Dynamically Analyzing WebAssembly with Wasabi

Daniel Lehmann and Michael Pradel
(TU Darmstadt)

Wasabi

A framework for dynamic analysis of WebAssembly programs, developed in the Software Lab at TU Darmstadt.

Last updated 2019-06-19.

We will offer a tutorial on how to use Wasabi for dynamically analyzing WebAssembly at PLDI 2019!

Introduction to Wasabi

Wasabi is a dynamic analysis framework for WebAssembly. What does this mean and why is it useful?

▸ **Dynamic analysis** means observing some properties of a program *while it is running*. Dynamic analysis is routinely used to find and fix bugs, identify performance bottlenecks, or to search for security problems.

▸ Analysis **frameworks**, such as Pin, Valgrind, or Jalangi, provide *generic APIs* on top of which *many different analyses* can be implemented. They solve low-level problems, e.g., how the analysis is interleaved with the program, once and for all, and let analysis authors focus on the analysis itself.

▸ **WebAssembly** is a new programming language (or more precisely: *byte code*) for browsers. It is faster, more low-level, and a better compilation target than JavaScript, the only option on the client-side until now. We expect it to be hugely successful in the near future.

(Click on the bullets for more information. Simplified for the sake of giving a quick intuition.)

How Does It Work?

Conceptually

The name Wasabi stands for **W**eb**As**sembly **a**nalysis using **b**inary **i**nstrumentation, which hints at the **two phases** Wasabi operates in:

1. It *statically* **instrument**s a WebAssembly binary (e.g., `program.wasm`). That is, it inserts additional instructions, such as function calls, in between the original instructions of the program. This happens before the execution. Since WebAssembly is a binary format, and to be independent of the source code (which is often not available when analyzing third-party code in websites), we directly modify the byte code.
2. To perform the *dynamic* **analysis**, the program is then executed (by opening the website with the now instrumented `program.wasm`). To make the user-written

Search or jump to... / Pull requests Issues Marketplace Explore

danleh / wasabi — Unwatch 8 — Star 223 — Fork 15

Code — Issues 1 — Pull requests 1 — Security — Insights — Settings

A dynamic analysis framework for WebAssembly programs. http://wasabi.software-lab.org — Edit

dynamic-analysis webassembly wasm javascript Manage topics

917 commits — 1 branch — 0 releases — 4 contributors — MIT

Branch: master — New pull request — Create new file — Upload files — Find File — Clone or download

danleh update overview README in tutorial — Latest commit eba7d5c 26 minutes ago

analyses	shorten cryptominer detection code to version of paper	11 months ago
eval	add script and results of instruction counts for eval programs	26 days ago
lib	use main_error crate for error printing, gitignore intellij files	26 days ago
src	fix compilation errors in test module	15 days ago
tests	add tests for issue #8 (TODO integrate with automated regression test...	26 days ago
tutorial	update overview README in tutorial	26 minutes ago
.gitignore	helper script to build in-browser tests from small .wat files	last year
.travis.yml	use at least Ubuntu 16.04 for building with Travis	15 days ago
Cargo.lock	use bencher crate instead of unstable test crate and #[bench] (WIP, b...	6 months ago
Cargo.toml	switch to Rust 2018, remove stabilized feature flag	6 months ago
Dockerfile	update dockerfile to use Rust stable 1.31	3 days ago
LICENSE	add license	10 months ago
README.md	update install instructions: Rust stable, official docs for dependencies	3 days ago
TODO.md	add potential bug in begin/end hooks	7 months ago

README.md

Wasabi

build passing

We will offer a tutorial on how to use Wasabi for dynamically analyzing WebAssembly at PLDI 2019!

