Refactoring Delta-Oriented Product Lines to Achieve Monotonicity

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Delta-oriented programming (DOP) is a flexible transformational approach to implement software product lines. In delta-oriented product lines, variants are generated by applying operations contained in delta modules to a (possibly empty) base program. These operations can add, remove or modify named elements in a program (e.g., classes, methods and fields in a Java program). This paper presents algorithms for refactoring a delta-oriented product line into monotonic form, i.e., either to contain add and modify operations only (monotonic increasing) or to contain remove and modify operations only (monotonic decreasing). Because of their simpler structure, monotonic delta-oriented product lines are easier to analyze. The algorithms are formalized by means of a core calculus for DOP of product lines of Java programs and their correctness and complexity are given.

1 Introduction

A Software Product Line (SPL) is a set of similar programs, called variants, that have a well documented variability and are generated from a common code base [4]. Delta-Oriented Programming (DOP) [14,3] is a flexible and modular transformational approach to implement SPLs. A DOP product line comprises a Feature Model (FM), a Configuration Knowledge (CK), and an Artifact Base (AB). The FM provides an abstract description of variants in terms of features (each representing an abstract description of functionality): each variant is described by a set of features, called a product. The AB provides the (language dependent) code artifacts used to build the variants, namely: a (possibly empty) base program from which variants are obtained by applying program transformations, described by delta modules, that can add, remove or modify code. The CK provides a mapping from products to variants by describing the connection between the code artifacts in the AB and the features in the FM: it associates to each delta module an activation condition over the features and specifies an application ordering between delta modules. DOP supports automated product derivation, i.e., once the features of a product are selected, the corresponding variant is generated by applying the activated delta modules to the base program according to the application ordering.

Delta modules are constructed from delta operations that can add, modify and remove content to and from the base program (e.g., for Java programs, a delta module can add, remove or modify classes interfaces, fields and methods). As pointed out in [15], such flexibility allows DOP to support proactive (i.e., planning all products in advance), reactive (i.e., developing an initial SPL comprising a limited set of products and evolving it as soon as new products are needed or new requirements arise), and extractive (i.e., gradually transforming a set of existing programs into an SPL) SPL development [10]. DOP allows...
for quick SPL evolution and extension, as modifying or adding products/variants can straightforwardly be achieved by adding to the SPL new delta modules that modify, remove and add code on top of the original implementation of the SPL. However, a number of such SPL evolution and extension phases lead, almost ineluctably, to a multiplication of opposite add and remove operations, making the resulting SPL complex, difficult to understand and to analyze [16].

Refactoring [6] is an established technique to reduce complexity and to prevent the process of software aging, and consists of program transformations that change the internal structure of a program without altering its external (visible) behavior. Refactoring for DOP product lines, i.e. changing the internal structure of an SPL without changing its products/variants, has been investigated in [16]. There, a catalogue of refactoring algorithms and code smells is presented. Most of these refactorings are based on object-oriented refactorings [6]. In particular, the refactorings that refer to delta modules focus on a single delta module or a pair of delta modules.

In this paper, we propose two new refactoring algorithms to automatically eliminate opposite add and remove operations across the whole SPL, consequently reducing the overall complexity of the refactored SPL and making it easier to analyze. These algorithms are constructed around the notion of monotonicity where increasing monotonic SPL corresponds to only adding new content to the base program, while decreasing monotonic SPL corresponds to only removing content from the base program. These two notions of monotonicity are discussed in Section 5 where we propose several definitions with different versions of these concepts. The refactoring algorithms do not introduce code duplication in the AB of the refactored SPL and have at most quadratic complexity in space and time. We formalize the notions of monotonicity and the refactoring algorithms by means of IMPERATIVE FEATHERWEIGHT DELTA JAVA (IFΔJ) [3], a core calculus for DOP product lines where variants are written in an imperative version of FEATHERWEIGHT JAVA (FJ) [8]. A prototypical implementation of the refactoring algorithms is available at [11].

Section 2 introduces our running example. Section 3 recalls IFΔJ. Section 4 introduces some auxiliary notations. Section 5 illustrates the notions of monotonicity, the refactoring algorithms, and their properties. Section 6 briefly discusses the related work and Section 7 concludes the paper.

2 Example

In order to illustrate the monotonicity concept and our refactoring algorithms, we use a variant of the expression product line (EPL) benchmark (see, e.g., [13, 8]). We consider the following grammar:

\[
\text{Exp ::= Lit | Add | Neg} \\
\text{Lit ::= <integers>} \\
\text{Add ::= Exp }+\text{ Exp} \\
\text{Neg ::= }-\text{ Exp}
\]

Two different operations can be performed on the expressions described by this grammar: printing, which returns the expression as a string, and evaluating, which returns the value of the expression, either as an int or as a literal expression.

