A right-to-left type system for mutually-recursive value definitions

Alban Reynaud, **Gabriel Scherer**, Jeremy Yallop

Parsifal, Inria Saclay, France

May 14, 2019

Section 1

Problem

```
let rec fac = function
| 0 -> 1
| n -> n * fac (n - 1);;
(* val fac : int -> int = <fun> *)
fac 8;;
(* - : int = 40320 *)

let rec ones = 1 :: ones;;
(* val ones : int list = [1; <cycle>] *)
List.nth ones 10_000;;
(* - : int = 1 *)

let rec alot = 1 + alot;;
(* Error: This kind of expression is not allowed
   as right-hand side of ‘let rec’ *)
```

Almost-killer app: toy interpreter

```
Adder := Fun(x): Fun(y): x+y
```

Almost-killer app: toy interpreter

```
Adder := Fun(x): Fun(y): x+y
```

$$\texttt{Adder}(1) \rightarrow^{\star} \mathsf{closure}([x \mapsto 1],\ y \mapsto x + y)$$

Almost-killer app: toy interpreter

```
Adder := Fun(x): Fun(y): x+y
```

$$\texttt{Adder}(1) \rightarrow^{\star} \text{closure}([x \mapsto 1],\ y \mapsto x + y)$$

```
type ast   = Var of var | ... | Fun of var * expr
type value = ... | Closure of env * var * expr
and env    = (var * value) list
```

Almost-killer app: toy interpreter

```
Adder := Fun(x): Fun(y): x+y
```

$$\texttt{Adder}(1) \rightarrow^{\star} \text{closure}([x \mapsto 1],\ y \mapsto x + y)$$

```
type ast   = Var of var | ... | Fun of var * expr
type value = ... | Closure of env * var * expr
and env    = (var * value) list

let rec eval env = function
| Var x -> List.assoc x env
| ...
| Fun (x, t) -> Closure(env, x, t)
```

Almost-killer app: toy interpreter

```
Factorial := FunRec(f,n): if n=0 then 1 else n*f(n-1)
Adder := Fun(x): Fun(y): x+y
```

$$\texttt{Adder}(1) \rightarrow^{\star} \text{closure}([x \mapsto 1],\ y \mapsto x + y)$$

```
type ast   = Var of var | ... | Fun of var * expr
type value = ... | Closure of env * var * expr
and env    = (var * value) list

let rec eval env = function
| Var x -> List.assoc x env
| ...
| Fun (x, t) -> Closure(env, x, t)
| FunRec (f, x, t) ->
```

Almost-killer app: toy interpreter

```
Factorial := FunRec(f,n): if n=0 then 1 else n*f(n-1)
Adder := Fun(x): Fun(y): x+y
```

$$\texttt{Adder}(1) \rightarrow^{\star} \text{closure}([x \mapsto 1],\ y \mapsto x + y)$$

```
type ast   = Var of var | ... | Fun of var * expr
type value = ... | Closure of env * var * expr
and env    = (var * value) list

let rec eval env = function
| Var x -> List.assoc x env
| ...
| Fun (x, t) -> Closure(env, x, t)
| FunRec (f, x, t) ->
  (* Closure((f, ?) :: env, x, t) *)
```

Almost-killer app: toy interpreter

```
Factorial := FunRec(f,n): if n=0 then 1 else n*f(n-1)
Adder := Fun(x): Fun(y): x+y
```

$$\texttt{Adder}(1) \rightarrow^{\star} \text{closure}([x \mapsto 1],\ y \mapsto x + y)$$

```
type ast   = Var of var | ... | Fun of var * expr
type value = ... | Closure of env * var * expr
and env    = (var * value) list

let rec eval env = function
| Var x -> List.assoc x env
| ...
| Fun (x, t) -> Closure(env, x, t)
| FunRec (f, x, t) ->
  (* Closure((f, ?) :: env, x, t) *)
  let rec clo = Closure((f,clo) :: env, x, t) in clo
```

State of the OCaml art

OCaml manual → Language Extensions → Recursive definitions of values

State of the OCaml art

OCaml manual → Language Extensions → Recursive definitions of values

Complex syntactic description.
Not composable.
Hard to trust.
Did not age very well with new language features.

