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Covariantly Adjusting Co-Types in Timor

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Abstract

This paper extends the idea of co-types (described in a companion paper) to include the concept of *adjustment hierarchies*. An adjustment hierarchy provides a parallel hierarchy to a subtyping hierarchy of a type being expanded by the co-type. This has a number of advantages including the predefinition of co-types for subtypes of an expanded type, and allowing automatic covariant adjustment of parameters for makers, binary methods and instance methods, without creating problems for static type safety.

1 INTRODUCTION

In a companion paper we described the basic concept of co-types and their integration into the Timor programming language [11]. In contrast with most conventional OO languages a Timor type definition consists only of a set of instance methods. It has no constructors, no binary methods and no class (static) methods. It can have several implementations, each of which may implement the type in a different way. An implementation consists of a definition of the instance data, code to implement the instance methods and a single constructor, which can have *implementation-oriented* parameters. These can vary both in number and type according to the needs of different implementations of the same type.

A co-type expands some other type by providing, as *instance* methods:

- *makers*, which can have *application-oriented* parameters relevant to the initialisation of instances of the expanded type. Makers are invoked by an application to create a new instance of the expanded type.
- *binary methods*, which have at least two parameters of the expanded type. These function by accessing the instance methods of their parameters as appropriate. Because they are instance methods of a different type, they avoid a number of problems associated with normal binary instance and class methods [2].
- normal *instance methods*, which can in effect play the role of class methods in other OO languages. The instance data in an implementation of a co-type can likewise play a role similar to that of class data in other OO languages.

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In the companion paper we showed that such an arrangement helps to deal with problems which would otherwise arise in a language such as Timor, because of its support for multiple implementations of a type and qualifying types with bracket methods.

We pointed out that a co-type can have subtypes, provided that these expand the *same* type as their supertype. We also drew attention to the fact that while subtypes of a co-type cannot expand subtypes of its expanded type, a close relationship nevertheless exists between subtype hierarchies of an expanded type and co-types for these subtypes. This paper describes the relationship between these hierarchies in the context of Timor. In doing so, we present a new concept, which we call *adjustment*. This mechanism allows co-type definitions and their implementations to serve as a pattern for co-types of subtypes of an expanded type and their implementations.

We also introduce a safe form of *automatic* covariant adjustment of the parameters of co-types, to reflect the different expanded types which occur in the subtype hierarchy of the initial expanded type. Thus for example in a `Person` hierarchy with subtypes `Student` and `Employee`, makers and/or binary methods appearing in a co-type for `Person` can optionally be adjusted automatically to serve as makers/binary methods for `Student` or `Employee`. This approach potentially spares the programmer from writing such methods explicitly and helps to ensure consistency between co-types which are related via an adjustment hierarchy.

Section 2 describes the aims of the adjustment concept in a general way. Section 3 introduces an example of a type hierarchy. Section 4 presents binary methods for a normal co-type and shows how similar binary methods can appear in co-types for subtypes of the expanded type. Section 5 uses this example to illustrate the idea of covariantly adjustable parameters. Sections 6 and 7 extend the idea to makers and to co-type instance methods. In section 8 it is shown how adjusted co-types are derived and can be modified. Sections 9 and 10 illustrate the reuse of code in adjustment hierarchies. A section then follows on related work and after that a conclusion.

2 THE AIMS OF ADJUSTMENT

An adjustment hierarchy consists of co-types that mirror a subtype hierarchy for an expanded type. Given a subtype hierarchy consisting of a root type `Person` with two subtypes `Student` and `Employee` (see Figure 1), an adjustment hierarchy could be created (cf. Figure 2), where `Persons` expands `Person`, `Students` expands `Student` and `Employees` expands `Employee`.

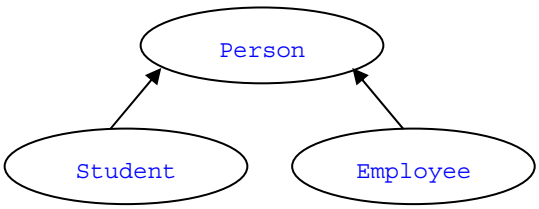


Figure 1: A subtype hierarchy

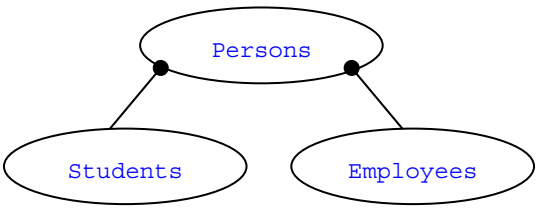
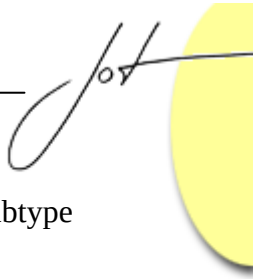


Figure 2: An adjustment hierarchy



Adjustment hierarchies preserve some features of inheritance without generating a subtype relationship.

