Vulnerabilities in WebAssembly: A Survey

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Figure 1: Seattle Mariners at Spring Training, 2010.

ABSTRACT

A clear and well-documented LaTeX document is presented as an article formatted for publication by ACM in a conference proceedings or journal publication. Based on the "acmart" document class, this article presents and explains many of the common variations, as well as many of the formatting elements an author may use in the preparation of the documentation of their work.

KEYWORDS

binary exploits, Webassembly, IT Security

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1 INTRODUCTION

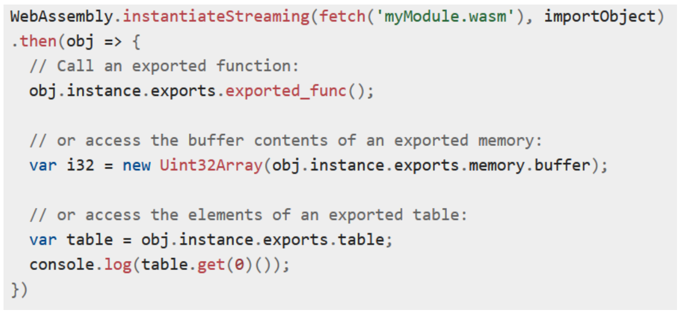
WebAssembly is a binary code format and compilation target meant to bring performance to web applications. The initial design of the API and binary format of WebAssembly got completed in 2017 [8]. Since then, most major browsers such as Firefox, Chrome or Safari implement many of the proposed features. Even in the backend it is possible to run code compiled to WebAssembly for example when using Nodejs. The promise of running code with near native performance in the browser is very attractive, as it allows for more demanding web applications and smoother user experiences. However, since any Website visited by the user can download and execute WebAssembly code just like Javascript, it immediately raises security concerns. On the one hand, a malicious website could execute malware on the host PC or use computing ressources by executing a crypto miner. On the other hand, a vulnerable WebAssembly program which takes user input could lead to cross site scripting attacks in the browser. Worse yet, as WebAssebly gets adopted in the backend or even in stand-alone applications, vulnerabilities in WebAssembly programs could enable attacks such as Remote Code Execution. This survey will mainly deal with issues of the latter kind, focusing on how WebAssembly programs might be vulnerable to binary exploits. In particular, we will focus on how the security mechanisms intrinsic to WebAssembly's design compare to binary exploit mitigations in native applications. The official spec adresses some of the security concerns by stating that "[...] code is validated and executes in a memory-safe*, sandboxed environment preventing data corruption or security breaches". However, it adds a footnote which specifies "*No program can break WebAssembly's memory model. Of course, it cannot guarantee that an unsafe language compiling to WebAssembly does not corrupt its own memory layout, e.g. inside WebAssembly's linear memory". Indeed, in the past years there have been a few puplications commenting on WebAssembly's lack of mitigations to common binary exploitation techniques, such as [5] or [4]. Additionally, there have been puplications researching the real-world assembly programs such as [6] or [3]. In this survey, we aim to cover the main points of these publications and try to recreate their main results. It is structured as follows: 2 will introduce WebAssembly with a focus on the features which will be important to our discussion later. ASDASDASDASD

2 WEBASSEMBLY

The following will give an Introduction to and and overview of WebAssembly, paying special attention to the parts relevant to a discussion of binary vulnerabilities. For more information, see the official specification at [7], or the Background section in [4].