State of the OCaml art

PR#7231: check too permissive with nested recursive bindings

```
let rec r = let rec x () = r
                and y () = x ()
            in y ()
        in r "oops"
```

State of the OCaml art

PR#7215: Unsoundness with GADTs and let rec

```
let is_int (type a) : (int, a) eq =
  let rec (p : (int, a) eq) =
    match p with Refl -> Refl
  in p
```

State of the OCaml art

PR#4989: Compiler rejects recursive definitions of values

```
let rec f = let g = fun x -> f x in g
```

State of the OCaml art

PR#6939: Segfault with improper use of let-rec and float arrays

```
let rec x = [| x |]; 1. in ()
```

Summary

Niche feature – too difficult to remove.

Fragile specification: bugs creeping in.

Time for science!

Section 2

Solution

The typical approach

We propose a *type system* to check recursive value definitions.

Our types are one of five *access modes* m, with a typing judgment $\Gamma \vdash t : m$. A recursive declaration is safe if the mode of the recursive variables is gentle enough.
The typing rules are formulated so that an algorithm can easily be extracted.

We wrote the corresponding code; it landed in the OCaml compiler (#556, April 2016; #1942, July 2018), fixing more bugs than we introduced.

The rest of this talk:

- the modes and typing rules
- how to prove soundness?
- other languages, related work, etc.

Access modes

The mode of x in t is:

Ignore	:	1
Delay	:	$\lambda y.\, x$, lazy x.
Guard	:	$K\,(x)$
Return	:	x, $\texttt{let}\ y = e\ \texttt{in}\ x$
Dereference	:	$1 + x$, $x\ y$, $f\ x$.

Access modes

The mode of x in t is:

$$\begin{aligned}
\text{Ignore} &: 1 \\
\text{Delay} &: \lambda y.\, x, \text{ lazy } x. \\
\text{Guard} &: K\,(x) \\
\text{Return} &: x, \texttt{let } y = e \texttt{ in } x \\
\text{Dereference} &: 1 + x,\ x\ y,\ f\ x.
\end{aligned}$$

$$\begin{aligned}
&\texttt{let rec } f = \lambda n.\, n * f\ (n-1) && f : \text{Delay} \vdash \lambda n.\, n * f\ (n-1) : \text{Return} \\
&\texttt{let rec } o = \texttt{Cons}(1, o) && o : \text{Guard} \vdash \mathit{Cons}\,(1, o) : \text{Return} \\
&\texttt{let rec } x = 1 + x && x : \text{Dereference} \vdash 1 + x : \text{Return} \\
&\texttt{let rec } x = \texttt{let } y = x \texttt{ in } y && x : \text{Return} \vdash \texttt{let } y = x \texttt{ in } y : \text{Return}
\end{aligned}$$

Access modes

The mode of x in t is:

$$\begin{aligned}
\text{Ignore} &: 1 \\
\text{Delay} &: \lambda y.\, x, \text{ lazy } x. \\
\text{Guard} &: K\,(x) \\
\text{Return} &: x, \texttt{let } y = e \texttt{ in } x \\
\text{Dereference} &: 1 + x,\ x\ y,\ f\ x.
\end{aligned}$$

$$\begin{aligned}
&\texttt{let rec } f = \lambda n.\, n * f\ (n-1) && f : \text{Delay} \vdash \lambda n.\, n * f\ (n-1) : \text{Return} \\
&\texttt{let rec } o = \texttt{Cons}(1, o) && o : \text{Guard} \vdash \mathit{Cons}\,(1, o) : \text{Return} \\
&\texttt{let rec } x = 1 + x && x : \text{Dereference} \vdash 1 + x : \text{Return} \\
&\texttt{let rec } x = \texttt{let } y = x \texttt{ in } y && x : \text{Return} \vdash \texttt{let } y = x \texttt{ in } y : \text{Return}
\end{aligned}$$

Safety criterion: recursive variables must have mode Guard or less.

Mode typing judgment $\Gamma \vdash t : m$

Using t at mode Guard: $K(t)$.

Two readings of the judgment $x : m_x \vdash t : m$:

left-to-right : If x is safe at mode m_x, then t can be used at m.

right-to-left : Using t at m requires using x at m_x.

