Continuing WebAssembly with Effect Handlers

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I am but one of many


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`https://wasmfx.dev`

WebAssembly (Wasm): neither web nor assembly (Haas et al. 2017)

What is Wasm?

- A low-level virtual machine
- Source language agnostic
- Platform independent target
- Formally specified[1] and mechanised
- A predictable performance model

Code format

- A Wasm "program" is a structured module
- Designed for streaming compilation
- The term language is *statically typed* and block-structured
- Control flow is structured (*i.e.* all CFGs are reducible)

`https://webassembly.org`

[1] Wasm 1.0 has a tiny bit of nondeterminism related to floating point NaNs

Wasm primer: stack machine

Stack machine

```
(i32.const 2)
(i32.const 5)
(i32.add)
```

Wasm primer: stack machine

Stack machine

```
(i32.const 2)
(i32.const 5)
(i32.add)        ⟶    (i32.const 7)
```

Wasm primer: stack machine

Stack machine

```
(i32.const 2)
(i32.const 5)
(i32.add)        ⟶    (i32.const 7)
```

Syntactic sugar: `(i32.add (i32.const 2) (i32.const 5))`

Wasm primer: stack typing

Stack typing

$$
\begin{aligned}
&\texttt{(}\textbf{\texttt{i32.const}}\texttt{ 2)} &:\quad& [] \to [\text{i32}]\\
&\texttt{(}\textbf{\texttt{i32.const}}\texttt{ 5)} &:\quad& [] \to [\text{i32}]\\
&\texttt{(}\textbf{\texttt{i32.add}}\texttt{)} &:\quad& [\text{i32 i32}] \to [\text{i32}]
\end{aligned}
$$

Wasm primer: structured control flow (1)

Structured control flow

```
(block $l
  ...
  (br $l)
  ...
)
```

Wasm primer: structured control flow (1)

Structured control flow

```
(block $l
  ...
  (br $l)
  ...
)
```

break

Wasm primer: structured control flow (1)

Structured control flow

```
(block $l
  ...
  (br $l)
  ...
)
```

break

```
(loop $l
  ...
  (br $l)
  ...
)
```

Wasm primer: structured control flow (1)

Structured control flow

```
(block $l
  ...
  (br $l)
  ...
)
```

break

```
(loop $l
  ...
  (br $l)
  ...
)
```

continue

Wasm primer: structured control flow (2)

Structured control flow

```
;; type : [] -> [i32]
(block $l (result i32)
  ...
  (br $l (i32.const 5))
  ...
)
```

break

```
;; type: [i32] -> []
(loop $l (param i32)
  ...
  (br $l (i32.const 5))
  ...
)
```

continue

Wasm 1.0 & 2.0+

Wasm 1.0 is tailored for C/C++

- The instruction set is an intersection of modern CPUs
- Memory model: a flat array of bytes
- Data types: `i32`, `i64`, `f32`, `f64`
- Modules, functions, and tables

Wasm 2.0 includes high-level language support

- Tail calls
- Typed function references
- Exception handling
- Garbage collection
- SIMD v128 data type (accounts for 236 out of 437 instructions)

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Beyond Wasm 2.0

- Multithreading
- Memory64
- Higher-order modules
- First-class control (this talk!)

The need for stack switching in Wasm

Non-local control is pervasive in programming languages

- Async/await (e.g. C++, C#, Dart, JavaScript, Rust, Swift)
- Coroutines (e.g. C++, Kotlin, Python, Swift)
- Lightweight threads (e.g. Erlang, Go, Haskell, Java, Swift)
- Generators and iterators (e.g. C#, Dart, Haskell, JavaScript, Kotlin, Python)
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The problem

How do I compile non-local control flow abstractions to Wasm?