2.1 High Level Overview

The name 'WebAssembly' (often abbreviated as WASM) is a slight misnomer, since it has a different form and function from typical assembly languages. The official spec refers to it as "low-level, assembly-like". It is a binary byte code format which is interpreted by a Virtual Machine, similar to for example Java. The Virtual Machine is most often implemented in a browser. Design goals were to make WebAssembly safe, hardware- and language independent and fast. In fact, WebAssembly is supposed to run at near-native speeds. There exists a human-readable format of WebAssembly binaries called 'wat'. Whenever we present WebAssembly Code, it will be in this format. While it is possible to hand-craft wasm binary, it is most often generated by compiling a high-level language such as C/C++ or Rust. The Binary is then instantiated by calling a Javascript function. See ??. By itself, a compiled WebAssembly module has now way of communicating with the host environment such as a Browser (assuming a Bug-free Virtual Machine). WebAssembly functionality can only be accessed by calling functions which are exported by the WebAssembly module. These exported functions can be called from Javascript code. Conversely, WebAssembly has no I/O other than what is directly supplied through imported Javascript functions.



```
WebAssembly.instantiateStreaming(fetch('myModule.wasm'), importObject)
.then(obj => {
  // Call an exported function:
  obj.instance.exports.exported_func();

  // or access the buffer contents of an exported memory:
  var i32 = new Uint32Array(obj.instance.exports.memory.buffer);

  // or access the elements of an exported table:
  var table = obj.instance.exports.table;
  console.log(table.get(0)());
})
```

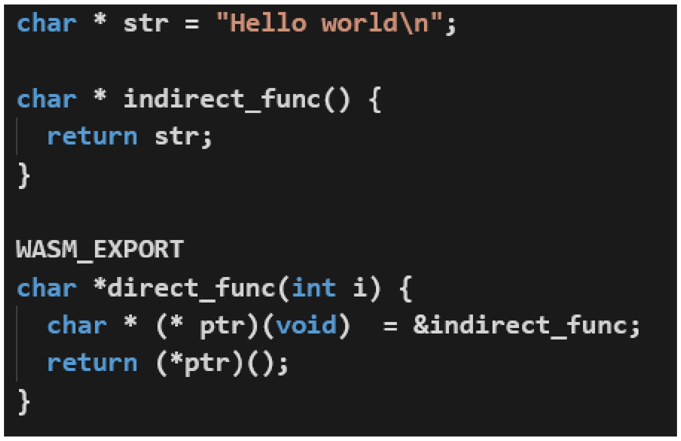
Figure 2: How to intantiate a WebAssembly module using Javascript. (https://developer.mozilla.org/en-US/docs/WebAssembly/Loading_and_running).

2.2 Modules

At the highest level, WebAssembly programs are organized into Modules. A module is what gets compiled and run by the Virtual Machine. Amongst other things, a module contains definitions for imports and exports, functions, types, tables and memories. All definitions are referenced by zero-based indices. As of the time of writing, only one memory may be defined in a module. This memory is indexed by 0 and implicitely referenced by all other constructs. More on memory in 2.5. Also as of time of writing the only table elements which are available are untyped function references. This is used to implement indirect function calls, see 2.6. For an example of WebAssembly code, see

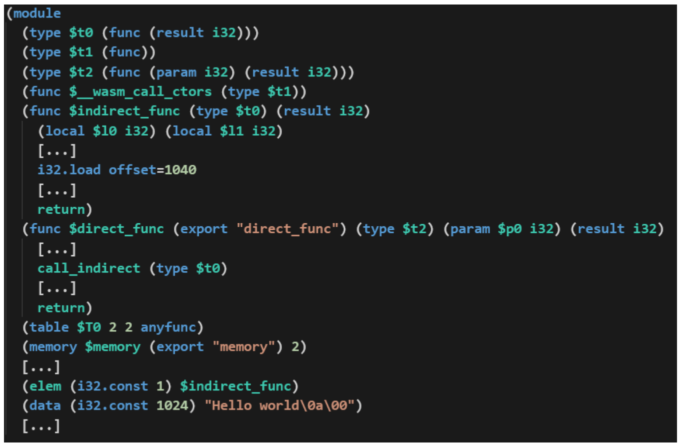
2.3 The Stack

The WebAssembly virtual machine is Stack based. Thus, it doesn't have registers. Instead, values are pushed on and popped of the stack. All instructions implicitely operate on the stack.



```
char * str = "Hello world\n";

char * indirect_func() {
  return str;
}

WASM_EXPORT
char *direct_func(int i) {
  char * (* ptr)(void)  = &indirect_func;
  return (*ptr)();
}
```