Right-to-left reading: t, m inputs, Γ output

$x : ?$ $\qquad\qquad$ $\vdash \texttt{Pair}\,(1, \texttt{fst}\ x) : \text{Return}$

Mode typing judgment $\Gamma \vdash t : m$

Using t at mode Guard: $K(t)$.

Two readings of the judgment $x : m_x \vdash t : m$:

left-to-right : If x is safe at mode m_x, then t can be used at m.

right-to-left : Using t at m requires using x at m_x.

Right-to-left reading: t, m inputs, Γ output

$$\dfrac{\dfrac{}{\emptyset \vdash 1 : \text{Guard}} \qquad \dfrac{}{x : ? \qquad \vdash \texttt{fst}\ x : \text{Guard}}}{x : ? \qquad \vdash \texttt{Pair}\,(1, \texttt{fst}\ x) : \text{Return}}$$

Mode typing judgment $\Gamma \vdash t : m$

Using t at mode Guard: $K(t)$.

Two readings of the judgment $x : m_x \vdash t : m$:

left-to-right : If x is safe at mode m_x, then t can be used at m.

right-to-left : Using t at m requires using x at m_x.

Right-to-left reading: t, m inputs, Γ output

$$\dfrac{\dfrac{}{\emptyset \vdash 1 : \text{Guard}} \qquad \dfrac{\dfrac{}{x : ? \vdash x : \text{Dereference}}}{x : ? \vdash \texttt{fst}\ x : \text{Guard}}}{x : ? \vdash \texttt{Pair}\,(1, \texttt{fst}\ x) : \text{Return}}$$

Mode typing judgment $\Gamma \vdash t : m$

Using t at mode Guard: $K(t)$.

Two readings of the judgment $x : m_x \vdash t : m$:

left-to-right : If x is safe at mode m_x, then t can be used at m.

right-to-left : Using t at m requires using x at m_x.

Right-to-left reading: t, m inputs, Γ output

$$\dfrac{\dfrac{}{\emptyset \vdash 1 : \text{Guard}} \qquad \dfrac{\dfrac{}{x : \text{Dereference} \vdash x : \text{Dereference}}}{x : ? \qquad \vdash \texttt{fst}\ x : \text{Guard}}}{x : ? \qquad \vdash \texttt{Pair}\,(1, \texttt{fst}\ x) : \text{Return}}$$

Mode typing judgment $\Gamma \vdash t : m$

Using t at mode Guard: $K(t)$.

Two readings of the judgment $x : m_x \vdash t : m$:

left-to-right : If x is safe at mode m_x, then t can be used at m.

right-to-left : Using t at m requires using x at m_x.

Right-to-left reading: t, m inputs, Γ output

$$\dfrac{\dfrac{}{\emptyset \vdash 1 : \text{Guard}} \qquad \dfrac{\dfrac{}{x : \text{Dereference} \vdash x : \text{Dereference}}}{x : \text{Dereference} \vdash \texttt{fst}\ x : \text{Guard}}}{x : ? \qquad \vdash \texttt{Pair}\,(1, \texttt{fst}\ x) : \text{Return}}$$

Mode typing judgment $\Gamma \vdash t : m$

Using t at mode Guard: $K(t)$.

Two readings of the judgment $x : m_x \vdash t : m$:

left-to-right : If x is safe at mode m_x, then t can be used at m.

right-to-left : Using t at m requires using x at m_x.

Right-to-left reading: t, m inputs, Γ output

$$\dfrac{\dfrac{}{\emptyset \vdash 1 : \text{Guard}} \qquad \dfrac{\dfrac{}{x : \text{Dereference} \vdash x : \text{Dereference}}}{x : \text{Dereference} \vdash \texttt{fst}\ x : \text{Guard}}}{x : \text{Dereference} \vdash \texttt{Pair}\,(1, \texttt{fst}\ x) : \text{Return}}$$

Access modes algebra

The mode of x in $C[x]$: the mode action of the context $C[\Box]$.

Ignore	:	1
Delay	:	$\lambda y.\,\Box$, lazy $\Box$.
Guard	:	$K\,(\Box)$
Return	:	$\Box$, $\texttt{let}\ y = e\ \texttt{in}\ \Box$
Dereference	:	$1 + \Box$, $\Box\ y$, $f\ \Box$.

