed in register rax too.

On a final note, as we mentioned in section 2.3, there exist differences in the parameters received in probe functions depending on the two variations of tracing programs. Therefore:

- kprobe, uprobe and *enter* tracepoints will receive the full parameters as we specified before, but not the return value of the function (since it is not executed yet).
- kretprobes, uretprobes and *exit* tracepoints will still receive the *struct pt_regs*, but without any of the parameters and with only the return value of the function.

Taking into account all the previous, the fact that tracing programs have read-only access to function arguments can be considered an useful and needed feature for tracing applications, but malicious eBPF can use this for purposes such as:

- Gather kernel and user data passed to a function as a parameter. In many cases this information can be potentially interesting for an attacker, such as passwords.
- Store in eBPF maps information about system activities, to be used by other malicious eBPF programs.

Usually, since many function arguments are pointers to user or kernel addresses (such as buffers where a string or a struct with data is located), eBPF tracing programs can use two eBPF helpers that enable to read large byte arrays from both kernel and user space:

- `bpf_probe_read_user()`
- `bpf_probe_read_kernel()`

These helpers, previously introduced in table 2.9, enable to read an arbitrary number of bytes from an user or kernel address respectively, allowing us to extract the information pointed by the parameters received by eBPF programs.

3.2.2. Reading memory out of bounds

As we introduced in the previous subsection, the `bpf_probe_read_user()` and `bpf_probe_read_kernel()` helpers can be used to access memory of pointers received as parameters in the hooked functions.

However, although in general the eBPF verifier attempts to reject illegal memory accesses, it does not prevent a malicious program from passing an arbitrary memory address (in kernel or user space) to the above helpers. This means that an eBPF program can potentially read any address in user or kernel space, (as long as it is marked as readable in the corresponding memory pages). Furthermore, an attacker can locate specific data structures and memory sections by taking the function parameter as a reference point in memory.

A particularly relevant case (which we will later use for our rootkit) involves accessing user memory via the parameters of tracepoints attached at system calls. Provided the nature of syscalls, whose purpose is to communicate user and kernel space, all parameters received will belong to the user space, and therefore any pointer passed will be an address in user memory. This enables an eBPF program to get a foothold into the virtual address space of the process calling the syscall, which it can proceed to scan looking for data or specific instructions. This technique will be further elaborated in section 3.3.4.

3.2.3. Overriding function return values

A potentially dangerous functionality in eBPF tracing programs is the ability to modify the return value of kernel functions[62][63]. This can be done via the eBPF helper `bpf_override_return`, and it works exclusively from kretprobes.

Apart from only working on kretprobes, additional restrictions are applied to this helper. It will only work if the kernel was compiled with the `CONFIG_BPF_KPROBE_OVERRIDE` flag, and only if the kretprobe is attached to a function to which, during the kernel development, the macro `ALLOW_ERROR_INJECTION()` has been indicated. Currently, only a small selection of functions include this macro, but most system calls can be found to implement it. The following code snippets show how a system call like `sys_open` is defined in kernel v5.11:

CODE 3.7. Definition of the syscall `sys_open` in the kernel [64]

```

1  SYSCALL_DEFINE3(open, const char __user *, filename, int, flags,
    umode_t, mode)
2  {
3      if (force_o_largefile())
4          flags |= O_LARGEFILE;
5      return do_sys_open(AT_FDCWD, filename, flags, mode);
6  }
```

CODE 3.8. Definition of the macro for creating syscalls, containing the error injection macro. Only relevant instructions included, complete macro can be found in the kernel [65]

```

1  #define SYSCALL_DEFINE3(name, ...) SYSCALL_DEFINEx(3, _##name,
    __VA_ARGS__)
2  #ifndef __SYSCALL_DEFINEx
```

```

3  #define __SYSCALL_DEFINE(x, name, ...) \
4      [...]
5      ALLOW_ERROR_INJECTION(sys##name, ERRNO); \
6      [...]

```

By looking at snippets 3.7 and 3.8, we can observe that the system call `sys_open` involves the inclusion of the `ALLOW_ERROR_INJECTION` macro. Therefore, any kretprobe attached to a system call function will be able to modify its return value.

In order to be able to modify the return value of functions, the aforementioned eBPF helper makes use of the fault injection framework of the Linux kernel[66], which was created before eBPF itself, and whose original purpose is to allow for generating errors in kernel programs for debugging purposes.

Taking the previous information into account, we can find that a malicious eBPF program, by tampering with the kernel-user space interface which are system calls, can mislead user programs, which trust the output of kernel code. This can lead to:

- A program believes a system call exited with an error, while in reality the kernel completed the operation with success, or viceversa. For instance, the result of a call to `sys_open` can mislead a user program into thinking that a file does not exist.
- A program receives incorrect data on purpose. For instance, a buffer may look empty or of a reduced size upon a `sys_read` call, while in reality more data is available to be read.

