

InvarGenT: Implementation

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Abstract

InvarGenT is a proof-of-concept system for invariant generation by full type inference with Guarded Algebraic Data Types and existential types encoded as automatically generated GADTs. This implementation documentation focuses on source code, refers to separate technical reports on theory and algorithms.

1 Data Structures and Concrete Syntax

Following [8], we have the following nodes in the abstract syntax of patterns and expressions:

- p-Empty.** 0: Pattern that never matches. Concrete syntax: `!`. Constructor: `Zero`.
- p-Wild.** 1: Pattern that always matches. Concrete syntax: `_`. Constructor: `One`.
- p-And.** $p_1 \wedge p_2$: Conjunctive pattern. Concrete syntax: e.g. `p1 as p2`. Constructor: `PAnd`.
- p-Var.** x : Pattern variable. Concrete syntax: lower-case identifier e.g. `x`. Constructor: `PVar`.
- p-Cstr.** $K p_1 \dots p_n$: Constructor pattern. Concrete syntax: e.g. `K (p1, p2)`. Constructor: `PCons`.
- Var.** x : Variable. Concrete syntax: lower-case identifier e.g. `x`. Constructor: `Var`. External functions are represented as variables in global environment.
- Cstr.** $K e_1 \dots e_n$: Constructor expression. Concrete syntax: e.g. `K (e1, e2)`. Constructor: `Cons`.
- App.** $e_1 e_2$: Application. Concrete syntax: e.g. `x y`. Constructor: `App`.
- LetRec.** `letrec $x = e_1$ in e_2` : Recursive definition. Concrete syntax: e.g. `let rec f = function ... in ...`. Constructor: `Letrec`.
- Abs.** $\lambda(c_1 \dots c_n)$: Function defined by cases. Concrete syntax: `function ... | ...;` for single branching via `fun` keyword, e.g. `fun x y -> f x y` translates as $\lambda(x.\lambda(y.(fx) y))$; for multiple branching via `match` keyword, e.g. `match e with ...` translates as $\lambda(\dots)e$. Constructor: `Lam`.
- Clause.** $p.e$: Branch of pattern matching. Concrete syntax: e.g. `p -> e`.
- CstrIntro.** Does not figure in neither concrete nor abstract syntax. Scope of existential types is thought to retroactively cover the whole program.
- ExCases.** $\lambda[K](p_1.e_1 \dots p_n.e_n)$: Function defined by cases and abstracting over the type of result. Concrete syntax: `efunction` and `ematch` keywords – e.g. `efunction Nil -> ... | Cons (x,xs) -> ...; ematch l with ...`. Parsing introduces a fresh identifier for K , but normalization keeps only one K for nested `ExCases` (unless nesting in body of local definition or in argument of an application). Constructor: `ExLam`.
- LetIn, ExLetIn.** `let $p = e_1$ in e_2` : Elimination of existentially quantified type. Concrete syntax: e.g. `let v = f e ... in ...`. Constructor: `Letin`.

We also have one sort-specific type of expression, numerals.

For type and formula connectives, we have ASCII and unicode syntactic variants (the difference is only in lexer). Quantified variables can be space or comma separated. Variables of various sorts have to start with specific letters: `a,b,c,r,s,t`, resp. `i,j,k,l,m,n`. Remaining letters are reserved for future sorts. The table below is analogous to information for expressions above. We pass variables environment `gamma` as function parameters. We keep constructors environment `sigma` as a global table. Existential type constructs introduce fresh identifiers K , we remember the identifiers in `ex_types` but store the information in `sigma`. Note that inferred existential types will not be nested, thanks to normalization of nested occurrences of $\lambda[K]$. The abstract syntax of types is not sort-safe, but type variables carry sorts determined by first letter of the variable. In the future, sorts could be inferred after parsing.

| | | | | |
|----------------------|--------------------------------|------------------------------------|-----------------------------|---|
| type variable: types | $\alpha, \beta, \gamma, \tau$ | $a, b, c, r, s, t, a_1, \dots$ | | $\text{TVar}(\text{VName}(\text{Type_sort}, \dots))$ |
| type variable: nums | k, m, n | $i, j, k, l, m, n, i_1, \dots$ | | $\text{TVar}(\text{VName}(\text{Num_sort}, \dots))$ |
| type constructor | List | List | | $\text{TCons}(\text{CNamed} \dots)$ |
| number (type) | 7 | 7 | | NCst |
| numeral (expr.) | 7 | 7 | | Num |
| numerical sum (type) | $m + n$ | $m+n$ | | Nadd |
| existential type | $\exists k, n[k \leq n]. \tau$ | $\text{ex } k \ n \ [k \leq n]. t$ | $\exists k, n[k \leq n]. t$ | $\text{TCons}(\text{Extype} \dots)$ |
| type sort | s_{ty} | type | | Type_sort |
| number sort | s_R | num | | Num_sort |
| function type | $\tau_1 \rightarrow \tau_2$ | $t_1 \rightarrow t_2$ | $t_1 \rightarrow t_2$ | Fun |
| equation | $a \doteq b$ | $a = b$ | | Eqty |
| inequation | $k \leq n$ | $k \leq n$ | $k \leq n$ | Leq |
| conjunction | $\varphi_1 \wedge \varphi_2$ | $a=b \ \&\& \ b=a$ | $a=b \wedge b=a$ | built-in lists |

Parts of the logic hidden from the user:

| | | |
|---------------------------|--------------------------|---|
| unary predicate variable | $\chi(\beta)$ | $\text{PredVarU}(\text{chi}, \text{TVar } "b", \text{loc})$ |
| binary predicate variable | $\chi_K(\gamma, \alpha)$ | $\text{PredVarB}(\text{chi}, \text{TVar } "g", \text{TVar } "a", \text{loc})$ |
| not an existential type | $\neg(\alpha)$ | $\text{NotEx}(\text{TVar } "a", \text{loc})$ |
| negation assert false | \mathbf{F} | CFalse loc |

Toplevel expressions (corresponding to structure items in OCaml) introduce types, type and value constructors, global variables with given type (external names) or inferred type (definitions).

| | | |
|---------------------|--|-----------|
| type constructor | <code>newtype List : type * num</code> | TypConstr |
| value constructor | <code>newcons Cons : all n a. a * List(a,n) --> List(a,n+1)</code> | ValConstr |
| | <code>newcons Cons : $\forall n, a. a * \text{List}(a, n) \rightarrow \text{List}(a, n+1)$</code> | |
| declaration | <code>external filter : $\forall n, a. \text{List}(a, n) \rightarrow \exists k[k \leq n]. \text{List}(a, k)$</code> | PrimVal |
| rec. definition | <code>let rec f =...</code> | LetRecVal |
| non-rec. definition | <code>let v =...</code> | LetVal |

For simplicity of theory and implementation, mutual non-nested recursion and or-patterns are not provided. For mutual recursion, nest one recursive definition inside another.

2 Generating and Normalizing Formulas

We inject the existential type and value constructors during parsing for user-provided existential types, and during constraint generation for inferred existential types, into the list of toplevel items. It facilitates exporting inference results as OCaml source code.

Functions `constr_gen_pat` and `envfrag_gen_pat` compute formulas according to table [?] in [8], and `constr_gen_expr` computes table [?]. Due to the presentation of the type system, we ensure in `ValConstr` that bounds on type parameters are introduced in the formula rather than being substituted into the result type. We preserve the FOL language presentation in the type `cnstrnt`, only limiting the expressivity in ways not requiring any preprocessing. The toplevel definitions (from type `struct_item`) `LetRecVal` and `LetVal` are processed by `constr_gen_letrec` and `constr_gen_let` respectively. They are analogous to `Letrec` and `Letin` or a `Lam` clause. We do not cover toplevel definitions in our formalism (without even a rudimentary module system, the toplevel is a matter of pragmatics rather than semantics).

Toplevel definitions are intended as boundaries for constraint solving. This way the programmer can decompose functions that could be too complex for the solver. `LetRecVal` only binds a single identifier, while `LetVal` binds variables in a pattern. To preserve the flexibility of expression-level pattern matching, `LetVal` has to pack the constraints $\llbracket \Sigma \vdash p \uparrow \alpha \rrbracket$ which the pattern makes available, into existential types. Each pattern variable is a separate entry to the global environment, therefore the connection between them is lost.

The `Letin` syntax has two uses: binding values of existential types means “eliminating the quantification” – the programmer has control over the scope of the existential constraint. The second use is if the value is not of existential type, the constraint is replaced by one that would be generated for a pattern matching branch. This recovers the common use of the `let...in` syntax, with exception of polymorphic `let` cases, where `let rec` needs to be used.

The second argument of the predicate variable $\chi_K(\gamma, \alpha)$ provides an “escape route” for free variables, i.e. precondition variables used in postcondition. In the implementation, we have user-defined existential types with explicit constraints in addition to inferred existential types. We expand the inferred existential types after they are solved into the fuller format. In the inferred form, the result type has a single parameter δ' , without loss of generality because the actual parameters are passed as a tuple type. In the full format we recover after inference, we extract the parameters $\delta' \doteq (\bar{\beta})$, the non-local variables of the existential type, and the partially abstract type $\delta \doteq \tau$, and store them separately, i.e. $\varepsilon_K(\bar{\beta}) = \forall \bar{\beta} \exists \bar{\alpha} [D]. \tau$. The variables $\bar{\beta}$ are instantiated whenever the constructor is used. For **LetVal**, we form existential types after solving the generated constraint, to have less intermediate variables in them.

