Wasocaml: compiling OCaml to WebAssembly

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ABSTRACT

The limitations of JavaScript as the default language of the web led to the development of Wasm, a secure, efficient and modular language. However, compiling garbage-collected languages to Wasm presents challenges, including the need to compile or reimplement the runtime. Some Wasm extensions such as Wasm-GC are developed by the Wasm working groups to facilitate the compilation of garbage-collected languages. We present Wasocaml, an OCaml to Wasm-GC compiler. It is the first compiler for a real-world functional programming language targeting Wasm-GC. Wasocaml confirms the adequacy of the Wasm-GC proposal for a functional language and had an impact on the design of the proposal. Moreover, the compilation strategies developed within Wasocaml are applicable to other compilers and languages. Indeed, two compilers already used a design similar to our. Finally, we describe how we plan to handle the C/JavaScript FFIs and effects handlers, in order to allow developers to easily deploy programs mixing C, JavaScript and OCaml code to the web, while maintaining good performances.

CCS CONCEPTS

• **Software and its engineering → Compilers**.

KEYWORDS

ocaml, wasm, compilation, value representation, memory, cps, ffi, effect handler

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1 CONTEXT

JavaScript is widely thought as being the de facto language of the web. However, it does show its limitations when it comes to performance, security and safety. In order to remedy this, WebAssembly (Wasm for short) [3] has been developped as a secure modular language of predictable performance. Its usage is expanding beyond the web: finding applications in the cloud (Fastly, Cloudflare) and in the creation of portable binaries.

The first version of Wasm was meant to compile libraries in languages such as C, C++ or Rust to expose them for consumption by a JavaScript program. It was designed with the explicit aim that future versions would catter to the specific needs of other languages and uses. This version of Wasm can be seen as simplified C. Here is an example:

```
(func $fact (param $x i32) (result i32)
  (if (i32.eq (local.get $x) (i32.const 0))
    (then (i32.const 1))
  (else
    (i32.mul
      (local.get $x)
      (call $fact
        (i32.sub (local.get $x) (i32.const 1)))))))
```

A Wasm module is executed inside what is called an *embedder* or a *host*. In the context of the web, it is a browser and the host language is JavaScript. A Wasm program only manipulates scalar values (integers and floats) but not garbage collected values coming from the host language, such as JavaScript objects. This would be useful in a browser context, but requires some interaction with the GC of the embedder. This led to various extensions that we describe in the next section.

1.1 Wasm Extensions

We discuss only the most notable ones, that is to say the tail call [19], reference types [20], typed function references [21], GC [18], and exception handling [17] extensions.

1.1.1 References and GC. The aim of these proposals is to allow the program to manipulate references to different kinds of values such as opaque objects, functions, and garbage-collected values. Since Wasm has to be memory safe, those values are not exposed as raw pointers. Instead, the type system guarantees the proper manipulation of such values.

```
(type $f1 (func (param i32) (result i32)))
(type $t1 (array i31ref))
(type $t2 (struct
  ((field $a (ref $t1))
   (field $b (ref $f1))
   (field $c i32))))

(func (param $x (ref $t2)) (result i32)
  (i31.get_u
```

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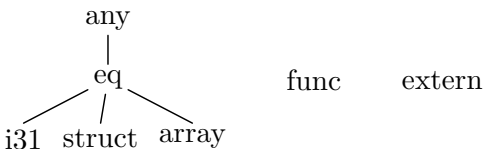
```
    (array.get $t1
      (i32.const 0)
      (struct.get $t2 $a (local.get $x)))))
```

However, Wasm is rather a compilation target than a programming language. It needs to be able to represent the values of any kind of source language. It was not deemed possible to have a type system powerful enough to do that. Instead, the decision was made to have a simple type system, but to rely on dynamic cast to fill the gaps, and guarantee that those casts are efficient.

There is a sub-typing relation that controls which casts are allowed. Some types are predefined by Wasm: **anyref**, **eqref**, **i31ref**, **funcref** and **funcref**. Others are user defined: array and struct. There is a structural sub-typing relation between user types. Upcasts are implicit, downcasts are explicit and incorrect ones lead to runtime errors. It is possible to dynamically test for type compatibility.



Contribution to the proposals. The general rule for the Wasm committee is to only include features with a demonstrated use case. As there are currently very few compilers targeting the GC-proposal, some features were lacking conclusive evidence of their usefulness. An example is the **i31ref** type that is not required by the Dart compiler (the only one targeting the GC-proposal at the time). Wasocaml demonstrates the usefulness of **i31ref**. It also validates the GC-proposal on a functional language. We presented Wasocaml to the Wasm-GC working group [2]. It helped in convincing the working group to keep **i31ref** in the proposal.

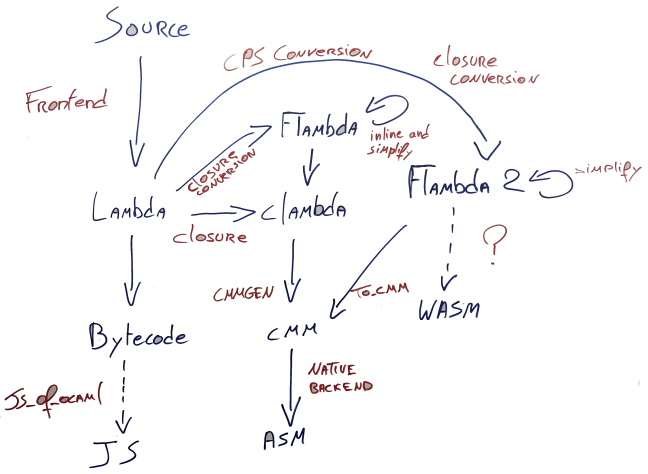
1.1.2 Exception. Another serious limitation of Wasm1 is the absence of an exception mechanism. This is not a problem for compiling either C or Rust, but C++ does require them. It is of course possible to encode exception, but this has a significant runtime cost and limits the interactions with JavaScript (that has exceptions).

1.1.3 Tail Calls. Wasm1 does not allow tail-calls to be optimized. This is a show-stopper when compiling functional languages. In the tail-call proposal, new instructions such as `return_call` guarantee that a tail-call will be optimized.

2 SOURCE LANGUAGE

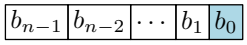
2.1 OCaml Intermediate Representation Choice

OCaml has many intermediate representations (IR for short). In the *Lambda* IR, closures are still implicit and the code has not been optimized. The *Bytecode* representation is not well optimized. The *Clambda* one is too low-level for Wasm because code pointers and values are mixed inside closures. *Cmm* is even more low-level: it has pointer arithmetic. The *Flambda* IR is simpler than *Flambda2*, thus it is the one we choosed for our first prototype. We will use Flambda2 in the future, as it provides better optimisations.