Several advantages can accrue from this concept.

1) Input parameters (and of course return types) in the corresponding methods of an adjustment hierarchy can be safely changed covariantly.
2) An adjustment hierarchy can help the co-type designer to ensure that all cases are covered, because it provides a systematic approach which allows methods to be predefined, and these are available even for subtypes which are added later in the subtype hierarchy. Thus if a type `Manager` is added as a subtype of `Employee`, then by definition a co-type `Managers` appears in the adjustment hierarchy under `Employees`. This is particularly helpful when co-types are designed as components which can be added to different systems.
3) For the application programmer the existence of an adjustment hierarchy can guarantee that where certain methods exist in a co-type for an expanded type, similar methods will exist in co-types for all the subtypes of the expanded type.
4) Implementations of co-types can be re-used in implementations of other co-types in the adjustment hierarchy.

Here are some of the differences between a subtype hierarchy and an adjustment hierarchy, as illustrated from Figures 1 and 2:

- Whereas `Student` and `Employee` are subtypes of `Person`, `Students` and `Employees` are *not* subtypes of `Persons`. Thus an instance of type `Student` can be assigned to a variable of type `Person`, but an instance of type `Students` cannot be assigned to a variable of type `Persons`.
- A co-type functions only for its corresponding expanded type. Thus `Students` cannot act as a co-type for `Person` or `Employee`.
- Whereas a subtype hierarchy is open-ended and is extended explicitly, an adjustment hierarchy has a parallel set of nodes corresponding to those in the subtype hierarchy, starting at the node where a new co-type is explicitly defined.
- Because co-types in an adjustment hierarchy are not subtypes of their adjusting ancestors, methods in a higher level co-type need not appear in corresponding lower level co-types.
- Since any type can serve as an expanded type for a new co-type, it is possible for example to define an additional co-type `Students2` for `Student`, and co-types derived by adjustment from `Students2` will not apply to `Person` or `Employee` or their subtypes, but only to subtypes of `Student`.

The terminology "adjusting" and "adjusted" are used in this paper to indicate co-types and methods which have an adjustment relationship to each other. The ancestor(s) and the children of a co-type in the adjustment hierarchy is/are called its predecessor(s) and its successor(s).

We now consider a subtype hierarchy and show how an adjustment hierarchy for this might appear.

3 AN EXAMPLE – THE TIMOR COLLECTION LIBRARY

The Timor Collection Library (TCL) is a subtype hierarchy based on an abstract type `Collection`. An outline of the TCL was first presented in an earlier paper [8], which in some respects is now superseded by the concept of co-types as presented in this and the companion paper. In this section we draw liberally on the example as presented in the earlier paper.

Following a collection concept developed initially for Collja [4, 12, 13], the TCL defines the organisation of general collections according to the following orthogonal properties of their elements:

- *duplication* of elements in three forms:
  - duplicates are allowed,
  - duplicates are ignored,
  - duplicates are signalled as exceptions.
- *ordering* of elements in three forms:
  - unordered,
  - user-ordered,
  - sorted by user-defined criteria.

The TCL thus has nine concrete collection types, reflecting all the combinations of these properties. These are as follows:

Collection Type Name	Duplication Criterion	Ordering Criterion
Bag	Allow duplicates	No ordering
Set	Ignore duplicates	No ordering
Table	Signal duplicates	No ordering
List	Allow duplicates	User ordered
OrderedSet	Ignore duplicates	User ordered
OrderedTable	Signal duplicates	User ordered
SortedList	Allow duplicates	Sorted
SortedSet	Ignore duplicates	Sorted
SortedTable	Signal duplicates	Sorted

To facilitate their polymorphic use with a high degree of flexibility there are also five abstract nodes:

- the root type `Collection` (which serves as a polymorphic supertype for *all* collections);
- the type `DuplFree` (derived from `Collection`, a polymorphic supertype for all collections which may not contain duplicate elements),

- the type `Ordered` (derived from `Collection`, a polymorphic supertype for all ordered collections),
- the type `UserOrdered` (derived from `Ordered`, a polymorphic supertype for all user ordered collections) and
- the type `Sorted` (derived from `Ordered`, a polymorphic supertype for all sorted collections).

The complete structure is illustrated in Figure 3.

