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Specification and Verification for Unrestricted Algebraic Effects and Handling

Artifacts Available acm V1.1

Artifacts Evaluated acm Functional V1.1

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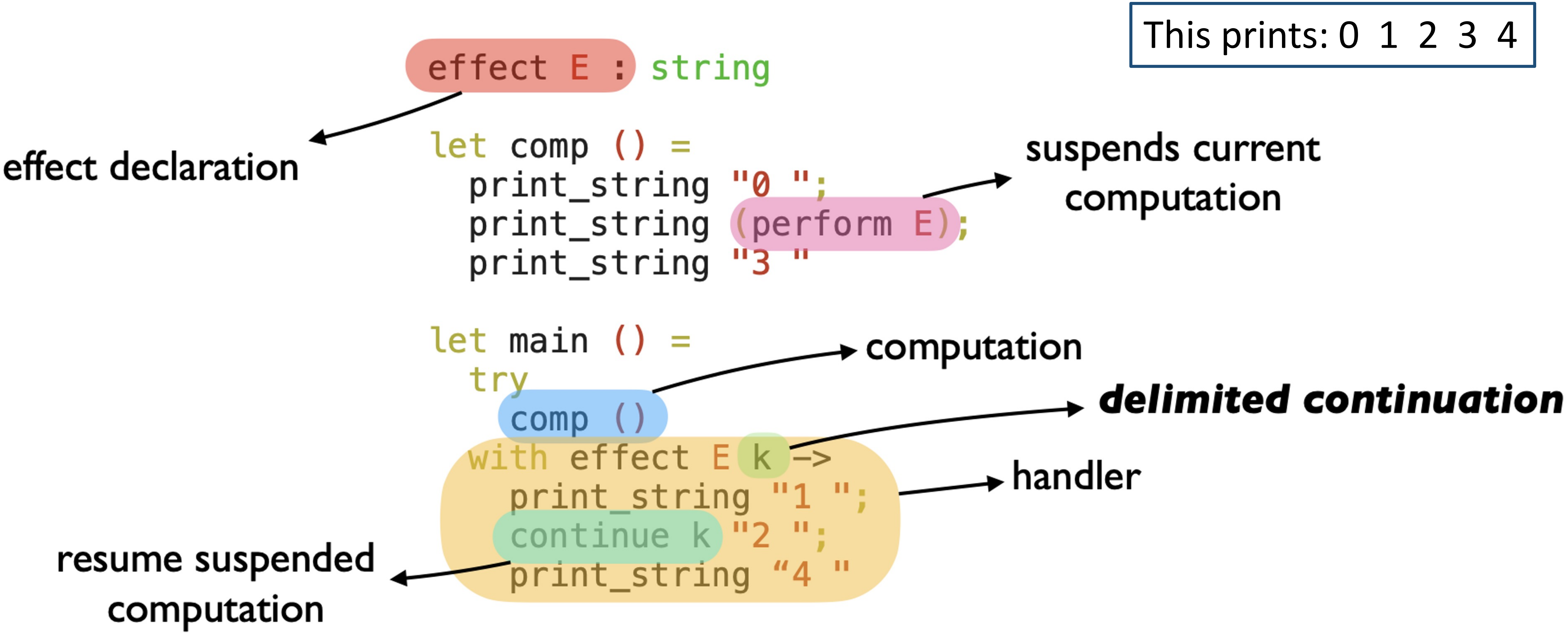
User-defined Effects and Handlers



This prints: 0 1 2 3 4

```
effect E : string

let comp () =
  print_string "0 ";
  print_string (perform E);
  print_string "3 "

let main () =
  try
    comp ()
  with effect E k ->
    print_string "1 ";
    continue k "2 ";
    print_string “4 "
```

effect declaration

suspends current computation

computation

delimited continuation

handler

resume suspended computation

Example taken from “Effect Handlers in Multicore OCaml” slides by KC Sivaramakrishnan.

Motivation Example

```
1  effect Label: int
2  (* User-defined effect, which will be resumed with int values *)
3
4  let callee () : int
5  = let x = ref 0 in                (* initialize x to zero *)
6    let ret = perform Label in      (* the handler has no access to x *)
7    x := !x + 1;                    (* increment x from zero to one *)
8    assert (!x = 1);                (* x now contains one *)
9    ret + 2                         (* return the resumed value + 2 *)
```

- Zero-shot handlers: abandon the continuation, just like exception handlers;
- One-shot handlers: resume the continuation once, the assertion on line 8 succeeds;
- Multi-shot handlers: resume the continuation more than once, the assertion on line 8 fails.

