Stop Hiding The Sharp Knives: The WebAssembly Linux Interface

Arjun Ramesh¹, Tianshu Huang¹, Ben L. Titzer¹, and Anthony Rowe^{1, 2}

¹Carnegie Mellon University, ²Bosch Research

Abstract

WebAssembly is gaining popularity as a portable binary format targetable from many programming languages. With a well-specified low-level virtual instruction set, minimal memory footprint and many high-performance implementations, it has been successfully adopted for lightweight in-process memory sandboxing in many contexts. Despite these advantages, WebAssembly lacks many standard system interfaces, making it difficult to reuse existing applications.

This paper proposes WALI: The WebAssembly Linux Interface, a thin layer over Linux's userspace system calls, creating a new class of virtualization where WebAssembly seamlessly interacts with native processes and the underlying operating system. By virtualizing the lowest level of userspace, WALI offers application portability with little effort and reuses existing compiler backends. With WebAssembly's control flow integrity guarantees, these modules gain an additional level of protection against remote code injection attacks. Furthermore, capability-based APIs can themselves be virtualized and implemented in terms of WALI, improving reuse and robustness through better layering. We present an implementation of WALI in a modern WebAssembly engine and evaluate its performance on a number of applications which we can now compile with mostly trivial effort.

1 Introduction

WebAssembly (Wasm) [39] has emerged as a lightweight, efficient virtualization solution applicable to many domains. As a portable low-level bytecode format with a strict formal specification [11], type system with machine-checked proofs [86], and high-performance implementations [12] with ever-increasing levels of verification [24], Wasm provides an efficient sandboxed execution environment which can run untrusted code at near-native speeds. First deployed in the Web, Wasm provides an efficient polyglot¹ compilation target (com-

pared to JavaScript transpilation) which has enabled many applications ranging from high-performance libraries [2] to games [7, 8] and desktop productivity apps.

Following its success in browsers, Wasm has gained broad adoption in cloud and edge computing contexts as a lightweight virtualization solution [4, 62, 80]. To operate outside browsers in these contexts, Wasm requires a system interface: its core specification is intentionally designed to only cover computation, requiring sandboxed Wasm modules to explicitly import all state and operations relating to system interfaces. Presently, the WebAssembly System Interface (WASI) [20] provides this functionality in cloud computing. Governed by an open standards body operating under the WebAssembly Community Group, WASI is a secure, crossplatform (OS-agnostic) Wasm interface specification that provides both a system interface and a new capability-based security model - filesystem isolation is faciliated by pre-opened directories, network isolation by constrained sockets, and environment variables by explicit enumeration.

Recent years have seen growing interest in extending WebAssembly to modern cyber-physical deployments incorporating highly-capable mobile and internet-connected embedded devices such as IoT [51–53,61], automotive [30,70], and industrial systems [90]. Unlike the cloud, these domains have several uniquely challenging requirements. Software in these domains often demand high performance and memory efficiency, operate in safety-critical physical environments, and combine components distributed by many vendors in their preferred choice of languages. Applications are also often deployed across a wide gamut of system configurations for long deployment periods. Many critical software stacks in manufacturing and automotive systems are hence presently frozen in time on legacy hardware and software ecosystems that cannot be effectively updated.

Wasm is a compelling solution for these problems, inherently addressing efficiency, safety, and polyglot concerns. However, high portability across software platforms, long deployments, and critical legacy software are system interface concerns which Wasm explicitly does not address. Yet, no

¹Many languages can compile to Wasm, including C/C++, Rust, Java, and C#, with the goal of eventually supporting all common languages.



Figure 1: Virtualization stack with WALI as a foundation.

standard system interface for Wasm adequately addresses these challenges. In particular, WASI's goals are fundamentally *misaligned* with these challenges:

- (1) As a *new* portable API across many operating systems, it must be reimplemented many times;
- (2) Its design exploration and evolution make it unstable and therefore unsuitable for long deployments; and
- (3) Its divergence from longstanding standards like POSIX means it cannot run existing software.

Furthermore, despite many years of standardization efforts, WASI remains an extremely simplified OS interface which lacks support for common OS features like memory-mapping, process fork/exec, asynchronous I/O, and signals. Many applications require these features and simply cannot run on WASI. Given the many benefits of Wasm as an execution format, we believe the lack of an effective system interface is a key stumbling block to future use cases.

In this paper, we present the the WebAssembly Linux Interface (WALI) as a new virtualization solution for Linux applications that leverages WebAssembly. Our key insight is that native operating systems' userspace syscall interfaces² are a highly stable, de facto standard upon which thousands of desktop, server, and embedded applications have been and continue to be built. By creating a thin Wasm interface for an existing operating system, we can easily virtualize entire software stacks from the bottom-up with little modification and run them on a diverse set of host ISAs. We show how this is achievable on Linux by solving several tricky yet important architectural decisions in modeling signals, processes, threads, and memory management in order to to bridge the mismatch between Wasm and Linux's execution model.

In contrast to state-of-the-art system interface approaches [20, 21] for Wasm, WALI does not define an entirely new API surface against which applications need to be refactored or rewritten, but rather faithfully models the underlying operating system. Our bottom-up approach means that porting applications only requires recompilation with a Wasm-enabled toolchain; this can be done with comparatively trivial effort, as their standard libraries and ABIs already operate over the Linux syscall API. Furthermore, WALI is complementary to WASI: a complete Linux interface specification allows complex high-level APIs like WASI to be implemented as individually-sandboxed layers over the engine in terms of WALI (Fig. 1). This makes API implementations ISA-portable and shareable across any Wasm engine implementing WALI, reducing Wasm engine complexity and shrinking the trusted computing base.