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- ~~Ceremoniously transform my entire source programs (e.g. Asyncify, CPS)~~
- ~~Add each abstraction as a primitive to Wasm~~
- Use *effect handlers* as a unified modular basis for control in Wasm

WasmFX at glance

WasmFX is a minimal and compatible extension

- 1 new data type
- 6 new instructions (3 are core, 3 are nice-to-have)
- No new block structure

WasmFX uses effect handlers to manage stacks

- Modular and extensible basis for stack switching
    - Structured form of delimited control (intuition: first-class resumable exceptions)
    - Easy encoding of *your favourite abstraction*
    - Control abstractions compose (due to effect forwarding)
- Based on practical evidence
    - 100+ peer reviewed papers
    - Available in many programming languages (e.g. C++, Haskell, Pyro, OCaml, Unison)
    - Deployed in industrial technologies (e.g. GitHub's semantic, Meta's React, Uber's Pyro)
- Restriction: single-shot continuations

Why effect handlers

Any control extension must work

- . . . without garbage collection
- . . . without closures
- . . . without the use of recursion
- . . . with simply typed stacks
- . . . with imperative control structure
- . . . with predicable cost model
- . . . with legacy code

Why effect handlers

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- . . . without garbage collection — ✓ reference counting suffices
- . . . without closures — ✓ first-order abstraction
- . . . without the use of recursion — ✓ no fundamental dependency
- . . . with simply typed stacks — ✓ straightforward typing
- . . . with imperative control structure — ✓ compatible with builtin side-effects
- . . . with predicable cost model — ✓ transparent cost of instructions
- . . . with legacy code — ✓ seamless interop

Variations on semantics of effect handlers

Deep allocation, capture, and resumption

$$\begin{aligned}
\mathbf{cont.new}\ V\ \mathbf{with}\ H &\rightsquigarrow \mathbf{cont}_{\langle H; V\rangle}, && \text{where } V = \lambda\langle\rangle.M \\
\mathbf{resume}\ V\ \mathbf{with}\ W &\rightsquigarrow \underline{\mathbf{handle}}\ \mathcal{E}[W]\ \underline{\mathbf{with}}\ H, && \text{where } V = \mathbf{cont}_{\langle H; \mathcal{E}\rangle} \\
\underline{\mathbf{handle}}\ \mathcal{E}[\mathsf{op}\ V]\ \underline{\mathbf{with}}\ H &\rightsquigarrow N[\mathbf{cont}_{\langle H; \mathcal{E}\rangle}/r, V/x], && \text{where } \{\mathsf{op}\ p\ r \mapsto N\} \in H
\end{aligned}$$

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Shallow allocation, capture, and resumption

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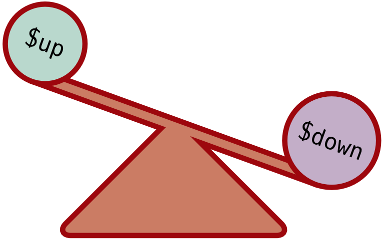
'Sheep' allocation, capture, and resumption

$$\begin{aligned}
\texttt{cont.new}\ V &\leadsto \texttt{cont}_{\langle V\rangle}, && \text{where } V = \lambda\langle\rangle.M \\
\texttt{resume}\ V\ \texttt{with}\ \langle H; W\rangle &\leadsto \underline{\texttt{handle}}\ \mathcal{E}[W]\ \underline{\texttt{with}}\ H, && \text{where } V = \texttt{cont}_{\langle\mathcal{E}\rangle} \\
\underline{\texttt{handle}}\ \mathcal{E}[\mathrm{op}\ V]\ \underline{\texttt{with}}\ H &\leadsto N[\texttt{cont}_{\langle\mathcal{E}\rangle}/r, V/x], && \text{where } \{\mathrm{op}\ p\ r \mapsto N\} \in H
\end{aligned}$$

Coroutines in WasmFX

'Seesaw' coroutines (Ganz, Friedman, and Wand 1999).