2.2 Native OCaml Value Representation

The various OCaml IRs are working on a uniform representation of values, known as pointer tagging. One bit is used to indicate if the value is a small scalar or a pointer to a heap-allocated block. Granted we are working on n bits values, we have to choose one bit that will be the *tag bit*. For instance, if we choose the least significant bit, we start by testing its value:

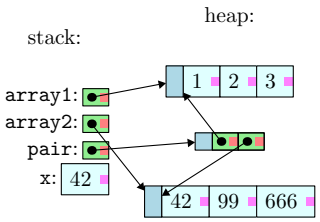


If $b_0 = 0$, then the whole value is a pointer:

If $b_1 = 1$, then the $n-1$ most significant bits are a small scalar and b_0 is ignored:

In the second case, we talk about *small scalars* instead of scalars because we can only represents 2^{n-1} values instead of the 2^n that are representable when all bits are available. For pointers, we do not lose anything as they need to be *aligned* anyway and the least significant bit is always zero.

```
let array1 = [| 1; 2; 3 |]
let array2 = [| 42; 99; 666 |]
let pair = (array1, array2)
let x = 42
```



2.3 Flambda semantics

We give a formal semantics for a subset of Flambda. Compared to the full Flambda it has the following limitations: the objects related primitives have been removed, functions only have one argument,

exceptions have been removed but we still have static exceptions that are described later.

2.3.1 Abstract syntax.

Value. A value v is either an integer n or an address a.

$$\begin{aligned} v &::= n && \text{(integer)} \\ &\mid a && \text{(address)} \end{aligned}$$

An integer represents a value of many types in the OCaml source language such as an **int**, a **bool**, a **char** or the constant constructors of a sum type. An address points to a heap-allocated values.

Store. A store $\mathscr{M}$ is a map from addresses to heap-allocated values. It is used to represent the state of the memory. Heap-allocated values can either be a closure $\mathscr{S}.x$, a set of closures $\mathscr{S}$ or a block made of a tag n and a list of values v^*. A closure is made of a set of closures $\mathscr{S}$ and of a name x which is its identifier inside the set.

$$\begin{aligned} \mathscr{M} &::= a \mapsto n, v^* && \text{(block)} \\ &\mid \mathscr{S}.x && \text{(closure)} \\ &\mid \mathscr{S} && \text{(set of closure)} \end{aligned}$$

Set of closure. A set of closures $\mathscr{S}$ represents a set of mutually recursives functions.

$$\mathscr{S} ::= \mathscr{V}, \mathscr{C}$$

It is made of two maps $\mathscr{V}$ and $\mathscr{C}$. The map $\mathscr{V}$ is the environment (the values captured by the closures). An environment is a map from names to values.

$$\mathscr{V} ::= x \mapsto v$$

The map $\mathscr{C}$ is the closure map (the code of each function). It is a map from names to codes.

$$\mathscr{C} ::= x \mapsto \lambda\, x\, x\, .\, t$$

The code is a function that takes two arguments and produces a term. The first argument is the real argument of the function. The second one is an address a to a closure $\mathscr{S}.x$. It is used to access the environment or to call other functions of the set $\mathscr{S}$.

Binary operator.

$$\begin{aligned} op &::= eq && \text{(equality)} \\ &\mid add && \text{(addition)} \\ &\mid sub && \text{(subtraction)} \end{aligned}$$

Branches.

$$\mathscr{B} ::= n \ \mapsto\ t$$

Term.

$$\begin{aligned} t &::= v && \text{(value)} \\ &\mid x && \text{(identifier)} \\ &\mid \texttt{let}\ x = t\ \texttt{in}\ t && \text{(let-binding)} \\ &\mid x\ x && \text{(application)} \\ &\mid x\ \texttt{<-}\ x && \text{(mutation)} \\ &\mid \texttt{if}\ x\ \texttt{then}\ t\ \texttt{else}\ t && \text{(conditional)} \\ &\mid \texttt{switch}\ x\ \mathscr{B}\ \mathscr{B} && \text{(switch)} \\ &\mid \texttt{sraise}\ x\ x^* && \text{(static raise)} \\ &\mid \texttt{scatch}\ t\ \texttt{with}\ x\ x^*\ t && \text{(static catch)} \\ &\mid \texttt{while}_t\ t\ \texttt{do}\ t && \text{(while loop)} \\ &\mid \texttt{get\_field}\ n\ x && \text{(block field read)} \\ &\mid \texttt{set\_field}\ n\ x\ x && \text{(block field write)} \\ &\mid \texttt{make\_block}\ n\ x^* && \text{(block creation)} \\ &\mid \texttt{project\_closure}\ x\ x && \text{(closure projection)} \\ &\mid \texttt{project\_var}\ x\ x && \text{(closure environment)} \\ &\mid \texttt{move\_within\_closure}\ x\ x && \text{(closure movement)} \\ &\mid \texttt{make\_set\_of\_closures}\ \mathscr{S} && \text{(closures allocation)} \\ &\mid \texttt{pop}\ t && \text{(pop environment)} \\ &\mid x\ op\ x && \text{(binary operator)} \end{aligned}$$

2.3.2 Small-step semantics.

Reduction context.

$$\begin{aligned} E ::= &\square \\ &\mid \texttt{let}\ x = E\ \texttt{in}\ t \\ &\mid \texttt{while}_t\ E\ \texttt{do}\ t \\ &\mid \texttt{scatch}\ E\ \texttt{with}\ x\ x^*\ t \\ &\mid \texttt{pop}\ E \end{aligned}$$

Reduction inside a context.

$$\frac{\mathscr{V}^*, \mathscr{M}, t_1 \rightarrow \mathscr{V}'^*, \mathscr{M}', t_2}{\mathscr{V}^*, \mathscr{M}, E(t_1) \rightarrow \mathscr{V}'^*, \mathscr{M}', E(t_2)}$$

Head reductions.

$$\frac{\mathscr{V}_0(x) = v}{\mathscr{V}_0\mathscr{V}^*, \mathscr{M}, x \rightarrow \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, v}$$

An identifier simply reduces to its image in the current environment.

$$\text{let-binding}\ \frac{}{\begin{array}{lll} \mathscr{V}_0\mathscr{V}^*, & \mathscr{M}, & \texttt{let}\ x = v\ \texttt{in}\ t \\ \rightarrow\ \mathscr{V}_0[x \leftarrow v]\mathscr{V}^*, & \mathscr{M}, & t \end{array}}$$

A let-binding $\texttt{let}\ x = v\ \texttt{in}\ t$ reduces to t and adds a binding from x to v in the current environment.

