

An Empirical Study of Partial Deduction for MINIKANREN*

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We explore partial deduction, an advanced specialization technique aimed at improving the performance of a relation in the given direction, in the context of MINIKANREN. On several examples, we demonstrate issues which arise during partial deduction of relational programs. We describe a novel approach to specialization of MINIKANREN based on partial deduction and supercompilation. Although the proposed approach does not give the best results in all cases, we view it as a stepping stone towards the efficient optimization of MINIKANREN.

CCS Concepts: • **Software and its engineering** → **Constraint and logic languages**; **Source code generation**.

Additional Key Words and Phrases: relational programming, partial deduction, specialization

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1 INTRODUCTION

The core feature of the family of relational programming languages MINIKANREN¹ is their ability to run a program in different directions. Having specified a relation for adding two numbers, one can also compute the subtraction of two numbers or find all pairs of numbers which can be summed up to get the given one. Program synthesis can be done by running *backwards* a relational interpreter for some language. In general, it is possible to create a solver for a recognizer by translating it into MINIKANREN and running in the appropriate direction [?].

The search employed in MINIKANREN is complete which means that every answer will be found, although it may take a long time. The promise of MINIKANREN falls short when speaking of performance. The running time of a program in MINIKANREN is highly unpredictable and varies greatly for different directions. What is even worse, it depends on the order of the relation calls within a program. One order can be good for one direction, but slow down the computation drastically in the other direction.

Specialization or partial evaluation [?] is a technique aimed at improving the performance of a program given some information about it beforehand. It may either be a known value of some argument, its structure (i.e. the length of an input list) or, in case of a relational program, — the direction in which it is intended to be run. An earlier paper [?] showed that *conjunctive partial deduction* [?] can sometimes improve the performance of MINIKANREN programs. Unfortunately, it may also not affect the running time of a program or even make it slower.

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¹MINIKANREN language web site: <http://minikanren.org>. Access date: 17.07.2020.

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Control issues in partial deduction of logic programming language PROLOG have been studied before [?]. The ideas described there are aimed at left-to-right evaluation strategy of PROLOG. Since the search in MINIKANREN is complete, it is safe to reorder some relation calls within the goal ahead-of-time for better performance. While sometimes conjunctive partial deduction gives great performance boost, sometimes it does not behave as well as it could have.

In this paper, we show on examples some issues which conjunctive partial deduction faces. We also describe *conservative partial deduction* — a novel specialization approach for the relational programming language MINIKANREN. We compare it to the existing specialization algorithms on several programs and discuss why some MINIKANREN programs run slower after specialization.

2 RELATED WORK

Specialization is an attractive technique aimed to improve the performance of a program if some of its arguments are known statically. Specialization is studied for functional, imperative and logic programming and comes in different forms: partial evaluation [?] and partial deduction [?], supercompilation [?], distillation [?], and many more.

The heart of supercompilation-based techniques is *driving* — a symbolic execution of a program through all possible execution paths. The result of driving is a *process tree* where nodes correspond to *configurations* which represent computation state. For example, in the case of pure functional programming languages, the computational state might be a term. Each path in the tree corresponds to some concrete program execution. The two main sources for supercompilation optimizations are aggressive information propagation about variables' values, equalities and disequalities, and precomputing of all deterministic semantic evaluation steps. The latter process, also known as *deforestation*, means combining of consecutive process tree nodes with no branching. When the tree is constructed, the resulting, or *residual*, program can be extracted from the process tree by the process called *residualization*. Of course, process tree can contain infinite branches. *Whistles* — heuristics to identify possibly infinite branches — are used to ensure supercompilation termination. If a whistle signals during the construction of some branch, then something should be done to ensure termination. The most common approaches are either to stop driving the infinite branch completely (no specialization is done in this case and the source code is blindly copied into the residual program) or to fold the process tree to a *process graph*. The main instrument to perform such a folding is *generalization*. Generalization, abstracting away some computed data about the current term, makes folding possible. One source of infinite branches is consecutive recursive calls to the same function with an accumulating parameter: by unfolding such a call further one can only increase the term size which leads to nontermination. The accumulating parameter can be removed by replacing the call with its generalization. There are several ways to ensure process correctness and termination, most-specific generalization (anti-unification) and *homeomorphic embedding* [? ?] as a whistle being the most common.

