Effect Handlers All the Way Down

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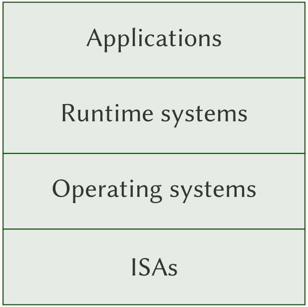
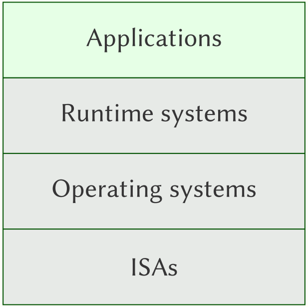
https://dhil.net

The Software Stack



The Software Stack: Applications



Control idioms

. . .

Non-local control idioms are pervasive

- 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)
- Yield-style generators (e.g. C#, Dart, Haskell, JavaScript, Kotlin, Python)

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Structured programming with continuations

- Effect handlers are a structured facility for programming with continuations
- Composable control idioms as user-defined libraries
- Seamless interoperability with native effects

Yield-style generators (1)

Effect interface

$$\mathrm{Gen} = \{\mathrm{Yield} : \mathrm{Int} \twoheadrightarrow \mathrm{Void}\}$$

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Example

$$\mathrm{sumUp}\ 10\ (\mathrm{ints}\ 0) \rightsquigarrow 55$$

Lightweight threads

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Applications

Applications in the wild

- Concurrency
  - Direct-style asynchronous I/O (e.g. OCaml)
  - Efficient user interface rendering (e.g. Facebook's React)
- Distribution
  - Content-addressed programming (e.g. Unison)
  - Build systems and deployment (e.g. srclang)
- Modular interpretation
  - Probabilistic programming (e.g. Pyro)
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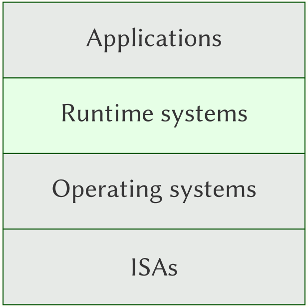
We have only scratched the surface for what effect handler oriented programming has to offer!

The Software Stack: Runtime systems

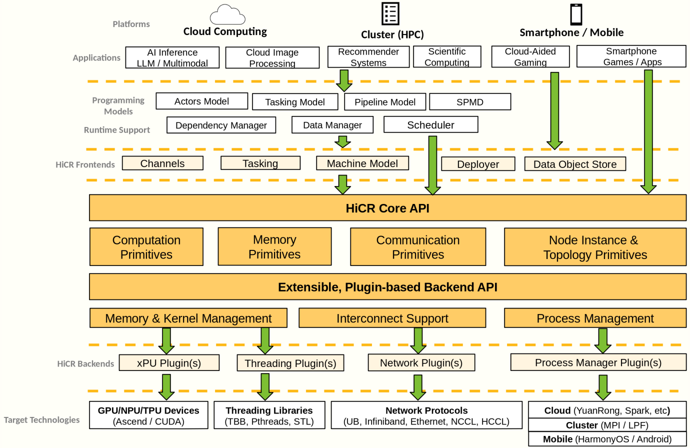


HiSilicon Common Runtime (HiCR)

(joint work with Sergio M. Martin, Kiril Dichev, Luca Terracciano, Orestis Korakitis, and Albert-Jan Yzelmann)

Executive summary

- A unified API for building portable runtime systems, providing seamless and efficient access to new technologies