Motivation Example

```
effect Label: int
(* User-defined effect, which will be resumed with int values *)

let callee () : int
= let x = ref 0 in              (* initialize x to zero *)
  let ret = perform Label in    (* the handler has no access to x *)
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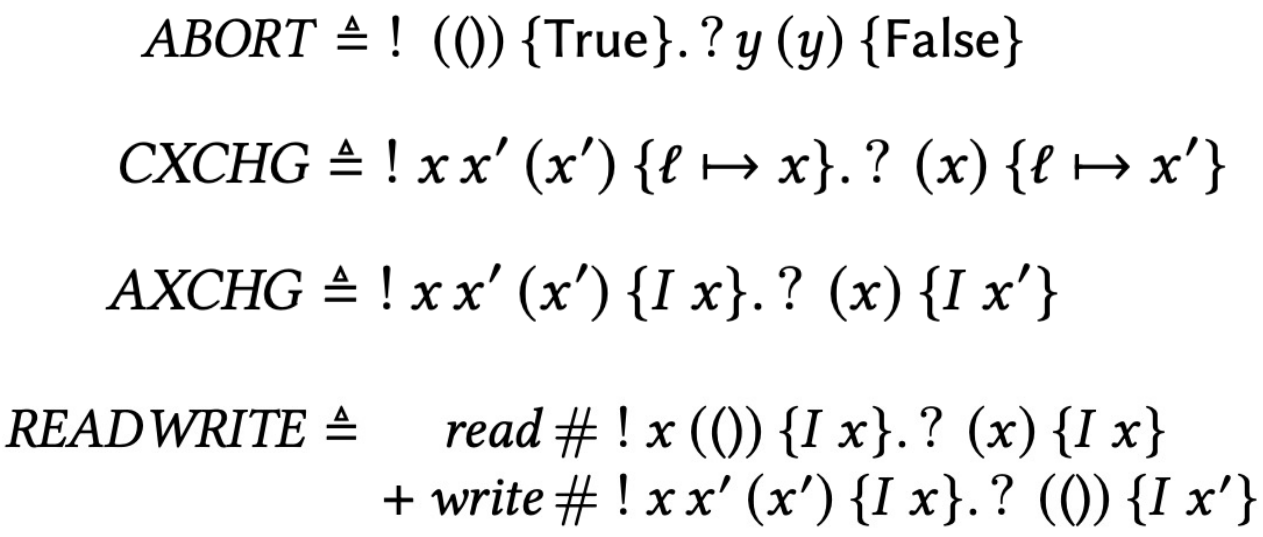
  ret + 2                       (* return the resumed value + 2 *)
```

Existing verification techniques:

- **multi-shot continuations + pure setting, e.g. [Song et al. 2022];**
- **heap manipulation + one-shot continuations, e.g. [de Vilhena and Pottier 2021];**
- **multi-shot + heap-manipulation, under a restricted frame rule, e.g. [de Vilhena 2022].**

Protocol Based Approach [de Vilhena and Pottier 2021]

- Hazel & Maze: Model client-handler interactions in the form of protocols
- Globally define the effects that clients perform and the replies they receive from handlers
- Global assumptions to provide explicit (or early) interpretation effects



$$\mathit{ABORT} \triangleq\ !\ \ (())\ \{\mathsf{True}\}.\ ?\, y\ (y)\ \{\mathsf{False}\}$$

$$\mathit{CXCHG} \triangleq\ !\, x\, x'\ (x')\ \{\ell \mapsto x\}.\ ?\ \ (x)\ \{\ell \mapsto x'\}$$

$$\mathit{AXCHG} \triangleq\ !\, x\, x'\ (x')\ \{I\ x\}.\ ?\ \ (x)\ \{I\ x'\}$$

$$\begin{aligned} \mathit{READWRITE} \triangleq\quad & \mathit{read}\ \#\ !\, x\ (())\ \{I\ x\}.\ ?\ \ (x)\ \{I\ x\} \\ & + \mathit{write}\ \#\ !\, x\, x'\ (x')\ \{I\ x\}.\ ?\ \ (())\ \{I\ x'\} \end{aligned}$$

Our Solution: Effectful Specification Logic (ESL)

- Fully Modular Per-Method Verification (no global assumption)
- Sequencing, ***$\varphi_1\,;\,\varphi_2$***

result

- Uninterpreted relations for ***unhandled effects*** and unknown functions, $E(x, r)$

input

- Reducible ***try-catch logic constructs***
- *Normalization: compact* each sequence of pre/post stages, via bi-abduction
- Use ***re-summarization*** (lemma) when handling recursive generated effects

$$\boxed{\begin{array}{lrcl} (ESL) & \varphi & ::= & \mathbf{req}\ P \mid \mathbf{ens}[r]\ Q \mid \varphi;\varphi \mid \varphi\vee\varphi \mid \exists\, x^*;\varphi \mid \\ & & & E(x, r) \mid f(x^*, r) \mid \mathbf{try}[\delta](\varphi)\ \mathbf{catch}\ \mathcal{H}_\Phi \end{array}}$$

$$D, P, Q ::= \sigma \wedge \pi \qquad\qquad \sigma ::= emp \mid x \mapsto y \mid \sigma * \sigma \mid \ldots$$