$$\text{application}\ \frac{\begin{array}{c}\mathscr{V}_0(x_1) = a \qquad \mathscr{M}(a) = \mathscr{S}.x \\ \mathscr{S} = \_, \mathscr{C} \qquad \mathscr{C}(x) = \lambda\ x_3\ x_4\ .\ t \\ \mathscr{V}_0(x_2) = v\end{array}}{\begin{array}{lll}\mathscr{V}_0\mathscr{V}^*, & \mathscr{M}, & x_1\ x_2 \\ \rightarrow \quad [x_3 \leftarrow v; x_4 \leftarrow a]\mathscr{V}_0\mathscr{V}^*, & \mathscr{M}, & \mathsf{pop}\ t\end{array}}$$

An application $x_1\ x_2$ looks for an address a in the current environment. The image of a in the store must be a closure $\mathscr{S}.x$ where the set of closures $\mathscr{S} = \_, \mathscr{C}$. Let the value of x in the closure map $\mathscr{C}$ be $\lambda\ x_3\ x_4\ .\ t$. The term reduces to $\mathsf{pop}\ t$ and we create a new environment containing two bindings: x_3 is mapped to the value of x_2 in the current environment and x_4 is mapped to a.

$$\text{mutate}\ \frac{\mathscr{V}_0(x_1) = v_1 \qquad \mathscr{V}_0(x_2) = v_2}{\mathscr{V}_0\mathscr{V}^*, \mathscr{M}, x_1\ \texttt{<-}\ x_2 \rightarrow \mathscr{V}_0[x_1 \leftarrow v_2]\mathscr{V}^*, \mathscr{M}, 0}$$

A mutation x_1 `<-` x_2 simply updates the value of x_1 to be the value of x_2 in the current environment. It reduces to 0 which corresponds to the value `()` : **`unit`** in OCaml.

$$\text{conditional 1}\ \frac{\mathscr{V}_0(x) = n \qquad n \neq 0}{\begin{array}{lll}\mathscr{V}_0\mathscr{V}^*, & \mathscr{M}, & \texttt{if}\ x\ \texttt{then}\ t_1\ \texttt{else}\ t_2 \\ \rightarrow \quad \mathscr{V}_0\mathscr{V}^*, & \mathscr{M}, & t_1\end{array}}$$

A conditional `if` x `then` t_1 `else` t_2 reduces to t_1 when the value of x in the current environment is not 0 (i.e. when it is `true` : **`bool`** in OCaml).

$$\text{conditional 2}\ \frac{\mathscr{V}_0(x) = n \qquad n = 0}{\begin{array}{lll}\mathscr{V}_0\mathscr{V}^*, & \mathscr{M}, & \texttt{if}\ x\ \texttt{then}\ t_1\ \texttt{else}\ t_2 \\ \rightarrow \quad \mathscr{V}_0\mathscr{V}^*, & \mathscr{M}, & t_2\end{array}}$$

Similarly, it reduces to t_2 when the value of x is 0 (i.e. when it is `false` : **`bool`** in OCaml).

$$\text{switch 1}\ \frac{\mathscr{V}_0(x) = n \qquad \mathscr{B}_1(n) = t}{\mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \texttt{switch}\ x\ \mathscr{B}_1\ \mathscr{B}_2 \rightarrow \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, t}$$

When the value of x in the current environment is an integer n, then `switch` $x\ \mathscr{B}_1\ \mathscr{B}_2$ reduces to the image of n in $\mathscr{B}_1$.

$$\text{switch 2}\ \frac{\mathscr{V}_0(x) = a \qquad \mathscr{M}(a) = n, v^* \qquad \mathscr{B}_2(n) = t}{\mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \texttt{switch}\ x\ \mathscr{B}_1\ \mathscr{B}_2 \rightarrow \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, t}$$

Similarly, when x is an address a and $\mathscr{M}(a)$ is a block with tag n, then `switch` $x\ \mathscr{B}_1\ \mathscr{B}_2$ reduces to the image of n in $\mathscr{B}_2$.

$$\text{raise 1}\ \frac{x_{exn} \neq x'_{exn}}{\begin{array}{l}\mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \\ \texttt{scatch}\ (\texttt{sraise}\ x_{exn}\ x^n)\ \texttt{with}\ x'_{exn}\ x'^n\ t \\ \rightarrow \quad \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \\ \texttt{sraise}\ x_{exn}\ x^n\end{array}}$$

If a raised exception does not match the exception expected by a static catch, then the catch is discarded and we re-raise the exception.

$$\text{raise 2}\ \frac{\begin{array}{cc}x_{exn} = x'_{exn} & x^n = x_0, \ldots, x_{n-1} \\ x'^n = x'_0, \ldots, x'_{n-1} & \forall i \in [0; n[, \mathscr{V}_0(x_i) = v_i\end{array}}{\begin{array}{l}\mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \\ \texttt{scatch}\ (\texttt{sraise}\ x_{exn}\ x^n)\ \texttt{with}\ x'_{exn}\ x'^n\ t \\ \rightarrow \quad \mathscr{V}_0[x'_0 \leftarrow v_0, \ldots, x'_{n-1} \leftarrow v_{n-1}]\mathscr{V}^*, \mathscr{M}, \\ t\end{array}}$$

On the contrary, when the two exceptions match, the identifiers specified in the catch are binded to the values of the identifiers transported by the exception. The values are taken in the current environment. We have the guarantee that if the transported identifiers were in the environment when we raised, then they are also in the environment when we catch. This is because static exceptions never cross a function application. Finally, the reduced term is the one attached to the catch.

$$\text{raise 3}\ \frac{}{\begin{array}{lll}\mathscr{V}^*, & \mathscr{M}, & \\ & \texttt{while}_{t'}\ (\texttt{sraise}\ x_{exn}\ x^*)\ \texttt{do}\ t & \\ \rightarrow \quad \mathscr{V}^*, & \mathscr{M}, & \\ & \texttt{sraise}\ x_{exn}\ x^* & \end{array}}$$

A while simply re-raises static exceptions.

$$\text{raise 4}\ \frac{}{\begin{array}{l}\mathscr{V}^*, \mathscr{M}, \texttt{let}\ x = (\texttt{sraise}\ x_{exn}\ x^*)\ \texttt{in}\ t \\ \rightarrow \quad \mathscr{V}^*, \mathscr{M}, \texttt{sraise}\ x_{exn}\ x^*\end{array}}$$

Similarly, a let-binding also re-raises static exceptions.

$$\text{while loop 1}\ \frac{n = 0}{\mathscr{V}^*, \mathscr{M}, \texttt{while}_{t'}\ n\ \texttt{do}\ t \rightarrow \mathscr{V}^*, \mathscr{M}, 0}$$

A loop $\texttt{while}_{t'}\ n\ \texttt{do}\ t$ reduces to 0 when $n = 0$.