Access modes algebra

The mode of x in $C[x]$: the mode action of the context $C[\square]$.

Ignore	:	1
Delay	:	$\lambda y.\,\square$, lazy $\square$.
Guard	:	$K\,(\square)$
Return	:	$\square$, $\texttt{let}\ y = e\ \texttt{in}\ \square$
Dereference	:	$1 + \square$, $\square\ y$, $f\ \square$.

Total order: Ignore $\prec$ Delay $\prec$ Guard $\prec$ Return $\prec$ Dereference.

Access modes algebra

The mode of x in $C[x]$: the mode action of the context $C[\Box]$.

Ignore	: 1
Delay	: $\lambda y.\,\Box$, lazy $\Box$.
Guard	: $K\,(\Box)$
Return	: $\Box$, $\texttt{let}\ y = e\ \texttt{in}\ \Box$
Dereference	: $1 + \Box$, $\Box\ y$, $f\ \Box$.

Total order: Ignore $\prec$ Delay $\prec$ Guard $\prec$ Return $\prec$ Dereference.
Mode composition: $C[C'[\Box]]$ has mode action $m\,[m']$.

Access modes algebra

The mode of x in $C[x]$: the mode action of the context $C[\Box]$.

Ignore	:	1
Delay	:	$\lambda y.\,\Box$, lazy $\Box$.
Guard	:	$K\,(\Box)$
Return	:	$\Box$, $\texttt{let}\ y = e\ \texttt{in}\ \Box$
Dereference	:	$1 + \Box$, $\Box\ y$, $f\ \Box$.

Total order: Ignore $\prec$ Delay $\prec$ Guard $\prec$ Return $\prec$ Dereference.
Mode composition: $C[C'[\Box]]$ has mode action $m\,[m']$.

$$
\begin{array}{lcl}
\text{Ignore}\,[m] & = & \text{Ignore} \quad = \quad m\,[\text{Ignore}] \\
\text{Delay}\,[m > \text{Ignore}] & = & \text{Delay} \\
\text{Guard}\,[\text{Return}] & = & \text{Guard} \\
\text{Guard}\,[m \neq \text{Return}] & = & m \\
\text{Return}\,[m] & = & m \\
\text{Dereference}\,[m > \text{Ignore}] & = & \text{Dereference}
\end{array}
$$

$\text{Dereference}\,[\text{Delay}] \neq \text{Delay}\,[\text{Dereference}]$ $\qquad f\ (\lambda x.\,\Box), \lambda x.\,(f\ \Box)$

Access mode typing rules

$$\frac{}{\Gamma, x : m \vdash x : m} \qquad \frac{\Gamma \vdash t : m \qquad m \succ m'}{\Gamma \vdash t : m'}$$

$$\frac{\Gamma, x : m_x \vdash t : m\,[\text{Delay}]}{\Gamma \vdash \lambda x.\, t : m} \qquad \frac{\Gamma_t \vdash t : m\,[\text{Dereference}] \qquad \Gamma_u \vdash u : m\,[\text{Dereference}]}{\Gamma_t + \Gamma_u \vdash t\ u : m}$$

$$\frac{(\Gamma_i \vdash t_i : m\,[\text{Guard}])^i}{\sum (\Gamma_i)^i \vdash K\,(t_i)^i : m} \qquad \text{(pattern matching rules...)}$$

$$\frac{\Gamma_u, x : m_{x \in u} \vdash u : m}{? \qquad \vdash \texttt{let rec}\ x = t\ \texttt{in}\ u : m}$$

Access mode typing rules

$$\frac{}{\Gamma, x : m \vdash x : m} \qquad \frac{\Gamma \vdash t : m \qquad m \succ m'}{\Gamma \vdash t : m'}$$

$$\frac{\Gamma, x : m_x \vdash t : m\,[\text{Delay}]}{\Gamma \vdash \lambda x.\, t : m} \qquad \frac{\Gamma_t \vdash t : m\,[\text{Dereference}] \qquad \Gamma_u \vdash u : m\,[\text{Dereference}]}{\Gamma_t + \Gamma_u \vdash t\ u : m}$$

$$\frac{(\Gamma_i \vdash t_i : m\,[\text{Guard}])^i}{\sum (\Gamma_i)^i \vdash K\,(t_i)^i : m} \qquad \text{(pattern matching rules...)}$$

$$\frac{\Gamma_t, x : m_{x \in t} \vdash t : \text{Return} \qquad \Gamma_u, x : m_{x \in u} \vdash u : m}{? \qquad \vdash \texttt{let rec}\ x = t\ \texttt{in}\ u : m}$$