While supercompilation generally improves the behaviour of input programs and distillation can even provide superlinear speedup, there are no ways to predict the effect of specialization on a given program in the general. What is worse, the efficiency of residual program from the target language evaluator point of view is rarely considered in the literature. The main optimization source is computing in advance all possible intermediate and statically-known semantics steps at program transformation-time. Other criteria, like the size of the generated program or possible optimizations and execution cost of different language constructions by the target language evaluator, are usually out of consideration [?]. It is known that supercompilation may adversely affect GHC optimizations yielding standalone compilation more powerful [? ?] and cause code explosion [?]. Moreover, it may be hard to predict the real speedup of any given program on concrete examples even disregarding the problems above because of the complexity of the transformation algorithm. The worst-case for partial evaluation is when all static variables are used in a dynamic context, and there is some advice on how to implement a partial evaluator as

well as a target program so that specialization indeed improves its performance [? ?]. There is a lack of research in determining the classes of programs which transformers would definitely speed up.

Conjunctive partial deduction [?] makes an effort to provide reasonable control for the left-to-right evaluation strategy of PROLOG. CPD constructs a tree which models goal evaluation and is similar to a SLDNF tree, then a residual program is generated from this tree. Partial deduction itself resembles driving in supercompilation [?]. The specialization is done in two levels of control: the local control determines the shape of the residual programs, while the global control ensures that every relation which can be called in the residual program is indeed defined. The leaves of local control trees become nodes of the global control tree. CPD analyses these nodes at the global level and runs local control for all those which are new.

At the local level, CPD examines a conjunction of atoms by considering each atom one-by-one from left to right. An atom is *unfolded* if it is deemed safe, i.e. a whistle based on homeomorphic embedding does not signal for the atom. When an atom is unfolded, a clause whose head can be unified with the atom is found, and a new node is added into the tree where the atom in the conjunction is replaced with the body of that clause. If there is more than one suitable head, then several branches are added into the tree which corresponds to the disjunction in the residualized program. An adaptation of CPD for the MINIKANREN programming language is described in [?].

The most well-behaved strategy of local control in CPD for PROLOG is *deterministic unfolding* [?]. An atom is unfolded only if precisely one suitable clause head exists for it with the single exception: it is allowed to unfold an atom non-deterministically once for one local control tree. This means that if a non-deterministic atom is the leftmost within a conjunction, it is most likely to be unfolded and to introduce many new relation calls within the conjunction. We believe this is the core problem with CPD which limits its power when applied to MINIKANREN. The strategy of unfolding atoms from left to right is reasonable in the context of PROLOG because it mimics the way programs in PROLOG execute. But it often leads to larger global control trees and, as a result, bigger, less efficient programs. The evaluation result of a MINIKANREN program does not depend on the order of atoms (relation calls) within a conjunction, thus we believe a better result can be achieved by selecting a relation call which can restrict the number of branches in the tree. We describe our approach which implements this idea in the next section.

3 CONSERVATIVE PARTIAL DEDUCTION

In this section, we describe a novel approach to relational programs specialization. This approach draws inspiration from both conjunctive partial deduction and supercompilation. The aim was to create a specialization algorithm which is simpler than conjunctive partial deduction and uses properties of MINIKANREN to improve the performance of the input programs.

The algorithm pseudocode is shown in Fig. 1. For the sake of brevity and clarity, we provide functions `drive_disj` and `drive_conj` which describe how to process disjunctions and conjunctions respectively. Driving itself is a trivial combination of the functions provided (line 2).

A driving process creates a process tree, from which a residual program is later created. The process tree is meant to mimic the execution of the input program. The nodes of the process tree include a *configuration* which describes the state of program evaluation at some point. In our case a configuration is a conjunction of relation calls. The substitution computed at each step is also stored in the tree node, although it is not included in the configuration.