Both during parsing and during inference, we inject new structure items to the program, which capture the existential types. In parsing, they arise only for **ValConstr** and **PrimVal** and are added by **Praser**. The inference happens only for **LetRecVal** and **LetVal** and injection is performed in **Infer**. During printing existential types in concrete syntax $\exists i: \bar{\beta} [\varphi]. t$ for an occurrence $\varepsilon_K((\bar{r}))$, the variables $\bar{\alpha}$ coming from $\delta' \doteq (\bar{\alpha}) \in \varphi$ are substituted-out by $[\bar{\alpha} := \bar{r}]$.

For simplicity, only toplevel definitions accept type and invariant annotations from the user. The constraints are modified according to the $\llbracket \Gamma, \Sigma \vdash \text{ce}: \forall \bar{\alpha} [D]. \tau \rrbracket$ rule. Where **Letrec** uses a fresh variable β , **LetRecVal** incorporates the type from the annotation. The annotation is considered partial, D becomes part of the constraint generated for the recursive function but more constraints will be added if needed. The polymorphism of $\forall \bar{\alpha}$ variables from the annotation is preserved since they are universally quantified in the generated constraint.

The constraints solver returns three components: the *residue*, which implies the constraint when the predicate variables are instantiated, and the solutions to unary and binary predicate variables. The residue and the predicate variable solutions are separated into *solved variables* part, which is a substitution, and remaining constraints (which are currently limited to linear inequalities). To get a predicate variable solution we look for the predicate variable identifier association and apply it to one or two type variable identifiers, which will instantiate the parameters of the predicate variable. We considered several ways to deal with multiple solutions:

1. report a failure to the user;
2. ask the user for decision;
3. silently pick one solution, if the wrong one is picked the subsequent program might fail;
4. perform backtracking search for the first solution that satisfies the subsequent program.

We use approach 3 as it is simplest to implement. Traditional type inference workflow rules out approach 2, approach 4 is computationally too expensive. We might use approach 1 in a future version of the system. Upon “multiple solutions” failure – or currently, when a wrong type or invariant is picked – the user can add **assert** clauses (e.g. **assert false** stating that a program branch is impossible), and **test** clauses. The **test** clauses are boolean expressions with operational semantics of run-time tests: the test clauses are executed right after the definition is executed, and run-time error is reported when a clause returns **false**. The constraints from test clauses are included in the constraint for the toplevel definition, thus propagate more efficiently than backtracking would. The **assert** clauses are: **assert = type e1 e2** which translates as equality of types of **e1** and **e2**, **assert false** which translates as **CFalse**, and **assert e1 <= e2**, which translates as inequality $n_1 \leq n_2$ assuming that **e1** has type **Num n1** and **e2** has type **Num n2**.

We treat a chain of single branch functions with only **assert false** in the body of the last function specially. We put all information about the type of the functions in the premise of the generated constraint. Therefore the user can use them to exclude unintended types. See the example `equal_assert.gadt`.

We make a slight adjustment to constraints $\llbracket \Gamma \vdash Kp.e_2: \alpha_0 \rightarrow \tau \rrbracket$ generated for eliminating an existential type $\varepsilon_K(\alpha)$ to be inferred, by adding a semantically redundant atom $v_K(\alpha)$ needed by the solver. Symbolically, $\llbracket Kp \downarrow \tau \rrbracket = \exists \alpha'. \varepsilon_K(\alpha') \doteq \tau \wedge v_K(\alpha') \wedge \dots$ in such cases. We use **PredVarU** for v_K for parsimony, but do not write $\chi_K(\cdot)$ to avoid confusion with invariants and with $\chi_K(\cdot, \cdot)$.

2.1 Normalization

We reduce the constraint to alternation-minimizing prenex-normal form, as in the formalization. We explored the option to preserve the scope relations, but it was less suited for determining quantifier violations. We return a `var_scope`-producing variable comparison function. The branches we return from normalization have unified conclusions, since we need to unify for solving disjunctions anyway.

Releasing constraints from under `Or` is done iteratively, somewhat similar to how disjunction would be treated in constraint solvers. Releasing the sub-constraints is essential for eliminating cases of further `Or` constraints. When at the end more than one disjunct remains, we assume it is the traditional `LetIn` rule and select its disjunct (the first one in the implementation).

When one $\lambda[K]$ expression is a branch of another $\lambda[K]$ expression, the corresponding branch does not introduce an `Or` constraint – the case is settled syntactically to be the same existential type.

2.1.1 Implementation details

The unsolved constraints are particularly weak with regard to variables constrained by predicate variables. We need to propagate which existential type to select for result type of recursive functions, if any. The information is collected from implication branches by `simplify_brs` in `normalize`; it is used by `check_chi_exty`. `normalize` starts by flattening constraints into implications with conjunctions of atoms as premises and conclusions, and disjunctions with disjuncts and additional information. `flat_dsj` is used to flatten each disjunct in a disjunction, the additional information kept is `guard_cnj`, conjunction of atoms that hold together with the disjunction. `solve_dsj` takes the result of `flat_dsj` and tries to eliminate disjuncts. If only one disjunct is left, or we decide to pick `LetIn` anyway (`step>0`), we return the disjunct. Otherwise we return the filtered disjunction. `prepare_brs` cleans up the initial flattened constraints or the constraints released from disjunctions: it calls `simplify_brs` on implications and `flat_dsj` on each disjunction.

We collect information about existential return types of recursive definitions in `simplify_brs`:

1. solving the conclusion of a branch together with additional conclusions `guard_cnj`, to know the return types of variables,
2. registering existential return types for all variables in the substitution,
3. traversing the premise and conclusion to find new variables that are types of recursive definitions,
4. registering as “type of recursive definition” the return types for all variables in the substitution registered as types of recursive definitions,
5. traversing all variables known to be types of recursive definitions, and registering existential type with recursive definition (i.e. unary predicate variable) if it has been learned,
6. traversing all variables known to be types of recursive definitions again, and registering existential type of the recursive definition (if any) with the variable.

2.2 Simplification

During normalization, we remove from a nested premise the atoms it is conjoined with (as in “modus ponens”).

After normalization, we simplify the constraints by removing redundant atoms. We remove atoms that bind variables not occurring anywhere else in the constraint, and in case of atoms not in premises, not universally quantified. The simplification step is not currently proven correct and might need refining. We merge implications with the same premise, unless one of them is non-recursive and the other is recursive. We call an implication branch recursive when an unary predicate variable χ (not a χ_K) appears in the conclusion.

3 Abduction

The formal specification of abduction in [4] provides a scheme for combining sorts that substitutes number sort subterms from type sort terms with variables, so that a single-sort term abduction algorithm can be called. Since we implement term abduction over the two-sorted datatype `typ`, we keep these *alien subterms* in terms passed to term abduction.

3.1 Simple constraint abduction for terms

Our initial implementation of simple constraint abduction for terms follows [3] p. 13. The mentioned algorithm only gives *fully maximal answers* which is loss of generality w.r.t. our requirements. To solve $D \Rightarrow C$ the algorithm starts with $U(D \wedge C)$ and iteratively replaces subterms by fresh variables $\alpha \in \bar{\alpha}$ for a final solution $\exists \bar{\alpha}.A$. To mitigate some of the limitations of fully maximal answers, we start from $U(\tilde{A}(D \wedge C))$, where $\exists \bar{\alpha}.A$ is the solution to previous problems solved by the joint abduction algorithm, and $\tilde{A}(\cdot)$ is the corresponding substitution. During abduction $\text{Abd}(\mathcal{Q}, \bar{\beta}, \bar{D}_i, \bar{C}_i)$, we ensure that the (partial as well as final) answer $\exists \bar{\alpha}.A$ satisfies $\models \mathcal{Q}.A[\bar{\alpha}\bar{\beta} := \bar{t}]$ for some \bar{t} . We achieve this by normalizing the answer using parameterized unification under quantifiers $U_{\bar{\alpha}\bar{\beta}}(\mathcal{Q}.A)$. $\bar{\zeta}$ are the parameters of the invariants.

In fact, when performing unification, we check more than $U_{\bar{\alpha}\bar{\beta}}(\mathcal{Q}.A)$ requires. We also ensure that the use of parameters will not cause problems in the `split` phase of the main algorithm.

In implementing [3] p. 13, we follow top-down approach where bigger subterms are abstracted first – replaced by fresh variable, together with an arbitrary selection of other occurrences of the subterm. If dropping the candidate atom maintains $T(F) \models A \wedge D \Rightarrow C$, we proceed to neighboring subterm or next equation. Otherwise, we try all of: replacing the subterm by the fresh variable; proceeding to subterms of the subterm; preserving the subterm; replacing the subterm by variables corresponding to earlier occurrences of the subterm. This results in a single, branching pass over all subterms considered. Finally, we clean up the solution by eliminating fresh variables when possible (i.e. substituting-out equations $x \doteq \alpha$ for variable x and fresh variable α).

Although there could be an infinite number of abduction answers, there is always finite number of *fully maximal* answers, one of which we compute. We use a search scheme that tests as soon as possible. The simple abduction algorithm takes a partial solution – a conjunction of candidate solutions for some other branches – and checks if the solution being generated is satisfiable together with the candidate partial solution. The algorithm also takes several indicators to let it select the expected answer:

- a number that determines how many correct solutions to skip;
- a validation procedure that checks whether the partial answer meets a condition, in joint abduction the condition is consistency with premise and conclusion of each branch;
- the parameters and candidates for parameters of the invariants, $\bar{\beta}$, updated as we add new atoms to the partial answer; existential variables that are not to the left of parameters and are connected to parameters become parameters; we process atoms containing parameters first;
- the quantifier \mathcal{Q} (source `q`) so that the partial answer $\exists \bar{\alpha}.A$ (source `vs, ans`) can be checked for validity with parameters: $\models \mathcal{Q}.A[\bar{\alpha} := \bar{t}]$ for some \bar{t} ;
- a discard list of partial answers to avoid (a tabu list) – implements backtracking, with answers from abductions raising “fallback” going there.