Figure 3: A c program, which, when compiled without optimization, gets translated to the code in Figure 4.



```
(module
  (type $t0 (func (result i32)))
  (type $t1 (func))
  (type $t2 (func (param i32) (result i32)))
  (func $__wasm_call_ctors (type $t1))
  (func $indirect_func (type $t0) (result i32)
    (local $l0 i32) (local $l1 i32)
    [...]
    i32.load offset=1040
    [...]
    return)
  (func $direct_func (export "direct_func") (type $t2) (param $p0 i32) (result i32)
    [...]
    call_indirect (type $t0)
    [...]
    return)
  (table $T0 2 2 anyfunc)
  (memory $memory (export "memory") 2)
  [...]
  (elem (i32.const 1) $indirect_func)
  (data (i32.const 1024) "Hello world\0a\00")
  [...]
```

Figure 4: The c program in Figure 3 gets compiled to this WebAssembly program (with uninteresting parts removed). Observe the function table and memory.

2.4 Control Flow

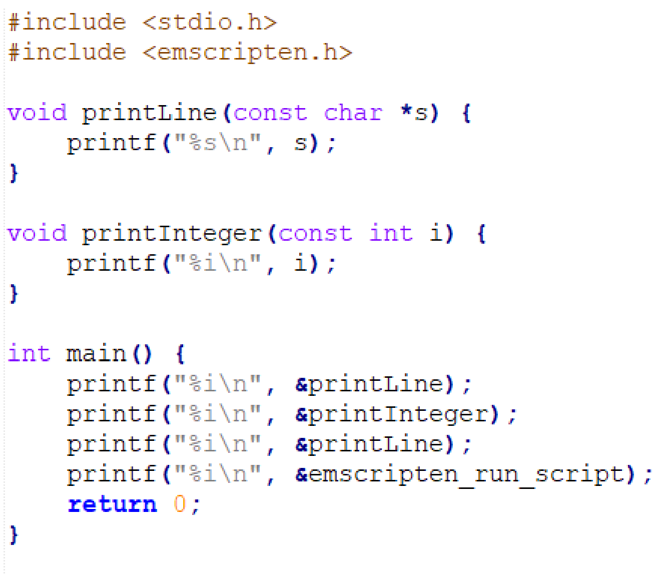
In contrast to native languages or even Java, WebAssembly enforces structured control flow. Code can only be organized into blocks. Control-flow commands can only jump to the beginning of such a block, and only within the current function. In addition, the bytecode never interacts with the underlying adresses of functions. These are only accesible to the Virtual Machine. This immediately makes many binary exploits infeasable, such as Return-Oriented Programming.

2.5 Memories

WebAssembly only supports four different primitive types: 32- and 64-bit Integers (i32, i64) and single- and double-precision floating point nubmers (f32, f64). As such, arrays, pointers, etc. have no explicit representation at the binary level. To see how they are implemented in binary programs, it is necessary to understand the way WebAssembly handles memory. The implementation of function pointers is discussed in 2.6. The Stack of a function which contains the return adress as well as any native data type whose adress is never taken is not accesible to the bytecode. As mentioned in 2.4, this in itself contributes to WebAssemblys inherent security. However, anything other than a value of native type or any value whose adress is taken needs to reside in the linear memory. This memory is a linear array of bytes. Adresses are referenced by 32 bit integers which serve as pointer types. The WebAssembly program can request more memory from the Host VM using the memory.grow operation. The linear memory is completely unmanaged. The way it is used is completely up to the program. Many WebAssembly toolchains such as Emscripten include an allocator which implements functions such as C's malloc and free. This unmanaged, linear memory is the main vector of attack of all vulnerabilities discussed in [4]. As will be discussed in section 3.