We propose ESL

$$(ESL) \qquad \varphi \quad ::= \quad \mathbf{req}\ P \mid \mathbf{ens}[r]\ Q \mid \varphi;\varphi \mid \varphi \vee \varphi \mid \exists\, x^*; \varphi \mid E(x, r) \mid f(x^*, r) \mid \mathbf{try}[\delta](\varphi)\ \mathbf{catch}\ \mathcal{H}_\Phi$$

```
1  effect Label: int
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9    ret + 2                        (* return the resumed value + 2 *)
```

$$\begin{aligned} callee(r_c) \ = \ & \exists x \cdot \mathbf{ens}\ \ x \mapsto 0\ ; && \text{// Line 5} \\ & \exists ret \cdot Label(ret)\ ; && \text{// Line 6} \\ & \exists z \cdot \mathbf{req}\ \ x \mapsto z \wedge z{+}1{=}1\ \ \mathbf{ens}[r_c]\ x \mapsto z{+}1 \wedge r_c{=}(ret{+}2) && \text{// Lines 7-9} \end{aligned}$$

We propose ESL

$$(ESL) \qquad \varphi \quad ::= \quad \mathbf{req}\ P \mid \mathbf{ens}[r]\ Q \mid \varphi;\varphi \mid \varphi\vee\varphi \mid \exists\, x^*;\varphi \mid \\ E(x,r) \mid f(x^*,r) \mid \mathbf{try}[\delta](\varphi)\ \mathbf{catch}\ \mathcal{H}_\Phi$$

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8    assert (!x = 1);              (* x now
9    ret + 2                       (* retur
```

Bi-abduction:

∃ z; req x→z;
     ens x→z+1;
∃ b; req x→b ∧ b=1

$$\begin{aligned} callee(r_c) \ = \ & \exists x \cdot \mathbf{ens}\ \ x{\mapsto}0\,; && //\ \text{Line } 5 \\ & \exists ret \cdot Label(ret)\,; && //\ \text{Line } 6 \\ & \exists z \cdot \mathbf{req}\ \ x{\mapsto}z \wedge z{+}1{=}1\ \ \mathbf{ens}[r_c]\ x{\mapsto}z{+}1 \wedge r_c{=}(ret{+}2) && //\ \text{Lines } 7\text{-}9 \end{aligned}$$

We propose ESL

$$(ESL) \qquad \varphi \; ::= \; \mathbf{req}\ P \mid \mathbf{ens}[r]\ Q \mid \varphi;\varphi \mid \varphi \vee \varphi \mid \exists\, x^*; \varphi \mid$$
$$E(x, r) \mid f(x^*, r) \mid \mathbf{try}[\delta](\varphi)\ \mathbf{catch}\ \mathcal{H}_\Phi$$

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1   effect Label: int
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```

Bi-abduction:

$\exists\ z;\ \mathrm{req}\ x \to z \wedge z+1=1;$
$\qquad \mathrm{ens}\ x \to z+1$

$$\begin{aligned} callee(r_c) \;=\; & \exists x \cdot \mathbf{ens}\ x \mapsto 0\,; && \text{// Line 5} \\ & \exists ret \cdot Label(ret)\,; && \text{// Line 6} \\ & \exists z \cdot \mathbf{req}\ x \mapsto z \wedge z{+}1{=}1\ \ \mathbf{ens}[r_c]\ x \mapsto z{+}1 \wedge r_c{=}(ret{+}2) && \text{// Lines 7-9} \end{aligned}$$

Try-Catch Reduction (Examples)

$$
\begin{aligned}
\mathit{callee}(r_c) \ = \ & \exists x \cdot \mathbf{ens}\ \ x {\mapsto} \mathit{0}\ ; && \text{// Line 5}\\
& \exists \mathit{ret} \cdot \mathit{Label}(\mathit{ret})\ ; && \text{// Line 6}\\
& \exists z \cdot \mathbf{req}\ \ x {\mapsto} z \wedge z{+}\mathit{1}{=}\mathit{1}\ \ \mathbf{ens}[r_c]\ x {\mapsto} z{+}\mathit{1} \wedge r_c{=}(\mathit{ret}{+}2) && \text{// Lines 7-9}
\end{aligned}
$$

```
let zero_shot () : int
(* zero_shot(r_z) = ∃x ; ens[r_z] x↦0 ∧ r_z=-1 *)
= match callee () with
| effect Label k -> -1
```