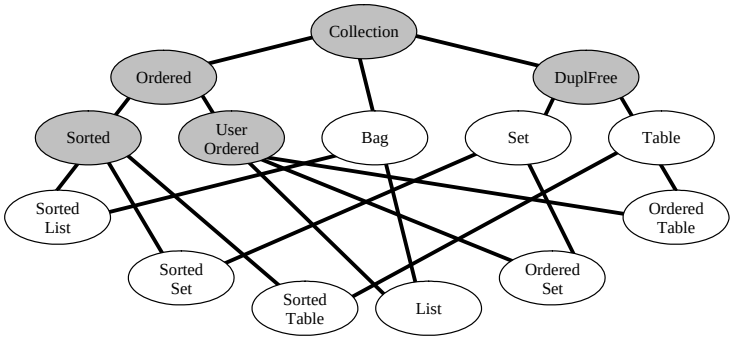


Figure 3: Structure of the Timor Collection Library

In order to guarantee behavioural conformity all the common methods of all collection types are initially defined in `Collection` with a maximum of behavioural flexibility. Thus its (abstract) method `insert`, for example, does *not* define

- how an insertion affects the ordering of the collection,
- whether the insertion will be successful if it involves inserting a duplicate,
- whether an exception will be thrown to indicate a duplicate (but it defines an exception DuplEx which might be thrown).

An abstract type with such methods is designed to allow a maximum of polymorphism. In derived types the actions of the `insert` method are specified more precisely, depending on the node in question. Thus the `insert` method of the abstract type `UserOrdered` defines that `insert` appends the element at the end of the collection (and adds new methods for inserting at other positions) but without defining its duplication properties further. On the other hand the `insert` method of the concrete type `Bag` is defined without specifying ordering, but indicating that duplicates are accepted (with the effect that the exception `DuplEx` can be removed from `Bag`'s `insert` method). The actual definitions of all the methods of `Collection` and its subtypes are not important in the present context.

4 BINARY METHODS

We now define a co-type which expands `Collection` with binary methods.

```
type Collections expands Collection {
binary:
```

```
 enq boolean equal(Collection*** c1, c2) throws NullPtr;
 // *** is the supertype of all modes of a type [5]
 // compares the elements of c1 and c2 for equality
 // ignoring their order (if any) but
 // taking into account the existence of duplicates.
}
```

This co-type does not include makers, because its expanded type `Collection` is abstract and therefore cannot be instantiated. However the co-type is a concrete type which provides a binary method for comparing concrete collection instances. The actual concrete types of the collections being compared are not important (provided that they are subtypes of `Collection`), because the comparisons are made ignoring the order (if any) of the elements. Similarly, because the comparison is made element by element it is not important how the actual collections are individually defined with respect to duplicates. (Notice also that the actual collections being compared can have different implementations, since the binary methods invoke the instance methods of their parameters to make the comparisons.)

Similar binary methods can be defined which use different criteria to make the comparisons. The `Collection` hierarchy provides an excellent pattern for defining these. For example, expanding the type `Ordered` results in the following co-type:

```
type Ordereds expands Ordered {
binary:
 enq boolean equal(Ordered*** c1, c2) throws NullPtr;
 // compares the elements of c1 and c2 for equality
 // taking into account their order and
 // taking into account the existence of duplicates.
}
```

Notice that in this case also, actual collections of different types can be compared, provided that they are subtypes of `Ordered`.

The following example compares concrete collections of the type `SortedSet`:

```
type SortedSets expands SortedSet {
binary:
 enq boolean equal(SortedSet*** c1, c2) throws NullPtr;
 // compares the elements of c1 and c2 for equality
 // taking into account their order.
 // Duplicates cannot exist in the parameters.
}
```

5 ADJUSTING PARAMETERS COVARIANTLY IN TIMOR

Each of the co-types defined above follows a similar pattern (in its definition), though in these examples the input parameters differ according to the type being expanded. For this reason it would not be safe to define them in a normal subtyping relationship.

The following co-type definition can form the basis for an adjustment hierarchy which has a co-type for each of the `Collection` subtypes. We have introduced three syntactic features which allow such a hierarchy to be defined.

```
type Collection&s expands Collection {
predefines binary:
 enq boolean equal(TheType*** c1, c2) throws NullPtr;
 // compares the elements of c1 and c2 for equality
 // ignoring their order (if any) but
 // taking into account the existence of duplicates.
 }
```

Since each co-type in an adjustment hierarchy is a separate type, it needs its own type identifier, and for all the successors of the highest node the identifier has to be created automatically. In order to achieve this, the type name of each adjusting co-type has three parts: the name of the expanded type (here `Collection`), the ampersand character (`&`) and a suffix (here `s`).

The names of adjusted co-types then consist of the appropriate subtype name, the ampersand character, and the same suffix, e.g. `Ordered&s, List&s`.

The ampersand character is not permitted in identifier names in Timor except in this context. This character signals that the co-type is part of an adjustment hierarchy. Several adjusting co-types can be created for the same expanded type, using different suffixes and co-types can be defined using normal identifiers, but the latter do not generate adjustment hierarchies.

