WASM-BPF: Streamlining eBPF Deployment in Cloud Environments with WebAssembly

Yusheng Zheng eunomia-bpf Community China yunwei356@gmail.com

Yiwei Yang UC Santa Cruz China yyang363@ucsc.edu Tong Yu
eunomia-bpf Community
China
yunwei356@gmail.com

Andrew Quinn
UC Santa Cruz
USA
aquinn@ucsc.edu

ABSTRACT

The extended Berkeley Packet Filter (eBPF) is extensively utilized for observability and performance analysis in cloudnative environments. However, deploying eBPF programs across a heterogeneous cloud environment presents challenges, including compatibility issues across different kernel versions, operating systems, runtimes, and architectures. Traditional deployment methods, such as standalone containers or tightly integrated core applications, are cumbersome and inefficient, particularly when dynamic plugin management is required. To address these challenges, we introduce Universal BPF (WASM-BPF), a lightweight runtime on WebAssembly (Wasm) and the WebAssembly System Interface (WASI). Leveraging Wasm's platform independence and WASI's standardized system interface, with enhanced relocation for different architectures, WASM-BPF ensures cross-platform compatibility for eBPF programs. It simplifies deployment by integrating with container toolchains, allowing eBPF programs to be packaged as Wasm modules that can be easily managed within cloud environments. Additionally, WASM-BPF supports dynamic plugin management in WebAssembly. Our implementation and evaluation demonstrate that Wasm-BPF introduces minimal overhead compared to native eBPF implementations while simplifying the deployment process.

1 INTRODUCTION

The extended Berkeley Packet Filter (eBPF) has emerged as a powerful technology for observability and performance in cloud-native environments[11, 26, 27, 31–33]. By enabling the execution of custom bytecode within the kernel, eBPF provides a versatile mechanism for monitoring and modifying system behavior without requiring kernel modifications. This capability is particularly valuable in containerized and cloud ecosystems where dynamism and scalability are critical.

However, deploying eBPF programs heterogeneously at scale presents several significant challenges. eBPF runtimes extend beyond the Linux kernel, encompassing environments such as Windows[7] and FreeBSD kernels, as well as userspace eBPF runtimes like ubpf[13], rbpf[24], and bpftime[30]. Additionally, eBPF must be compatible across multiple operating system versions, each with unique kernel data structures, eBPF features, and capabilities, resulting in inconsistent application behavior. Although Compile Once - Run Everywhere (CO-RE) support can mitigate some issues, it also introduces further complexity to the deployment process.

Current methods for deploying eBPF programs in containers are often inefficient and cumbersome. Standalone containers, commonly used for eBPF deployment, do not optimize for the typically small and namespace-unaware nature of eBPF programs, leading to resource inefficiencies and management difficulties. Large-scale projects like Cilium[2], Pixie[12], Tetragon[3], and Deepflow[27] often integrate monitoring or management tools directly within the core application or "control plane", which can complicate management, especially in dynamic environments requiring frequent updates. Comprehensive observability agents like Deepflow necessitate dynamic plugin management to adapt to varying scenarios, a feature not adequately supported by traditional tools. Alternatively, some approaches use Remote Procedure Calls (RPCs) to interface between control plane applications and dedicated BPF daemons, as seen in tools like bpfman[5], Inspektor-Gadget[6], and bpfd[8]. While effective for specific eBPF tools, these methods are better suited for smaller-scale deployments and do not fully address broader compatibility and scalability issues.

To illustrate, consider a scenario where we need to monitor network traffic across a heterogeneous cloud environment with nodes running different kernels and instruction sets. These nodes might include older versions of Linux that do not natively support eBPF, newer versions of Linux with full eBPF support, Windows, and servers with diverse architectures such as ARM64 and x86. To ensuring that the observed data is aware of container metadata and correlates with other data sources, such as API requests, developers may integrate this monitoring as a plugin with observability agents like Deepflow allows for comprehensive data collection and correlation. With traditional methods, deploying eBPF programs in this diverse environment would require significant effort to ensure compatibility across different kernels and architectures. This process could involve building and maintaining separate versions of eBPF programs for each environment, leading to increased complexity and potential errors.