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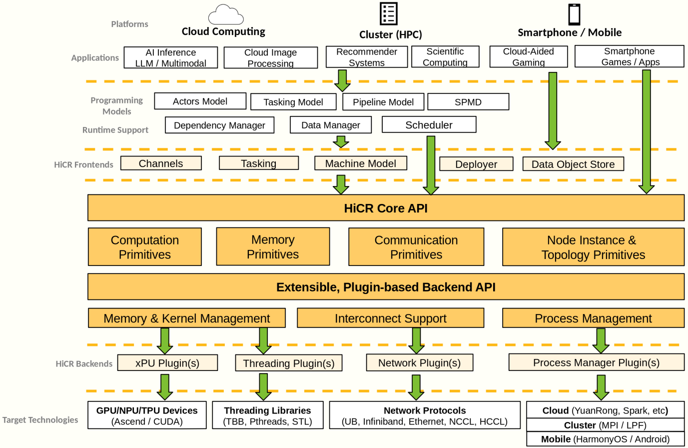

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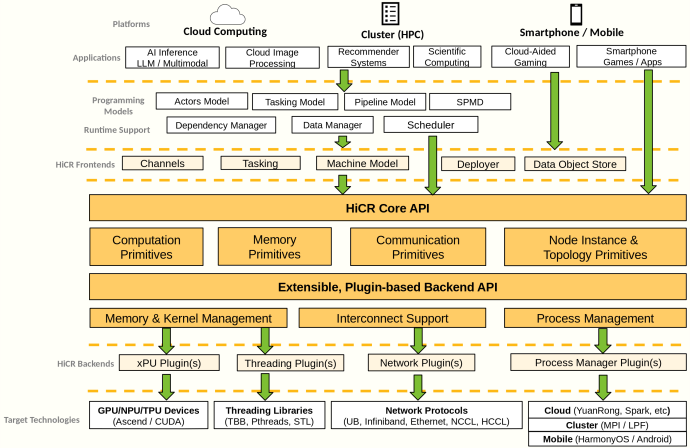

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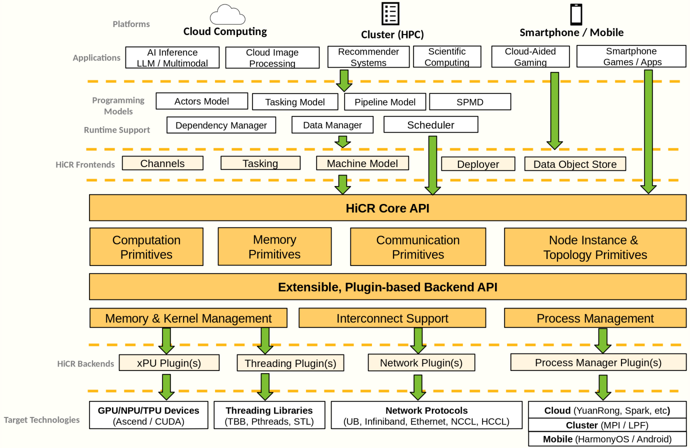
- **Backend**: Extensible plugin-based API for integrating computational fabrics



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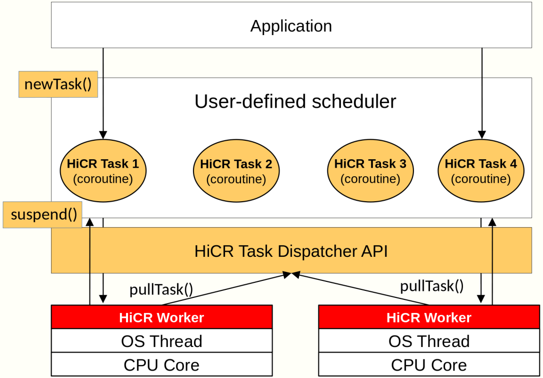
Application-specific scheduling

Customised task scheduling

- Domain-tailored task scheduler
- HiCR coroutines interact with their environment
  - **`newTask`**: spawn new coroutine
  - **`suspend`**: yield control



