Effect-Driven QuickChecking of Compilers

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ICFP'17, Oxford

```
exit (-369469277365242727 2)
```

```
int_of_string (exit ((/) ((/) (-1) 5) (abs 5)))
```

What are these?

```
(fun e -> pred 10) (if if true then false else false then
   fun n -> [] else fun o -> [])
```

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```
let a = let s = (let x = exit (lnot (-47628762612628909 7))
    in fun r -> fun k -> "zsqykify") () in exit (exit (let c
     = (mod) 516587874847912894 (-45340071501207836 48) in 0)
    ) in (asr) (if (fun x -> let h = 2 in false) (let r = (@
    ) [] [] in (lsl) 2273200848021743825 0) then 466 else if
     let b = "" in false then ( * ) 2 (-4611686018427387904)
     else let m = 2 in m) ((fun e -> if exit 5 then
    int_of_string "vgjgme" else (land) 4 7) (fun m -> (&&) (
    let i = () in false) (if true then true else true)))
```

What are these?

```
(-) (let a = (^) ((let o = fun c -> let s = (^) "srtwbawql"
    "fbe" in List.hd [] in let i = (fun x -> []) (fun s ->
   "r") in fun k -> string_of_int (-38239439737450152 93)) (
   ignore [8239; 51660285336868583 0; ])) (if (=) (if false