To address these challenges, we introduce WASM-BPF, a lightweight runtime based on WebAssembly (Wasm) [4, 9, 25] and the WebAssembly System Interface (WASI) [1]. WASM-BPF is designed to streamline the distribution and compatibility of eBPF programs in cloud-native environments. By leveraging Wasm's platform independence and designing a standardized system interface based on WASI, WASM-BPF ensures seamless cross-platform compatibility for both eBPF and control-plane programs. It includes WebAssembly libraries for C, Go, and Rust toolchains, and provides runtime support for loading and executing eBPF programs from the Wasm module. Wasm-bpf features an automatic mechanism for selecting appropriate runtimes—whether in the kernel or userspace—and supports various eBPF features such as ring buffers and perf events. Additionally, WASM-BPF enhances Compile Once - Run Everywhere (CO-RE) capabilities, ensuring support across different architectures and runtimes, without serialization overhead for complex data types shared between user-space Wasm runtime and kernel eBPF runtime. Moreover, Wasm-bpf integrates seamlessly with container toolchains, simplifying the deployment and orchestration of eBPF programs within cloud environments. This integration addresses the complexities associated with current deployment methods, offering a more efficient and scalable solution.

In summary, our contributions are:

- Heterogeneous Platform Compatibility: Wasm-BPF introduces a lightweight runtime ensuring compatibility across different architectures and operating systems for both eBPF and control-plane programs, based on standard WASI and Wasm. It includes features like arch-aware relocation, automatic BTF preparing and facilitates selecting between different runtimes and eBPF features. It can run various eBPF programs with binary compatible on different OS and runtimes.
- Minor Performance Overhead We analyze the additional overhead introduced by the compatibility layer, including costs associated with BPF syscalls, ring buffer handling, and initialization latency.

• Faster and Easier Deployment WASM-BPF integrates seamlessly with container toolchains, simplifying the deployment and orchestration of eBPF programs in cloud-native environments.

2 BACKGROUND

This section overviews eBPF and WebAssembly (Wasm) applications and their importance in cloud computing environments.

2.1 eBPF application

Initially developed for the Linux kernel to execute custom bytecode, eBPF has expanded to userspace runtimes like ubpf[13], rbpf[24], and bpftime[30], as well as in other operating system kernels such as Windows[18] and FreeBSD[10]. An eBPF application typically consists of kernel bytecode and a userspace control plane application that loads this bytecode into the kernel and communicates through eBPF maps. The userspace application loads the eBPF bytecode, attaches it to the tracepoint sched_wakeup, creates BPF maps for communication, and periodically reads these maps to print the histogram. This structure allows dynamic and flexible interaction between userspace applications and eBPF programs running within the kernel.

2.2 Wasm and WASI

WebAssembly (Wasm)[4] is a binary instruction format designed for safe and efficient execution of code across different environments. Originally developed for web browsers, Wasm has evolved to support a wide range of applications beyond the browser, including server-side[28, 29], embedded systems[23] and containers[17]. Its key advantages include platform independence, security through sandboxing, and near-native performance. By compiling programs into a portable binary format, Wasm ensures that they can run consistently across diverse architectures and operating systems without requiring source code modifications. This makes Wasm an ideal foundation for building cross-platform compatibility layers, such as WASM-BPF.

The WebAssembly System Interface (WASI) extends the capabilities of Wasm by providing a standardized API for interacting with the underlying operating system. WASI abstracts system-level functionalities such as file and network I/O, enabling Wasm modules to perform operations that would otherwise require platform-specific code. This abstraction layer allows developers to write code that is both portable and powerful, leveraging the full capabilities of the host environment while maintaining cross-platform compatibility.

3 EBPF DEPLOYMENT CHALLENGES

This section outlines key challenges in deploying eBPF programs, including compatibility issues, cloud deployment complexities, and versioning difficulties.

3.1 Compatibility issues Across Different Runtimes and Architectures

eBPF was initially designed for the Linux kernel, but its utility has led to implementations in other environments, such as Windows[18] and FreeBSD kernels[10], as well as userspace runtimes. Despite these diverse and heterogeneous runtimes adhering to the same instruction standard, they lack a unified standard for loading and deploying eBPF programs. Each operating system and runtime employs different methods to load eBPF bytecode. For instance, Linux utilizes bpf-related syscalls that directly accept eBPF bytecode. The eBPF-for-Windows project provides source code level compatibility with the Linux kernel and a libbpf API, but still requires some code modifications to most applications. Userspace runtimes like uBPF and rBPF do not support using libbpf as a loader, making them incompatible with existing control plane applications. Different runtimes also support different features. For example, uprobe can be used by userspace eBPF runtimes and the Linux kernel but is not available on Windows. Additionally, varying support for eBPF features like ring buffers or perf events across different Linux versions complicates deployment. The lack of a standardized method for recognizing and distributing these features further complicates deployment. The Compile Once - Run Everywhere (CO-RE)[19] addresses varying kernel version issues by using BPF Type Format (BTF)[15] data, allowing eBPF programs to adapt dynamically and run on any compatible kernel without source code modifications, but this is still limited.