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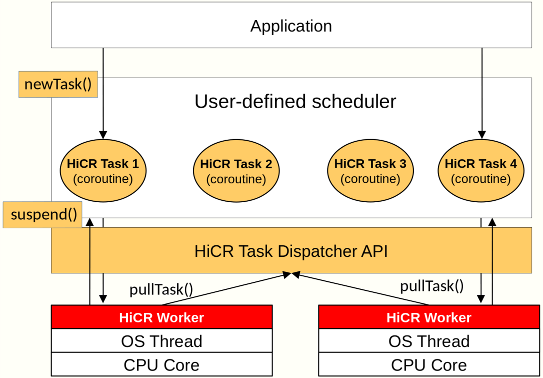

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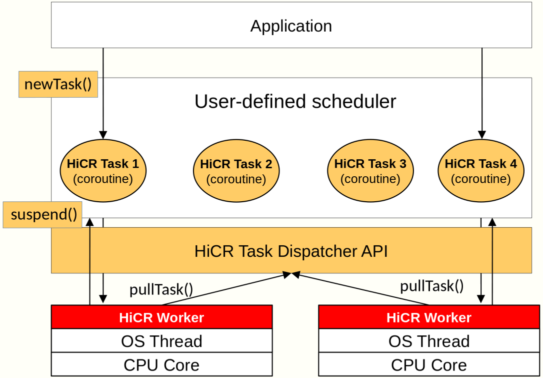
Handlers yield benefits

- It just works™
- Seamless composition with builtin effects (e.g. exceptions)
- Anecdotally, easy fancy control programming



More effects in HiCR

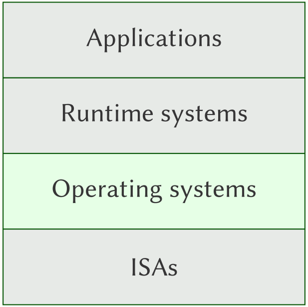
Growing demand for effect handlers

- Bespoke frontend for effect handlers
- Core building blocks for effect handlers
- Custom stack allocation policies
- Support for stackless coroutines

Liberating parallel programming

- No support for colocation (e.g. needed for multi-tenant systems)
- Virtualise parallel resources (e.g. ‘virtual memory’ for parallel programming)

The Software Stack: Operating systems



Effect handlers as composable microkernels

System calls and kernels

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System calls *as* effectful operations
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Composable interactive microkernels

- Domain-specific interactive (micro)kernels
- Virtualisation of operating system facilities
- Composability inherited from handlers

Dynamic multi user environments

Effect interface

$$\mathrm{Env} = \{\mathrm{Get} : \mathrm{String} \twoheadrightarrow \mathrm{String}\}$$

Environment — tail-resumptive handler

$$\begin{aligned}
&\mathrm{env} : \mathrm{List}\ (\mathrm{String} \times \mathrm{String}) \to \alpha!\mathrm{Env} \Rightarrow \alpha \\
&\mathrm{env}\ \mathit{xs} = \{\ \mathbf{return}\ \mathit{ans} \ \ \mapsto \mathit{ans} \\
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&\qquad\qquad\qquad\qquad \langle\!\langle \mathrm{Su}\ \mathit{user} \twoheadrightarrow r\rangle\!\rangle \mapsto \mathrm{env}\ (\mathrm{assoc}\ \mathit{user}\ \mathit{es})(r\ \langle\rangle)\}
\end{aligned}$$

Example

$$\begin{aligned}
&\mathrm{shell}\ \langle[\langle \mathrm{Alice}, [\langle \texttt{"USER"}, \texttt{"Alice"}\rangle]\rangle, \langle \mathrm{Bob}, \ldots\rangle],\\
&\qquad \lambda\langle\rangle.\langle \mathbf{do}\ \mathrm{Su}\ \mathrm{Alice}; \mathbf{do}\ \mathrm{Get}\ \texttt{"USER"}, \mathbf{do}\ \mathrm{Su}\ \mathrm{Bob}; \mathbf{do}\ \mathrm{Get}\ \texttt{"USER"}\rangle\rangle\\
&\rightsquigarrow \langle \texttt{"Alice"}, \texttt{"Bob"}\rangle
\end{aligned}$$

Process duplication via UNIX fork

$$\begin{array}{l}\texttt{let}\ \mathit{pid} \leftarrow \mathrm{fork}\ \langle\rangle\ \texttt{in}\\ \texttt{if}\ \mathit{pid} = 0\ \texttt{then}\ \mathit{child\ continuation}\\ \texttt{else}\ \mathit{parent\ continuation}\end{array}$$

Note, fork causes execution of both continuations, i.e. it returns twice!