Since an atom can be mistakenly discarded when some variable could be considered an invariant parameter but is not at the time, we process atoms incident with candidates for invariant parameters first. A variable becomes a candidate for a parameter if there is a parameter that depends on it. That is, we process atoms $x \doteq t$ such that $x \in \bar{\beta}$ first, and if equation $x \doteq t$ is added to the partial solution, we add to $\bar{\beta}$ existential variables in t . Note that $x \doteq t$ can stand for either $x := t$, or $y := x$ for $t = y$.

To recapitulate, the implementation is:

- `abstract` is the entry point.
- If `cand=[]` – no more candidates to add to the partial solution: check for repeated answers, skipping, and discarded answers.

- Otherwise, pick the next atom $FV(c) \cap \bar{\beta} \neq \emptyset$ if any, reordering the candidates until one is found.
- **step** works through a single atom of the form $x = t$.
- The **abstract/step** choices are:
 1. Try to drop the atom (if the partial answer + remaining candidates can still be completed to a correct answer).
 2. Replace the current subterm of the atom with a fresh parameter, adding the subterm to replacements; if at the root of the atom, check connected and validate before proceeding to remaining candidates.
 3. Step into subterms of the current subterm, if any, and if at the sort of types.
 4. Keep the current part of the atom unchanged; if at the root of the atom, check connected and validate before proceeding to remaining candidates.
 5. Replace the current subterm with a parameter introduced for an earlier occurrence; branch over all matching parameters; if at the root of the atom, check connected and validate before proceeding to remaining candidates.
 6. Keep a variant of the original atom, but with universal variables and constants substituted-out. Redundant, and optional: only when **more_general** is false.
- Choices 2-6 are guarded by **try-with**, as tests raise **Contradiction** if they fail, choice 1 only tests **implies_concl** which returns a boolean.
- We provide an option **more_general**, which when set to false reorders the choices into: 1, 6, 4, 2, 3, 5 – pushing 4 up minimizes the amount of branching in 5.
- Form initial candidates $U(\tilde{A}(D \wedge C))$.
- Form the choice-6 counterparts of initial candidate atoms. Replace $\alpha_1 := \tau, \dots, \alpha_n := \tau$ with $\alpha_1 := \alpha_i, \dots, \alpha_n := \alpha_i, \tau := \alpha_i$ (excluding $\alpha_i := \alpha_i$) where α_i is the most upstream existential variable and τ is a universal variable or constant, and propagate the substitution.
- Sort the initial candidates by increasing size, so that replacements of step 2 are formed at a root position before they are used in step 5 – instead of forming a replacement at a subterm, and using it in step 5 at a root.

The above ordering of choices ensures that more general answers are tried first. Moreover:

- choice 1 could be dropped as it is equivalent to choice 2 applied on the root term;
- choices 4 and 5 could be reordered but having choice 4 as soon as possible is important for efficiency.

We perform a two-layer iterative deepening when **more_general** is false: in the first run we only try choices 1 and 6. It is an imperfect optimization since the running time gets longer whenever choices 2-5 are needed.

3.1.1 Heuristic for better answers to invariants

We implement an optional heuristic in forming the candidates proposed by choice 6. It may lead to better invariants when multiple maximally general types are possible, but also it may lead to getting the most general type without the need for backtracking across iterations of the main algorithm, which unfortunately often takes prohibitively long.

We look at the types of substitutions for the invariant-holding variables **bvs** in partial answer **ans**, and try to form the initial candidates for choice 6 so that the return type variables cover the most of argument types variables, for each **bvs** type found. We select from the candidates equations between any variable (case **sb**) or only non-argument-type variable (case **b_sb**), and a $FV(\text{argument types}) \setminus FV(\text{return type})$ variable – we turn the equation so that the latter is the RHS. We locate the equations among the candidates that have a **bvs** variable or a $FV(\text{return type}) \setminus FV(\text{argument types})$ variable as LHS. We apply the substitution **sb** (or **b_sb**) to the RHS of these equations (**b_sb** if the LHS is in **bvs**). We preserve the order of equations in the candidate list.

3.2 Joint constraint abduction

We further lose generality by using a heuristic search scheme instead of testing all combinations of simple abduction answers. In particular, our search scheme returns from joint abduction for types with a single answer, which eliminates deeper interaction between the sort of types and other sorts. Some amount of interaction is provided by the validation procedure, which checks for consistency of the partial answer, the premise and the conclusion of each branch, including consistency for other sorts.

We accumulate simple abduction answers into the partial abduction answer, we set aside branches that do not have any answer satisfiable with the partial answer so far. After all branches have been tried and the partial answer is not an empty conjunction (i.e. not \top), we retry the set-aside branches. If during the retry, any of the set-aside branches fails, we add the partial answer to discarded answers – which are avoided during simple abduction – and restart. If, when left with set-aside branches only, the partial answer is an empty conjunction, i.e. all the answer-contributing branches have been set aside, we fail – return \perp from the joint abduction. This does not perform complete backtracking (no completeness guarantee), but is therefore quicker to report unsolvable cases and does sufficient backtracking. After an answer working for all branches has been found, we perform additional check, which encapsulates negative constraints introduced by `assert false` construct. If the check fails, we add the answer to discarded answers and repeat the search.

We keep a count of conflicts for the runouts so that in case of overall failure, we can report a branch likely to be among those preventing abduction.

If a partial answer becomes as strong as one of the discarded answers inside SCA, simple constraint abduction skips to find a different answer. The discarded answers are initialized with a discard list passed from the main algorithm.

As described in [7], to check validity of answers, we use a modified variant of unification under quantifiers: unification with parameters, where the parameters do not interact with the quantifiers and thus can be freely used and eliminated. Note that to compute conjunction of the candidate answer with a premise, unification does not check for validity under quantifiers.

Because it would be difficult to track other sort constraints while updating the partial answer, we discard numeric sort constraints in simple abduction algorithm, and recover them after the final answer for terms (i.e. for the type sort) is found.

Searching for abduction answer can fail in only one way: we have set aside all the branches that could contribute to the answer. It is difficult to pin-point the culprit. We remember which branch caused the restart when the number of set-aside branches was the smallest. We raise exception `Suspect` that contains the conclusion of that branch.

The core algorithm shared across sorts is provided in the `Joint` module.

3.3 Abduction for terms with Alien Subterms

The JCAQPAS problem is more complex than simply substituting alien subterms with variables and performing joint constraint abduction on resulting implications. The ability to “outsource” constraints to the alien sorts enables more general answers to the target sort, in our case the term algebra $T(F)$. Term abduction will offer answers that cannot be extended to multisort answers.

One might mitigate the problem by preserving the joint abduction for terms algorithm, and after a solution $\exists \bar{\alpha}. A$ is found, “*dissociating*” the alien subterms (including variables) in A as follows. We replace every alien subterm n_s in A (including variables, even parameters) with a fresh variable α_s , which results in A' (in particular $A'[\bar{\alpha}_s := \bar{n}_s] = A$). Subsets $A_p^i \wedge A_c^i = A^i \subset \bar{\alpha}_s \bar{\alpha}_s$ such that $\exists \bar{\alpha}_s. A', A_p^i, A_c^i$ is a JCAQPAS answer will be recovered automatically by a residuum-finding process at the end of `ans_typ`. This process is needed regardless of the “dissociation” issue, to uncover the full content of numeric sort constraints.

To face efficiency of numerical abduction with many variables, we modify the approach. On the first iteration of the main algorithm, we remove alien subterms both from the branches and from the answer (the **purge** function), but we do not perform other-sort abduction at all. On the next iteration, we do not purge alien subterms, neither from the branches nor from the answer, as we expect the dissociation in the partial answers (to predicate variables) from the first step to be sufficient. Other-sort abduction algorithms now have less work, because only a fraction of alien subterm variables α_s remain in the partial answers (see main algorithm in section 5). They also have more information to work with, present in the instantiation of partial answers. However, this optimization violates completeness guarantees of the combination of sorts algorithm.

3.4 Simple constraint abduction for linear arithmetic

For checking validity or satisfiability, we use *Fourier-Motzkin elimination*. To avoid complexities we only handle the rational number domain. To extend the algorithm to integers, *Omega-test* procedure as presented in [1] needs to be adapted. The major operations are:

- *Elimination* of a variable takes an equation and selects a variable that is not upstream, i.e. to the left in Q regarding alternations, of any other variable of the equation, and substitutes-out this variable from the rest of the constraint. The solved form contains an equation for this variable.
- *Projection* of a variable takes a variable x that is not upstream of any other variable in the unsolved part of the constraint, and reduces all inequalities containing x to the form $x \leq a$ or $b \leq x$, depending on whether the coefficient of x is positive or negative. For each such pair of inequalities: if $b = a$, we add $x = a$ to implicit equalities; otherwise, we add the inequality $b \leq a$ to the unsolved part of the constraint.

We use elimination to solve all equations before we proceed to inequalities. The starting point of our algorithm is [1] section 4.2 *Online Fourier-Motzkin Elimination for Reals*. We add detection of implicit equalities, and more online treatment of equations, introducing known inequalities on eliminated variables to the projection process.