   then true else false) ((||) (not false) (not false))
   then string_of_int (if true then 8 else (-1)) else if
   exit 2 then string_of_int (-309435526309293195 5) else
   (^) "yvvqp" "el") in (fun b -> 92960247249054152 7) (let
   z = 5 in fun q -> (let c = if false then () else () in
   fun f -> not) (string_of_int (let t = true in 0)))) ((+)
    (let z = let g = let u = string_of_int (let e = () in
   let p = false in 332628035944507958 0) in 2 in let t =
   let i = let c = "ng" in 18 in g in fun b -> (fun w ->
   false) (if false then () else ()) in (fun a -> let e =
   [] in let t = string_of_bool false in if false then
   425635096218227740 else (-116261721431635920 7)) ()) ((
   fun e -> 68) (let x = (fun p -> fun d -> 6) ((fun p ->
   487301623237005908) (let o = "bxztzffio" in [])) ((let i
    = let g = 818 in 1 in fun h -> []) (fun b -> succ 59))
   in (let t = let m = fun p -> "taodmjmcrd" in true in (
   fun o -> string_of_bool) (fun g ->
   (-159253077253349266 7))) ((&&) true (let v = [] in (||)
```

What are these?

They are arbitrary ML programs

(with terrible indentation)

What are these?

What do they do?

What are these?

