INTRODUCTION TO eBPF

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SHADIL A M

Abstract

The Extended Berkeley Packet Filter (eBPF) represents a transformative technology in modern operating systems, enabling the safe and dynamic execution of custom programs within the Linux kernel without requiring kernel modification or reboot. It provides developers with a powerful framework for extending kernel functionality, improving observability, and enhancing performance in areas such as networking, security, and system monitoring. This seminar report explores the design principles, architecture, and methodology of eBPF, emphasizing its programmability, flexibility, and runtime efficiency. Through detailed evaluation across metrics such as ease of use, verifier performance, compatibility, and real-time observability, the study highlights both the strengths and current limitations of eBPF. Despite challenges like a steep learning curve, limited tooling, and kernel version dependencies, eBPF demonstrates exceptional potential as a foundation for next-generation observability and performance engineering. The report concludes with future directions including cross-platform support, AI/ML integration, and improved developer tooling, underscoring eBPF's pivotal role in shaping the future of dynamic kernel-level computing.

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Chapter 1

Introduction

The Linux kernel forms the backbone of modern computing, providing core services such as process scheduling, memory management, and hardware interaction. Traditionally, extending kernel functionality has been risky: modifying kernel source code can introduce instability or system crashes. **eBPF** (extended Berkeley Packet Filter) revolutionizes kernel programming by enabling developers to safely execute sandboxed programs directly within the kernel without altering its source code. eBPF programs are compiled to verified bytecode, loaded dynamically, and executed at predefined kernel hooks. This methodology ensures safety, high performance, and flexibility, allowing dynamic monitoring, tracing, and custom logic execution in real time.

Figure 1.1: Logo of eBPF

1.1 Background and Motivation

Extending kernel functionality traditionally requires modifying kernel source code, which is error-prone and may destabilize the system. eBPF addresses this challenge by offering a secure, dynamic, and efficient way to add custom kernel logic without compromising system stability.

1.2 Objectives of the Study

The main objectives of this study are:

- To understand the capabilities and working of eBPF.
- To explore practical applications in monitoring, networking, security, and performance analysis.
- To evaluate the impact of eBPF on modern computing infrastructure.

1.3 Capabilities of eBPF

With eBPF, developers can extend kernel functionality in several ways:

- **Custom Monitoring:** Track system calls, network packets, or file operations dynamically.
- **Security Enforcement:** Block, log, or alert on specific actions in the kernel.
- **Kernel Tracing:** Inspect internal kernel activities to debug or optimize system behavior.
- **Feature Extension:** Add new scheduling strategies, task filtering, or packet processing methods without recompiling the kernel.

1.4 Applications

eBPF powers a diverse ecosystem of tools and frameworks:

- **Monitoring & Observability:** Tools like `bcc` and `bpftrace` allow real-time insight into kernel activity.
- **Networking:** Frameworks such as Cilium and XDP leverage eBPF to accelerate and control network traffic efficiently.
- **Security:** Tools like Falco and Tracee detect intrusions and unusual kernel-level behavior.
- **Performance Analysis:** eBPF enables identification of bottlenecks and optimization of critical system paths.

1.5 Impact

eBPF represents a paradigm shift in kernel extensibility:

- **Safe Kernel Extensions:** Programs run securely without modifying kernel source code.
- **High Performance:** Near-native execution through JIT compilation.
- **Dynamic and Flexible:** Developers can attach programs to kernel hooks at runtime.
- **Cross-Domain Utility:** eBPF is used in monitoring, networking, security, observability, and performance analysis.

Chapter 2

Background and Basic Principles of eBPF

2.1 Background

The kernel is the core of any operating system, responsible for managing hardware resources, processes, memory, networking, and system security. Traditionally, extending kernel functionality or adding custom monitoring required modifying the kernel source or writing kernel modules. While powerful, this approach is inherently risky: a single bug in kernel code can crash the entire system or introduce security vulnerabilities. Moreover, updating or maintaining custom kernel modules is complex, especially across different kernel versions.

