WEBASSEMBLY

WASI

FROM ZERO TO PRODUCTION

A COMPLETE GUIDE TO **SANDBOXED, PORTABLE COMPONENTS**

- CAPABILITY-BASED SECURITY
- COMPONENT MODEL & WIT
- RUST, C, GO & JAVASCRIPT
- WASMTIME & RUNTIMES
- DEPLOY TO CLOUD, EDGE & BEYOND

BUILD SECURE | SHIP ANYWHERE | RUN EVERYWHERE

WALTER H. WHITMORE

WebAssembly System Interface (WASI)

From Zero to Production — A Complete Guide to Sandboxed, Portable Components

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Contents

From Zero to Production — A Complete Guide to Sandboxed, Portable Components

This book takes you from no WebAssembly experience to building production-grade WASI applications and component architectures. You will learn the foundations of WebAssembly execution, the capability-based security model that makes WASI unique, the modern Component Model with WIT interface definitions, practical development across Rust, C, Go, and JavaScript, deep runtime configuration with Wasmtime and alternatives, and real-world deployment patterns for serverless, edge computing, plugins, and microservices. Every concept is explained with accurate mental models before diving into hands-on implementation. Code examples are complete, annotated, and tested against current tooling. This book functions both as a structured learning resource and as a reference manual you will return to when building real systems.

Introduction

The Problem That Started It All

A team ships their application to production inside Docker containers. They feel safe: processes are isolated, dependencies are packaged, the same image runs everywhere. Then an attacker finds a container escape vulnerability. Suddenly that "isolated" process has kernel access. The blast radius is everything.

The same team also runs user-submitted plugins in their system. They compile them to native code and run them as separate processes. It works until a buggy plugin leaks memory, hogs CPU, or reads files it should not see. Process isolation helps, but it is heavy, slow to start, and still relies on the operating system kernel doing the right thing.

Both problems boil down to the same question: how do you run untrusted or semi-trusted code safely, efficiently, and portably?

Containers try to answer this by wrapping processes in namespaces and cgroups. Virtual machines answer it by virtualizing hardware. Both are effective but heavyweight. They carry operating system overhead, megabytes or gigabytes of image size, and startup times measured in hundreds of milliseconds or seconds. For serverless functions, edge computing, plugin architectures, and multi-tenant systems, that overhead is not just inconvenient: it changes the economics of the entire architecture.

WebAssembly was designed to solve a different problem originally: running high-performance code in web browsers safely. It succeeded brilliantly. But WebAssembly outside the browser hit a wall. The format was great for sandboxed execution, but modules had no standard way to interact with operating system resources like files, networks, or clocks. Each runtime invented its own approach. Code written for one runtime would not run on another.

WASI — the WebAssembly System Interface — was created to fix this.

What WASI Is and Why It Matters

WASI is a set of standards-track API specifications that define how WebAssembly modules interact with their host environment [1]. It provides filesystem access, standard I/O, clocks, randomness, environment variables, and more through a capability-based security model that gives modules exactly the permissions they need and nothing more.

The key insight behind WASI is simple but powerful: instead of asking WebAssembly modules to trust their host, or asking hosts to expose arbitrary system calls, define a minimal, well-specified interface that any compliant runtime can implement. The module declares what it needs through imports. The host provides those capabilities explicitly. If the module tries to do something without a capability, it cannot: there is no function to call, no syscall number to invoke, no backdoor to find.

This design has profound implications:

- **Security**: WASI modules start with zero ambient authority. They cannot access files, networks, or any host resources unless explicitly granted capabilities at runtime. This is fundamentally different from a native process that inherits permissions from its user and environment.
- **Portability**: The same WebAssembly binary runs on any WASI-compliant runtime – Wasmtime, WasmEdge, Wasmer, Spin, and others – across x86, ARM, RISC-V, and more architectures. Compile once, truly run everywhere.
- **Sandboxing**: The execution boundary is defined by the WebAssembly virtual machine itself, not by operating system features like namespaces or seccomp filters. This makes WASI sandboxes lighter, faster to start, and harder to escape than traditional containers.

The Evolution: From Preview 1 to the Component Model

WASI has evolved significantly since its inception. Understanding this evolution is critical because you will encounter legacy code and documentation that refer to older versions.

WASI Preview 1 (now WASI 0.1) was released in 2019 as a snapshot of the design at that time [2]. It provided POSIX-like system calls through flat function

imports named `wasi_snapshot_preview1::fd_read`, `wasi_snapshot_preview1::path_open`, and similar. It worked well enough to prove the concept and power many early WASI applications. However, its design was fundamentally limited: all arguments were raw memory pointers (`i32` offsets into linear memory), making it awkward for high-level language interoperability. Preview 1 is now considered legacy but remains widely deployed.

WASI Preview 2 (now WASI 0.2), launched in January 2024, introduced the WebAssembly Component Model and WebAssembly Interface Types (WIT) [3]. This was not an incremental update: it was a fundamental rethinking of how WebAssembly components declare their interfaces and interact with hosts. Components expose typed interfaces — strings, lists, records, variants — instead of raw memory pointers. The Canonical ABI defines exactly how these types are laid out in memory, enabling safe cross-language composition. WASI 0.2 is the current stable release recommended for new development.