$$\text{while loop 2}\ \frac{n \neq 0}{\begin{array}{l}\mathscr{V}^*, \mathscr{M}, \texttt{while}_{t'}\ n\ \texttt{do}\ t \\ \rightarrow \quad \mathscr{V}^*, \mathscr{M}, \texttt{let}\ \_ = t\ \texttt{in}\ \texttt{while}_{t'}\ t'\ \texttt{do}\ t\end{array}}$$

On the contrary, when $n \neq 0$, it reduces to $\texttt{let}\ \_ = t\ \texttt{in}\ \texttt{while}_{t'}\ t'\ \texttt{do}\ t$. The term t' corresponds to the original term that was used as a condition.

$$\text{field read}\ \frac{\begin{array}{c}\mathscr{V}_0(x) = a \qquad \mathscr{M}(a) = tag, v^* \\ v^* = v_0, \ldots, v_{m-1} \qquad m > n \geq 0\end{array}}{\mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \texttt{get\_field}\ n\ x \rightarrow \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, v_n}$$

The term `get_field` $n\ x$ reduces to the n^{th} value of the block stored at address a with a being the value of x in the current environment.

$$\text{field write}\ \frac{\begin{array}{c}\mathscr{V}_0(x_1) = a \qquad \mathscr{M}(a) = tag, v^* \qquad v^* = v_0, \ldots, v_{m-1} \\ m > n \geq 0 \qquad\qquad \mathscr{V}_0(x_2) = v\end{array}}{\begin{array}{l}\mathscr{V}_0\mathscr{V}^*, \\ \mathscr{M}, \\ \texttt{set\_field}\ n\ x_1\ x_2 \\ \rightarrow\ \mathscr{V}_0\mathscr{V}^*, \\ \mathscr{M}[a \leftarrow tag, v_0, \ldots, v_{n-1}, v, v_{n+1}, \ldots, v_{m-1}], \\ 0\end{array}}$$

If x_1 is the address a in the current environment, then the term `set_field` $n\ x_1\ x_2$ sets the n^{th} value of the block stored at address a to the value of x_2 in the current environment.

$$\text{block creation}\ \frac{\mathscr{V}_0(x_0) = v_0, \ldots, \mathscr{V}_0(x_{n-1}) = v_{n-1} \qquad a \notin \text{dom}(\mathscr{M})}{\begin{array}{rl}& \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \texttt{make\_block}\ n_{tag}\ x_0, \ldots, x_{n-1} \\ \rightarrow & \mathscr{V}_0\mathscr{V}^*, \mathscr{M}[a \leftarrow n_{tag}, v_0, \ldots, v_{n-1}], 0\end{array}}$$

This creates a new block in the store at a fresh address. The tag is given as a value while the others values of the block are read from the current environment.

$$\text{closure projection}\ \frac{\begin{array}{c}\mathscr{V}_0(x_2) = a_1 \\ \mathscr{M}(a_1) = \mathscr{S} \qquad \mathscr{M}(a_2) = \mathscr{S}.x_1\end{array}}{\begin{array}{rl}& \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \texttt{project\_closure}\ x_1\ x_2 \\ \rightarrow & \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, a_2\end{array}}$$

This reduces to the address a_2 of the closure which has the identifier x_1 in the set of closures at address a_1, with a_1 being the value of x_2 in the current environment. In short, it allows to get a particular function from a previously allocated set of closures.

$$\text{variable projection}\ \frac{\begin{array}{c}\mathscr{V}_0(x_2) = a \qquad \mathscr{M}(a) = \mathscr{S}.x \\ \mathscr{S} = \mathscr{V}, \_ \qquad \mathscr{V}(x_1) = v\end{array}}{\mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \texttt{project\_var}\ x_1\ x_2 \rightarrow \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, v}$$

This reduces to the value of x_1 in the environment of the set of closures that contains the closure at address a_a, with a_a being the vaue of x_2 in the current environment. In short, when inside a closure, it allows to read a variable from the set of closures the closure belongs to.

$$\text{closure movement}\ \frac{\begin{array}{c}\mathscr{V}_0(x_2) = a_1 \\ \mathscr{M}(a_1) = \mathscr{S}.x \qquad \mathscr{M}(a_2) = \mathscr{S}.x_1\end{array}}{\begin{array}{rl}& \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \texttt{move\_within\_closure}\ x_1\ x_2 \\ \rightarrow & \mathscr{V}_0\mathscr{V}^*, \mathscr{M}, a_2\end{array}}$$

This reduces to the address a_2 of the closure x_1 in the set of closures to which the closure at address a_1 belongs to. In short, when inside a closure, it allows to get another closure in the current set of closures.

$$\text{pop environment}\ \frac{}{\mathscr{V}_0\mathscr{V}^*, \mathscr{M}, \text{pop}\ v \rightarrow \mathscr{V}^*, \mathscr{M}, v}$$

This simply throws away the current environment. This is used to model the call stack. A pop is inserted around each function application and removed once the function is fully evaluated to a value.

$$\text{set alloc}\ \frac{\begin{array}{c}\mathscr{S} = \_, \mathscr{C} \qquad x_0 \in \text{dom}(\mathscr{C}), \ldots, x_{n-1} \in \text{dom}(\mathscr{C}) \\ \forall a \in [a_0, \ldots, a_n], a \notin \text{dom}(\mathscr{M})\end{array}}{\begin{array}{rl}& \mathscr{V}^*, \mathscr{M}, \texttt{make\_set\_of\_closures}\ \mathscr{S} \\ \rightarrow & \mathscr{V}^*, \\ & \mathscr{M}[a_n \leftarrow \mathscr{S}; a_0 \leftarrow \mathscr{S}.x_0; \ldots; a_{n-1} \leftarrow \mathscr{S}.x_{n-1}], \\ & a_n\end{array}}$$

This maps the set of closures $\mathscr{S}$ and all its closures to fresh addresses in the store. The term reduces to the address of the set.

2.4 Example

The following OCaml code:

```
let f = print_int
let rec iter f l =
  match l with
  | [] -> ()
  | hd :: tl ->
    f hd;
    iter f tl
let () =
  let iter_print = iter f in
  iter_print [2; 1]
```

Would corresponds to the following Flambda code:

```
let f =
  let s =
    make_closures
    | cl_f { x } env -> print_int x
    with vars
    end
  in
  project_closure cl_f from s
in

let iter =
  let set =
    make_closures
    | cl_iter { f } env ->
      let otherset =
        make_closures
        | cl_iter_f { l } envtwo ->
          switch l
          with int
          | 0 -> const 0
          with tag
          | 0 ->
            let x = get_field 0 l in
            let f = project_var f from envtwo in
            let dummy = f x in
            let tl = get_field 1 l in
            envtwo tl
          end
        with vars
        | f -> f
        end
      in
```

```
      project_closure cl_iter_f from otherset
    with vars
    end
  in
  project_closure cl_iter from set
in

let lempty = const 0 in
let one = const 1 in
let lone = make_block 0 one lempty in
let two = const 2 in
let ltwo = make_block 0 two lone in
let iter_print = iter f in
iter_print ltwo
```

3 COMPILING FLAMBDA TO WASM

There have been attempts at targeting the early versions of Wasm from OCaml. The first one, *OCamlrun WebAssembly* [7] simply compiles the OCaml runtime (including the GC) and interpreter using emscripten [13] (a C to Wasm compiler). The second one, WASICaml [11] is a smarter and more efficient version of the same approach.