2.1 The Feature Model

The functionalities in the EPL can be described by two sets of features: the ones concerned with the data are Lit (for literals), Add (for the addition) and Neg (for the negation); the ones concerned with the operations are Print (for the classic toString method), Eval1 (for the eval1 method returning an int) and Eval2 (for the eval1 method returning a literal expression). The features Lit and Print are mandatory, while Add, Neg, Eval1 and Eval2 are optional. Moreover, as Eval1 and Eval2 define the same method, they are mutually exclusive. Figure 1 shows the feature model of the EPL represented as a feature diagram.
class Exp extends Object { // only used as a type
    String toString() { return null; }
}
class Lit extends Exp {
    int value;
    Lit setLit(int n) { value = n; return this; }
    String toString() { return value + ""; }
}
class Add extends Exp {
    Exp expr1;
    Exp expr2;
    Add setAdd(Exp a, Exp b) { expr1 = a; expr2 = b; return this; }
    String toString() { return expr1.toString() + " + " + expr2.toString(); }
}

class Neg extends Exp {
    Exp expr;
    Neg setNeg(Exp a) { expr = a; return this; }
}

delta DNeg {
    adds class Neg extends Exp {
        Exp expr;
        Neg setNeg(Exp a) { expr = a; return this; }
    }
}
delta DNegPrint {
    modifies Neg {
        adds String toString() { return "-" + expr.toString(); }
    }
}
delta DOptionalPrint {
    modifies Add {
        modifies String toString() {
            return "(" + original() + ")";
        }
    }
}

Figure 1: Expression Product Line: Feature Model

Figure 2: Base Program

2.2 The Artifact Base

Base Program. In our example, the EPL is constructed from the base program shown in Figure 2, which is the variant implementing features Lit, Add and Print. This program comprises the class Exp, the class Lit for literal expressions and the class Add for addition expressions. All these classes implement the toString method. Moreover, Lit and Add also have a setter method.

Implementing Feature Neg. Figure 3 presents the three delta modules (introduced by the keyword delta) that add the feature Neg to the base program. Namely: DNeg adds the class Neg with a simple setter; DNegPrint adds to class Neg the toString method (relevant for the Print feature); and DOptionalPrint adds glue code to ensure that the two optional features Add and Neg cooperate properly: it modifies the implementation of the toString method of the class Add by putting parentheses around the textual representation of a sum expression, thus avoiding ambiguity in printing. E.g., without applying DOptionalPrint both the following expressions

\[
\begin{align*}
& (new Add()).setAdd(new Lit()).setLit(3)) \text{ new Lit().setLit(5)) } // (-3 + 5 \\
& (new Neg()).setNeg(new Add()).setAdd(new Lit()).setLit(3), new Lit().setLit(5)) } // -(3+5)
\end{align*}
\]

would be printed as “-3+5”; while after applying DOptionalPrint the former is printed as “(-3+5)” and the latter is printed as “-(3+5)”. Delta module DOptionalPrint illustrates the usage of the special

Figure 3: Delta Modules for the Neg Feature
method `original` which allows here to call the original implementation of the method `toString`, and surround the resulting string with parenthesis.

**Implementing Features Eval1 and Eval2.** Figure 4 presents the delta modules that add the features Eval1 and Eval2 (on the left and on the right, respectively). The delta module `DLitEval1` (resp. `DLitEval2`) modifies the classes `Exp` and `Lit` by adding to them the `eval` method corresponding to the Eval1 (resp. Eval2) feature: `eval` takes no parameter and returns an int (resp. a `Lit` object). The delta module `DAddEval1` (resp. `DAddEval2`) does the same operation on the `Add` class; and the delta module `DNegEval1` (resp. `DNegEval2`) does the same operation on the `Neg` class.

**Removing the Add Feature.** If the feature `Add` is not selected, the generated variant must not contain the class `Add`. This is ensured by the delta module `DremAdd` in Figure 5 which removes the class `Add` from the program.

### 2.3 The Configuration Knowledge

The configuration knowledge specifies how variants are generated by i) specifying for which product (i.e., set of selected features) each delta module is activated, and ii) specifying a partial application order on the delta modules. Figure 6 presents the activation conditions and the partial order of the delta modules. The activation conditions and the partial order reflect the explanations about the delta modules of the EPL given in Section 2.2. For instance, the delta module `DNeg` is activated whenever the feature `Neg` is activated, the delta module `DremAdd` is activated whenever the feature `Add` is not selected, and the delta module `DOptionalPrint` is activated whenever both features `Add` and `Neg` are activated (recall that feature `Print` is mandatory).
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| Delta Module       | Activation |
|--------------------|------------|
| DNeg               | Neg        |
| DNegPrint          | Neg ∧ Print|
| DOptionalPrint     | Neg ∧ Add  |

| Delta Module       | Activation |
|--------------------|------------|
| DLitEval1          | Eval1      |
| DAddEval1          | Eval1 ∧ Add|
| DNegEval1          | Neg ∧ Eval1|

| Delta Module       | Activation |
|--------------------|------------|
| DLitEval2          | Eval2      |
| DAddEval2          | Eval2 ∧ Add|
| DNegEval2          | Neg ∧ Eval2|
| DremAdd            | ¬Add       |

Order: DNeg < {DNegPrint, DOptionalPrint} < {DLitEval1, DAddEval1, DNegEval1} < {DLitEval2, DAddEval2, DNegEval2} < DremAdd

Figure 6: Expression Product Line: Configuration Knowledge

Following [3], the partial order is specified as a total order on a partition of the set of delta modules. The partial order must ensure that the variants of the EPL can be generated. Therefore, it states that the delta modules DNeg (that adds the class Neg) must be applied before DNegPrint, DNegEval1 and DNegEval2 (that modify class Neg). The partial order also ensures that, independently from the activation conditions, the delta modules occurring in the same partition perform disjoint delta operations (thus guaranteeing that applying any subset of them in any possible order always produces the same transformation)—this guarantees that the product line is unambiguous (i.e., applying the activated delta modules in any possible total order that respects the application order produces the same variant). Therefore, the delta modules for feature Eval1 and the delta modules for feature Eval2 are put in two different parts; and the delta module DremAdd (that removes the class Add) is applied after DAddEval1, DAddEval2 and DOptionalPrint (that modify class Add).