WebAssembly for Cyber-physical Systems Modern cyberphysical systems are complex pieces of software deployed on highly-customized hardware platforms whose operation is driven by interactions with unpredictable physical environments. Virtualization for software stacks in these systems typically has the following requirements:

- (1) High engine portability: Applications in manufacturing equipment, appliances, or automotive systems are deployed across a wide array of systems and engines. A simple interface implementation must be easily able to port complex software stacks across many engines.
- (2) Long deployments: Many applications are deployed for decades without modification. Supporting such deployments requires a target with a stable set of features that is complete but not rapidly changing.
- (3) Critical legacy software stacks: Factory automation, automotive software, and infrastructure such as power plants have large actively-deployed legacy codebases that cannot easily be rewritten. Applications should be virtualizable "as-is", with simple update mechanisms allowing for incremental software improvements.
- (4) Efficiency: Efficient CPU/memory usage and package size is moreso critical in resource-constrained devices deployed in the wild. Highly reactive environments may also depend on quick application startup times.
- (5) Safety and Security: Since these applications and hardware are deployed in the safety-critical physical environments, safe execution and resource control are critical. Applications must be statically-typed, verifiable, and isolated from other colocated applications.
- (6) Polyglot: Applications should be easy to develop and port from a variety of programming languages. With embedded platforms now embracing modern languages like Rust and Python, they also rely on the vast software libraries currently available to these languages.

Given the stakes, security should be paramount for a new virtualization solution, especially in actively-deployed systems that need protection against remote code injection attacks. Existing solutions with bytecode virtual machines (e.g. Java and CLR) are typically considered for application-

²We liken syscalls to knives because they penetrate deeper system layers, yet come with risks.

specific virtualization because they also offer security and portability. However, application development for these technologies is restricted to specific families of languages, and non-deterministic features like garbage-collection make them unsuitable in embedded contexts. In contrast, Wasm offers a secure, efficient compilation target for a wide set of languages.

WebAssembly offers control-flow-integrity [15] (CFI) by design, a security property where buffer-overruns and other memory-safety vulnerabilities cannot affect the control flow of the program, ruling out remote-code-execution or return-oriented-programming attacks. Wasm executes as a stack-based virtual machine where modules cannot access external state unless explicitly specified through imports, and unlike native code, this execution stack is not aliased by memory.³ This safety feature is not inherently provided by native binaries used in containerization solutions like Docker.

Furthermore, real system deployments often include not just applications but dozens or even hundreds of system services (e.g. remote logins, authentication services, daemons) and libraries. CFI with Wasm prevents remote code injection attacks, protecting these services from their own bugs which could result in arbitrary code execution exploits. For example, using WALI to sandbox system daemons⁴ would have avoided a recent OpenSSH exploit [14].

The Need for a Complete Wasm OS Interface Wasm as a virtualization solution for cyber-physical systems is clearly promising, but high portability, long deployments, and legacy software support can only be addressed with the right system interface compatible with these goals. Unlike in the Web, where Wasm programs can access JavaScript APIs, Wasm programs running in the cloud or edge require standard host interfaces. Current standardization efforts include:

- WASI [20]: a W3C standardization effort with the goal of making a completely portable interface in the form of Wasm APIs with a strict capability security model, fine-grained access controls, and simplified filesystem and socket virtualization.
- WASIX [21]: a rogue superset of WASI, proposed by the Wasmer [9] team that adds missing POSIX functionality to jumpstart WASI development.

Both WASI and WASIX seek to enable application portability across any operating system – particularly in the cloud – with a refined capability-based security model. Design difficulties hence arise in maintaining legacy application compatibility due to the mismatch of POSIX, other Linux concepts, and the new security model: features like signals, for example, have been abandoned altogether in the WASI Preview 2 release. Instead of facing the difficult problem of defining a new portable interface over many operating systems, we focus on the already stable but much lower-level Linux system call (syscall) interface. While this comes at the cost of portability to non-Linux platforms⁵, our approach has the benefit of perfectly aligning with Linux applications.

WALI adopts a layering approach to API design, serving the role of a thin OS translation layer unlike WASI(X), which has complex interactions and state with concomitant engine implementation requirements. While currently a small system interface, WASI implementations are large⁶ and often internally riddled with bugs [42]. This is likely to worsen with proposal standardization for complex features (e.g. machine learning, HTTP, key-value stores, etc), as every engine must internally implement these features. With just 2000 lines of code, our WALI implementation offers a nearly complete set of OS features to WebAssembly for running complex legacy applications, with a large enough subset to even implement WASI over it (Sec. 4). This approach allows engines to offer just one stable syscall interface – achieving stability via feature completeness - while supporting a plethora of high-level APIs as layers above.

Contributions WALI serves as a thin virtualization layer, providing ISA-portability and robustness to user-space Linux software stacks. We make the following contributions:

- We propose a ISA-agnostic virtualization platform at the OS syscall level for Linux leveraging WebAssembly;
- (2) We explore the design space of process and threading models for WALI, and develop a robust implementation of WALI on a modern WebAssembly engine;
- (3) We evaluate our WALI implementation on several realworld applications, and compile libuvwasi, a popular implementation of WASI, unmodified over WALI;

WALI is fully open source and available at https://github. com/arjunr2/WALI.

2 Scoping the existing Linux System Calls

Linux features a daunting set of hundreds of system calls, numbered differently across architectures, some of which are platform-specific. While reimplementing all of these calls across all platforms seems like a gargantuan task, we conducted a study of real-world applications, and find that syscalls have enough commonality in *actual use* that a WALI implementation can easily cover the vast majority of Linux functionality in a lightweight, portable way.

How prevalent are syscalls in real applications? We first evaluated the feasibility of system-call based virtualization to scope our work on WALI by studying the number and frequency of Linux syscalls across a variety of applications.

³The stack is not only not-executable, but not even addressable. Instead, for address-taken stack-allocated data, toolchains maintain a *shadow stack* and a *shadow stack pointer* as a hidden global variable in Wasm modules.

⁴We compiled the entire *OpenSSH* suite without modification and ran it WALI, which is beyond the capability of existing WASI efforts.

⁵While WALI binaries can run in Windows in WSL, we envision that important and widely deployed kernels would also have their own standard Wasm interfaces, such as Windows, BSD, Darwin, and QNX.

⁶libuvwasi [5] is over 6,000 lines of code in the engine, not including *libuv* itself which is several thousand more.



Figure 2: Log normalized syscall profile sorted by Aggregate frequency; the top row shows the distribution of syscalls across all benchmarks sorted by frequency, and the rows below show the syscall frequency for various applications using the same ordering.