WASI Preview 3 (now WASI 0.3) was released on June 11, 2026, adding native async support through `async func`, `stream<T>`, and `future<T>` primitives built into the Component Model [4]. This enables idiomatic asynchronous I/O without polling loops or callback gymnastics. Preview 3 is available in Wasmtime 43+ and represents the cutting edge of WASI development.

This book teaches you modern WASI (Preview 2 and Preview 3) as the primary approach, while also covering Preview 1 so you can understand and migrate existing codebases.

What You Will Learn

The structure of this book follows a deliberate learning progression:

Part I: Foundations establishes the mental models you need. You will learn what WebAssembly is at its core — its instruction set, memory model, and execution semantics. You will understand why WASI exists by examining the real problems it solves. You will explore capability-based security as a design philosophy that predates WASI but finds its most practical modern expression in it.

Part II: Getting Started gets your hands dirty. You will install toolchains for Rust, C/C++, Go, and JavaScript. You will compile your first WebAssembly modules, run them with Wasmtime, inspect their internals, and debug common

issues. By the end of this part you will have a working development environment and confidence in the basic workflow.

Part III: The Modern WASI Stack covers the Component Model, WIT interface definitions, and WASI Preview 2 and 3 in depth. You will learn to define interfaces in WIT, generate bindings for multiple languages, compose components together, and understand how resources flow across language boundaries. This is where the real power of modern WASI becomes clear.

Part IV: Building WASI Applications teaches practical development patterns. You will build command-line tools, work with filesystems and streams, handle networking where available, design custom host capabilities, and implement complete applications across multiple languages. Each topic includes working code, expected outputs, and explanations of what each piece does.

Part V: Runtime Deep Dive focuses on Wasmtime as the reference WASI runtime, covering configuration, permissions, embedding APIs, observability, and performance tuning. You will also learn about alternative runtimes – Spin for serverless, WasmEdge for edge computing, Wasmer for multi-language embedding – and when to choose each.

Part VI: Security and Sandboxing examines WASI security in depth: capability-based design, least privilege enforcement, trust boundaries, sandbox escape considerations, resource exhaustion attacks, supply chain risks, and production hardening practices. You will understand both what guarantees WASI provides and where its limits lie.

Part VII: Advanced Topics dives into runtime internals, the Canonical ABI specification, async execution models, dynamic plugin architectures, performance profiling, benchmarking methodology, and deployment at the edge and in cloud environments. This is for when you need to understand how things work under the hood or optimize for production scale.

Part VIII: Real-World Projects walks through complete end-to-end implementations: a portable CLI tool suite, a multi-language component system, an embedded plugin runtime, and a production HTTP service. Each project goes from requirements and architecture planning through implementation, testing, packaging, deployment, observability, and security hardening.

Part IX: Reference and Roadmap provides migration guidance from Preview 1 to modern WASI, a comprehensive troubleshooting reference, glossary of terms, ecosystem map of tools and projects, and a forward-looking view of the WASI roadmap including current proposals and future directions.

How to Use This Book

Read it sequentially if you are new to WebAssembly and want a thorough understanding from the ground up. Each chapter builds on previous concepts, and the progression is designed so that by the time you reach advanced topics you will have the context to appreciate them.

If you already know WebAssembly basics, skim Parts I and II, then focus on Part III for the Component Model and WIT, followed by whichever parts match your immediate needs: security (Part VI), deployment (Parts V and VII), or specific projects (Part VIII).

Use the book as a reference when building real systems. The troubleshooting chapter, compatibility tables, and glossary are designed to be lookup resources you return to repeatedly.

Prerequisites and Assumptions

This book assumes:

- Basic programming knowledge in at least one language. Rust experience is helpful but not required; all code examples are explained thoroughly.
- Familiarity with command-line tools and basic development workflows (compiling, running tests, using package managers).
- Access to a Linux, macOS, or Windows machine for following along with hands-on sections.

No prior WebAssembly or WASI experience is assumed. Every concept is introduced from first principles before building toward complexity.

Version Notes

WebAssembly and WASI are evolving rapidly. This book targets the following versions and maturity levels:

- **WASI 0.3 (Preview 3)**: Native async support, released June 2026. Available in Wasmtime 43+. Used for cutting-edge examples where async is beneficial.

- **WASI 0.2 (Preview 2)**: Stable Component Model-based WASI, released January 2024. The recommended baseline for new development throughout this book.
- **WASI 0.1 (Preview 1)**: Legacy POSIX-style WASI. Covered for compatibility and migration purposes, clearly marked as deprecated for new development.
- **Wasmtime**: Version 47+ assumed for most examples. Specific version requirements are noted where commands or APIs differ.
- **Rust**: Edition 2021 with stable toolchain (1.82+) assumed. WASI targets `wasm32-wasip1` and `wasm32-wasip2` used as appropriate.
- **WASI SDK**: Version 33+ for C/C++ compilation.
- **wit-bindgen**: Used throughout for binding generation; note that its CLI is still evolving.