3 The IFΔJ Calculus

In this section we briefly recall the IFΔJ [3] core calculus for DOP. We present the calculus in two steps: (i) we introduce the IFJ calculus, which is an imperative version of FJ [8]; and (ii) we introduce the constructs for variability on top of it. The full description of IFΔJ is given in [3], where a type-checking technique for ensuring type soundness of all variants is presented. The version of IFΔJ presented in this paper is indeed a slight extension of the one presented in [3]: the AB contains also an IFJ program outside of any delta module. This makes the IFΔJ syntax a direct extension of the IFJ syntax.

The abstract syntax of IFJ is presented in Figure 7 (top). Following [8], we use the overline notation for (possibly empty) sequences of elements: for instance \( \overline{e} \) stands for a sequence of expressions. Variables \( x \) include the special variable this (implicitly bound in any method declaration \( MD \)), which may not be used as the name of a formal parameter of a method. A program \( P \) is a sequence of class declarations \( \overline{CD} \). A class declaration \( \text{class } C \text{ extends } C' \{ \overline{AD} \} \) comprises the name \( C \) of the class, the name \( C' \) of the superclass (which must always be specified, even if it is the built-in class Object), and a list of field
and method declarations $\overline{AD}$. All fields and methods are public, there is no field shadowing, there is no method overloading, and each class is assumed to have an implicit constructor that initializes all fields to null. The subtyping relation $\prec$: on classes, which is the reflexive and transitive closure of the immediate subclass relation (given by the extends clauses in class declarations), is supposed to be acyclic.

The abstract syntax of the language $\text{IF}\overline{\Delta}$ is given in Figure 7 (bottom). An IF$\overline{\Delta}$ SPL $L$ comprises: a possibly empty or incomplete IF$J$ program $P$; a set of delta modules $\overline{A}$ that, together with the base program $P$, represents the artifact base; a feature model $FM$ specifying the features and the products of the SPL; and a configuration knowledge $CK$ (i.e., the ordering between delta modules and their activation conditions).

To simplify the presentation, we do not give a syntactic description of $FM$ nor of $CK$ and we rely on getter functions as follows: $L$.features is the set of features; $L$.products specifies the products (i.e., a subset of the power set $2^{L$.features$}$); $L$.activation maps each delta module name $d$ to its activation condition; and $L$.order (or $<_L$, for short) is the application ordering between the delta modules.

A delta module declaration $\Delta$ comprises the name $d$ of the delta module and class operations $\overline{CO}$ representing the transformations performed when the delta module is applied to an IF$J$ program. A class operation can add, remove, or modify a class. A class can be modified by (possibly) changing its super class and performing attribute operations $\overline{AO}$ on its body. An attribute name $a$ is either a field name $f$ or a method name $m$. An attribute operation can add or remove fields and methods, and modify the implementation of a method by replacing its body. The new body may call the special method original, which is implicitly bound to the previous implementation of the method and may not be used as the name of a method.

The projection of a product line on a subset of its products is obtained by restricting $L$.products to describe only the products in the subset and by dropping delta modules that are never activated.

Example 1. For instance, the AB of the projection of the EPL on the products without feature Neg is obtained by dropping the delta modules $DNeg$, $DNegPrint$ and $DOptionalPrint$; and the AB of the projection of the EPL on the products without feature Eval2 is obtained by dropping the delta modules $DLitEval2$, $DAddEval2$ and $DNegEval2$.

4 Auxiliary Notations

In this section we introduce some auxiliary notations that will be used in Section 5. Our first notation relates the modifies operators on methods to the concept of monotonicity. Indeed, in general modifies on methods is not monotonic: the body of the method is replaced by some code that can be entirely different. However, we can distinguish two cases in which modifies can be considered monotonic: when it calls original, the generated variant contains the original body of the method, and so modifies can be considered increasing monotonic; when the body of the method is voided (i.e., it is replaced by return null) modifies can be considered decreasing monotonic.

Notation 1 (wraps and voids). Let wraps denote a modifies operation on method that calls original, and voids denote a modifies operation that removes the content of a method: voids $m$ corresponds to modifies $C\ m(\cdots)\ \{\text{return null}\}$. 

