Web Evolution and WebAssembly

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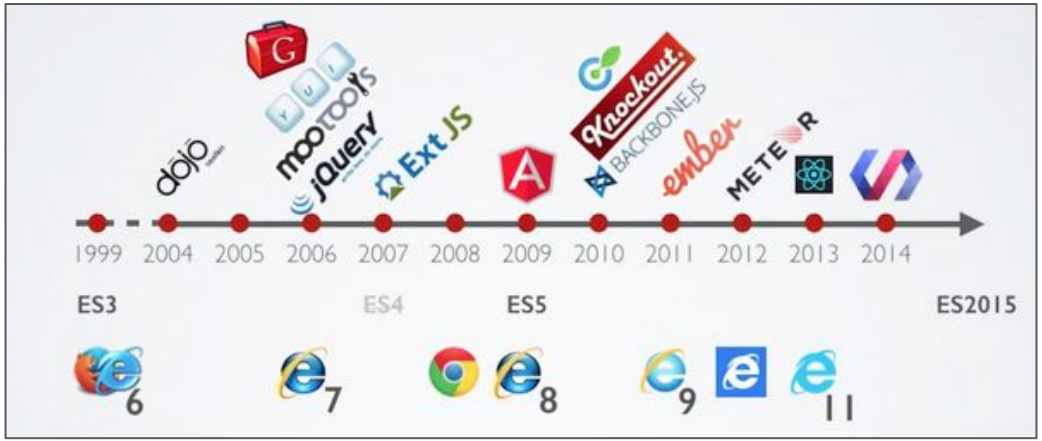
Contents

- Limitations of JavaScript
- Evolution of Web performance via asm.js
- WebAssembly
  - Design
  - Pipeline
    - Decoding
    - Validation
    - Execution
  - Examples

JavaScript - What is JavaScript?

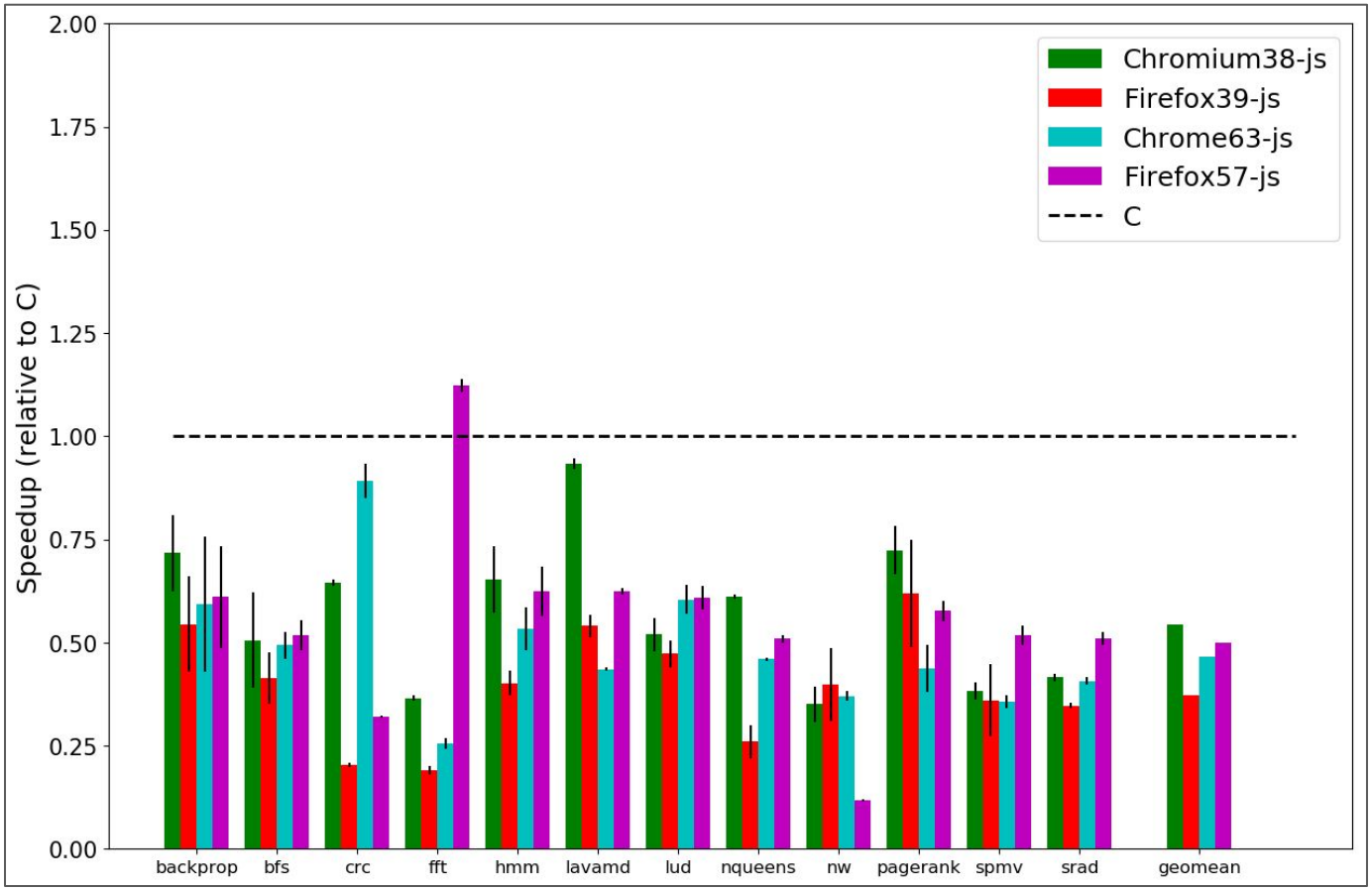
- **Dynamic**, high-level language
- **10 days!,** Famously designed and prototyped in ten days by Brendan Eich
- **Little Performance Design:** Language was not designed with performance in mind.
- **Web Language:** Has been the main programming language for the web since 1999