These approaches suffer from the same problem as C programs running on Wasm: they cannot natively manipulate external values, such as DOM objects in the browser. Indeed, in the first versions of Wasm, the only types are scalars (**i32**, **i64**, **f32** and **f64**). There is no way to directly manipulate values from the embedder (*e.g.* JavaScript objects). It could be possible to identify objects with an integer and map them to their corresponding objects on the embedder side. This approach comes with the usual limitations of having two runtimes manipulating (indirectly) garbage-collected values: it is tedious and easily leads to memory leaks (cycles between the two runtimes cannot be collected).

To properly interact with the embedder, we need to leverage the reference extension. This extension adds new types to the language, e.g. **externref** which is an opaque type representing a value from the embedder. References cannot be stored in the linear memory of Wasm thus they cannot appear inside OCaml values when using the previously described compilation scheme.

In order to use references, we require a completely different compilation strategy. We do not use the linear memory. Our strategy is close to the native OCaml one, which we describe now.

We use the Flambda IR of the OCaml compiler as input for the Wasm generation. This is a step of the compilation chain where most of the high-level OCaml-specific optimisations are already applied. Also in this IR, the closure conversion pass is already performed. Most of the constructions of this IR maps quite directly to Wasm ones.

Wasocaml is a compiler for the full Flambda IR. We describe the full compilation scheme but for the sake of simplicity we only formalize a subset of Flambda.

3.1 OCaml Value Representation in Wasm

As in native OCaml, we use a uniform representation. We cannot use integers, as they cannot be used as pointers. We need to use a reference type. The most general one is **anyref**. We can be more precise and use **eqref**. This is the type of all values that can be tested for physical equality. It is a super type of OCaml values. This also allows us to test for equality without requiring an additional cast.

Small scalars. All OCaml values that are represented as integers in the native OCaml are represented as **i31ref**. This includes the **int** and **char** types, but also all constant constructors of sum types.

Arrays. The OCaml array type is directly represented as a Wasm array.

Blocks. For other kinds of blocks, there are two possible choices: we can either use a struct with a field for the tag and one field per OCaml value field, or use arrays of **eqref** with the tag stored at position 0.

3.1.1 Blocks as Structs. A block of size one is represented using the type `$block1` while for size two it is `$block2`:

```
(type $block1 (struct
  (field $tag i8)
  (field $field0 eqref)))

(type $block2 (sub $block1) (struct
  (field $tag i8)
  (field $field0 eqref)
  (field $field1 eqref)))
```

The type `$block2` is declared as a subtype of `$block1` because in the OCaml IRs, the primitive for accessing a block field is untyped: when accessing the n-th field of the block the only available information is that the block has size at least $n+1$. It could be possible to propagate size metadata in the IRs but that wouldn't be sufficient because of untyped primitives such as **Obj**`.field` that we need to support in order to be compatible with existing code.

```
(func $snd (param $x eqref) (result eqref)
  (struct.get $block2 1
    (ref.cast $block2 (local.get $x))))
```

3.1.2 Blocks as Arrays. We represent blocks with an array of eqref:

```
(type $block (array eqref))
```

The tag is stored in the cell at index 0 of the array. Reading its value is implemented by getting the cell and casting it to an integer:

```
(func $tag (param $x eqref) (result i32)
  (i31.get_u (ref.cast i31ref
    (array.get $block
      (i32.const 0)
      (ref.cast $block (local.get $x))))))
```

Thus accessing the field n of the OCaml block amounts to accessing the field $n+1$ of the array:

```
(func $snd (param $x eqref) (result eqref)
  (array.get $block
    (i32.const 2)
    (ref.cast $block (local.get $x))))
```

3.1.3 Block Representation Tradeoffs. The array representation is simpler but requires (implicit) bound checks at each field access and a cast to read the tag.

On the other hand, the struct representation requires a more complex cast for the Wasm runtime (a subtyping test). A compiler propagating more types could use finer Wasm type information, providing a precise type for each struct field. This would allow fewer casts.

The V8 runtime allows to consider casts as no-ops (only for test purposes). The speedup we measured is around 10%. That gives us an upper bound on the actual runtime cost of casts.

OCaml blocks can be arbitrarily large, and very large ones do occur in practice. In particular, modules are compiled as blocks and tend to be on the larger side. We have seen in the wild some examples containing thousands of fields. Wasm only allows a subtyping chain of length 64, which is far from sufficient for the struct encoding.

In the formalization we use the *blocks as arrays* representation.

3.1.4 Boxed Numbers. Raw Wasm scalars are not subtypes of `eqref` thus they cannot be used directly to represent OCaml boxed numbers. We need to box them inside a struct in order to make them compatible with our representation:

```
(type $boxed_float (struct (field $v f64)))
(type $boxed_int64 (struct (field $v i64)))
```

3.1.5 Closures. Wasm `funcref` are functions, not closures, hence we need to produce values containing both the function and its environment. The only Wasm type construction that can contain both `funcref` and other values are structs. Thus, a closure is a struct containing a `funcref` and the captured variables. As an example, here is the type of a closure with two captured variables:

```
(type $closure1 (struct
  (field funcref)
  (field $v1 eqref)
  (field $v2 eqref)))
```

In order to reduce casts and to handle mutually recursive functions, the actual representation is a bit more complex. This is the only place where we need recursive Wasm types.

3.2 Control flow

Control flow and continuations have a direct equivalent with Wasm `block`, `loop`, `br_table`, and `if` instructions. Low level OCaml primitives to handle exceptions are quite similar to Wasm ones. In OCaml, it is possible to generate new exceptions at runtime by using *e.g.* the `let exception` syntax or functors and first-class modules. This is not possible in the Wasm exception proposal. Thus, we use the same Wasm exception everywhere and manage the rest on the side by ourselves, using an identifier to discriminate between different exceptions.