We will have two modules

- `co2` implementing the coroutine runtime
- `example` interleaved streams of natural numbers

Running example: coroutines (1)

```
;; interface for running two coroutines
;; non-interleaving implementation
(module $co2
  ;; type alias task = [] -> []
  (type $task (func))

  ;; yield : [] -> []
  (func $yield (export "yield")
    (nop))

  ;; run : [(ref $task) (ref $task)] -> []
  (func $run (export "run") (param $task1 (ref $task)) (param $task2 (ref $task))
    ;; run the tasks sequentially
    (call_ref $task (local.get $task1))
    (call_ref $task (local.get $task2))
  )
)
```

Running example: coroutines (2)

```
(module $example    ;; main example: streams of odd and even naturals
  ...
  ;; imports yield : [] -> []
  (func $yield (import "co2" "yield"))

  ...
)
```

Running example: coroutines (3)

```
(module $example
  ...
  ;; odd : [i32] -> []
  ;; prints the first $niter odd natural numbers
  (func $odd (param $niter i32)
    (local $n i32)                                              ;; next odd number
    (local $i i32)                                              ;; iterator
    (local.set $n (i32.const 1))                                ;; initialise locals
    (local.set $i (i32.const 1))                                ;; ...
    (block $b
      (loop $l
        (br_if $b (i32.gt_u (local.get $i) (local.get $niter))) ;; termination condition
        (call $print (local.get $n))                            ;; print the current odd number
        (local.set $n (i32.add (local.get $n) (i32.const 2)))   ;; compute next odd number
        (local.set $i (i32.add (local.get $i) (i32.const 1)))   ;; increment the iterator
        (call $yield)                                           ;; yield control
        (br $l))))                                              ;; repeat

  ;; even : [i32] -> []
  ;; prints the first $niter even natural numbers
  (func $even (param $niter i32) ...)
  ...
)
```

Running example: coroutines (4)

```
(module $example
  ...
  ;; odd5, even5 : [] -> []
  (func $odd5 (export "odd5")
     (call $odd (i32.const 5)))
  (func $even5 (export "even5")
     (call $even (i32.const 5)))
)


;; calling $run with $odd5 and $even5...
(call $run (ref.func $odd5) (ref.func $even5))
;; ... prints 1 3 5 7 9 2 4 6 8 10
```

Instructions: declaring control tags

Control tag declaration

$$(\texttt{\textbf{tag}}\ \$\textit{tag}\ (\texttt{\textbf{param}}\ \sigma^*)\ (\texttt{\textbf{result}}\ \tau^*))$$

it's a mild extension of Wasm's *exception tags*

(known in the literature as an 'operation symbol' (Plotkin and Pretnar 2013))

Refactoring the co2 module (1)

```
(module $co2
  ;; type alias task = [] -> []
  (type $task (func))

  ;; yield : [] -> []
  (tag $yield)

  ;; yield : [] -> []
  (func $yield (export "yield")
    (nop))

  ;; run : [(ref $task) (ref $task)] -> []
  (func $run (export "run") (param $task1 (ref $task)) (param $task2 (ref $task))
    ...)
)
```

Instructions: creating continuations

Continuation type

$$(\texttt{cont}\ \$\mathit{ft})$$

cont is a new reference type constructor parameterised by a function type, $\$\mathit{ft} : [\sigma^*] \to [\tau^*]$

Continuation allocation

$$\texttt{cont.new}\ \$\mathit{ct} : [(\texttt{ref null}\ \$\mathit{ft})] \to [(\texttt{ref}\ \$\mathit{ct})]$$

where $\$\mathit{ft} : [\sigma^*] \to [\tau^*]$
and $\$\mathit{ct} : \texttt{cont}\ \$\mathit{ft}$

Refactoring the co2 module (2)

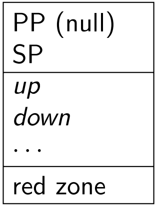
```
(module $co2
  ;; type alias $task = [] -> []
  (type $task (func))

  ;; type alias $ct = $task
  (type $ct   (cont $task))

  ...

  ;; run : [(ref $task) (ref $task)] -> []
  ;; implements a ’seesaw’ (c.f. Ganz et al. (ICFP@99))
  (func $run (export "run") (param $task1 (ref $task)) (param $task2 (ref $task))
    ;; locals to manage continuations
    (local $up   (ref null $ct))
    (local $down (ref null $ct))
    (local $isOtherDone i32)
    ;; initialise locals
    (local.set $up   (cont.new $ct (local.get $task1)))
    (local.set $down (cont.new $ct (local.get $task2)))
    ...)
)
```