Our abduction algorithm follows a familiar incrementally-generate-and-test scheme as in term abduction. During the iteration, we build a lazy list of possible transformations with linear combinations involving atoms a that will not be part of the answer but are implied by $D \wedge C$.

Abduction algorithm:

1. Reduce $\hat{A}_i(D \wedge C \wedge A_i^{\leq})$ to solved form whose substitution part is C_0^- . Let $C_0^{\leq} = C_0^-(C^{\leq})$ and $D_0^{\leq} = C_0^-(D^{\leq})$.
 - C_0^- includes the implicit equalities of $A_i \wedge D \wedge C$.
2. Prepare the initial transformations from atoms in $\hat{A}_i(D)$.
 - a. For equations a , add combinations $k^s a + b$ for $k = -n \dots n, s = -1, 1$ to the stack of transformations to be tried for atoms $b \in C$.
 - b. For inequalities a , add combinations $k^s a + b$ for $k = 0 \dots n, s = -1, 1$ to the stack of transformations to be tried only for inequalities $b \in C$.
 - c. The final transformations have the form: $b \mapsto b + \sum_{a \in D} k_a^{s_a} a$.
3. Prepare a list of default-choice transformations C_6 of $C_0^- \wedge C_0^{\leq}$ (corresponding to choice 6 in term abduction) and let C_0 be the atoms in $C_0^- \wedge C_0^{\leq}$ reordered to match C_6 .
 - a. Replace $\alpha_1 := k_1 \beta + c_1, \dots, \alpha_n := k_n \beta + c_n$ with $\alpha_i := k_i \beta + c_i, \alpha_1 := \frac{k_1}{k_i} \alpha_i + \left(c_1 - \frac{k_1 c_i}{k_i}\right), \dots, \alpha_n := \frac{k_n}{k_i} \alpha_i + \left(c_n - \frac{k_n c_i}{k_i}\right)$ (excluding $\alpha_i := \alpha_i$) where α_i is the most upstream existential variable and β is a universal variable, and propagate the substitution $\beta := \frac{1}{k_i} \alpha_i + \frac{-c_i}{k_i}$.
 - b. Replace $\alpha_1 := c, \dots, \alpha_n := c$ with $\alpha_i := c, \alpha_1 := \alpha_i, \dots, \alpha_n := \alpha_i$ (excluding $\alpha_i := \alpha_i$) where α_i is the most upstream existential variable and c is a constant.
4. Start from $\text{Acc} := \{\}$. Try atoms $C_0 = a C_0'$ and $C_6 = a_6 C_6'$ in some order.
5. Let $B = A_i \wedge D \wedge C_0' \wedge \text{Acc}$.

6. If a is a tautology ($0 \doteq 0$ or $c \leq 0$ for $c \leq 0$) or $B \Rightarrow C$, repeat with $C_0 := C'_0$, $C_6 := C'_6$. Corresponds to choice 1 of term abduction.
7. If $B \not\Rightarrow C$, for a transformation a' of a , starting with a_6 , which passes validation against other branches in a joint problem: $\text{Acc} := \text{Acc} \cup \{a'\}$, or fail if all a' fail. Choice point, corresponding to choice 6 of term abduction if a_6 is selected, choice 4 if identity transformation is selected, choice 5 if a later transformation is selected.
 - a. Let a' be a with some transformations applied.
 - b. If $A_i \wedge (\text{Acc} \cup \{a'\})$ does not pass **validate** for all a' , fail.
 - c. Optionally, if $A_i \wedge (\text{Acc} \cup \{a'\})$ passes **validate** for inequality a , add a' to transformations as in step (6).
 - d. If $A_i \wedge (\text{Acc} \cup \{a'\})$ passes **validate**, repeat with $C_0 := C'_0$, $C_6 := C'_6$, $\text{Acc} := \text{Acc} \cup \{a'\}$.
8. The answers are $A_{i+1} = A_i \wedge \text{Acc}$.

Note that if an equation $a \in \text{Acc}$, linear combinations with it $a + b \wedge \text{Acc}$ would remain equivalent to original $b \wedge \text{Acc}$. For inequalities $a \in \text{Acc}$, combinations $a + b \wedge \text{Acc}$ are weaker than $b \wedge \text{Acc}$, thus the optional step (7c). We precompute the transformation variants to try out. The parameter n is called **abd_rotations** and defaults to a small value (2 or 3). It would be beneficial to eliminate constants, universal variables, and rightmost remaining variables from candidate atoms, as we do in term abduction. We generate such preferred candidates, in steps (1) and (3). Surprisingly, it is required to get tighter, i.e. stronger, postconditions.

To check whether $B \Rightarrow C$, we check for each $c \in C$:

- if $c = x \doteq y$, that $A(x) = A(y)$, where $A(\cdot)$ is the substitution corresponding to equations and implicit equalities in A ;
- if $c = x \dot{\leq} y$, that $B \wedge y \dot{<} x$ is not satisfiable.

We use the **nums** library for exact precision rationals.

Our algorithm finds only fully maximal answers. Unfortunately this means that for many invariant inference problems, some implication branches in initial steps of the main algorithm are insolvable. That is, when the instantiations of the invariants found so far are not informative enough, the expected answer of the JCA problem is not a fully maximal SCA answer to these branches. We mitigate this problem by removing, in the first call to numerical abduction (the second iteration of the main algorithm), branches that contain unary predicate variables in the conclusion, i.e. we only use the “non-recursive” branches.

4 Disjunction Elimination

Disjunction elimination answers are the maximally specific conjunctions of atoms that are implied by each of a given set of conjunction of atoms. In case of term equations the disjunction elimination algorithm is based on the *anti-unification* algorithm. In case of linear arithmetic inequalities, disjunction elimination is exactly finding the convex hull of a set of possibly unbounded polyhedra. We roughly follow [5], but depart from the algorithm presented there because we employ our unification algorithm to separate sorts. Since as a result we do not introduce variables for *alien subterms*, we include the variables introduced by anti-unification in constraints sent to disjunction elimination for their respective sorts.

The adjusted algorithm looks as follows:

1. Let $\wedge_s D_{i,s} \equiv U(D_i)$ where $D_{i,s}$ is of sort s , be the result of our sort-separating unification.
2. For the sort s_{ty} :
 - a. Let $V = \{x_j, \overline{t_{i,j}} \mid \forall i \exists t_{i,j}. x_j \doteq t_{i,j} \in D_{i,s_{ty}}\}$.
 - b. Let $G = \{\bar{\alpha}_j, u_j, \overline{\theta_{i,j}} \mid \theta_{i,j} = [\bar{\alpha}_j := \bar{g}_j], \theta_{i,j}(u_j) = t_{i,j}\}$ be the most specific anti-unifiers of $\overline{t_{i,j}}$ for each j .
 - c. Let $D_i^u = \wedge_j \bar{\alpha}_j \doteq \bar{g}_j^i$ and $D_i^g = D_{i,s_{ty}} \wedge D_i^u$.

- d. Let $D_i^v = \{x \dot{=} y \mid x \dot{=} t_1 \in D_i^g, y \dot{=} t_2 \in D_i^g, D_i^g \models t_1 \dot{=} t_2\}$.
- e. Let $A_{s_{ty}} = \bigwedge_j x_j \dot{=} u_j \wedge \bigcap_i (D_i^g \wedge D_i^v)$ (where conjunctions are treated as sets of conjuncts and equations are ordered so that only one of $a \dot{=} b, b \dot{=} a$ appears anywhere), and $\bar{\alpha}_{s_{ty}} = \bar{\alpha}_j$.
- f. Let $\bigwedge_s D_{i,s}^u \equiv D_i^u$ for $D_{i,s}^u$ of sort s .
- 3. For sorts $s \neq s_{ty}$, let $\exists \bar{\alpha}_s. A_s = \text{DisjElim}_s(\bar{D}_i^s \wedge \bar{D}_{i,s}^u)$.
- 4. The answer is $\exists \bar{\alpha}_i^j \bar{\alpha}_s. \bigwedge_s A_s$.

We simplify the result by substituting-out redundant answer variables.

We follow the anti-unification algorithm provided in [9], fig. 2.

4.1 Extended convex hull

[2] provides a polynomial-time algorithm to find the half-space represented convex hull of closed polytopes. It can be generalized to unbounded polytopes – conjunctions of linear inequalities. Our implementation is inspired by this algorithm but very much simpler, at cost of losing the maximality requirement.

First we find among the given inequalities those which are also the faces of resulting convex hull. The negation of such inequality is not satisfiable in conjunction with any of the polytopes – any of the given sets of inequalities. Next we iterate over *ridges* touching the selected faces: pairs of the selected face and another face from the same polytope. We rotate one face towards the other: we compute a convex combination of the two faces of a ridge. We add to the result those half-spaces whose complements lie outside of the convex hull (i.e. negation of the inequality is unsatisfiable in conjunction with every polytope). For a given ridge, we add at most one face, the one which is farthest away from the already selected face, i.e. the coefficient of the selected face in the convex combination is smallest. We check a small number of rotations, where the algorithm from [2] would solve a linear programming problem to find the rotation which exactly touches another one of the polytopes.

When all variables of an equation $a \dot{=} b$ appear in all branches D_i , we can turn the equation $a \dot{=} b$ into pair of inequalities $a \leq b \wedge b \leq a$. We eliminate all equations and implicit equalities which contain a variable not shared by all D_i , by substituting out such variables. We pass the resulting inequalities to the convex hull algorithm.