Installation from Source

- Dependencies and tools
  - Git, CMake, and GCC or Clang for building the dependencies (those for sure, but possibly more)
  - **Firefox** >= 52 (which is what I use, or Chrome >= 57) for running WebAssembly
  - **WebAssembly Binary Toolkit (WABT)**: `wat2wasm` / `wasm2wat` for converting Wasm binaries to/from text, `wasm-objdump` for inspecting binaries, and `wasm-interp` for a simple interpreter. (See https://github.com/WebAssembly/wabt#cloning.)

```
git clone --recursive https://github.com/WebAssembly/wabt
```

http://wasabi.software-lab.org

https://github.com/danleh/wasabi/

Tutorial Goals

- Tell you (a bit) about WebAssembly and Wasabi
- Set-up Wasabi and show that it’s easy “to get going”
- Show examples of what you can do
- Get feedback from (potential) users

→ Active participation and interaction ☺

Part 1:
Introduction to WebAssembly

What is WebAssembly?

Bringing the Web up to Speed with WebAssembly

Andreas Haas Andreas Rossberg Derek L. Schuff* Ben L. Titzer
Google GmbH, Germany / *Google Inc, USA
{ahaas,rossberg,dschuff,titzer}@google.com

Michael Holman
Microsoft Inc, USA
michael.holman@microsoft.com

Dan Gohman Luke Wagner Alon Zakai
Mozilla Inc, USA
{sunfishcode,luke,azakai}@mozilla.com

JF Bastien
Apple Inc, USA
jfbastien@apple.com

Abstract

The maturation of the Web platform has given rise to sophisticated and demanding Web applications such as interactive 3D visualization, audio and video software, and games. With that, efficiency and security of code on the Web has become more important than ever. Yet JavaScript as the only built-in language of the Web is not well-equipped to meet these

device types. By historical accident, JavaScript is the only natively supported programming language on the Web, its widespread usage unmatched by other technologies available only via plugins like ActiveX, Java or Flash. Because of JavaScript's ubiquity, rapid performance improvements in modern VMs, and perhaps through sheer necessity, it has become a compilation target for other languages. Through Emscripten [43], even C and C++ programs can be compiled to

WA

WEBASSEMBLY

Overview | Getting Started | Docs | Spec | Community | Roadmap | FAQ

WebAssembly 1.0 has shipped in 4 major browser engines. Learn more

WebAssembly (abbreviated *Wasm*) is a binary instruction format for a stack-based virtual machine. Wasm is designed as a portable target for compilation of high-level languages like C/C++/Rust, enabling deployment on the web for client and server applications.

Haas et al., PLDI 2017

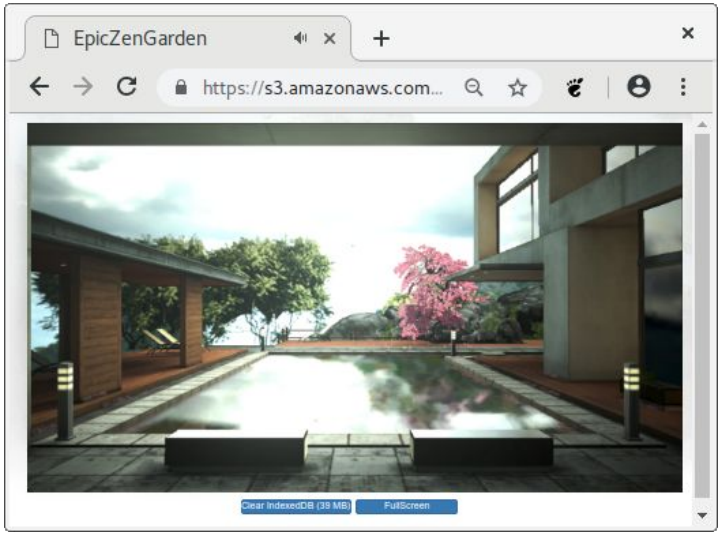
https://webassembly.org/

What is WebAssembly?