3.2.4. Sending signals to user programs

Another eBPF helper that is subject to malicious purposes is `bpf_send_signal`. This helper enables to send an arbitrary signal to the thread of the process running a hooked function.

Therefore, this helper can be used to forcefully terminate running user processes, by sending the `SIGKILL` signal. In this way, combined with the observability into the parameters received at a function call, malicious eBPF can kill and deactivate processes to favour its malicious purposes.

3.2.5. Conclusion

As a summary, a malicious eBPF program loaded and attached as a tracing program undermines the existing trust between user programs and the kernel space.

Its ability to access sensitive data in function parameters and reading arbitrary memory can lead to gathering extensive information on the running processes of a system, whilst the malicious use of eBPF helpers enables the modification of the data passed to the user space from the kernel, and the control over which programs are allowed to be running on the system.

3.3. Memory corruption

In the previous section we described how tracing programs can read user memory out of the bounds of function parameters via the helpers `bpf_probe_read_user()` and `bpf_probe_read_kernel()`. In this section, we will analyse another eBPF helper can be found to be the heart of malicious programs.

Privileged eBPF programs (or those with at least `CAP_BPF` + `CAP_PERFMON` capabilities) have the potential to use an experimental (it is labelled as so [38]) helper called `bpf_probe_write_user()`. This helper enables to write into user memory from within an eBPF program.

However, this helper has certain limitations that restrict its use. We will now proceed to review some background into how user memory works and, afterwards, we will analyse the restrictions and possible uses of this eBPF helper in the context of malicious applications.

3.3.1. Memory management in Linux

Linux systems divide the available random access memory (RAM) into 'pages', subsections of an specific length, usually 4 KB. The collection of all pages is called physical memory.

Likewise, individual memory sections need to be assigned to each running process in the system, but instead of assigning a set of pages from physical memory, a new address space is defined, named virtual memory, which is divided into pages as well. These virtual memory pages are related to physical memory pages via a page table, so that each virtual memory address of a process can be translated into a real, physical memory address in RAM[67]. Figure 3.1 shows a diagram of the described architecture.

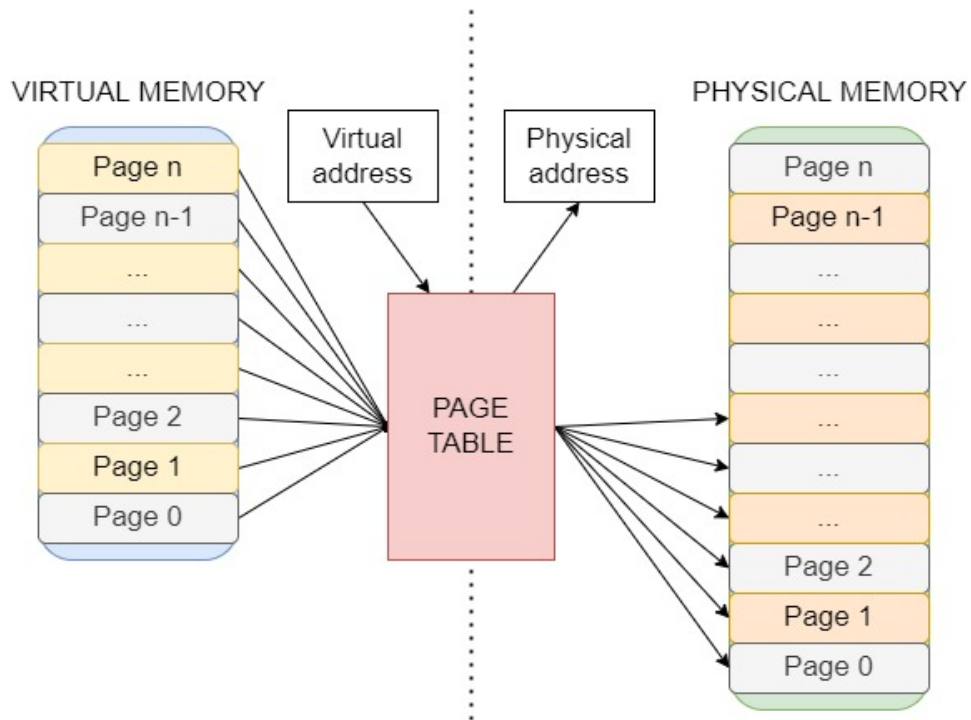


Fig. 3.1. Memory translation of virtual pages to physical pages.

As we can observe in the figure, each virtual page is related to one physical page. However, RAM needs to maintain multiple processes and data simultaneously, and therefore sometimes the operating system (OS) will remove them from physical memory when it believes they are no longer being used. This leads to the occurrence of two type of memory events[68]:

- **Major page faults** occur when a process tries to access a virtual page, but the related physical page has been removed from RAM. In this case, the OS will need to request a secondary storage (such as a hard disk) for the data removed, and allocate a new physical page for the virtual page. Figure 3.2 illustrates a major page fault.