Timesharing with UNIX fork

Effect interface

$$\mathsf{Timeshare} = \{\mathsf{Fork} : \mathsf{Void} \to \mathsf{Int}, \mathsf{Interrupt} : \mathsf{Void} \twoheadrightarrow \mathsf{Void}, \mathsf{Wait} : \mathsf{Int} \twoheadrightarrow \mathsf{Int}\}$$

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Scheduler — multi-shot handler

$$\begin{array}{l} \mathsf{tmshare} : \mathsf{State} \to \alpha!\mathsf{Timeshare} \Rightarrow \mathsf{List}\ (\mathsf{Int} \times \alpha) \\ \mathsf{tmshare}\ \mathit{st} = \{ \\ \hspace{30em} \} \end{array}$$

Timesharing with UNIX fork

Effect interface

$$\mathrm{Timeshare} = \{\mathrm{Fork} : \mathrm{Void} \to \mathrm{Int}, \mathrm{Interrupt} : \mathrm{Void} \twoheadrightarrow \mathrm{Void}, \mathrm{Wait} : \mathrm{Int} \twoheadrightarrow \mathrm{Int}\}$$

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$$
\begin{array}{l}
\mathrm{tmshare} : \mathrm{State} \to \alpha!\mathrm{Timeshare} \Rightarrow \mathrm{List}\;(\mathrm{Int} \times \alpha) \\
\mathrm{tmshare}\; \mathit{st} = \{ \\
\qquad \langle\!\langle \mathrm{Fork}\;\langle\rangle \twoheadrightarrow r \rangle\!\rangle \;\mapsto\; \mathbf{let}\; \mathit{pid} \leftarrow \mathrm{incr}\; \mathit{st}.\mathit{next\_pid}\; \mathbf{in} \\
\qquad\qquad\qquad\qquad\quad \mathrm{runNext}\;\langle \mathit{st}\; \mathbf{with}\; \mathit{rq} = \langle \mathit{st}.\mathit{cur}, \lambda\langle\rangle.r\;0\rangle :: \langle \lambda\langle\rangle.r\;\mathit{pid}\rangle :: \mathit{st}.\mathit{rq}\rangle \\
\}
\end{array}
$$

Timesharing with UNIX fork

Effect interface

$$\text{Timeshare} = \{\text{Fork} : \text{Void} \to \text{Int}, \text{Interrupt} : \text{Void} \twoheadrightarrow \text{Void}, \text{Wait} : \text{Int} \twoheadrightarrow \text{Int}\}$$

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&\qquad\qquad\qquad\qquad\quad\ \text{runNext}\ \langle \mathit{st}\ \textbf{with}\ \mathit{rq} = \langle \mathit{st}.\mathit{cur}, \lambda\langle\rangle.r\ 0\rangle :: \langle \lambda\langle\rangle.r\ \mathit{pid}\rangle :: \mathit{st}.\mathit{rq}\rangle\\
&\}
\end{aligned}
$$