To address these challenges, the Linux community developed eBPF (extended Berkeley Packet Filter), a technology that allows safe, dynamic extensions of kernel behavior without altering the kernel source code. eBPF provides a sandboxed execution environment within the kernel, enabling developers to run small programs that interact with kernel events, monitor system performance, and implement custom security or networking logic.

2.2 Basic Principles of eBPF

2.2.1 What is eBPF?

eBPF is a lightweight, in-kernel virtual machine that executes custom programs safely. These programs can observe, filter, and modify system behavior at runtime. Before execution, all eBPF programs are verified for safety, preventing unsafe memory access, infinite loops, or operations that could destabilize the kernel.

Key advantages of eBPF include:

- **Safe Kernel Extensions:** Add new functionality without kernel source modifications.
- **Dynamic Observability:** Trace system calls, network packets, or kernel events in real time.
- **Flexibility:** Programs can be loaded, updated, or removed at runtime without rebooting.
- **Performance:** Supports JIT compilation for near-native execution speeds.

2.2.2 eBPF vs Traditional BPF

The original Berkeley Packet Filter (BPF) was designed for efficient packet filtering in networking. eBPF extends this concept:

- **General-Purpose:** Not limited to networking; supports observability, security, and performance monitoring.
- **Safety Verification:** eBPF programs are verified before execution, ensuring they cannot crash the kernel.
- **Enhanced Functionality:** Supports maps, helper functions, and hooks to communicate between user space and kernel space.
- **JIT Compilation:** Improves performance by compiling bytecode to native instructions at runtime.

Chapter 3

Literature Review

3.1 The eBPF Runtime in the Linux Kernel

The extended Berkeley Packet Filter (eBPF) runtime has transformed the Linux kernel into a programmable environment capable of dynamic observation and control. According to Smith, Chen, and Kumar (2024), eBPF introduces a secure, sandboxed mechanism for executing user-defined bytecode directly within kernel space. This allows developers to attach custom logic to networking, tracing, and security hooks without requiring kernel recompilation. The study presents the evolution of eBPF as a high-performance virtual machine supporting efficient in-kernel execution through Just-In-Time (JIT) compilation. The authors further explore its architectural integration with Linux subsystems, demonstrating its ability to enhance both runtime adaptability and maintain strong isolation guarantees. The work highlights how eBPF bridges the gap between user and kernel space programmability while preserving system safety and scalability. **Limitation:** While the study covers runtime execution and integration, it does not address AI agent telemetry or automated analysis of agent behaviors.

3.2 Leveraging eBPF for Runtime Security

Building upon its foundational role in observability, Patel, Wang, and Rao (2024) explore eBPF's potential as a real-time security enforcement layer. The study emphasizes how eBPF enables lightweight, dynamic instrumentation for intrusion detection, anomaly tracking, and policy enforcement at runtime. By intercepting kernel events with minimal performance overhead, eBPF-based frameworks can define context-aware rules that dynamically adapt to emerging threats. The authors demonstrate its applicability in containerized and cloud-native environments, where runtime visibility and zero-trust principles are critical. Their findings underscore eBPF's ability to deliver proactive security analytics by correlating low-level kernel events with high-level behavioral insights, thus establishing it as a cornerstone for modern runtime defense systems. **Limitation:** This work focuses on security instrumentation but does not address automated program generation or integration with AI-driven observability frameworks.

3.3 AgentSight: System-Level Observability for AI Agents Using eBPF

Hernandez, Liu, and Tan (2025) introduce *AgentSight*, a framework that leverages eBPF to extend system-level observability into the domain of AI agent operations. Their approach utilizes eBPF probes to collect fine-grained telemetry from kernel and user-space activities associated with AI workloads. The research addresses challenges related to tracing AI agents' real-time interactions with hardware, memory subsystems, and communication layers. By integrating eBPF with performance counters and event streams, *AgentSight* provides a unified observability layer that enhances explainability, resource optimization, and fault detection. The paper also outlines strategies for correlating low-level execution metrics with model-level behaviors, marking a significant advancement in AI systems monitoring and debugging using in-kernel observability primitives. **Limitation:** While *AgentSight* improves AI agent observability, it does not provide automated program synthesis or integrate runtime security enforcement.