Access mode typing rules

$$\frac{}{\Gamma, x : m \vdash x : m} \qquad \frac{\Gamma \vdash t : m \qquad m \succ m'}{\Gamma \vdash t : m'}$$

$$\frac{\Gamma, x : m_x \vdash t : m\,[\text{Delay}]}{\Gamma \vdash \lambda x.\, t : m} \qquad \frac{\Gamma_t \vdash t : m\,[\text{Dereference}] \qquad \Gamma_u \vdash u : m\,[\text{Dereference}]}{\Gamma_t + \Gamma_u \vdash t\ u : m}$$

$$\frac{(\Gamma_i \vdash t_i : m\,[\text{Guard}])^i}{\sum (\Gamma_i)^i \vdash K\,(t_i)^i : m} \qquad \text{(pattern matching rules...)}$$

$$\frac{\begin{array}{c} m_{x \in t} \leq \text{Guard} \\ \Gamma_t, x : m_{x \in t} \vdash t : \text{Return} \end{array} \qquad \Gamma_u, x : m_{x \in u} \vdash u : m}{? \qquad \vdash \texttt{let rec}\ x = t\ \texttt{in}\ u : m}$$

Access mode typing rules

$$\frac{}{\Gamma, x : m \vdash x : m} \qquad \frac{\Gamma \vdash t : m \qquad m \succ m'}{\Gamma \vdash t : m'}$$

$$\frac{\Gamma, x : m_x \vdash t : m\,[\text{Delay}]}{\Gamma \vdash \lambda x.\, t : m} \qquad \frac{\Gamma_t \vdash t : m\,[\text{Dereference}] \qquad \Gamma_u \vdash u : m\,[\text{Dereference}]}{\Gamma_t + \Gamma_u \vdash t\ u : m}$$

$$\frac{(\Gamma_i \vdash t_i : m\,[\text{Guard}])^i}{\sum (\Gamma_i)^i \vdash K\,(t_i)^i : m} \qquad \text{(pattern matching rules...)}$$

$$\frac{\begin{array}{c} m_{x \in t} \leq \text{Guard} \\ \Gamma_t, x : m_{x \in t} \vdash t : \text{Return} \end{array} \qquad \Gamma_u, x : m_{x \in u} \vdash u : m}{m_{x \in u}\,[\Gamma_t] + \Gamma_u \vdash \texttt{let rec}\ x = t\ \texttt{in}\ u : m}$$

Access mode typing rules

$$\frac{}{\Gamma, x : m \vdash x : m} \qquad \frac{\Gamma \vdash t : m \qquad m \succ m'}{\Gamma \vdash t : m'}$$

$$\frac{\Gamma, x : m_x \vdash t : m\,[\text{Delay}]}{\Gamma \vdash \lambda x.\, t : m} \qquad \frac{\Gamma_t \vdash t : m\,[\text{Dereference}] \qquad \Gamma_u \vdash u : m\,[\text{Dereference}]}{\Gamma_t + \Gamma_u \vdash t\ u : m}$$

$$\frac{(\Gamma_i \vdash t_i : m\,[\text{Guard}])^i}{\sum (\Gamma_i)^i \vdash K\,(t_i)^i : m} \qquad \text{(pattern matching rules...)}$$

$$\frac{\begin{array}{c} m_{x \in t} \leq \text{Guard} \\ \Gamma_t, x : m_{x \in t} \vdash t : \text{Return} \end{array} \qquad \Gamma_u, x : m_{x \in u} \vdash u : m}{m_{x \in u}\,[\Gamma_t] + \Gamma_u \vdash \texttt{let rec}\ x = t\ \texttt{in}\ u : m}$$