When a command, API, or behavior is version-sensitive, the book states which version it applies to and notes any known changes in newer releases.

The Promise

By the end of this book you will be able to:

- Explain WebAssembly's architecture, memory model, and execution semantics clearly.
- Describe WASI's capability-based security model and contrast it with traditional OS interfaces.
- Build, compile, run, debug, and deploy WASI applications in Rust, C/C++, Go, and JavaScript.
- Define component interfaces using WIT and generate bindings across languages.
- Compose multi-language WebAssembly components into cohesive systems.
- Embed WebAssembly runtimes in host applications and implement custom capabilities.
- Configure production-grade security, resource limits, and observability for WASI deployments.
- Make informed architectural decisions about when to use WASI versus containers, native binaries, or other technologies.
- Understand the current state and future direction of the WASI ecosystem.

Let us begin.

Part I: Foundations

Chapter 1: Why WASI Exists — The Problem with Portable Execution

The Container Paradox — Security vs Practicality

Linux containers revolutionized software deployment. They gave developers a way to package applications with their dependencies and run them consistently across environments, from laptops to data centers to the cloud. Docker became ubiquitous. Kubernetes orchestrated thousands of containers at scale.

Containers work by leveraging Linux kernel features: namespaces isolate processes' views of system resources like filesystems, networks, and process IDs. Control groups (cgroups) limit resource usage. Seccomp-bpf filters restrict which system calls a container can make. Together these mechanisms create the illusion of separate machines while sharing a single kernel.

This approach has two fundamental problems.

The first is security. Container isolation depends entirely on the Linux kernel doing the right thing. When kernel vulnerabilities are discovered – and they are, regularly – containers become breachable. CVE-2019-5736 allowed container escape via a dirty pipe vulnerability in the overlay filesystem. CVE-2022-0492 (Dirty Pipe) let unprivileged processes overwrite arbitrary files. Each vulnerability required patching kernels across entire fleets and restarting thousands of containers.

The second problem is overhead. Even "lightweight" containers carry significant weight. A minimal Alpine Linux image is several megabytes. Typical application images are tens or hundreds of megabytes, containing the application binary plus a full userspace: shell, package manager, dynamic linker, shared libraries, configuration files. Starting a container requires loading that image into memory and initializing the process environment, taking hundreds of milliseconds to seconds for cold starts.

For serverless computing, where functions are invoked on demand and billed by execution time, cold start latency is not just annoying: it directly impacts user experience and cost. For edge computing on resource-constrained devices, image size matters because storage and memory are limited. For plugin systems running untrusted third-party code, kernel-level isolation is overkill and slow.

Containers solve the deployment problem brilliantly but were never designed as a sandboxing technology for untrusted code. Using them that way works in practice most of the time but relies on defense-in-depth rather than formal guarantees.

Sandboxed Plugins — A Recurring Dream

Plugin architectures are everywhere: browser extensions, IDE plugins, game mods, CMS themes, workflow automation steps. The pattern is always the same: a host application provides an API, and third-party developers write code that plugs into that API to extend functionality.

The challenge is always security and stability. A buggy or malicious plugin can crash the host application, leak memory, read sensitive data, or perform unauthorized actions. Traditional approaches have included:

- **In-process plugins**: Compiled as shared libraries loaded at runtime. Fast but dangerous — a crash in any plugin crashes the entire host. Memory corruption in one plugin can affect others.
- **Out-of-process plugins**: Run as separate processes communicating via IPC (pipes, sockets, shared memory). More isolated but slower due to serialization overhead and context switching. Still rely on OS-level security.
- **Sandboxed environments**: Using technologies like Chrome's sandboxing, App Sandbox on macOS, or seccomp filters. Effective but complex to implement correctly and platform-specific.

Each approach involves trade-offs between performance, security, ease of development, and portability. None of them works well across all platforms and languages simultaneously.

WebAssembly was designed from the ground up as a sandboxed execution environment. It provides memory safety by design: arrays are bounds-checked, pointers cannot be arithmetic'd arbitrarily, there is no undefined

behavior like buffer overflows or use-after-free. The instruction set is verified before execution, ensuring that all control flow and memory access stays within defined bounds.

But raw WebAssembly modules have no way to interact with the outside world. They are hermetically sealed: they can compute but cannot read files, make network requests, or access system time. For a plugin system, this is useless — plugins need to do something beyond pure computation.

This is exactly what WASI solves.

WebAssembly Leaves the Browser

WebAssembly began as a browser technology. Mozilla, Google, Microsoft, and Apple collaborated starting in 2015 to create a portable compilation target that could deliver near-native performance for web applications [5]. The goal was ambitious: allow languages like C++, Rust, and others to compile to a binary format that browsers could execute safely and efficiently, enabling complex applications — games, video editors, CAD tools — to run in the browser without plugins or native code.

WebAssembly succeeded spectacularly. By 2017 all major browsers supported it. Today billions of web pages use WebAssembly for performance-critical workloads: image processing, audio synthesis, cryptographic operations, physics simulations, and more.