- “Byte code for the web”
  - Very rough idea: “JVM, without 3rd party plugins, directly in the browser”
  - Lower-level than JavaScript
- Fast
  - Compact binary format → quicker to parse
  - Instructions map closely to common hardware
  - Linear memory, no garbage collector
- Safe
  - Typed, separated code and data, modules, ...
- Portable
  - Support by all 4 major browsers, x86/ARM

Use Cases

- Designed as compilation target
  - For low-level languages
  - From C, C++ with Emscripten
  - Rust, Go, …
- Application domains
  - Audio/video processing, codecs, e.g., AV1
  - Compression, e.g., Brotli
  - Games, simulations, e.g., Unreal Engine 4
  - Language runtimes, e.g., Blazor (C#)
  - Complex web applications, e.g., AutoCAD



https://s3.amazonaws.com/mozilla-games/ZenGarden/EpicZenGarden.html

Binary and Text Format

WebAssembly Code Explorer

```
0x00000000  00 61 73 6D 01 00 00 00 01 07 01 60 02 7F 7F 01   .asm.......`....
0x00000010  7F 03 02 01 00 07 07 01 03 61 64 64 00 00 0A 09   .........add....
0x00000020  01 07 00 20 00 20 01 6A 0B 00 1C 04 6E 61 6D 65   ... . .j....name
0x00000030  01 06 01 00 03 61 64 64 02 0D 01 00 02 00 03 6C   .....add.......l
0x00000040  68 73 01 03 72 68 73                              hs..rhs
```

```
(module
  (type $type0 (func (param i32 i32) (result i32)))
  (export "add" (func $func0))
  (func $func0 (param $var0 i32) (param $var1 i32) (result i32)
    get_local $var0
    get_local $var1
    i32.add
  )
)
```

https://webassembly.studio/

Text Format: Overview

- Syntax: S-expressions
- 1 file = 1 module
- 1 module : n sections
  - Types
  - Imports/Exports
  - Functions
  - Globals
  - Data

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  ...
  (import "env" "b" (func $env.b (type $t4)))
  ...
  (func $f7 (param i32 i32) (result i32)
    (local $l0 i32) ...
    get_global $g2
    i32.const 48
    i32.add
    set_global $g2
    ...
    i32.load
    ...
  (global $g2 (mut i32))
  (export "h" (func $h))
  (data (i32.const 1152) "Hello, world!")
)
```

Text Format: Instructions

- Code is organized in functions
  - No OOP: no objects or methods
- Globals, per-function locals
- Stack machine
- 4 types: i32, i64, f32, f64
- Linear, unmanaged memory
  - 32-bit addresses

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  ...
  (import "env" "b" (func $env.b (type $t4)))
  ...
  (func $f7 (param i32 i32) (result i32)
    (local $l0 i32) ...
    get_global $g2
    i32.const 48
    i32.add
    set_global $g2
    ...
    i32.load
    ...
  (global $g2 (mut i32))
  (export "h" (func $h))
  (data (i32.const 1152) "Hello, world!")
)
```

Structured Control-Flow

- Well-nested blocks
  - Branches (`br`) reference blocks by numerical *label*
- Block types: block, if, loop

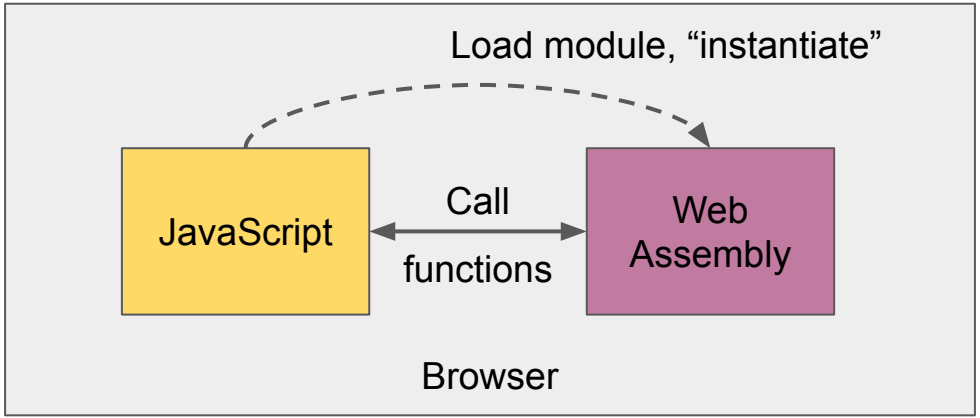
```
block
  ...
  br_if 0
  ...
end
...
```

```
;; infinite loop
loop
  ...
  br 0
end
...
```

```
i32.const 0
if
  ...
else
  ...
end
...
```