No idea, we didn't write them

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We wrote a **generator**
that **wrote them**

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$ ocamlc -o prog.byte prog.ml
$ ocamlopt -o prog.native prog.ml
$ ./prog.byte > byte.out
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$ diff -q byte.out native.out
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Any observed `diff` is suspicious

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in 0
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Bytecode result:

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Bytecode result: newline printed, `0`
Native code result: `0` (effect delayed indefinitely)

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This work is the story of how we pulled this off.

For more bugs: read the paper

Program generation: a refinement story

Program generation, take 1

Generate arbitrary strings:

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```
"␣𝕎"
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```
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"y?V&TIW%D$R\\@i5dRh>2EvF\nv<N:0%CGv>\nvJ[KJ1hR_:,M|RBP!aj>
   ymY7|3\"=N1]3r)]gmf[u:01v8Ln;.&`c@q9R;u3Mzczhhn;27\"zU.)
   x|[pIm.=e|DSdXsd1[;3B}2o@(s_|LV0irR'CH-su>8J49h-l-MARkQ
   [4+O(lyQu\"nZ)!K*5Yh#r!;rs+O9,I*oW6BY9VWZ\nan(VnI!N=PKv,
   wJS\\CU298\nzeA3<*Ag<@#Qu_]!T3A6X'^P7s/Q[RP.K}\\#5e+Q`"
```

Program generation, take 1

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```
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```

```
"y?V&TIW%D$R\\@i5dRh>2EvF\nv<N:0%CGv>\nvJ[KJ1hR_:,M|RBP!aj>
   ymY7|3\"=N1]3r)]gmf[u:01v8Ln;.&`c@q9R;u3Mzczhhn;27\"zU.)
   x|[pIm.=e|DSdXsd1[;3B}2o@(s_|LV0irR'CH-su>8J49h-l-MARkQ
   [4+O(lyQu\"nZ)!K*5Yh#r!;rs+O9,I*oW6BY9VWZ\nan(VnI!N=PKv,
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```

Few of these will make it through the lexer and the parser. . .

Program generation, take 2

Follow the grammar (Celento-al:SPE80):

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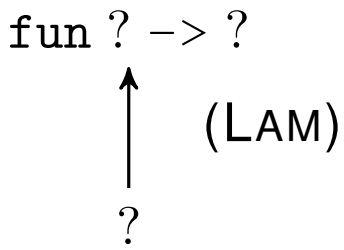

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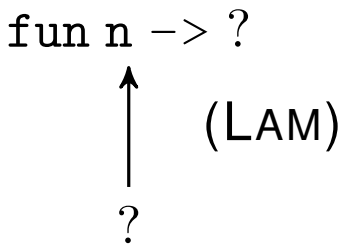

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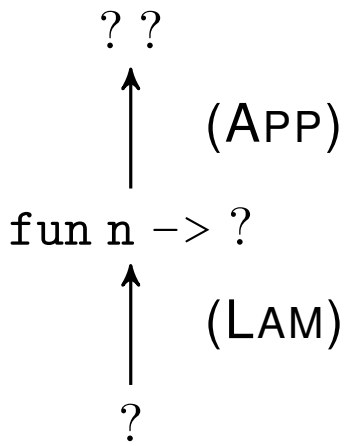

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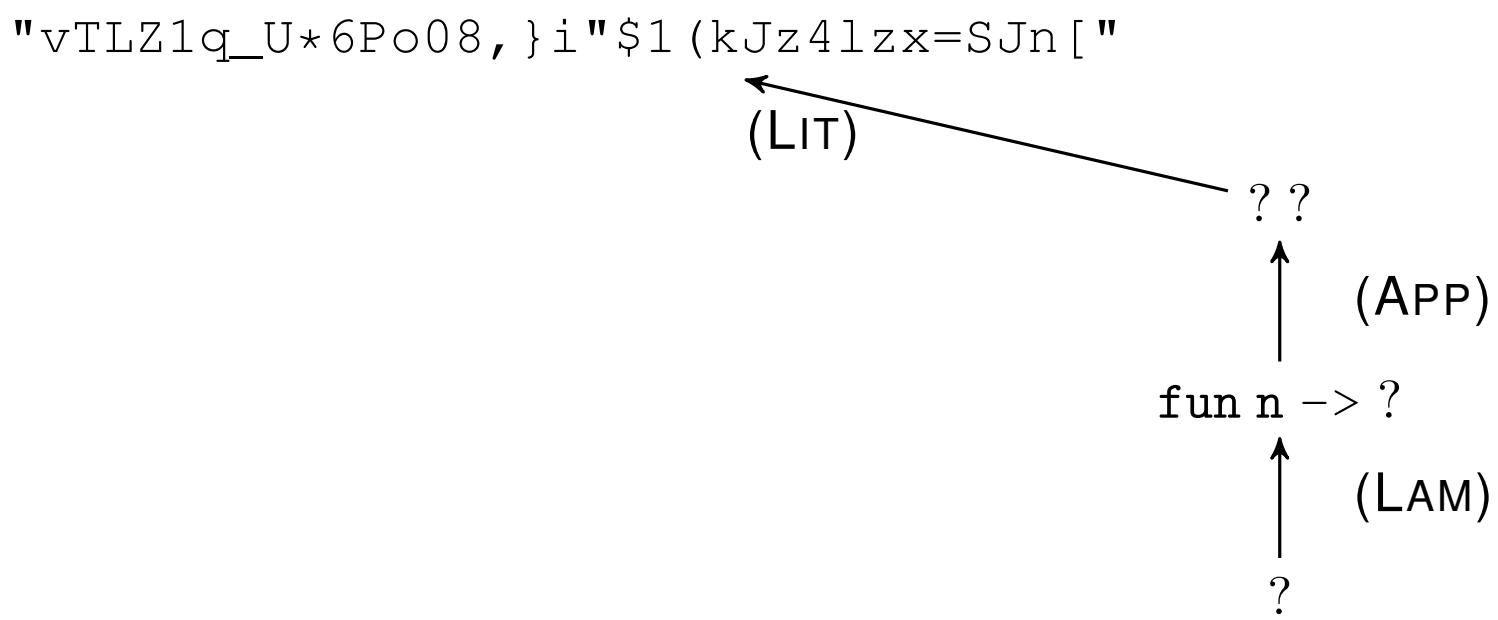