Timesharing with UNIX fork

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&\qquad\qquad \text{runNext}\ \langle \mathit{st}\ \mathbf{with}\ \mathit{rq} = \langle \mathit{st}.\mathit{cur}, \lambda\langle\rangle.r\ 0\rangle :: \langle \lambda\langle\rangle.r\ \mathit{pid}\rangle :: \mathit{st}.\mathit{rq}\rangle\\
&\qquad \langle\!\langle \text{Interrupt}\ \langle\rangle \twoheadrightarrow r \rangle\!\rangle \mapsto \text{runNext}\ \langle \mathit{st}\ \mathbf{with}\ \mathit{rq} = \langle \mathit{st}.\mathit{cur}, \lambda\langle\rangle.r\ \langle\rangle\rangle :: \mathit{st}.\mathit{rq}\rangle\\
&\}
\end{aligned}$$

Timesharing with UNIX fork

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\begin{array}{l}
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\begin{array}{rcl}
\quad \langle\!\langle \mathsf{Fork}\ \langle\rangle \twoheadrightarrow r \rangle\!\rangle & \mapsto & \mathbf{let}\ pid \leftarrow \mathsf{incr}\ st.next\_pid\ \mathbf{in} \\
& & \mathsf{runNext}\ \langle st\ \mathbf{with}\ rq = \langle st.cur, \lambda\langle\rangle.r\ 0\rangle :: \langle \lambda\langle\rangle.r\ pid\rangle :: st.rq\rangle \\
\langle\!\langle \mathsf{Interrupt}\ \langle\rangle \twoheadrightarrow r \rangle\!\rangle & \mapsto & \mathsf{runNext}\ \langle st\ \mathbf{with}\ rq = \langle st.cur, \lambda\langle\rangle.r\ \langle\rangle\rangle :: st.rq\rangle \\
\langle\!\langle \mathsf{Wait}\ pid \twoheadrightarrow r \rangle\!\rangle & \mapsto & \mathsf{runNext}\ \langle st\ \mathbf{with}\ bq = \langle pid, \langle st.cur, \lambda\langle\rangle.r\ \langle\rangle\rangle\rangle :: st.bq\rangle
\end{array} \\
\hfill \}
\end{array}
$$

Timesharing with UNIX fork

Effect interface

$$\mathsf{Timeshare} = \{\mathsf{Fork} : \mathsf{Void} \to \mathsf{Int}, \mathsf{Interrupt} : \mathsf{Void} \twoheadrightarrow \mathsf{Void}, \mathsf{Wait} : \mathsf{Int} \twoheadrightarrow \mathsf{Int}\}$$

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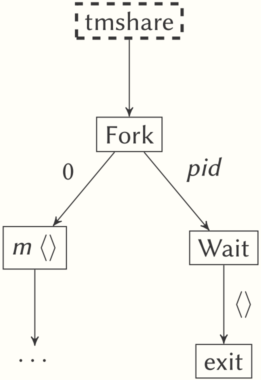
& & \mathsf{runNext}\ \langle st\ \mathbf{with}\ rq = \langle st.cur, \lambda\langle\rangle.r\ 0\rangle :: \langle \lambda\langle\rangle.r\ pid\rangle :: st.rq\rangle \\
\langle\!\langle \mathsf{Interrupt}\ \langle\rangle \twoheadrightarrow r \rangle\!\rangle & \mapsto & \mathsf{runNext}\ \langle st\ \mathbf{with}\ rq = \langle st.cur, \lambda\langle\rangle.r\ \langle\rangle\rangle :: st.rq\rangle \\
\langle\!\langle \mathsf{Wait}\ pid \twoheadrightarrow r \rangle\!\rangle & \mapsto & \mathsf{runNext}\ \langle st\ \mathbf{with}\ bq = \langle pid, \langle st.cur, \lambda\langle\rangle.r\ \langle\rangle\rangle\rangle :: st.bq\rangle \\
\mathbf{return}\ ans & \mapsto & \mathbf{let}\ \langle rq', bq'\rangle = \mathsf{pop}\ st.cur\ st.bq\ \mathbf{in} \\
& & \mathsf{runNext}\ \langle st\ \mathbf{with}\ rq = st.rq \mathbin{+\!\!+} rq', bq = bq', done = \langle st.cur, ans\rangle :: st.done\rangle\}
\end{array}
\end{array}
$$