Limitations of JavaScript

- **Tough Target:** Dynamically typed nature makes it a “tough target” of static languages such as C and C++, as well as a relatively slow language.
- **Lacks Parallelism:** No real parallelism supported natively. (At least not widely supported by all browsers, or general with full control)
- **Number type**: Numbers are restricted to doubles, float64. This means that for instance, an i64 number cannot be represented natively in JavaScript.

Let’s look at speed



JavaScript as a target language for C/C++?

- **Is it Doable?** Yes, since JavaScript is turing complete, it should be able to represent any sort of weird semantics.
- **Is it efficient?** Let’s look at **Emscripten**

What is Emscripten and asm.js?

- **Emscripten** is a static compiler from LLVM to JavaScript created in 2011
- **Asm.js** is a“typed” subset of JavaScript which serves as a target for Emscripten
- Initial goal was to support a large enough subset of C and C++ constructs that could be run on the web.
- Any language that has front-end to **LLVM** can compile to **asm.js**

Let’s look at some of the problems faced by asm.js

Main memory representation

How do we represent C main memory in JavaScript?

Main memory representation

How do we represent C main memory in JavaScript?

How about just a simple array?

```
var HEAP = new Array(size);
```

- This **HEAP** will serve as both C's **stack** and **heap**
- Every element represents a byte, and the addresses are integer indices to the array.

Ok, let’s do something simple

What does this code do?

```
int x = 12345;
printf("The first byte: %d\n", *((char *)&x));
```

- **Recall**: An integer normally has 4 bytes in c, while a char is made up of 1 byte.

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How do we represent it in JavaScript?

Char from Int in JavaScript

Here is the JavaScript Implementation:

```
var x_value = 12345;
var x_addr = stackAlloc(4);
HEAP[x_addr] = (x_value >> 0 ) & 255;
HEAP[x_addr+1] = (x_value >> 8 ) & 255;
HEAP[x_addr+2] = (x_value >> 16 ) & 255;
HEAP[x_addr+3] = (x_value >> 24 ) & 255;
printf("first byte: %d\n",HEAP[x_addr]); //Implemented in JavaScript
```

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- What is the problem?
  - 8 operations and 4 accesses to simply set an integer value!

What was **asm.js** solution to this problem?

- Only support programs that respect **Load-Store Consistency.**
- How do we make sure that a program respects it? Is it efficient?

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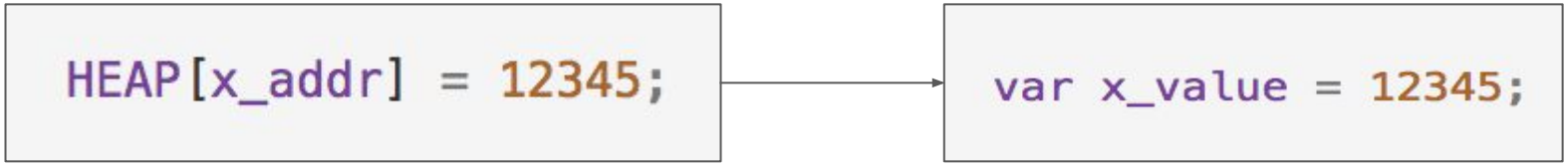
Solution: Don’t check for it!

- Assume property holds and offer a compiler flag to check
- Now we can simply represent an integer with one element in the array.
- Further optimize with **variable nativization**



Continuing with asm.js...

Source: https://blogs.unity3d.com/2014/10/14/first-unity-game-in-webgl-owlchemy-labs-conversion-of-aaaaa-to-asm-js/

Continuing with asm.js...

- Novel ideas from asm.js
  - Supporting a large subset of C and C++ efficiently.
    - The C/C++ programs supported must be cut down in order to perform operations efficiently
  - Make a typed subset of JavaScript which can be highly optimized by a specialized section of the JavaScript JIT compilers.