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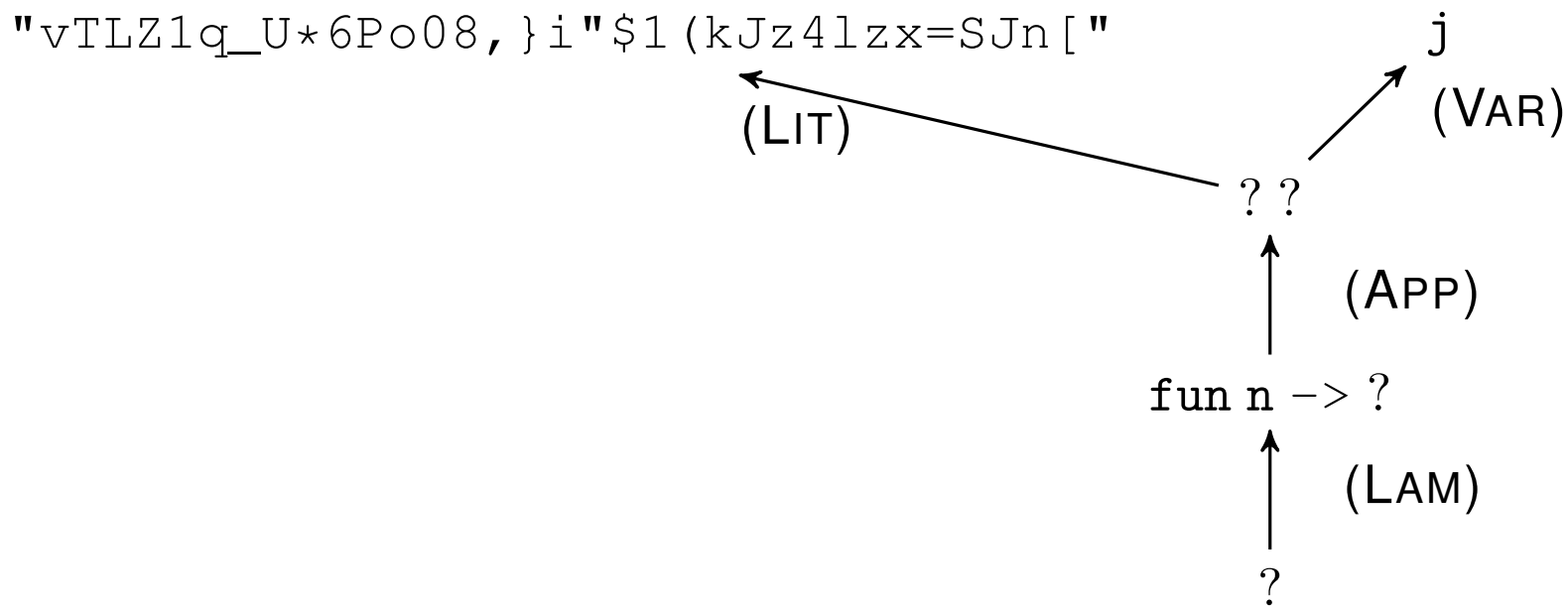

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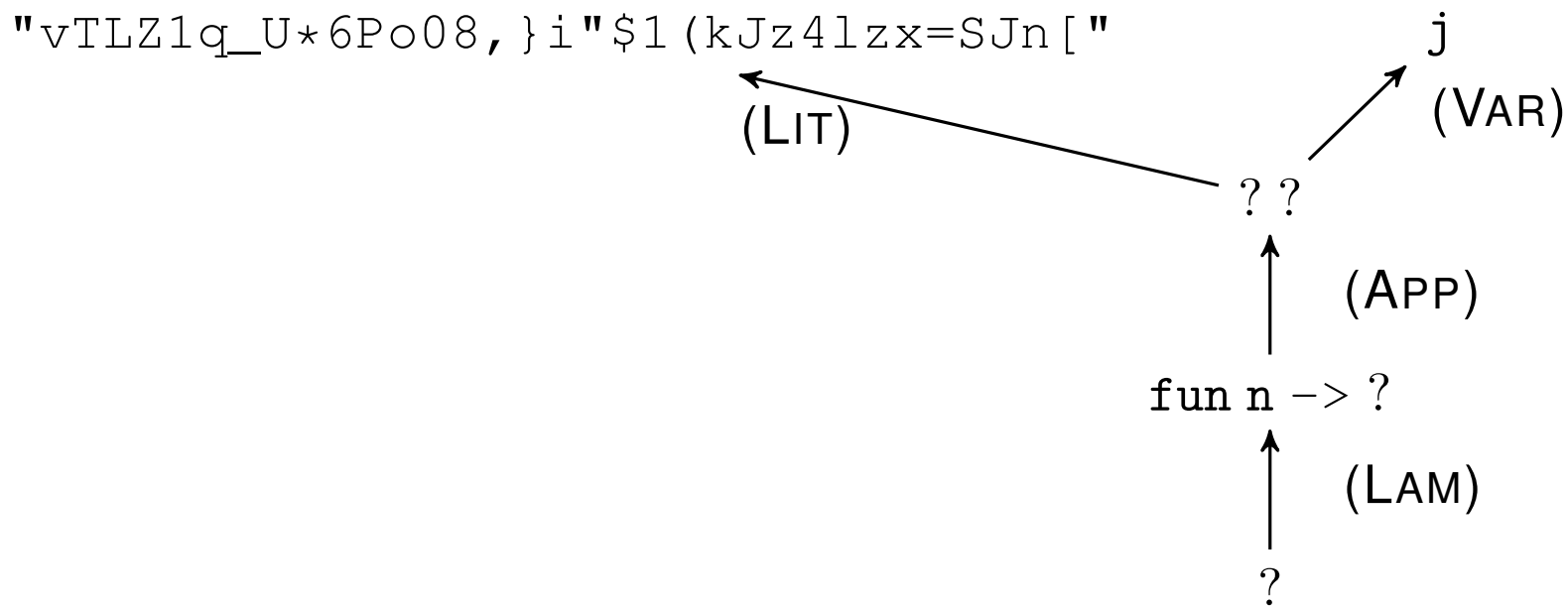

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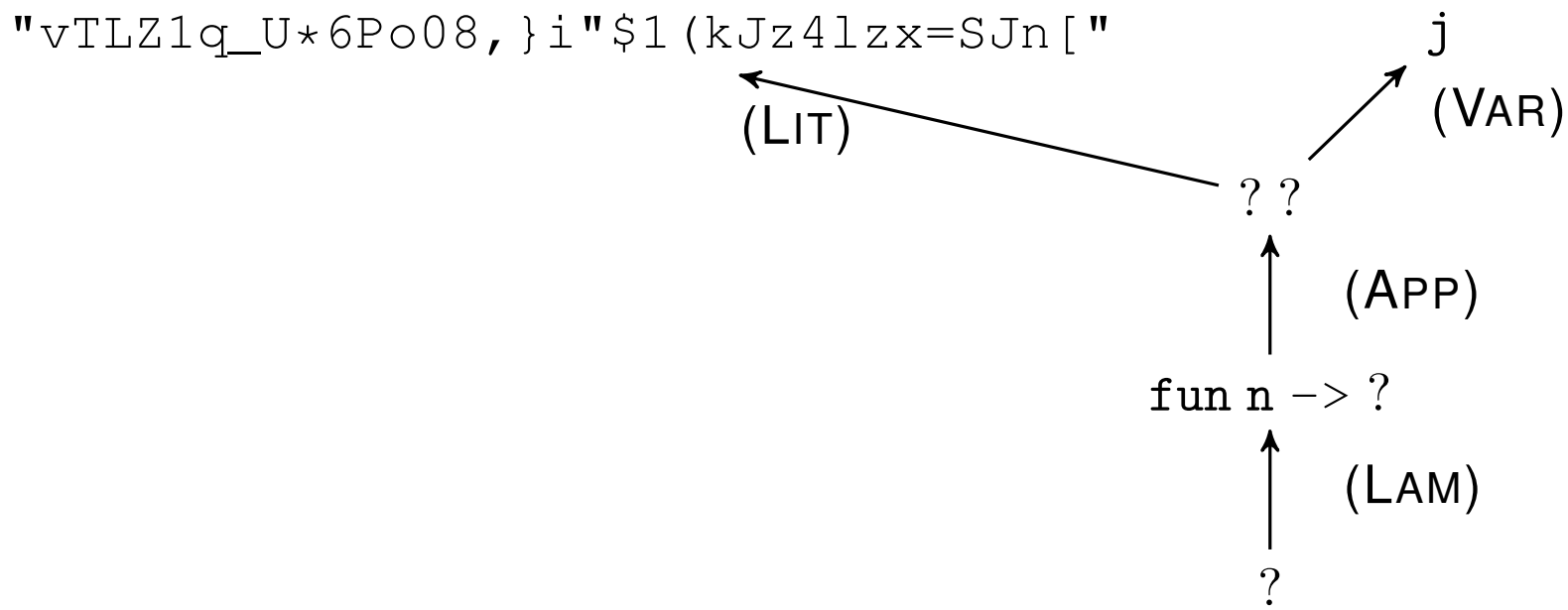

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Variant: de Bruijn notation

(+ count the number of enclosing binders)

Program generation, take 3

Consider the standard simply-typed λ-calculus rules:

$$\frac{\Delta(c) = \tau}{\Delta; \Gamma \vdash c : \tau}\ (\textsc{Const}) \qquad \frac{(\mathtt{x} : \tau) \in \Gamma}{\Delta; \Gamma \vdash \mathtt{x} : \tau}\ (\textsc{Var})$$

$$\frac{\Delta; \Gamma, (\mathtt{x} : \tau_1) \vdash e : \tau_2}{\Delta; \Gamma \vdash \mathtt{fun\ x\ ->}\ e : \tau_1 \to \tau_2}\ (\textsc{Lam})$$

$$\frac{\Delta; \Gamma \vdash e_0 : \tau_1 \to \tau_2 \qquad \Delta; \Gamma \vdash e_1 : \tau_1}{\Delta; \Gamma \vdash e_0\ e_1 : \tau_2}\ (\textsc{App})$$

Explicit parameter Δ: a type environment for literals

Program generation, take 3

Bottom-up reading of the typing relation (Pałka-al:AST11):