3.4 KEN: Kernel Extensions LLM Agent for eBPF Program Synthesis

Recent developments in AI-assisted kernel programming are exemplified by *KEN*, a large language model (LLM) agent designed for automated eBPF program synthesis. Brown, Singh, and Zhao (2024) present this system as a fusion of natural language understanding and low-level kernel extension generation. *KEN* translates high-level policy descriptions into verified eBPF bytecode, reducing human intervention and potential coding errors. By leveraging reinforcement learning and static verification tools, the framework ensures that generated programs adhere to kernel safety rules and performance constraints. The study reveals *KEN*'s capability to generalize across observability, security, and performance tuning tasks, effectively democratizing eBPF development and accelerating innovation in programmable kernel extensibility. **Limitation:** Although *KEN* automates program synthesis, it does not handle complex real-time kernel observability or integrate runtime security enforcement for AI workloads.

Chapter 4

Methodology

eBPF (extended Berkeley Packet Filter) represents a revolutionary approach to extending the Linux kernel dynamically and safely. It allows developers to inject programs at runtime into kernel hooks without modifying core kernel code. This paradigm provides unmatched flexibility, safety, and performance for tasks such as monitoring, networking, security, and observability. The methodology of eBPF revolves around program design, verification, loading, execution, and data interaction through helper functions and maps.

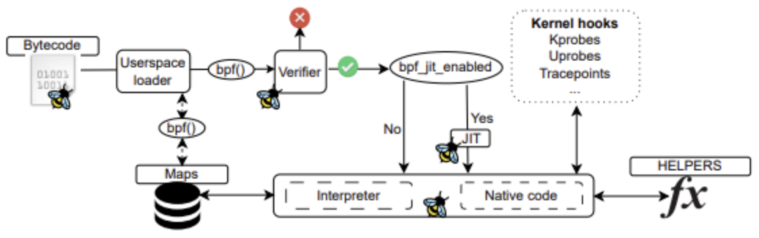

Figure 1: An overview of the eBPF key components and their correlation based on [24].

Figure 4.1: Overview of eBPF Key Components and Their Correlation

4.1 Restricted C: Writing eBPF Programs

eBPF programs are written in *Restricted C*, a subset of the C programming language designed to ensure verifiability and safety within the kernel. Key restrictions include:

- No infinite loops: Loops must have statically determinable bounds.
- No general function calls: Only predefined kernel-provided helper functions can be called.
- No floating-point operations: Ensures deterministic execution across CPU architectures.

Programs written in Restricted C are compiled into eBPF bytecode, a low-level, platform-independent representation that the kernel can safely execute.

```
// simple_execve.c
#include <uapi/linux/ptrace.h>
#include <linux/sched.h>

SEC("kprobe/__x64_sys_execve")
int bpf_prog(struct pt_regs *ctx) {
    bpf_printk("Program executed!\n");
    return 0;
}
```

```
# Compile eBPF program to bytecode
clang -O2 -target bpf -c simple_execve.c -o simple_execve.o
```

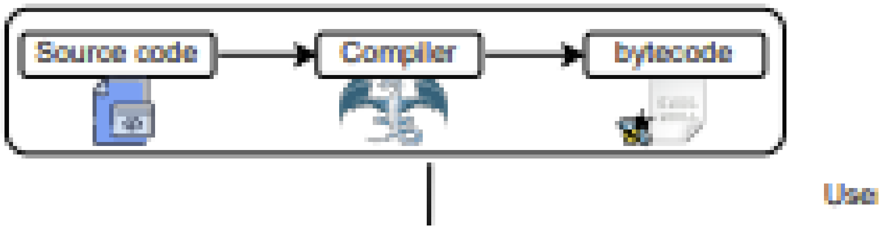

Figure 4.2: Compilation Workflow from Restricted C to eBPF Bytecode

4.2 Loading eBPF Programs

eBPF programs are loaded into the kernel using user-space tools like `bpftool`, which internally invoke the kernel's `bpf()` system call. Programs are loaded into a special filesystem location (/sys/fs/bpf) for management and attachment.

```
# Load eBPF program into kernel
sudo bpftool prog load simple_execve.o /sys/fs/bpf/simple_execve
```