4.2 Issues in inferring postconditions

Although finding recursive function invariants – predicate variables solved by abduction – could theoretically fail to converge for both the type sort and the numerical sort constraints, neither problem was observed. Finding existential type constraints can only fail to converge for numerical sort, because solutions are expected to decrease in strength. But such diverging numerical constraints are commonplace. The main algorithm starts by performing disjunction elimination only on implication branches corresponding to non-recursive cases, i.e. without binary predicate variables in premise (or unary predicate variables in conclusion). This generates a stronger constraint than the correct one. Subsequent iterations include all branches in disjunction elimination, weakening the constraints, and so still weaker constraints are fed to disjunction elimination in each following step. To ensure convergence of the numerical part, starting from some step of the main loop, we compare consecutive solutions and extrapolate the trend. Currently we simply intersect the sets of atoms, but first we expand equations into pairs of inequalities.

Disjunction elimination limited to non-recursive branches, the initial iteration of postcondition inference, will often generate constraints that contradict other branches. For another iteration to go through, the partial solutions need to be consistent. Therefore we filter the constraints using the same validation mechanism as in abduction. We add atoms to a constraint greedily, but to favor relevant atoms, we do the filtering while computing the connected component of disjunction elimination result. See the details of the main algorithm in section 5.3.

While reading section 5.3, you will notice that postconditions are not subjected to stratification. This is because the type system does not support nested existential types.

4.3 Abductive disjunction elimination under quantifier prefix

We extend the notion of disjunction elimination: $\exists \bar{\alpha}.A$ is an answer to *abductive disjunction elimination under quantifier prefix* problem $\mathcal{Q}.D_i$ when there exist $\exists \bar{\beta}_{i,j}.B_{i,j}$ and U_i such that:

1. $\models (\exists \bar{\beta}_{i,j}.D_i \wedge_j B_{i,j}) \Leftrightarrow (D_i \wedge U_i)$;
2. $(\forall i) \models D_i \wedge U_i \Rightarrow \exists \bar{\alpha} \setminus \text{FV}(U_i).A$;
3. $(\forall i, j) \models D_j \Rightarrow \exists \bar{\beta}_{i,j}.B_{i,j}$;
4. $\models \forall \bar{\beta}_{i,j} \mathcal{Q} \wedge_{i,j} B_{i,j}$ and $\models \mathcal{Q} \wedge_i U_i$.

We currently do not pursue a complete algorithm for abductive disjunction elimination. Rather, we extend our algorithms in a natural way, that satisfies the requirements of abductive disjunction elimination and suffices in practice. The sort-integrating algorithm essentially does not change:

1. Let $\wedge_s D_{i,s} \equiv U(D_i)$ where $D_{i,s}$ is of sort s , be the result of our sort-separating unification.
2. For the sort s_{ty} :
 - a. Let $V = \{x_j, \bar{t}_{i,j} \mid \forall i \exists t_{i,j}.x_j \doteq t_{i,j} \in D_{i,s_{\text{ty}}}\}$.
 - b. Let $G = \{\bar{\alpha}_j, g_j, \bar{u}_i, \bar{\theta}_{i,j} \mid \theta_{i,j} = [\bar{\alpha}_j := \bar{g}_j^i], \theta_{i,j}(g_j) = u_i(t_{i,j})\}$ be the most specific anti-unifiers of $u_i(t_{i,j})$ for each j , where u_i is a part of U_i .
 - c. Let $D_i^u = \wedge_j \bar{\alpha}_j \doteq \bar{g}_j^i$ and $D_i^g = D_{i,s_{\text{ty}}} \wedge D_i^u$.
 - d. Let $D_i^v = \{x \doteq y \mid x \doteq t_1 \in D_i^g, y \doteq t_2 \in D_i^g, D_i^g \models t_1 \doteq t_2\}$.
 - e. Let $A_{s_{\text{ty}}} = \wedge_j x_j \doteq u_j \wedge \bigcap_i (D_i^g \wedge D_i^v)$ (where conjunctions are treated as sets of conjuncts and equations are ordered so that only one of $a \doteq b, b \doteq a$ appears anywhere), and $\bar{\alpha}_{s_{\text{ty}}} = \bar{\alpha}_j$.
 - f. Let $\wedge_s D_{i,s}^u \equiv D_i^u$ for $D_{i,s}^u$ of sort s .
3. For sorts $s \neq s_{\text{ty}}$, let $\exists \bar{\alpha}_s.A_s = \text{DisjElim}_s(\overline{D_i^s \wedge D_{i,s}^u})$.
4. The answer is $\exists \bar{\alpha}_i^j \bar{\alpha}_s \wedge_s A_s$.

Our current generalized anti-unification algorithm:

$$\begin{aligned}
\text{au}_{U,G}(t; \dots; t) &= \emptyset, t, U, G \\
\text{au}_{U,G}(f(\bar{t}^1); \dots; f(\bar{t}^n)) &= \bar{\alpha}, f(\bar{g}), U', G' \\
\text{where } \bar{\alpha}, \bar{g}, U', G' &= \text{aun}_{U,G}(\bar{t}^1; \dots; \bar{t}^n) \\
\text{au}_{U,G}(t_1; \dots; t_n) &= \emptyset, \alpha, U, G \\
\text{when } ([t_1; \dots; t_n] \mapsto \alpha) &\in G \\
\text{au}_{U,G}(\dots; \beta_i; \dots; f(\bar{t}^j); \dots) &= \bar{\alpha}\bar{\alpha}', g, U'', G' \\
\text{where } \bar{\alpha}', g, U'', G' &= \text{au}_{U',G}(\dots; f(\bar{\alpha}); \dots; f(\bar{t}^j)[\beta_i := f(\bar{\alpha})]; \dots) \\
U' &= U[\beta_i := f(\bar{\alpha})] \wedge \beta_i \doteq f(\bar{\alpha}) \\
\text{when } \exists \beta_i \in \mathcal{Q}, \text{ treat } \bar{\alpha} &\text{ as quantified with } \exists \beta_i \\
\text{au}_{U,G}(\dots; \beta_i; \dots; \beta_j; \dots) &= \bar{\alpha}', g, U'', G' \\
\text{where } \bar{\alpha}', g, U'', G' &= \text{au}_{U',G}(\dots; \beta_j; \dots; \beta_j; \dots) \\
U' &= U[\beta_i := \beta_j] \wedge \beta_i \doteq \beta_j \\
\text{when } \exists \beta_i \in \mathcal{Q}, \beta_j &\leq_{\mathcal{Q}} \beta_i \\
\text{au}_{U,G}(t_1; \dots; t_n) &= \alpha, \alpha, U, ([t_1; \dots; t_n] \mapsto \alpha)G \\
\text{otherwise, where } \alpha \# \text{FV}(t_1; \dots; t_n, U, G) & \\
\text{aun}_{U,G}(\emptyset) &= \emptyset, \emptyset, U, G \\
\text{aun}_{U,G}(\emptyset; \dots) &= \emptyset, \emptyset, U, G \\
\text{aun}_{U,G}(t_1^1, \bar{t}^1; \dots; t_1^n, \bar{t}^n) &= \bar{\alpha}\bar{\alpha}', g\bar{g}', U'', G'' \\
\text{where } \bar{\alpha}, g, U', G' &= \text{au}_{U,G}(t_1^1; \dots; t_1^n) \\
\text{and } \bar{\alpha}', \bar{g}', U'', G'' &= \text{aun}_{U',G'}(\bar{t}^1; \dots; \bar{t}^n)
\end{aligned}$$

The notational shorthand $\dots; \beta_i; \dots; f(\bar{t}^j); \dots$ represents the case where all terms are either existential variables or start with a function symbol f . Similarly, $\dots; \beta_i; \dots; \beta_j; \dots$ represents the case when there is a variable β_j such that all terms are either β_j or are existential variables to the right of β_j in the quantifier.

Due to greater flexibility of the numerical domain, abductive extension of numerical disjunction elimination it does not seem necessary.

5 Solving for Predicate Variables

As we decided to provide the first solution to abduction problems, we similarly simplify the task of solving for predicate variables. Instead of a tree of solutions being refined, we have a single sequence which we unfold until reaching fixpoint or contradiction. Another choice point besides abduction in the original algorithm is the selection of invariants that leaves a consistent subset of atoms as residuum. Here we also select the first solution found. We introduce a form of backtracking, described in section 5.5.

5.1 Invariant Parameter Candidates

We start from the variables β_χ that participate in negative occurrences of predicate variables: $\chi(\beta_\chi)$ or $\chi(\beta_\chi, \alpha)$. We select sets of variables $\beta_\chi \bar{\zeta}^\chi$, the *parameter candidates*, by considering all atoms of the generated constraints. $\bar{\zeta}^\chi$ are existential variables that: are connected with β_χ in the hypergraph whose nodes are variables and hyperedges are atoms of the constraints, and are not connected with $\beta_{\chi'}$ for any $\beta_{\chi'}$ that is within scope of β_χ . If $\text{FV}(c) \cap \beta_\chi \bar{\zeta}^\chi \neq \emptyset$ for an atom c , and β_χ is not in the scope of $\beta_{\chi'}$ for which $\text{FV}(c) \cap \beta_{\chi'} \bar{\zeta}^{\chi'} \neq \emptyset$, then c is a candidate for atoms of the solution of χ .

5.2 Solving for Predicates in Negative Positions

The core of our inference algorithm consists of distributing atoms of an abduction answer among the predicate variables. The negative occurrences of predicate variables, when instantiated with the updated solution, enrich the premises so that the next round of abduction leads to a smaller answer (in number of atoms).