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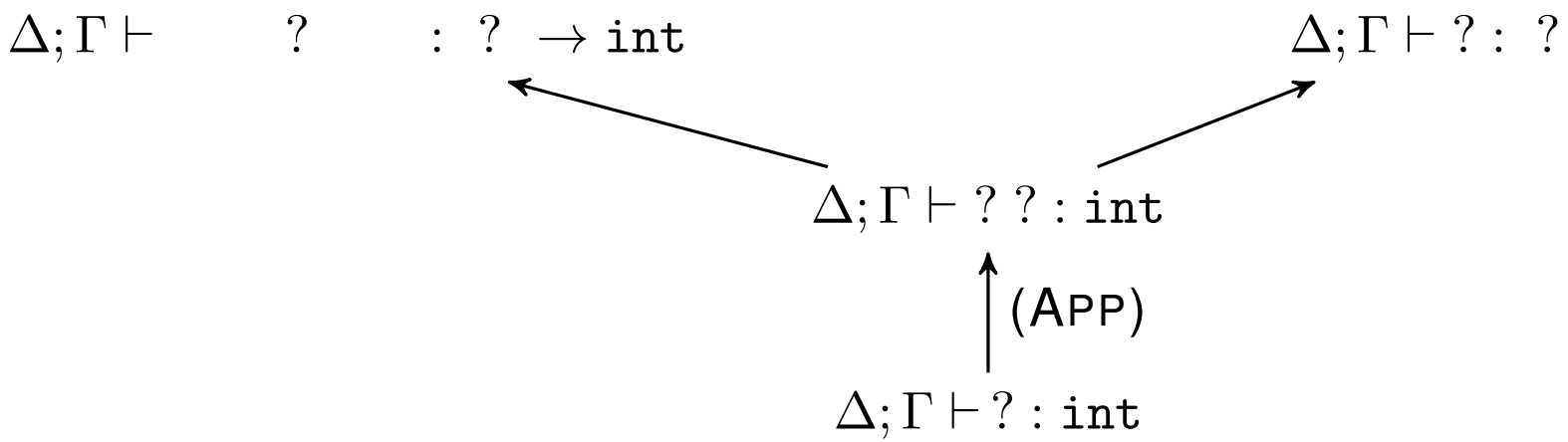

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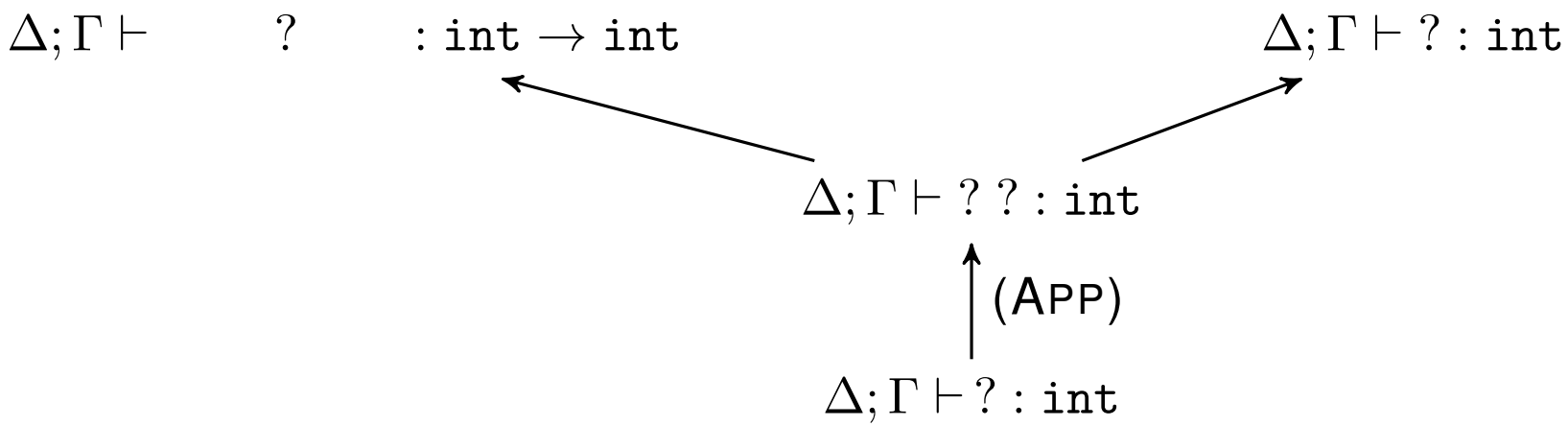

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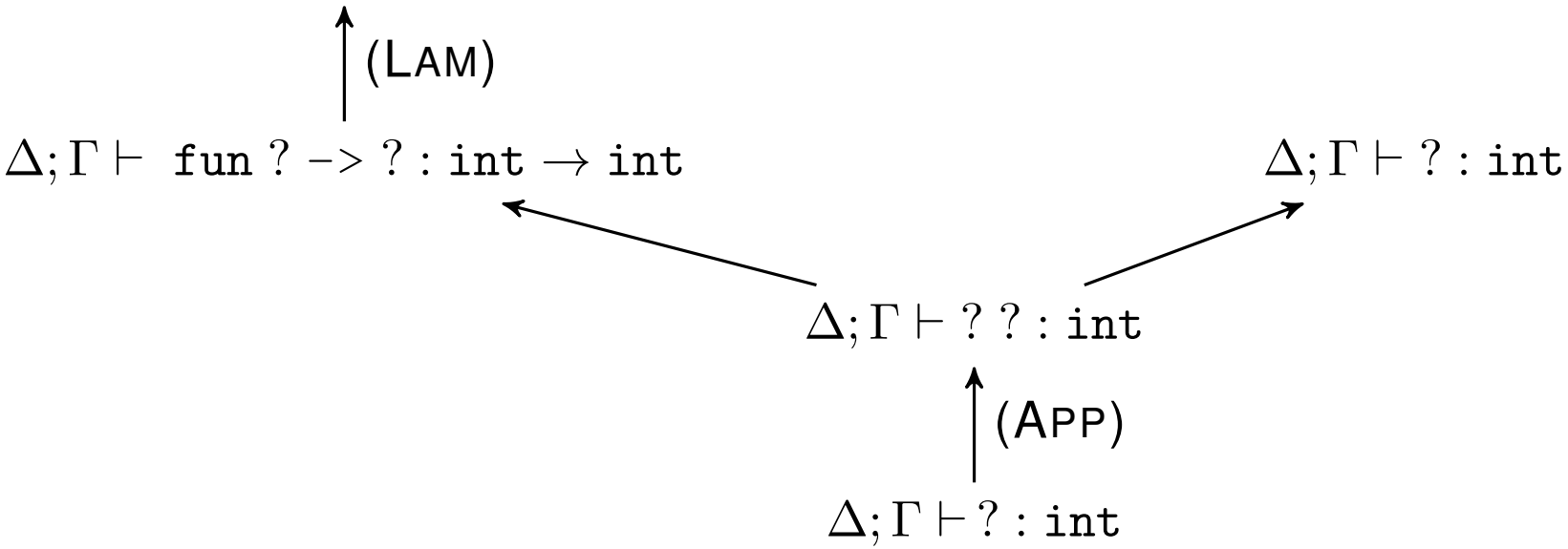

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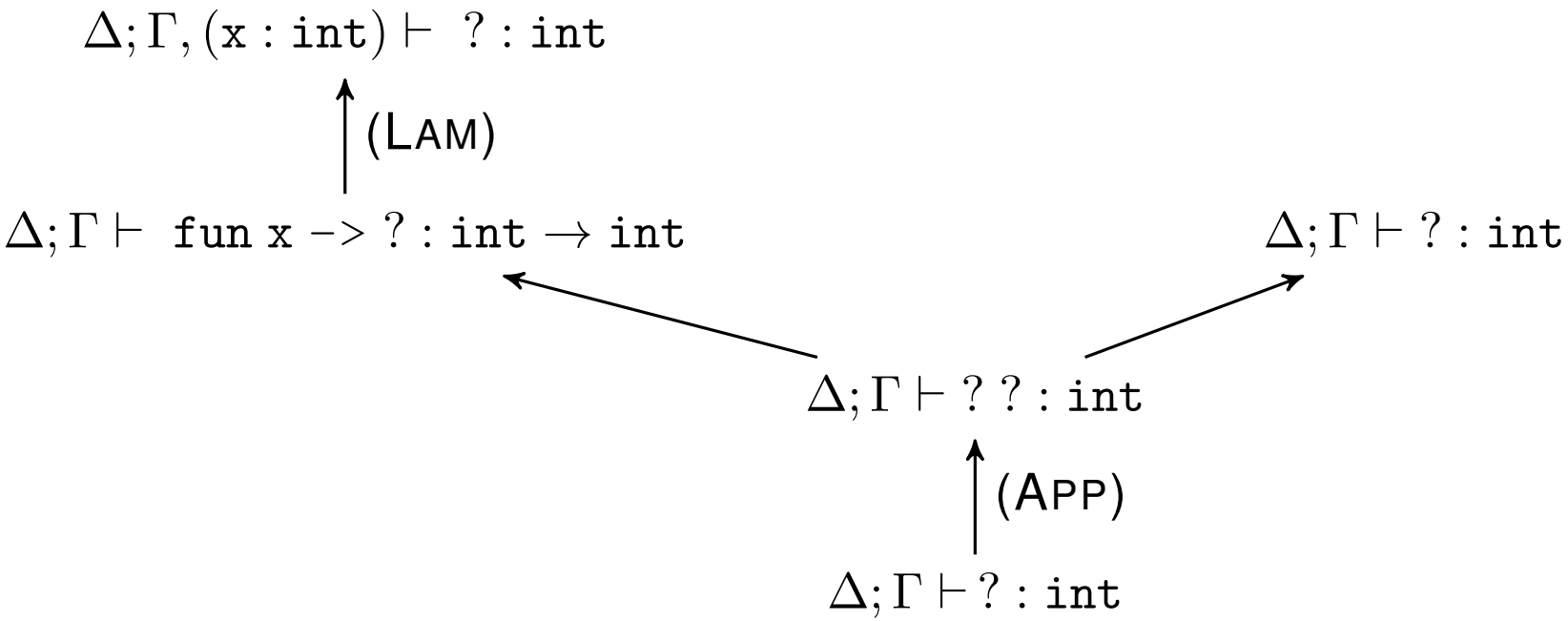

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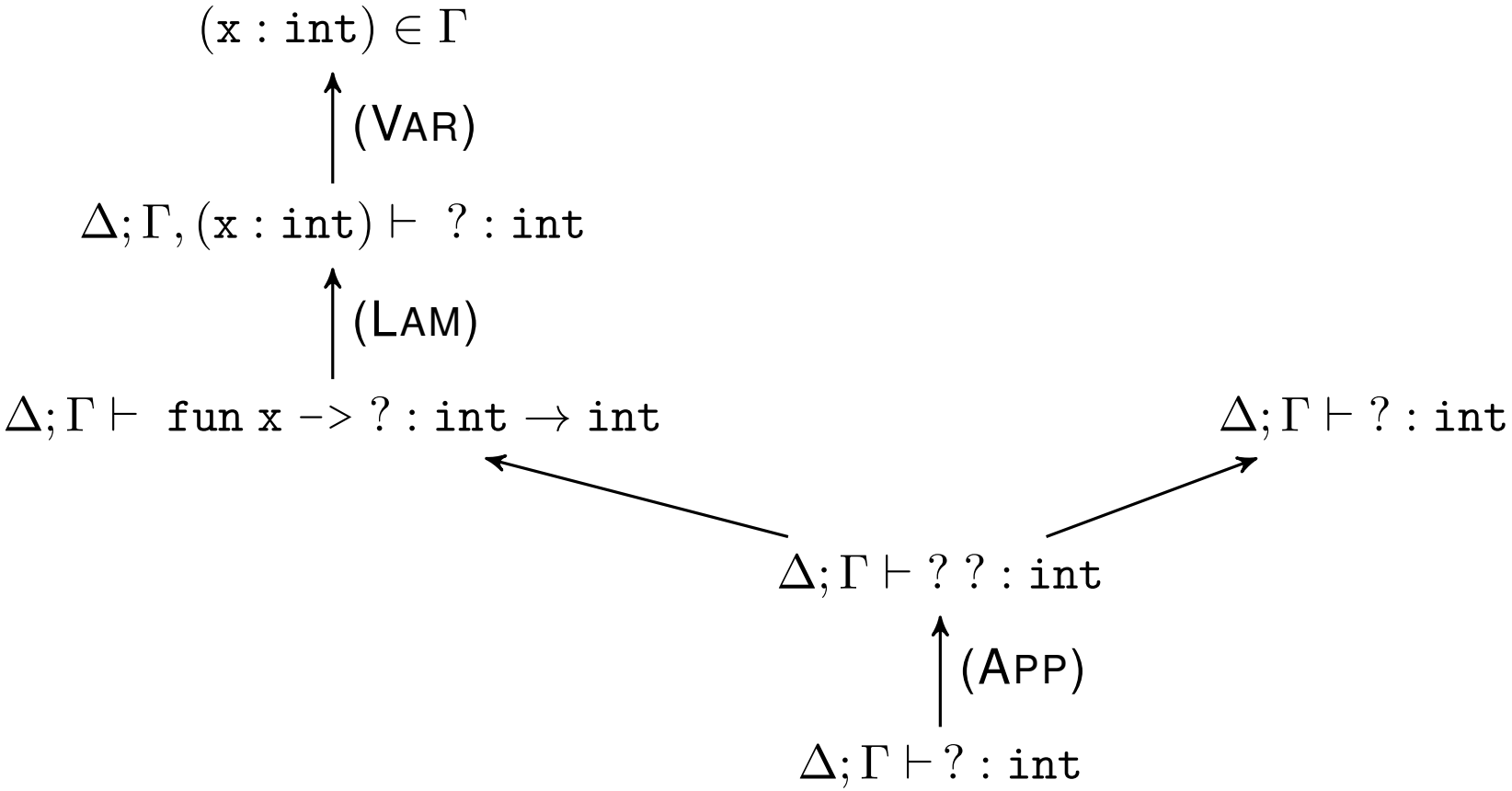

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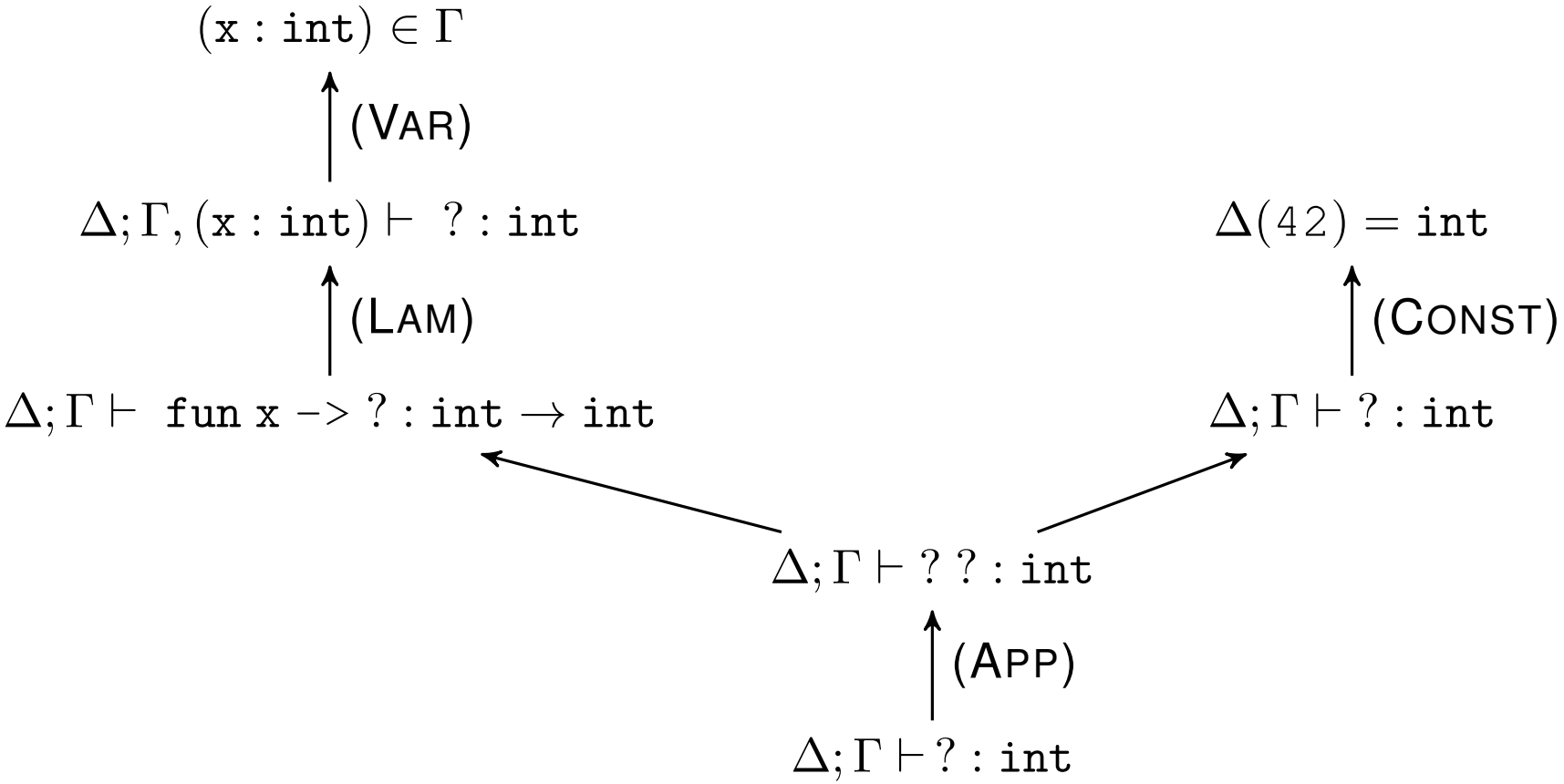

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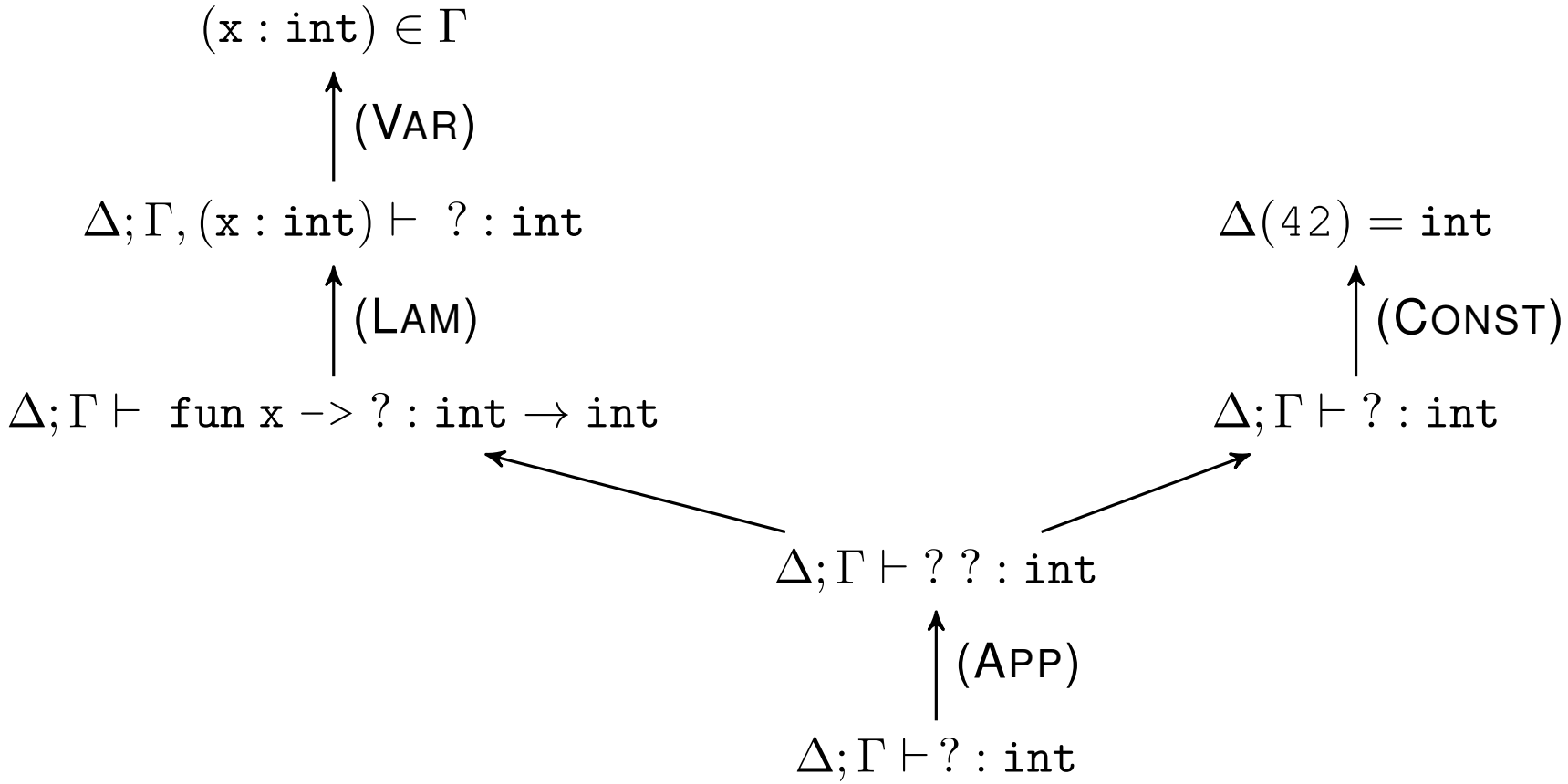

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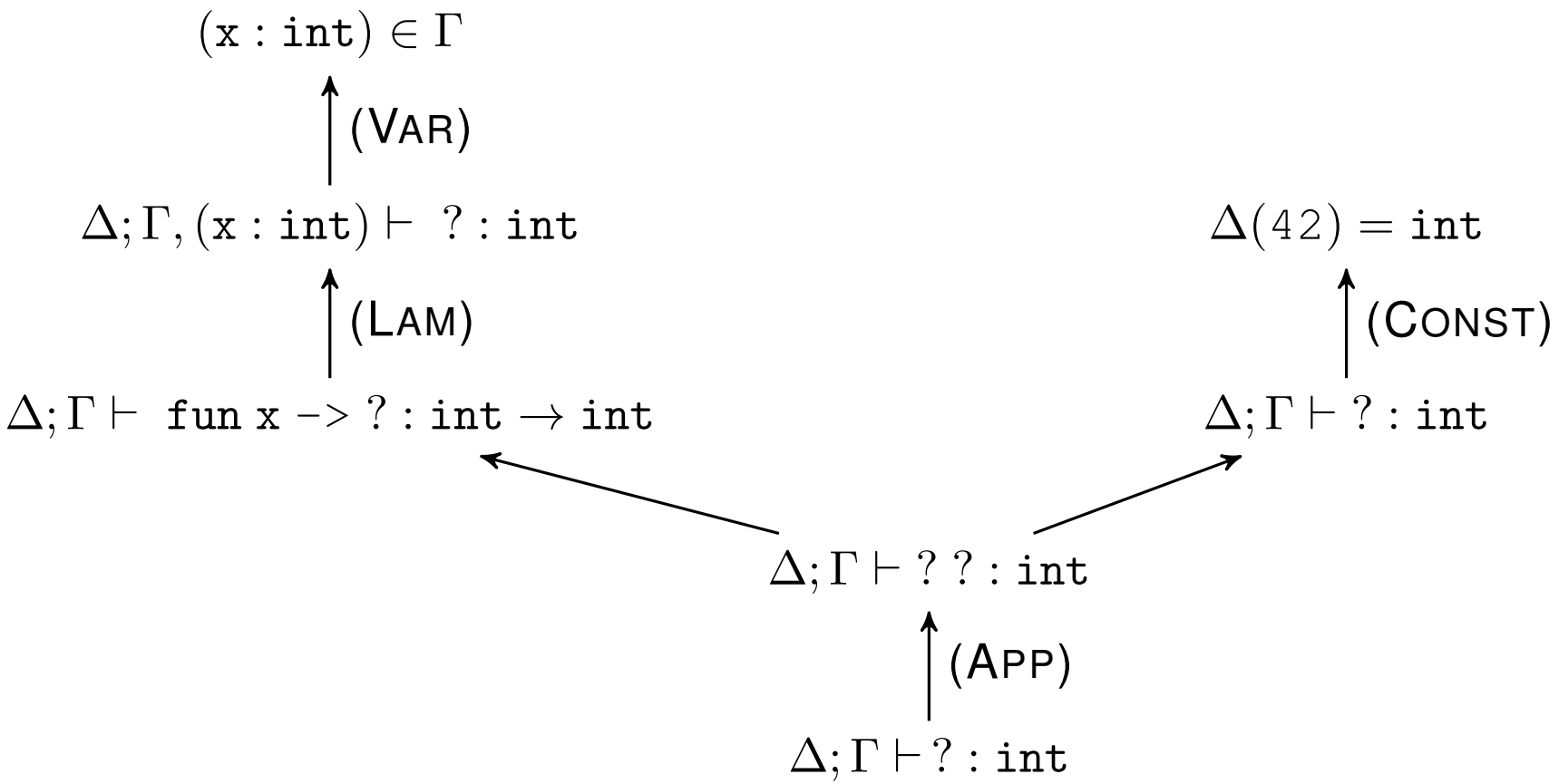

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Parameters: initial type environment and the goal type

Evaluation-order dependence

The observed behavior of an OCaml program may depend on the evaluation order:

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              (print_int 0)) (print_int 1)
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In OCaml (and many other languages, like C, C++, Scheme, . . .) the evaluation order is unspecified