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- Novel ideas from asm.js
  - Supporting a large subset of C and C++ efficiently.
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  - Make a typed subset of JavaScript which can be highly optimized by a specialized section of the JavaScript JIT compilers.
- **asm.js** has since grown to be supported by most browser vendors.
- In 2013, typed arrays became the standard, all due to **asm.js**
  - ***Int8Array***, ***Int16Array, Int32Array, Float64Array, Float32Array etc.***
  - All of this have an ***ArrayBuffer*** as their underlying representation. This array buffer is a byte array.

Limitations of asm.js

- **Parallelism,** JavaScript still does not support parallelism
  - No data parallelism, e.g. no SIMD instructions
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- **Slow,** Compilation and initialization of an asm.js module is slow.
  - Still has to parse normal JavaScript
  - JavaScript does not come in a “compressed” format i.e. a binary syntax
- **Hard to scale,** in order to grow **asm.js** to support more constructs from typed languages, JavaScript must also grow

Enter WebAssembly…

- WebAssembly, or "wasm", is a general-purpose virtual ISA designed to be a compilation target for a wide variety of programming languages.
- Similar to **JVM,** the IR is stack based
- Currently supported AND in active development by **all** the major browser vendors
- Promises to bridge the gap in performance through different mechanisms

WebAssembly enhancing performance

How?

- Support for various integer, and floating types natively
- Support for data parallelism via SIMD instruction set
- Support for task parallelism via threads.
- Increase in loading speed via a fast binary decoding, and streaming compilation.
- A garbage collector for the “main” memory

WebAssembly - Contents

- Design goals
- Performance
- Representation
- Pipeline
  - Encoding/Decoding
  - Validation
  - Execution
- Examples

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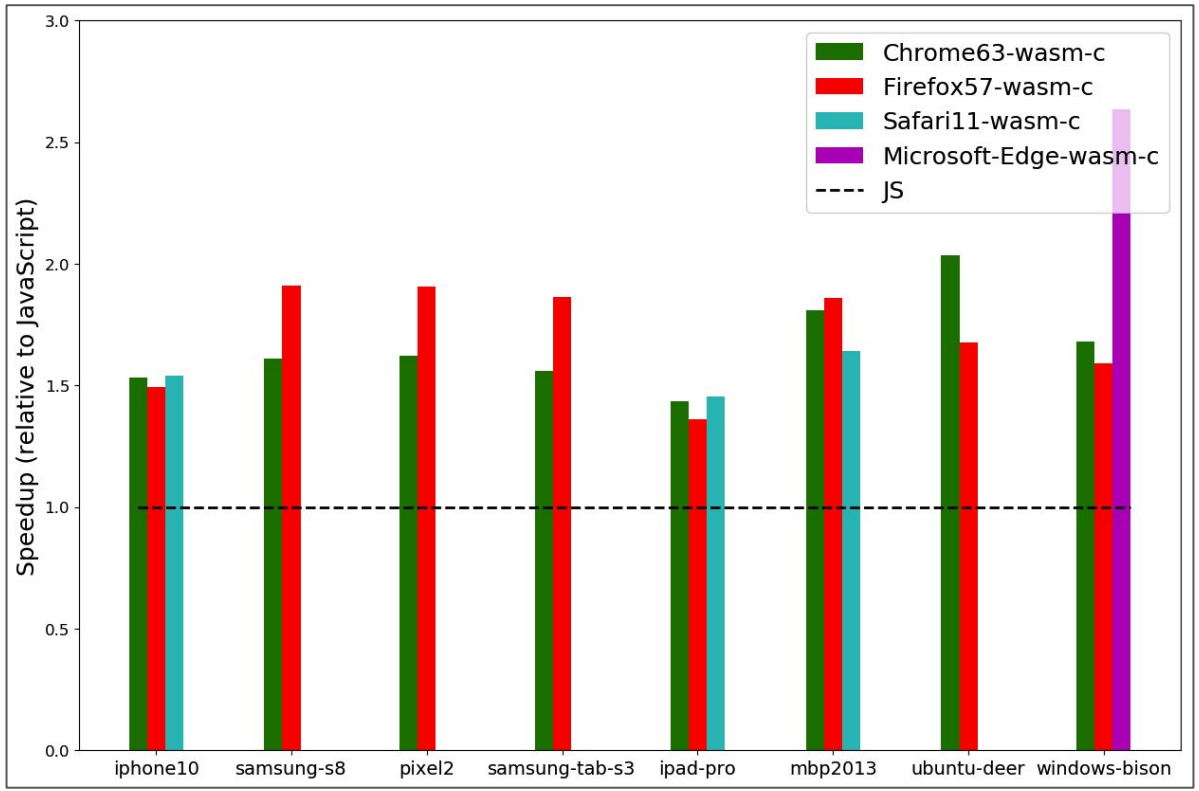
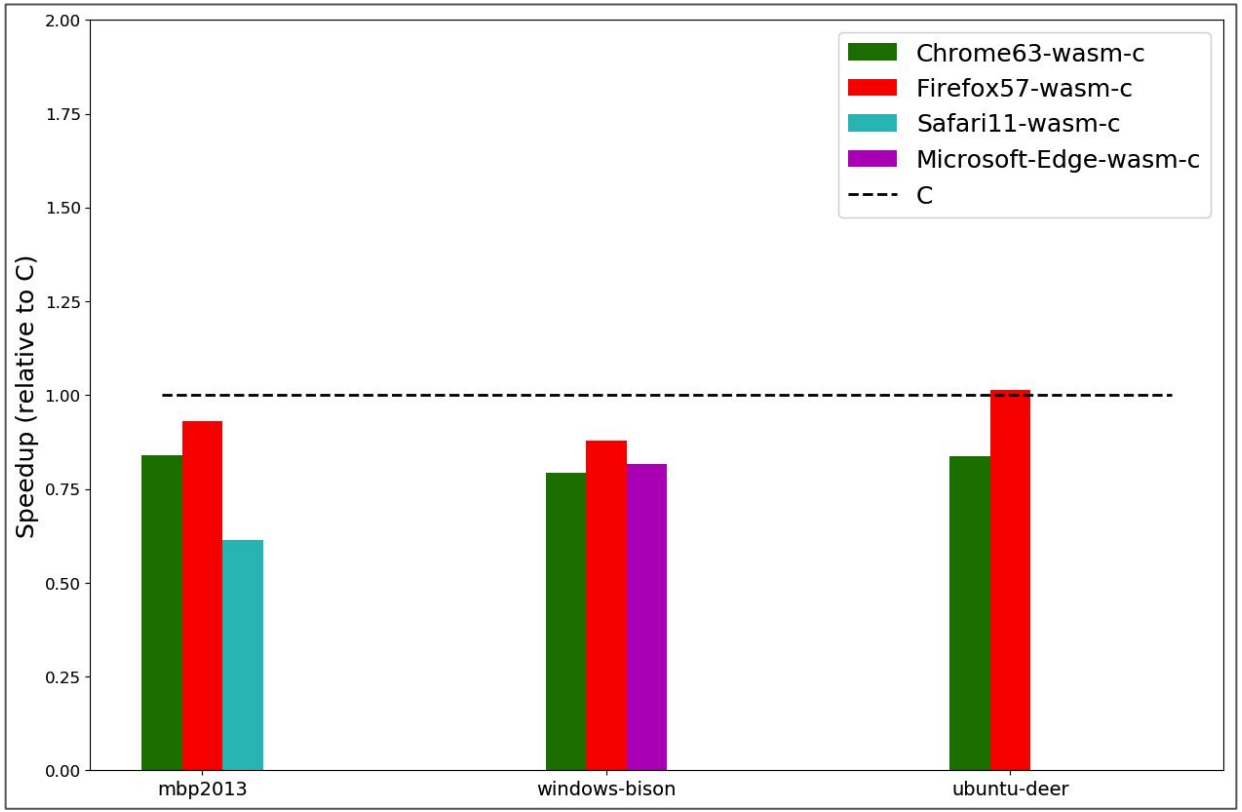
- **Language-Independent**: Does not favor any particular language, Object Model, or programming model, in terms of its semantics.
- **Platform-Independent**: Does not depend on the Web, it can run as an independent VM in any environment,.