Compatibility across architectures introduces additional complexities, such as the kprobe and uprobe eBPF program uses **pt_regs**, a structure that varies between different architectures. Differences in data structure layouts, endianness, and pointer widths also pose challenges.

3.2 Deployment challenges in Cloud Environments

Orchestrating the lifecycle of eBPF programs in the cloud is complex, involving various states such as loading, attaching, detaching, and unloading eBPF programs.

One common strategy is tight integration, where monitoring or management tools are integrated within the control plane application. This approach, used by projects like Cilium[2], Pixie[12], Tetragon[3], and Deepflow[27], allows seamless interaction with system internals for efficient observation and manipulation of low-level operations. However,

it has drawbacks. Deploying smaller eBPF tools or probes using traditional containers can be resource-consuming. This method often requires extensive permissions, posing security risks due to its extensive privileges[11]. More granular capabilities like CAP_PERFMON and CAP_BPF have been introduced, but they still lack namespace constraints. Managing multi-user environments can also lead to conflicts where one eBPF program overrides another, resulting in silent failures or unpredictable behavior.

An alternative strategy is using Remote Procedure Calls (RPCs) to communicate between the control plane application and a dedicated BPF daemon. Tools like bpfman[5], Inspektor-Gadget[6], and bpfd[8] use this approach. The BPF daemon manages the BPF lifecycle and permissions, decoupling the BPF functionality from the application. While this adds a layer of abstraction, it also introduces challenges. The addition of a critical component in production increases the risk of failures, making troubleshooting and debugging more difficult. Maintaining consistency during updates can be problematic; when new kernel features are introduced, both the kernel dependency and the daemon need updates, which can delay the adoption of new capabilities. This model also imposes an additional support burden, as loaders must be compatible with tight integration and daemon delegation scenarios, complicating the upgrade or downgrade process and potentially leading to compatibility issues. Furthermore, operating system distributions or cloud providers may introduce different daemons, leading to a fragmented ecosystem.

3.3 Challenges with Versioning and Pluggability

Current eBPF tight coupling deployments make it difficult to version the eBPF program independently from its userspace counterpart. For example, suppose users must customize eBPF programs to track new proprietary protocols or analyze encrypted traffic with a specific userspace library. In that case, they must recompile the eBPF program and the userspace library, release a new version, and redeploy. This process becomes even more complex when the developer of the observability agent and the end user are from different organizations, as the developer may not have access to the proprietary protocols.

Additionally, the lack of a standardized method for packaging and distributing eBPF programs leads to inconsistencies and management difficulties. Each user or organization may develop their own approach, resulting in fragmented and incompatible deployments. This lack of versioning and pluggability affects the flexibility and adaptability of eBPF programs, making updates cumbersome and error-prone. Without a modular and versioned approach, users cannot easily roll

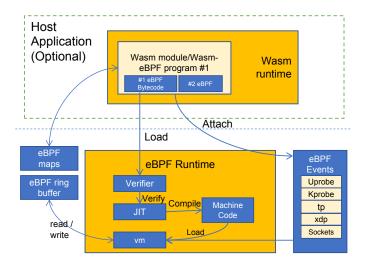


Figure 1: The runtime of WASM-BPF

back to previous versions in case of issues, increasing the risk associated with deploying updates.

4 DESIGN OF WASM-BPF

This section details the design of WASM-BPF, which can package the eBPF application, include userspace control-plane code into a Wasm module, and deploy it either as a standalone container and utilizing existing container tools to deploy eBPF programs, or as an embedded runtime, managing eBPF application plugins within host applications.

4.1 Architecture Overview

The architecture of Wasm-bpf addresses the challenges associated with deploying eBPF programs across diverse environments, managing their lifecycle in containers, and handling versioning and pluggability. Wasm-bpf includes a WebAssembly (Wasm) library, toolchain, and runtime support for loading and executing eBPF programs, ensuring a consistent execution environment regardless of the underlying platform. Figure 1 illustrates the runtime architecture of Wasm-bpf.