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For testing purposes: Signal-to-noise ratio too low

(How) Can we avoid generating such programs?

First refinement: expressions may have effect

One bit $ef \in \{\texttt{tt}, \texttt{ff}\}$ tracks potential run-time effects:

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$$\frac{\Delta(c) = \tau \qquad \tau \sqsubseteq \tau'}{\Delta; \Gamma \vdash c : \tau' \,\&\, ef} \text{ (ECONST)} \qquad \frac{(\texttt{x} : \tau) \in \Gamma \qquad \tau \sqsubseteq \tau'}{\Delta; \Gamma \vdash \texttt{x} : \tau' \,\&\, ef} \text{ (EVAR)}$$

$$\frac{\Delta; \Gamma, (\texttt{x} : \tau_1) \vdash e : \tau_2 \,\&\, ef_1}{\Delta; \Gamma \vdash \texttt{fun x -> } e : \tau_1 \xrightarrow{ef_1} \tau_2 \,\&\, ef} \text{ (ELAM)}$$

$$\frac{\Delta; \Gamma \vdash e_0 : \tau_1 \xrightarrow{ef} \tau_2 \,\&\, ef_0 \qquad \Delta; \Gamma \vdash e_1 : \tau_1 \,\&\, ef_1 \qquad ef \vee ef_0 \vee ef_1 \implies ef'}{\Delta; \Gamma \vdash e_0\ e_1 : \tau_2 \,\&\, ef'} \text{ (EAPP)}$$

Sub-effecting allows non-effectful e to replace effectful e

From 'may-effects' to evaluation-order dep.