2.6 Indirect Function Calls

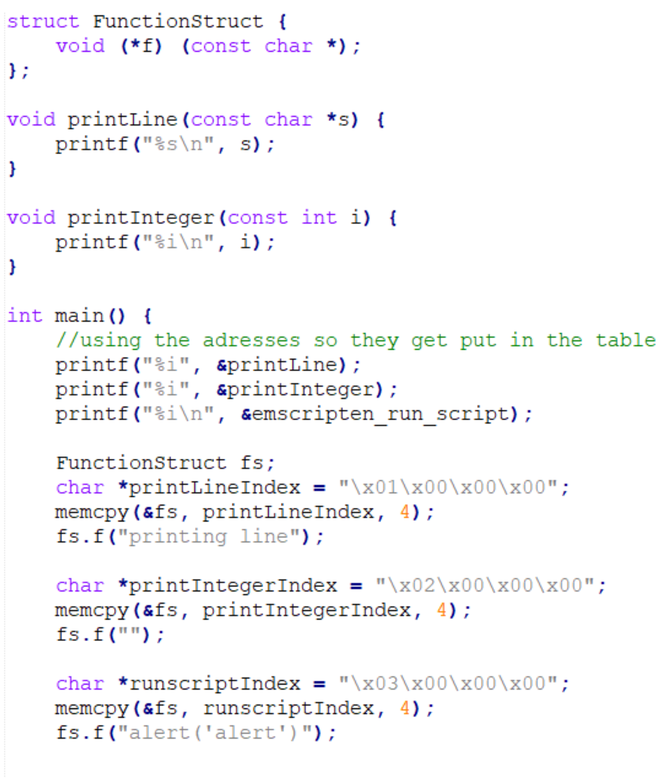
To implement indirect function calls, any function which may get called indirectly or used as a function pointer has an entry in the table section. The **call_indirect** operation pops an index from the stack which is used to reference an entry in the table section. This table maps the index to a function. This limits which functions can be called indirectly. Figure 5 shows example code to make this more intuitive. This code prints 1,2,1,3 to the console when running it in the browser.



```
#include <stdio.h>
#include <emscripten.h>

void printLine(const char *s) {
    printf("%s\n", s);
}

void printInteger(const int i) {
    printf("%i\n", i);
}

int main() {
    printf("%i\n", &printLine);
    printf("%i\n", &printInteger);
    printf("%i\n", &printLine);
    printf("%i\n", &emscripten_run_script);
    return 0;
}
```

Figure 5: This Code demonstrates how WebAssembly handles function pointers. This code prints 1,2,1,3 to the console when running it in the browser.

Additionally, functions in WebAssembly are type checked. The **call_indirect** operation has the function type statically encoded. Thus, an indirect call can only call functions which have the same signature. It must be remarked however that this is less limiting than it might first appear, since WebAssembly only has four native types. Thus, a function taking a pointer (or a string) has the same signature as a function taking an 32-bit Integer. This is demonstrated by the code in . By copying the index of different functions directly into the function pointer, different functions get called indirectly. The function pointer supposedly takes a pointer to a char as argument. However, it is possible to use the index of a function taking an Integer as parameter.



```
struct FunctionStruct {
    void (*f) (const char *);
};

void printLine(const char *s) {
    printf("%s\n", s);
}

void printInteger(const int i) {
    printf("%i\n", i);
}

int main() {
    //using the adresses so they get put in the table
    printf("%i", &printLine);
    printf("%i", &printInteger);
    printf("%i\n", &emscripten_run_script);

    FunctionStruct fs;
    char *printLineIndex = "\x01\x00\x00\x00";
    memcpy(&fs, printLineIndex, 4);
    fs.f("printing line");

    char *printIntegerIndex = "\x02\x00\x00\x00";
    memcpy(&fs, printIntegerIndex, 4);
    fs.f("");

    char *runscriptIndex = "\x03\x00\x00\x00";
    memcpy(&fs, runscriptIndex, 4);
    fs.f("alert('alert')");
```

Figure 6: Example demonstrating how function pointer type checking works.