In the runtime, a Wasm module can correspond to multiple eBPF programs. An eBPF program instance can be dynamically loaded into the kernel from the Wasm sandbox. This allows the selection of the desired attach point and control over the lifecycle of multiple eBPF bytecode objects. Wasmbpf supports various types of maps and enables bidirectional communication with the kernel, including support for most map types. It efficiently transfers information between kernel and user space through ring buffers polling (or vice versa) and map accesses. Wasm-bpf is adaptable to nearly all use cases involving eBPF programs and can evolve and extend as kernel functionality evolves.

```
/// Lookup a bpf map fd by name.
int wasm_bpf_map_fd_by_name(bpf_object_skel, const char*);
/// Detach and close a bpf program.
int wasm_close_bpf_object(bpf_object_skel);
/// CO-RE load a bpf object into the kernel.
bpf object skel wasm load bpf object(const void* buf, int sz);
/// Attach a bpf program to a kernel hook.
int wasm attach bpf program(bpf object skel obj,
 const char* name, const char* attach_target);
/// Poll a bpf buffer, and call a wasm callback indicated by
/// sample_func. The first call to this function will
/// open and create a bpf buffer.
int wasm_bpf_buffer_poll(bpf_object_skel program, int fd,
 int32_t sample_func, uint32_t ctx, char* data, int max_size,
 int timeout ms);
/// Lookup, update, delete, and get_next_key operations on map.
int wasm_bpf_map_operate(int fd, int cmd, void* key,
 void* value, void* next key, uint64 t flags);
```

Figure 2: WASM-BPF's ABI design

4.2 Wasm-BPF ABI Design

The ABI (Application Binary Interface) for Wasm-bpf is designed to facilitate interaction between the Wasm runtime and eBPF programs. The ABI exports functions to the WebAssembly System Interface (WASI), the code snippet below illustrates the ABI functions provided by Wasm-bpf.

We define the WASI ABI interface in Figure 2 to ensure standardized interactions between eBPF programs and the Wasm runtime environment. The ABI functions cover operations such as loading eBPF objects, attaching eBPF programs to kernel hooks, polling eBPF buffers, and performing map operations. This design allows for robust and flexible management of eBPF programs within Wasm-bpF, enabling their deployment and operation across various environments with minimal friction.

4.3 Cross-Platform Compatibility

While eBPF instructions themselves are inherently crossplatform, the userspace control applications that interact with the runtime are typically native binaries. This can lead to compatibility issues across different platforms. Wasm-bpf addresses this challenge by leveraging WebAssembly (Wasm) and the WebAssembly System Interface (WASI) for userspace control plane applications, creating a robust and portable compatibility layer.

To ensure cross-platform access to function parameters in kprobe contexts, Wasm-bpf incorporates a specific Compile Once – Run Everywhere (CO-RE) [19] relocation pass for kprobe function parameters. This involves replacing pt_regs data structures with newer architecture-specific versions and modifying the BTF[15] information of the program. Consequently, Wasm-bpf can provide consistent access to function parameters in pt_regs across different platforms.

WASM-BPF automatically selects the appropriate runtime—whethen herently 64-bit, differences in data structure layouts, enin the kernel or userspace—and eBPF features to handle the varying capabilities of different environments. This selection process ensures optimal performance and compatibility by adapting to the target environment's specific characteristics. For instance, in a Linux environment, WASM-BPF checks the kernel configuration and version to determine the available kernel features and then utilizes the suitable ones. Examples include using ring buffers to pass events to userspace in newer kernel versions and using perf events in older kernel versions. If kernel eBPF is not available and the eBPF program is intended for uprobe, WASM-BPF can automatically use bpftime[30] as the userspace runtime.

WASM-BPF also enhances the CO-RE capabilities by incorporating mechanisms to ensure compatibility across different runtimes. This includes automatic BTF downloading in the runtime to ensure that necessary BTF data is available on the host, and provide BTF for userspace eBPF runtimes and host applications. As for a rich tapestry of kernel feature-interoperability issues, we require minor updates to the Wasm runtime code to make them compatible.