The methods which must appear in each successor are listed in a section where the section name (here `binary`) is preceded by the keyword `predefines`.

The keyword `TheType`, which is not limited to predefining sections, indicates where covariant parameter adjustment takes place. In each individual co-type in the adjustment hierarchy the name of the corresponding expanded subtype is implicitly substituted for this keyword.

Although the use of `TheType` allows signatures for similar methods to be automatically generated, the methods themselves may need to be redefined in terms of their functionality and/or may need individual implementations.

6 COVARIANT MAKERS

We omitted makers from the co-type `Collections` (and the above version of `Collection&s)`, because their expanded type `Collection` is an abstract type, which cannot therefore be instantiated.

However, introducing adjustment allows makers to be predefined in a co-type for an abstract type, such that these only become run-time methods in co-types for its concrete subtypes. To achieve this we simply predefine makers in an analogous way to the predefinitions of binary methods.

We change the example of `Collection&s` to include predefined makers:

```
type Collection&s expands Collection {
predefines maker:
 op TheType init();
```

```
    // Returns a new empty collection value of type TheType.
    // Increments the count of collections of type TheType.
   op TheType convert(Collection*** c1) throws NullPtr;
    // Returns a new collection value of type TheType which
    // contains each element in c1 (possibly ordered and
    // possibly without duplicates). Increments the count of
    // collections of TheType.
  predefines binary:
   enq boolean equal(TheType*** c1, c2) throws NullPtr;
  }
```

Notice that the input parameter of the maker `convert` is not defined as covariantly adjustable. The reason is that it should be possible to create an instance of a specific collection type from instances of any subtypes of `Collection`, e.g. by merging them in such a way that the resulting order and duplication properties conform to the definition of the expanded type. This technique allows an instance of any concrete collection type to be converted (by copying the relevant elements) to an instance of any other concrete collection type.

7 INSTANCE METHODS

Instance methods of co-types can have parameters of the expanded type, and in this case parameters declared as `TheType` are adjusted covariantly in adjusted successor co-types.

Instance methods of co-types which play a role similar to that of class methods in conventional OO languages typically do not have parameters of the expanded type. Nevertheless it can make sense to provide these as predefined methods, even in cases where the expanded type is an abstract type. For example each co-type might maintain a count of the number of instances which its makers have created. Then each co-type could provide an instance method which returns the value of the count.

```
singleton type Collection&s expands Collection {
predefines instance:
 enq int instances();
  // returns the current count of instances of TheType
```

In this example the keyword `predefines` ensures that an appropriate instance method would exist in each co-type in the hierarchy. Timor ensures that `singleton` types have only one instance within a persistent file, see [11].

Instance Methods which are not Predefined

There are cases where it can be useful to define instance methods (but also binary methods and makers) which are not intended to appear in their adjusted co-types. For example if each collection object were to be provided with a unique serial number, then it would be possible to organise the allocation of serial numbers in a singleton object of the co-type `Collection&s`, e.g.

```
singleton type Collection&s expands Collection {
instance: // the following method is not predefined
 protected op int getNextSerialNumber();
  // returns the serial number for a new collection
...
}
```

In this case the makers for concrete subtypes of `Collection` would call the method and then initialise the newly created collection with the serial number. The method is not predefined, because only the singleton object instantiated from `Collection&s` would control the issuing of serial numbers.

Protected Methods and Co-type Hierarchies

As the above example illustrates, co-types can define `protected` methods as a mechanism by which controlled access is provided for other co-types in the same adjustment hierarchy.

8 DEFINING ADJUSTMENT HIERARCHIES

This section describes how successor co-types in an adjustment hierarchy can be defined in a manner analogous to the definition of subtypes in a conventional object oriented programming language, modifying the syntax for Timor's derived types where appropriate.

An Example Definition of Collection&s

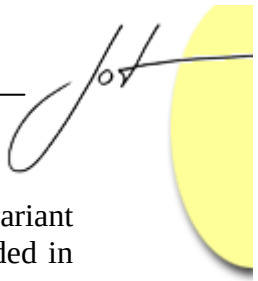
We begin by drawing together the previous examples to provide an overview of a co-type `Collection&s`, which includes a subset of the methods provided in the TCL. This serves as starting point for illustrating the principles of adjustment.

```
singleton type Collection&s expands Collection {
predefines maker:
 // A maker in an abstract type provides a pattern for
 // makers of concrete subtypes.
 // Makers in successors of Collection&s increase a count of
 // instances of the respective expanded types.
 op TheType init();
  // Successors for concrete expanded types return a new
  // empty collection value of type TheType.
 op TheType convert(Collection*** c1) throws NullPtr;
  // Successors for concrete expanded types return a new
  // collection value of type TheType containing relevant
  // elements in c1 in accordance with the definition
  // of TheType. For duplicate free types duplicates
  // are eliminated, but exceptions are not raised.
predefines binary:
 enq boolean equal(TheType*** c1, c2) throws NullPtr;
  // compares the elements of c1 and c2 for equality
  // ignoring their order (if any) but taking into account
  // the existence of duplicates.
predefines instance:
 enq int instances();
  // returns the number of instances created for TheType
  // which for Collection&s (and co-types of other abstract
  // expanded types) is always zero
}
```