But WebAssembly's properties — sandboxed execution, language neutrality, small binary size, fast startup — made it attractive far beyond the browser. Developers wanted to run WebAssembly on servers, at network edges, in embedded devices, as plugins, in serverless platforms. The format was perfect for these use cases: portable across architectures, secure by design, and lightweight compared to virtual machines or containers.

The problem was portability of system access. Inside the browser, WebAssembly interacts with JavaScript, which provides APIs for DOM manipulation, networking (Fetch API), storage, and more. Outside the browser, there is no JavaScript host. Each runtime that wanted to support WebAssembly had to invent its own mechanism for exposing system functionality:

- One runtime might expose filesystem access through custom imported functions named `host_read_file` and `host_write_file`.

- Another might use a different naming convention or parameter layout.
- A third might support networking but not filesystems.

Code compiled for one runtime would not run on another. The portability promise of WebAssembly was broken at the system interface layer.

In 2017, Brendan Eich (creator of JavaScript and co-founder of Mozilla) proposed WASI: a standard set of system interfaces that any WebAssembly runtime could implement, allowing modules to interact with operating systems in a portable way [6]. The proposal gained traction quickly. The Bytecode Alliance — founded in 2019 by Cloudflare, Fastly, Intel, Mozilla, and Red Hat specifically to advance WebAssembly outside the browser — became the home for WASI development [7].

WASI was not designed to replicate POSIX or any existing operating system API. It was designed from scratch with three principles:

1. **Minimalism**: Expose only what is needed, nothing more.
2. **Capability-based security**: Modules get explicit permissions for specific resources, not blanket access.
3. **Portability**: The same interface works on any platform that implements it.

What WASI Promises

WASI makes four promises to developers and operators:

First: true portability. A WebAssembly module compiled with WASI imports will run on any compliant runtime without modification, regardless of the underlying operating system or CPU architecture. This is stronger than "write once, run anywhere" because it is enforced by the binary format itself: if a module imports `wasi:filesystem/preopens/open`, that function must exist and behave according to specification in any WASI-compliant environment.

Second: security without complexity. Unlike containers that require careful configuration of namespaces, capabilities, and seccomp profiles, WASI modules start with zero permissions. The runtime grants capabilities explicitly at instantiation time. There is no ambient authority to accidentally inherit, no global namespace to search for vulnerabilities. If a module does not import a function, it cannot call it — period.

Third: lightweight execution. WebAssembly modules are small (kilobytes to megabytes instead of gigabytes for containers), start fast (milliseconds instead of seconds), and use less memory. This makes WASI ideal for serverless functions where cold start matters, edge computing where resources are constrained, and plugin systems where many instances run concurrently.

Fourth: language neutrality. Any language that compiles to WebAssembly can use WASI: Rust, C, C++, Go, AssemblyScript, Python (via Pyodide and similar), and more. The Component Model extends this further by enabling components written in different languages to compose together through typed interfaces.

These promises are not marketing slogans. They are architectural properties that follow from WebAssembly's design and WASI's specification. Understanding them requires understanding the underlying technology, which is what the next chapters cover.

Before diving into technical details, it is worth noting what WASI does not promise:

- **WASI is not a replacement for containers** in all scenarios. Containers excel at packaging complex applications with many dependencies, system libraries, and configuration files. WASI is better suited for simpler workloads, plugin systems, and cases where security isolation matters more than full OS access.
- **WASI is not yet feature-complete.** Networking support has been a long-standing gap. While WASI 0.3 improves async I/O capabilities, full socket-level networking is still evolving through proposals like wasi-sockets [8]. For workloads requiring complex network operations today, containers or native processes may be more practical.
- **WASI does not eliminate the need for trust.** The WebAssembly binary must come from a trusted source, and the runtime itself must be trustworthy. WASI provides sandboxing but not supply chain security – that requires additional mechanisms like code signing.

The rest of this book explores these promises in detail, shows you how to build systems that leverage them, and honestly addresses their limitations.

Chapter 2: WebAssembly Fundamentals

A Stack Machine for the Modern Era

WebAssembly is a stack-based virtual machine instruction set. This means that operations work by pushing values onto a stack and popping them off to compute results, rather than using registers like traditional CPUs.

Consider adding two numbers. In x86 assembly you might write:

```
mov eax, 5
add eax, 3
```

The value 5 is loaded into register eax, then 3 is added to it.

In WebAssembly the equivalent is:

```
i32.const 5
i32.const 3
i32.add
```

The instruction `i32.const 5` pushes the integer 5 onto the stack. `i32.const 3` pushes 3 on top of it. `i32.add` pops the two top values (3 and 5), adds them, and pushes the result (8) back onto the stack.

This model has several important properties:

Compact encoding: Stack machines need fewer instructions because there is no need to specify which registers to use. This contributes to WebAssembly's small binary size.

Type safety: Every value on the stack has a known type. The instruction `i32.add` expects two 32-bit integers and produces one. If the types do not match, the module fails validation before it ever runs. There is no accidental integer-to-pointer cast or undefined behavior.

