Higher-Order unification for free

Reusing the meta-language unification for the object language

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Metaprogramming for type-class resolution

- Our goal:
  - Type-class solver for Coq in Elpi
  - The goal of a type-class solver is to back-chain lemmas taken from a database of 'type-class instances'.
- Our problem:
  - Elpi cannot unify correctly Coq's HO terms
  - But we want/need to use Elpi's unification algorithm
- Our contribution:
  - Reusing the meta-language unification for the object language

A type-class problem in Coq

```
Instance forall_dec: ∀A P, Finite A →                 (* r3 *)
  (∀x:A, Decision (P x)) → Decision (∀x:A, P x).
```

```
Goal Decision (∀x: fin 7, nfact x 3).                 (* g *)
```

A type-class problem in Coq

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Instance forall_dec: ∀A P, Finite A →               (* r3 *)
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Goal Decision (∀x: fin 7, nfact x 3).               (* g *)
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- $\{A \mapsto \mathit{fin}\ 7; P \mapsto \lambda x.(\mathit{nfact}\ x\ 3)\}$

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Goal Decision (∀x: fin 7, nfact x 3).                (* g *)
```

- $\{A \mapsto \mathit{fin}\ 7; P \mapsto \lambda x.(\mathit{nfact}\ x\ 3)\}$
- subgoals:
  `Finite (fin 7)` and `(∀x:A, Decision ((λ x.(nfact x 3)) x))`

Coq terms in Elpi : HOAS

Coq	Elpi
f	`c"f"`
$f \cdot a$	`app[c"f", c"a"]`
$\lambda(x : T).F \cdot x$	`fun T (x\ app[F, x])`
$\forall(x : T), F \cdot x$	`all T (x\ app[F, x])`
$\dots$	$\dots$

Benefits of this encoding:

- variable bindings and substitutions are for free
- easy term inspection (no need of the functor/3 and arg/3 primitives)

The above type-class problem in Elpi

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↓

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Instance forall_dec: ∀A P, Finite A →              (* r3 *)
  (∀x:A, Decision (P x)) → Decision (∀x:A, P x).

Goal Decision (∀x: fin 7, nfact x 3).              (* g *)
```

$$\downarrow$$

```
decision (all A (x\ app [P, x])) :- finite A,        % r3
  pi w\ decision (app [P, w]).

?- decision (all (app [c"fin", c"7"])                  % g
                 (x\ app [c"nfact", x, c"3"])).
```

Solving the goal in Elpi

```
decision (all A (x\ app [P, x] )) :- finite A,        % r3
  pi w\ decision (app [P, w]).

?- decision (all (app [c"fin", c"7"])                 % g
                    (x\ app [c"nfact", x, c"3"] )).
```

What we propose

1. Compilation:
   - Recognize *problematic subterms* $p_1, \ldots, p_n$
     There are three kinds: $\diamond\beta$, $\diamond\eta$, $\diamond\mathcal{L}_\lambda$
   - Replace p_i with fresh unification variables X_i
   - *Link* p_i with X_i
     A link is a suspended unification problem
2. Runtime:
   - Execute unification of terms
   - If some condition hold, trigger links
3. Lastly:
   - Decompile remaining links

The idea

```
decision (all A (x\ P' x)) :-                          % r3
  link P' (fun A (x\ app[P, x])),
  finite A,
  pi w\ decision (P' w).

?- decision (all (app ["fin", "7"])                    % g
                  (x\ app [c"nfact", x, c"3"] )).
```

Some notations

- $\mathbb{P}$: the unification problems in Coq (ol)
- $\mathbb{Q}$: the unification problems in Elpi (ml)
- $\mathbb{L}$, $\mathbb{M}$: the link store, the unification-variable map