3.3 Currification

The main difference revolves around functions. In OCaml, functions take only one argument. However, in pratice, functions look like they have more than one. Without any special management this would mean that most of the code would be functions producing closures that would be immediately applied. To handle that, internally, OCaml does have functions taking multiple arguments, with some special handling for times when they are partially applied. This information is explicit at the Flambda level. In the native OCaml compiler, the transformation handling that occurs in a later step called cmmgen. Hence, we have to duplicate this in Wasocaml. Compiling this requires some kind of structural subtyping on closures such that, closures for functions of arity one are supertypes of all the other closures. Thankfully there are easy encodings for that in Wasm.

3.4 Stack Representation

Most of the remaining work revolves around translating from let bound expressions to a stack based language without producing overly naive code. Also, we do not need to care too much about low level Wasm specific optimisations as we rely on Binaryen [16] (a quite efficient Wasm to Wasm optimizer) for those.

3.5 Unboxing

The main optimisation available in native OCaml that we are missing is number unboxing. As OCaml values have a uniform representation, only small scalars can fit in a true OCaml value. This means that the types `nativeint`, `int32`, `int64` and `float` have to be boxed. In numerical code, lots of intermediate values of type float are created, and in that case, the allocation time to box numbers completely dominates the actual computation time. To limit that problem, there is an optimisation called unboxing performed during the cmmgen pass that tends to eliminate most of the useless allocations. As this pass is performed after Flambda, and was not required to produce a complete working compiler, this was left for future work. Note that the end plan is to use the next version of Flambda, which does a much better job at unboxing. For the time being, we can expect Binaryen to perform local unboxing in some cases.

3.6 Expected Performances

We are able to run the classical functional microbenchmarks using the experimental branch of V8 and the results are quite convincing. While we do not expect to be competitive with the native code compiler, the performance degradation seems to be almost constant (around twice slower).

We are currently working on producing benchmarks on real sized programs, it is not easy as Wasocaml is still a prototype and is not yet integrated Wasocaml is still a prototype and is not yet integrated into existing build systems. Nonetheless, we are able to compile an OCaml implementation of the Knuth-Bendix algorithm [5]. On V8 the Wasm exception handling proposal is really slow compared to native OCaml: a raise is around a hundred times slower. In SpiderMonkey (the Firefox engine) they are much faster but other proposals are missing and we can't run code we generate. We have to discuss with the V8 team if this is expected and if this can be improved.

Compared to a JavaScript VM, a Wasm compiler is a much simpler beast that can compile ahead of time. For this reason, various Wasm engines are expected to behave quite similarly. They do not show any of the wild impredictability that browsers tend to demonstrate with JavaScript. Indeed, compiling OCaml to JS using jsoo leads to results that are usually also twice as slow as native code in the best cases, but can sometimes be much slower in an unpredictable fashion.

Currently there is no other Wasm runtime supporting all the extensions we require. SpiderMonkey does not have tail-call. The reference interpreter implementation of the various extensions are split in separate repository and merging them requires some work. Nevertheless, we expect performances of Wasm-GC to vary across implementations in a not too different way than they do for C-compiled Wasm programs. Although the implementation choices space is larger when it comes to a full GC than when implementing what is needed in Wasm1 (*e.g.* register allocation).

4 FORMALIZED COMPILATION SCHEME

When compiling a program, we start with the following template:

```
(module $wasocaml_generated_modul

  (type $mlfun (sub final
    (func (param eqref) (param eqref) (result eqref))))

  (type $data (sub final
    (array (mut (ref null eq)))))

  (type $block (sub final (struct
    (field i32)
    (field (ref null $data)))))

  (type $vars (sub final (array (mut eqref))))

  (rec
    (type $set_of_closures (sub final (struct
      (field (mut (ref null $closures)))
      (field (ref null $vars)))))

    (type $closures (sub final
      (array (mut (ref $closure)))))

    (type $closure (sub final (struct
      (field (ref $mlfun))
      (field (mut (ref null $set_of_closures)))))))

  (global $tmp_set_of_closures
    (mut (ref null $set_of_closures))
    ref.null $set_of_closures)
  (global $tmp_switch_value
    (mut i32) i32.const 0)

  (elem declare (ref $mlfun)
    ;; ...
  )

  (func $start
    ;; ...
    drop
  )

  (start $start)
)
```

To compile a term we define a function $\mathscr{T}$ from Flambda terms to Wasm expressions. We define it case by case. Here we do not only use the S-expression notation for Wasm but also use the stack notation which makes these rules clearer.

$$\mathscr{T}(n) = \texttt{i32.const}\ n$$
$$\texttt{i31.new}$$

An integer literal is turned into an **i31ref** in order to match with the uniform representation.

$$\mathscr{T}(x) = \texttt{local.get}\ \$x$$

To access the value of an identifier, we simply access the value stored in the local variable of the current function.

$$\mathscr{T}(\texttt{let}\ x = t_1\ \texttt{in}\ t_2) = \mathscr{T}(t_1)$$
$$\texttt{local.set}\ \$x$$
$$\mathscr{T}(t_2)$$

A let-binding is compiled by evaluating t_1, storing its result in the local x and evaluating t_2.

$$\begin{aligned}\mathscr{T}(x_1\ x_2) = {}& \texttt{local.get}\ \$x_1\\ & \texttt{ref.cast}\ (\texttt{ref}\ \$\texttt{closure})\\ & \texttt{local.get}\ \$x_2\\ & \texttt{ref.as\_non\_null}\\ & \texttt{local.get}\ \$x_1\\ & \texttt{ref.cast}\ (\texttt{ref}\ \$\texttt{closure})\\ & \texttt{struct.get}\ \$\texttt{closure}\ 0\\ & \texttt{call\_ref}\ \$\texttt{mlfun}\end{aligned}$$

To apply a function t_1 to a value t_2 we first put the two parameters of the function on the stack. The first one is the closure itself, which is needed to access the environment and other functions in the set of closures. The second one can be any value of type **eqref**. Then we need to put the function of the stack. This is done by accessing the field 0 of the closure, which is a **funcref**. Then we use `call_ref` to call the function with its two arguments. The type of the function reference is always `$mlfun`.

$$\begin{aligned}\mathscr{T}(x_1 \texttt{<-}\ x_2) = {}& \texttt{local.get}\ \$x_2\\ & \texttt{local.set}\ \$x_1\\ & \texttt{i32.const}\ 0\\ & \texttt{i31.new}\end{aligned}$$

A mutation simply puts the content of x_2 into x_1 and leaves 0 on the stack (this is `() : unit` in OCaml).

$$\mathscr{T}(\texttt{if } x_1 \texttt{ then } t_1 \texttt{ else } t_2) =$$
```
local.get $x1
ref.cast i31ref
i31.get_s
(if (result (ref null eq))
    (then T(t1))
    (else T(t2)))
ref.as_non_null
```

A conditional converts the value of x_1 to an **i32** and then uses a Wasm **if**. The two branches are simply the result of compiling t_1 and t_2.