Does it deliver on the “close-to-native” performance?

Let’s first see versus JavaScript



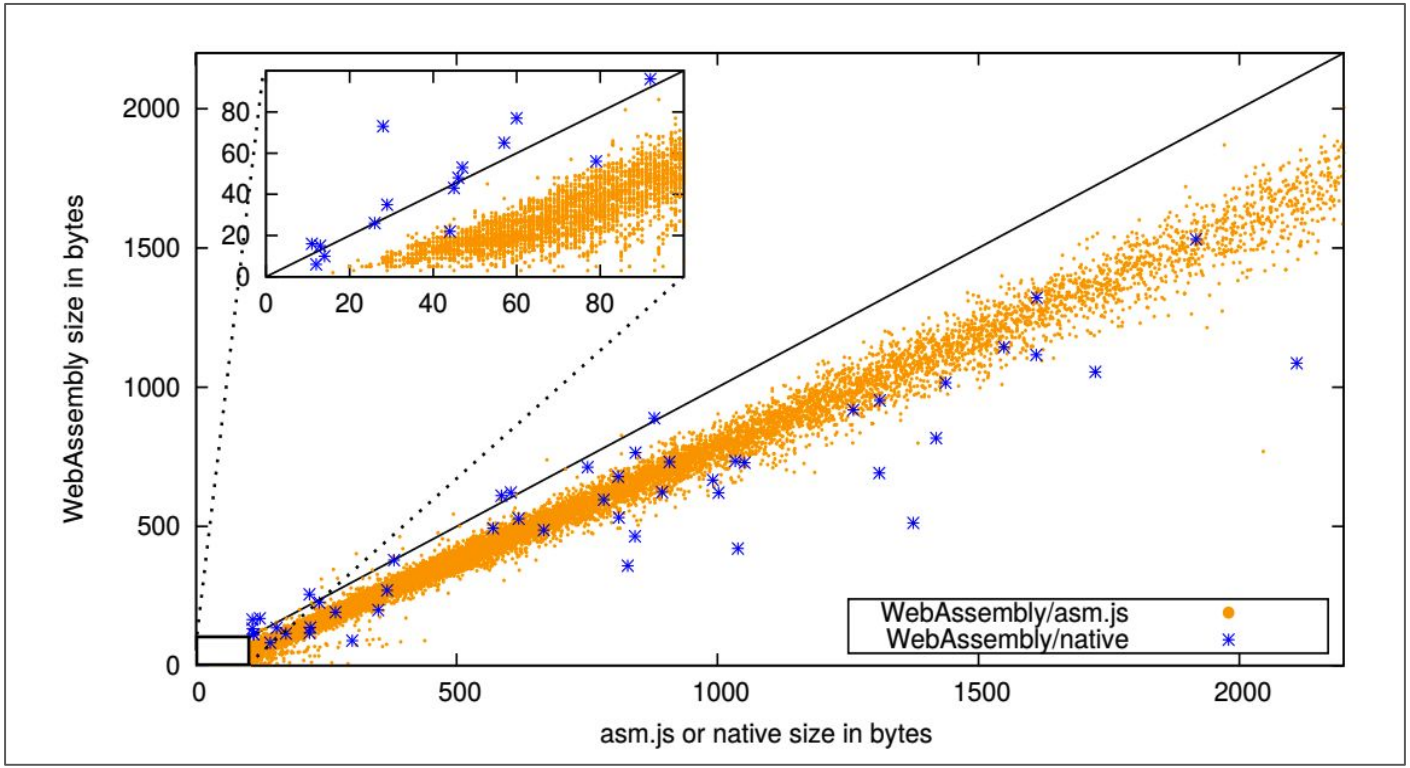
What about versus C?



Representation Design

- **Compact,** binary representation
- **Modular**, can be split up into smaller parts that can be transmitted, cached and consumed separately
- **Efficient,** can be decoded, validated and compiled in a fast single pass, with a JIT or AOT compilation
- **Streamable,** allows decoding, validation and compilation and fast as possible
- **Parallelizable,** allows validation, compilation and splitting into many parallel tasks.

How good is this binary representation?



Source: https://dl.acm.org/citation.cfm?id=3062363

Representations

- **Textual,** Human-readable, debuggable.
- **Binary,** actual representation used by the computer. Easy to decode, and smaller to transmit.

Representations - Textual - .wat

- Human readable, textual representation

```
(module $main
  (import "console" "mem" (func $print (param i32 i32) (result i32)))
  (import "mem" "main" (memory 1))
  (global $MEM_TOP i32 (i32.const 16))
  (table 0 anyfunc)
  (data (i32.const 16) "Hello World\n\00")
  (export "sayHello" (func $hello))
  (func $hello (; 1 ;) (result i32)
    get_global $MEM_TOP
    i32.const 12
    call $print
  )
)
```

- Compile to wasm: **`$wat2wasm say_hello.wat -o say_hello.wasm`**

Representations - binary - .wasm

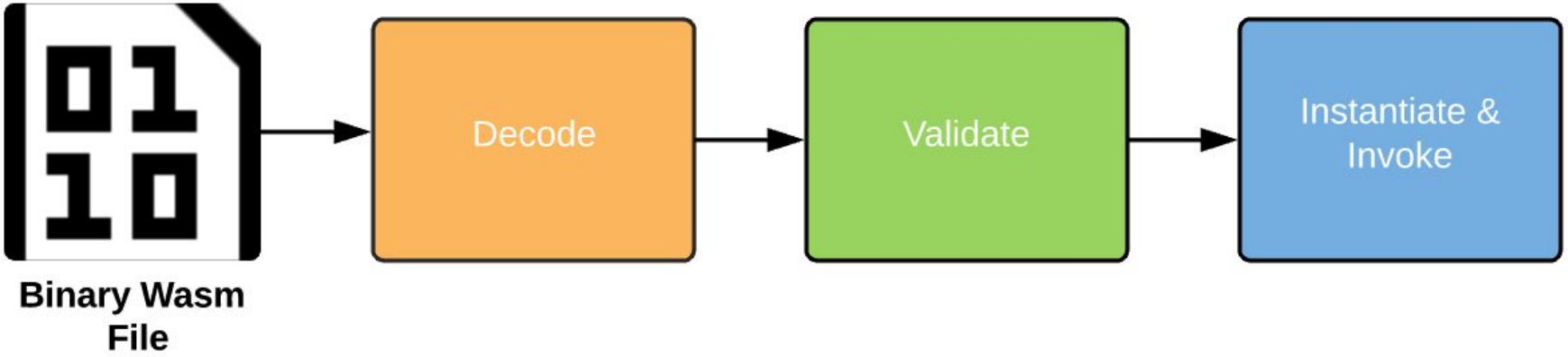
- Binary representation

```
➜  src git:(master) ✗ hexdump -C print_string.wasm
00000000  00 61 73 6d 01 00 00 00  01 0b 02 60 02 7f 7f 01  |.asm.......`....|
00000010  7f 60 00 01 7f 02 1b 02  07 63 6f 6e 73 6f 6c 65  |.`.......console|
00000020  03 6d 65 6d 00 00 03 6d  65 6d 04 6d 61 69 6e 02  |.mem...mem.main.|
00000030  00 01 03 02 01 01 04 04  01 70 00 00 06 06 01 7f  |.........p......|
00000040  00 41 10 0b 07 0c 01 08  73 61 79 48 65 6c 6c 6f  |.A......sayHello|
00000050  00 01 0a 0a 01 08 00 23  00 41 0c 10 00 0b 0b 13  |.......#.A......|
00000060  01 00 41 10 0b 0d 48 65  6c 6c 6f 20 57 6f 72 6c  |..A...Hello Worl|
00000070  64 0a 00                                          |d..|
00000073
```

