This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 834146.

This material is based upon work supported by the Air Force Office of Scientific Research under award number FA9550-17-1-0326.

DANEL AHMAN MATIJA PRETNAR

UNIVERSITY OF LJUBLJANA, SLOVENIA

07.01.2021

ASYNCHRONOUS EFFECTS

THE PROBLEM

THE SETTING WE WORK IN

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- Effectful programming with algebraic effects and effect handlers

[Plotkin & Power '02, Plotkin & Pretnar '09]

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- Effectful programming with algebraic effects and effect handlers

$$M, N \quad ::= \quad \ldots \quad | \quad \mathsf{op}\,(V, y\,.\,M) \quad | \quad \mathsf{handle}\; M \;\mathsf{with}\; H$$

$$H \quad ::= \quad \{\ \ldots\ ,\ \mathsf{op_i}\; x\; k \mapsto M_{\mathsf{op_i}}\ ,\ \ldots\ ,\ \mathsf{return}\; x \mapsto N_{\mathsf{ret}}\ \}$$

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- Separates (operation-based) interfaces from (user-definable) implementations

[Plotkin & Power '02, Plotkin & Pretnar '09]

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- Separates (operation-based) **interfaces** from (user-definable) **implementations**

$$\mathsf{handle}\ (\mathsf{return}\ V)\ \mathsf{with}\ H \quad \rightsquigarrow \quad N_{\mathsf{ret}}[V/x]$$

$$\mathsf{handle}\ (\mathsf{op}\ (V, y\,.\,M))\ \mathsf{with}\ H \quad \rightsquigarrow \quad M_{\mathsf{op}}[V/x, (\mathsf{fun}\ y \mapsto \mathsf{handle}\ M\ \mathsf{with}\ H)/k]$$

[Plotkin & Power '02, Plotkin & Pretnar '09]

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- Effectful programming with **algebraic effects** and **effect handlers**

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$$\mathsf{handle}\ (\mathsf{return}\ V)\ \mathsf{with}\ H \quad \rightsquigarrow \quad N_{\mathsf{ret}}[V/x]$$

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- State, rollbacks, exceptions, non-determ., concurrency, prob. programming, ...

[Plotkin & Power '02, Plotkin & Pretnar '09]

THE PROBLEM WITH ALGEBRAIC EFFECTS

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$$
\begin{array}{ccc}
 & & M_{\mathsf{op}}[V/x] \\
 & & \uparrow \\
\ldots & \rightsquigarrow & \mathsf{op}\ (V, y\,.\,M)
\end{array}
$$

THE PROBLEM WITH ALGEBRAIC EFFECTS

- Conventional treatment of algebraic effects is inherently synchronous

* top-level implementation
* effect handler
* runner of alg. effects

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$$M_{\mathsf{op}}[V/x] \quad \rightsquigarrow^* \quad \mathsf{return}\ W$$

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$$\uparrow$$

$$\ldots \quad \rightsquigarrow \quad \mathsf{op}\ (V, y\,.\,M)$$

continuation is blocked until W is computed

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$$
\begin{tikzcd}
 & M_{\mathsf{op}}[V/x] \arrow[rr, rightsquigarrow, "*"] & & \mathsf{return}\ W \arrow[d] & \\
\ldots \arrow[r, rightsquigarrow] & \mathsf{op}\ (V, y\,.\,M) \arrow[u] & & M[W/y] \arrow[r, rightsquigarrow] & \ldots
\end{tikzcd}
$$

- Blocking needed in the presence of (non-linear) general effect handlers, and to avoid having to reduce open terms (y is bound immediately)

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Koka [Leijen '17], Multicore OCaml [Dolan et al. '18]

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This paper: How to capture asynchrony in a self-contained core language?

THE IDEA

THE THREE PHASES OF ALGEBRAIC OPERATION CALLS

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$$
\begin{array}{ccccccc}
 & & M_{\mathsf{op}}[V/x] & \leadsto^{*} & \mathsf{return}\ W & & \\
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\ldots & \leadsto & \mathsf{op}\,(V, y\,.\,M) & & M[W/y] & \leadsto & \ldots
\end{array}
$$

THE THREE PHASES OF ALGEBRAIC OPERATION CALLS

executing op's impl.