If both e_0 and e_1 in $e_0\ e_1$ may have effects

then the application is evaluation-order dependent

We can model this with a second bit ev

The effect is now a pair of bits:

$$\varphi ::= ef\,/\,ev \qquad \text{with } ef, ev \in \{\texttt{tt}, \texttt{ff}\}$$

These are both ordered by implication ordering

(componentwise lifted to pairs)

(Sub-)Effect-system

$$\frac{\Delta(c) = \tau \qquad \tau \sqsubseteq \tau'}{\Delta; \Gamma \vdash c : \tau' \,\&\, \varphi}\ (\textsc{EConst}) \qquad \frac{(\mathtt{x} : \tau) \in \Gamma \qquad \tau \sqsubseteq \tau'}{\Delta; \Gamma \vdash \mathtt{x} : \tau' \,\&\, \varphi}\ (\textsc{EVar})$$

$$\frac{\Delta; \Gamma, (\mathtt{x} : \tau_1) \vdash e : \tau_2 \,\&\, \varphi_1}{\Delta; \Gamma \vdash \mathtt{fun\ x\ ->}\ e : \tau_1 \xrightarrow{\varphi_1} \tau_2 \,\&\, \varphi}\ (\textsc{ELam})$$

$$\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \,\&\, \varphi_1 \qquad \Delta; \Gamma \vdash e_0 : \tau_1 \xrightarrow{\varphi} \tau_2 \,\&\, \varphi_0 \qquad \varphi \sqcup \varphi_0 \sqcup \varphi_1 \sqsubseteq \varphi' \qquad \varphi_0 \sqcap \varphi_1 \Rrightarrow \varphi'}{\Delta; \Gamma \vdash e_0\ e_1 : \tau_2 \,\&\, \varphi'}\ (\textsc{EApp})$$

The $\Rrightarrow$ operator over pairs propagates from ef to ev

Intermezzo: soundness

Operational semantics of non-det. eval. order

$$\frac{e_0 \xrightarrow{\eta} e_0'}{e_0\ e_1 \xrightarrow{\eta} e_0'\ e_1}\ (\textsc{AppL}) \qquad \frac{e_1 \xrightarrow{\eta} e_1'}{e_0\ e_1 \xrightarrow{\eta} e_0\ e_1'}\ (\textsc{AppR})$$

$$\frac{}{(\texttt{fun x -> } e)\ val \xrightarrow{\epsilon} e[\texttt{x} \mapsto val]}\ (\textsc{AppLam})$$

$$\frac{\delta(c\ val_1\ \ldots\ val_n) = (val, \eta)}{c\ val_1\ \ldots\ val_n \xrightarrow{\eta} val}\ (\textsc{AppDelta})$$

This specifies a call-by-value semantics

Note how (AppL) and (AppR) allows for both left-to-right and right-to-left evaluation (and even interleaved evaluation)

Soundness of formalization (1/2)

Theorem: Preservation and progress

- if $\Delta; \cdot \vdash e : \tau \,\&\, \varphi$ and there exists e' such that $e \xrightarrow{\eta} e'$ then $\Delta; \cdot \vdash e' : \tau \,\&\, \varphi$

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- if $\Delta; \cdot \vdash e : \tau \,\&\, \varphi$ then either $e = val$ or there exists e' such that $e \xrightarrow{\eta} e'$

This ensures correctness of the underlying type system

It says nothing about effects

Soundness of formalization (2/2)

Theorem: Soundness of effect bit

If $\Delta; \Gamma \vdash e : \tau \,\&\, ef \,/\, ev$ and $e \xrightarrow{\eta_1} e_1 \xrightarrow{\eta_2} \ldots \xrightarrow{\eta_n} e_n$ and there exists i such that $\eta_i \neq \epsilon$ then $ef = \texttt{tt}$

Read: ef correctly anticipates run-time effects

Soundness of formalization (2/2)

Theorem: Soundness of effect bit

If $\Delta; \Gamma \vdash e : \tau \,\&\, ef \,/\, ev$ and $e \xrightarrow{\eta_1} e_1 \xrightarrow{\eta_2} \ldots \xrightarrow{\eta_n} e_n$ and there exists i such that $\eta_i \neq \epsilon$ then $ef = \texttt{tt}$

Read: ef correctly anticipates run-time effects

Theorem: Soundness of evaluation-order bit

If $\Delta; \Gamma \vdash e : \tau \,\&\, ef \,/\, ev$ and $e \xrightarrow{\eta_1} e_1 \xrightarrow{\eta_2} \ldots \xrightarrow{\eta_n} e_n = val$ and $e \xrightarrow{\eta'_1} e'_1 \xrightarrow{\eta'_2} \ldots \xrightarrow{\eta'_{n'}} e'_{n'} = val'$ and $ev = \texttt{ff}$ then $\eta_1 \eta_2 \ldots \eta_n = \eta'_1 \eta'_2 \ldots \eta'_{n'}$

Read: ev correctly anticipates evaluation order dependence (think contrapositively)

Enough refinement: Back to testing

- We can now read the effect-system bottom-up to drive a generator
- If our goal is $\tau \,\&\, \texttt{tt}/\texttt{ff}$ the output programs may have effects but not depend on evaluation order

Enough refinement: Back to testing

- We can now read the effect-system bottom-up to drive a generator
- If our goal is τ `&` `tt/ff` the output programs may have effects but not depend on evaluation order
- Our prototype implementation
  - also supports `let` and `if` and more builtin types
  - uses a selection of bindings from `Pervasives` as its initial typing environment
  - uses `int` `&` `tt/ff` as its goal
  - wraps result in `let i = _ in print_int i` to ensure some output
  - compares the output of 500 programs

From counterexample to bug report

On the need for shrinking (1/2)

Dear Xavier et al.

I believe I've found a bug in one of the compiler backends. Please consider the attached program, which exhibits different behaviour when compiled with the two backends.

Yours truly,

Jan

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```
let i = (let a = let s = (let x = exit (lnot
    (-47628762612628909 7)) in fun r -> fun k -> "zsqykify")
    () in exit (exit (let c = (mod) 516587874847912894
    (-453400715012078364 8) in 0)) in (asr) (if (fun x -> let
     h = 2 in false) (let r = (@) [] [] in (lsl)
    2273200848021743825 0) then 466 else if let b = "" in
    false then ( * ) 2 (-4611686018427387904) else let m = 2
     in m) ((fun e -> if exit 5 then int_of_string "vgjgme"
    else (land) 4 7) (fun m -> (&&) (let i = () in false) (
    if true then true else true)))) in print_int i
```

On the need for shrinking (2/2)

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Yours truly,

Jan

```
let s = (let x = exit 0 in fun r -> fun k -> "") () in 0
```

Shrinking counterexample programs

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```
fun x -> e ⇝ fun x -> e'  if e ⇝ e'
```
(rec. shrink body)

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$$\texttt{if e then e' else e''} \rightsquigarrow \texttt{e'} \qquad \text{(keep branch)}$$

Summary and conclusion

- An effect system for evaluation order dependence, formalized and proved sound
- We let the effect system drive a program generator in a prototype compiler tester, incl. a shrinker
- A principled approach to FP generation, that combines core techniques from our community.
- We found 4 bugs (and rediscovered 2) in the OCaml native code backend this way. All fixed in 4.05.0.
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Thanks