Semantics for init

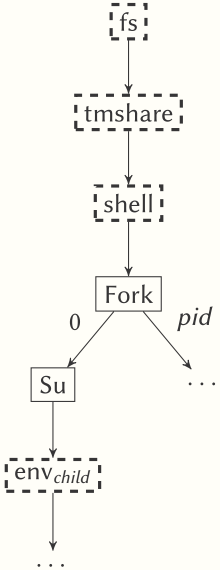
$\text{init} : (\text{Void} \to \alpha!\text{Timeshare}) \to \alpha$
$\text{init}\ m = \texttt{let}\ \mathit{pid} \leftarrow \texttt{do}\ \text{Fork}\ \langle\rangle\ \texttt{in}$
$\qquad \texttt{if}\ \mathit{pid} = 0\ \texttt{then}\ m\ \langle\rangle$
$\qquad \texttt{else}\ \texttt{do}\ \text{Wait}\ \mathit{pid}; \text{exit}\ 0$



Composition confers functionality

Functionality through composition

- Suppose we have a file system handler fs
- Then (fs ∘ tmshare ∘ env) yields a basic operating system!
- Every process share the same filesystem…



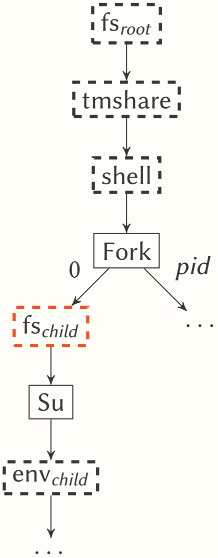
Composition confers functionality

Functionality through composition

- Suppose we have a file system handler fs
- Then (fs ∘ tmshare ∘ env) yields a basic operating system!
- Every process share the same filesystem...

Sandboxing through composition

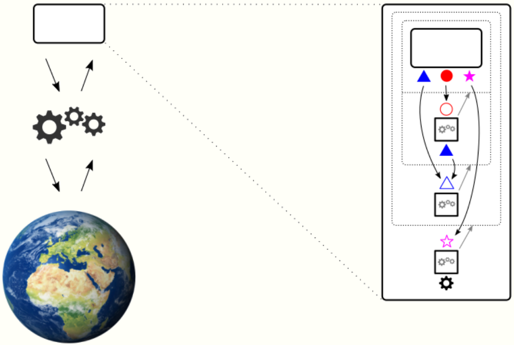
- Suppose we want each process to have its own filesystem?
- Easy: fs ∘ tmshare ∘ env ∘ fs



The future

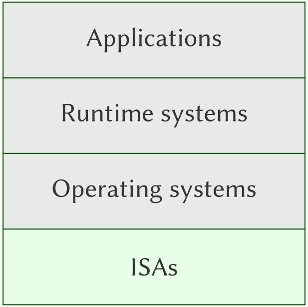
(figure courtesy of Sam Lindley)

The future



(figure courtesy of Sam Lindley)

The Software Stack: ISAs



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

What is Wasm?

- A virtual instruction set architecture
- An abstraction of the hardware
- Secure, sandboxed execution environment

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)

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How do I compile my control idioms to Wasm?

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Problem

How do I compile my control idioms to Wasm?

Solution

A **global restructuring scheme** for programs (e.g. CPS, Asyncify)

Asyncify is the current state-of-the-art (1)

```
(func $doSomething (param $arg i32) (result i32)
  (call $foo
    (call $bar (local.get $arg))))
```

Asyncify is the current state-of-the-art (2)

```
(func $doSomething (param $arg i32) (result i32)
  (call $foo
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```

can `$bar` suspend?

Asyncify is the current state-of-the-art (2)

can `$foo` suspend?