Let us discuss the algorithm from [6] for $\text{Split}(\mathcal{Q}, \bar{\alpha}, A, \bar{\beta}^\chi, \bar{\zeta}, \bar{\rho}^\chi, \bar{A}_\chi^0)$. Note that due to existential types predicates, we actually compute $\text{Split}(\mathcal{Q}, \bar{\alpha}, A, \bar{\beta}^{\beta_\chi}, \bar{\zeta}, \bar{\rho}^{\beta_\chi}, \bar{A}_{\beta_\chi}^0)$, i.e. we index by β_χ (which can be multiple for a single χ) rather than χ . We retain the notation from [6] here as it better conveys the intent. We do not pass quantifiers around to reflect the source code: the helper function `loop avs ans sol` of function `split` corresponds to $\text{Split}(\bar{\alpha}, A, \bar{A}_{\beta_\chi}^0)$.

$$\begin{aligned}
\alpha < \beta &\equiv \alpha <_{\mathcal{Q}} \beta \vee (\alpha \leq_{\mathcal{Q}} \beta \wedge \beta \not<_{\mathcal{Q}} \alpha \wedge \alpha \in \bar{\beta}^\chi \wedge \beta \notin \bar{\beta}^\chi) \\
A_0 &= A \setminus \{ \beta \doteq \alpha \in A \mid \beta \in \bar{\beta}^\chi \wedge (\exists \alpha) \in \mathcal{Q} \wedge \beta < \alpha \} \\
A_\chi^1 &= \text{Connected}(\bar{\beta}^\chi, A_0) \\
A_\chi^2 &= \{ c \in A_\chi^1 \mid c \text{ is not localized in branch without } \chi \text{ in premise} \} \\
A_\chi^3 &= A_\chi^2 \setminus \cup_{\chi' >_{\mathcal{Q}} \chi} A_{\chi'}^2 \\
A_\chi^4 &= \text{Connected}_{\text{undir}}(\text{FV}(A_\chi^3) \cap \bar{\zeta}, A_0) \\
&\text{if } \not\models \forall \bar{\alpha} \mathcal{Q}. A \setminus A_\chi^4 \\
&\text{then return } \perp \\
&\text{for all } \bar{A}_\chi^+ \text{ min. w.r.t. } \subset \text{ s.t. } \wedge_\chi (A_\chi^+ \subset A_\chi^4) \wedge \models \forall \bar{\alpha} \mathcal{Q}. A \setminus \cup_\chi A_\chi^+ : \\
&\quad \text{if } \text{Strat}(\text{Connected}(\bar{\beta}^\chi, A_\chi^+), \bar{\beta}^\chi) \text{ returns } \perp \text{ for some } \chi \\
&\text{then return } \perp
\end{aligned}$$

$$\begin{aligned}
& \text{else } \bar{\alpha}_+^\chi, A_\chi^L, A_\chi^R = \text{Strat}(\text{Connected}(\bar{\beta}^\chi, A_\chi^+), \bar{\beta}^\chi) \\
& \quad A_\chi = A_\chi^0 \cup A_\chi^L \\
& \quad \bar{\alpha}_0^\chi = \bar{\alpha} \cap \text{FV}(A_\chi) \\
& \quad \bar{\alpha}^\chi = \left(\bar{\alpha}_0^\chi \setminus \bigcup_{\chi' <_{\mathcal{Q}} \chi} \bar{\alpha}_0^{\chi'} \right) \bar{\alpha}_+^\chi \\
& \quad A_+ = \bigcup_\chi A_\chi^R \\
& \quad A_{\text{res}} = A_+ \cup \hat{A}_+(A \setminus \bigcup_\chi A_\chi^+) \\
& \quad \text{if } \bigcup_\chi \bar{\alpha}_+^\chi \neq \emptyset \text{ then} \\
& \quad \mathcal{Q}', \bar{\alpha}_+^{\chi'}, A'_{\text{res}}, \exists \bar{\alpha}^{\chi'}. A'_\chi \in \text{Split}(\mathcal{Q}[\forall \bar{\beta}^\chi := \overline{\forall(\bar{\beta}^\chi \cup \bar{\alpha}^\chi)}], \bar{\alpha} \setminus \bigcup_\chi \bar{\alpha}^\chi, A_{\text{res}}, \overline{\bar{\beta}^\chi \cup \bar{\alpha}^\chi}, \bar{A}_\chi) \\
& \quad \text{return } \mathcal{Q}', \bar{\alpha}_+^{\chi'} \bar{\alpha}_+^{\chi'}, A'_{\text{res}}, \exists \bar{\alpha}^{\chi'} \bar{\alpha}^{\chi'}. A'_\chi \\
& \quad \text{else return } \forall(\bar{\alpha} \setminus \bigcup_\chi \bar{\alpha}^\chi) \mathcal{Q}, \bar{\alpha}_+^\chi, A_{\text{res}}, \exists \bar{\alpha}^\chi. A_\chi
\end{aligned}$$

where $\text{Strat}(A, \bar{\beta}^\chi)$ is computed as follows: for every $c \in A$, and for every $\beta_2 \in \text{FV}(c)$ such that $\beta_1 <_{\mathcal{Q}} \beta_2$ for $\beta_1 \in \bar{\beta}^\chi$, if β_2 is universally quantified in \mathcal{Q} , then return \perp ; otherwise, introduce a fresh variable α_f , replace $c := c[\beta_2 := \alpha_f]$, add $\beta_2 \doteq \alpha_f$ to A_χ^R and α_f to $\bar{\alpha}_+^\chi$, after replacing all such β_2 add the resulting c to A_χ^L .

As an additional measure to detect misleading splits early, we pass an approximate information about which branch D_i , C_i of the JCA problem atoms $a \in A$ originate from: $\rho(a)$, and which branches contain χ in premise: ρ^χ , so that an atom a is put into solution A_χ^+ only if D_i contains χ .

Description of the algorithm in more detail: FIXME

1. $\alpha \prec \beta \equiv \alpha <_{\mathcal{Q}} \beta \vee (\alpha \leq_{\mathcal{Q}} \beta \wedge \beta \not\prec_{\mathcal{Q}} \alpha \wedge \alpha \in \bar{\beta}^\chi \wedge \beta \notin \bar{\beta}^\chi)$ The variables $\bar{\beta}^\chi$ are the answer variables of the solution from the previous round. We need to keep them apart from other variables even when they're not separated by quantifier alternation.
2. $A_0 = A \setminus \{\beta \doteq \alpha \in A \mid \beta \in \bar{\beta}^\chi \wedge (\exists \alpha) \in \mathcal{Q} \wedge \beta \prec \alpha\}$ We handle information carried in $\beta \doteq \alpha$ by substituting α with β .
3. $A_\chi^1 = \text{Connected}(\bar{\beta}^\chi, A_0)$ Initial, tight filtering of candidates. $\text{Connected}(\bar{\beta}, A_0)$ is the subset of atoms-edges of A_0 reachable from nodes $\bar{\beta}$, where variables are considered directly connected when they co-occur in an atom. The edges incident to term variables are directed, for solved form atom in term domain, $\alpha := t$ means that α is connected with each of $\text{FV}(t)$, but not vice-versa.
4. $A_\chi^2 = \{c \in A_\chi^1 \mid c \text{ is not localized in branch without } \chi \text{ in premise}\}$ Guard against misplacing abduction answer atoms. Unfortunately localization information can be too general for this step alone to be sufficient at splitting the answer.
5. $A_\chi^3 = A_\chi^2 \setminus \bigcup_{\chi' >_{\mathcal{Q}} \chi} A_\chi^2$ If a premise has an χ' atom then it has an χ atom for $\beta^{\chi'}$ downstream of b^χ .
6. $A_\chi^4 = \text{Connected}_{\text{undir}}(\text{FV}(A_\chi^3) \cap \bar{\zeta}, A_0)$ Recompute the connected component to gather atoms with subterms of terms in A_χ^1 , which should not remain in the residuum. $\text{Connected}_{\text{undir}}(\bar{\zeta}, A_0)$ finds atoms-edges of A_0 connected to $\bar{\zeta}$ without treating term atoms as directed edges.
7. if $\not\models \forall \bar{\alpha} \mathcal{Q}. A \setminus \bigcup_\chi A_\chi^4$ then return \perp Failed solution attempt. A common example is when the use site of recursive definition, resp. the existential type introduction site, is not in scope of a defining site of recursive definition, resp. an existential type elimination site, and has too strong requirements.
8. for all \bar{A}_χ^+ minimal w.r.t. \subset such that $\bigwedge_\chi (A_\chi^+ \subset A_\chi^4) \wedge \models \mathcal{Q}. A \setminus \bigcup_\chi A_\chi^+$: Select invariants such that the residuum $A \setminus \bigcup_\chi A_\chi^+$ is consistent. The final residuum A_{res} represents the global constraints, the solution for global type variables. The solutions A_χ^+ represent the invariants, the solution for invariant type parameters.