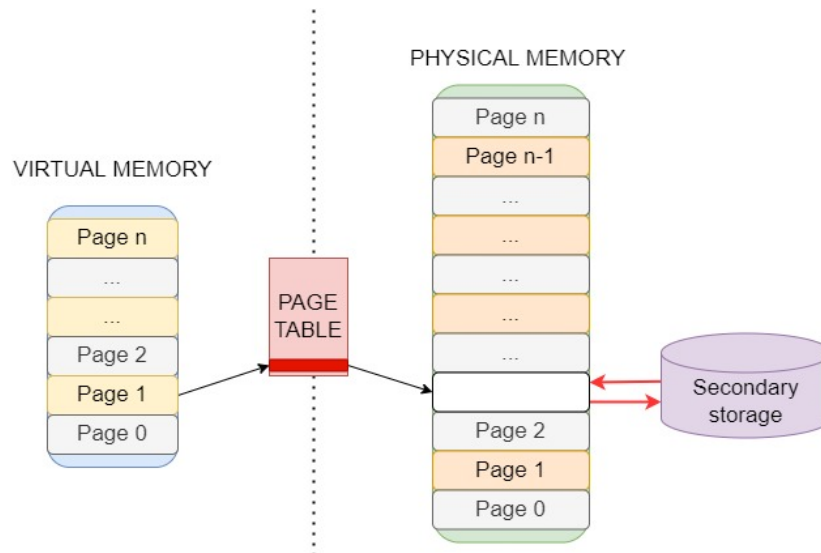


Fig. 3.2. Major page fault after a page was removed from RAM.

- Minor page faults** occur when a process tries to access a virtual page, and although the related physical page exists, the connection in the page table has not been completed. A common event when these fault happen is on `fork()` calls, since with the purpose of making the call more efficient, the page table of the parent is not always completely copied into the child, leading into multiple minor page faults once the child tries to access the data on them. Figure 3.3 illustrates a minor page fault after a fork.

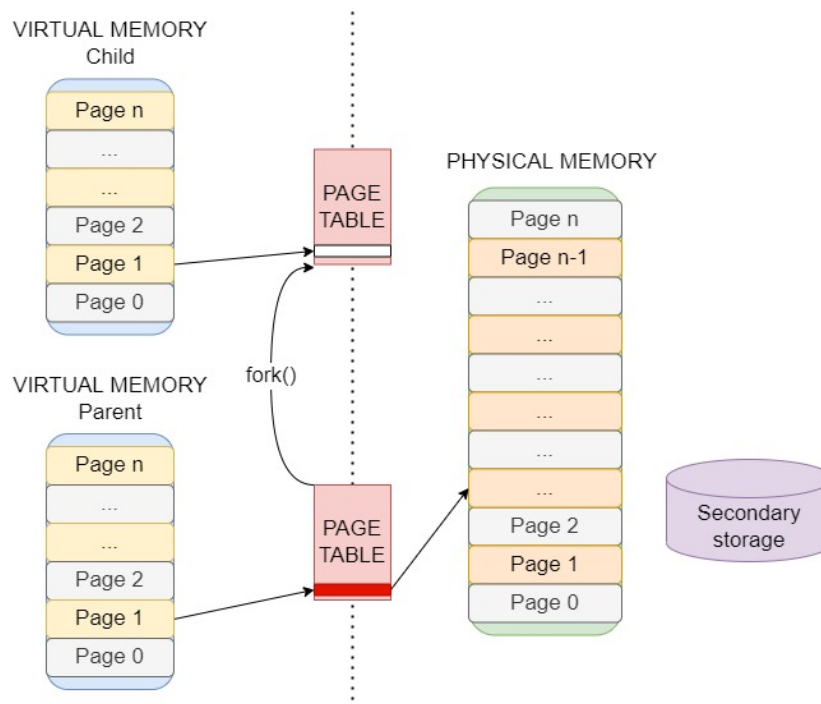


Fig. 3.3. Minor page fault after a `fork()` in which the page table was not copied completely.

3.3.2. Process virtual memory

In the previous subsection we have studied that each process disposes of a virtual address space. We will now describe how this virtual memory is organized in a Linux system.

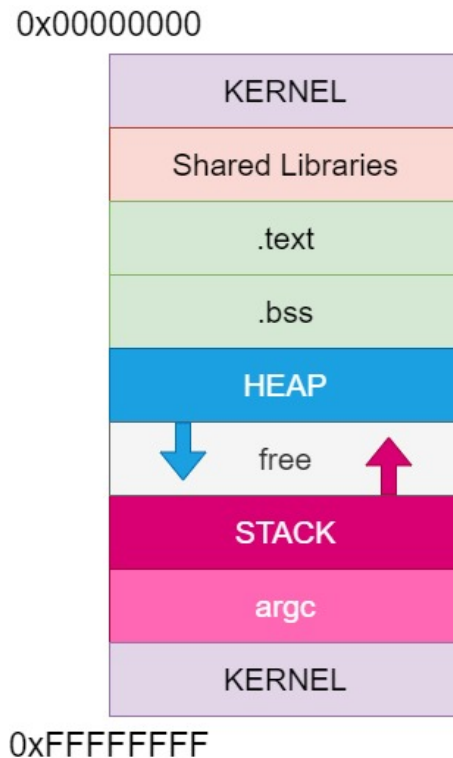


Fig. 3.4. Virtual memory architecture of a process[69].