```
(func $doSomething (param $arg i32) (result i32)
  (call $foo
    (call $bar (local.get $arg))))
```

can `$bar` suspend?

Asyncify is the current state-of-the-art (2)

```
(func $doSomething (param $arg i32) (result i32)
  (local $call_idx i32)
  (local $ret i32)
  (if (i32.eq (global.get $asyncify_mode) (i32.const 2))                  ;; test rewind state
    (then (local.set $arg                                                 ;; store local $arg
            (i32.load offset=4 (global.get $asyncify_heap_ptr)))
          (local.set $call_idx                                            ;; continuation point
            (i32.load offset=8 (global.get $asyncify_heap_ptr)))
    (else))
  (block $call_foo (result i32)
    (block $restore_foo (result i32)
      (block $call_bar (result i32)
        (local.get $arg)
        (if (i32.eq (global.get $asyncify_mode) (i32.const 2)) (result i32)
          (then (if (i32.eq (local.get $call_idx) (i32.const 0))
                (then (br $call_bar))                                      ;; restore $call_bar
                (else (br $restore_foo))))
          (else (br $call_bar))))                                          ;; regular $call_bar
      (local.set $ret (call $bar (local.get 0)))
      (if (i32.eq (global.get $asyncify_mode) (i32.const 1)) (result i32)    ;; test unwind state
            (then (i32.store offset=4 (global.get $asyncify_heap_ptr) (local.get $arg))
                (i32.store offset=8 (global.get $asyncify_heap_ptr (i32.const 0))
                (return (i32.const 0)))  ...))))))
```

Asyncify is the current state-of-the-art (2)

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            (i32.load offset=4 (global.get $asyncify_heap_ptr)))
          (local.set $call_idx                                             ;; continuation point
            (i32.load offset=8 (global.get $asyncify_heap_ptr)))
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      (block $call_bar (result i32)
        (local.get $arg)
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          (then (if (i32.eq (local.get $call_idx) (i32.const 0))
                  (then (br $call_bar))                                     ;; restore $call_bar
                  (else (br $restore_foo))))
          (else (br $call_bar))))                                           ;; regular $call_bar
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Asyncify is the current state-of-the-art (2)

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                  (return (i32.const 0)))  ...))))))
```

A basis for stack switching

Can we do better?

A basis for stack switching

Can we do better?

- Yes! Effect handlers!
- Intuition: a continuation is a handle to a stack
- Aligns with the design restrictions of Wasm

The WasmFX instruction set extension (1)

(joint work with Arjun Guha, Andreas Rossberg, Daan Leijen, Frank Emrich, KC Sivaramakrishnan, Luna Phipps-Costin, Matija Pretnar, and Sam Lindley)

Types

- $\texttt{\textbf{cont}}\ \$\mathit{ft}$

Tags

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

Core instructions

- $\texttt{\textbf{cont.new}}\ \$\mathit{ct} : [(\texttt{\textbf{ref}}\ \$\mathit{ft})] \to [(\texttt{\textbf{ref}}\ \$\mathit{ct})]$
- $\texttt{\textbf{suspend}}\ \$\mathit{tag} : [\sigma^*] \to [\tau^*]$
- $\texttt{\textbf{resume}}\ \$\mathit{ct}\ (\texttt{\textbf{tag}}\ \$\mathit{tag}\ \$h) : [\sigma^*(\texttt{\textbf{ref}}\ \$\mathit{ct})] \to [\tau^*]$

We call this extension **WasmFX**

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Types

- **`cont`** $\$ft$

  where $\$ft : [\sigma^*] \to [\tau^*]$

Tags

- **`tag`** $\$tag : [\sigma^*] \to [\tau^*]$

Core instructions

- **`cont.new`** $\$ct : [(\mathbf{ref}\ \$ft)] \to [(\mathbf{ref}\ \$ct)]$
- **`suspend`** $\$tag : [\sigma^*] \to [\tau^*]$
- **`resume`** $\$ct\ (\mathbf{tag}\ \$tag\ \$h) : [\sigma^*(\mathbf{ref}\ \$ct)] \to [\tau^*]$