$$\mathscr{T}(\texttt{switch } x\ \mathscr{B}_1\ \mathscr{B}_2) = TODO$$

$$\mathscr{T}(\texttt{sraise } x_{exn}\ x^n) =$$
```
local.get $x_{n-1}
...
local.get $x_0
br $exn_x_exn
```

A static raise puts all the value transported by the exception on the stack and branches to the block corresponding to the raise.

$$\mathscr{T}(\texttt{scatch } t_1 \texttt{ with } x_{exn}\ x^n\ t_2) =$$
```
(block $after_try_catch) (result (ref null eq))
    (block $exn_x_exn
        (result (ref null eq)) ;; 0
        (result (ref null eq)) ;; ...
        (result (ref null eq)) ;; n - 1
        T(t1)
        br $after_try_catch)
    local.set $x0
    ...
    local.set $x_{n-1}
    T(t2) )
```

A catch has two nested blocks. The first one is used in case no exception is raised and directly returns the value of t_1. The second one corresponds to the case where an exception is raised. It needs to have many results corresponding to all the values transported by the exception. It will put all theses values in the right locals.

$$\mathscr{T}(\texttt{while}_{t_1}\ t_1 \texttt{ do } t_2) =$$
```
(block $exit_while_loop
    (loop $while_loop
        T(t1)
        i31.get_s
        i32.eqz
        br_if $exit_while_loop
        T(t2)
        drop
        br $while_loop ))
i32.const 0
i31.new
```

A while loop maps quite directly to a Wasm **loop**. We also need an other block in order to exit the loop when the condition is false.

$$\mathscr{T}(\texttt{get\_field } n\ x) =$$
```
local.get $x
ref.cast (ref $block)
struct.get $block 1
ref.as_non_null
i32.const n
array.get $data
```

To read a field of a block, we need to cast it to a block, access its second fields which contains the values of the block (the first field being the tag). Then we simply read the element at the index n.

$$\mathscr{T}(\texttt{set\_field } n\ x_1\ x_2) =$$
```
local.get $x1
ref.cast (ref $block)
struct.get $block 1
ref.cast (ref $data)
i32.const x
local.get $x2
array.set $data
i32.const 0
i31.new
```

Similarly, to set a field of a block, we cast it, access its data field and then set the element at index n to the value of x_2. There array is mutable and there is no need to update the structure after the element has been set.

$$\mathscr{T}(\texttt{make\_block } n\ x_0, \ldots, x_{m-1}) =$$
```
i32.const n
local.get $x0
...
local.get $x_{m-1}
array.new_fixed $data m
struct.new $block
```

To create a new block, we put its tag on the stack. Then we put all its data and make a new array from it. With the tag and the array we then make a new structure of type `$block`.

$$\mathscr{T}(\texttt{project\_closure}\ x_1\ x_2) =$$
```
local.get $x2
ref.cast (ref $set_of_closures)
struct.get $set_of_closures 0
global.get $closure_offset_within_set_x1
array.get $closures
```

To read a closure from a set of closures, we cast x_2 to a set. Then we access its first field, which is an array of closures. Then we look for the offset of x_1 and access it.

$$\mathscr{T}(\texttt{project\_var}\ x_1\ x_2) =$$
```
local.get $x2
ref.cast (ref $closure)
struct.get $closure 1
ref.as_non_null
struct.get $set_of_closures 1
global.get $var_offset_within_set_x1
array.get $vars
```

This is similar to the closure case but the difference here is that x_2 is a closure and not a set. We need to access its parent first. Then we access the second field, which is the array of the captured variables. Then we need again to look for the offset of the variable before reading the array.

$$\mathscr{T}(\texttt{move\_within\_closure}\ x_1\ x_2) =$$
```
local.get $x2
ref.cast (ref $closure)
struct.get $closure 1
ref.as_non_null
struct.get $set_of_closures 0
global.get $closure_offset_within_set_x1
array.get $closures
```

This is the same as the previous case: x_2 is a closure and not a set. The only difference being that we look in the first field instead of the second one.

$$\mathscr{T}(\texttt{make\_set\_of\_closures}\ \mathscr{S}) = \mathit{TODO}$$

The code of the compiled Flambda program is inserted as the code of the `$start` function. But we also need to analyse the term in order to do a few more things. Each function defined in a set of closures is also added as a new Wasm function and marked as a declarative element (in order to be referenced by the `ref.func` instruction). Moreover, each function and each variable in a set of closures has its own offset stored as a global variable (for instance `global $closure_offset_within_set_myfunc`). Finally, each function is analysed in order to find which locals it requires to be declared.

For now, we don't have a proof of the correcteness of our compilation scheme. The formal semantics of the various Wasm extensions we are needing is still an ongoing work by the various working groups. We would like to use these semantics in the future.

4.1 Example of generated code

The example given in 2.4 would be compiled to the following Wasm code:

```
(module $wasocaml_generated_modul
  (func $start (local $f (ref null eq));; ...
    ref.null $closures
    array.new_fixed $vars 0
    struct.new $set_of_closures
    global.set $tmp_set_of_closures
    global.get $tmp_set_of_closures
    ref.func $cl_f
    ;; ...
    local.get $iter_print
    ref.cast (ref  $closure)
    struct.get $closure 0
    call_ref $mlfun
    drop)
  (func $cl_f (param $env eqref) (param $x eqref)
              (result eqref)
    local.get $x
    ref.cast (ref  i31)
    i31.get_u
    call $print_i32
    i32.const 0
    i31.new)
(func $cl_iter_f (param $envtwo eqref) (param $l eqref)
(result eqref) (local $x eqref) (local $f eqref)
(local $dummy eqref) (local $tl eqref)
  (block $switch_a  (result (ref null eq))
    (block $switch_b  (result (ref null eq))
      local.get $l
      br_on_cast $switch_b (ref null eq) i31ref
      ref.cast (ref  $block)
      struct.get $block 0
      global.set $tmp_switch_value
      global.get $tmp_switch_value
      i32.const 0
      i32.eq
      (if (result (ref null eq))
        (then
          local.get $l
          ref.cast (ref  $block)
          struct.get $block 1
          ;; ...
          local.get $envtwo
          ref.cast (ref  $closure)
          struct.get $closure 0
```

```
            call_ref $mlfun)
          (else unreachable))
        br $switch_a)
      ref.cast (ref  i31)
      i31.get_s
      global.set $tmp_switch_value
      global.get $tmp_switch_value
      i32.const 0
      i32.eq
      (if (result (ref null eq))
        (then
          i32.const 0
          i31.new)
        (else
          unreachable))))
  (func $cl_iter ;; ...
  ))
```

5 PERSPECTIVES

As the first version of the implementation was intended as a demonstration, it remains a bit rough around the edges. In particular only a fraction of the externals from the standard library externals are provided as handwritten Wasm. The only unsupported part of the language is the objects fragment (by lack of time rather than due to any specific complexity). The source code of Wasocaml is publicly available [1].