2.7 Deployment, Compilers and Toolchains

It would be very impractical (albeit possible) to write WebAssembly from scratch. Thus, several Backends exist to generate WebAssembly bytecode from high-level languages such as C, Go or Rust. Emscripten [1] can not only generate the Bytecode from C/C++ but also generate Html and Javascript to load and run the WebAssembly module. It also comes with C Headers to interact with the Browser and implements several common libraries such as SDL2 [2].

3 BINARY VULNERABILITIES OF WEBASSEMBLY PROGRAMS

In this section we will discuss the security vulnerabilities of WebAssembly as presented in [5] and [4]. [4] begin by discussing the security related aspects of the linear unmanaged memory. As mentioned in 2.5, every scalar value whose adress is never taken, as well as function return adresses are completely controlled by the virtual machine. This mitigates many well-known attacks. However, all non-scalar types such as arrays or any value whose adress is ever taken must lie in the unmanaged memory. This memory is usually controlled by an allocator provided by the compilation toolchain. Most allocators seperate the memory in three distinct regions: The Stack, Heap and Data sections. To distinguish between the function call stack managed by the VM and the call stack created by the compiler, [4] call the latter the **unmanaged** stack. We will use the same nomenclature here. One must keep in mind however, that there are no underlying mechanisms provided by the VM to seperate between these three regions. This seperation is only implemented by the compiler. Initially, it is just a single contiguous linear array of bytes.

3.1 Exploitation potential of unmanaged memory

[5] discuss serveral common exploit mitigation techniques which are used in binary programs. Table **??** provides a summary and shows whether these techniques are present in WebAssembly.

[4] similary discuss common mitigations such as ASLR and page protection flags which are not present in WebAssembly. In particular, since there are no guard pages between the different sections of the linear memory , an overflow in any section can corrupt data in any other section. And since there is no concept of read-only memory, even data which is marked as constant in the source code can be overwritten during execution.

4 EXPLOITING VULNERABILITIES

Having analyzed WebAssemblys main vulnerability, the unmanaged linear memory, there are several ways to exploit it. [5] show two attack primitives, format-string attacks and stack-based buffer overflows. They use these attack primitives to implement a proof of concept of a cross-site scripting attack, and remote code execution on a server. [4] similarly first demonstrate two write primitves. They first introduce a stack-based buffer overlfow. They also demonstrate how the allocator supplied by emscripten is succeptible to the so-called unlink exploit. This can be utilized to allow an attacker to write an arbitrary value to an arbitrary adress. However, we couldn't recreate their exploit using the current version of emscripten. Nevertheless, we will quickly summarize the presented attack primitives. Afterwards we will demonstrate our attempt to recreate these attack primitives. It must be remarked that the main source of security of WebAssembly comes from the fact that it is isolated from the surrounding environment by the Virtual Machine. Thus, for an exploit to be dangerous in the browser it needs to manipulate data that gets passed to functions which can have an effect outside the isolated program. In the broser, such functions will be imported from Javscript. Examples are functions such as **eval** or functions which manipulate the DOM. **Eval** is a Javascript function which will execute any string passed to it as Javascript code. They also quickly describe how user-supplied data could lead to a stack overflow. Since WebAssembly has no guard pages, a stack overflow could overwrite data following the stack. However, no example of an exploit is given.