Figure 3.4 describes how virtual memory is distributed within a process in the x86_64 architecture. As we can observe, it is partitioned into multiple sections:

- Lower and upper memory addresses are reserved for the kernel.
- A section where shared libraries code is stored.
- A .text section, which contains the code of the program being run.
- A .bss section, which contains global static variables.
- The heap, a section which grows from lower to higher memory addresses, and which contains memory dynamically allocated by the program.
- The stack, a section which grows from higher to lower memory addresses, towards the heap. It is a Last In First Out (LIFO) structure used to store local variables, function parameters and return addresses.
- Right at the start of the stack we can find the arguments with which the programs has been executed.

3.3.3. The process stack

Between all the sections we identified in a process virtual memory, the stack will be particularly relevant during our research. We will therefore study it now in detail.

Firstly, we will present how the stack is structured, and which operations can be executed on it. Figure 3.5 presents a stack during the execution of a program. Table 3.5 explains the purpose of the most relevant registers related to the stack and program execution:

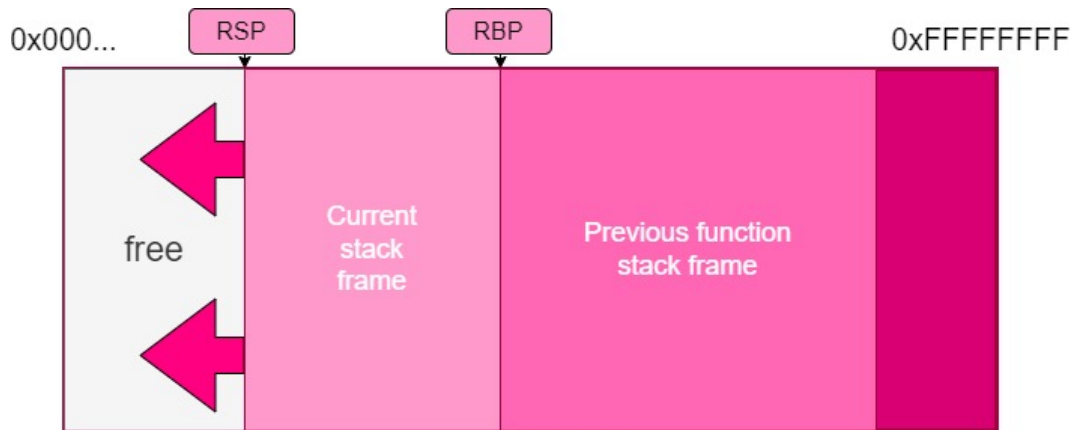


Fig. 3.5. Simplified stack representation showing only stack frames.

Register	Purpose
rip	Instruction Pointer - Memory address of the next instruction to execute
rsp	Stack Pointer - Memory address where next stack operation takes place
rbp	Base/Frame Pointer - Memory address of the start of the stack frame

Table 3.5. Relevant registers in x86_64 for the stack and control flow and their purpose.

As it can be observed in figure 3.5, the stack grows towards lower memory addresses, and it is organized in stack frames, delimited by the registers `rsp` and `rbp`. A stack frame is a division of the stack which contains all the data (variables, call arguments...) belonging to a single function execution. When a function is exited, its stack frame is removed, and if a function calls a nested function, then its stack frame is preserved and a new stack frame is inserted into the stack.

As table 3.5 explains, the `rbp` and `rsp` registers are used for keeping track of the starting and final position of the current stack frame respectively. We can see in figure 3.5 that their value is a memory address pointing to their stack positions. On the other hand,

the rip register does not point to the stack, but rather to the .text section (see figure 3.4), where it points to the next instruction to be executed. However, as we will now see, its value must also be stored in the stack frame when a nested function is called, since after the nested function exits we need to restore the execution in the same instruction of the original function.

As with any LIFO structure, the stack supports two main operations: *push* and *pop*. In the x86_64 architecture, it operates with chunks of data of either 16, 32 or 64 bytes.

- A **push** operation writes data in the free memory pointed by register *rsp*. It then moves the value of *rsp* to point to the new end of the stack.
- A **pop** operation moves the value of *rsp* by 16, 32 or 64 bytes, and reads the data previously saved in that position.