WebAssembly Types

- There are four basic types:
  - i32, i64, f32, f64
- There is no distinction between signed and unsigned integer types, instead operations are specialized to be signed or unsigned.
- There is a full-matrix of operations for conversions between the types
- i32 integers serve as booleans, addresses, and values.

WebAssembly Pipeline



Decoding/Encoding

- This follows a simple Grammar! Or Binary Grammar, just like the ones you have been doing for your assignments!
- **Procedure:** Decode from binary to hex, then use the grammar!

Let’s go see some rules of this grammar

- Bytes encode themselves

```
byte  ::=  0x00  ⇒  0x00
       |        ...
       |   0xFF  ⇒  0xFF
```

- Types:

```
valtype  ::=  0x7F  ⇒  i32
           |  0x7E  ⇒  i64
           |  0x7D  ⇒  f32
           |  0x7C  ⇒  f64
```

Source:https://webassembly.github.io/spec/core/binary/types.html

Validation

- Usually done along with decoding, in one pass
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- Decoded values for a given type are valid for that type and within appropriate limits, i.e. an i32 constant in the encoding does not overflow

Validation

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- All declarations, imports and function types defined on top of the file

What to validate?

- Decoded values for a given type are valid for that type and within appropriate limits, i.e. an i32 literal does not overflow
- ***Stack,*** *what about the stack?*

Stack Validation

- Similar to **JVM** stack height must remain consistent after each instructions
- Stack contents must have the right type after each operation
- Examples:
  - At the end of a function, we have the right type and height for returning.
  - When we set a local of certain type, the stack height is of at least 1 and has the same type as the local.
  - When adding two i32 numbers, the stack height decreases by 1 and the type on top of the stack is i32.

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  - When adding two i32 numbers, the stack height decreases by 1 and the type on top of the stack is i32.
- **Type rules,** validation has been formally defined in terms of type rules

Validation - Set/Get Local

- **Usage:**

```
;; set_local
(local $arg1 i32)
i32.const 32
set_local $arg1
```

```
;; get_local
(local $arg1 i32)

get_local $arg1
```

- **Validation Typerules**:

$$\frac{C.\,\text{locals}[x] = t}{C \vdash \text{set\_local}\ x : [t] \to []}$$

$$\frac{C.\,\text{locals}[x] = t}{C \vdash \text{get\_local}\ x : [] \to [t]}$$

Source:https://webassembly.github.io/spec/core/valid/instructions.html#control-instructions

Validation - Let’s see a few examples

- **Binops**: add | sub | mul | div_sx | rem_sx | and | or | xor | shl | shr_sx | rotl | rotr
  - **Usage:**

```
(param $arg1 f64)
get_local $arg1
f64.const 5.0
f64.add
```

```
(param $arg1 i32)
get_local $arg1
i32.const 5.0
i32.add
```

  - **Validation Typerule**:

$$\frac{}{C \vdash t.binop : [t\ t] \to [t]}$$

Source: https://webassembly.github.io/spec/core/valid/instructions.html#control-instructions

Execution

- Finally after a module is verified, it goes through two phases:
  - ***Instantiation****:* Dynamic representation of a module, the module imports are loaded, global tables, and memory segments are intialized, and its own execution stack and state are set. Finally its start function is ran.
  - ***Invocation****:* Once instantiated, a module instance is ready to be used by its host/embedding environment via the exported functions defined in the module.
  - The task of Instantiation and invocation is the responsibility of the host environment.

Stack

- We talked about validation of the stack, similar to ***static typing.***
- During execution we care about the actual values
- Again, this was formally defined using, **reduction rules.**

Stack

- We talked about validation of the stack, similar to ***static typing.***
- During execution we care about the actual values
- Again, this was formally defined using formal, **reduction rules.**
- There are three types of stack contents
  - **Values,** i32, i64, f32, f64 constants.
  - **Labels**, branching labels/targets
  - **Frames,** a function's run-time representation
- Other implementations may choose to have three separate stacks but the interleaving of the three stack values makes the implementation simpler.