```
let one_shot () : int
(* one_shot(r_o) = ∃x ; ens[r_o] x↦1 ∧ r_o=5 *)
= match callee () with
| effect Label k -> resume k 3
```

Try-Catch Reduction (Examples)

$$\begin{aligned} \mathit{callee}(r_c) \;=\; & \exists x \cdot \mathbf{ens}\;\; x{\mapsto}\mathit{0}\,; && \text{// Line 5}\\ & \exists \mathit{ret} \cdot \mathit{Label}(\mathit{ret})\,; && \text{// Line 6}\\ & \exists z \cdot \mathbf{req}\;\; x{\mapsto}z \wedge z{+}\mathit{1}{=}\mathit{1}\;\; \mathbf{ens}[r_c]\; x{\mapsto}z{+}\mathit{1} \wedge r_c{=}(\mathit{ret}{+}\mathit{2}) && \text{// Lines 7-9} \end{aligned}$$

```
let zero_shot () : int
(* $\mathit{zero\_shot}(r_z) = \exists x\,;\, \mathbf{ens}[r_z]\; x{\mapsto}\mathit{0} \wedge r_z{=}{-}\mathit{1}$ *)
= match callee () with
| effect Label k -> -1
```

```
let one_shot () : int
(* $\mathit{one\_shot}(r_o) = \exists x\,;\, \mathbf{ens}[r_o]\; x{\mapsto}\mathit{1} \wedge r_o{=}\mathit{5}$ *)
= match callee () with
| effect Label k -> resume k 3
```

```
let multi_shot () : int
(* $\mathit{multi\_shot}(r_m) = \mathbf{req}\;\mathit{false}$ *)
= match callee () with
| effect Label k ->
  let _ = resume k 4 in resume k 5
```

Try-Catch Reduction (Examples)

$$
\begin{aligned}
\mathit{callee}(r_c) \;=\;& \exists x \cdot \mathbf{ens}\;\; x{\mapsto}0\;; && \text{// Line 5}\\
& \exists \mathit{ret} \cdot \mathit{Label}(\mathit{ret})\;; && \text{// Line 6}\\
& \exists z \cdot \mathbf{req}\;\; x{\mapsto}z \wedge z{+}1{=}1\;\; \mathbf{ens}[r_c]\; x{\mapsto}z{+}1 \wedge r_c{=}(\mathit{ret}{+}2) && \text{// Lines 7-9}
\end{aligned}
$$

```
let zero_shot () : int
(* zero_shot(r_z) = ∃x ; ens[r_z] x↦0 ∧ r_z=-1 *)
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```
let one_shot () : int
(* one_shot(r_o) = ∃x ; ens[r_o] x↦1 ∧ r_o=5 *)
= match callee () with
| effect Label k -> resume k 3
```

```
let multi_shot () : int
(* multi_shot(r_m) = req false *)
= match callee () with
| effect Label k ->
  let _ = resume k 4 in resume k 5
```

Intuition:

- ➢ Explicit access to continuation
- ➢ Modular verification:
  - try-catch reduction
  - normalization via bi-abduction

Try-Catch Reduction (Selected Rules)

- The base case:

$$\frac{(x \longrightarrow \Phi_n) \in \mathcal{H}_\Phi}{\textbf{try}[\delta](\mathcal{N}[r])\ \textbf{catch}\ \mathcal{H}_\Phi \rightsquigarrow \mathcal{N}[r]\ ;\ \Phi_n[r/x]}\ [\mathcal{R}\textit{-Normal}]$$

- When handling an effect, first reason about the behaviours of its continuation

$$\frac{\mathcal{E} = \mathcal{N}\ ;\ E(x, r) \qquad E \in dom(\mathcal{H}_\Phi) \qquad \textbf{try}[d](\theta)\ \textbf{catch}\ \mathcal{H}_\Phi \rightsquigarrow \Phi}{\textbf{try}[d](\mathcal{E}\ ;\ \theta)\ \textbf{catch}\ \mathcal{H}_\Phi \rightsquigarrow \textbf{try}[d](\mathcal{E}\ \#\ \Phi)\ \textbf{catch}\ \mathcal{H}_\Phi}\ [\mathcal{R}\textit{-Deep}]$$

- Instantiate the high-order predicate k using the continuation’s specification

$$\frac{\mathcal{E} = \mathcal{N}\ ;\ E(x, r) \qquad (E(y)k \longrightarrow \Phi) \in \mathcal{H}_\Phi \qquad \Phi' = \Phi[x/y, (\lambda(r, r_c) \rightarrow \Phi[r_c])/k]}{\textbf{try}[\delta](\mathcal{E}\ \#\ \Phi[r_c])\ \textbf{catch}\ \mathcal{H}_\Phi \rightsquigarrow \mathcal{N}\ ;\ \Phi'}\ [\mathcal{R}\textit{-Eff-Handle}]$$

Try-Catch Reduction (Selected Rules)

- The base case:

$$\frac{(x \longrightarrow \Phi_n) \in \mathcal{H}_\Phi}{\mathbf{try}[\delta](\mathcal{N}[r])\ \mathbf{catch}\ \mathcal{H}_\Phi \rightsquigarrow \mathcal{N}[r]\ ;\ \Phi_n[r/x]}\ [\mathcal{R}\text{-}\mathit{Normal}]$$

- When handling an effect, first reason about the behaviours of its continuation

$$\frac{\mathcal{E} = \mathcal{N}\ ;\ E(x, r) \qquad E \in \mathit{dom}(\mathcal{H}_\Phi) \qquad \mathbf{try}[d](\theta)\ \mathbf{catch}\ \mathcal{H}_\Phi \rightsquigarrow \Phi}{\mathbf{try}[d](\mathcal{E}\ ;\ \theta)\ \mathbf{catch}\ \mathcal{H}_\Phi \rightsquigarrow \mathbf{try}[d](\mathcal{E}\ \#\ \Phi)\ \mathbf{catch}\ \mathcal{H}_\Phi}\ [\mathcal{R}\text{-}\mathit{Deep}]$$

effect-free (wrt H_ϕ) after #

- Instantiate the high-order predicate k using the continuation's specification

$$\frac{\mathcal{E} = \mathcal{N}\ ;\ E(x, r) \qquad (E(y)k \longrightarrow \Phi) \in \mathcal{H}_\Phi \qquad \Phi' = \Phi[x/y, \boxed{(\lambda(r, r_c) \rightarrow \Phi[r_c])/k}]}{\mathbf{try}[\delta](\mathcal{E}\ \#\ \Phi[r_c])\ \mathbf{catch}\ \mathcal{H}_\Phi \rightsquigarrow \mathcal{N}\ ;\ \Phi'}\ [\mathcal{R}\text{-}\mathit{Eff}\text{-}\mathit{Handle}]$$

Binding the effect free continuation to k

Higher-Order Function meets Unresolved Try-Catch Construct