Access mode typing rules

$$\frac{}{\Gamma, x : m \vdash x : m} \qquad \frac{\Gamma \vdash t : m \qquad m \succ m'}{\Gamma \vdash t : m'}$$

$$\frac{\Gamma, x : m_x \vdash t : m\,[\text{Delay}]}{\Gamma \vdash \lambda x.\, t : m} \qquad \frac{\Gamma_t \vdash t : m\,[\text{Dereference}] \qquad \Gamma_u \vdash u : m\,[\text{Dereference}]}{\Gamma_t + \Gamma_u \vdash t\ u : m}$$

$$\frac{(\Gamma_i \vdash t_i : m\,[\text{Guard}])^i}{\sum (\Gamma_i)^i \vdash K\,(t_i)^i : m} \qquad \text{(pattern matching rules...)}$$

$$\frac{\begin{array}{c} m_{x\in t} \leq \text{Guard} \\ \Gamma_t, x : m_{x\in t} \vdash t : \text{Return} \end{array} \qquad \begin{array}{c} m'_{x\in u} \stackrel{\text{def}}{=} \max(m_{x\in u}, \text{Guard}) \\ \Gamma_u, x : m_{x\in u} \vdash u : m \end{array}}{m'_{x\in u}\,[\Gamma_t] + \Gamma_u \vdash \texttt{let rec}\ x = t\ \texttt{in}\ u : m}$$

Section 3

Evaluation

Recap

Access modes $m ::= \mathsf{Ignore} \mid \mathsf{Delay} \mid \mathsf{Guard} \mid \mathsf{Return} \mid \mathsf{Dereference}$

Typing judgment $\Gamma \vdash t : m$

Typing rules

$$\frac{\begin{array}{cc} m_{x \in t} \leq \mathsf{Guard} & m'_{x \in u} \stackrel{\mathsf{def}}{=} \max(m_{x \in u}, \mathsf{Guard}) \\ \Gamma_t, x : m_{x \in t} \vdash t : \mathsf{Return} & \Gamma_u, x : m_{x \in u} \vdash u : m \end{array}}{m'_{x \in u}\,[\Gamma_t] + \Gamma_u \vdash \texttt{let rec}\ x = t\ \texttt{in}\ u : m}$$

Implementation

What's left?

Soundness theorem

If $\emptyset \vdash t$: Return
and $t \rightarrow^{\star} t'$
then t' is not going horribly wrong.

Soundness theorem

If $\emptyset \vdash t : \text{Return}$
and $t \to^\star t'$
then t' is not going horribly wrong.

What's a good operational semantics for `letrec`?

Source-level approach

A source-level approach to `letrec`: explicit substitutions.

Hirschowitz, Leroy, and Wells (2003, 2009)

Nordlander, Carlsson, and Gill (2008)

Source term syntax

$$
\begin{aligned}
\text{Terms} \ni t, u ::= {} & x, y, z \\
& \mid \texttt{let rec } b \texttt{ in } u \\
& \mid \lambda x.\, t \mid t\ u \\
& \mid K\,(t_i)^i \mid \texttt{match } t \texttt{ with } h
\end{aligned}
$$

$$
\begin{aligned}
\text{Bindings} \ni b &::= (x_i = t_i)^i \\
\text{Handlers} \ni h &::= (p_i \to t_i)^i \\
\text{Patterns} \ni p, q &::= K\,(x_i)^i
\end{aligned}
$$

$$
\begin{aligned}
\text{Values} \ni v &::= \lambda x.\, t \mid K\,(w_i)^i \mid L[v] \\
\text{WeakValues} \ni w &::= x \mid v \mid L[w] \\
\text{ValueBindings} \ni B &::= (x_i = v_i)^i \\
\text{BindingCtx} \ni L &::= \Box \mid \texttt{let rec}\ B\ \texttt{in}\ L
\end{aligned}
$$

$$
\begin{aligned}
\text{Values} \ni v &::= \lambda x.\, t \mid K\,(w_i)^i \mid L[v] \\
\text{WeakValues} \ni w &::= x \mid v \mid L[w] \\
\text{ValueBindings} \ni B &::= (x_i = v_i)^i \\
\text{BindingCtx} \ni L &::= \Box \mid \texttt{let rec}\ B\ \texttt{in}\ L \\
\text{EvalCtx} \ni E &::= \Box \mid E[F] \\
\text{EvalFrame} \ni F
\end{aligned}
$$