Hereafter, we consider all goals and relation bodies to be in *canonical normal form* — a disjunction of conjunctions of either calls or unifications. Moreover, we assume all fresh variables to be introduced into the scope and all unifications to be computed at each step. Those disjuncts in which unifications fail are removed. Each other disjunct takes the form of a possibly empty conjunction of relation calls accompanied with a substitution computed

```

1 | ncpd goal = residualize ◦ drive ◦ normalize (goal)
2 | drive      = drive_disj ∪ drive_conj
3 |
4 | drive_disj :: Disjunction → Process_Tree
5 | drive_disj D@(c1, ..., cn) =  $\bigvee_{i=1}^n t_i \leftarrow \text{drive\_conj } (c_i)$ 
6 |
7 | drive_conj :: (Conjunction, Substitution) → Process_Tree
8 | drive_conj ((r1, ..., rn), subst) =
9 |   C@(r1, ..., rn) ← propagate_substitution subst on r1, ..., rn
10 |   case whistle (C) of
11 |     | instance (C', subst')      ⇒ create_fold_node (C', subst')
12 |     | embedded_but_not_instance ⇒ create_stop_node (C, subst)
13 |     | otherwise ⇒
14 |       | case heuristically_select_a_call (r1, ..., rn) of
15 |         | Just r ⇒
16 |           | t ← drive ◦ normalize ◦ unfold (r)
17 |           | if trivial ◦ leafs (t)
18 |           | then
19 |             | C' ← propagate_substitution (C \ r, extract_substitution (t))
20 |             | drive C'[r ↦ extract_calls (t)]
21 |           | else
22 |             | t ∧ drive (C \ r, subst)
23 |             | Nothing ⇒  $\bigwedge_{i=1}^n t_i \leftarrow \text{drive} \circ \text{normalize} \circ \text{unfold } (r_i)$ 

```

Fig. 1. Conservative Partial Deduction Pseudo Code

from unifications. Any MINIKANREN term can be trivially transformed into the described form. In Fig. 1 the function `normalize` is assumed to perform term normalization. The code is omitted for brevity.

There are several core ideas behind this algorithm. The first is to select an arbitrary relation to unfold, not necessarily the leftmost which is safe. The second idea is to use a heuristic which decides if unfolding a relation call can lead to discovery of contradictions between conjuncts which in turn leads to restriction of the answer set at specialization-time (line 14; `heuristically_select_a_call` stands for heuristics combination, see section 3.2 for details). If those contradictions are found, then they are exposed by considering the conjunction as a whole and replacing the selected relation call with the result of its unfolding thus *joining* the conjunction back together instead of using *split* as in CPD (lines 15–22). Joining instead of splitting is why we call our transformer *conservative* partial deduction. Finally, if the heuristic fails to select a potentially good call, then the conjunction is split into individual calls which are driven in isolation and are never joined (line 23).

When the heuristic selects a call to unfold (line 15), a process tree is constructed for the selected call *in isolation* (line 16). The leaves of the computed tree are examined. If all leaves are either computed substitutions or are instances of some relations accompanied with non-empty substitutions, then the leaves are collected and each of them replaces the considered call in the root conjunction (lines 19–20). If the selected call does not suit the criteria, the results of its unfolding are not propagated onto other relation calls within the conjunction, instead, the next suitable call is selected (line 22). According to the denotational semantics of MINIKANREN it is safe to compute individual conjuncts in any order, thus it is ok to drive any call and then propagate its results onto the other calls.

This process creates branchings whenever a disjunction is examined (lines 4–5). At each step, we make sure that we do not start driving a conjunction which we have already examined. To do this, we check if the current conjunction is a renaming of any other configuration in the tree (line 11). If it is, then we fold the tree by creating a special node which then is residualized into a call to the corresponding relation.

In this approach, we decided not to generalize in the same fashion as CPD or supercompilation. Our conjunctions are always split into individual calls and are joined back together only if it is meaningful. If the need for generalization arises, i.e. homeomorphic embedding of conjunctions [?] is detected, then we immediately stop driving this conjunction (line 12). When residualizing such a conjunction, we just generate a conjunction of calls to the input program before specialization.

3.1 Unfolding

Unfolding in our case is done by substitution of some relation call by its body with simultaneous normalization and computation of unifications. The unfolding itself is straightforward however it is not always clear what to unfold and when to *stop* unfolding. Unfolding in the specialization of functional programming languages, as well as inlining in imperative languages, is usually considered to be safe from the residual program efficiency point of view. It may only lead to code explosion or code duplication which is mostly left to a target program compiler optimization or even is out of consideration at all if a specializer is considered as a standalone tool [?].

