



Relational Interpreters for Search Problems

Petr Lozov, **Kate Verbitskaia**, Dmitry Boulytchev

JetBrains Research, Programming Languages and Tools Lab
Saint Petersburg State University

22.08.2019

Solvers from Verifiers

Relational interpreter = verifier

Relational interpreter being run backward = solver

`evalo prog ?? res`

`isPatho path graph res`

`unifyo term term' subst res`

run `q (isPatho q graph True)` — searches for all paths in the graph

- Implement a functional program which verifies the solution for a program
- Transform it into a relation
- Specialize for the backward direction
- The result can search for solutions

Relational programming is complicated, why not let users write a verifier as a function and then translate it into miniKanren?

- Introduce a new variable for each subexpression
- For every n -ary function create an $(n+1)$ -ary relation, where the last argument is unified with the result
- Transform **if**-expressions and pattern matchings into disjunctions with unifications for patterns
- Introduce into scope free variables (with **fresh**)
- Pop unifications to the top

Relational Conversion: Step 1

Introduce a new variable for each subexpression

```
let rec append a b =  
  match a with  
  | []          → b  
  | x :: xs    →  
    x :: append xs b
```

```
let rec append a b =  
  match a with  
  | []          → b  
  | x :: xs    →  
    let q = append xs b in  
    x :: q
```

Relational Conversion: Step 2

Introduce a new variable for each subexpression

`let rec append a b = ...` `let rec appendo a b c = ...`

Relational Conversion: Step 3

Transform **if**-expressions and pattern matchings into disjunctions with unifications for patterns

```
let rec append a b =  
  match a with  
  | []          → b  
  | x :: xs →  
    let q = append xs b in  
    x :: q
```

```
let rec appendo a b c =  
  (a ≡ [] ∧ b ≡ c) ∨  
  ( (a ≡ x :: xs) ∧  
    (appendo xs b q) ∧  
    (c ≡ x :: q))
```

Relational Conversion: Step 4

Introduce free variables into scope (with **fresh**)

```
let rec appendo a b c =  
  (a ≡ [] ∧ b ≡ c) ∨  
  ( (a ≡ x :: xs) ∧  
    (appendo xs b q) ∧  
    (c ≡ x :: q))
```

```
let rec appendo a b c =  
  (a ≡ [] ∧ b ≡ c) ∨  
  (fresh (x xs q) (  
    (a ≡ x :: xs) ∧  
    (appendo xs b q) ∧  
    (c ≡ x :: q)))
```

Relational Conversion: Step 5

Pop unifications to the top

```
let rec appendo a b c =  
  (a ≡ [] ∧ b ≡ c) ∨  
  (fresh (x xs q) (  
    (a ≡ x :: xs) ∧  
    (appendo xs b q) ∧  
    (c ≡ x :: q)))
```

```
let rec appendo a b c =  
  (a ≡ [] ∧ b ≡ c) ∨  
  (fresh (x xs q) (  
    (a ≡ x :: xs) ∧  
    (c ≡ x :: q) ∧  
    (appendo xs b q)))
```


Forward Execution is Efficient, Backward Execution is not

Forward execution is efficient, since it mimics the execution of a function

Relational conversion for $f_1\ x_1 \ \&\& \ f_2\ x_2$:

```
 $\lambda\ res \rightarrow$   
  fresh (p) (  
    ( $f_1\ x_1\ p$ )  $\wedge$   
    (conde [  
      ( $p \equiv \uparrow\mathbf{false} \wedge res \equiv \uparrow\mathbf{false}$ );  
      ( $p \equiv \uparrow\mathbf{true} \wedge f_2\ x_2\ res$ )]))
```

Computes $f_2\ x_2\ res$ only if $f_1\ x_1\ p$ fails

It is not the best strategy, if res is known

Relational Conversion Aimed at Backward Execution

This conversion of $f_1\ x_1 \ \&\& \ f_2\ x_2$ is better for backward execution, but not forward

```
 $\lambda\ res \rightarrow$   
  conde [  
    ( $res \equiv \uparrow\mathbf{false} \ \wedge \ f_1\ x_1 \ \uparrow\mathbf{false}$ );  
    ( $f_1\ x_1 \ \uparrow\mathbf{true} \ \wedge \ f_2\ x_2\ res$ )]
```