$$
\begin{aligned}
F ::= {} & \Box\ t \ \mid\ t\ \Box \\
& \mid K\,((t_i)^i, \Box, (t_j)^j) \\
& \mid \texttt{match}\ \Box\ \texttt{with}\ h \\
& \mid \texttt{let rec}\ b, x = \Box, b'\ \texttt{in}\ u \\
& \mid \texttt{let rec}\ B\ \texttt{in}\ \Box
\end{aligned}
$$

$$
\begin{aligned}
\text{Values} \ni v &::= \lambda x.\, t \mid K\,(w_i)^i \mid L[v] \\
\text{WeakValues} \ni w &::= x \mid v \mid L[w] \\
\text{ValueBindings} \ni B &::= (x_i = v_i)^i \\
\text{BindingCtx} \ni L &::= \Box \mid \texttt{let rec}\ B\ \texttt{in}\ L \\
\text{EvalCtx} \ni E &::= \Box \mid E[F] \\
\text{EvalFrame} \ni F
\end{aligned}
$$

$$
\begin{aligned}
F ::= {} & \Box\ t \mid t\ \Box \\
& \mid K\,((t_i)^i, \Box, (t_j)^j) \\
& \mid \texttt{match}\ \Box\ \texttt{with}\ h \\
& \mid \texttt{let rec}\ b, x = \Box, b'\ \texttt{in}\ u \\
& \mid \texttt{let rec}\ B\ \texttt{in}\ \Box
\end{aligned}
$$

$$
\frac{(x = v) \overset{\text{ctx}}{\in} E}{E[x] \to E[v]} \qquad \frac{t \to^{\text{hd}} t'}{E[t] \to E[t']}
$$

$$
\begin{aligned}
\text{Values} \ni v &::= \lambda x.\, t \mid K\,(w_i)^i \mid L[v] \\
\text{WeakValues} \ni w &::= x \mid v \mid L[w] \\
\text{ValueBindings} \ni B &::= (x_i = v_i)^i \\
\text{BindingCtx} \ni L &::= \square \mid \texttt{let rec}\ B\ \texttt{in}\ L \\
\text{EvalCtx} \ni E &::= \square \mid E[F] \\
\text{EvalFrame} \ni F
\end{aligned}
$$

$$
\begin{aligned}
F ::= {} & \square\ t \mid t\ \square \\
& \mid K\,((t_i)^i, \square, (t_j)^j) \\
& \mid \texttt{match}\ \square\ \texttt{with}\ h \\
& \mid \texttt{let rec}\ b, x = \square, b'\ \texttt{in}\ u \\
& \mid \texttt{let rec}\ B\ \texttt{in}\ \square
\end{aligned}
$$

$$\frac{(x = v) \overset{\text{ctx}}{\in} E}{E[x] \to E[v]} \qquad \frac{t \to^{\text{hd}} t'}{E[t] \to E[t']}$$

$$\frac{(x = v) \overset{\text{frame}}{\in} F \quad \vee \quad (x = v) \overset{\text{ctx}}{\in} E}{(x = v) \overset{\text{ctx}}{\in} E[F]}$$

$$\frac{(x = v) \in B}{(x = v) \overset{\text{frame}}{\in} \texttt{let rec}\ B\ \texttt{in}\ \square} \qquad \frac{(x = v) \in (b \cup b')}{(x = v) \overset{\text{frame}}{\in} \texttt{let rec}\ b, y = \square, b'\ \texttt{in}\ u}$$

$$
\begin{aligned}
\text{Values} \ni v &::= \lambda x.\, t \mid K\,(w_i)^i \mid L[v] \\
\text{WeakValues} \ni w &::= x \mid v \mid L[w] \\
\text{ValueBindings} \ni B &::= (x_i = v_i)^i \\
\text{BindingCtx} \ni L &::= \Box \mid \texttt{let rec}\ B\ \texttt{in}\ L \\
\text{EvalCtx} \ni E &::= \Box \mid E[F] \\
\text{EvalFrame} \ni F
\end{aligned}
\qquad
\begin{aligned}
F ::= {} & \Box\ t \mid t\ \Box \\
& \mid K\,((t_i)^i, \Box, (t_j)^j) \\
& \mid \texttt{match}\ \Box\ \texttt{with}\ h \\
& \mid \texttt{let rec}\ b, x = \Box, b'\ \texttt{in}\ u \\
& \mid \texttt{let rec}\ B\ \texttt{in}\ \Box
\end{aligned}
$$