---

- $\mathrm{run}_o(\mathbb{P}, n) \mapsto \rho$: the run of n unif pb in the ol
- $\mathrm{run}_m(\mathbb{P}, n) \mapsto \rho'$: the run of n unif pb in the ml
- $\mathrm{step}_o(\mathbb{P}, i, \rho_{i-1}) \mapsto \rho_i$: the execution of the i^{th} unif pb in ol
- $\mathrm{step}_m(\mathbb{Q}, i, \sigma_{i-1}, \mathbb{L}_{i-1}) \mapsto (\sigma_i, \mathbb{L}_i)$: the exec of the i^{th} unif pb in ml

A zoom on run_m

$$\mathrm{step}_m(\mathbb{Q}, p, \sigma, \mathbb{L}) \mapsto (\sigma'', \mathbb{L}') \overset{def}{=\!=} \\ \sigma\mathbb{Q}_{p_l} \simeq_m \sigma\mathbb{Q}_{p_r} \mapsto \sigma' \wedge \mathrm{progress}(\mathbb{L}, \sigma') \mapsto (\mathbb{L}', \sigma'')$$

$$\mathrm{run}_m(\mathbb{P}, n) \mapsto \rho_n \overset{def}{=\!=}$$

$$\begin{array}{ll} \mathbb{Q} \times \mathbb{M} \times \mathbb{L}_0 = \{(t, m, l) | s \in \mathbb{P}, \langle s \rangle \mapsto (t, m, l)\} & := \texttt{compilation} \\ \bigwedge_{p=1}^{n} \mathrm{step}_m(\mathbb{Q}, p, \sigma_{p-1}, \mathbb{L}_{p-1}) \mapsto (\sigma_p, \mathbb{L}_p) & := \texttt{runtime} \\ \langle \sigma_n, \mathbb{M}, \mathbb{L}_n \rangle^{-1} \mapsto \rho_n & := \texttt{decompilation} \end{array}$$

Proven properties

Run Equivalence $\forall \mathbb{P}, \forall n$, if each subterm in $\mathbb{P}$ is in the pattern fragment

$$\mathrm{run}_o(\mathbb{P}, n) \mapsto \rho \wedge \mathrm{run}_m(\mathbb{P}, n) \mapsto \rho' \Rightarrow \forall s \in \mathbb{P}, \rho s =_o \rho' s$$

Simulation fidelity $\forall \mathbb{P}$, in the context of run_o and run_m, $\forall i \in 1 \ldots n$,

$$\mathrm{step}_o(\mathbb{P}, i, \rho_{i-1}) \mapsto \rho_i \Leftrightarrow \mathrm{step}_m(\mathbb{Q}, i, \sigma_{i-1}, \mathbb{L}_{i-1}) \mapsto (\sigma_i, \mathbb{L}_i)$$

Compilation round trip If $\langle s \rangle \mapsto (t, m, l)$ and $l \in \mathbb{L}$ and $m \in \mathbb{M}$ and $\sigma = \{A \mapsto t\}$ and $X \mapsto A \in \mathbb{M}$ then

$$\langle \sigma, \mathbb{M}, \mathbb{L} \rangle^{-1} \mapsto \rho \text{ and } \rho X =_o \rho s.$$

Problematic subterm recognition

Sketch of $\diamond\beta$ terms : the problem

- An example: given a bound variable x

$$
\begin{aligned}
\mathbb{P} &= \{ \quad Y \cdot x \ \simeq_o \ f \cdot x \cdot a \quad \} \\
\mathbb{Q} &= \{ \ \texttt{app[A, x]} \ \simeq_m \ \texttt{app[c"f",x,c"a"]} \ \} \\
\mathbb{M} &= \{ \ Y \mapsto \texttt{A} \ \}
\end{aligned}
$$

- Unification fails...