The goal of the two following notations is to unify delta operations on classes and on attributes in a single model, in order to manage uniformly these two kind of operations in our refactoring algorithms. Using these notations simplifies the description of our refactoring algorithms.
Notation 2. A reference, written $\rho$, is either a class name $C$ or a qualified attribute name $C.a$ and we write $\rho \leq \rho'$ if $\rho = \rho'$ or if $\rho$ is a prefix of $\rho'$. By abuse of notation, we also consider the extends clause as an attribute of its class, and consider $C$.extends as a valid reference.

Notation 3. We abstract a delta module by a set of Abstract Delta Operations (ADO) which are triplets $(dok, \rho, D)$ where: i) $dok$ is a delta operation keyword (adds, removes or modifies), ii) $\rho$ is the reference on which $dok$ is applied, iii) $D$ is the data associated with this operations, and iv) if $dok = modifies$ then $\rho$ is not a class name. Given an ADO $o$, we denote its operator as $o$.dok, its reference as $o.\rho$ and its data as $o.D$.

These two notations are illustrated by the following examples. In particular, the first example shows that a modifies operation on a class $C$ that contains only adds operations on attributes is represented by the set of ADOs containing only the adds operations: the modifies $C$ operation is only a syntactic construction to introduce these adds operations and is not included in our representation.

Example 2. The delta module DLitEval2 in Figure 4 that modifies classes Exp and Lit by adding a method eval to each of them, is modeled with only two ADOs:

$$(\text{adds, Exp.eval, } \text{Lit.eval() \{ return null; \}}) \text{ and } (\text{adds, Lit.eval, } \text{Lit.eval() \{ return this; \}})$$

These ADOs model the addition of the eval methods, the modification of classes Exp and Lit being implicit as Exp (resp. Lit) is a prefix of Exp.eval (resp. Lit.eval).

Example 3. The delta module DOptionalPrint in Figure 3 that modifies the class Add by modifying the method toString, is modeled with only one ADO:

$$(\text{modifies, Add.toString, } \text{String toString() \{ return "(" + original() + ")"; \}})$$

Example 4. Note that, according to Definition 3 the projection of the EPL on the products without feature Neg does not contain modifies operations.

Our last notations are used to iterate over delta modules: first, we present the notations to get a set of delta module names, then we present the notations to order such a set so to iterate over it in a for loop.

Notation 4. The set of delta module names declared in $L$ is denoted as $\text{dm}(L)$. When $L$ is clear from the context, we write $\text{before}(d)$ the set of delta module names that are before $d$ for $L$ order.

Notation 5. Given a set of delta names $S = \{d_i | i \in I\}$, we denote $\uparrow_S$ (resp. $\downarrow_S$) a sequence $(d_1, \ldots, d_n)$ of all the names in $S$ that respects the partial order (resp. the partial order opposite from the one) specified by $L$ order.

5 Monotonicity and Refactoring Algorithms

In the introduction, we pointed out that the flexibility provided by delta operations, being very useful for easily constructing SPLs, can lead to unnecessary complexity with many adding and removing operations cancelling each other. Monotonicity is a natural approach to lower such complexity as it forbids opposite adding and removing operations: informally, increasing monotonicity is constructing a variant only by adding new content to the base program and is in principle similar to Feature-Oriented Programming (FOP); on the other hand, decreasing monotonicity is constructing it only by removing content from the base program and share similarities with annotative approaches (see, e.g., [5, 9]).

As pointed out in [13], DOP is a generalization of FOP: the AB of a FOP product line consists of a set of feature modules which are delta modules that correspond one-to-one to features and do not contain remove operations.
Section 5.1 focuses on increasing monotonicity: it formalizes and motivates different levels of purity for it, then presents a refactoring algorithm transforming an SPL into an increasing monotonic equivalent and illustrates it on the EPL example. Section 5.2 formalizes decreasing monotonicity, presents a refactoring algorithm and its application to the EPL. Section 5.3 gives correctness and complexity of the refactoring algorithms.

5.1 Increasing Monotonicity

Before presenting the first refactoring algorithm, we gradually introduce three notions of increasing monotonicity, from the most intuitive one, called strictly-increasing, to the most flexible one, called pseudo-increasing. Depending on the properties of the input SPL, the algorithm can produce SPLs corresponding to any of the three notions. A first intuitive notion of increasing monotonicity is only to allow adds operations:

Definition 1 (Strictly-increasing monotonic). An SPL is strictly-increasing monotonic iff it only contains adds operations.

Note that this notion is quite restrictive, as it does not allow the extension of method implementation, or the modification of the extends clause of a class, two operations possible in FOP. The following more liberal notion allows to increase the body of existing methods by using the modifies operator by always calling original. Still, it does not include the modification of the extends clause of a class present in FOP.

Definition 2 (Increasing Monotonic). An SPL is increasing monotonic iff it only contains adds and wraps operations.

The last notion, which is a generalization of FOP, is to allow modifies also to modify the extends clause of a class and to replace the implementation of a method, leaving only removes as a forbidden operation:

Definition 3 (Pseudo-increasing monotonic). An SPL is pseudo-increasing monotonic iff it does not contain removes operations.

We have qualified the above notion as pseudo-, since it allows delta modules to replace the extends clause of a class and to remove or entirely replace content from the body of method definitions. Thus, it does not reflect the informal definition of increasing monotonicity given at the beginning of Section 5.