Determinism: Given the same inputs, WebAssembly execution always produces the same outputs (barring imported functions that introduce external effects). This determinism is valuable for reproducibility, testing, and security analysis.

WebAssembly's instruction set includes operations for:

- Integer arithmetic (i32, i64): add, sub, mul, div, bitwise operations, shifts
- Floating-point arithmetic (f32, f64): IEEE 754 compliant operations
- Memory access: load and store from linear memory at specified offsets
- Control flow: blocks, loops, conditionals, calls, returns, branches
- Type conversions: between integer and float types, narrowing and widening

The instruction set is intentionally small and orthogonal. It is designed as a compilation target, not a language you write in directly. Compilers from high-level languages emit WebAssembly instructions that implement the source program's logic.

The Module — WebAssembly's Unit of Code

A WebAssembly module is a self-contained unit of code and data. Think of it as analogous to a compiled object file or shared library in traditional systems, but with stronger guarantees about its structure and behavior.

Every module has a defined structure:

- **Type section**: Declares the signatures of all functions (parameter types and return types).
- **Import section**: Lists functions, memories, tables, and globals that the module expects from its host environment.
- **Function section**: Declares which type each function in the module uses.
- **Table section**: Declares tables (used for indirect function calls).
- **Memory section**: Declares linear memories available to the module.
- **Global section**: Declares global variables (constants or mutable).
- **Export section**: Lists functions, memories, tables, and globals that the module makes available to its host.
- **Start section**: Optionally specifies a function to run when the module is instantiated.
- **Element section**: Initializes table entries with function references.
- **Data section**: Initializes memory with static data (like string literals).

The critical sections for understanding WASI are imports and exports. A module declares what it needs through imports and what it provides through exports. This explicit contract is the foundation of WebAssembly's security

model: a module can only interact with the outside world through its declared imports, and the host can only access the module through its declared exports.

WebAssembly modules have two representation formats:

- **Binary format (.wasm)**: The primary distribution format. Compact, efficient to parse, and designed for fast loading. This is what runtimes execute.
- **Text format (.wat)**: A human-readable S-expression syntax called WebAssembly Text format. Useful for understanding module structure, debugging, and learning. Tools like `wasm2wat` can convert binary modules to text.

Here is a simple module in text format that exports an addition function:

```
(module
  (func (export "add") (param $a i32) (param $b i32) (result i32)
    local.get $a
    local.get $b
    i32.add)
)
```

This module has one function that takes two i32 parameters and returns their sum. The function is exported with the name "add", making it callable from the host environment.

Linear Memory and Its Constraints

WebAssembly memory is fundamentally different from traditional process memory. Each module has one or more linear memories: flat, contiguous arrays of bytes that grow in fixed-size pages.

Key properties of WebAssembly linear memory:

Flat address space: Memory is a single byte array indexed by offsets (i32 values). There are no segments, no virtual memory mappings visible to the module, no distinction between stack and heap from the module's perspective. The runtime or compiler manages these distinctions internally.

Page-based growth: Memories are allocated in pages of 64 KiB each. A module declares an initial size (number of pages) and optionally a maximum

size. Memory can grow at runtime but only by whole pages, and only up to the declared maximum. If no maximum is declared, memory can grow indefinitely (within system limits). Growth is explicit: the `memory.grow` instruction adds pages and returns the previous size, or -1 if growth failed.

Bounds checking: Every memory access is bounds-checked. If code tries to read or write beyond the current memory size, the module traps (analogous to an exception or panic). This prevents buffer overflows and out-of-bounds reads — common security vulnerabilities in native code.

Shared but controlled: In the browser, JavaScript and WebAssembly can share the same linear memory through ArrayBuffer. Outside the browser, memories are typically isolated per module instance unless explicitly shared. The Component Model further restricts direct memory sharing to enforce stronger encapsulation.

Consider how a C program compiled to WebAssembly uses linear memory:

```
1  int add(int a, int b) {
2      return a + b;
3  }
```

The compiler generates code that reads parameters from stack locations in linear memory, performs the addition, and writes the result to a return location. The compiler's runtime library also implements malloc/free by carving space out of linear memory using a simple allocator. From the module's perspective it is just bytes at offsets; the structure is imposed entirely by the compiled code.

This simplicity has consequences:

- **No pointer arithmetic safety**: While bounds are checked, WebAssembly itself does not prevent a program from treating arbitrary bytes as pointers and dereferencing them. Memory safety depends on the source language (Rust enforces it at compile time; C does not).
- **Limited address space**: With 32-bit offsets, the maximum memory is 4 GiB (65536 pages × 64 KiB). This is sufficient for most workloads but limits very large in-memory datasets. WebAssembly 2.0 proposals include 64-bit memories to address this.
- **Explicit data transfer**: To pass complex data between host and guest, you must copy bytes into or out of linear memory. The Component Model's Canonical ABI automates much of this copying for typed values.