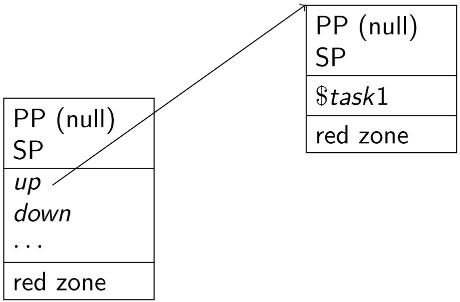
Thinking of **cont.new** in terms of stacks



`cont.new` allocates a new stack segment

New segments are initially suspended

Thinking of **`cont.new`** in terms of stacks



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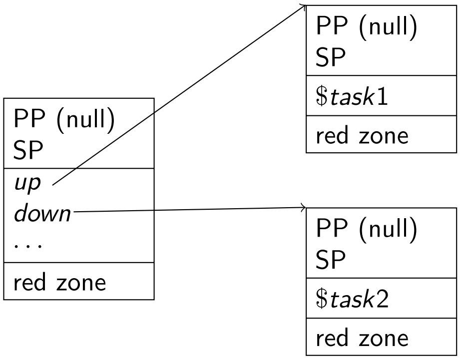

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New segments are initially suspended

Instructions: invoking continuations

Continuation resumption

$$\textbf{resume}\ \$ct\ (\textbf{tag}\ \$tag\ \$h)^* : [\sigma^*\ (\textbf{ref null}\ \$ct)] \to [\tau^*]$$

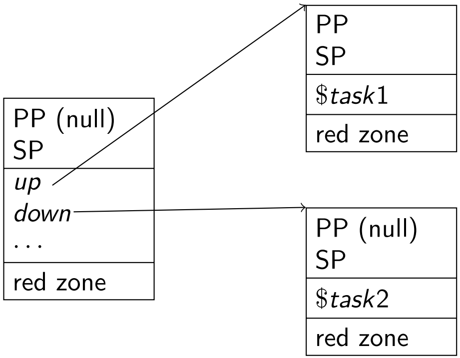
$$\begin{array}{l} \text{where}\ \ \{\$tag_i : [\sigma_i^*] \to [\tau_i^*]\ \ \text{and}\ \ \$h_i : [\sigma_i^*\ (\textbf{ref null}\ \$ct_i)]\ \text{and} \\ \qquad\qquad \$ct_i : \textbf{cont}\ \$ft_i\ \ \ \ \text{and}\ \ \$ft_i : [\tau_i^*] \to [\tau^*]\}_i \\ \quad \text{and}\ \$ct : \textbf{cont}\ \$ft \\ \quad \text{and}\ \$ft : [\sigma^*] \to [\tau^*] \end{array}$$

The instruction fully consume the continuation argument

Refactoring the co2 module (3)

```
(module $co2
  ...                                                   ;; declarations of $task, $yield, etc
  ;; run : [(ref $task) (ref $task)] -> []
  (func $run (export "run") (param $task1 (ref $task)) (param $task2 (ref $task))
    ...                                                 ;; initialisation of $up and $down
    ;; run $up
    (loop $h                                            ;; handling loop
      (block $on_yield (result (ref $ct))
        (resume $ct (tag $yield $on_yield) (local.get $up))  ;; resume $up; handle $yield using $on_yield
        (if (i32.eq (local.get $isOtherDone) (i32.const 1))  ;; $up finished; $down is already done?
          (then (return)))                              ;; ... then exit
        (local.get $down)                               ;; ... otherwise prepare to run $down
        (local.set $up)                                 ;; $up := $down
        (local.set $isOtherDone (i32.const 1))          ;; mark other as done
        (br $h)                                         ;; repeat
      )                                                 ;; yield-case definition; stack: [(cont $ct)]
      (local.set $up)                                   ;; set $up to the current continuation
      (if (i32.eqz (local.get $isOtherDone))            ;; is $down already done?
        (then (local.get $down)                         ;; ... then swap $up and $down
              (local.set $down (local.get $up))
              (local.set $up)))
      (br $h)))                                         ;; repeat
)
```