While there are clear differences between applications, most programs use fewer than 100 of the 300-400 kernel syscalls available in Linux (Fig. 2). Thus a first implementation of WALI only needs to support a fraction of the total system call interface to run most applications.

How diverse are the syscalls available on Linux's many supported architectures? Due to a long history of porting efforts and the demands of dozens of (sometimes very unconventional) architectures, Linux supports approximately 500 [43] syscalls in the main kernel source tree. However, not all syscalls are available on all architectures: in fact, several dozen are only supported on one architecture each, either as vestiges of specific porting and emulation efforts (OSF and S390) or to serve a specific hardware feature or quirk. We found that there is a large common core on all architectures; both Arm and RISC-V are nearly identical and largely a subset of x86-64 with a handful of differences (Fig. 3).

3 WALI Design

WALI specifies a system interface as a set of WebAssembly host functions that can be imported into a Wasm module using the standard import mechanism. As host functions, WALI implementations do not require a custom-built Wasm runtime system, but can in principle be built as an extension to any existing runtime system.

WALI comprises three major components: syscalls, command-line and environment parameters, and language-specific support. WALI syscalls correspond nearly 1-to-1 with native Linux syscalls, and must translate data between the virtualized syscall interface and the native Linux syscall interface and vice versa. Most syscalls can surprisingly be supported solely as simple "pass-through" operations with conversion between memory addresses in Linux and WebAssembly memory space, incurring low overhead. WALI seamlessly supports passing command-line and environment parameters from the host to Wasm, commonly used in Linux applica-



Figure 3: Similarity of Linux Syscall Interface across architectures.

tions. Language-specific support mostly includes startup features, but may involve special hardware register accesses for signal handling, execution stack access, or non-local gotos (setjmp/longjmp).

Considering all these components, WALI must make fundamental important design decisions to bridge the Linux and WebAssembly execution environments — primarily for the process/thread model, memory management model, signal handling, security model, and cross-platform support.

3.1 Process and Thread Model

Most operating systems support concurrency using a process and thread model. However, as a virtual ISA, WebAssembly provides no notion of such a process/thread model. This requires WALI to provide a process/thread model that faithfully represents the behavior of native Linux processes in order to seamlessly interact with each other and with native processes.

In Linux, user-space threads are implemented as lightweight processes (LWPs), which, unlike regular processes, can share many kernel resources with their parent process such as the same virtual address space, filesystem information, and signal handlers. Conventional Linux processes commonly interact with each other using pipes, shared memory, or signals, while threads often share a common memory space and communicate using synchronized memory operations. Many syscalls additionally use *process ids* (PIDs) to target processes for calls that involve signals, usage statistics, scheduling characteristics, and status updates.

To replicate this behavior, we explore three models along the spectrum of possible WALI implementations (Fig. 4):

I-to-1 model Each WALI process is assigned a unique native Linux process with its own PID. A key advantage of this model is the ease of implementation and verification: most process-oriented or thread-oriented WALI syscalls, including fork, can be implemented as pass-through syscalls directly to the kernel. While this design also relieves the engine from maintaining any WALI native process/thread state, the engine is limited by the Linux kernel for any optimizations in performance or inter-process communication. For our WALI implementation, we adopt this simplistic design solution.

N-to-1 model The *N-to-1* model runs multiple WALI processes as *LWPs* within a single Linux process. *Threadbased* LWPs require virtualization of all unshared native process state, significantly increasing implementation com-



Figure 4: Process Model Spectrum for varying configurations of Native and Wasm processes; WALI must implement the **bolded** components.

plexity. Luckily, clone supports a precise specification for fine-grained resource sharing with the child process, allowing WALI implementations to optimize tradeoffs on the spectrum between conventional "processes" and "threads", e.g.:

- Setting CLONE_VM allows the child LWPs to share the parent's virtual address space, enabling potential memory usage optimizations.
- Disabling CLONE_THREAD makes interactions with virtual LWPs identical to conventional processes: they obtain a unique thread-group ID (TGID) and possess their own scheduling properties.

Co-locating multiple WALI processes in one native processes also allows sharing filesystem information and signals, allowing fast inter-process communication without syscalls which may even outperform native Linux IPC.

"Threadless" model Mode switch overheads for kernel calls are becoming more significant with recent exponential improvements in CPU and memory performance [93]. Since Wasm instances are sandboxed, further reduction in overhead could be achieved by avoiding an LWP-backed process model altogether in favor of a hyper-optimized process model that runs Ring-0 delegated tasks in user-space [88]. We envision a *threadless* model that supports context switches as fast interinstance function calls within the Wasm engine in user-space, eliminating mode switch overheads altogether. TGID-based process identification can be emulated using a *dummy* native process that forwards any process-based interaction to the WALI engine, or by adding basic kernel support for providing raw TGID identifiers.

3.2 Memory Model

Wasm module memory is a 32-bit byte-addressable, boundschecked linear address-space instantiated as subset of the host process's memory space. This memory model inconsistency necessitates design choices to support syscalls that operate on data in memory or assist in memory management techniques. Module memory declarations statically specify an initial and maximum number of (64KiB) pages that are shareable by multiple parallel computations (i.e, *threads* on WASI and WALI). At runtime, Wasm programs perform loads and stores with explicit instructions with a static *offset* and dynamic index that together determine a 33-bit index into memory. With WALI, we address transparently supporting all memory-oriented syscall operations with the following techniques:

Address-Space Translation For many native Linux syscalls that accept arguments representing pointers to regions in the process's memory, WebAssembly memory "pointers" cannot be directly forwarded to native syscalls as pointer types. For such WALI syscalls, the engine must perform an *address-space translation* of memory references between Wasm and native process memory. This fast linear translation – with just simple bounds checks for enforcing safety – allows most WALI syscalls to be performed as *zero-copy*, enabling high-performance I/O.