WASM-BPF integrates seamlessly with container toolchains[14] and Kubernetes. By replacing the standard containerd-shim with ctrd-wasmedge-shim and adhering to the specified implementation, WASM-BPF enables eBPF programs to be packaged as Open Container Initiative[20] (OCI) images and managed using standard container tools, streamlining the workflow for deploying and maintaining eBPF programs within cloud environments.

Versioning and Pluggability

Leveraging Wasm toolchains, WASM-BPF packages eBPF applications into Wasm OCI images and uses the ORAS [21] tools to simplify storage and distribution in cloud environments. This standardized approach ensures consistent behavior across environments and simplifies large-scale management. The Wasm component model [22] describes how wasm binary modules interact, allowing Wasm-BPF applications to function as versioned plugins or libraries. This modularity facilitates updates and customizations without needing to recompile and redeploy the entire application. Independent versioning reduces deployment risks, enhances adaptability, and makes it easier to roll back to previous versions if issues arise.

4.5 **Performance Considerations**

Ensuring minimal performance overhead while facilitating robust communication between Wasm and eBPF environments is a critical aspect of WASM-BPF. Given that Wasm can operate in both 32-bit and 64-bit modes, while eBPF is

dianness, and pointer widths can pose challenges. In the WASM-BPF project, communication between Wasm and eBPF virtual machines is optimized to eliminate the need for serialization and deserialization. Utilizing code generation techniques and support for BTF information in the toolchain, Wasm-bpf ensures correct communication across different memory layouts with negligible runtime overhead. Data can be directly copied from kernel space to the Wasm virtual machine's memory, avoiding the additional overhead of multiple data transfers. Additionally, automatically generating eBPF program skeletons and type definitions enhances the development experience, making it more efficient and developer-friendly.

EVALUATION

We implemented WASM-BPF using approximately 1386 lines of Rust code and 510 lines of C++ code to answer the following research questions: the effectiveness of WASM-BPF and its compatibility. The toolchain includes a modified version of bpftool, which generates eBPF skeletons for development and facilitates serialization-free communication between the eBPF runtime and the Wasm runtime. To enable the development of eBPF programs within a Wasm environment, we implemented the WASM-BPF library in C, Go, and Rust (e.g., libbpf-wasm). This library interacts with the WASI interface and loads eBPF bytecode into the eBPF runtime. Additionally, we built the WASM-BPF runtime on top of WasmEdge[16], enabling interaction with the eBPF runtime and integration with container tools.

Our evaluation focuses on the following research questions:

- RQ1: How effective is WASM-BPF at running control plane eBPF applications compared to native?
- RQ2: How does the start-up latency and binary size of Wasm-bpf compare to standalone container deploy-
- *RQ3*: What is the compatibility of the eBPF programs across different platforms?

5.1 Effectiveness

The test environment includes an Intel Xeon E5-2697v2 @ 3.5GHz, with kernel version 6.6. We conducted microbenchmarks to evaluate the performance of WASM-BPF compared to native eBPF implementations in Table 2. Map Access measures the average time to access eBPF maps via syscall in both Wasm and native environments. Ring Buffer Polling measures the average latency per event for ring

Program	Linux 5.5	Linux 6.10	Linux 6.10 arm64	Windows	Userspace eBPF
bootstrap	-/O	X/O	X/O	-/-	-/-
lsm	-/-	X/O	X/O	-/-	-/-
opensnoop	X/O	X/O	X/O	-/-	-/O
sockops	X/O	X/O	X/O	-/O	-/-
kprobe	X/O	X/O	-/O	-/-	-/-
uprobe	X/O	X/O	-/O	-/-	-/O
xdp	X/O	X/O	X/O	-/-	-/O

Table 1: Compatibility matrix showing support for various eBPF programs and features across different platforms for both native and Wasm-BPF implementations.

buffer polling operations in both Wasm and native environments. The results show that the Wasm abstraction introduces acceptable overhead compared to the native environment.

Benchmark	Wasm (avg ns)	Native (avg ns)
Map Access	1885.26	1117.43
Ring Buffer Polling	3186.83	1509.18

Table 2: Micro benchmark results for map access and ring buffer polling operations comparing Wasm and native environments.

5.2 Container Deployment

We measured the start-up latency using the bootstrap program, from the start of the container to the loading and attaching of eBPF programs. The results are presented in Table 3.

Wasm Lightweight Container	Docker	
0.176	0.656	

Table 3: Start-up latency for loading and attaching eBPF programs using the bootstrap program.