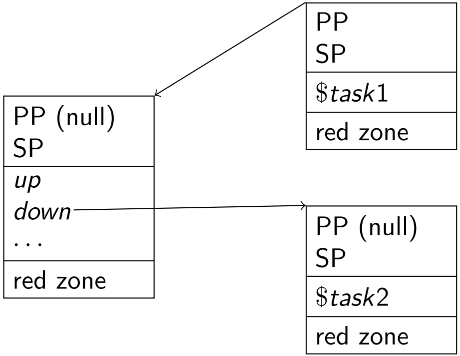
Thinking of **resume** in terms of stacks



resume transfers control from the parent to the child stack

The pointer between parent and child is inverted

Thinking of **resume** in terms of stacks



resume transfers control from the parent to the child stack

The pointer between parent and child is inverted

Instructions: suspending continuations

Continuation suspension

$$\texttt{\textbf{suspend}}\ \$\mathit{tag} : [\sigma^*] \to [\tau^*]$$

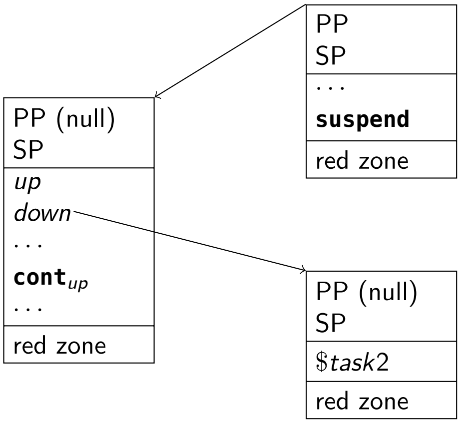
where $\$\mathit{tag} : [\sigma^*] \to [\tau^*]$

Refactoring the co2 module (4)

```
(module $co2
  ;; type alias task = [] -> []
  (type $task (func))
  ;; type alias   ct = $task
  (type $ct   (cont $task))

  ;; yield : [] -> []
  (tag $yield (param) (result))

  ;; yield : [] -> []
  (func $yield (export "yield")
    (suspend $yield))

  ;; run : [(ref $task) (ref $task)] -> []
  ;; implements a 'seesaw' (c.f. Ganz et al. (ICFP@99))
  (func $run (export "run") (param $task1 (ref $task)) (param $task2 (ref $task))
    ... )
)
```

Now `(call $run (ref.func $odd5) (ref.func $even5))` prints `1 2 3 4 5 6 7 8 9 10`

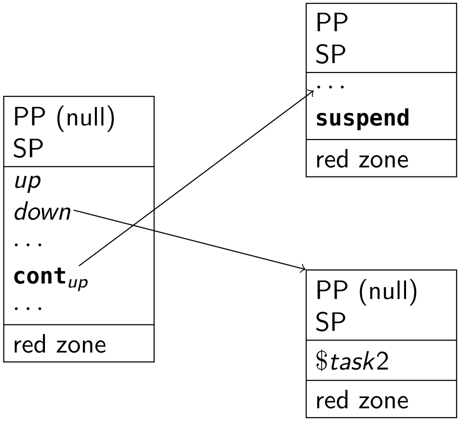
Thinking of **suspend** in terms of stacks



suspend transfers control a child to a (grand)parent

The pointer between child and parent is inverted

Thinking of **suspend** in terms of stacks



suspend transfers control a child to a (grand)parent

The pointer between child and parent is inverted

Current status of the proposal

What has already been done

- Formal specification
- Informal explainer documentation
- Reference implementation
- A proof-of-concept implementation in Wasmtime

What is happening now

- Fine-tune the implementation

What is going to happen next

- Gathering performance evidence

Preliminary performance results

Context switching microbenchmark

	Relative speed	Binary size	Memory usage
Asyncify	-	36 kb	66.0 mb
Bespoke	0.5×	27 kb	15.7 mb
WasmFX	0.25×	24 kb	63.9 mb