Layout Conversion While syscalls that accept pointers to untyped memory regions require only simple address-space translation, some native Linux syscalls accept pointers to complex structured-typed arguments. The expected byte-level layout and size of structs for native syscalls may vary across architectures, making it impossible for WebAssembly to provide these as platform-independent zero-copy syscalls. In such situations, WALI must explicitly perform Wasm-tonative struct copies for input arguments and native-to-Wasm copies for output arguments. Few syscalls (<10%) use such arguments and their sizes are usually small and fixed, imposing minimal overhead.

Memory Management WALI allows nearly all use cases of mmap, mremap, and munmap, including mapping files and other resources with unconstrained address ranges. Our implementation automatically grows Wasm memory for new mappings, up to the memory declaration's self-imposed limit, failing if the size grows beyond the maximum⁷. Subsequent unmapping with munmap is performed as a direct passthrough native syscall with normal bounds-checking. Deprecated syscalls

⁷We utilize the MAP_FIXED/MREMAP_FIXED flag to native mmap/mremap syscall to map pages at specific addresses in Wasm memory.

like brk are ignored (no-op) in WALI since enlargement of the Wasm memory instance is implicitly performed by mmap.

Languages built over Wasm allocate source-level data structures with language-specific mechanisms compiled into the Wasm code, including the implementation of malloc for C/C++, or region-based allocation and garbage collection for other languages. Before WALI, malloc libraries usually required modification to run on Wasm, e.g. to grow the Wasm memory using the built-in memory.grow instruction rather than the common approach of using mmap, munmap, and mremap syscalls when running natively. With WALI, existing malloc implementations with more sophisticated mapping strategies work without any modification whatsoever.

While memory mapping comes with minimal overhead in WALI with native calls, the engine must manage state to allocate mapped and free segments. Our implementation prototype allows mapping a region at most once in the engine, tracking only the base address of the allocation pool. In the long run, WALI engines may need to avoid fragmentation with a more sophisticated strategy rather than our simple strategy. These sophisticated strategies may even be implemented as Wasm modules that use memory.grow and WALI's memorymapping primitives to reduce engine complexity.

3.3 Signal Model

Both synchronous and asynchronous signal handling are critical features used by many common Linux libraries and applications. Synchronous signals are generated and delivered immediately to processes in reaction to most hardware faults, e.g. memory access faults, illegal instructions, bus errors, or arithmetic exceptions. These are easy to catch and often overridden with *traps* in the Wasm engine for safe exception handling (e.g. SIGFPE for integer division-by-zero).

Asynchronous signals are more challenging: they may be generated and delivered at any point in a process's lifespan, even while the target process is suspended, and are frequently used in applications for software interrupts, job control, termination, or asynchronous I/O. WebAssembly, at the time of writing, has no standardized instructions for asynchronous callback operations. As a result, the WALI engine must provide explicit support for delivering asynchronous native signals within the current synchronous WebAssembly execution model. This requires a selection of specific code locations to execute signal handlers.

Asynchronous Signal Handling WALI engines must be capable of performing asynchronous signal delivery, masking, and execution of application Wasm functions that handle signals, similar to that of native processes. This must even include typical synchronous signals sent asynchronously to processes using the kill syscall. To fully support asynchronous signal handling, the Wasm engine must be capable of allowing a host function to safely call back into the same Wasm module from which it was invoked. WALI implementations leverage



Figure 5: WALI Asynchronous Signal Handling Sequence Diagram

this capability to effectively virtualize the main stages in a Linux signal's lifecycle: signal registration, generation, delivery, and handler execution (Fig. 5).

(1) Signal Registration: Wasm modules must be able to configure callback functions with a rt_sigaction equivalent syscall, just like native processes, for asynchronous signal handling. To support this, the WALI engine internally maintains a virtual *sigtable* of registered signals, mapping every Linux signal to a target callback function in the Wasm module. When Wasm modules invoke their virtual wali_rt_sigaction syscall, two things occurs:

- The Wasm function pointer (index into a Wasm table) is dereferenced and registered in the *sigtable*; and
- The native rt_sigaction is called within the engine to register a *native handler* for the signal that performs virtual signal generation

The Wasm function pointer is also saved in the *sigtable* to return back the old action (*old_wint_hdl* in figure) to the module for future invocations of wali_rt_sigaction.

(2) Generation: The engine stores a bit-vector and a queue of pending signals per WALI process to serve as the virtual signal generation mechanism. Since we use rt_sigaction, native signal generation is performed by the underlying kernel which WALI, as a user-space interface, uses to set the signal's bit-vector element and add it to the pending queue.

(3) **Delivery:** Generated signals remain pending and are delivered shortly after to the native process. However, signals may be blocked using a *signal mask* (with the rt_sigprocmask syscall) to prevent delivery until explicitly unblocked. WALI

supports virtual signal blocking by maintaining a signal mask per WALI process. Luckily, since signal masks are stored independently for each *thread* and initial masks are inherited from the parent thread, for any process and thread-model that uses the underlying clone syscall, WALI can use the Linux process's signal mask as is. Delivered signals are then picked up during execution by any WALI thread in the thread group as a result of native Linux's process model.

(4) Handler Execution: Finally, the WALI engine must react to any delivered signals and trigger the execution of the registered virtual signal handler in Wasm. Since asynchronous signals do not directly impede execution in a process, WALI engines can choose to delay the signal delivery and handling to a later time if required. However, arbitrary invocations of signal handlers during critical sections in the engine that modify module instance state (memory, tables, globals), execution environment state during call/return instructions, or internal WALI state can break consistency guarantees of the WebAssembly execution model. Therefore, WALI implementations must deliver signals at *safepoints* (*sigcheck* in figure) such that this state consistency is preserved.

WebAssembly instruction boundaries are a natural location for safepoints, but frequent polling for signals hurts performance. Given fast reactivity is typically not a primary concern, our implementation only inserts safepoints (polls for asynchronous signals) at loop headers.

Basic signal delivery guarantees in Linux must also be maintained within the WALI implementation. For example, if a call to rt_sigprocmask blocks a pending virtual signal, virtual signal delivery must not take place until the same is unblocked. This can be avoided by inserting an additional safepoint immediately after invoking the native rt_sigprocmask call within the engine, adding negligible overhead compared to the actual overhead of the syscall but handling any outstanding generated signals before entering the Wasm critical section. Additionally, when SA_NODEFER flag is unset and handlers receive the same signal, the engine must not service the delivered signal until the current handler execution completes. A stack containing nested signal state can be used to easily identify any matching deferred handlers.