There is no one strategy suitable for all cases

Better is to use an automatic specializer

Specialization

Interpreter: given a program and input computes an output

`eval prog input == output`

Consider that a part of the input is known: `input == (static, dynamic)`

Specializer: given a program and static input, generates a new program, which evaluates to the same output as the original

`spec prog static \Rightarrow progspec`

`eval prog (static, dynamic) == eval progspec dynamic`

Conjunctive Partial Deduction

- Fully automatic program transformation
- For pure logic language
- Features:
 - Specialization
 - Deforestation
 - Tupling

Deforestation

Deforestation — program transformation which eliminates intermediate data structures

```
let doubleAppendo x y z xyz =  
  (fresh (t) (  
    (appendo x y t) ∧  
    (appendo t z xyz)))
```

```
let rec appendo x y xy = conde [  
  (x ≡ nil () ∧ xy ≡ y);  
  (fresh (h t ty) (  
    (x ≡ h % t) ∧  
    (xy ≡ h % t') ∧  
    (appendo t y t')))]
```

```
let rec doubleAppendo x y z xyz = conde [  
  (x ≡ nil () ∧ appendo y z xyz);  
  (fresh (h t t') (  
    (x ≡ h % t) ∧  
    (xyz ≡ h % t') ∧  
    (doubleAppendo t y z t')))]
```

Tupling

Tupling — program transformation which eliminates multiple traversals of the same data structure

```
let maxLengtho xs m l = maxo xs m ∧ lengtho xs l
```

```
let rec lengtho xs l = conde [  
  (xs ≡ nil () ∧ l ≡ zero ());  
  (fresh (h t m) (  
    xs ≡ h % t ∧ l ≡ succ m ∧ lengtho t m)))]
```

```
let maxo xs m = max1o xs (zero ()) m
```

```
let rec max1o xs n m = conde [  
  (xs ≡ nil () ∧ m ≡ n);  
  (fresh (h t) (  
    (xs ≡ h % t) ∧  
    (conde [  
      (leo h n ↑true ∧ max1o t n m);  
      (gto h n ↑true ∧ max1o t h m)])))]
```

Tupling

Tupling — program transformation which eliminates multiple traversals of the same data structure

```
let maxLengtho xs m l = maxLength1o xs m (zero ()) l
```

```
let rec maxLength1o xs m n l = conde [  
  (xs ≡ nil () ∧ m ≡ n ∧ l ≡ zero ());  
  (fresh (h t l1)  
    (xs ≡ h % t) ∧  
    (l ≡ succ l1) ∧  
    (conde [  
      (leo h n ∧ maxLength1o t m n l);  
      (gto h n ∧ maxLength1o t m h l)])))]
```

- Local control: compute a partial SLDNF-tree per a relation of interest
 - Having a conjunction of atoms, which atom should be selected?
 - When to stop building a tree?
- Global control: determine which relations are of interest
 - Do not process the same conjunction twice
 - If a conjunction *embeds* something processed before, *generalize* it
 - How to define *embedding*?
 - How to *generalize*?

- Local control
 - Deterministic unfold (only one nondeterministic unfold per tree)
 - Selectable conjunct: leftmost atom which do not have any predecessor embedded into it
 - Variant check
 - Stop when there are no selectable atoms
- Global control
 - Variant check
 - Generalization: split conjunction in maximally connected subconjunctions + most specific generalization
 - Homeomorphic embedding extended for conjunctions
- Residualization
 - A definition per a partial SLDNF-tree
 - Redundant Argument Filtering

Compare

- Unnesting
- Unnesting strategy aimed at backward execution
- Unnesting + CPD
- Interpretation of functional verifier with relational interpreter

Tasks

- Path search
- Search for a unifier of two terms

Path Search

Directed graph is a tuple $(N, E, start, end)$, where:

- N — set of nodes
- E — set of edges
- Functions $start, end : E \rightarrow N$ return a start (end) node of an edge

Path is a sequence $\langle n_0, e_0, n_1, e_1, \dots, n_k, e_k, n_{k+1} \rangle$, such that

$$\forall i \in \{0 \dots k\} : n_i = start(e_i) \text{ and } n_{i+1} = end(e_i)$$

Path search problem is to find the set of paths in a given graph

Path Search: Relational Conversion

```
let rec isPath ns g =  
  match ns with  
  | x1 :: x2 :: xs → elem (x1, x2) g && isPath (x2 :: xs) g  
  | [-]             → true
```