Table: Performance characteristics for webserver microbenchmark

Binary file size microbenchmarks

	main-kjp.go	coroutines.go
Asyncify	597 kb	40.0 kb
WasmFX	156 kb	7.2 kb

Table: Binary size comparison for TinyGo Programs

Summary

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- Effect handlers provide a modular and extensible basis for stack switching in Wasm
- Effect handlers are a proven technology
- WasmFX is a minimal and compatible extension to Wasm
- Proof-of-concept implementation in Wasmtime

The work is actively being turned into a proposal; for more details see

`https://wasmfx.dev`

Comments and feedback are welcome!

References

Sitaram, Dorai (1993). “Handling Control”. In: *PLDI*. ACM, pp. 147–155.

Ganz, Steven E., Daniel P. Friedman, and Mitchell Wand (1999). “Trampolined Style”. In: *ICFP*. ACM, pp. 18–27.

Plotkin, Gordon D. and Matija Pretnar (2013). “Handling Algebraic Effects”. In: *Logical Methods in Computer Science* 9.4.

Haas, Andreas et al. (2017). “Bringing the web up to speed with WebAssembly”. In: *PLDI*. ACM, pp. 185–200.

Forster, Yannick et al. (2019). “On the expressive power of user-defined effects: Effect handlers, monadic reflection, delimited control”. In: *J. Funct. Program.* 29, e15.

Hillerström, Daniel (2021). “Foundations for Programming and Implementing Effect Handlers”. PhD thesis. The University of Edinburgh, Scotland, UK.

Sivaramakrishnan, K. C. et al. (2021). “Retrofitting effect handlers onto OCaml”. In: *PLDI*. ACM, pp. 206–221.

Ghica, Dan et al. (2022). “High-Level Type-Safe Effect Handlers in C++”. In: *Proc. ACM Program. Lang.* 6.OOPSLA, pp. 1–30.

Thomson, Patrick et al. (2022). “Fusing industry and academia at GitHub (experience report)”. In: *Proc. ACM Program. Lang.* 6.ICFP, pp. 496–511.

Continuation binding, cancellation, and trapping

Partial continuation application

$$\textbf{cont.bind}\ (\textbf{type}\ \$ct) : [\sigma_0^*\ (\textbf{ref null}\ \$ct)] \to [(\textbf{ref}\ \$ct')]$$

$$\begin{array}{ll} \text{where } \$ct\ : \textbf{cont}\ \$ft\ \text{ and } \$ft\ : [\sigma_0^*\ \sigma_1^*] \to [\tau^*] \\ \quad \text{and } \$ct' : \textbf{cont}\ \$ft' \text{ and } \$ft' : [\sigma_1^*] \to [\tau^*] \end{array}$$

Continuation cancellation

$$\textbf{resume\_throw}\ (\textbf{tag}\ \$exn)\ (\textbf{tag}\ \$tag\ \$h)^* : [\sigma_0^*\ (\textbf{ref null}\ \$ct)] \to [\tau^*]$$

$$\begin{array}{l} \text{where}\ \ \$exn : [\sigma_0^*] \to [],\ \{\$tag_i : [\sigma_i^*] \to [\tau_i^*]\ \text{ and }\ \$h_i : [\sigma_i^*\ (\textbf{ref null}\ \$ct_i)]\ \text{and} \\ \qquad\qquad\qquad\qquad\qquad \$ct_i\ : \textbf{cont}\ \$ft_i \quad \text{and}\ \ \$ft_i : [\tau_i^*] \to [\tau^*]\}_i \\ \quad \text{and}\ \ \$ct : \textbf{cont}\ ([\sigma^*] \to [\tau^*]) \end{array}$$

Control barriers

$$\textbf{barrier}\ \$lbl\ (\textbf{type}\ \$bt)\ instr^* : [\sigma^*] \to [\tau^*]$$

where $\$bt = [\sigma^*] \to [\tau^*]$ and $instr^* : [\sigma^*] \to [\tau^*]$