(2)

$$M_{\mathsf{op}}[V/x] \quad \rightsquigarrow^* \quad \mathsf{return}\ W$$

signalling to execute some impl. of op

(1) $\uparrow$

$\downarrow$ (3)

interrupting M's blocking

$$\ldots \quad \rightsquigarrow \quad \mathsf{op}\ (V, y\,.\,M) \qquad\qquad M[W/y] \quad \rightsquigarrow \quad \ldots$$

- Execution of algebraic operation calls has **three distinct phases**

THE THREE PHASES OF ALGEBRAIC OPERATION CALLS

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$$(1) \uparrow \qquad\qquad \downarrow (3)$$

$$\ldots \quad \rightsquigarrow \quad \mathsf{op}\ (V, y\,.\,M) \qquad\qquad M[W/y] \quad \rightsquigarrow \quad \ldots$$

- Execution of algebraic operation calls has three distinct phases
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THE THREE PHASES OF ALGEBRAIC OPERATION CALLS

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$$\dots \quad \rightsquigarrow \quad \mathsf{op}\ (V, y\,.\,M) \qquad\qquad M[W/y] \quad \rightsquigarrow \quad \dots$$

- Execution of algebraic operation calls has three distinct phases
- Idea: Decouple all three phases into separate programming constructs, so that
  - M would not block while (2) happens asynchronously,
  - programmers could choose if/when to block M for (3) to happen, and
  - (3) could happen without originating from (1) $\qquad$ (and vice versa)

THE APPROACH

THE SIGNALS

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- Our computations can issue outgoing signals

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$$M, N \quad ::= \quad \ldots \quad | \quad \uparrow \mathsf{op}\,(V, M)$$

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signal name

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$$M, N \quad ::= \quad \ldots \quad | \quad \uparrow \underbrace{\mathsf{op}}_{\text{signal name}} (\underbrace{V}_{\text{payload}}, M)$$

THE SIGNALS

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signal name

payload

$$M, N \quad ::= \quad \ldots \quad | \quad \uparrow \mathsf{op}\,(V, M)$$

continuation

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  - propagate outwards ($\uparrow$-notation) (just like algebraic operations)

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  - propagate outwards (↑-notation) (just like algebraic operations)

$$\begin{aligned} & \mathsf{let}\ x = \big(\uparrow \mathsf{op}\,(V, M)\,\big)\ \mathsf{in}\ N \\ \rightsquigarrow \quad & \uparrow \mathsf{op}\,\big(V, (\mathsf{let}\ x = M\ \mathsf{in}\ N)\big) \end{aligned}$$

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$$\ldots \quad \rightsquigarrow \quad \uparrow \mathsf{op}\,(V, M) \qquad \xrightarrow{\mathsf{op}\ V}$$

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$$\ldots \quad \rightsquigarrow \quad \uparrow \mathsf{op}\,(V, M) \quad \rightsquigarrow \quad M$$

$\mathsf{op}\ V \uparrow$

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- Example: scrolling through a seemingly infinite feed (user & client & server)

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$$\uparrow \mathsf{request}\,(\mathit{cachedSize} + 1, M_{\mathsf{feedClient}})$$

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$$\uparrow \mathsf{request}\ (\mathit{cachedSize} + 1, M_{\mathsf{feedClient}}) \qquad \uparrow \mathsf{display}\ (\mathit{message}, M_{\mathsf{feedClient}})$$

THE INTERRUPTS

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$$M, N \quad ::= \quad \ldots \quad | \quad \downarrow \mathsf{op}\,(W, M)$$

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interrupt name

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THE INTERRUPTS

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$$M, N \quad ::= \quad \ldots \quad | \quad \downarrow \mathsf{op}\ (W, M)$$

continuation

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$$\begin{aligned} & \downarrow \mathsf{op}\ \big(W,\ \uparrow \mathsf{op}'\ (V, M)\big) \\ \rightsquigarrow \quad & \uparrow \mathsf{op}'\ \big(V,\ \downarrow \mathsf{op}\ (W, M)\big) \end{aligned}$$

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$$\begin{aligned} & \downarrow \mathsf{op}\, (W, \mathsf{return}\ V) \\ \rightsquigarrow \quad & \mathsf{return}\ V \end{aligned}$$

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$$\ldots \quad \rightsquigarrow \quad M$$

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$$\ldots \rightsquigarrow \underset{\big\downarrow\, \mathsf{op}\ W}{M} \rightsquigarrow \downarrow \mathsf{op}\,(W, M) \rightsquigarrow \ldots$$

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$$\downarrow \mathsf{response}\ (newBatch, M_{\mathsf{feedClient}}) \qquad \downarrow \mathsf{nextItem}\ ((), M_{\mathsf{feedClient}})$$

THE SIGNAL FOR THE SENDER IS AN INTERRUPT TO THE RECEIVER

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(propagate)

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(propagate)

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(broadcast)

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THE SIGNAL FOR THE SENDER IS AN INTERRUPT TO THE RECEIVER

- Programmers are not expected to write interrupts explicitly in their programs!
- Instead, interrupts are (commonly) induced by signals from other processes

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- But interrupts can also appear spontaneously!
  - e.g. the user clicking a button or the environment preempting a process