Special handlers like SIG_IGN, SIG_DFL, and SIG_ERR require internal engine implementations. The engine may allow these to bypass virtual signal handling entirely as passthrough calls to the kernel with special trap handlers to provide safe handling and debug information. Currently, registered signal callbacks through WALI only support the strictlytyped single argument signature in favor of portability and simplicity. The three argument signature includes additional context information regarding the stack, program counter, and machine-dependent registers. This information is inherently system-dependent with very limited use-cases.

3.4 External Parameters

The WALI specification includes methods for supporting application-external host parameters like command-line arguments and environment variables within the sandbox.

Command-line Arguments WALI transparently supports transfer of command-line arguments from the host to the application. To minimize state and increase safety in the engine, WALI delegates the ownership of these variables to the standard library Wasm code. On startup, the standard library allocates an appropriately sized argument vector using two API methods – get_argc and get_argv_len. Safe copying of each argument into the WALI process is performed post-allocation using a copy_argv method. As a result, any security vulnerabilities exposed through buffer overflows during parsing remain entirely contained within the sandbox.

Environment Variables Initialization of environment variables works similarly to command-line arguments in WALI, where values are not inherited from the parent shell for security reasons but rather explicitly specified when invoking the engine. However, a subtle edge-case arises when executing programs internally invoke execve (a common occurrence for fork-exec), which must pass virtual environment variables to the child WALI process as opposed to the host engine. One potential solution for engines that initialize WALI environment variables through a command line argument is to append the current virtual environment to the argv when invoking a WALI binary. An alternative elegant engine-agnostic technique we adopt is to use a shared-memory segment identifiable by the WALI process ID to store the virtual environment state before invoking the host execve call. The WALI process startup sequence picks up this shared-memory segment and uses it to initialize its initial virtual environment.

3.5 Cross-Platform Support

Architecture-agnostic packaging of Wasm binaries has been a major thrust for adopting WebAssembly in many contexts, and hence is of prime importance for WALI. Syscalls, however, are inherently non-portable and vary across architectures in both their syscall numbers and their functionality. For example, x86 still supports redundant syscalls stat and lstat to maintain backwards compatibility, which are not present in newer architectures like RISC-V where fstatat is a superset of same. WALI addresses these challenges with the following techniques:

Name-bound syscalls Since portability requires a clear distinction between the functionality of a syscall and its syscall number on the platform it is running on, WALI uses *namebound syscalls* with statically defined type-signatures. These *virtual syscalls*, consisting of a union of all syscalls across all supported architectures, serve as the single, complete WALI syscall specification. Luckily, Linux syscalls show high com-



Figure 6: Minimal WALI implementation virtualizes the WASI API.

monality between platforms (Sec. 2), simplifying host implementation efforts. The standard library contains the definitions for these virtual syscall numbers, and uses their mapping to name-bound syscalls to also support invocation by syscall number. WALI implementations in the host are thus only responsible for faithfully attempting to execute a call, trapping if it cannot do so.

Architecture-Specific Kernel Interfaces Syscall arguments like struct kstat and file status flags, used by all statrelated syscalls and file control syscalls respectively, have different byte-level representations across architectures. In such scenarios, the host engine is responsible for translation to-and-from architecture-specific representations and WALIspecific representations to maintain execution consistency. Pointers to thread-local state, which are typically stored in native hardware registers and updated during a context switch, uses a Wasm global in WALI to address TLS data, similar in approach to WASI threads. Native page sizes also differ across platforms, but the 64KiB WebAssembly page size was conveniently chosen as a least-common multiple of popular platforms today, allowing native mmap calls to perform memory allocation with their own host page granularities.

3.6 Security Model

While all APIs for Wasm today place security at the forefront of their design specification, this limits their ability to port a large range of existing applications. WALI adopts a different design philosophy to security enforcement – intended to be purely descriptive of the underlying system, i.e. Linux, it aims to be as thin as possible with only absolutely essential security enforcement, allowing security policies to be implemented in higher layers of the stack. WALI applications run with the privilege of the user that invokes the engine with complete access to relevant resources, allowing full control for layers above as a virtualization platform. **Minimal TCB** Unlike WASI, WALI does not prescribe capability-based security for filesystem and sockets. Instead, the relaxed security model of WALI allows existing APIs (e.g. WASI) to be implemented over it (Fig. 6). In addition to decoupling feature completeness from the security model and pushing API implementations outside the trusted computing base (TCB) of the engine, WALI-based API implementations are portable across any engine that supports WALI. By using multiple isolated memories [13], security models can also be designated their own privileged memory by the compiler toolchain to prevent memory corruption from the application. Finally, introducing such relaxations offers low-level system applications in WALI flexibility in choosing a security model⁸ when standards like WASI are infeasible.

Seccomp Policies Security-oriented virtualization technologies (e.g. Nabla containers) typically use seccomp policies to restrict applications syscall access capabilities. In WALI, virtual syscalls enable seccomp-like policies to completely be implemented in user-space, increasing the granularity of control these security policies can enforce. This makes existing implementations in syscall-based security policies like Draco [72] complimentary to our work.

In the long run, this may also pave the way for the development of specialized environments like simple, verifiable runtimes that support a constrained set of WALI's features. With name-bound syscalls, WALI binaries also provide guarantees about all syscalls it may invoke, which can be statically analyzed for potential vulnerabilities and ease efforts to generate certified binaries.

Restrictions While WALI covers a large breadth of features to support porting existing software, it does impose some restrictions on capabilities that can be virtualized inherent in maintaining soundness of the WebAssembly execution model. Non-local gotos using long imp are not supported since they violate basic CFI design properties of Wasm. The common use case for this feature is exception handling, which will eventually be supported through the exception handling language proposal [3]. Native processor state (ucontext, mcontext) and direct hardware access are also disallowed through WALI in favor of portability and security. While the above restrictions are engine-agnostic, certain engine implementations themselves may introduce limitations: Wasm engines may internally use signal handlers for handling synchronous signals like SIGSEGV and SIGFPE. As a result, while WALI provides maximum flexibility, engines should consider limiting programs from overriding these internal signals.