Unfortunately, this is not the case for the specialization of a relational programming language. Unlike in functional and imperative languages, in logic and relational programming languages unfolding may easily affect the target program's efficiency [?]. Unfolding too much may create extra unifications, which is by itself a costly operation, or even introduce duplicated computations by propagating the unfolding's results onto neighbouring conjuncts.

There is a fine edge between too much unfolding and not enough unfolding. The former is maybe even worse than the latter. We believe that the following heuristic provides a reasonable approach to unfolding control.

3.2 Less-Branching Heuristic

This heuristic is aimed at selecting a relation call within a conjunction which is both safe to unfold and may lead to discovering contradictions within the conjunction. An unsafe unfolding leads to an uncontrollable increase in the number of relation calls in a conjunction. It is best to first unfold those relation calls which can be fully computed up to substitutions.

We deem every static (non-recursive) conjunct to be safe because they never lead to growth in the number of conjunctions. Those calls which unfold deterministically, meaning there is only one disjunct in the unfolded relation, are also considered to be safe.

Those relation calls which are neither static nor deterministic are examined with what we call the *less-branching* heuristic. It identifies the case when the unfolded relation contains fewer disjuncts than it could possibly have. This means that we found some contradiction, some computations were gotten rid of, and thus the answer set was restricted, which is desirable when unfolding. To compute this heuristic we precompute the maximum possible number of disjuncts in each relation and compare this number with the number of disjuncts when unfolding a concrete relation call. The maximum number of disjuncts is computed by unfolding the body of the relation in which all relation calls were replaced by a unification which always succeeds.

```

1 | heuristically_select_a_call :: Conjunction → Maybe Call
2 | heuristically_select_a_call C = find heuristic C
3 |
4 | heuristic :: Call → Bool
5 | heuristic r = isStatic r || isDeterministic r || isLessBranching r
```

Fig. 2. Heuristic selection pseudocode

The pseudocode describing our heuristic is shown in Fig. 2. Selecting a good relation call can fail (line 1). The implementation works such that we first select those relation calls which are static, and only if there are none, we

proceed to consider deterministic unfoldings and then we search for those which are less branching. We believe this heuristic provides a good balance in unfolding.

4 EVALUATION

We implemented the new conservative partial deduction² and compared it with the CPD adaptation for MINIKANREN of [?]. We have also employed the branching heuristic instead of the deterministic unfolding in the CPD to check whether it can improve the quality of the specialization.

We used the following programs to test the specializers.

- Two implementations of an evaluator of logic formulas.
- A program to compute a unifier of two terms.
- A program to search for paths of a specific length in a graph.

The last two relations are described in [?] thus we will not describe them here.

4.1 Evaluator of Logic Formulas

The relation eval^o describes an evaluation of a subset of first-order logic formulas in a given substitution. It has 3 arguments. The first argument is a list of boolean values which serves as a substitution. The i -th value of the substitution is the value of the i -th variable. The second argument is a formula with the following abstract syntax. A formula is either a *variable* represented with a Peano number, a *negation* of a formula, a *conjunction* of two formulas or a *disjunction* of two formulas. The third argument is the value of the formula in the given substitution.

All examples of MINIKANREN relations in this paper are written in OCANREN³ syntax. We specialize the eval^o relation to synthesize formulas which evaluate to $\uparrow \text{true}$ ⁴. To do so, we run the specializer for the goal with the last argument fixed to $\uparrow \text{true}$, while the first two arguments remain free variables. Depending on the way the eval^o is implemented, different specializers generate significantly different residual programs.

4.1.1 The Order of Relation Calls. One possible implementation of the evaluator in the syntax of OCANREN is presented in Listing 1. Here the relation $\text{elem}^o \text{ subst } v \text{ res}$ unifies res with the value of the variable v in the list subst . The relations and^o , or^o , and not^o encode corresponding boolean operations.

```

let rec  $\text{eval}^o \text{ subst } \text{fm } \text{res} = \text{conde } [$ 
  fresh ( $x \ y \ z \ v \ w$ ) ( $(\text{fm} \equiv \text{var } v \wedge \text{elem}^o \text{ subst } v \text{ res});$ 
     $(\text{fm} \equiv \text{conj } x \ y \wedge \text{eval}^o \text{ st } x \ v \wedge \text{eval}^o \text{ st } y \ w \wedge \text{and}^o \ v \ w \text{ res});$ 
     $(\text{fm} \equiv \text{disj } x \ y \wedge \text{eval}^o \text{ st } x \ v \wedge \text{eval}^o \text{ st } y \ w \wedge \text{or}^o \ v \ w \text{ res});$ 
     $(\text{fm} \equiv \text{neg } x \wedge \text{eval}^o \text{ st } x \ v \wedge \text{not}^o \ v \text{ res}))]$ 