This example automatically implies that co-types, which have the same predefining methods, exist for all the subtypes of `Collection`, and that these have names such as `Bag&s`, `List&s`, etc. These can be used without being explicitly defined, unless the programmer needs to make explicit modifications to the predefined methods or add new methods (which can but need not) be predefining.

Explicitly Modifying Implicit Co-Type Definitions

- To make changes to an implicit successor co-type the programmer provides an explicit definition of this which is introduced with the keyword `adjusts` (in an analogous way to the use of `extends` or `includes` for defining derived types in Timor [10, 9, 8, 7]).
- Methods with semantics which need to be redefined are explicitly described in a `redefines` section and in the adjusted co-type these *replace* the corresponding methods from the adjusting type, provided that the signature does not change (analogous to "overriding"). Changes involving only the meaning of `TheType` are not considered to be changes in this sense, and therefore require no redefinition.
- New methods can be added in the usual way in appropriate sections. If a new method is defined which has the same identifier as that of a predefined method but with a changed signature (other than changes involving only the meaning of `TheType`) then this method is considered to be a new method (analogous to “overloading”). In this case both the predefined method and the new method are present in the adjusted type.



- Where signatures of predefined methods need not be changed (except for covariant adjustments), neither the relevant section nor its methods need (but can) be included in the redefinition of the co-type.

Redefining Co-Type Methods: An Example

The binary method in this example needs a semantic redefinition in the co-type for ordered collections. Here is an extract illustrating this.

```
type Ordered&s expands Ordered {
adjusts: Collection&s;
redefines:
 enq boolean equal(TheType*** c1, c2) throws NullPtr;
 // compares the elements of c1 and c2 for equality,
 // taking into account their order and
 // taking into account the existence of duplicates.
 ...
}
```

Adding New Methods: An Example

A key difference between `UserOrdered&s` and its predecessor `Ordered&s` is that it introduces a new maker which creates a new collection that has the reverse order of its parameter, i.e.

```
type UserOrdered&s expands UserOrdered {
adjusts: Ordered&s;
predefines maker:
 op TheType reverse(Ordered*** c1) throws NullPtr;
  // Returns a new ordered value of type TheType
  // which contains elements in the reverse order from c1
  // Increments the count of collections of TheType.
 }
}
```

Notice that a `reverse` operation cannot be defined in `Ordered&s` because there is no reversal order which can produce a sorted collection (because these are ordered according to explicitly provided sorting criteria which affect the type definition). However, a sorted collection can be reversed, in which case it becomes a user-ordered collection. Unordered collections cannot be reversed, as they have no order.

Merging of Multiply Adjusted Co-Types for Diamond Inheritance

When an expanded type has two or more supertypes (as in the case of most of the concrete types in the collection hierarchy) the question of merging the corresponding adjusted co-types arises. This issue resembles that which arises in a subtyping hierarchy with diamond inheritance and is handled in an analogous way (see [8]).

Type Adjustment Rule 1: If in an adjusted type multiple methods which result from a common adjusting predecessor and which have the same signature (in this context including

parameters defined using the keyword `TheType`), they are treated as a single method (unless they have return types which differ from each other, in which case a compile time error arises). According to this definition makers, binary methods and instance methods can all be merged.

Type Adjustment Rule 2: If the definitions of such methods differ (i.e. if one or more of them has been redefined differently from the definition in their closest common predecessor), they must also be listed in a `redefines` clause in the type being defined.

Rule 2 in effect requires that conflicting definitions are clarified. Where a definition in one of the ancestors can be used in the new type this can be signalled by the use of the keyword `from` followed by the name of the appropriate co-type.

For example `List&s` is adjusted from both `UserOrdered&s` and `Bag&s`. One of the methods which it derives from both is the binary method `equal`, which can be redefined as follows:

```
type List&s expands List {
adjusts: Userordered&s, Bag&s;
redefines:
 boolean equal(TheType*** c1, c2) throws NullPtr
                                          from UserOrdered&s;
}
```

Merging of Multiply Adjusted Co-Types for Parts

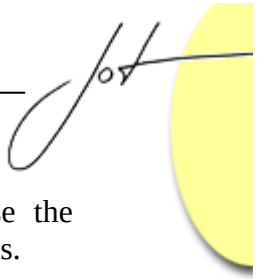
Lack of space prevents us from providing a detailed description of co-types for types which result from the multiple inheritance of separate types. However, the principles basically follow *mutatis mutandis* those used in defining the types themselves (see [9]). In the co-type the keyword `adjusts` is used instead of `extends` or `includes`, and in the case of repeated inheritance multiple co-type methods for a repeated expanded type are not required.