Let’s take a step back - control flow instructions

- WebAssembly, unlike other low-level languages is based on **structured control flow**
- **if/else:**

```
i32.const 1 ;; [1]
if (result i32) ;;[]
    ;; instruction*
else
    ;; instruction*
end
;;[t:i32]
```

loop/block/br statements

C while loop

```
int i;
i = 0;
while(i<5)
{
    // instructions
    i++;
}
```

WebAssembly

```
i32.const 0
set_local $i
loop $l1
    block $l0
        get_local $i
        i32.const 5
        i32.ge_s
        br_if $l0
        ;; instructions
        i32.const 1
        get_local $i
        i32.add
        set_local $i
        br $l1
    end
end
```

Initialization

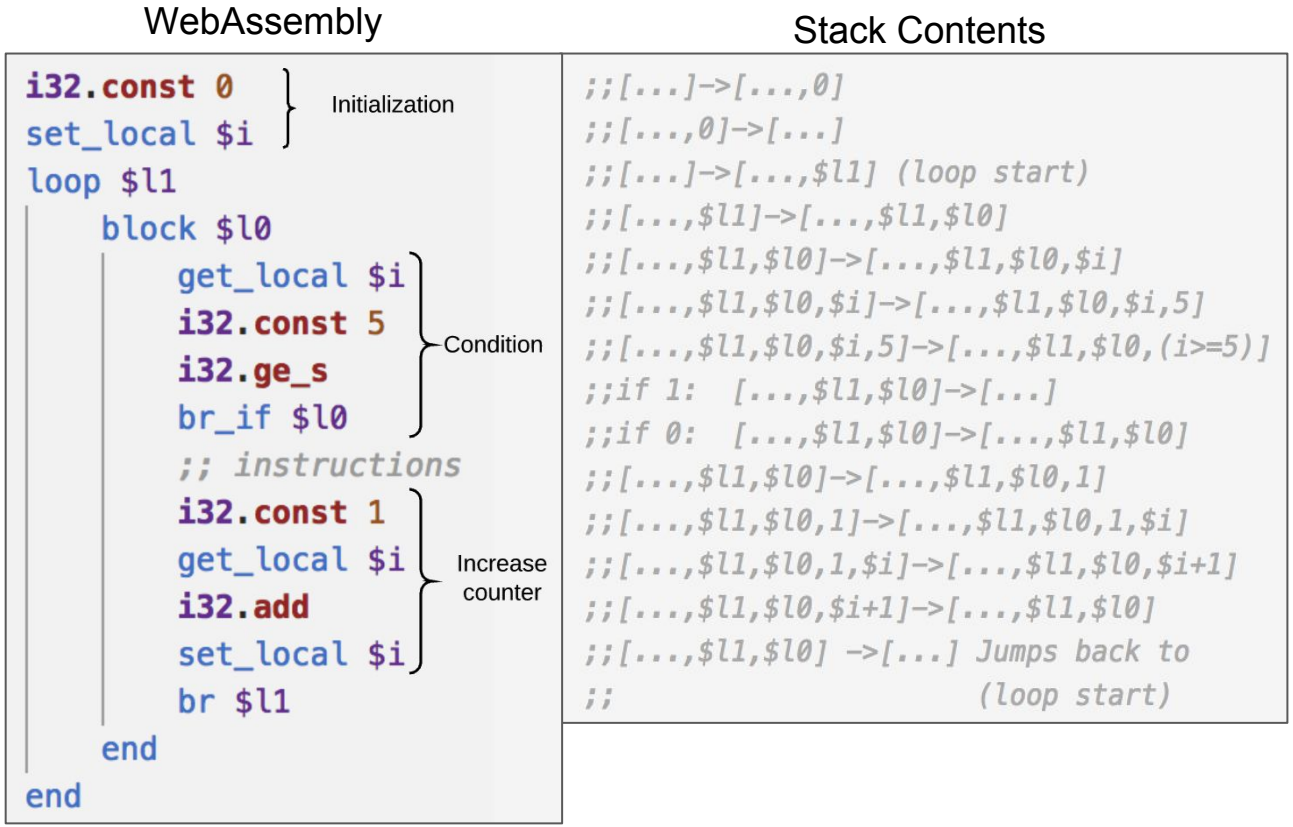
Condition

Increase counter

Stack Contents

```
;;[...]->[...,0]
;;[...,0]->[...]
;;[...]->[...,$l1] (loop start)
;;[...,$l1]->[...,$l1,$l0]
;;[...,$l1,$l0]->[...,$l1,$l0,$i]
;;[...,$l1,$l0,$i]->[...,$l1,$l0,$i,5]
;;[...,$l1,$l0,$i,5]->[...,$l1,$l0,(i>=5)]
;;if 1:  [...,$l1,$l0]->[...]
;;if 0:  [...,$l1,$l0]->[...,$l1,$l0]
;;[...,$l1,$l0]->[...,$l1,$l0,1]
;;[...,$l1,$l0,1]->[...,$l1,$l0,1,$i]
;;[...,$l1,$l0,1,$i]->[...,$l1,$l0,$i+1]
;;[...,$l1,$l0,$i+1]->[...,$l1,$l0]
;;[...,$l1,$l0] ->[...] Jumps back to
;;                      (loop start)
```

loop/block/br statements



Falling through **end** of block

- As mentioned, WebAssembly has been formally defined in terms of ***small-steps rules***

func end_block(stack,L)