Host Embedding

- WebAssembly itself is agnostic of its *host*
  - No functions defined by default
  - No system calls/IO routines by default
- Most common embedding: web browsers



WebAssembly API in JavaScript

```
1   let importObject = {
2       env: {
3           print: function(s) {
4               console.log(s);
5           },
6       }
7   };
8
9   fetch("hello.wasm")
10      .then(response => response.arrayBuffer())
11      .then(buffer => WebAssembly.instantiate(buffer, importObject))
12      .then(object => {
13          let inputs = ...;
14          let result = object.instance.exports.somefun(inputs);
15          ...
16      });
```

WebAssembly API in JavaScript

- WebAssembly global object
- Usual lifecycle:
  - Load .wasm file with fetch()
  - Instantiate the file = compile and provide imports
  - Call exported functions on the instance
- Instantiation methods
  - Blocking: `new WebAssembly.Instance(...)`
  - Async: `await WebAssembly.instantiate(buffer, imports)`
  - Streaming: `await WebAssembly.instantiateStreaming(fetch(...), imports)`

Tooling and Documentation

- Emscripten: C → WebAssembly compiler
  - https://emscripten.org/
- WebAssembly Binary Toolkit
  - https://github.com/WebAssembly/wabt
  - wat2wasm
  - wasm2wat
  - wasm-objdump
- WebAssembly Specification
  - https://webassembly.github.io/spec/
  - E.g., instructions: https://webassembly.github.io/spec/core/bikeshed/index.html#instructions

Setup for Hands-On Tasks

- Download VirtualBox https://www.virtualbox.org/
- Copy or download VM image
  - USB stick
  - http://wasabi.software-lab.org/tutorial-pldi2019/
- “Import Appliance”
- $ cd ~/tutorial/wasabi/

  $ git pull

  $ cd ./tutorial/

Task 0.1: A Minimal WebAssembly Program

- Goals
  - Understand the text format
  - Convert between text and binary format
  - Embed a WebAssembly binary in a website
  - Run it in the browser
- Prerequisites
  - WebAssembly Binary Toolkit: https://github.com/WebAssembly/wabt
- Instructions
  - See README in https://github.com/danleh/wasabi/tree/master/tutorial/task0/1-hello

Task 0.2: Addition in WebAssembly

- Goals
  - Write a more useful function in WebAssembly
  - How to call WebAssembly functions from JavaScript
  - Bonus: WebAssembly i32 != JavaScript number
- Prerequisites
  - WebAssembly Binary Toolkit: https://github.com/WebAssembly/wabt
- Instructions
  - See README in https://github.com/danleh/wasabi/tree/master/tutorial/task0/2-add

Task 0.3: Compiling C to WebAssembly

- Goals
  - Learn about Emscripten
  - Compile C code to WebAssembly + HTML harness with Emscripten
  - See that you can “run C code in the browser”
- Prerequisites
  - Emscripten: https://emscripten.org/docs/getting_started/downloads.html
- Instructions
  - See README in https://github.com/danleh/wasabi/tree/master/tutorial/task0/3-hello-c