9 IMPLEMENTING ADJUSTMENT HIERARCHIES

In accordance with the normal Timor implementation approach [10, 8] any type (including a co-type) can have different implementations coded in different ways. Code is inherited neither in implementations of subtypes nor in successor co-types, and like any other type, these can be implemented from scratch. The only relationship which might exist between implementations of related types is via re-use variables. However re-use variables can also, where appropriate, be based on implementations of types which are unrelated to the type which is currently being implemented [6, 9][1].

As at the type level, the keyword `TheType` can appear anywhere in the code of a co-type implementation as if it were the name of the expanded type of the co-type currently being

[1] The re-use variable technique is related to delegation, but is more efficient. If the types of re-use variables have interface methods which match those of the type being implemented, then the corresponding method implementations are treated as the required implementations, unless the method is explicitly re-implemented. A re-use variable can also be used like any other internal variable.



implemented. The keyword `predefines` is not used in implementations, because the compiler does not automatically produce adjusted implementations of successor co-types.

We illustrate an implementation of `Collection&s` and then show how this can be re-used to implement successor co-types.

An Example Implementation of Collection&s

For illustration purposes the makers in this example return a linked implementation of the corresponding expanded `Collection` type. (An algorithm which chooses between different implementations of the expanded type could of course be used, but this would unnecessarily complicate the example.)

```
impl Collection&s::Impl {// implementation names consist of
// the type name and an implementation name, separated by ::
state:
 int instanceCount = 0;
maker:
 op TheType init() { // implementations can be provided for
  // makers in a co-type for an abstract expanded type
  // for re-use in successor co-types.
  instanceCount++;
  return TheType::LinkedImpl();
 }
 op TheType convert(Collection*** c1) throws NullPtr {
  // this algorithm functions correctly for all concrete TCL
  // subtypes despite differing definitions of the expanded
  // types but in some cases more efficient code is possible
  if (c1 == null) throw new NullPtr;
  TheType c = TheType::LinkedImpl();
  for (ELEM x in c1) { // ELEM is the generic type of
    // elements in a collection. Generic issues have been
    // ignored in this paper, but will be the subject
    // of a later paper.
   try { c.insert(x); }
   catch (DuplEx de) { /* ignore it!*/ };
   }
  instanceCount++;
  return c;
 }
binary:
 // binary methods can be invoked, even if TheType is
 // abstract.
 enq boolean equal(TheType*** c1, c2) throws NullPtr {
  // This algorithm needs modification for co-types of
  // subtypes of some expanded types
  if (c1 == null || c2 == null) throw new NullPtr;
  if (c1.size() != c2.size()) return false;
   for (ELEM x in c1) {
    if (c1.occurrences(x) != c2.occurrences(x))
    return false;
```

```
    }
    return true;
  }
  enq int instances() {
   return instanceCount;
  }
}
```

Implementing the Successor Co-Types

We now try to use the normal Timor re-use variable technique (see [6, 9]) in an attempt to implement `Bag&s`. Our first attempt might be along the follow lines:

```
impl Bag&s::Impl {
state:
^Collection&s collections s = Collection&s::Impl();
  // a re-use variable is indicated by a hat symbol
}
```

The methods of `Collection&s` match those of `Bag&s`, and in principle the implementations require no changes, since neither new methods nor code overriding is required. However in the process of matching the methods of `Collection&s` to those of `Bag&s` a type problem arises because the relevant parameters have not been covariantly adjusted.

To overcome this problem we extend the idea of re-use variables to take covariant adjustment into account, and to make this clear such re-use variables are denoted by a double hat symbol, as follows

```
impl Bag&s::Impl {
state:
^^Collection&s collections = Collection&s::Impl();
  // an adjusted re-use variable is indicated by a double
  // hat symbol
};
```

To achieve the adjustment each use of `TheType` in `Collection&s::Impl` is adjusted to the expanded type of the current implementation, i.e. in this case each occurrence of `TheType` is treated as if it means `Bag`.