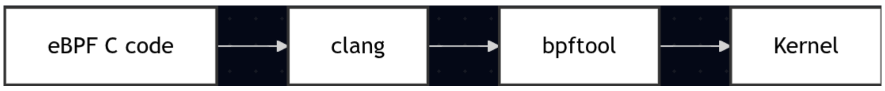

Figure 4.3: User-Space to Kernel Program Loading

4.3 Verification: Ensuring Safety and Correctness

Before execution, eBPF programs pass through a kernel verifier, a static analyzer designed to guarantee safety, correctness, and determinism. The verifier ensures that eBPF programs cannot crash the kernel or compromise memory safety. Its operations include:

- **Control Flow Graph (CFG) Validation:** Checks for unreachable code, infinite loops, and illegal jumps.
- **Symbolic Execution:** Explores all possible execution paths to track register and stack usage.
- **Optimization & Transformation:** Eliminates dead code, simplifies instructions, and ensures efficient execution.

4.4 Execution: Interpreter vs JIT

eBPF bytecode can be executed in two modes:

- **Interpreter Mode:** Kernel reads each instruction sequentially and simulates execution. Safe but slower.
- **Just-In-Time (JIT) Compilation:** Converts bytecode to native CPU instructions for near-native performance.

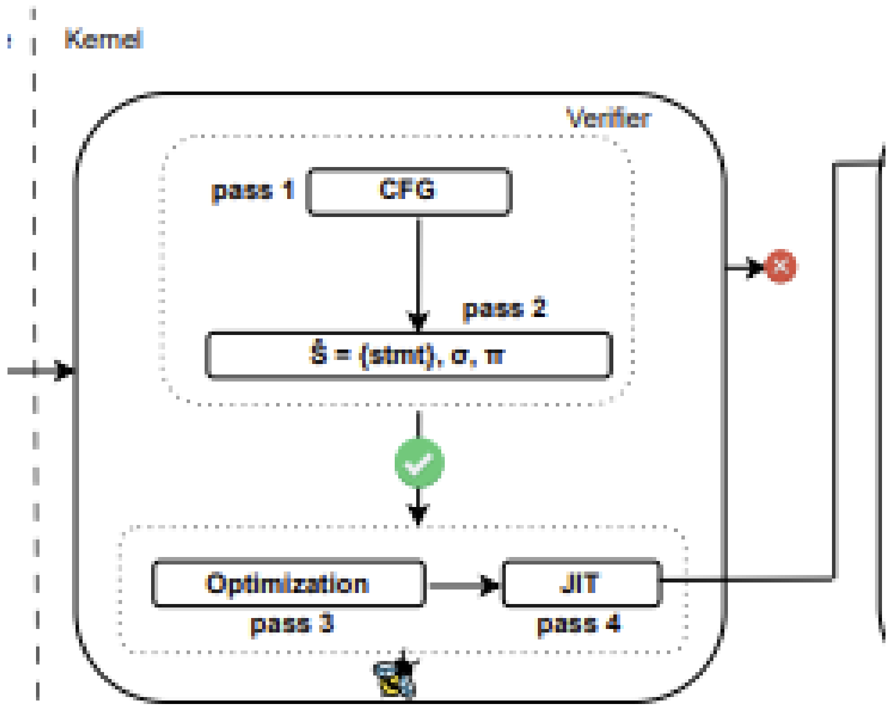

Figure 4.4: eBPF Verification Pipeline

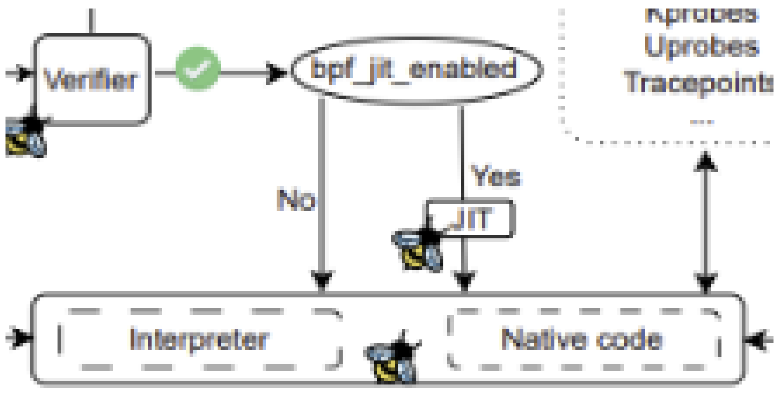

Figure 4.5: Interpreter Execution Pipeline

```
// JIT Compilation steps:
1. Memory Allocation: Reserve memory for native instructions.