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  $$\begin{aligned} \text{where}\quad & \$\mathit{ft} : [\sigma^*] \to [\tau^*] \\ \text{and}\quad & \$\mathit{ct} : \texttt{cont}\ \$\mathit{ft} \end{aligned}$$

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

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- $\texttt{resume}\ \$\mathit{ct}\ (\texttt{tag}\ \$\mathit{tag}\ \$h) : [\sigma^*(\texttt{ref}\ \$\mathit{ct})] \to [\tau^*]$

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

We call this extension **WasmFX**

Example: Yield-style generators

```
(tag $gen (param i32))

(func $ints
  (local $i i32) ;; zero-initialised local
  (loop $produce-next
    (suspend $gen (local.get $i))
    (local.set $i
      (i32.add (local.get $i)
               (i32.const 1)))
    (br $produce-next) ;; continue next
  )
)
```

Example: Yield-style generators

```
(tag $gen (param i32))

(func $ints
  (local $i i32) ;; zero-initialised local
  (loop $produce-next
    (suspend $gen (local.get $i))
    (local.set $i
      (i32.add (local.get $i)
               (i32.const 1)))
    (br $produce-next) ;; continue next
  )
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```

```
(func $sumUp (param $upto i32) (param $k (cont [] -> []))
  (local $n i32) ;; current value
  (local $s i32) ;; accumulator
  (loop $consume-next
    (block $on_gen (result i32 (cont [] -> []))
      (resume (tag $gen $on_gen) (local.get $k)
      (call $print (local.get $s))
    ) ;; stack: [i32 (cont [] -> [])]
    (local.set $k) ;; save next continuation
    (local.set $n) ;; save current value
    (local.set $s (i32.add (local.get $s)
                           (local.get $n)))
    (br_if $consume-next
      (i32.lt_u (local.get $n) (local.get $upto)))
  )
  (call $print ((local.get $s)))
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Example: Yield-style generators

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    (local.set $s (i32.add (local.get $s)
                           (local.get $n)))
    (br_if $consume-next
      (i32.lt_u (local.get $n) (local.get $upto)))
  )
  (call $print ((local.get $s)))
)
```

`(call $sumUp (i32.const 10) (cont.new (ref.func $ints)))` returns 55

The WasmFX instruction set extension (2)

(joint work with Arjun Guha, Andreas Rossberg, Daan Leijen, Frank Emrich, KC Sivaramakrishnan, Luna Phipps-Costin, Matija Pretnar, and Sam Lindley)

Types

- $\texttt{cont}\ \$\mathit{ft}$

Tags

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

Core instructions

- $\texttt{cont.new}\ \$\mathit{ct} : [(\texttt{ref}\ \$\mathit{ft})] \to [(\texttt{ref}\ \$\mathit{ct})]$
- $\texttt{suspend}\ \$\mathit{tag} : [\sigma^*] \to [\tau^*]$
- $\texttt{resume}\ \$\mathit{ct}\ (\texttt{tag}\ \$\mathit{tag}\ \$h) : [\sigma^*(\texttt{ref}\ \$\mathit{ct})] \to [\tau^*]$

We call this extension **WasmFX**

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Legend

- Spec'ed
- Reference impl.
- Wasmtime impl.

We call this extension **WasmFX**

Effect handlers for WebAssembly

Key properties provided by handlers

- A structured facility for non-local control flow
- Just works with builtin effects (e.g. exceptions, threads)
- Seamless interoperability with host
- Compatible with standard debuggers and profilers

Conclusions and future work

Summary

- Effect handlers provide a universal abstraction for non-local control
- Flexible and customisable control flow
- Compositional virtualisation of system effects

Future work

- More prominent applications!
- Implementation strategies
- Hardware support for effect handlers?

References

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