Part 2:
Introduction to Wasabi

Dynamic Analysis Frameworks

- New platform → Need for dynamic analysis tools


Correctness


Performance


Security

- Framework as a basis

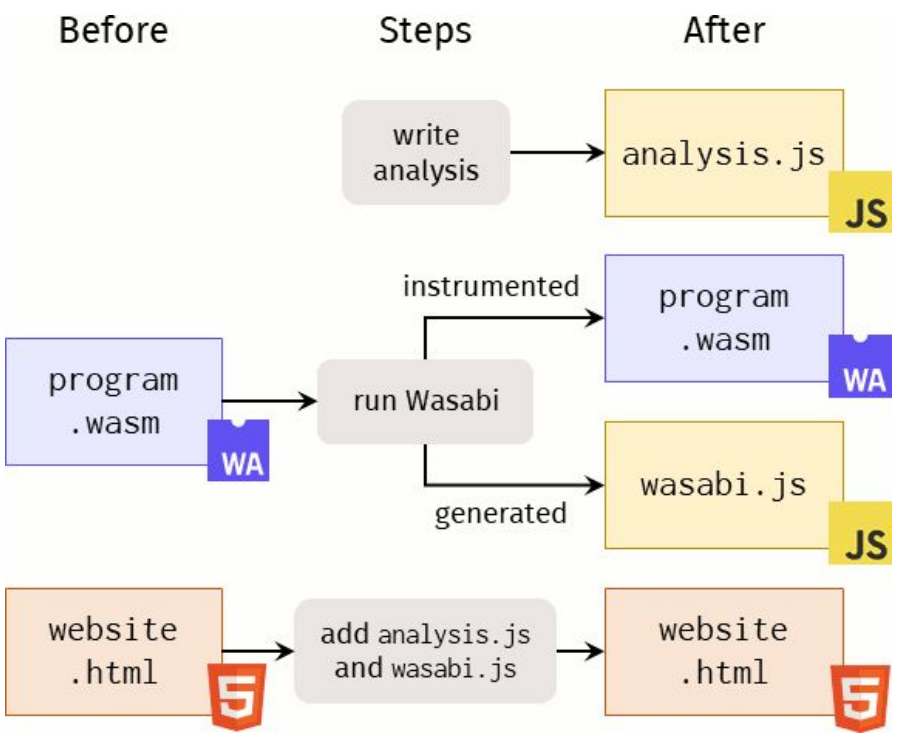
	Pin	Valgrind	RoadRunner	Jalangi	Wasabi
Platform	x86-64		JVM	JavaScript	WebAssembly
Instrumentation	native binaries		byte code	source code	binary code
Analysis Language	C/C++		Java	JavaScript	JavaScript

Wasabi:
Dynamic Analysis Framework for WebAssembly

- Observe any operation
- Analysis API in JavaScript
- Static, binary instrumentation
  - Why binary? Why static?
    - Different producers of WebAssembly
    - Source code not always available
    - Static instrumentation is reliable
- Open source: http://wasabi.software-lab.org

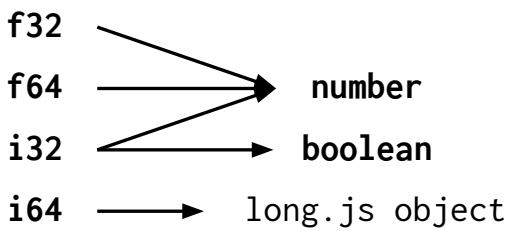
Wasabi

Instrument and Analyze



Analysis API: Overview

- Every instruction can be observed
  - Location, inputs, outputs
- Grouping of similar instructions
  - Similar instructions have a single API hook
  - 23 hooks instead of >100
- Statically pre-computed information
  - E.g., resolve relative branch targets
- Type mapping:
  - WebAssembly → JavaScript



Example Analysis: Detecting Cryptominers

- Dynamic analysis to identify cryptomining code
- 11-line re-implementation of Wang et al. [ESORICS'18]
- Gather instruction profile
- No manual instrumentation

```
let inst = {};
Wasabi.binary = function(loc, op, args) {
  switch (op) {
    case "i32.add":
    case "i32.and":
    case "i32.shl":
    case "i32.shr_u":
    case "i32.xor":
      inst[op] = (inst[op] || 0)+1;
  }
};
```

Analysis API: Memory Operations

- Stack: Manipulation of the value stack
  - const: Constant is pushed onto the stack
  - drop: Top-of-stack value is discarded
  - select: Conditional push of one of two given values
- Heap: Manipulation of global heap values
  - load: Load value from memory
  - store: Store value into memory
- Locals/globals: Manipulation of variables
  - local: Reads and writes of local variables
  - global: Reads and writes of global variables

```
(module
  (func $myfunction (local $locA i32)
    i32.const 7
    set_local $locA
  )
  (start $myfunction)
)
```