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$$\begin{aligned} & \mathsf{let}\ y = \left(\mathsf{promise}\ (\mathsf{op}\ x \ \mapsto\ M_1)\ \mathsf{as}\ p\ \mathsf{in}\ M_2\right)\ \mathsf{in}\ N \\ \leadsto \quad & \mathsf{promise}\ (\mathsf{op}\ x \ \mapsto\ M_1)\ \mathsf{as}\ p\ \mathsf{in}\ \left(\mathsf{let}\ x = M_2\ \mathsf{in}\ N\right) \end{aligned}$$

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$$\begin{aligned} & \downarrow \mathsf{op}\ \big(V, \mathsf{promise}\ (\mathsf{op}'\ x \ \mapsto\ M)\ \mathsf{as}\ p\ \mathsf{in}\ N\big) \\ \rightsquigarrow\ & \mathsf{promise}\ (\mathsf{op}'\ x \ \mapsto\ M)\ \mathsf{as}\ p\ \mathsf{in} \downarrow \mathsf{op}\ (V, N) \end{aligned} \qquad (\mathsf{op} \neq \mathsf{op}')$$

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execution of open terms

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promise types ensure type safety!

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$$\textsf{await}\ p\ \textsf{until}\ \langle x \rangle\ \textsf{in}\ N$$

$$\not\rightsquigarrow$$

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Example: client blocks until server sends its batch size

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  $\uparrow \textsf{op-sig}\ \big(V, \textsf{promise}\ (\textsf{op-int}\ x \ \mapsto\ \textsf{return}\ \langle x \rangle)\ \textsf{as}\ p\ \textsf{in}\ (\textsf{await}\ p\ \textsf{until}\ \langle y \rangle\ \textsf{in}\ M)\big)$

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$$\mathsf{promise}\ (\text{op-sig}\ x\ \mapsto\ \langle M_{\text{op}} \rangle)\ \mathsf{as}\ p\ \mathsf{in}\ \big(\mathsf{await}\ p\ \mathsf{until}\ \langle y \rangle\ \mathsf{in}\ \uparrow \text{op-int}\ (y, \mathsf{return}\ ())\big)$$

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let client () =
  ↑ batchSizeRequest ();
  promise (batchSizeResponse batchSize ↦ return ⟨batchSize⟩) as batchSizePromise in

  let (cachedData , requestInProgress , currentItem) = (ref [] , ref false , ref 0) in

  let requestNewData offset =
    requestInProgress := true;
    ↑ request offset;
    promise (response newBatch ↦
      cachedData := !cachedData @ newBatch;
      requestInProgress := false; return ⟨()⟩
    ) as _ in return ()
  in

  let rec clientLoop batchSize =
    promise (nextItem () ↦
      let cachedSize = length !cachedData in
      (if (!currentItem > cachedSize − batchSize / 2) && (not !requestInProgress) then
         requestNewData (cachedSize + 1)
       else
         return ());
      (if !currentItem < cachedSize then
         ↑ display (toString (nth !cachedData !currentItem));
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  await batchSizePromise until ⟨batchSize⟩ in clientLoop batchSize
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* request server's settings,
* install int. handler for the response, and
* block until they arrive (but only after useful work)

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client's main loop is a rec. defined int. handler

* reacts to next item interrupts from user
* issues display signals or new data requests

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  let rec waitForRequest () =
    promise (request offset ↦
      let payload = map (fun x ↦ 10 ∗ x) (range offset (offset + batchSize − 1)) in
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server processes are commonly rec. defined int. handlers

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let rec user () =
  let rec wait n =
    if n = 0 then return () else wait (n − 1)
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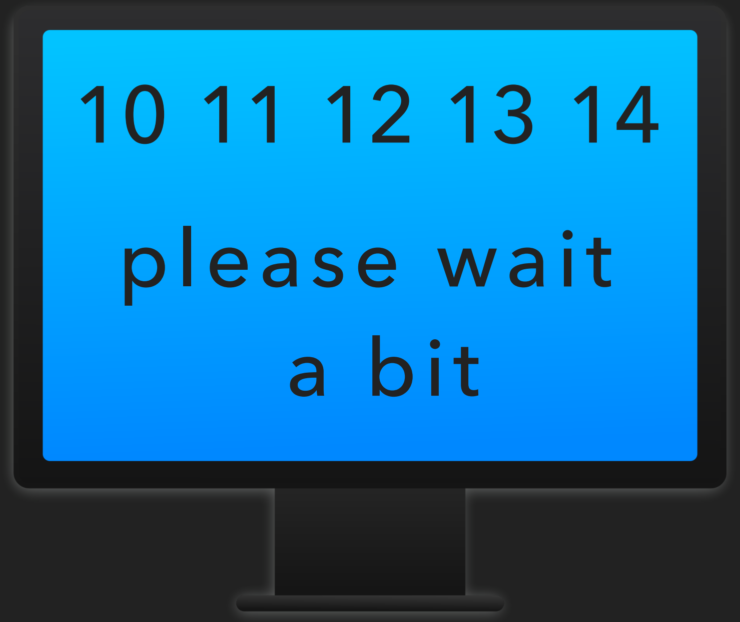