```
let foo f : int
(* foo(f,r) = try (∃res · f(res))  catch { Label k → k(5,r) } *)
= match f() with
| effect Label k -> resume k 5
```

Keep the try-catch constructs in the specification, which allows modular verification.

```
let goo () : int (* goo(r)  =  ∃x · ens[r] x↦0 ∧ r=15 *)
= let f = (fun () -> let x = ref 0 in (perform Label) + 10)
  in foo f
```

Instantiate the unknown function

$$goo(r) = \exists f \cdot \mathbf{ens}\ f(res) = (\exists x, y \cdot \mathbf{ens}\ x \mapsto 0; Label(y); \mathbf{ens}[res]\ res{=}y{+}10)\ ;\ foo(f, r)$$

$$\rightsquigarrow\ \mathbf{try}\ \exists\, res, x, y \cdot \mathbf{ens}\ x \mapsto 0; Label(y); \mathbf{ens}[res]\ res{=}y{+}10\ \mathbf{catch}\ \{\, Label\ k \to k(5, r) \,\}$$

$$\rightsquigarrow^{*}\ \exists x \cdot \mathbf{ens}[r]\ x \mapsto 0 \wedge r{=}15$$

Reducing the try-catch construct

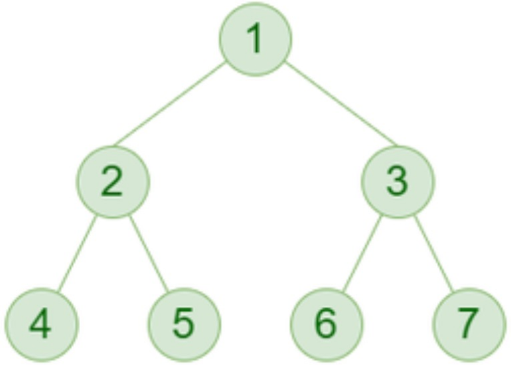
Inductive Proofs via Lemmas

```
effect Flip : bool

let tossN n
(* $tossN(n, res) = \exists r_0 ; \mathbf{ens}\ n{=}1; Flip(r_0); \mathbf{ens}[res]\ res{=}r_0 \lor$
                    $\exists r_1 ; \mathbf{ens}\ n{>}1; Flip(r_1); \exists r_2 ; tossN(n-1, r_2); \mathbf{ens}[res]\ res{=}(r_1 \land r_2)$ *)
= match n with
| 1 -> perform Flip
| n -> let r1 = perform Flip in
       let r2 = tossN (n-1) in r1 && r2

let all_results counter n
(* $all\_results(n, r) = \exists z ; \mathbf{req}\ counter \mapsto z \land n{>}0\ \mathbf{ens}[r]\ counter \mapsto z{+}(2^{n+1}{-}2) \land r{=}1$ *)
= match tossN n with
  | x -> if x then 1 else 0
  | effect Flip k ->
      counter := !counter + 1;          (* increase the counter *)
      let res1 = resume k true in       (* resume with true      *)
      counter := !counter + 1;          (* increase the counter *)
      let res2 = resume k false in      (* resume with false     *)
      res1 + res2                       (* gather the results    *)
```

Conjunct each Flip result



n=1, counter = 2, res = 1

n=2, counter = 6, res =1

n=3, counter=14, res =1

...

Inductive Proofs via Lemmas