5.1.1 Increasing Monotonicity Refactoring Algorithm

The refactoring algorithm, presented in Figure 8 transforms its input DOP product line \( L \) by eliminating all removes operations and without eliminating or introducing new modifies operations. Therefore, the refactored SPL is

- strictly-increasing, if \( L \) does not contain modifies operations;
- increasing, if all the modifies operations in \( L \) are wraps operations; and
- pseudo-increasing, otherwise.

Note that the algorithm may turn an existing delta module into an empty delta module which can then be removed by a straightforward algorithm (see [16]).

To illustrate how the refactoring algorithm works, consider a delta module \( d \) containing a removal operation on an element \( \rho \) (either a class or an attribute). This operation would be applied only when \( d \) is activated, and would remove all declarations (and modification) of \( \rho \) that are done before the application
mergeToBase();

Operation: $o_1, o_2$;

Set of Delta Module Name: $S$;

refactor($L$) =
for $d_1 \in \text{dom}(L)$ do
    for $o_1 \in L(d_1)$ do
        if ($o_1$.dok = removes)
            $L(d_1)$ ← $L(d_1)$ \ $o_1$
        manageOperation()
fi
done

manageOperation() =
$S$ ← $\emptyset$
for $d_2 \in \text{before}(d_1)$ do
    for $o_2 \in L(d_2)$ do
        if ($o_1$.order ≤ $o_2$.order) mergeOperations() fi
    done
mergeToBase();

mergeOperations() =
$S$ ← $S$ ∪ {$d_2$}
$L(d_2)$ ← $L(d_2)$ \ $o_2$
if($L(d_2)$ = {}) $L$ ← $L$ \ $d_2$ fi
$L$ ← $L$ + $d$ fresh with {} $L(d)$ ← {} $o_2$
$L$.$\text{activation}(d)$ ← $d_2$ ∧ ¬$d_1$
$L$.$\text{order}(d)$ ← $L$.$\text{order}(d_2)$
}
}

mergeToBase() =
$D$ ← $L$.P($o_1$.ρ)
if($D \neq \bot$)
    $L$ ← $L$ + $d$ fresh with {} $L(d)$ ← {} {$\text{adds}, o_1.\rho, D$}
    $L$.$\text{activation}(d)$ ← ¬$d_1$
    $L$.$\text{order}(d)$ ← $\text{before}(S)$
fi;

Figure 8: Refactoring Algorithm for Increasing Monotonic SPL

of $d$. Hence, to cancel this removal operation, we can simply transform the SPL so that $\rho$ is never declared before $d$ and when it is activated.

The algorithm is structured in four functions with four global variables. The main function of our algorithm is refactor which takes the SPL to refactor as parameter. This function looks in order at all the delta modules and when finding a removes operation $o_1$ inside a delta module $d_1$, it cancels it from $d_1$ and calls the manageOperation function. The goal of the manageOperation function is to transform the SPL for the $o_1$ operation as described before. It is structured in two parts. First, it looks in order at all the delta operations applied before $d_1$, and upon finding an operation $o_2$ in a delta module $d_2$ that manipulates $o_1.\rho$, it calls mergeOperation which extracts that operation from $d_2$ and changes the application condition of $o_2$ (using a freshly created delta module $d$) so it is executed only when $o_1$ would not be executed. Second, it calls mergeToBase which looks if the element removed by $o_1$ is declared in the base program, and if so, extracts it from the base program into a fresh opposite delta module $d$ that is activated only when $o_1$ would not be executed. The addition of this new delta module is done in lines 37–41 where we state that $L$ is changed by adding a fresh delta module $d$ with the following characteristics: its set of ADO $L(d)$ is the singleton ($\text{adds}, o_1.\rho, D$) that adds $o_1.\rho$ again to the base program; its activation condition $L$.$\text{activation}(d)$ is the opposite of $d_1$; and its ordering $L$.$\text{order}(d)$ states that it must be applied before all the delta modules in $S$.

There are three subtleties in this algorithm. First, to deal with the fact that removing a class also removes all its attributes, the condition in line 19 is “$o_1.\rho$ ≤ $o_2.\rho$” meaning that: if $o_1$ removes a class $C$, then previous additions and modifications of $C$ and its attributes will be changed with mergeOperation. Second, in line 26, empty delta modules are eliminated to avoid creating too much of them. Third, we compute in $S$ the set of all delta modules manipulating $o_1.\rho$ before $d_1$ to set the order relation of the delta module created in the mergeToBase function.
delta DNotDremAdd {
  adds class Add extends Exp {
    Exp expr1;
    Exp expr2;
    Add setAdd(Exp a, Exp b) {
      expr1 = a; expr2 = b; return this;
      String toString() { return expr1.toString() + " + " + expr2.toString(); }
      }
  }
}

delta DAddEval1DremAdd {
  modifies Add {
    adds int eval() {
      return expr1.eval() + expr2.eval();
      }
  }
}

delta DAddEval2DremAdd {
  modifies Add {
    adds Lit eval() {
      Lit res = exp1.eval();
      return res.setLit(res.value + exp2.eval());
      }
  }
}

delta DOptionalPrintDremAdd {
  modifies Add {
    modifies String toString() {
      return "(" + original() + ")";
      }
  }
}

Figure 9: Delta Modules of the EPL Changed by the Increasing Refactoring Algorithm

5.1.2 Example: Refactoring the EPL into Increasing Monotonicity

We applied our implementation of this algorithm on the EPL given in Section 2. It contains only one removes operation, in the DremAdd delta module, removing the Add class. Thus, by construction of our algorithm, only the delta modules DAddEval1, DAddEval2, DOptionalPrint and the base program, that modify and declare the Add class (respectively), are changed by the refactoring process.