Path Search: Relational Conversion

```
let rec isPath ns g =  
  match ns with  
  | x1 :: x2 :: xs → elem (x1, x2) g && isPath (x2 :: xs) g  
  | [-]           → true
```

```
let rec isPatho ns g res = conde [  
  (fresh (el) ((ns ≡ el % nil ()) ∧ (res ≡ ↑true)));  
  (fresh (x1 x2 xs resElem resIsPath) (  
    (ns ≡ x1 % (x2 % xs)) ∧  
    (elemo (pair x1 x2) g resElem) ∧  
    (isPatho (x2 % xs) g resIsPath) ∧  
    (conde [  
      (resElem ≡ ↑false ∧ res ≡ ↑false);  
      (resElem ≡ ↑true ∧ res ≡ resIsPath)])))]
```

This relation is inefficient for “isPath^o q <graph> true”

Path Search: Specialized Relation

```
let rec isPatho ns g res = conde [  
  (fresh (e1) ((ns ≡ e1 % nil ()) ∧ (res ≡ ↑true)));  
  (fresh (x1 x2 xs resElem resIsPath) (  
    (resElem ≡ ↑true) ∧  
    (resIsPath ≡ ↑true) ∧  
    (ns ≡ x1 % (x2 % xs)) ∧  
    (elemo (pair x1 x2) g resElem) ∧  
    (isPatho (x2 % xs) g resIsPath)))]
```

Better performance for “isPath^o q <graph> true”

Path Search: Specialized Relation

```
let rec isPatho ns g res = conde [  
  (fresh (el) ((ns ≡ el % nil ()) ∧ (res ≡ ↑true)));  
  (fresh (x1 x2 xs resElem resIsPath) (  
    (resElem ≡ ↑true) ∧  
    (resIsPath ≡ ↑true) ∧  
    (ns ≡ x1 % (x2 % xs)) ∧  
    (elemo (pair x1 x2) g resElem) ∧  
    (isPatho (x2 % xs) g resIsPath)))]
```

Better performance for “isPath^o q <graph> true”

This can be achieved automatically with CPD

Evaluation: Path Search

Path length	5	7	9	11	13	15
Only conversion	0.01	1.39	82.13	>300	—	—
Backward oriented conversion	0.01	0.37	2.68	2.91	4.88	10.63
Conversion and CPD	0.01	0.06	0.34	2.66	3.65	6.22
Scheme interpreter	0.80	8.22	88.14	191.44	>300	—

Table: Searching for paths in the graph (seconds)

Unification

Term:

- Variable (X, Y, \dots)
- Some constructor applied to terms ($nil, cons(H, T), \dots$)

Substitution maps variables to terms

Substitution can be *applied* to a term by simultaneously substituting variables for their images

Unifier is a substitution σ which equalizes terms: $t\sigma = s\sigma$

Problem: given two terms with free variables, find their unifier

Unification: Functional Verifier

```
let rec check_uni subst t1 t2 =  
  match t1, t2 with  
  | Constr (n1, a1), Constr (n2, a2) →  
    eq_nat n1 n2 && forall2 subst a1 a2  
  | Var_ v      , Constr (n, a)  →  
    begin match get_term v subst with  
    | None   → false  
    | Some t → check_uni subst t t2  
    end  
  | Constr (n, a) , Var_ v      →  
    begin match get_term v subst with  
    | None   → false  
    | Some t → check_uni subst t1 t  
    end  
  | Var_ v1      , Var_ v2      →  
    match get_term v1 subst with  
    | Some t1' → check_uni subst t1' t2  
    | None     → match get_term v2 subst with  
                  | Some _ → false  
                  | None   → eq_nat v1 v2
```

Unification: Relational Conversion

Does not fit the slide.

Evaluation: Unification

Terms	$f(X, a)$	$f(a \% b \% nil, c \% d \% nil, L)$	$f(X, X, g(Z, t))$
	$f(a, X)$	$f(X \% XS, YS, X \% ZS)$	$f(g(p, L), Y, Y)$
Only conversion	0.01	>300	>300
Backward oriented conversion	0.01	0.11	2.26
Conversion and CPD	0.01	0.07	0.90
Scheme interpreter	0.04	5.15	>300

Table: Searching for a unifier of two terms (seconds)

Conclusion & Future Work

Functional verifier + unnesting + specialization = solver

Future

- Generate functional program from relational to reduce interpretation overhead
- Another specialization technique, less ad-hoc than CPD