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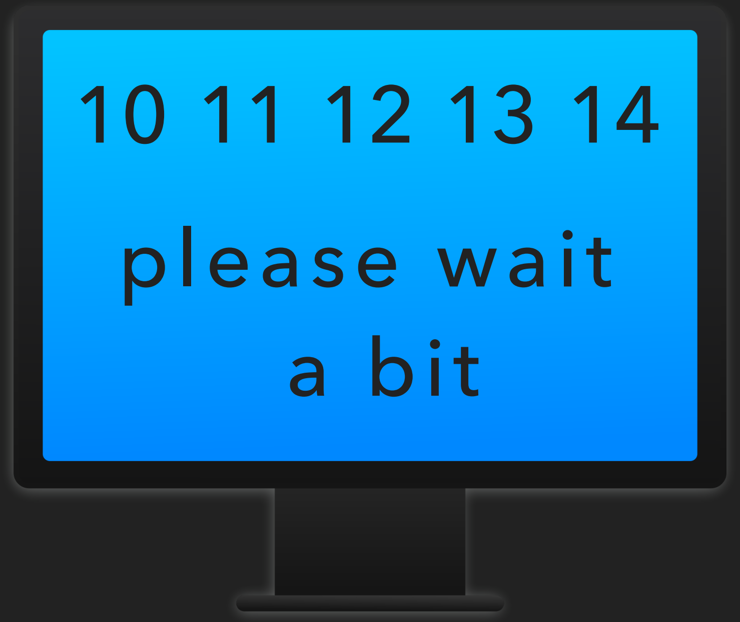

THE CALCULUS

THE $\lambda_{æ}$-CALCULUS

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- Extension of the **fine-grain call-by-value λ-calculus** [Levy et al. '03]
  - values

    $$V, W \quad ::= \quad \ldots \mid \langle V \rangle$$

  - computations

    $$M, N \quad ::= \quad \ldots \mid \text{gen. recursion} \mid \text{previously shown computations}$$

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    $$P, Q \quad ::= \quad \mathsf{run}\ M \mid P \,||\, Q \mid \uparrow \mathsf{op}\,(V, P) \mid \downarrow \mathsf{op}\,(W, P)$$

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    a fulfilled promise

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  match the structure of processes

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$$\frac{\mathsf{op} \in o \qquad \Gamma \vdash V : A_{\mathsf{op}} \qquad \Gamma \vdash M : X \,!\, (o, \iota)}{\Gamma \vdash \uparrow \mathsf{op}\,(V, M) : X \,!\, (o, \iota)}$$

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action of interrupts
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$$\boxed{\mathsf{op} \downarrow (o, \iota) \; = \; \begin{cases} (o \cup o', \iota[\mathsf{op} \mapsto \bot] \cup \iota') & \text{if } \; \iota(\mathsf{op}) = (o', \iota') \\ (o, \iota) & \text{otherwise} \end{cases}}$$

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$$\frac{\iota'(\mathsf{op}) = (o, \iota) \qquad \Gamma, x : A_{\mathsf{op}} \vdash M : \langle X \rangle \,!\, (o, \iota) \qquad \Gamma, p : \langle X \rangle \vdash N : Y \,!\, (o', \iota')}{\Gamma \vdash \mathsf{promise}\ (\mathsf{op}\ x \ \mapsto \ M)\ \mathsf{as}\ p\ \mathsf{in}\ N : Y \,!\, (o', \iota')}$$

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effects of op's handlers

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THE TYPING RULES

payload value matches op's signature $\mathsf{op} : A_{\mathsf{op}}$

op is allowed to happen

$$\frac{\mathsf{op} \in o \qquad \Gamma \vdash V : A_{\mathsf{op}} \qquad \Gamma \vdash M : X \,!\, (o, \iota)}{\Gamma \vdash \ \uparrow \mathsf{op}\,(V, M) : X \,!\, (o, \iota)}$$

effects of op's handlers

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* signals
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* individual computation result forms (w/o signals)

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process types also "reduce"

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- $\mathcal{P} \rightsquigarrow \mathsf{op} \downarrow \mathcal{P}$
- $\mathcal{P} \rightsquigarrow \mathcal{Q} \implies \mathsf{op} \downarrow \mathcal{P} \rightsquigarrow \mathsf{op} \downarrow \mathcal{Q}$

where

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  - web interface (possible to explore all reduction sequences)

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