The expanded type `Bag` is a concrete type, but `Collection&s::Impl` was framed in such a way that no further change is necessary. In fact the following further co-types could be implemented in a similar way: `DuplFree`, `Set`, `Table`. However, all three could be more efficiently implemented, e.g. as follows:

```
impl DuplFree&s::Impl {
state:
^^Collection&s collections = Collection&s::Impl();
binary:
 enq boolean equal(TheType*** c1, c2) throws NullPtr {
  if (c1 == null || c2 == null) throw new NullPtr;
  if (c1.size() != c2.size()) return false;
   for (ELEM x in c1) {
    if (!(x in c2)) return false;
  }
  return true;
 }
}
```

In this case we have simply "overridden" the `equal` method from `Collection&s` with more efficient code. (There is no confusion with matching, since a method which is explicitly re-implemented results in a non-match with the re-use variable.) But now `Set&s` (and `Table&s`) could be implemented as

```
impl Set&s::Impl {
state:
^^DuplFree&s duplfrees = DuplFree&s::Impl;
}
```

Implementing the Co-Types for Ordered Collections

The same principles can easily be applied to `Ordered&s` and its successors, where in this case the ordering of elements is important for the binary method `equal`.

```
impl Ordered&s::Impl {
state:
^^Collection&s collections = Collection&s::Impl();;
binary:
 enq boolean equal(TheType*** c1, c2) throws NullPtr {
  if (c1 == null || c2 == null) throw new NullPtr;
  if (c1.size() != c2.size()) return false;
  int pos = 0;
   for (ELEM x in c1) {
    if (x != c2[pos]) return false;
    pos++;
  }
  return true;
 }
}
```

This co-type implementation could, for example be re-used in `UserOrdered&s`, which also needs an additional maker, e.g.

```
impl UserOrdered&s::Impl {
state:
^^Ordered&s ordereds = Ordered&s::Impl;
maker:
 op TheType reverse(Ordered*** c1) throws NullPtr;
```

```
    TheType c = TheType::LinkedImpl();
    for (ELEM x in c1) {
     try { c.insertAtPos(0); }
     catch (DuplEx de) { /* ignore it!*/ };
     }
    instanceCount++;
    return c;
   }
  }
```

Handling Multiple Predecessors

In this example some co-types have multiple predecessors. In principle it would be possible to nominate multiple re-use variables (which could be relevant for cases involving parts inheritance [9]), but in this example it is not necessary to do so. For example `List&s` has two predecessors, but its implementation can simply re-use `UserOrdered&s`.

Alternative Implementations

As we demonstrated for example in [8] the way in which re-use variables are applied need not follow a pattern similar to subclassing. It would for example be equally feasible to begin the implementations with an implementation of `List&s` and re-use this to implement the other co-types in the TCL.

10 FURTHER CODE RE-USE TECHNIQUES

The techniques described previously can result in very significant savings both at the type and implementation levels. However, they do not illustrate how the code of predecessor co-types can be re-used in cases where methods are not predefined.

Suppose that a type `Person` has been defined with three abstract variables `name`, `address` and `dateOfBirth`. A co-type `Persons` might expand `Person` by defining a maker `init` with parameters for initialising the three abstract variables and a binary method `equal` which compares the values of the three abstract variables. It is not intended that successor co-types should have exactly equivalent makers or binary methods and therefore these are not declared as predefining. As we shall see it can nevertheless help with re-use if the methods are coded in terms of `TheType`:

```
type Persons expands Person {
maker:  // not predefining
 op TheType init(String name, addr; Date dob);
binary: // not predefining
 enq boolean equal(TheType p1, p2);
}
```

Here is an implementation of `Persons`:

```
impl Persons::Impl {
maker:
 op TheType init(String name, addr; Date dob) {
  TheType p = TheType::Impl();
  p.name = name; p.addr = addr; p.dob = dob;
  return p;
 }
binary: // not predefining
 enq boolean equal(TheType p1, p2) {
  return ((p1.name == p2.name) &&
          (p1.addr == p2.addr) &&
          (p1.dob == p2.dob));

 }
}
```

A type `Student` might extend `Person` by adding two abstract variables `uniName` and `matricDate` and this could have a co-type `Students` which defines a maker with parameters for initialising both `Person`-related and `Student`-related variables. A binary method might compare the values of all five abstract variables. The co-type for `Student` is not adjusted from `Persons`. We use different method names to emphasize this.

```
type Students expands Student {
maker:  // not predefining
 op TheType newStudent(String name, addr; Date dob;
                       String uniName; Date matricDate);
binary: // not predefining
 enq boolean compare(TheType p1, p2);
}
```

Because `Persons` is defined in terms of `TheType` an implementation of `Students` could re-use an implementation of `Persons` as follows:

```
impl Students::Impl {
state:
 ^^Persons persons = Persons::Impl();
maker:
 op TheType newStudent(String name, addr; Date dob;
                 String uniName; Date matricDate) {
  TheType s = persons.init(name, addr, dob);
  s.uniName = uniName; s.matricDate = matricDate;
  return s;
 }
binary:
 enq boolean compare(TheType p1, p2) {
  return ((persons.equal(p1. p2)) &&
          (p1.uniName == p2.uniName) &&
          (p1.matricDate == p2.matricDate));
 }
}
```

Thus `Students::Impl` re-uses the code of `Persons::Impl` in order to initialise/compare the `Person` details and then adds further code to initialise/compare the `Student` details. Notice that in this context *any* implementation of `Persons` could be re-used.