Let us illustrate the modification done on the delta modules by considering DAddEval1: the function mergeOperations extract the only operation inside this delta module (line 25), removes DAddEval1 as it is now empty (line 26), and then basically recreates it (line 27), with the activation condition extended with ¬DremAdd, corresponding to Add. Hence, the delta modules are simply renamed by the algorithm. However, the base program is changed by the function mergeToBase which removes the class Add from it, and creates a new delta module reintroducing that class with the activation condition ¬DremAdd which corresponds to Add.

The modified delta modules are shown in Figure 9. The modified base program, which is not shown, is obtained from the original base program (see Figure 2) by dropping the declaration of class Add. Note that, since all the modifies operations of the original SPL were wraps operations, the refactored SPL is increasing monotonic. On the other hand, since the projection of the original EPL on the products without feature Neg does not contain modifies operations (see Example 3 in Section 3), its increasing monotonic refactoring would produce a strict-increasing product line.

5.2 Decreasing Monotonicity

Like for increasing monotonicity, we introduce several levels of purity for decreasing monotonicity before presenting the refactoring algorithm. Straightforward adaptations of Definition 1, 2 and 3 lead to the following definitions of strictly-decreasing, decreasing and pseudo-decreasing monotonicity.

Definition 4 (Strictly-decreasing monotonic). An SPL is strictly-decreasing monotonic iff it only contains removes operations.

Definition 5 (Decreasing Monotonic). An SPL is decreasing monotonic iff it only contains removes operations and voids operations.

Definition 6 (Pseudo-decreasing monotonic). An SPL is pseudo-decreasing monotonic iff it only contains removes and modifies operations.

Unfortunately, the three above notions suffer of a major drawback: not all product lines can be expressed by following their prescriptions. For instance, in order to conform to any of Definition 4, 5 and 6 the base program of the EPL (cf. Section 2) must contain the class declaration
that contains two method declarations with same signature \texttt{eval()} and therefore is not valid in Java. In order to overcome this drawback, we introduce the following notation to express the notion of “readding” (i.e., to remove and to immediately add) an attribute.

Notation 6 (\texttt{readds}). Let \((\texttt{readds}, \rho, D)\) denotes the sequence of removing the attribute \(\rho\), and then performing \((\texttt{adds}, \rho, D)\).

We can now give the definitions of read-strictly-decreasing, readd-decreasing and read-pseudo-decreasing monotonicity that does not suffer of the above drawback.

Definition 7 (Readd-strictly-decreasing monotonic). An SPL is readd-strictly-decreasing monotonic iff it only contains \texttt{readds} and \texttt{removes} operations.

Definition 8 (Readd-decreasing monotonic). An SPL is readd-decreasing monotonic iff it only contains \texttt{readds} operations, \texttt{removes} operations and \texttt{voids} operations.

Definition 9 (Readd-pseudo-decreasing monotonic). An SPL is readd-pseudo-decreasing monotonic iff it only contains \texttt{readds}, \texttt{removes} and \texttt{modifies} operations.

5.2.1 Decreasing Monotonicity Refactoring Algorithm

Our algorithm, presented in Figure 10, refactors a DOP product line \(L\) by eliminating all \texttt{adds} operations and without eliminating or introducing new \texttt{modifies} operations. Therefore, the refactored SPL is

- readd-strictly-decreasing if \(L\) does not contain \texttt{modifies} operations;
- readd-decreasing if all the \texttt{modifies} operations in \(L\) are \texttt{voids} operations; and
- readd-pseudo-decreasing, otherwise.

The decreasing monotonic refactoring algorithm may introduce empty new delta modules. As pointed out in the discussion at the beginning of Section 5.1.1 empty delta modules can be removed from the refactored product line by a straightforward algorithm. Moreover, if each class/attribute is introduced (i.e., either declared in the base program or added by a deltamodule) only once, then decreasing monotonic refactoring does not introduce \texttt{readds} operations.