Imports, Exports, and Host Interaction

Imports and exports are how WebAssembly modules interact with their environment. This mechanism is simple but powerful: the module declares a contract, and the host fulfills it.

Imports are functions, memories, tables, or globals that the module expects to be provided by the host at instantiation time. The import is identified by a module name and a field name (both strings). For example:

```
(import "wasi_snapshot_preview1" "fd_write"
  (func $fd_write (param i32 i32 i32 i32) (result i32)))
```

This import declares that the module expects a function named `fd_write` from a module called `wasi_snapshot_preview1`. The host must provide this function when instantiating the module, or instantiation fails.

Exports are functions, memories, tables, or globals that the module makes available to the host. For example:

```
(export "run" (func $main))
```

After instantiation, the host can call the exported `run` function. The host accesses exports by name through the runtime's API.

This import/export mechanism is the foundation of WebAssembly's security model:

- A module cannot access anything it does not import. There are no hidden system calls, no direct hardware access, no global environment to query.
- A module cannot expose anything it does not export. The host can only interact with the module through declared interfaces.
- Both imports and exports are type-checked at instantiation time. If types do not match, instantiation fails.

For WASI specifically, the entire system interface is exposed as a set of imports. A WASI module imports functions like `fd_read`, `path_open`, `clock_time_get`, etc. The WASI runtime implements these functions and provides them during instantiation. The module calls them like any other function, but

they are implemented by the host and can access real system resources (subject to capability restrictions).

This design means that:

- If you remove a WASI import from what you provide to a module, that functionality becomes unavailable. You cannot accidentally grant filesystem access by forgetting to configure something — you must explicitly provide the imports.
- The same binary can run in different environments with different capabilities simply by providing different implementations of the imported functions. A test environment might implement `fd_read` to return mock data; a production environment implements it to read real files.

Execution Model and Determinism

WebAssembly execution follows a well-defined model that ensures predictable behavior:

Validation: Before a module can be instantiated, it must pass validation. The validator checks that the module is structurally sound: all types are used correctly, all references are valid, control flow is well-formed, memory accesses use correct types. Validation catches many errors statically and guarantees certain properties about execution (like no out-of-bounds type usage).

Instantiation: Instantiating a module creates an instance with its own memory, globals, and function implementations. The host provides implementations for all imports. If any import is missing or has the wrong type, instantiation fails. If a start function is declared, it runs automatically after instantiation.

Invocation: The host invokes exported functions by name, passing arguments according to their types. The function executes using the module's instruction set, accessing its memory and globals. When the function returns (or traps), control returns to the host with any return values.

Trapping: If execution encounters an error condition — division by zero, out-of-bounds memory access, invalid type conversion, unreachable code — the module traps. Trapping is like an unrecoverable exception: it aborts the

current function call and propagates up the call stack. The host receives a trap notification but the module's state remains intact for potential future calls (unless the trap occurred during initialization).

Determinism: WebAssembly execution is deterministic given the same inputs and environment. The instruction set has no non-deterministic operations. Floating-point operations follow IEEE 754 precisely. Memory access order is defined by the program's control flow. This determinism means:

- Tests are reproducible across platforms.
- Security analysis can reason about all possible execution paths.
- Multiple instances of the same module with the same inputs will produce identical outputs.

The key exception to determinism is imported functions. If a module imports a function that reads from a clock, generates random numbers, or accesses a network socket, those external effects introduce non-determinism. But the WebAssembly execution itself remains deterministic: given the same return values from imports, it will always execute the same way.

This execution model is what makes WebAssembly suitable for security-sensitive contexts. The behavior is constrained, predictable, and analyzable. There are no hidden behaviors, no platform-specific quirks that could be exploited. The sandbox boundary is defined by the virtual machine itself, not by external mechanisms like kernel namespaces or security modules.

Understanding these fundamentals – the stack machine model, module structure, linear memory, imports/exports, and execution semantics – is essential for understanding WASI. Every WASI feature builds on these foundations: capabilities are implemented through selective import provision, filesystem access works through linear memory buffers passed to imported functions, and security boundaries are enforced by the execution model itself.

Chapter 3: From Browser to System — Enter WASI

The Missing Piece — System Calls for WebAssembly

We now understand what WebAssembly is: a portable, sandboxed binary format with a stack-based execution model, linear memory, and explicit imports/exports. We also understand the problem: modules need to interact

with system resources (files, networks, clocks) but there was no standard way to do so outside the browser.

WASI fills this gap by defining a standard set of imported functions that provide system-level functionality. When a WebAssembly module is compiled with WASI support, it imports functions from WASI namespaces. A WASI-compliant runtime implements those functions and provides them during instantiation.

The mental model is simple:

- The **guest** is the WebAssembly module running inside the sandbox. It makes requests for system services by calling imported functions.
- The **host** is the runtime environment that executes the module. It implements the imported functions, mediating access to real system resources.
- **WASI** is the specification that defines what functions are available and how they behave, ensuring compatibility across different hosts and guests.

This guest-host model is analogous to how operating systems work: user-space programs (guests) make system calls to the kernel (host) to access resources. But WASI differs from traditional system call interfaces in important ways, particularly around security.