We also compared the binary sizes of Docker and Wasm eBPF programs, considering the size of the minimal image for container deployments. The results are shown in Table 4. The results indicate that Wasm-based programs are significantly smaller compared to docker, making them more suitable for lightweight container deployments.

5.3 Compatibility

To evaluate the compatibility of Wasm-BPF, we tested various eBPF programs across different platforms, including multiple Linux versions, Windows, and userspace eBPF environments. The platforms considered include Linux 5.5, Linux 6.10, Linux 6.10 on ARM64 architecture, Windows, and userspace eBPF.

Program	Docker Size	Wasm Size
bootstrap	1.3M	72K
execve	1.3M	37K
lsm	1.3M	46K
opensnoop	1.3M	64K
runqlat	1.3M	92K
sockfilter	1.3M	47K
sockops	1.3M	49K
uprobe	1.3M	45K
xdp	1.3M	44K
rust-bootstrap	5.0M	1.7M
tcpconnlat-libbpf-rs	5.1M	1.8M

Table 4: Binary sizes of native and Wasm eBPF programs.

The matrix in Table 1 provides a view of the support for each eBPF program in both native and Wasm-bpf environments. The symbols used in the table are "X" for native eBPF and "O" for Wasm-bpf, while "-" indicates that the platform is not applicable.

The compatibility results demonstrate that WASM-BPF can effectively run a wide range of eBPF programs across different platforms, ensuring binary-level compatibility.

6 RELATED WORK

WALI[25] extends the WebAssembly System Interface (WASI) by providing an interface for Wasm and the Linux kernel space to share resources. It supports various system calls, including execv and fork, along with auxiliary data. This extension enables a new class of virtualization where WebAssembly modules can interact with the host system more effectively. WebAssembly's control flow integrity guarantees provide an additional level of protection against remote code injection attacks for modules using WALI. Furthermore, capability-based APIs can be virtualized and implemented in

terms of WALI, enhancing reuse and robustness through better layering. Our work efficiently extends the eBPF program to the WASI layer for getting all the toolchain benefits.

7 CONCLUSION

This paper introduced Wasm-Bpf, a system leveraging WebAssembly (Wasm) and the WASI's standardized system interface to address the challenges of deploying eBPF programs across diverse environments. Wasm-Bpf ensures crossplatform compatibility, eliminates serialization overhead and introduces minimal overhead. It integrates seamlessly with container tools, simplifying the deployment and orchestration of eBPF programs within containerized ecosystems.

REFERENCES

- [1] W. author. Wasi: Webassembly system interface. GitHub repository, 2023. https://github.com/WebAssembly/WASI.
- [2] C. Authors. Cilium hubble: Network, service and security observability for kubernetes using ebpf, 2023. https://github.com/cilium/hubble.
- [3] T. Authors. Tetragon: ebpf-based security observability and runtime enforcement, 2023. https://tetragon.io/.
- [4] W. Authors. Webassembly specifications, 2024. https://webassembly.github.io/spec/.
- [5] bpfman. An ebpf manager for linux and kubernetes, 2024. https://github.com/bpfman/bpfman.
- [6] bpfman. The ebpf tool and systems inspection framework for kubernetes, containers and linux hosts, 2024. https://github.com/inspektorgadget/inspektor-gadget.
- [7] eBPF for Windows Contributors. ebpf for windows, 2023. https://github.com/microsoft/ebpf-for-windows.
- [8] genuinetools. The ebpf tool and systems inspection framework for kubernetes, containers and linux hosts., 2024. https://github.com/ genuinetools/bpfd.
- [9] A. Haas, A. Rossberg, D. L. Schuff, B. L. Titzer, M. Holman, D. Gohman, L. Wagner, A. Zakai, and J. Bastien. Bringing the web up to speed with webassembly. In Proceedings of the 38th ACM SIGPLAN Conference on Programming Language Design and Implementation, pages 185–200, 2017
- [10] Y. Hayakawa. Ebpf implementation for freebsd, 2024. https://papers.freebsd.org/2018/bsdcan/hayakawa-ebpf_implementation_for_freebsd/.
- [11] Y. He, R. Guo, Y. Xing, X. Che, K. Sun, Z. Liu, K. Xu, and Q. Li. Cross container attacks: The bewildered {eBPF} on clouds. In 32nd USENIX Security Symposium (USENIX Security 23), pages 5971–5988, 2023.
- $[12]\,$ N. R. Inc. Pixie labs homepage, 2023. https://px.dev/.
- [13] iovisor. Userspace ebpf vm, 2024. https://github.com/iovisor/ubpf.
- [14] M. Irwin. Introducing the docker+wasm technical preview, 2024. https://www.docker.com/blog/docker-wasm-technical-preview/.
- [15] L. kernel maintainers. Bpf type format (btf), 2024. https://docs.kernel. org/bpf/btf.html.
- [16] J. Long, H.-Y. Tai, S.-T. Hsieh, and M. J. Yuan. A lightweight design for serverless function as a service. IEEE Software, 38(1):75–80, 2020.
- [17] N. Mäkitalo, T. Mikkonen, C. Pautasso, V. Bankowski, P. Daubaris, R. Mikkola, and O. Beletski. Webassembly modules as lightweight containers for liquid iot applications. In *International Conference on Web Engineering*, pages 328–336. Springer, 2021.
- [18] microsoft. ebpf for windows, 2024. https://github.com/microsoft/ebpffor-windows.