```
effect Flip : bool

let tossN n
(* tossN(n, res) = ∃r0 ; ens n=1; Flip(r0); ens[res] res=r0 ∨
                   ∃r1 ; ens n>1; Flip(r1) ; ∃r2 ; tossN(n−1, r2) ; ens[res] res=(r1∧r2) *)
= match n with
| 1 -> perform Flip
| n -> let r1 = perform Flip in
       let r2 = tossN (n-1) in r1 && r2

let all_results counter n
(* all_results(n, r) = ∃z ; req counter ↦ z ∧ n>0 ens[r] counter ↦ z+(2^(n+1)−2) ∧ r=1 *)
= match tossN n with
  | x -> if x then 1 else 0
  | effect Flip k ->
      counter := !counter + 1;          (* increase the counter *)
      let res1 = resume k true in       (* resume with true     *)
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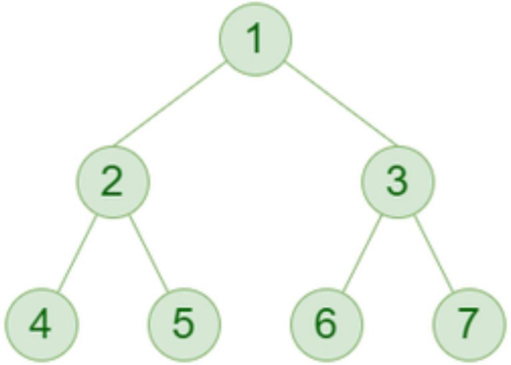
```

Conjunct each Flip result

Sum up how many back tracking branches leads to all true



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…

Inductive Proofs via Lemmas

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effect Flip : bool

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$$(\ast\ \mathit{tossN}(n, \mathit{res}) = \exists r_0 ; \textbf{ens}\ \ n{=}1; \mathit{Flip}(r_0); \textbf{ens}[\mathit{res}]\ \mathit{res}{=}r_0\ \vee$$
$$\exists r_1 ; \textbf{ens}\ \ n{>}1 ; \mathit{Flip}(r_1) ; \exists r_2 ; \mathit{tossN}(n{-}1, r_2) ; \textbf{ens}[\mathit{res}]\ \mathit{res}{=}(r_1 {\wedge} r_2)\ \ \ast)$$

```
= match n with
| 1 -> perform Flip
| n -> let r1 = perform Flip in
       let r2 = tossN (n-1) in r1 && r2

let all_results counter n
```

$$(\ast\ \mathit{all\_results}(n, r) = \exists z ; \textbf{req}\ \ \mathit{counter} \mapsto z \wedge n{>}0\ \ \textbf{ens}[r]\ \mathit{counter} \mapsto z{+}(2^{n+1}{-}2) \wedge r{=}1\ \ \ast)$$

```
= match tossN n with
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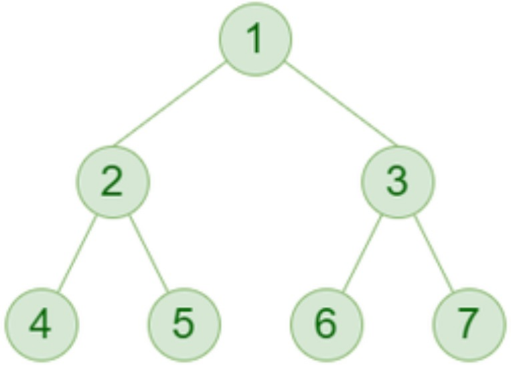