4.1 Overflowing the unmanaged stack

Overflowing buffers on the stack is one of the most widely used binary exploitation technique. It can happen whenever user-supplied data is copied into a buffer on the stack (such as a fixed-size array) without checking the bounds. The most common example of a function which has this vulnerability is the C function **gets**. The linux manual even states "never use gets". There are many ways to exploit a stack based buffer overflow. In native binaries without mitigations such as stack canaries, a buffer overflow can be used to overwrite the functions return adress. This can lead to executing arbitrary code with the permissions of the program. However, since the WebAssembly Virtual Machine manages return adresses seperately, one could assume that stack based buffer overflows can't be as easily abused. However, if the function has non-scalar data, it will have memory on the unmanaged stack. In fact, since there exist no stack canaries in WebAssembly, a buffer overflow can overwrite any memory before the functions stack frame. This can even include parent frames. Additionally, there are no guard pages in WebAssembly so a stack based buffer overflow can grow into other memory regions such as the heap. [4] have serveral examples to demonstrate this vulnerability. 7 shows an example inspired by them. The parent function **f** has a seemingly const string which gets added to the dom. If the user provided input overflows the local buffer and into the string, it can be used to cause damage outside the isolated program.

```
void f() {
    const char html[8];
    vulnerable();
    add_to_dom(html);
}

void vulnerable() {
    char vuln_buffer[8];
    copy_user_input_to_buffer(vuln_buffer);
}
```

Figure 7: This c program has a stack overflow vulnerability. This can be exploited by the user supplying a buffer which overflows into the parent frame and replaces the string meant to be added to the DOM.

4.2 Redirecting Control Flow

Can we influence the program control flow using an overflow as introduced in 4.1? Since the return adresses are managed by the Virtual machine, the answer seems to be no. However, it is possible to overwrite indirect function calls. As discussed in 2.6, WebAssembly references functions by an Integer. The indirect function call can be influenced if two conditions are met:

- The Integer which identifies the called function lies somewhere in unmanaged memory.
- The originally called function has the same arguments and return type as the newly called function.

Also, if we wish to influence the parameters passed to the newly passed function they too must be within unmanaged memory. The most interesting fact is that, since WebAssembly has no way to mark memory as read-only, it is possible to overwrite supposedly

Exploit mitigation	Protect against	Effect in Native Binaries	WebAssembly
Address Space Layout Randomization (ASLR)	Attacks on Control-Flow	Randomizes the base adress of an executable as well as the heap and stack adresses and adresses of libraries. This is meant to make exploitation techniques such as Return Oriented Programming harder. It also makes exploiting other vulnerabilities more challenging	ASLR has no equivalent mechanism in WebAssembly. However, since the user can't access Return Adresses, many exploits that rely on changing control flow are infeasible. In addition, since WebAssembly only provides 32-bit adresses, it is assumed to have to little entropy for ASLR to be effective. Also, since functions are directly accessed by indices instead of memory adresses, ASLR could not be used to obfuscate function adresses.
Stack Canaries	Stack-based Buffer overflows	Stack Canaries are placed on the stack such that a stack-based buffer overflow will overwrite them before corrupting the functions return adress. This enables the program to detect and handle these overflows	Stack canaries don't exist in WebAssembly, since the return adresses are entirely managed by the VM
Heap Hardening	Manipulating Allocator Metadata	Heap Hardening comprises several different programming techniques to make Allocators more secure against attacks. By corrupting heap metadata, an attacker can use the allocator to execute arbitrary writes on the heap.	Since size is a concern, many toolchains deploy with their own smaller allocator which might have vulnerabilities.
Data Execution Prevention (DEP)	Code injection	This mitigation is part of a family of mitigations which modify memory pages to only allow certain behaviour. These can modify whether the contents of certain memory pages can be executed. In native binaries, this can prevent the injection of malicious code	In webassembly, there is a strict seperation between code and data. Hence, DEP is not needed.

constant data. [5] demonstrate a proof of concept of using a overflow to manipulate control flow. We couldn't recreate their exact example, however a slight modification did work. The example in Figure **??** works on Firefox version 88.0.1 64-Bit when compiled with emscripten version 1.39.16. The imagined scenario is that of a legacy application being ported to WebAssembly. It is possible to send messages and handle them using different functions. A spcially crafted payload can be used to overflow into the **msg_len** and **out** member fields, changing the program behaviour. Again, it uses an unchecked memory copy to alter the control flow. This is used to implement a cross-site scripting attack. When the code is executed in the browser, it displays an alert. Of course, one can imagine using this to steal cookies, etc.

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