Capability-Based Security Explained

Traditional operating systems like Linux use identity-based access control. A process runs as a user (identified by a UID), and the kernel checks whether that user has permission to access a resource based on file ownership, group membership, and permission bits (read/write/execute). This model has well-known problems:

- **Ambient authority**: A process inherits all permissions of its user. If you run as root, every program you launch can do anything root can do. There is no way to give a program access to /var/log without also giving it access to /etc/shadow (unless you use complex mechanisms like sudo rules or capabilities).
- **Global namespaces**: File paths are global. Any process that knows the path /etc/passwd can try to read it. Security relies on permission checks at access time, not on whether the process should know about the resource at all.

- **Privilege escalation**: If a vulnerability exists in any program running with elevated privileges, an attacker can exploit it to gain those privileges. The blast radius is everything that privilege level allows.

Capability-based security flips this model. Instead of asking "who are you and what are you allowed to do?", it asks "what tokens do you hold?" A capability is an unforgeable token that grants its holder permission to perform specific operations on a specific resource [12].

Key properties of capabilities:

- **Unforgeable**: Only the system (or the current holder) can create valid capabilities. A process cannot fabricate a capability it does not possess.
- **Specific**: Each capability grants access to a particular resource with particular permissions. A capability might grant read-only access to a specific directory, nothing more.
- **Transferable (optionally)**: Capabilities can be passed between processes, enabling controlled delegation. But only the holder can transfer, and only what they possess.
- **No ambient authority**: A process starts with no capabilities unless explicitly granted some. It cannot do anything beyond what its capabilities allow.

WASI implements capability-based security through its import system. Consider filesystem access:

In a traditional Linux process, if you have read permission on /etc/passwd (which most users do), your program can open and read it simply by calling `open("/etc/passwd", O_RDONLY)`. The path is globally known, and the permission check happens based on your user identity.

In WASI, there is no global filesystem namespace accessible to the module. Instead:

1. The host selects specific directories to make available (called "preopened directories").
2. For each preopened directory, the host provides a file descriptor (an integer handle) through the capability system.
3. The module can only open files relative to those preopened directories using `path_open(fd, path)`.

4. There is no way for the module to construct an absolute path like `/etc/passwd` or escape from the preopened directories through symlinks (the host resolves paths and enforces boundaries).

If the host does not preopen a directory, the module literally cannot access it. There is no function that takes an arbitrary path string and opens a file anywhere on the filesystem. The capability (the preopened directory descriptor) must be held to access anything within it.

This design has powerful security properties:

- **Least privilege by default**: Modules start with zero filesystem access. Grant only what is needed.
- **No path guessing attacks**: An attacker cannot try to read `/etc/shadow` because there is no mechanism to specify that path.
- **Contained blast radius**: If a module is compromised, the attacker can only access resources the module was given capabilities for.

The same principle applies to other resources:

- **Standard I/O**: The host provides file descriptors 0 (stdin), 1 (stdout), and 2 (stderr) as capabilities. A module can read from stdin or write to stdout/stderr, but cannot redirect them arbitrarily.
- **Environment variables**: Only explicitly provided environment variables are accessible. The module cannot enumerate all system environment variables.
- **Clocks and randomness**: Access to time and random number generation is controlled through specific imported functions that the host implements.

Capability-based security is not a new idea — it dates back to operating systems research in the 1960s and 1970s (Capricorn, Hydra, KeyKOS) [13]. But WASI brings it to mainstream software development in a practical, standardized form that works across platforms and languages.

WASI vs POSIX — Design Philosophy

WASI was influenced by POSIX but deliberately diverges from it in several ways. Understanding these differences is important because developers coming from

traditional systems programming might expect POSIX-like behavior and be surprised.

POSIX design philosophy:

- Comprehensive: Provide everything a program might need (filesystems, processes, signals, threads, networking, terminals, IPC).
- Backward compatible: Never remove or change existing APIs, even if they are problematic.
- Identity-based security: Use user/groups/permissions model inherited from Unix.
- Global namespaces: Paths, environment variables, and system state are globally accessible.

WASI design philosophy:

- Minimal: Provide only what is commonly needed; everything else through extensions or host-specific APIs.
- Evolvable: New versions can introduce breaking changes (hence "Preview" in early version names).
- Capability-based security: No ambient authority; explicit resource grants.
- No global namespaces: Resources are accessed through capabilities, not global paths.