n=1, counter = 2, res = 1

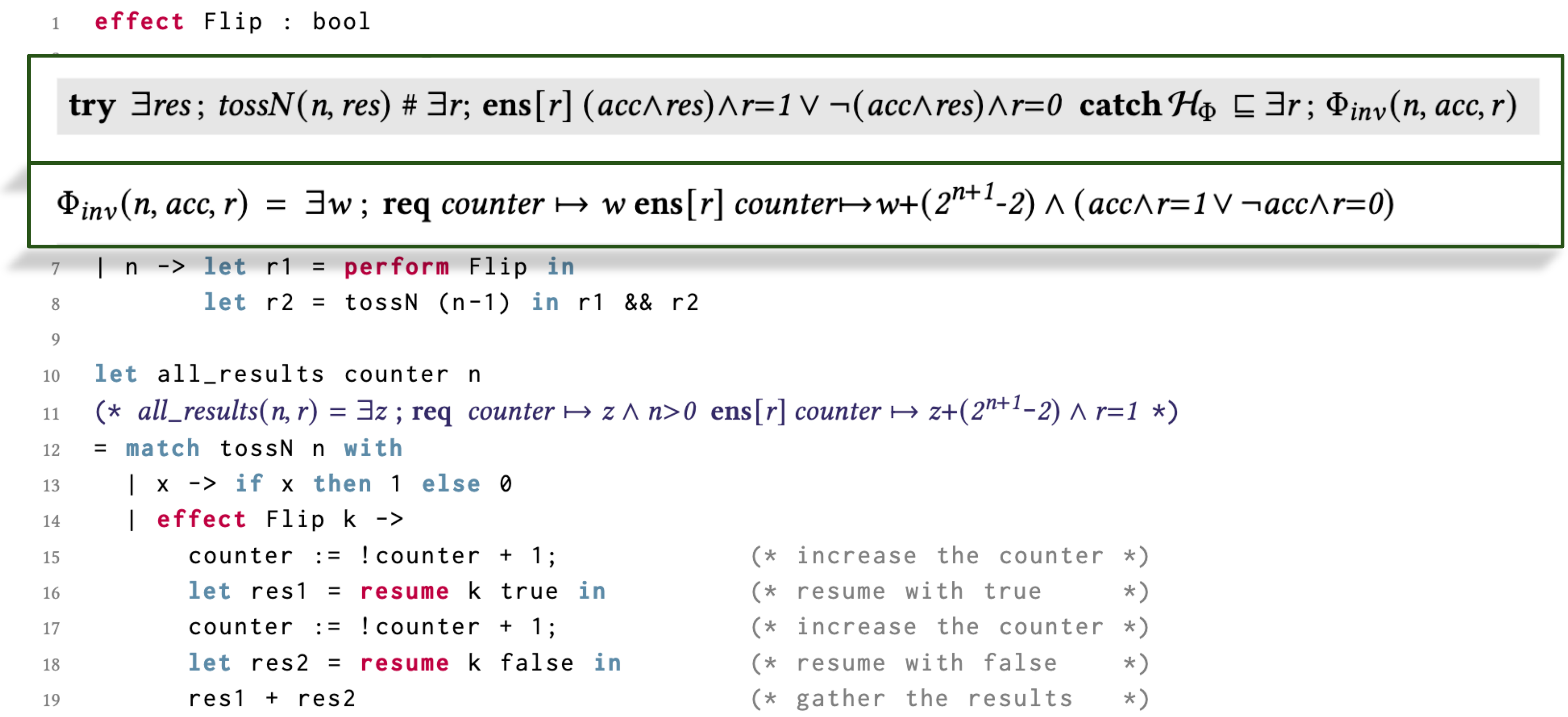
n=2, counter = 6, res =1

n=3, counter=14, res =1

…

… , counter = 2^{n+1}-2, res=1

Inductive Proofs via Lemmas



```
effect Flip : bool
```

$$\textbf{try}\ \exists res\,;\ tossN(n, res)\ \#\ \exists r;\ \textbf{ens}[r]\ (acc \wedge res) \wedge r{=}1 \vee \neg(acc \wedge res) \wedge r{=}0\ \ \textbf{catch}\ \mathcal{H}_\Phi\ \sqsubseteq \exists r\,;\ \Phi_{inv}(n, acc, r)$$