⁸The raw WALI API still provides fundamental WebAssembly safety guarantees of in-memory sandboxing, CFI, and RCE safety. WALI is thus viable for both minimal security use-cases *and* safely layering high-level security models over it.

Codebase	Description	Source Code Changes					
bash	Shell/Interpreter	Fix function pointer type- checking violations					
lua	Interpreter	-					
memcached	System Daemon	-					
openssh	System Services	-					
sqlite	Database	-					
paho-mqtt	MQTT App						
make	CLI Tool	-					
vim	CLI Tool	-					
libuvwasi	WASI Lib	-					
zlib	Compression Lib	-					
libevent	System Lib	-					
libncurses	System Lib	-					

Table 1: Porting effort of WALI toolchain for some popular builds

4 Evaluation

We evaluated WALI by compiling and executing several realworld applications, build systems, and libraries. We find that this enables Wasm binaries to effortlessly plug into existing ecosystems with both minimal code changes and minimal API-instrinsic overhead, demonstrating its potential in pushing Wasm to new domains like cyber-physical systems.

Implementation Choices We evaluate WALI with a reference implementation in the WebAssembly Micro Runtime (WAMR) [12], which we chose because it supports many architectures, has extensive functionality, and has a high-performance AOT compiler in addition to an interpreter. For simplicity and completeness, we implement the *1-to-1* process model and insert safepoints for signal polling only at loop headers to reduce overhead. Our WALI implementation in WAMR successfully runs on x86-64, aarch64, and riscv-64; all evaluations on WALI are collected using this fully-featured runtime on AoT compiled code.

Coverage Using our diagnostic analysis (Fig. 2), we implemented the 137 most common syscalls that cover a wide range of applications compiled against WALI to date. The WALI implementation is ≈ 2000 lines of C code, with < 100 lines of code of architecture-specific code per platform. We created a lightly modified version of *musl-libc* [6] to serve as the WALI C standard library with these notable features:

- All syscalls used are bound by name.
- We provide Wasm support for threads/TLS.
- We use portable versions of architecture-specific structures and flags (kstat, file-creation flags, ksigaction)
- We omit the dynamic-linking library, which is not currently supported by the WebAssembly ecosystem.

Porting Effort We collected a suite of common Linux applications, ranging across various domains, that compile using a custom WALI clang target with minimal changes to the existing WASI target (Table 1). Most required changes are a result of strict type-checking enforcement for Wasm indirect calls unlike that of the C standard.



Figure 7: Runtime breakdown of WALI across system stack.

Surprisingly, our WALI-enabled LLVM toolchain seamlessly integrates into complex build systems. WALI binaries registered on Linux systems as a miscellaneous binary format can allow transparent execution of Wasm binaries, allowing many build scripts to be used directly without modification. Amusingly, the *bash* build generates and executes intermediate binaries to determine features like pipe size capacity, which run transparently without modification with WALI⁹. Our toolchain was also used to build the *libuvwasi* implementation and most of the currently supported user-space syscall tests in Linux Test Project [1] that compile with LLVM as well as their corresponding test harnesses which uses complex signalling and shared memory for job control.

4.1 Intrinsics Costs

The performance of a WALI implementation is highly dependent on the underlying Wasm engine, which can vary drastically in performance based on its execution tiers [79]. Our prototype implementation on WAMR can help shed light on the *intrinsic cost* of using WALI that does not scale proportionally with improvements in Wasm runtimes. Experiments were run on a 11th Gen Intel Core i7-1185G7 machine (x86-64) which we intentionally underclocked to 1.2 GHz to reduce performance variance. Since architecture-specific code re-routes mostly undefined syscalls and occasionally swaps a few flags, the intrinsic cost measured here are fairly consistent across architectures on macrobenchmarks.

Syscall Interface Most WALI syscalls require under 10 lines of code to implement – mostly performing basic addressspace translation¹⁰ – and have an absolute overhead vs native syscalls in the order of a *few hundred nanoseconds* (Table 2). To put these overheads in a practical context, less than 1% of the execution time is spent in the WALI interface in most cases, which is negligible compared to the inherent overheads of the Wasm app or kernel time (Fig. 7).

The clone syscall for spawning threads is a glaring outlier, which adds about $500\mu s$ of overhead. This is not an API-intrinsic cost of WALI, but rather that of the internal implementation of the thread manager in the WAMR runtime,

⁹When bringing up bash on WALI, we almost didn't notice that WALI binaries were running as part of its build!

¹⁰Calls like rt_sigaction and mmap typically need extra instructions to manage internal state for signal handling and memory allocation respectively, incurring a higher cost. These calls are the exception, not the norm.

Syscall	Overhead	LOC	State	Syscall	Overhead	LOC	State	Syscall	Overhead	LOC	State
read	167 ns	4	Ν	stat	112 ns	8	N	geteuid	123 ns	1	Ν
write	151 ns	5	Ν	futex	141 ns	6	N	poll	128 ns	12	Ν
mmap	512 ns	30	Y	rt_sigprocmask	114 ns	5	N	getrusage	151 ns	5	Ν
open	156 ns	4	Ν	getpid	168 ns	1	Ν	getegid	164 ns	1	Ν
close	187 ns	3	Ν	writev	387 ns	10	N	getgid	165 ns	1	Ν
fstat	171 ns	4	Ν	munmap	246 ns	12	Y	lstat	142 ns	6	Ν
mprotect	120 ns	4	Ν	fcntl	160 ns	10	N	ioctl	127 ns	4	Ν
pread64	671 ns	4	Ν	access	202 ns	8	Ν	clone	554873 ns	100 +	Y
lseek	178 ns	3	Ν	recvfrom	116 ns	8	Ν	prlimit64	139 ns	5	Ν
rt_sigaction	711 ns	40	Y	getuid	151 ns	1	Ν	fork	345 ns	1	Ν

Table 2: WALI implementation statistics for top-30 common syscalls identified from Fig 2, indicating the overhead, implementation size (LOC — Lines of Code), and whether the syscall is stateful.