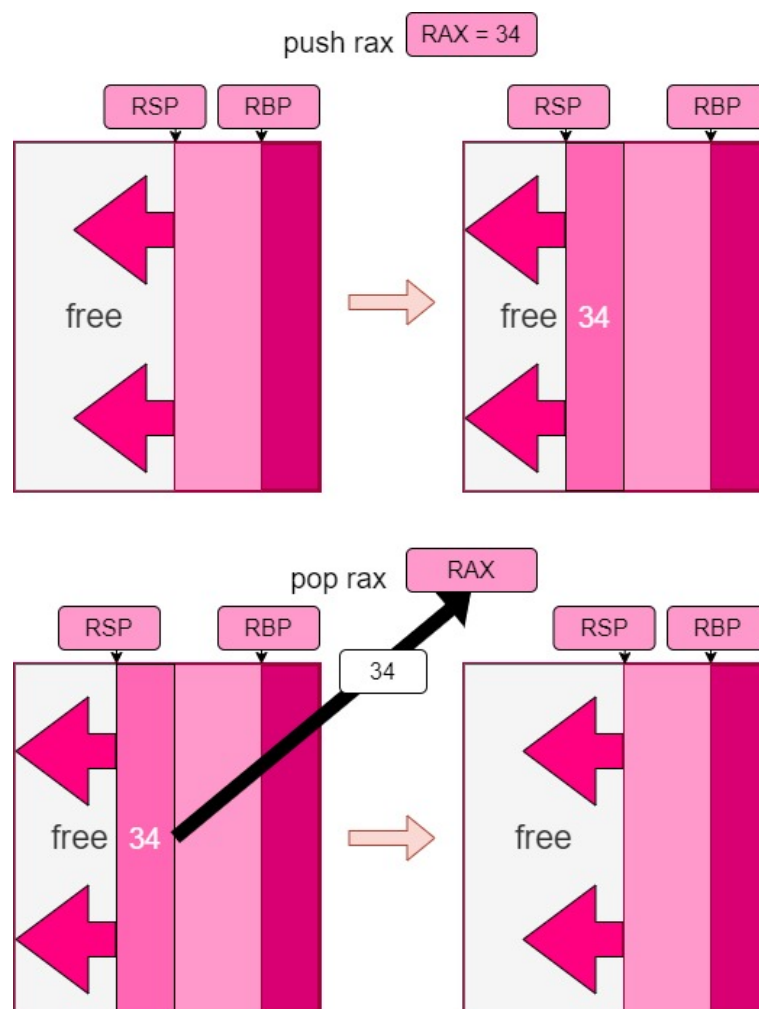


Fig. 3.6. Representation of push and pop operations in the stack.

As we mentioned, the stack stores function parameters, return addresses and local variables inside a stack frame. We will now study how the processor uses the stack in

order to call, execute, and exit a function. To illustrate this process, we will simulate the execution of function `func(char* a, char* b, char* c)` :

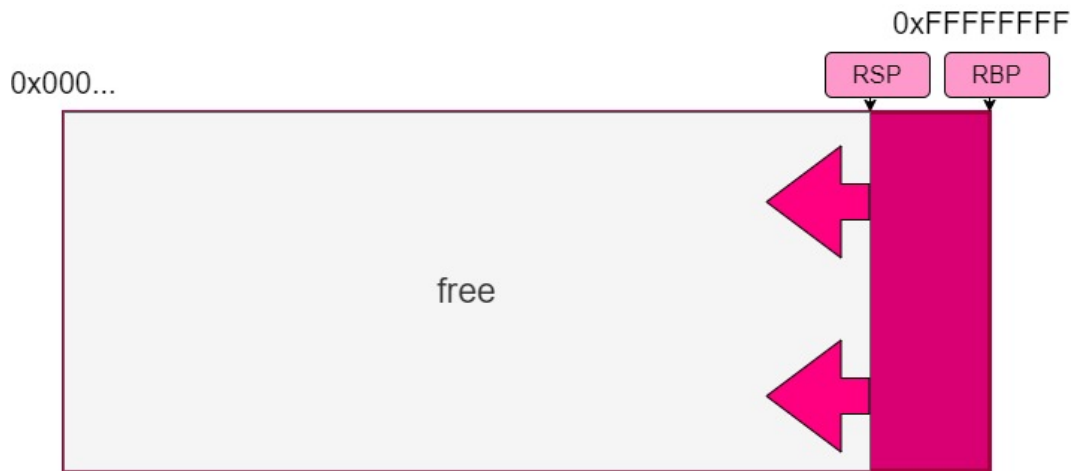


Fig. 3.7. Stack representation right before starting the function call process.