$$\Phi_{inv}(n, acc, r)\ =\ \exists w\,;\ \textbf{req}\ counter \mapsto\ w\ \textbf{ens}[r]\ counter{\mapsto} w{+}(2^{n+1}{-}2) \wedge (acc \wedge r{=}1 \vee \neg acc \wedge r{=}0)$$

```
| n -> let r1 = perform Flip in
       let r2 = tossN (n-1) in r1 && r2

let all_results counter n
(* all_results(n, r) = ∃z ; req  counter ↦ z ∧ n>0  ens[r] counter ↦ z+(2^{n+1}−2) ∧ r=1 *)
= match tossN n with
  | x -> if x then 1 else 0
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      counter := !counter + 1;          (* increase the counter *)
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Inductive Proofs via Lemmas

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```
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      counter := !counter + 1;
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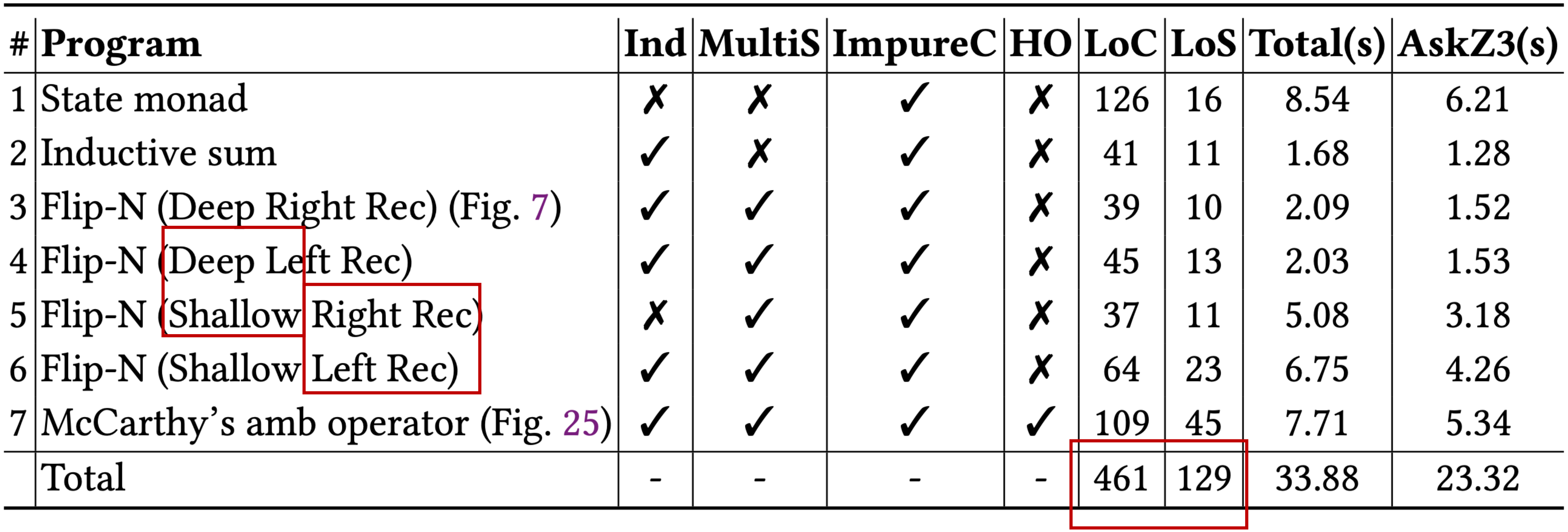
      counter := !counter + 1;
      let res2 = resume k false in
      res1 + res2
```

- Proving via applying lemmas
- Lemmas are proved based on:
  - ✓ Try-catch reduction
  - ✓ Unfolding and rewriting (entailment rules)

Implementation and Evaluation

- 5K LoC on top of OCaml 5
- Benchmark programs with features: (Ind) proof is inductive, (MultiS)multi-shot handlers, (ImpureC) impure continuations, (HO) program is higher-order.



#	Program	Ind	MultiS	ImpureC	HO	LoC	LoS	Total(s)	AskZ3(s)
1	State monad	✗	✗	✓	✗	126	16	8.54	6.21
2	Inductive sum	✓	✗	✓	✗	41	11	1.68	1.28
3	Flip-N (Deep Right Rec) (Fig. 7)	✓	✓	✓	✗	39	10	2.09	1.52
4	Flip-N (Deep Left Rec)	✓	✓	✓	✗	45	13	2.03	1.53
5	Flip-N (Shallow Right Rec)	✗	✓	✓	✗	37	11	5.08	3.18
6	Flip-N (Shallow Left Rec)	✓	✓	✓	✗	64	23	6.75	4.26
7	McCarthy's amb operator (Fig. 25)	✓	✓	✓	✓	109	45	7.71	5.34
	Total	-	-	-	-	461	129	33.88	23.32

LoS/LoC < 30%

Summary

- ✓ **Scope**: Zero/one/multi-shots + impure continuations, deep/shallow handlers, left/right recursion
- ✓ **Effectful Specification Logic**: Staged specifications + unhandled effects + try-catch logic constructs
- ✓ **Hoare-style Verifier**: ML-like language + imperative higher-order + algebraic effects.
- ✓ **The Back-end Checker for ESL**: Normalization rules + reduction process of try-catch constructs.
- ✓ **Prototype (Multicore OCaml):** Proven correctness, report on experimental results, and case studies.

Summary

- ✓ **Scope**: Zero/one/multi-shots + impure continuations, deep/shallow handlers, left/right recursion
- ✓ **Effectful Specification Logic**: Staged specifications + unhandled effects + try-catch logic constructs
- ✓ **Hoare-style Verifier**: ML-like language + imperative higher-order + algebraic effects.
- ✓ **The Back-end Checker for ESL**: Normalization rules + reduction process of try-catch constructs.
- ✓ **Prototype (Multicore OCaml):** Proven correctness, report on experimental results, and case studies.

Take Away:

1) **Try not to assume,** for both HO functions and effects!
2) Staged logic + try-catch enable modular specifications without global assumptions (protocols).
3) Explicit access to the continuations, which can be composed as needed.

I am currently on the academic job market, looking for research positions!

Thanks for listening!