$$
\frac{(x = v) \overset{\text{ctx}}{\in} E}{E[x] \to E[v]}
\qquad
\frac{t \to^{\text{hd}} t'}{E[t] \to E[t']}
\qquad
\frac{(x = v) \overset{\text{frame}}{\in} F \quad \vee \quad (x = v) \overset{\text{ctx}}{\in} E}{(x = v) \overset{\text{ctx}}{\in} E[F]}
$$

$$
\frac{(x = v) \in B}{(x = v) \overset{\text{frame}}{\in} \texttt{let rec}\ B\ \texttt{in}\ \Box}
\qquad
\frac{(x = v) \in (b \cup b')}{(x = v) \overset{\text{frame}}{\in} \texttt{let rec}\ b, y = \Box, b'\ \texttt{in}\ u}
$$

$$
\frac{}{L[\lambda x.\, t]\ v \to^{\text{hd}} L[t[v/x]]}
$$

$$
\frac{}{\texttt{match}\ L[K\,(w_i)^i]\ \texttt{with}\ (\ldots \mid K\,(x_i)^i \to u \mid \ldots) \to^{\text{hd}} L[u[(w_i/x_i)^i]]}
$$

$$\begin{aligned} \text{ForcingFrame} \ni F_\mathsf{f} &::= \square\ v \mid v\ \square \mid \texttt{match}\ \square\ \texttt{with}\ h \\ \text{ForcingCtx} \ni E_\mathsf{f} &::= F_\mathsf{f} \mid E[E_\mathsf{f}] \mid E_\mathsf{f}[L] \end{aligned}$$

$$\text{Vicious} \stackrel{\text{def}}{=} \{E_\mathsf{f}[x] \mid \nexists v, (x = v) \stackrel{\text{ctx}}{\in} E_\mathsf{f}\}$$

Theorem

If

$$\emptyset \vdash t : \text{Return}$$

and

$$t \to^\star t'$$

then

$$t' \notin \text{Vicious}$$

Proof.

Subject Reduction. □

Section 4

Conclusion

Related Work

Backward analyses We describe them as type systems. Syntax!

Modal type theories This is an instance of one – uni-typed.

Modal type theories for (co)recursion We have a nice inference algorithm.

Degrees Elaborate systems for objects and ML functors, need to accept more programs. Not uni-typed.

Graphs as types We don't.

Operational semantics Best order vs. worst order.

For more details, see our full paper:

https://arxiv.org/abs/1811.08134

End.

Tom Hirschowitz, Xavier Leroy, and J. B. Wells. Compilation of extended recursion in call-by-value functional languages. In *PPDP*, 2003.

Tom Hirschowitz, Xavier Leroy, and J. B. Wells. Compilation of extended recursion in call-by-value functional languages. *Higher Order Symbol. Comput.*, 22(1), March 2009.

Johan Nordlander, Magnus Carlsson, and Andy J. Gill. Unrestricted pure call-by-value recursion. In *ML Workshop*, 2008.

Bonus slide: mutual recursion

$$\frac{(x_i : \Gamma_i)^i \vdash \texttt{rec}\ b \qquad (m'_i)^i \stackrel{\text{def}}{=} (\max(m_i, \text{Guard}))^i \qquad \Gamma_u, (x_i : m_i)^i \vdash u : m}{\sum (m'_i\,[\Gamma_i])^i + \Gamma_u \vdash \texttt{let rec}\ b\ \texttt{in}\ u : m}$$

$$\frac{(\Gamma_i, (x_j : m_{i,j})^{j \in I} \vdash t_i : \text{Return})^{i \in I} \qquad (m_{i,j} \preceq \text{Guard})^{i,j} \qquad (\Gamma'_i = \Gamma_i + \sum (m_{i,j}\,[\Gamma'_j])^j)^i}{(x_i : \Gamma'_i)^{i \in I} \vdash \texttt{rec}\ (x_i = t_i)^{i \in I}}$$