Арр	Loop (%)	Function (%)	All (%)
bash	7.1	10.0	187.0
lua	4.1	2.8	100.3
sqlite3	11.3	5.2	164.2
paho-bench	0.5	1.1	17.8

Table 3: Cost of polling for asynchronous signal handling with different safe-point insertion schemes – **Loop**: after loop bytecode, **Func**: start of every function, **All**: after every instruction

which performs a large amount of memory allocation and creates a new copy of the Wasm module's execution environment. This cost can be made cheaper through various runtime optimizations – for example, the Wasmtime [10] engine has optimized instance creation heavily through lazy loading and copy-on-write paging optimizations, which WALI can leverage for clone, resulting in overheads as low as at $5\mu s$. In our experience however, spawning threads is relatively infrequent and mostly occurs during the initialization stages of an application, which we believe does not critically affect our overhead in our intended use cases.

Asynchronous Signal Polling The number of executed safepoints plays a critical role in execution overhead¹¹. As expected, we find that polling after every instruction is at least an order of magnitude slower than polling at loops or functions (Table 3). The latter two are comparable in performance, typically incurring under 10% slowdown over WALI without signal polling. Both are also reasonable choices in practice, as the function scheme may favor compiler optimizations better while the loop scheme may enable more reactive signal handling while executing large, monolithic functions.

4.2 Extrinsic Costs: Virtualization Overhead

We compare our WALI implementation against Docker [59] and QEMU [23], the two most popular container and emulator technologies respectively, and evaluate their effect characteristics on popular Linux applications – *bash*, *lua*, and *sqlite*. **WebAssembly Runtime Overhead** For CPU-bound applications, the overhead of WALI versus native applications is dominated by the Wasm engine. A plethora of works have studied both execution and memory overheads of Wasm [73,84,85], including potential optimization techniques for startup [74] and bounds-checking [77]. The efficiency of Wasm programs is a complex subject and orthogonal to this work, since it is fundamentally a compiler problem that boils down to the ability of the Wasm engine to produce good native code. To provide a baseline, recent analysis of Wasm runtime performance [31] shows a median slowdown (on performancefocused Wasm engines) of 2.32 times over native execution.

Memory While peak memory utilization scales similarly for all virtualization solutions, base memory utilization can vary drastically (8a). Unlike WALI, which only virtualizes the target application, Docker containers incur a high base overhead (\approx 30 MB) to support intermediate layers for storage drivers and isolated software libraries. On the other hand, QEMU maintains a low overhead using a number of optimizations – lazy allocation, balloon drivers, and KVM virtualization – leading to comparable results to WALI for small applications.

Execution Time Fig. 8b-8d compares the composite execution time of WALI, Docker, and QEMU. As expected of emulators, QEMU is an order of magnitude slower than Docker, which executes at near-native speed directly on the CPU. While our WALI implementation is 2x slower than Docker on average, the startup time is only several milliseconds as opposed to nearly half a second for containers, which requires instantiation of internal layers and namespace isolation.

We observe a *cross-over point* for each application based on start-up time and relative overheads, before which WALI is faster than Docker. Applications with short-lived execution or those like *Lua*, which executes up to 60% slower than native in Docker due to frequent memory allocation requests, are hence good candidates for execution in WALI.

Summary WALI strikes a middle ground between memory and execution overhead between emulation and container technologies with very low startup time. Additionally, features like a non-addressible execution stack and CFI provide additional security benefits over container technologies like

¹¹Note that safepoint overheads are mostly negligible for applications like the paho-bench that spend the majority of time suspended.



Figure 8: Peak memory (8a) and execution time (including startup time) (8b-8d) comparison for Lua, Bash, and Sqlite benchmarks showing each virtualization method's efficiency versus its native counterpart; all three benchmarks are combined into a single plot for peak memory.

Docker. Finally, as Wasm engines evolve, we envision that the performance gap between Wasm and native execution will be bridged, increasing WALI reach as a feasible virtualization technique even for compute-intensive workloads.

5 Discussion and Future Outlook

WALI can potentially unlock a number of fruitful future directions, particularly in software layers above it. Legacy software that uses layers above the system call interface, e.g. the standard C library libc, can now completely run sandboxed on WebAssembly with little to no modification. This capability now opens up opportunities such as:

Accelerating WASI development and adoption The design and implementation of new APIs for WASI are bottle-necked on their implementation. Prior to WALI, WASI capabilities were *necessarily* part of the engine implementation, since it alone contained sufficient privileges to access OS primitives. WALI now decouples WASI development from engine development; a new version, API, bugfix, or extension of WASI could be deployed as a layer over any WALI-supported engine. This greatly accelerates the evolution and adoption of WASI on new platforms.

Robustness by modularizing the Wasm runtime system Though simpler than heavily-optimized virtual machines for JavaScript and Java, Wasm engines are still complex pieces of software with many moving parts. The V8 JavaScript/Wasm engine is over 900,000 lines of code and includes multiple JIT compilers, garbage collection, a complex dynamic object model, and a flexible embedding API. Typical WASI implementations themselves contain many thousands of lines of code. Vulnerabilities in *any* of this code could compromise the memory safety of the entire process. In contrast, WALI's *thin* syscall interface layer pushes more responsibility outside the trusted runtime system, reducing engine implementation complexity, increasing API stability, and sandboxing higher level APIs above the engine.

Portable packaging and distribution of Linux binaries Linux distributions offer pre-compiled packages containing native binaries. These ready-to-run binary packages are compact, more stable, and negate the need for complex build environments and toolchains for various source languages. While such binaries lack portability across CPU architectures, techniques such as fat binaries and multi-arch Docker images have attempted to bring portability to pre-built binaries. Notably, WALI executables, as showcased in this work, are inherently portable across CPU architectures. This raises the exciting prospect that Linux packaging technology could ultimately achieve full ISA portability with WebAssembly.