The structure of this refactoring algorithm is similar to the one to get increasing monotonicity: the main function \texttt{refactor} takes as parameter the SPL to refactor, and iterates over all the delta modules to find an \texttt{adds} operator to remove. Upon finding an operation \(o_1\) with an \texttt{adds} operator in a delta module \(d_1\), the function \texttt{manageOperation} is called. This function, like for the increasing refactoring algorithm, is structured in two parts. First, it looks in order at all the delta operations applied before \(d_1\), and upon finding an operation \(o_2\) in a delta module \(d_2\) that manipulates \(o_1, \rho\) with a \texttt{removes} operator, it calls \texttt{mergeOperation} which extracts that operation from \(d_2\) and update the application condition of \(o_2\) as done in the other algorithm. Second, it calls \texttt{mergeToBase} which integrates the operations \(o_1\) in the base program as follows: first, it completes the base program with all the declarations introduced in \(o_1\) that was missing from it; second, it creates a new delta module \(d\) that readds (see Definition 6) all the declarations originally done in the base program by the ones done in \(o_1\); finally, it creates a new delta module \(d'\) opposite to \(o_1\) that removes all the declarations done in \(o_1\) if these operations would not be executed. For the creation of these delta modules in lines 35–43, we use the following notations: \(\text{dom}(o)\) is the set of references that are declared in that operations, and \(o(\rho)\) is the data \(D\) associated to \(\rho\) in \(o\). For instance, with \(o\) being the \texttt{adds} operation in the \texttt{DNeg} delta module, we have
Delta Module Name \(d_1, d_2\);
Operation \(o_1, o_2\);
refactor(\(L\) = 
for module \(d_1 \in \downarrow \text{dm}(L)\) do 
for \(o_1 \in L(d_1)\) do 
if \((o_1.dok = \text{adds})\) 
\(L(d_1) \leftarrow L(d_1) \setminus o_1\)
manageOperation()
fi 
done;
done;

manageOperation() = 
for module \(d_2 \in \downarrow \text{before}(d_1)\) do 
for \(o_2 \in L(d_2)\) do 
if \((o_2.\rho \in \text{dom}(o_1)) \& (o_2.dok = \text{removes}))\) 
mergeOperations()
fi 
done;
done;
mergeToBase();

mergeOperations() = 
\(L(d_2) \leftarrow L(d_2) \setminus o_2\)
if \((L(d_2) = \emptyset)\) \(L \leftarrow L \setminus d_2\) fi 
\(L \leftarrow L + d\) fresh with 
\(L(d) \leftarrow \{ o_2 \}\)
\(L.\text{activation}(d) \leftarrow d_2 \land \neg d_1\)
\(L.\text{order}(d) \leftarrow L.\text{order}(d_2)\)
};

mergeToBase() = 
Set of reference: \(S \leftarrow \text{dom}(L.\text{P})\)
\(L.\text{P} \leftarrow L.\text{P} \cup \{ \rho.\text{D} \mid (\text{adds}, \rho.\text{D}) \in o_1 \land \rho \notin S\}\);
\(L \leftarrow L + d\) fresh with 
\(L(d) \leftarrow \{ (\text{reads}, \text{c.a}, o_1(\rho)) \mid \text{c.a} \in \text{dom}(o_1) \cap S\}\)
\(L.\text{activation}(d) \leftarrow d_1\)
\(L.\text{order}(d) \leftarrow L.\text{order}(d_1)\)
}\} + d’ fresh with 
\(L(d’) \leftarrow \{ (\text{removes}, \rho, \emptyset) \mid \rho \in \text{dom}(o_1) \setminus S\}\)
\(L.\text{activation}(d’) \leftarrow d_1\)
\(L.\text{order}(d’) \leftarrow L.\text{order}(d_1)\)
}\);

Figure 10: Refactoring Algorithm for Decreasing Monotonic SPL

\(\text{dom}(o) = \{ \text{Neg}, \text{Neg.exp}, \text{Neg.setNeg} \}\) and, e.g., \(o(\text{Neg.exp}) = \{ \text{Exp}, \text{expr} \}\)

There are two subtleties in this algorithm. First, it can occur that before an \text{adds} operation adding a class \(C\), removal operations can be applied on the \text{attributes} of \(C\), and so, the condition in line 17 “\(o_2.\rho \in \text{dom}(o_1)\)” captures all possible attributes of \(o_1.\rho\). Second, in line 36, we only read attributes, not classes, to ensure that the base program contains every elements declared in the SPL. Note also that in this example, there is no need of a set \(S\) to define the order of the delta modules created in \text{mergeToBase}: the order simply is the one of the original \(d_1\) delta module.

5.2.2 Example: Refactoring the EPL into Decreasing Monotonicity

We applied this refactoring algorithm to the EPL example. All its delta modules but \text{DremAdd} and \text{DOptionalPrint} add new content to the base program, and all of them are modified by the refactoring as follows: they are emptied out by the \text{refactor} function which removes the \text{adds} operations, that are then reintroduced to the SPL by the \text{mergeToBase} in the base program with few new delta modules. The structure of the resulting SPL is presented in Figure[13]—it contains 8 empty delta modules (lines 27, 29, 31, 33, 38, 41, 44 and 47), which can be straightforwardly removed. The left part of Figure[14] contains the new base program which now contains all the elements declared in the SPL: the class \text{Neg} as well as the attributes \text{toString} and \text{eval} are declared in the base program. Note that as the delta modules implementing the \text{Eval1} feature are before the ones implementing the \text{Eval2} feature, the new base program contains the \text{Eval1} version of the \text{eval} methods. The right part of Figure[14] presents the newly added delta modules. The names of these delta modules are constructed in two parts: first the operation they perform, and then the delta module that created them. For instance, \text{DremNeg.DNeg} is the removing delta module created in the \text{mergeToBase} function from the \text{DNeg} delta module: it removes the \text{Neg} class when the feature \text{Neg} is not selected. The second delta module \text{DremNegToString.DNegPrint} is the delta module removing the method \text{Neg.to}String when neither \text{Neg} nor \text{Print} are selected. The second
set of delta modules (from line 27 to 34) corresponds to the integrations of the Eval1 feature in the base program. For instance, DreaddNegEval1_DNegEval1 is the d delta module created by the mergeToBase function (line 35 in Figure 10), and does not contain any operations as the base program did not originally contain the eval method; DreaddExpEval1_DLitEval1 is the d’ delta module created by the mergeToBase function (line 39 in Figure 10), and removes the Neg.eval method when the feature Eval1 or Neg is not selected. The last set of delta modules (from line 36 to 47) corresponds to the integrations of the Eval2 feature in the base program. As when including this feature in the base program, the delta modules for Eval1 already have been integrated, the readding delta modules contains the implementation of the Eval2 version of the eval method; and on the opposite, the removing delta modules are empty.