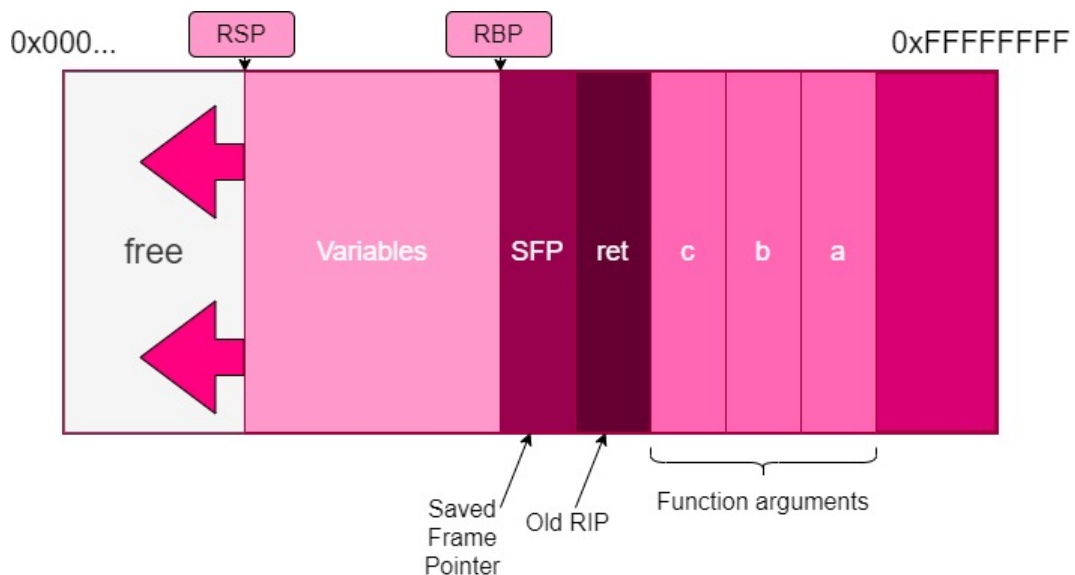


Fig. 3.8. Stack representation right after the function preamble.

1. The function arguments are pushed into the stack. We can see them in the stack in reverse order.
2. The function is called:
 - (a) The value of register `rip` is pushed into the stack, so that it is saved for when the function exists. We can see it on the figure as 'ret'.
 - (b) The value of `rip` changes to point to the first instruction of the called function.
 - (c) We execute what is called as the *function preamble*[\[70\]](#), which prepares the stack frame for the called function:

- (d) The value of `rbp` is pushed into the stack, so that we can restore the previous stack frame when the function exits. We can see it on the figure as the 'saved frame pointer'.
 - (e) The value of `rsp` is moved into `rbp`. Therefore, now `rbp` points to the end of the previous stack frame.
 - (f) The value of `rsp` is usually decremented (since the stack needs to go to lower memory addresses) so that we allocate some space for function variables.
3. The function instructions are executed. The stack may be further modified, but on its end `rsp` must point to the same address of the beginning. Register `rbp` always keeps pointing to the end of the stack.
 4. We execute what is called as the *function epilogue*, which removes the stack frame and restores the original function:
 - (a) The value of `rbp` is moved into `rsp`, so that `rsp` points to the start of the previous stack frame. All data allocated in the previous stack frame is considered to be free.
 - (b) The value of the saved frame pointer is popped and stored into `rbp`, so that `rbp` now points to the start of the previous stack frame.
 - (c) The value of the saved `rip` value is popped into register `rip`, so that the next instruction to execute is the instruction right after the function call.
 5. Since the function arguments were pushed into the stack, they are popped now.

3.3.4. Attacks and limitations of `bpf_probe_write_user()`

Provided the background into memory architecture and the stack operation, we will now study the offensive capabilities of the `bpf_probe_write_user()` helper and which restrictions are imposed into its use by eBPF programs.

The `bpf_probe_write_user()` helper, when used from a tracing eBPF program, can write into any memory address in the user space of the process responsible for calling the hooked function. However, the write operation fails has some restrictions:

- The operation fails if the memory space pointed by the address is marked as non-writable by the user space process. For instance, if we try to write into the `.text` section, the helper fails because this section is only marked as readable and executable (for protection reasons). Therefore, the process must indicate a writable flag in the memory section for the helper to succeed.
- The operation fails if the memory page is served with a minor or major page fault. As we saw in section 2.2.3, eBPF programs are restricted from executing any sleeping or blocking operations, to prevent hanging the kernel. Therefore, since during a

page fault the operating system needs to block the execution and write into the page table or retrieve data from the secondary disk, `bpf_probe_write_user()` is defined as a non-faulting helper[71], meaning that instead of issuing a page fault for accessing data, it will just return and fail.

- Each time the helper is called, an alert message is written into the kernel logs, alerting that a potentially dangerous eBPF program is making use of the helper. Note that this message appears when the eBPF program is attached, and not each time the helper is called. This will be particularly relevant since we will be able to bypass this alert by taking advantage of this.