2. Prologue Emission: Save CPU registers and frame pointers.
3. Instruction Translation: Map each eBPF instruction to CPU instructions.
4. Epilogue Emission: Restore CPU state for seamless return to kernel execu
```

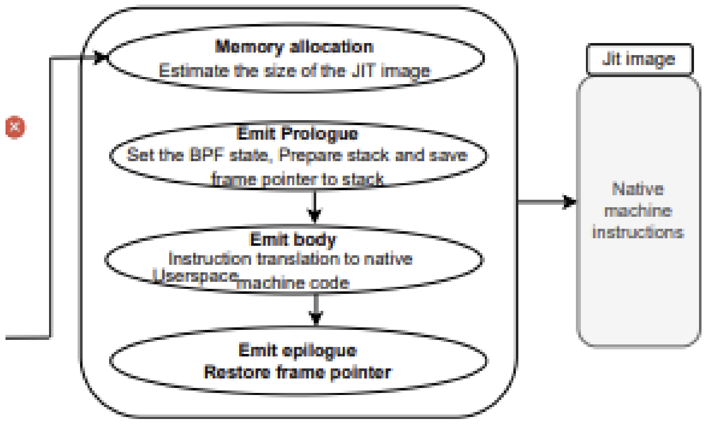
Memory allocation
Estimate the size of the JIT image
Emit Prologue
Set the BPF state, Prepare stack and save frame pointer to stack
Emit body
Instruction translation to native machine code
Userspace
Emit epilogue
Restore frame pointer
Jit image
Native machine instructions

Figure 4.6: JIT Compilation Pipeline

4.5 Hooks and Dynamic Execution Points

eBPF programs attach to various kernel hooks:

- Kprobes: Trace kernel function entry points.
- Tracepoints: Observe specific kernel events.
- Sockets and XDP: Monitor/manipulate network packets.
- cgroups and LSM hooks: Enforce security and resource policies.

```
// Example of eBPF Hash Map
struct bpf_map_def SEC("maps") my_map = {
    .type = BPF_MAP_TYPE_HASH,
    .key_size = sizeof(int),
    .value_size = sizeof(long),
    .max_entries = 1024,
};
```

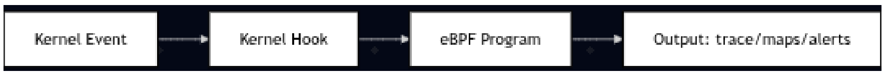

Figure 4.7: Kernel Hooks Attachment

4.6 Helper Functions and Maps

The kernel exposes helper functions eBPF programs can safely invoke, e.g., `bpf_map_lookup_elem()`, `bpf_map_update_elem()`, `bpf_get_current_pid_tgid()`.