Hooks receive: Involved values, memory addresses, and code location

Analysis API: Control Flow

- Branches
  - br, br_if : Unconditional and conditional branch
  - br_table: Branch via lookup table
  - if: Enters block if condition is true

Hooks receive: Branch target(s), condition, and code location

- Function calls
  - call_pre: Just before a function call (at the call site)
  - call_post: Just after a function call (at the call site)
  - return: Just before a function return (in the callee)

Hooks receive: Arguments, return value, function (for direct calls) or function table (for indirect calls), and code location

```
(module
    (func $foo (result i32)
        i32.const 5
    )

    (func $f (local $loc i32)
        call $foo
        set_local $loc
    )

    (start $f)
)
```

Analysis API: Operations

- unary: Operations with a single operand
- binary: Operations with two operands

Hooks receive: Input value(s), output value, and code location

```
(module
    (func $f
        i32.const 3
        i32.const 2
        i32.add
        drop
    )

    (start $f)
)
```

Analysis API: Other Hooks

- Blocks:
  - begin
  - end

  Hooks receive: type of block (function, loops, block, if, else) and code location

- Memory management:
  - memory_grow
  - memory_size

  Hooks receive: Current memory size, delta in size, code location

- Others:
  - start, nop, unreachable

```
(module
    (func $f
        i32.const 3
        i32.const 2
        i32.add
        drop
    )

    (start $f)
)
```

WASM Instructions versus API Hooks

- 0..1 to N mapping from WASM instructions to API hooks
  - Most instructions trigger exactly one hook
  - Some instructions trigger multiple hooks (e.g., if → if + begin of block)
  - Some hooks are triggered without any explicit instruction (e.g., begin of function)

```
(module
    (func $f
        i32.const 3
        i32.const 2
        i32.add
        drop
    )

    (start $f)
)
```

begin hook

const hook

Code Locations

- All hooks receive the corresponding code locations
- Code locations are w.r.t. original binary, not instrumented binary
- Locations consist of two parts:
  - Function index: Unique identifier of a function within a module
  - Instruction index: Sequential order in function body (start at zero)
    - -1 for hooks that do not correspond to any specific instruction in the body

Example:

```
▸ Object { func: 1, instr: -1 } start
▸ Object { func: 1, instr: -1 } begin function
▸ Object { func: 1, instr: 0 } const, value = 42
▸ Object { func: 1, instr: 1 } direct call to func # 0 args = ▸ Array [ 42 ]
```

Static Information

In addition to runtime hooks, Wasabi provides some static information about the analyzed WebAssembly module:

- Functions
- Branch tables
- Global variables

Access this information via `Wasabi.module`

- `Example:`

```
Wasabi.module
▼ {…}
  ▶ exports: Object {  }
  ▼ info: {…}
    ▶ brTables: Array []
    ▶ functions: Array [ {…}, {…} ]
      globals: ""
      start: 1
      tableExportName: null
```

Part 3:
Writing Your Own Wasabi Analyses

Task 1: Your First Wasabi Analysis

- Goal
  - Build and run a very simple analysis on a minimalistic WebAssembly module
- Prerequisite
  - Wasabi installed
    - You have it after the previous tasks
- Once Wasabi is installed:

  See https://github.com/danleh/wasabi/tree/master/tutorial/task1

Task 2: Dynamic Call Graph of a 3D Game

- Goals
  - Apply Wasabi to a larger program, here: WebAssembly port of C game engine
  - Write dynamic call graph analysis, which is often a building block for other analyses
- Prerequisites
  - Wasabi installed
    - You have it after the previous tasks
  - Graphviz
    - For Ubuntu: sudo apt install graphviz
- Instructions
  - See README in https://github.com/danleh/wasabi/tree/master/tutorial/task2

Task 3: Reverse Engineering

- Goals
  - Very simple WebAssembly “reverse engineering”
  - Why dynamic analysis is sometimes useful/easier
- Prerequisites
  - wasm2wat (from WebAssembly Binary Toolkit) or just browser developer tools
  - Wasabi
- Instructions
  - See README in https://github.com/danleh/wasabi/tree/master/tutorial/task3