Although we will not be able to modify kernel memory or the instructions of a program, this eBPF helper opens a range of possible attacks:

- Modify any of the arguments with which a system call is called (either with a tracepoint or a kprobe). Therefore, a malicious program can hijack any call to the kernel with its own arguments.
- Modify user-provided arguments in kernel functions. When reading kernel code, we can find that data provided by the user is marked with the keyword `__user`. For instance, an internal kernel function in a nested call of the system call `sys_read` receives an user buffer:

CODE 3.9. Definition of kernel function `vfs_read`. [72]

```
1 ssize_t vfs_read(struct file *file, char __user *buf, size_t count
    , loff_t *pos)
```

Then, if we attach a kprobe to `vfs_read`, we would be able to modify the value of the buffer.

- Modify process memory by taking function parameters as a reference and scanning the stack. This technique, first introduced in section 3.2.2 when we mentioned that tracing programs can read any user memory location with the `bpf_probe_read_user()` helper, consists of:
 1. Take an user-passed parameter received on a tracing program. The parameter must be a pointer to a memory location (such as a pointer to a buffer), so that we can use that memory address as the reference point in user space. According to the x86_64 documentation, this parameter will be stored in the stack[73], so we will receive an stack address.
 2. Locate the target data which we aim to write. There are two main methods for this:
 - Sequentially read the stack, using `bpf_probe_read_user()`, until we locate the bytes we are looking for. This requires knowing which data we want to overwrite.

- By previously reverse engineering the user program, we can calculate the offset at which an specific data section will be stored in virtual memory with respect to the reference address we received as a parameter.
3. Overwrite the memory buffer using `bpf_probe_write_user()`.

Figure 3.9 illustrates a high-level overview of the stack scanning technique previously described:

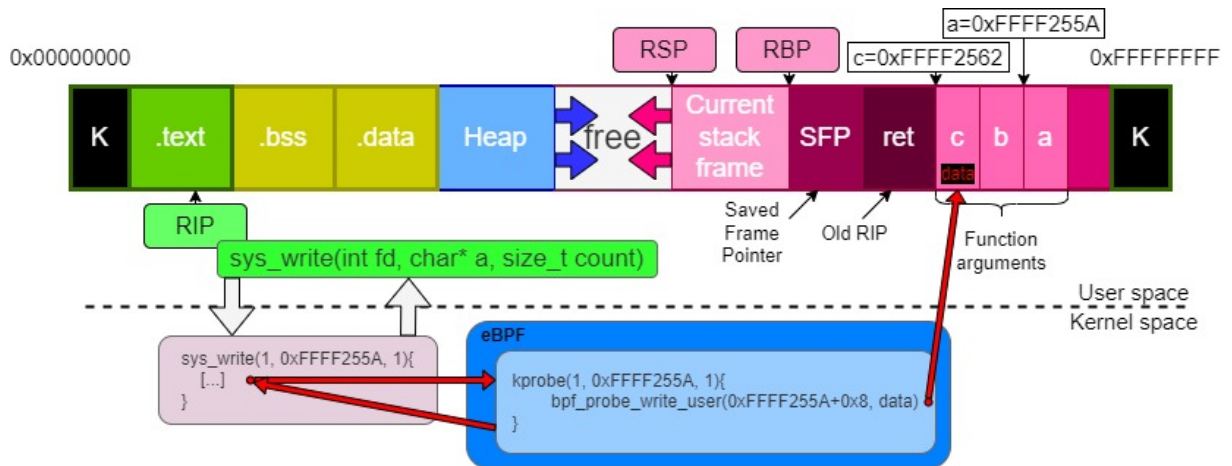


Fig. 3.9. Overview of stack scanning and writing technique.

The above figure shows process memory executing a program similar to the following:

CODE 3.10. Sample program being executed on figure 3.9.

```

1 void func(char* a, char* b, char* c){
2     int fd = open("FILE", 0);
3     write(fd, a, 1);
4 }
5
6 int main(){
7     char a[] = "AAA";
8     char b[] = "BBB";
9     char c[] = "CCC";
10    func(a, b, c);
11 }

```

In the figure, we can clearly observe how the technique is used to overwrite an specific buffer. The attacker goal is to overwrite buffer `c` with some other bytes, but the kprobe program only has direct access to buffer `a`:

1. By reverse engineering the program (we will see how this process works in section ??) we notice that buffer `c` is stored 8 bytes lower on the stack than buffer `a`.
2. When register `rip` points to the `write()` instruction, the processor executes the instruction and a system call is issued to `sys_write()`.

3. The kprobe eBPF program hooked to the syscall hijacks the program execution. Since it has access to the memory address of buffer *a* and it knows the relative position of buffer *c*, it writes to that location whatever it wants (e.g.: "DDD") with the `bpf_probe_write_user()` helper.
4. The eBPF program ends and the control flow goes back to the system call. It ends its execution successfully, and returns a value to the user space. The result of the program is that 1 byte has been written into file "FILE", and that buffer *c* now contains "DDD".