Note that, since the original SPL contains method modifies operations that are not voids, the refactored SPL is readds-pseudo-decreasing monotonic. On the other hand, since in the projection of the original EPL on the products without feature Eval2 each class/attribute is added only once (see Example 1 in Section 3), its decreasing monotonic refactoring would produce a pseudo-decreasing product line.

5.3 Properties

We finally present the main properties of these two refactoring algorithms. As they both share the same characteristics, we state our theorems for both of them.

**Theorem 1 (Correctness).** Applying one of the refactor algorithms on one SPL L is a monotonic SPL that have the same products and variants as L.

**Proof (sketch).** Let us consider the increasing version of the refactor algorithm (proving the result for the decreasing version is similar), and let us denote L’ as refactor(L). The fact that L’ is monotonic is a direct consequence of the algorithm iterating over all delta operations and deleting all the removes operations. The fact that L’ has the same products as L is a direct consequence of refactor not changing the FM of L. The fact that L’ has the same variants as L can be proven by checking that each product
$p$ of $L$ generates the same variant in $L'$ and in $L$: this can be done by induction on the number of delta modules and delta operations used to generate the variant of $p$ in $L$.

Recall that the notion of increasing (resp. decreasing) monotonicity satisfied by the refactored SPL depends on the properties of the original SPL, as pointed out at the beginning of Section 5.1.1 (resp. Section 5.2.1).

Theorem 2 (Complexity). The space complexity of the refactor algorithms is: i) constant in the size of IFJ code; ii) linear in the number of delta operations; and iii) linear in the number of delta operations times the number of delta modules for the generation of the activation condition of the new delta modules.

The time complexity of the refactor algorithms is quadratic in the number of delta operations.

Proof (sketch). i) is a direct consequence of the algorithm not creating or duplicating IFJ code. ii) is more subtle: in the increasing refactor, $o_1$ is replaced by one delta module containing one operation, and $o_2$ is kept as it is; however in the decreasing refactor, to match all the readds and removes operations generated in mergeToBase, we need to consider that adding a class corresponds to one adds operation for the class name, and one adds operation for each of its fields. iii) it is straightforward to see that the length of the activation condition of the delta module created in function mergeOperations is linear in the number of delta modules in $L$. Finally, refactor is quadratic in time in the number of delta operations as it iterates over them with two inner loops (one in function refactor, one in function manageOperation).

6 Related Work

To the best of our knowledge, refactoring in the context of DOP has been studied only in [16] and [7]. The former considers product lines of Java programs, while the latter considers delta modeling of software architectures. We refer to [16] for the related work in the FOP or annotative approaches. Note that both of these approaches are monotonic by construction (FOP being increasing, and annotative being decreasing), and so no refactoring algorithms to achieve monotonicity exist for them. In [16], a catalogue of refactoring and code smells is presented, and most of them focus on changing one delta module, one feature at a time. Two of their refactorings are related to ours. Resolve Modification Action replaces a modifies operations that does not call original with an adds operation, by modifying the activation condition of previous modifies and adds operations. Resolve Removal Action eliminates removes operations also by changing the application condition of previous modifies and adds operations. Other refactoring algorithms focus on how to enable extractive SPL development for FOP [1, 12]. These works are related to ours, as DOP natively supports extractive SPL development: refactoring such a SPL into an increasing monotonic one using our algorithms is close to adapting this SPL to FOP.

7 Conclusion and Future Work

In this paper, we presented two refactoring algorithms with the goal of lowering the complexity of the input SPL, by removing opposite adds and removes operations. These algorithms work by removing one kind of operation from the input SPL, either adds or removes, and so they do not duplicate code nor change the structure of the input SPL, except for the parts related to the removed operation.

We plan four lines of future work for monotonicity in DOP. First, we would like to investigate alternative means to reach (a possibly more flexible version of) monotonicity. Second, complementarily
to our algorithms, one could consider also refactoring code. For instance, splitting the definition of a method into several ones would help into transforming modifies operations in voids operations. Third, we would like to identify specific analysis scenarios where monotone product lines are simpler to analyze. Fourth, we plan to develop case studies in order to evaluate the advantages and the drawbacks of the proposed refactorings.

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