- [19] nakryiko. Bpf co-re reference guide, 2024. https://nakryiko.com/posts/ bpf-core-reference-guide/.
- [20] opencontainers. Oci image format, 2024. https://github.com/ opencontainers/image-spec.
- [21] oras project. Oci registry client managing content like artifacts, images, packages, 2024. https://github.com/oras-project/oras.
- [22] W. org. Repository for design and specification of the component model, 2024. https://github.com/WebAssembly/component-model.
- [23] N. Pereira, A. Rowe, M. W. Farb, I. Liang, E. Lu, and E. Riebling. Arena: The augmented reality edge networking architecture. In 2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), pages 479–488. IEEE, 2021.
- [24] qmonnet. Rust virtual machine and jit compiler for ebpf programs, 2024. https://github.com/qmonnet/rbpf.
- [25] A. Ramesh, T. Huang, B. L. Titzer, and A. Rowe. Stop hiding the sharp knives: The webassembly linux interface. arXiv preprint arXiv:2312.03858. 2023.
- [26] B. Sharma and D. Nadig. ebpf-enhanced complete observability solution for cloud-native microservices.
- [27] J. Shen, H. Zhang, Y. Xiang, X. Shi, X. Li, Y. Shen, Z. Zhang, Y. Wu, X. Yin, J. Wang, et al. Network-centric distributed tracing with deep-flow: Troubleshooting your microservices in zero code. In *Proceedings of the ACM SIGCOMM 2023 Conference*, pages 420–437, 2023.
- [28] S. Shillaker and P. Pietzuch. Faasm: Lightweight isolation for efficient stateful serverless computing. In 2020 USENIX Annual Technical Conference (USENIX ATC 20), pages 419–433, 2020.
- [29] S. Shillaker, C. Segarra, E. Mappoura, M. Fournial, L. Vilanova, and P. Pietzuch. Faabric: Fine-grained distribution of scientific workloads in the cloud. arXiv preprint arXiv:2302.11358, 2023.
- [30] Y. Zheng, T. Yu, Y. Yang, Y. Hu, X. Lai, and A. Quinn. bpftime: userspace ebpf runtime for uprobe, syscall and kernel-user interactions. arXiv preprint arXiv:2311.07923, 2023.
- [31] Y. Zhong, H. Li, Y. J. Wu, I. Zarkadas, J. Tao, E. Mesterhazy, M. Makris, J. Yang, A. Tai, R. Stutsman, and A. Cidon. XRP: In-Kernel storage functions with eBPF. In 16th USENIX Symposium on Operating Systems Design and Implementation (OSDI 22), pages 375–393, Carlsbad, CA, July 2022. USENIX Association. ISBN 978-1-939133-28-1. URL https://www.usenix.org/conference/osdi22/presentation/zhong.
- [32] Y. Zhou, Z. Wang, S. Dharanipragada, and M. Yu. Electrode: Accelerating distributed protocols with {eBPF}. In 20th USENIX Symposium on Networked Systems Design and Implementation (NSDI 23), pages 1391–1407, 2023.
- [33] Y. Zhou, X. Xiang, M. Kiley, S. Dharanipragada, and M. Yu. {DINT}: Fast {In-Kernel} distributed transactions with {eBPF}. In 21st USENIX Symposium on Networked Systems Design and Implementation (NSDI 24), pages 401–417, 2024.