3.3.5. Conclusion

As a summary, the `bpf_probe_write_user()` helper is one of the main attack vectors for malicious eBPF programs. Although it does contain some restrictions, its ability to overwrite any user parameter enables it to, in practice, execute arbitrary code by hijacking that of others. When it is combined with tracing programs' ability to read memory out of bounds, it unlocks a wide range of attacks, since any writeable section of the process memory is a possible target.

Therefore, if on the conclusion of section 3.2.5 we discussed that the ability to change the return value of kernel functions and kill processes hinders the trust between the user and kernel space (since what the kernel returns may not be a correct result), then the ability to directly overwrite process data is a complete disrupt of trust in any of the data in the user space itself, since it is subject to the control of a malicious eBPF program.

Moreover, in the next sections we will discuss how we can create advanced attacks on the basis of the background and techniques previously discussed. We will research further into which sections of a process memory are writeable and whether they can lead to new attack vectors.

3.4. Abusing networking programs

The final main piece of a malicious eBPF program comes from taking advantage of the networking capabilities of TC and XDP programs. As we mentioned during sections 2.3.1 and 2.3.2, these type of programs have access to network traffic:

- Traffic Control programs can be placed either on egress or ingress traffic, and receive a struct `sk_buff`, containing the packet bytes and meta data that helps operating on it.
- External Data Path programs can only be attached to ingress traffic, but in turn they receive the packet before any kernel processing (as a struct `xdp_md`) being able to access the raw data directly.

Networking eBPF programs not only have read access to the network packets, but also write access:

- XDP programs can directly modify the raw packet via `memcpy()` operations. They can also increment or reduce the size of the packet by any of its ends (adding bytes before the head or after the packet tail). This is done via the multiple helpers previously presented on table 2.11.
- TC programs can also modify the packet via the helpers presented on table 2.13. The packet can be expanded or reduced via these eBPF helpers too.

Apart from write access to the packet, the other critical feature of networking programs is their ability to drop packets. As we presented in tables 2.10 and 2.12, this can be achieved by returning specific values.

3.4.1. Attacks and limitations of networking programs

Multiple restrictions exist on network eBPF programs:

- Read and write access to the packet is heavily controlled by the eBPF verifier. It is not possible to read or write data out of bounds. Extreme care must also be taken before attempting to read any data inside the packet, since the verifier first requires making lots of checks beforehand. For any access to take place, the program must first classify the packet according to the network protocol it belongs, and later check that every header of every network layer is well defined (e.g: Ethernet, IP and TCP). Only after that, the headers can be modified.

If the program also wants to modify the packet payload, then it must be checked to be between the bounds of the packet and well defined according to the packet headers. Also, after using any of the helpers that enlarge or reduce the size of the packet, all check operations must be repeated again before any subsequent operation.

Finally, note that after any modification in the packet, some network protocols (such as IP and TCP) require to recalculate their checksum fields.

- XDP and TC programs are not able to create packets, they can only operate over existing traffic.

4. RESULTS

5. CONCLUSION AND FUTURE WORK

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APPENDIX A - BPF TOOL COMMANDS

eBPF-related kernel compilation flags

```
1 | $ bpftool feature
```

```
CONFIG_BPF is set to y
CONFIG_BPF_SYSCALL is set to y
CONFIG_HAVE_EBPF_JIT is set to y
CONFIG_BPF_JIT is set to y
CONFIG_BPF_JIT_ALWAYS_ON is set to y
CONFIG_CGROUPS is set to y
CONFIG_CGROUP_BPF is set to y
CONFIG_CGROUP_NET_CLASSID is set to y
CONFIG_SOCK_CGROUP_DATA is set to y
CONFIG_BPF_EVENTS is set to y
CONFIG_KPROBE_EVENTS is set to y
CONFIG_UPROBE_EVENTS is set to y
CONFIG_TRACING is set to y
CONFIG_FTRACE_SYSCALLS is set to y
CONFIG_FUNCTION_ERROR_INJECTION is set to y
CONFIG_BPF_KPROBE_OVERRIDE is set to y
CONFIG_NET is set to y
CONFIG_XDP_SOCKETS is set to y
CONFIG_LWTUNNEL_BPF is set to y
CONFIG_NET_ACT_BPF is set to m
CONFIG_NET_CLS_BPF is set to m
CONFIG_NET_CLS_ACT is set to y
CONFIG_NET_SCH_INGRESS is set to m
CONFIG_XFRM is set to y
CONFIG_IP_ROUTE_CLASSID is set to y
CONFIG_IPV6_SEG6_BPF is set to y
CONFIG_BPF_LIRC_MODE2 is not set
CONFIG_BPF_STREAM_PARSER is set to y
CONFIG_NETFILTER_XT_MATCH_BPF is set to m
CONFIG_BPFILTER is set to y
CONFIG_BPFILTER_UMH is set to m
CONFIG_TEST_BPF is set to m
CONFIG_HZ is set to 250
```


APPENDIX B