Concrete differences:

Aspect	POSIX	WASI Preview 1	WASI Preview 2+
File access	`open("/path", flags)` — any path	`path_open(fd, path)` — relative to preopened fd	Resource-based: open via directory handle
Processes	`fork()`, `exec()` — create child processes	Not supported (no process spawning)	Not directly supported; composition via components

Aspect	POSIX	WASI Preview 1	WASI Preview 2+
Threads	`pthread_create()` – native threads	Limited support (wasm32-wasip1-threads target)	Evolving with Component Model async/threads proposals
Networking	Sockets API – full Berkeley sockets	Not included	wasi:http for HTTP; socket proposals in progress
Signals	Complex signal handling	Not supported	Not supported
Environment	`getenv()` – any environment variable	`environ_get()` – only provided variables	Configuration through typed interfaces

The absence of certain POSIX features is deliberate:

- **No fork/exec**: Creating child processes breaks the sandbox model. A spawned process could potentially escape the WebAssembly sandbox. Instead, WASI encourages composition through components or host-managed task execution.
- **No signals**: Signal handling is complex and platform-specific. WASI omits it to keep the interface simple and portable.
- **Limited networking**: Full socket access was considered risky for sandboxing and complex to standardize across platforms. WASI started with HTTP-level interfaces (wasi:http) rather than raw sockets, though socket proposals are under development.

These omissions mean that not every POSIX program can be compiled to WASI without modification. Programs that rely on fork/exec, signals, or low-level networking will need to be refactored. But for a large class of workloads – command-line tools, data processing, HTTP services, plugins – WASI provides sufficient functionality with stronger security guarantees than a full POSIX environment.

Host and Guest — The Execution Boundary

The host-guest boundary is the fundamental security boundary in WASI. Understanding exactly where this boundary lies and what it enforces is critical for building secure systems.

What the guest can do:

- Execute WebAssembly instructions within its module.
- Access its own linear memory (within bounds).
- Call imported functions provided by the host.
- Use exported functions to be called by the host.

What the guest cannot do:

- Access host memory directly.
- Execute native code on the host.
- Make system calls directly to the operating system.
- Access resources for which it has no capability.
- Escape its sandbox through buffer overflows, use-after-free, or other memory corruption (the WebAssembly execution model prevents these).

What the host does:

- Validates and loads the WebAssembly module.
- Provides implementations for imported functions.
- Manages capabilities: deciding which resources to expose and how.
- Enforces resource limits (memory, CPU time, file descriptors).
- Handles traps and errors from guest execution.
- Mediates all access to external resources through capability checks.

The boundary is enforced by the WebAssembly runtime itself. When a guest calls an imported function, control transfers to host code. The host implementation decides what to do: read a real file, return mock data for testing, deny access, etc. The guest sees only the function call and its return value; it has no visibility into the host's implementation or the underlying operating system.

This architecture enables several important patterns:

- **Testing**: Provide mock implementations of WASI imports to test modules without accessing real filesystems or networks.
- **Virtualization**: Implement WASI functions to access virtual filesystems, in-memory databases, or other abstracted resources.
- **Multi-tenancy**: Run many guest modules in a single host process, each with different capabilities, all safely isolated.
- **Policy enforcement**: The host can log all resource accesses, enforce quotas, apply rate limiting, or implement custom security policies.

The strength of the sandbox depends on the correctness of the runtime implementation. If the runtime has a bug – a buffer overflow in its own code, an incorrect capability check, a memory safety issue – the guest might be able to escape. This is why WASI runtimes like Wasmtime are implemented in memory-safe languages (Rust) and undergo rigorous security review, fuzzing, and formal verification efforts [14].

The WASI Preview 1 Era

WASI Preview 1 (now formally called WASI 0.1) was the first widely deployed version of WASI, released as a snapshot in 2019 [15]. It defined a flat namespace of imported functions under `wasi_snapshot_preview1`:

```
(import "wasi_snapshot_preview1" "fd_read"
  (func $fd_read (param i32 i32 i32 i32) (result i32)))
(import "wasi_snapshot_preview1" "path_open"
  (func $path_open (param i32 i32 i32 i32 i32 i64 i64 i32 i32) (result i32)))
(import "wasi_snapshot_preview1" "clock_time_get"
  (func $clock_time_get (param i32 i64 i32) (result i32)))
```

Every parameter was an `i32` – a pointer into linear memory. To read from a file, the guest would:

1. Allocate a buffer in its linear memory.
2. Create an iovec structure (pointer to buffer and length) in linear memory.
3. Call `fd_read(fd, &iovec, 1, &nread)` with pointers as i32 values.
4. The host reads from the file into the guest's memory buffer at the specified offset.

This worked but had significant limitations:

- **No type safety**: Everything was a raw pointer. The host and guest had to agree on data layouts through conventions, not types.
- **Language impedance mismatch**: High-level languages like Rust or Go had to manually manage memory buffers and pointer arithmetic just to call simple APIs.
- **Error handling**: Errors were returned as numeric codes that needed interpretation. No structured error types.
- **No composability**: There was no way for one WebAssembly module to safely use functionality from another module with typed interfaces.

Preview 1 proved the concept: WASI could provide portable system access to WebAssembly modules in a secure, capability-based way. It powered early WASI applications and demonstrated real-world viability. But its design limitations motivated the development of Preview 2 and the Component Model, which addressed these issues through richer type systems and interface definitions.

Preview 1 is now considered legacy. New development should target WASI 0.2 or later. However, many existing tools, libraries, and examples still use Preview 1, so understanding it remains valuable for migration and compatibility. The next chapters cover both the legacy Preview 1 approach and the modern Component Model-based approach in detail.

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