Maps are kernel-resident data structures for storing and sharing data. Example:

```
// Example of eBPF Hash Map
struct bpf_map_def SEC("maps") my_map = {
    .type = BPF_MAP_TYPE_HASH,
    .key_size = sizeof(int),
    .value_size = sizeof(long),
    .max_entries = 1024,
};
```

4.7 Data Flow Overview

The eBPF methodology workflow:

Write Program in Restricted C → Compile to Bytecode → Load via bpftool → Verify Safety → Execute at Kernel Hook → Interact via Helpers and Maps

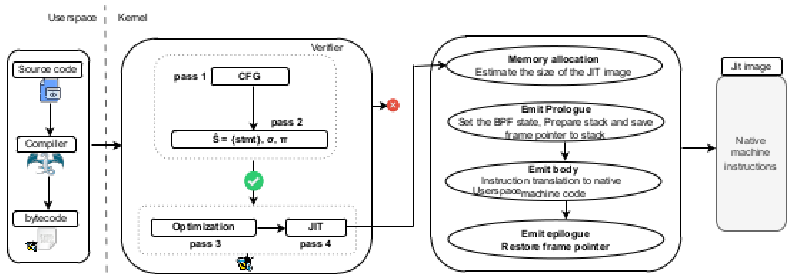

Figure 4.8: End-to-End eBPF Execution Workflow

Chapter 5

Challenges and Limitations

Despite its powerful capabilities, eBPF faces several challenges and limitations that affect adoption, performance, and maintainability. This chapter discusses the major issues in detail.

5.1 Complexity of eBPF Programming

Writing eBPF programs requires a deep understanding of the Linux kernel and low-level system behavior. Developers must be familiar with restricted C, kernel APIs, and the interaction between user space and kernel space. This steep learning curve slows adoption and increases the likelihood of programming errors. Furthermore, reasoning about the impact of eBPF programs on system performance and stability can be difficult, especially in large-scale deployments.

5.2 Verification and Performance Issues

The eBPF verifier ensures that programs are safe to execute in kernel space, preventing unsafe memory access or infinite loops. However, this verification process can become a bottleneck:

- **Program Complexity:** Complex or highly optimized programs may fail verification, limiting the expressiveness of eBPF.

- **Performance Overhead:** While eBPF is designed to be efficient, poorly written programs or excessive hooks can degrade system performance.
- **Debugging Difficulty:** Since programs run in kernel space, traditional debugging tools are limited, making it challenging to identify performance bottlenecks.

5.3 Security Risks and Mitigations

Although eBPF enhances security observability, it also introduces potential risks:

- **Privilege Escalation:** Malicious or buggy eBPF programs could exploit kernel vulnerabilities if verification is bypassed.
- **Misconfiguration:** Incorrect use of maps, hooks, or helper functions can expose sensitive data or affect system integrity.

Mitigation strategies include strict verification, careful program design, kernel version awareness, and using modern tools such as bpftool for monitoring and debugging.

5.4 Compatibility and Portability Challenges

eBPF programs are closely tied to specific kernel versions. Kernel upgrades can break existing programs due to changes in APIs, helpers, or internal kernel structures. Additionally, differences in architectures (x86, ARM, etc.) may require platform-specific adjustments. Maintaining cross-platform and forward-compatible eBPF programs requires continuous testing, abstraction, and careful program design.

5.5 Other Limitations

- **Limited Tooling:** There is a shortage of comprehensive, user-friendly frameworks and documentation, slowing developer adoption.
- **Debugging Complexity:** Tracing and reasoning about complex interactions across multiple eBPF programs is difficult.

Chapter 6

Applications and Case Studies

6.1 Applications of eBPF

6.1.1 Monitoring Tools (bcc, bpftrace)

eBPF-based tools like `bcc` and `bpftrace` enable real-time system monitoring by attaching to various kernel tracepoints. These tools provide deep visibility into system performance, allowing for efficient debugging and performance tuning without the need for kernel modifications.

6.1.2 Networking (Cilium, XDP)

eBPF enhances networking capabilities through technologies like `Cilium` and `XDP`. `Cilium` leverages eBPF for high-performance networking, security, and load balancing in containerized environments. `XDP` (eXpress Data Path) allows for high-performance packet processing directly at the network driver level, reducing latency and CPU usage.

6.1.3 Security (Falco, Tracee)

Security tools such as `Falco` and `Tracee` utilize eBPF to monitor system calls and detect anomalous behavior in real-time. These tools provide runtime security by observing kernel-level activities and identifying potential threats without significant performance overhead.