5.1 FFI

A lot of OCaml code in the wild interacts with C or JavaScript code through bindings written using dedicated FFI mechanisms. We plan to allow re-use of existing bindings when compiling to Wasm. Currently, using C bindings when targeting the browser is not possible. People have to rewrite their code in pure OCaml or using JavaScript bindings. Compiling C bindings directly to Wasm allows to re-use them as-is.

C bindings. Some extensions recently added to Clang [6] allow to compile C code to Wasm in a way that makes reusing existing OCaml bindings to C code possible with almost no change. We would only have to provide a modified version of the OCaml native FFI headers files, replacing the usual macros with hand written Wasm functions. The only limitation that we forsee is that the `Field` macro will not be an l-value anymore; a new `Set_field` macro will be needed instead (as it was originally proposed for OCaml 5).

JavaScript bindings. To re-use existing bindings of OCaml to JavaScript code, we need one more extension: the reference-typed strings proposal [24]. Almost all external calls in the JavaScript FFI goes through the `Js.Unsafe.meth_call` function which has the type `'a -> string -> any array -> 'b`. It can be exposed to the Wasm module by the embedder as a function of type:

```
(func $meth_call
  (param $obj externref)
  (param $method stringref)
  (param $args $anyarray)
  (result externref))
```

This calls a method of name `$method` on the object `$obj` with the arguments `$args`. The JavaScript side manages all the dynamic typing.

5.2 Effect Handlers Support

Our compiler is based on OCaml 4.14. So effect handlers were out of the scope. There are three strategies to handle them.

CPS Compilation. It is possible to represent effect handlers as continuations, using whole-program CPS transformation [4]. However it is not ideal for two reasons. It requires the program to contain OCaml code only. Moreover, it prevents the use of the stack of the target language and instead stores that stack in the heap, with a non-negligible cost. It can be mitigated by only applying the transformation to code that cannot be proved to not use effect handlers but then it is no longer compatible with separate compilation and the optimisation needs to be done as a whole program transformation. This is the choice made by Js_of_ocaml.

Wasm Stack Switching. There is an ongoing proposal, called stack switching [23], that exactly matches the needs for OCaml effect handlers. With it the translation would be quite straightforward.

JavaScript Promise Integration. Another strategy is available for runtimes providing both Wasm and JavaScript. There is another ongoing proposal called JavaScript promise integration [22]. With this proposal, effects handlers can be implemented with a JavaScript device. This proposal is likely to land before the proper stack switching one. It might be a temporary solution.

6 RELATED WORK

6.1 Garbage Collected Languages to Wasm

6.1.1 *Targeting Wasm1.*

Go. Go compiles to Wasm1 [9]. In order to be able to re-use the Go GC, it must be able to inspect the stack. This is not possible within Wasm. Thus it has to maintain the stack by itself using the memory, which is much slower than using the Wasm stack.

Haskell. Haskell also compiles to Wasm [10]. It has constraints similar to Go and uses similar solutions. In particular, it also uses the memory to manage the stack.

6.1.2 *Targeting Wasm-GC.*

Dart. Dart [12] compiles to Wasm-GC. It does not uses `i31ref` and boxes scalars in a `struct`.

Scheme. The last addition to the small family of compiler targeting Wasm-GC is the Guile Scheme compiler. Scheme has many similar constraints as OCaml and Guile uses many similar solutions. The compiler was presented to the Wasm-GC working group [26]. A more detailed explanation is published [25]. The implementation and its in-depth technical description are available [27].

6.2 OCaml Web Compilers

The history of OCaml compilers targeting web languages is quite crowded. Surely thanks to the great pleasure that is writing compilers in OCaml.

6.2.1 *Targeting JavaScript.*

There are multiple OCaml compilers targeting JavaScript. Many approaches where experimented, the main two live ones are jsoo and melange. Naive compilation of OCaml to JavaScript is quite simple as it can almost be summarized as "type erasure". There are some limitations in JavaScript that prevent that to be a complete compilation strategy, and, of course, a proper compiler producing efficient and small JavaScript code is quite more complex.

Jsoo. Jsoo [15] tries to be as close as possible from the native semantics. It compiles OCaml bytecode programs to JavaScript by decompiling it back to a simple untyped lambda calculus then performs many optimisation and minimisation passes.

Melange. Melange [8] tries to produce readable JavaScript, with a closer integration in the JavaScript module system. Melange starts from a modified version of the lambda IR which provides more type information. This allows the use of JavaScript features that match the uses of source features at the cost of some small semantical differences.

6.2.2 *Targeting Wasm.*

OCamlrun WebAssembly. OCamlrun WebAssembly [7] compiles the OCaml runtime and interpreter to Wasm. They are both written in C so it is possible without any Wasm extension. In some cases, it allows to start executing code faster than when compilin OCaml to Wasm. This is because there is less WebAssembly code to compile for the embedder. On the other hand, the execution is slower as it is interpreting OCaml bytecode inside Wasm instead of running a compiled version.

WASICaml. WASICaml [11] is quite similar to OCamlrun WebAssembly. The main difference being that WASICaml does not interpret the bytecode directly but translates it partially to Wasm. It leads to a faster execution.

Wasm_of_ocaml. Wasm_of_ocaml [14] is a fork of Js_of_ocaml. It compiles the bytecode to Wasm-GC and re-uses many of the techniques developed by Wasocaml. It does not benefit from the optimisations provided by Flambda. It is also quite restricted in its value representation choice and must use a representation based on arrays.

7 CONCLUSION

The original goal of this implementation was to validate the Wasm-GC proposal and discuss its limits. This part was successful. No major changes were required for OCaml (mainly keeping the `i31ref` type and changes to the maximal length of subtyping chains). And we are quite happy to claim that Wasm-GC is, to our opinion a very good design, that is a perfect compilation target for a garbage collected functional language like OCaml. And we think that the experience for most other garbage-collected languages will probably be similar.

As a side-effect, we now have an OCaml to Wasm-GC compiler. It is not yet usable because there are no user-side Wasm-GC runtime available. In order to test our compiler we are using V8 with various flags to enable experimental features such as the GC support. The design of the various extensions required by Wasocaml is stable and quite close to completion, but some details are still in flux. For this reason, we cannot expect it them be widely available soon. On the other hand, it means that our compiler will be ready when browsers start deploying new Wasm extensions.

Our future plans are to complete the Wasm implementations of OCaml externals, to implement the various FFI mechanisms, support effect handlers and to move Wasocaml to Flambda2. All of these would allow to easily deploy multi-language software on the browser while having good and predictable performances.

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