In summary, although the methods of a co-type may not be predefining (nor even have the same names) the modified re-use technique can be applied to good effect to re-use the co-type in implementations of related co-types.

11 RELATED WORK

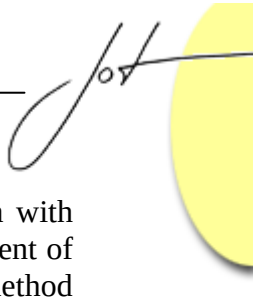
Co-type adjustment represents a limited form of covariant parameter adjustment as found for example in Eiffel [15, 14]. This technique has fallen into disrepute because in the case of input parameters[2] it can lead to breaches of static type safety in connection with subtyping (cf. [3, 16, 17]).

Bruce et al. [2] examined this issue with respect to binary methods in considerable detail. The essence of their discussion is that covariant adjustment of parameter types cannot be fully reconciled with inheritance, that there can be a loss of symmetry and that privileged access to the code of one binary parameter can be lost. In the Timor philosophy privileged access is not encouraged, because we see it as a violation of the information hiding principle. It will be evident to readers that Timor treats binary method parameters symmetrically in co-types, albeit not in the sense of Bruce et al.

More significantly, by defining binary methods as instance methods in co-types Timor side-steps the issue of reconciling covariant adjustment with inheritance. This separation makes covariance possible in an adjustment hierarchy (not only for binary methods but also for makers and instance methods), leaving the possibility of subtype polymorphism open not only for expanded types but also (independently) for co-types, provided that they expand the same type. Hence all the aims formulated by Bruce et al. are reconciled in Timor, albeit in an unconventional way.

The benefits of covariant input parameters for binary methods can be partly achieved via overloading, e.g. with Java and C++. When overriding inherited methods the number and types of input parameters must be retained unchanged, but the same-named methods with covariant parameter types can be added in subtypes. However, using this possibility can easily lead to confusion, if attention is not paid to the fact that the selection of the fitting method at compile-time depends on the statically declared types of the objects involved. Therefore explicit type conversions may be necessary to ensure that the desired methods will be called. Type checks and type conversions at run-time are inevitably incurred when overriding an inherited binary method, but using overloaded methods instead does not always eliminate these. Overloading the Java equals-methods for example is not recommended, because it is considered costly and error-prone (see [1] pp.26-35). By contrast the Timor approach simplifies the programmer's task and avoids additional run-time checks.

[2] Covariant changes to return types were added to the 1998 version of C++ and to the 2005 version of Java, because this does not create breaches of static type safety.



Finally, in his PhD thesis [16] Schmolitzky proposed avoiding a further problem with binary class methods which arises as a result of static binding, by allowing the equivalent of Timor's `TheType` to be used to select, for example, the appropriate `equal` method dynamically, i.e. by using a syntax which in Timor might look like `TheType.equal(p1, p2)`. However, because Timor co-types do not use static binding, this problem does not exist and therefore Timor does not support this use of `TheType`.

12 CONCLUSION

The paper builds on the concept of co-types described in a companion paper [11], adding the idea that co-types can be enhanced in a new hierarchical arrangement which superficially resembles subtyping but which has some crucial differences. The basic idea of an adjustment hierarchy is that the definitions and implementations of makers, binary methods and instance methods (corresponding to static methods in conventional class based languages) for expanded types can be adjusted covariantly to match the subtyping hierarchy of the expanded types without creating problems for static type safety. Some of the additional advantages of this technique are as follows.

Using adjustment hierarchies can help the co-type designer to ensure that all cases are covered, because they provide a systematic approach by predefining methods. The implementer of a hierarchy can also take advantage of implementations of other co-types in that the compiler can automatically adjust re-use variables covariantly.

For the application programmer using co-types an adjustment hierarchy guarantees that certain makers, binary methods and instance methods (i.e. those which are predefined) exist in co-types for all the types in a subtype hierarchy.

From the technical viewpoint covariant adjustment can be used not only for return types but also for input parameters in a type safe manner.

Over and above this, the idea of co-types as such is very useful, providing a modular basis on which types and their co-types can be expanded in different ways, allowing them to be designed and implemented as separate components by software houses and even to be concurrently used in a single system, in contrast with the conventional idea of supporting a single hidden "class object" associated with each class.

Finally we note that adjustment hierarchies (and all their advantages) can be used not only where the expanded type has a hierarchy of subtypes, but also where expanded types are derived by inclusion and therefore do not have a subtyping relationship [10].

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