6.1.4 Performance Analysis

eBPF facilitates detailed performance analysis by enabling the collection of metrics at various levels of the system stack. This capability allows for precise identification of performance bottlenecks and efficient optimization strategies.

6.1.5 Impact

- **High Performance Scalability:** eBPF's low overhead and high efficiency make it suitable for large-scale deployments, handling thousands of nodes and services with minimal resource consumption.
- **Better Observability Troubleshooting:** The granular visibility provided by eBPF tools aids in quick identification and resolution of issues, enhancing system reliability.

6.2 Case Studies

6.2.1 5.5.1 Azure

Microsoft Azure integrates eBPF into its networking infrastructure to enhance observability and security. Through the use of `Cilium` and the Azure-native `Retina` platform, Azure provides deep insights into network traffic and performance across Kubernetes clusters. These tools leverage eBPF to monitor pod-to-pod communication, DNS resolution, and service interactions, enabling efficient troubleshooting and optimization of network resources.

6.2.2 5.5.2 Netflix

Netflix employs eBPF for high-performance telemetry and network observability in its microservices architecture. By utilizing eBPF tracepoints, Netflix captures TCP flow data in near real-time, providing comprehensive visibility into service interactions. This approach allows for accurate attribution of network flows to specific workloads, facilitating efficient monitoring and troubleshooting across their extensive cloud infrastructure.

Chapter 7

Future Directions

7.1 Emerging Trends in eBPF

eBPF continues to evolve rapidly, with several trends shaping its future:

- **Cross-OS Support:** Efforts are underway to extend eBPF support beyond Linux, targeting operating systems like Windows and BSD. This expansion will broaden its applicability in heterogeneous environments and facilitate adoption in enterprise infrastructures.
- **Easier Programming:** High-level programming abstractions, SDKs, and GUI-based frameworks are being developed to lower the barrier for writing eBPF programs, making it accessible to developers without deep kernel expertise.
- **Verifier Enhancements:** Improvements to the eBPF verifier will increase efficiency and allow more complex programs to execute safely, reducing development friction while maintaining kernel stability.

7.2 Integration with AI and Cloud Systems

The combination of eBPF with AI/ML and cloud computing is a promising direction:

- **AI/ML Integration:** eBPF provides fine-grained system telemetry that can feed machine learning models for automated insights, anomaly detection, predictive maintenance, and intelligent system behavior.

- **Cloud Observability:** Cloud providers can leverage eBPF for enhanced observability, enabling real-time monitoring of network, storage, and compute resources without significant performance overhead.

7.3 Potential for New Security and Observability Tools

eBPF enables innovation in security and system monitoring:

- **Runtime Security:** Using eBPF for intrusion detection, runtime monitoring, and automated mitigation allows systems to dynamically respond to threats.
- **Performance Tuning and Analytics:** eBPF facilitates detailed performance profiling, tracing, and logging, helping administrators optimize workloads and analyze system behavior in real-time.
- **Expanded Applications:** Beyond traditional networking and security, eBPF can support research experiments, real-time analytics, service mesh optimization, and custom observability solutions in modern distributed systems.

Chapter 8

Conclusion

8.1 Summary of Findings

eBPF represents a paradigm shift in operating system design by making the kernel both flexible and programmable. It allows developers to inject custom logic into the kernel without modifying its core code, maintaining stability and security. Leveraging Just-In-Time (JIT) compilation, eBPF achieves near-native performance for complex tasks. One unified framework can now address monitoring, networking, and security needs simultaneously, reducing overhead and simplifying operations. Real-time visibility into system behavior enables advanced performance tuning and research insights. eBPF programs operate safely under the kernel's verifier, ensuring that injected logic cannot compromise system integrity.

8.2 Final Thoughts

However, challenges remain, including scaling the verifier for complex programs, handling diverse program complexity, and ensuring cross-kernel compatibility. The combination of programmability, efficiency, and safety makes eBPF a cornerstone for modern observability and security solutions. Its adoption continues to grow across cloud, enterprise, and research environments. Overall, eBPF exemplifies how modern operating system paradigms can evolve without sacrificing performance or reliability.

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