9. if $\text{Strat}(\text{Connected}(\bar{\beta}^\chi, A_\chi^+), \bar{\beta}^\chi)$ returns \perp for some χ then return \perp In the implementation, we address stratification issues already during abduction.
10. $\bar{\alpha}_+^\chi, A_\chi^L, A_\chi^R = \text{Strat}(\text{Connected}(\bar{\beta}^\chi, A_\chi^+), \bar{\beta}^\chi)$ is computed as follows: for every $c \in \text{Connected}(\bar{\beta}^\chi, A_\chi^+)$, and for every $\beta_2 \in \text{FV}(c)$ such that $\beta_1 <_{\mathcal{Q}} \beta_2$ for $\beta_1 \in \bar{\beta}^\chi$, if β_2 is universally quantified in \mathcal{Q} , then return \perp ; otherwise, introduce a fresh variable α_f , replace $c := c[\beta_2 := \alpha_f]$, add $\beta_2 \doteq \alpha_f$ to A_χ^R and α_f to $\bar{\alpha}_+^\chi$, after replacing all such β_2 add the resulting c to A_χ^L .
 - We drop atoms not connected to the answer we seek. This appears to break correctness as some atoms might be not accounted for: neither lifted to the premise, nor kept in the residuum. The theoretical goal is to show that the dropped atoms are implied by the lifted atoms together with the premises – a fix to the algorithm might be needed.
 - We add $\bar{\alpha}_+^\chi$ to $\bar{\beta}^\chi$.
11. $A_\chi = A_\chi^0 \cup A_\chi^L$ is the updated solution formula for χ , where A_χ^0 is the solution from previous round.
12. $\bar{\alpha}_0^\chi = \bar{\alpha} \cap \text{FV}(A_\chi)$ are the additional solution parameters coming from variables generated by abduction.
13. $\bar{\alpha}^\chi = (\bar{\alpha}_0^\chi \setminus \bigcup_{\chi' <_{\mathcal{Q}} \chi} \bar{\alpha}_0^{\chi'}) \bar{\alpha}_+^\chi$ The final solution parameters also include the variables generated by Strat.
14. $A_+ = \bigcup_\chi A_\chi^R$ and $A_{\text{res}} = A_+ \cup \tilde{A}_+(A \setminus \bigcup_\chi A_\chi^+)$ is the resulting global constraint, where \tilde{A}_+ is the substitution corresponding to A_+ .
15. if $\bigcup_\chi \bar{\alpha}_+^\chi \neq \emptyset$ then – If Strat generated new variables, we need to redistribute the $\tilde{A}_+(A \setminus \bigcup_\chi A_\chi^+)$ atoms to make $\mathcal{Q}'.A_{\text{res}}$ valid again.
16. $\mathcal{Q}', \bar{\alpha}_+^{\chi'}, A_{\text{res}}, \overline{\bar{\alpha}^{\chi'}.A_\chi^R} \in \text{Split}(\mathcal{Q}[\forall \bar{\beta}^\chi := \overline{\bar{\beta}^\chi \cup \bar{\alpha}^\chi}], \bar{\alpha} \setminus \bigcup_\chi \bar{\alpha}^\chi, A_{\text{res}}, \bar{\beta}^\chi \cup \bar{\alpha}^\chi, \bar{A}_\chi)$
Recursive call includes $\bar{\alpha}_+^{\chi'}$ in $\bar{\beta}^\chi$ so that, among other things, A_+ are redistributed into A_χ .
17. return $\mathcal{Q}', \bar{\alpha}_+^{\chi'} \bar{\alpha}_+^{\chi'}, A_{\text{res}}, \overline{\bar{\alpha}^{\chi'} \bar{\alpha}_+^{\chi'}.A_\chi^R}$ We do not add $\forall \bar{\alpha}$ in front of \mathcal{Q}' because it already includes these variables. $\bar{\alpha}_+^{\chi'} \bar{\alpha}_+^{\chi'}$ lists all variables introduced by Strat.
18. else return $\forall(\bar{\alpha} \setminus \bigcup_\chi \bar{\alpha}^\chi) \mathcal{Q}, \bar{\alpha}_+^{\chi'}, A_{\text{res}}, \overline{\bar{\alpha}^{\chi'}.A_\chi^R}$ Note that $\bar{\alpha} \setminus \bigcup_\chi \bar{\alpha}^\chi$ does not contain the current $\bar{\beta}^\chi$, because $\bar{\alpha}$ does not contain it initially and the recursive call maintains that: $\bar{\alpha} := \bar{\alpha} \setminus \bigcup_\chi \bar{\alpha}^\chi, \bar{\beta}^\chi := \bar{\beta}^\chi \bar{\alpha}^\chi$.

Finally we define $\text{Split}(\bar{\alpha}, A) := \text{Split}(\bar{\alpha}, A, \bar{\top})$. The complete algorithm for solving predicate variables is presented in the next section.

5.3 Solving for Existential Types Predicates and Main Algorithm

The general scheme is that we perform disjunction elimination on branches with positive occurrences of existential type predicate variables on each round. Since the branches are substituted with the solution from previous round, disjunction elimination will automatically preserve monotonicity. We retain existential types predicate variables in the later abduction step.

What differentiates existential type predicate variables from recursive definition predicate variables is that the former are not local to context in our implementation, we ignore the **CstrIntro** rule, while the latter are treated as local to context in the implementation. It means that free variables need to be bound in the former while they are retained in the latter.

In the algorithm we operate on all predicate variables, and perform additional operations on existential type predicate variables; there are no operations pertaining only to recursive definition predicate variables. The equation numbers (N) below are matched by comment numbers ($* N *$) in the source code. Step k of the loop of the final algorithm:

$$\begin{aligned} \overline{\exists \bar{\beta}^{\chi, k}. F_\chi} &= S_k \\ \text{Prune}(A) &= A \setminus \overline{\alpha_K^K \doteq \dots} \end{aligned} \quad (1)$$

$$\begin{aligned} S'_k = \overline{\exists \bar{\beta}^{\chi, k}. F'_\chi} &= \overline{\exists \bar{\beta}^{\chi, k}. \text{Prune}(F_\chi)} \\ D_K^\alpha \Rightarrow C_K^\alpha \in R_k^- S'_k(\Phi) &= \text{all such that } \chi_K(\alpha, \alpha_K^K) \in C_K^\alpha, \\ \overline{C_j^\alpha} &= \{C \mid D \Rightarrow C \in S_k(\Phi) \wedge D \subseteq D_K^\alpha\} \end{aligned} \quad (2)$$

$$\exists \bar{\alpha}_g^{\chi_K}. G_{\chi_K} = \text{Connected}_0 \left(\delta, \text{DisjElim} \left(\overline{\delta \doteq \alpha \wedge D_K^\alpha \wedge_j C_j^\alpha}_{\alpha \in \overline{\alpha_3^{i, K}}} \right) \right) \quad (3)$$

$$\exists \bar{\alpha}^{\chi_K}. G'_{\chi_K} = \text{Simpl}(\text{FV}(G_{\chi_K}). G_{\chi_K}) \quad (4)$$

$$\vec{\tau}_{\varepsilon_K} = \overline{\text{FV}(G'_{\chi_K}) \setminus \delta \delta' \bar{\alpha}_g^{\chi_K}}$$

$$\begin{aligned} \Xi(\exists \bar{\alpha}_g^{\chi_K}. G_{\chi_K}) &= \exists \bar{\alpha}^{\chi_K}. \delta' \doteq \vec{\tau}_{\varepsilon_K} \wedge G'_{\chi_K} \\ R_g(\chi_K) = \exists \bar{\alpha}^{\chi_K}. F_{\chi_K} &= H(R_k(\chi_K), \Xi(\exists \bar{\alpha}_g^{\chi_K}. G_{\chi_K})) \end{aligned} \quad (5)$$

$$P_g(\chi_K) = \delta' \doteq \vec{\tau}_{\varepsilon_K} \wedge \exists \bar{\alpha}_g^{\chi_K}. F_{\chi_K}$$

$$P_g(v_K(\beta)) = \exists \bar{\alpha}. \beta \doteq \bar{\alpha} \text{ where } |\vec{\tau}_{\varepsilon_K}| = |\bar{\alpha}|$$

$$F''_\chi = F'_\chi[\varepsilon_K(\cdot) := \varepsilon_K(\vec{\tau}_{\varepsilon_K})]$$

$$S''_k = \overline{\exists \bar{\beta}^{\chi, k} \{ \alpha \in \text{FV}(F''_\chi) \mid \beta_\chi <_{\mathcal{Q}} \alpha \}. F''_\chi} \quad (6)$$

$$\mathcal{Q}'. \wedge_i (D_i \Rightarrow C_i) = R_g^- P_g^+ S''_k(\Phi)$$

$$\text{At later iterations, check negative constraints.} \quad (7)$$

$$\exists \bar{\alpha}. A = \text{Abd}(\mathcal{Q}' \setminus \overline{\forall \beta_\chi \bar{\beta}^{\chi}}, \bar{\beta} = \overline{\beta_\chi \bar{\beta}^{\chi}}, \overline{D_i}, \overline{C_i}) \quad (8)$$

$$(\mathcal{Q}^{k+1}, \overline{\alpha_+^{\chi}}, A_{\text{res}}, \overline{\exists \bar{\alpha}^{\beta_\chi}. A_{\beta_\chi}}) = \text{Split}(\mathcal{Q}', \bar{\alpha}, A, \overline{\beta_\chi \bar{\beta}^{\chi}}, \overline{\zeta^{\chi}})$$

$$\vec{\tau}'_{\varepsilon_K} = \overline{\text{FV}(A_{\text{res}}(\vec{\tau}_{\varepsilon_K}))}$$

$$\begin{aligned} R_{k+1}(\chi_K) &= \exists \bar{\beta}^{\chi_K, k}. \delta' \doteq \vec{\tau}'_{\varepsilon_K} \wedge \text{Simpl} \left(\exists \bar{\alpha}^{\chi_K} \overline{\bar{\alpha}^{\beta_{\chi_K}}} . A_{\text{res}}(F_{\chi_K} \setminus \delta' \doteq \dots) \right. \\ &\quad \left. \wedge_{\chi_K} A_{\beta_{\chi_K}} \left[\overline{\beta_{\chi_K} \bar{\beta}^{\beta_{\chi_K}}} := \overline{\delta \bar{\beta}^{\chi_K, k}} \right] \right) \end{aligned} \quad (9)$$