Sketch of $\diamond\beta$ terms : the solution

- An example, let x be a bound variable:

$$\begin{aligned} \mathbb{P} &= \{\ Y \cdot x \simeq_o f \cdot x \cdot a \ \} \\ \mathbb{Q} &= \{\ \texttt{A x} \simeq_m \texttt{app[c"f",x,c"a"]}\ \} \\ \mathbb{M} &= \{\ Y \mapsto \texttt{A}\ \} \end{aligned}$$

- Unification of $\mathbb{Q}_0$ gives: $\{A \mapsto$ `(w\ app[c"f", w, c"a"])`$\}$
- Decompilation of A gives $\{Y \mapsto \lambda x.f \cdot x \cdot a\}$

Sketch of $\diamond\eta$ terms

- $\lambda x.s \in \diamond\eta$, if $\exists \rho, \rho(\lambda x.s)$ is an η-redex
- Detection of $\diamond\eta$ terms is not trivial:
- $$\begin{array}{lll} \lambda x.f \cdot (A \cdot x) & \in \diamond\eta & \rho = \{\ A \mapsto \lambda x.x\ \} \\ \lambda x.f \cdot (A \cdot x) \cdot x & \in \diamond\eta & \rho = \{\ A \mapsto \lambda x.a\ \} \\ \lambda x.\lambda y.f \cdot (A \cdot x) \cdot (B \cdot y \cdot x) & \in \diamond\eta & \rho = \{\ A \mapsto \lambda x.x\ ;\ B \mapsto \lambda y.\lambda x.y\ \} \\ \lambda x.f \cdot x \cdot (A \cdot x) & \notin \diamond\eta & \end{array}$$

Sketch of $\diamond\eta$ link : the problem

- An example:

$$\begin{aligned}
\mathbb{P} &= \{ \quad f \simeq_o \lambda x.(f \cdot (Y \cdot x)) \quad \} \\
\mathbb{Q} &= \{ \ \texttt{c"f"} \simeq_m \texttt{fun (x\textbackslash\ app[c"f", B x])} \ \} \\
\mathbb{M} &= \{ \ Y \mapsto \texttt{B} \ \}
\end{aligned}$$

- We have recognized the $\diamond\beta$ subterm $Y \cdot x$
- But the unification problem in $\mathbb{Q}$ raises a failure...

Sketch of $\diamond\eta$ link: the solution

- An example:

$$
\begin{aligned}
\mathbb{P} &= \{ \quad f \simeq_o \lambda x.(f \cdot (Y \cdot x)) \ \} \\
\mathbb{Q} &= \{ \ \texttt{c"f"} \simeq_m \texttt{A} \qquad\qquad \} \\
\mathbb{M} &= \{ \ Y \mapsto \texttt{B} \ \} \\
\mathbb{L} &= \{ \ \texttt{eta-link A (fun (x\textbackslash\ app[c"f", B x]))} \ \}
\end{aligned}
$$

- After unification of `c"f"` with `A`,
  its η-expansion is unified with `fun (x\ app[c"f", B x])`
  Hence `B` is assigned to `x\x`
- Decompilation will assign $\lambda x.x$ to Y

Going further: the Constraint Handling Rules

- Elpi has CHR for goal suspension and resumption
- This fits well our notion of link: a suspended unification problem

```
pred eta-link i:term, i:term.
eta-link A (fun _ _ B as T) :- not (var A), not (var B), !,
  unify-left-right A T.
eta-link A B :- progress-eta-right B B', !, A = B'.
eta-link A B :- progress-eta-left  A A', !, A' = B.
eta-link A B :- scope-check A B, get-vars B Vars,
  declare_constraint (eta-link A B) [A|Vars].
```

This can easily introduce new unification behaviors

- Add heuristic for HO unification outside the pattern fragment

```
% By def, R is not in the pattern fragment
llam-link L R :- not (var L), unif-heuristic L R.
```

Conclusion

- Takes advantage of the unification capabilities of the meta language at the price of handling problematic sub-terms on the side.
- TC search up to $\beta\eta$ can be implemented via Elpi rules
- Our approach is flexible enough to accommodate different strategies and **heuristics** to handle terms outside the pattern fragment

Thanks!

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Questions ?