```

Listing 1. Evaluator of formulas with boolean operation last

Note, that the calls to boolean relations and^o , or^o , and not^o are placed last within each conjunction. This poses a challenge to the CPD-based specializers. Conjunctive partial deduction unfolds relation calls from left to right, so when specializing this relation for running backwards (i.e. considering the goal $\text{eval}^o \text{ subst } \text{fm } \uparrow \text{true}$), it fails to propagate the direction data onto recursive calls of eval^o . Knowing that res is $\uparrow \text{true}$, we can conclude

²The repository of the MINIKANREN specialization project: https://github.com/kajigor/uKanren_transformations. Access date: 17.07.2020.

³OCANREN: statically typed MINIKANREN embedding in OCAML. The repository of the project: <https://github.com/JetBrains-Research/OCanren>. Access date: 17.07.2020.

⁴An arrow lifts ordinary values to the logic domain.

that in the call $\text{and}^o v w \text{ res}$ variables v and w have to be $\uparrow\text{true}$ as well. There are three possible options for these variables in the call $\text{or}^o v w \text{ res}$ and one for the call not^o . These variables are used in recursive calls of eval^o and thus restrict the result of driving them. CPD fails to recognize this, and thus unfolds recursive calls of eval^o applied to fresh variables. It leads to over-unfolding, big residual programs and poor performance.

The conservative partial deduction first unfolds those calls which are selected with the heuristic. Since exploring boolean operations makes more sense, they are unfolded before recursive calls of eval^o . The way conservative partial deduction treats this program is the same as it treats the other implementation in which boolean operations are moved to the left, as shown in Listing 2. This program is easier for CPD to transform which demonstrates how unequal the behaviour of CPD for similar programs is.

```

let rec evalo subst fm res = conde [
  fresh (x y z v w) (
    (fm ≡ var v ∧ elemo subst v res);
    (fm ≡ conj x y ∧ ando v w res ∧ evalo st x v ∧ evalo st y w);
    (fm ≡ disj x y ∧ oro v w res ∧ evalo st x v ∧ evalo st y w);
    (fm ≡ neg x ∧ noto v res ∧ evalo st x v)))]

```

Listing 2. Evaluator of formulas with boolean operation second

4.1.2 Unfolding of Complex Relations. Depending on the way a relation is implemented, it may take a different number of driving steps to reach the point when any useful information is derived through its unfolding. Partial deduction tries to unfold every relation call unless it is unsafe, but not all relation calls serve to restrict the search space and thus not every relation call should be unfolded. In the implementation of eval^o boolean operations can effectively restrict variables within the conjunctions and should be unfolded until they do. But depending on the way boolean operations are implemented, different number of driving steps should be performed for that. The simplest way to implement these relations is with a table as demonstrated with the implementation of not^o in Listing 3. It is enough to unfold such relation calls once to derive useful information about variables.

```

let noto x y = conde [
  (x ≡  $\uparrow\text{true}$  ∧ y ≡  $\uparrow\text{false}$  ;
  x ≡  $\uparrow\text{false}$  ∧ y ≡  $\uparrow\text{true}$ )]

```

Listing 3. Implementation of boolean not as a table

The other way to implement boolean operations is via one basic boolean relation such as nand^o which has, in turn, a table-based implementation (see Listing 4). It will take several sequential unfoldings to derive that variables v and w should be $\uparrow\text{true}$ when considering a call $\text{and}^o v w \uparrow\text{true}$ implemented via a basic relation. Conservative partial deduction drives the selected call until it derives useful substitutions for the variables involved. CPD with deterministic unfolding may fail to derive useful substitutions.