// Let **m** be the number of values on
// top of the stack

- Pop **m** values from stack
- **Assert:** Due to validation, **L** should be the label on top of the sack
- Pop **L**
- Push the **m** values back in the stack
- Jump to instruction immediately after block

end

$$\text{label}_n\{instr^*\}\ val^m\ \text{end} \quad \hookrightarrow \quad val^m$$

Examples

Example - Factorial

```
int factorial(int n) {
    int i, sum;
    sum = 1;
    i = 2;
    while (i <= n) {
        sum = sum * i;
        i = i + 1;
    }
    return sum;
}
```

```
(func $factorial (param $n i32) (result i32)
    (local $i i32)(;int i;) (local $sum i32)(;int n;)
    ;; sum=1;
    i32.const 1 ;; ;push i32 1 onto stack-> [1]
    set_local $sum ;; sum = 1; pop top from stack set $sum
    ;; i=2;
    i32.const 2;; ;push i32 2 onto stack-> [1]
    set_local $i ;; i=2; pop top from stack set $i
    ;;....while....
```

Example - Factorial

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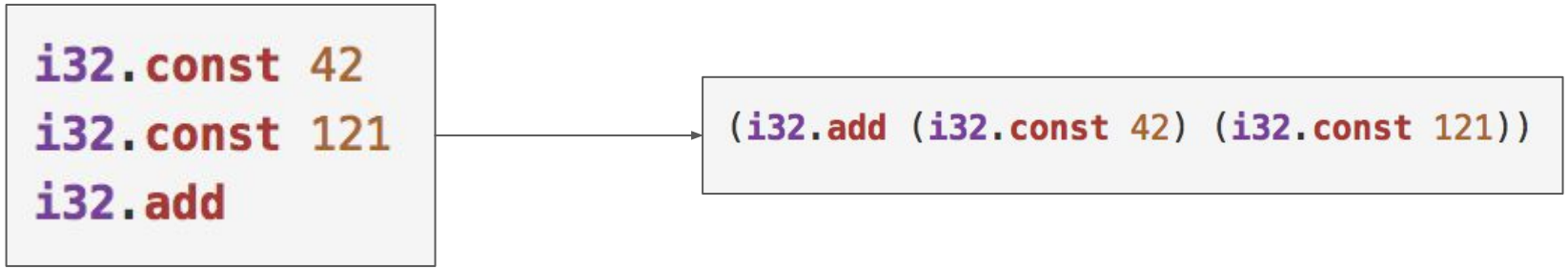
    }
    return sum;
}
```

```
;; while(i<=n)
loop $l0 ;;@1
    block $l1;;@0
        ;;Evaluate condition
        get_local $i ;; load i
        get_local $n ;; load n
        i32.gt_s ;; i > n
        br_if $l1 ;; if i > n go to end of block
        ;; sum = sum * i;
        get_local $sum ;; ;push value of $sum onto stack
        get_local $i ;; ;push value of $i onto stack
        i32.mul ;; sum * i; pop top two values, push i32 result
        set_local $sum ;; sum = sum * i;
        ;; i = i+1;
        get_local $i ;; load i onto stack
        i32.const 1 ;; load 1 onto stack
        i32.add ;; pop $i and 1, add and push i32 result
        set_local $i ;; pop result and set i
        br $l0 ;; Break to beginning of loop
    end $l1;;@0
end $l0;;@1
;; return sum;
get_local $sum ;; push local $sum to stack
return
```

Textual Representation - S-Expressions

- Finally the textual presentation, can be compressed a little bit by the use of ***s-expressions***
- Parenthesis indicate the start of a new child
- The order of evaluation is **child** then **parent**
- For a binary operation, **left child, right child, parent**.
- Example:



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```
(func $factorial (param $n i32) (result i32)
        (local $i i32)(;int i;) (local $sum i32)(;int n;)
        (set_local $sum (i32.const 1)) ;; sum=1;
        (set_local $i (i32.const 2)) ;; i=2;
        loop $l0 ;;@1 ;; while(i<=n)
            block $l1;;@0
                ;;Evaluate condition
                (i32.gt_s (get_local $i) (get_local $n));; i > n
                br_if $l1 ;; if i > n go to end of block
                ;; sum = sum * i;
                (i32.mul (get_local $sum) (get_local $i))
                ;; i = i+1;
                (set_local $i (i32.add (get_local $i)(i32.const 1)))
                br $l0 ;; Break to beginning of loop
            end $l1;;@0
        end $l0;;@1
        (return (get_local $sum))  ;; return sum;
)
```

The End

Thank you!