$$= R'_g(\chi_K)$$

$$\begin{aligned} S_{k+1}(\chi) &= \exists \bar{\beta}^{\chi, k}. \text{Simpl}(\overline{\exists \bar{\alpha}^{\beta_\chi}. F''_\chi} \\ &\quad \wedge A_{\beta_\chi} \left[\overline{\beta_\chi \bar{\beta}^{\chi}} := \overline{\delta \bar{\beta}^{\chi, k}} \right]) \end{aligned} \quad (10)$$

$$\text{if } (\forall \chi) S_{k+1}(\chi) \subseteq S_k(\chi), \quad (11)$$

$$(\forall \chi_K) R_{k+1}(\chi_K) = R_k(\chi_K),$$

$$k > 1$$

$$\text{then return } A_{\text{res}}, S_{k+1}, R_{k+1}$$

$$\text{repeat } k := k + 1 \quad (12)$$

The initial candidates for parameters of invariants are the already known parameters of invariants – more candidates are added during abduction. Note that Split returns $\overline{\exists \bar{\alpha}^{\beta_\chi}. A_{\beta_\chi}}$ rather than $\overline{\exists \bar{\alpha}^{\chi}. A_\chi}$. This is because in case of existential type predicate variables χ_K , there can be multiple negative position occurrences $\chi_K(\beta_{\chi_K}, \cdot)$ with different β_{χ_K} when the corresponding value is used in multiple **let ... in** expressions. The variant of the algorithm to achieve completeness as conjectured in [6] would compute all answers for variants of Abd and Split algorithms that return multiple answers. Unary predicate variables $\chi(\beta_\chi)$ can also have multiple negative occurrences in the normalized form, but always with the same argument β_χ . The substitution $\left[\overline{\beta_{\chi_K} \bar{\beta}^{\beta_{\chi_K}}} := \overline{\delta \bar{\beta}^{\chi_K, k}} \right]$ replaces the instance parameters introduced in $\chi_K(\beta_{\chi_K}, \cdot)$ by the formal parameters used in $R_k(\chi_K)$. The renamings from instance parameters to formal parameters are stored as `q.b_renaming`.

Even for a fixed K , the same branch $D_K^\alpha \Rightarrow C_K^\alpha$ can contribute to multiple disjuncts, with different $\alpha = \alpha_3^{i,K}$. Substitution R_g^- substitutes only negative occurrences of χ_K , i.e. it affects only the premises. Substitution P_g^+ substitutes only positive occurrences of χ_K , i.e. it affects only the conclusions. P_g^+ ensures that the parameter instances of the postcondition are connected with the argument variables. At position 1 we remove the parameter constraints from solutions, since they will be reintroduced by P_g with values adjusted to the postconditions derived in the next step.

We start with $S_0 := \bar{\top}$ and $R_0 := \bar{\top}$. S_k grow in strength by definition. The disjunction elimination parts G_{χ_K} of R_1 and R_2 are computed from non-recursive branches only. Starting from R_2 , R_k are expected to decrease in strength, but monotonicity is not guaranteed because of contributions from abduction: mostly in form of $A_{\beta_{\chi_K}}$, but also from stronger premises due to S_k .

$\text{Connected}(\alpha, G)$ is the connected component of hypergraph G containing node α , where nodes are variables $\text{FV}(G)$ and hyperedges are atoms $c \in G$. $\text{Connected}_0(\delta, (\bar{\alpha}, G))$ additionally removes atoms $c: \text{FV}(c) \# \delta \bar{\alpha}$. In initial iterations, when the branches $D_K^\alpha \Rightarrow C_K^\alpha$ are selected from non-recursive branches only, we include a connected atom only if it is satisfiable in all branches. $H(R_k, R_{k+1})$ is a convergence improving heuristic, with $H(R_k, R_{k+1}) = R_{k+1}$ for early iterations and “roughly” $H(R_k, R_{k+1}) = R_k \cap R_{k+1}$ later.

We introduced the **assert false** construct into the programming language to indicate that a branch of code should not be reached. Type inference generates for it the logical connective **F** (falsehood). We partition the implication branches D_i, C_i into $\{D_i, C_i | \mathbf{F} \notin C_i\}$ which are fed to the algorithm and $\Phi_{\mathbf{F}} = \{(D_i, C_i) | \mathbf{F} \in C_i\}$. After the main algorithm ends we check that for each $(D_i, C_i) \in \Phi_{\mathbf{F}}$, $S_k(D_i)$ fails. Optionally, but by default, we perform the check in each iteration. Turning this option *on* gives a limited way to express negative constraints. With the option *off*, the inferred type is the same as it would be without the impossible pattern matching branch in the program, but the check statically guarantees that the branch is in fact impossible. The option should be turned *off* when a single iteration (plus fallback backtracking described below) is insufficient to solve for the invariants.

We implement backtracking using a tabu-search-like discard list. When abduction raises an exception: for example contradiction arises in the branches $S_k(\Phi)$ passed to it, or it cannot find an answer and raises **Suspect** with information on potential problem, we fall-back to step $k - 1$. Similarly, with checking for negative constraints *on*, when the check of negative branches $(D_i, C_i) \in \Phi_{\mathbf{F}}$, $\not\exists \text{FV}(S_k(D_i)).S_k(D_i)$ fails. In step $k - 1$, we maintain a discard list of different answers found in this step: initially empty, after fall-back we add there the latest answer. We redo step $k - 1$ starting from $S_{k-1}(\Phi)$. Infinite loop is avoided because answers already attempted are discarded. When step $k - 1$ cannot find a new answer, we fall back to step $k - 2$, etc. We store discard lists for distinct sorts separately and we only add to the discard list of the sort that caused fallback. Unfortunately this means a slight loss of completeness, as an error in another sort might be due to bad choice in the sort of types. The loss is “slight” because of the dissociation step described previously. Moreover, the sort information from checking negative branches is likewise only approximate.

5.4 Stages of iteration

Changes in the algorithm between iterations were mentioned above but not clearly exposed. Invariant inference and postcondition inference go through similar stages. Invariants, solved by abduction:

1. $k = j_0 = 0$ Only term abduction – invariants of type shapes – is performed, for all branches.
2. $k = j_1 = 1$ Both term abduction and numerical abduction are performed, but numerical abduction only for non-recursive branches.
3. $k \geq j_2 = 2$ Abduction is performed on all branches – type and numerical invariants are found.

For testing purposes, we have option **early_num_abduction** that sets $j_2 = 1$. In a single iteration, disjunction elimination precedes abduction.

1. $k_0 \leq k < k_1$ Term disjunction elimination – invariants of type shapes – is performed, only for non-recursive branches.

2. $k_1 \leq k < k_2$ Both term and numerical disjunction elimination are performed, but only for non-recursive branches.
3. $k_2 \leq k < k_3$ Disjunction elimination is performed on all branches – type and numerical postconditions are found.
4. $k_3 \leq k$ Additionally, we enforce convergence by intersecting the result with the previous-iteration result.

Our current choice of parameters is $[k_0; k_1; k_2; k_3] = \text{disj_step} = [0; 0; 2; 4]$.

When existential types are used, the expected number of iterations is $k = 5$ (six iterations), because the last iteration needs to verify that the last-but-one iteration has found the correct answer. The minimal number of iterations is $k = 2$ (three iterations), so that all branches are considered.

5.5 Implementation details

We represent $\vec{\alpha}$ as a tuple type rather than as a function type. We modify the quantifier \mathcal{Q} imperatively, because it mostly grows monotonically, and when variables are dropped they do not conflict with fresh variables generated later.

The code that selects $\wedge_{\chi}(A_{\chi}^+ \subset A_{\chi}^{\text{cap}}) \wedge \models \mathcal{Q}.A \setminus \cup_{\chi} A_{\chi}^+$ is an incremental validity checker. It starts with $A \setminus \cup_{\chi} A_{\chi}^{\text{cap}}$ and tries to add as many atoms $c \in \cup_{\chi} A_{\chi}^{\text{cap}}$ as possible to what in effect becomes A_{res} . The remaining atoms are distributed among $A_{\beta_{\chi}}^+$ by putting them into the last β_{χ} in \mathcal{Q} , i.e. the first **b** in the `q.negbs` list, for which $x \prec (\bar{\beta}^x \bar{\zeta}^x \cap \text{FV}(c)) \cap \bar{\beta}^x \bar{\zeta}^x \neq \emptyset$.

We count the number of iterations of the main loop, a fallback decreases the iteration number to the previous value. The main loop decides whether multisort abduction should dissociate alien subterms – in the first iteration of the loop – or should perform abductions for other sorts – in subsequent iteration. See discussion in subsection 3.3. In the first two iterations, we remove branches that contain unary predicate variables in the conclusion (or binary predicate variables in the premise, keeping only `nonrec` branches), as discussed at the end of subsection 3.4 and beginning of subsection 4.2. As discussed in subsection 4.2, starting from the fourth iteration ($k = 3$), we enforce convergence on solutions for binary predicate variables.

Computing abduction is the “axis” of the main loop. If anything fails, the previous abduction answer is the culprit. We add the previous answer to the discard list and retry, without incrementing the iteration number. If abduction and splitting succeeds, we reset the discard list and increment the iteration number. We use recursion for backtracking, instead of making `loop` tail-recursive.

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