4.2 Evaluation Results

In our study, we considered two implementations of eval^o , one we call *plain* and the other — *last*, and compared how specializers behave on them. The *plain* relation uses table-based boolean operations and places them further to the left in each conjunction. The relation *last* employs boolean operations implemented via nand^o and places them at the end of each conjunction. These two programs are complete opposites from the standpoint of CPD.

```

let noto x y = nando x x y

let oro x y z = nando x x xx  $\wedge$  nando y y yy  $\wedge$  nando xx yy z

let ando x y z = nando x y xy  $\wedge$  nando xy xy z

let nando a b c = conde [
  ( a  $\equiv$   $\uparrow$ false  $\wedge$  b  $\equiv$   $\uparrow$ false  $\wedge$  c  $\equiv$   $\uparrow$ true );
  ( a  $\equiv$   $\uparrow$ false  $\wedge$  b  $\equiv$   $\uparrow$ true  $\wedge$  c  $\equiv$   $\uparrow$ true );
  ( a  $\equiv$   $\uparrow$ true  $\wedge$  b  $\equiv$   $\uparrow$ false  $\wedge$  c  $\equiv$   $\uparrow$ true );
  ( a  $\equiv$   $\uparrow$ true  $\wedge$  b  $\equiv$   $\uparrow$ true  $\wedge$  c  $\equiv$   $\uparrow$ false )]

```

Listing 4. Implementation of boolean operations via nand

	last	plain	unify	isPath
Original	1.06s	1.84s	—	—
CPD	—	1.13s	14.12s	3.62s
ConsPD	0.93s	0.99s	0.96s	2.51s
Branching	3.11s	7.53s	3.53s	0.54s

Table 1. Evaluation results

We measured the time necessary to generate 1000 formulas over two variables which evaluate to \uparrow **true**. We compared the results of specialization of the goal `evalo subst fm \uparrow true` by our implementation of CPD, the new conservative partial deduction, and the CPD modified with the less-branching heuristic. Our evaluation confirmed that CPD behaves very differently on these two implementations of the same relation. CPD improves the execution time of the `plain` relation, however CPD performs too much unfolding of the `last` relation which is why the specialized relation `last` fails to terminate in under 10 seconds. The execution time of two programs generated with the novel conservative partial deduction is very similar and it is a little bit better than the best by CPD. CPD with the less-branching heuristic constructs residual programs of different quality, worsening the execution time for both implementations. The results are shown in table 1.

Besides the evaluator of logic formulas we also run the transformers on the relation `unify`, which searches for a unifier of two terms, and the relation `isPath` specialized to search for paths in a graph. These two relations are described in paper [?] so we will not go into too many details here.

The `unify` relation was executed to find a unifier of the terms $f(X, X, g(Z, t))$ and $f(g(p, L), Y, Y)$. The original MINIKANREN program fails to terminate on this goal in 30 seconds. On this example, the most performant is the program generated by conservative partial deduction (0.96 seconds).

The last test executed the `isPath` relation to search for 5 paths in a graph with 20 vertices and 30 edges. The original MINIKANREN program fails to terminate on this goal in 30 seconds. On this program, CPD with branching heuristic showed much better transformation result than both CPD and conservative partial deduction, although all specialized versions show improvement as compared with the original relation.

All evaluation results are presented in the table 1. Each column corresponds to the relation being run as described above. The row marked “Original” contains the execution time of the original MINIKANREN relation before specialization, “CPD” and “ConsPD” correspond to conjunctive and conservative partial deduction respectively while “Branching” is for the CPD modified with the branching heuristic.

5 CONCLUSION

In this paper, we discussed some issues which arise in partial deduction of a relational programming language, MINIKANREN. We presented a novel approach to partial deduction which uses less-branching heuristic to select the most suitable relation call to unfold at each step of driving. We compared this approach to the earlier implementation of conjunctive partial deduction and the implementation of CPD equipped with the new less-branching heuristic.

The conservative partial deduction improved the execution time of all relations while the implementations of CPD degraded the performance of some of them. However, CPD equipped with the less-branching heuristic improved the execution time of one relation the most compared with the other specializers. We conclude that there is still no one good technique which definitely speeds up every relational program. More research is needed to develop models to predict performance of relations, these models can further be used in specialization.

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