The dream of verifying the whole tower Software verification has made great strides, as fully-verified kernels [47], compilers [50], and libraries [94] are now penetrating mainstream technology. Efforts in software verification of native binaries are underway [37], underpinned by work on formally specifying instruction sets [18,69] using formal semantics; the semantics of system calls are also a subject of research [78]. As Wasm has well-specified semantics and with engines undergoing verification research, it may be possible in the near future to combine machine-checked proofs of Wasm module properties [68] with verified compilers, runtime systems and kernels to achieve the holy grail of verification: a tower of proofs that certify a program and its entire software stack.

Letting languages use the sharp knives too! Wasm modules can only do what their imported APIs allow. This is a double-edged sword: it provides for excellent sandboxing, but constantly limits Wasm applications by their system APIs. With many programming languages now targeting Wasm, will they always be at the mercy of what Web APIs and WASI allow? We maintain that since Wasm is an abstraction over hardware, programming languages should be able to make full use of the platform they target, including using the sharp knives of low-level system calls. It's up to layers higher in the stack to define abstractions and libraries that make the low-level interface usable, more convenient, and safer.

Attenuating, auditing, and interposing on WALI calls Like any Wasm API, WALI calls can be interposed on by libraries that log, restrict, profile, or fault-inject. Unlike native Linux syscalls which are specified by a runtime syscall number, WALI calls are bound by name, allowing both static and dynamic policies in the future. Restricted subsets can be specified, allowing some platforms to offer a limited interface for simplicity or security. Many tools aimed at enhancing security at the syscall layer, e.g. seccomp [28] and Draco [72], are hence complementary to this work.

6 Related Work

We organize our discussion of virtualization technologies into four broad areas: (1) Emulators, (2) Hypervisors, (3) OS interface virtualization, and (4) Language virtualization.

Emulators ISA emulators provide a mechanism for virtualizing an entire system stack including hardware, operating system, and application. Popular solutions like QEMU [23] and Bochs [48] have sparked further research into emulator performance optimizations [40] for niche use-cases [87], which is currently an obstacle to widespread adoption. These are mostly used as prototyping tools, unless KVM [46] is used when ISA emulation is unnecessary, since most binaries can run anywhere as-is, but unlike WALI, is challenging to extend to high-performance resource-constrained systems.

Hypervisors Hypervisor technology virtualizes the guest operating system kernel and its services over the same hardware. Bare-metal (type-1) hypervisors like vSphere [38] and Xen [27] are typically used in cloud settings, while hosted (type-2) hypervisors like Fusion [32] or Parallels Desktop are typically used by end users. Today, in-built type-1 hypervisor capability like Hyper-V [60] and KVM [46] in modern OSes are commonly leveraged for high performance virtualization (e.g. WSL2 [71], Firecracker [16])

In timing constrained embedded systems, real-time hypervisors like BlueVisor [41], Composite [63], and Xvisor [64] are now gaining popularity for cost reduction and improved resource utilization where KVM and Xen technologies cannot operate. Highly secure virtualization for safety critical systems [57], with isolation support from hardware like ARM TrustZone [65], is an appealing direction for many cyberphysical software designers. Similar approaches that leverage hardware techniques for lightweight sandboxing [35] can also enable WebAssembly performance improvements.

OS interface virtualization OS interfaces can also be virtualized independent of the underlying ISA. At a fundamental level, system compatibility layers like Wine [17] enable Windows applications to run on Linux but does not provide any security advantages like traditional virtualization. For isolated, high performance execution with relatively low memory overhead virtualization in the cloud, container technologies typically use OS support to virtualize system interface layers. Linux Containers (LXC) [55], OpenVZ [19], and Docker [59] have used basic isolation provided by namespace and cgroups for decades to control resources and isolate applications. However, while containers run natively on the

CPU, intermediate layers for isolation can incur significant costs, particularly on the file system.

[26] studied Docker performance in more detail than this work, for several different kinds of overhead, finding, for example, between 10% and 30% overhead for disk I/O and 5-10% overhead when enforcing CPU quotas. Optimizing resource isolation [83] and startup time [34, 56] for niche use-cases has been a large focus of the container ecosystem, more recently for domain-specific and heterogeneous hardware [33]. In parallel, solutions like Nabla containers [89] and gVisor [92] investigate secure system interface capabilities by controlling the syscall layer. Via Wasm however, WALI offers sandboxing with ISA portability not currently available to containers, adding additional security for defense-in-depth.

Language Virtualization In the same vein as WebAssembly, numerous languages like Java, Javascript, Python, and .NET offer application-level virtualization. Browsix [66] was the first POSIX-like API for in-browser applications implemented in JavaScript, emulating filesystem and sockets, but pays a high penalty in performance efficiency inherent to Javascript. [75] proposed a Java OSEK interface for embedded devices in modern automotive systems, but face adoption challenges due to non-determinism and memory overheads. Java-based virtualization has even studied for extending existing kernel features and devices driver implementation [91]. .NET, while well-utilized in the cloud [81], is not suitable for real-time embedded domains due to unbounded-execution on garbage collection and threading non-determinism [54].

In the WebAssembly ecosystem, besides WASI(X) [20,21], most research efforts [36, 51, 51, 62] are directed towards designing effective Wasm platforms for edge contexts, and techniques to improve security for the Wasm ecosystem [44,49,76], which are complementary to our work with WALI. With growing interest in deeply embedded [58,82] Wasm runtimes, imminent APIs for domain-specific system interfaces may benefit from being virtualized over WALI.

7 Conclusion

While virtualization with WebAssembly is compelling outside of the Web, its lack of standard OS interfaces has hindered reuse and growth of applications. We develop WALI, an abstraction over userspace syscalls that enables an ISA-portable virtualization solution for Linux application using existing compiler backends and enhances application security with CFI by design. WALI's complete yet simple design specification only needs to be implemented on modern engines once, allowing most Linux applications and WebAssembly APIs to run on WebAssembly with minimal effort. We envision WALI furthering WebAssembly's reach to deeply-embedded system applications and improving the development, distribution, and adoption of new WebAssembly APIs such as WASI.

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