Using Object-Oriented Principles to Optimize Update Propagation to Materialized Views [*]

Harumi A. Kuno and Elke A. Rundensteiner
Dept. of Elect. Engineering and Computer Science
Software Systems Research Laboratory
The University of Michigan, 1301 Beal Avenue
Ann Arbor, MI 48109-2122
e-mail: kuno@umich.edu, rundenst@eecs.umich.edu
fax: (313) 763-1503
phone: (313) 936-2971

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Abstract

View materialization is known to be a valuable technique for performance optimization in relational databases, and much work has been done addressing the problem of consistently maintaining relational views under update operations. However, little progress has been made thus far regarding the topic of view materialization in object-oriented databases (OODBs). In this paper, we demonstrate that there are several significant differences between the relational and object-oriented paradigms that can be exploited when addressing the object-oriented view materialization problem. For example, we can use the subsumption relationships between classes to identify branches of classes to which we do not need to propagate updates. Similarly, we can use encapsulated interfaces combined with the fact that any unique database property is inherited from a single location to provide a "registration" service by which virtual classes can register their interest in specific properties and be notified upon modification of those properties. We describe a number of techniques that take advantage of such data model differences to optimize the maintenance of materialized views in the object-oriented model. We have successfully implemented all proposed techniques in the *MultiView* system, which provides updatable materialized classes and virtual schemata on top of the GemStone OODBMS. In this paper, we also report results from the experimental studies we have run on the *MultiView* system measuring the impact of various optimization strategies incorporated into our materialization update algorithms.

Keywords: Incremental view maintenance, object-oriented views, distributed registration, classification, view updatability.

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1 Introduction

Views have been established as an effective tool by which database programmers can virtually restructure a schema so that it meets the needs of specific applications. Typically, the contents of a view are derived using the view's stored query, in which case each query upon the extent of a view must be translated into a query upon the view's source classes. In relational systems, this is known as *query modification* [9].

View materialization, i.e., the maintenance of derived extents of views as opposed to recomputing them upon demand, has been demonstrated in the relational model to improve the performance of queries. If the view is materialized, then its contents must be maintained in the face of updates to the view's sources. While a number of researchers have proposed view systems in the context of object-oriented databases (OODBs) [1, 11, 17, 27, 24, 25, 26], little work has been done on the support of materialized OODB views. Here at the University of Michigan, we are developing *MultiView*, a view management system capable of supporting updatable materialized object-oriented views [24, 16, 25, 26, 19].

In a previous paper [19], we introduced our implementation (using object-slicing techniques) of the *MultiView* model for object-oriented view materialization. In this paper, we present the results of our research regarding the optimization of update propagation. First, we identify potential inefficiencies that can affect propagation algorithms (e.g., the propagation of updates to irrelevant derived classes and the propagation of self-cancelling updates). Second, we propose new techniques to propagate updates efficiently using object-oriented principles. Third, we discuss experimental studies we have conducted to evaluate the performance impact of our optimizations on the *MultiView* prototype.

We draw upon several techniques from previous relational work in the area. For example, [6] perform incremental view maintenance using production rules that are triggered by update operations. [3, 4] test modified tuples to see if they fulfill view predicates. We also use these strategies of triggering incremental view maintenance and filtering irrelevant updates. However, our current work exploits unique features of the object-oriented paradigm to adapt these solutions to the OODB view materialization problem. The generalization hierarchy structure makes the subsumption relationships between classes readily apparent. We thus propose an update propagation algorithm that identifies branches of classes to which we do not need to propagate updates. In addition, because we integrate virtual classes into the global schema as full-fledged citizens, we can use encapsulated interfaces combined with the fact that any unique database property is inherited from a single location to provide a "registration" service. Our registration strategy allows virtual classes to register their interest in specific properties and be notified upon modification of those properties. We introduce in this paper an *optimized distributed registration* technique that exploits knowledge about the subsumption relationships between classes to distribute the registrations along the generalization hierarchy and avoid unnecessary propagation.

We present a performance analysis that assesses the costs and benefits of our materialization techniques. Because we have implemented the *MultiView* system [1], we were able to evaluate actual implementations of each proposed update propagation algorithm (rather than just simulations). Specifically, we analyze the performance of non-materialized views, incrementally updated materialized views, and optimized incrementally-updated materialized views. In constructing our cost models, we identify a number of factors that affect the cost of propagating updates to materialized views and retrieving the contents of non-materialized views. The results of our experiments validate our cost models.

We begin by discussing work related to ours in Section 2. In Section 3, we review the *MultiView* object model and describe the representational model underlying our implementation. We exploit unique features of the object-oriented model in Section 4 to develop efficient update propagation techniques. In Section 5 we derive cost formulae and compare the performance of each of the proposed algorithms in terms of representative models. Finally, in Section 6 we present conclusions and propose future work.

2 Related Work

Relational and object-oriented systems share a common motivation for view materialization: the goal of improving query performance. Although not much work has been done regarding OODB view materialization, object-oriented and relational systems both must address a number of common issues when designing a view materialization system, such as when to evaluate updates and how much to update. Our research on view materialization in OODBs borrows several techniques from the relational arena. [3, 4] tests modified tuples to see if they fulfill view predicates, thereby detecting irrelevant and autonomously computable updates. This resembles our solution of filtering irrelevant updates by exploiting the generalization hierarchy

[1]The current *MultiView* prototype has been built on top of Servio Corporation's GemStone OODBB product.

and the derivation structure. The system provided by [6] performs incremental view maintenance using production rules that are triggered by update operations. Similarly, we override generic-update operations with type-specific update operators for virtual classes.

However, there are significant differences between view materialization in OODBs and relational systems.

- Tables in relational databases (RDBs) are arranged in a "flat" fashion in the schema. There is no information about the subset or subtype relationships contained between tables in the schema. Both virtual and base classes in the *MultiView* model are arranged in an *integrated generalization hierarchy*. Information about the relations between the types and extents of OODB classes can thus be easily recognized by database users. Furthermore, update propagation techniques can be designed to exploit the object membership information that is implicit in the hierarchical structure in order to terminate propagation as soon as appropriate.

- Views in RDBs refer to virtual tables that are formed by applying query operations to base tables. Because an OODB schema is organized into a generalization hierarchy, OODB views include both virtual classes (formed by applying query operations to base classes) and virtual schema (formed by applying query operations to a base or view schema).

- Attributes in RDBs are identified only as the names of columns in tables. If two relational tables each have an attribute with the same name, there is no guarantee that the two attributes refer to the same property. Each property in the *MultiView* model is defined at a single class and using property inheritance shared by other classes. Database users can thus unambiguously identify whether or not two properties represent the same instance variable or method. In addition, when a predicate term in a virtual class's query invokes a given property, we can identify exactly which class defines that property, enabling us to *localize the effects of updates*.

- Attributes in RDBs are associated with simple values. Although the simple value can be a foreign key referring to a row in another table, RDB attributes cannot contain sets or other complex data structures. Instance variables in OODBs, on the other hand, can contain references to actual objects or sets of objects. OODBs thus contain *aggregation relationships* that can be used in view formation queries.

- The values of relational attributes are updated using generic queries, and thus update procedures must be implemented for the general case. On the other hand, because OODBs support *encapsulation*, updates to attributes are localized to specific accessing methods that are themselves defined at a single identifiable class. We can embed our update propagation methods into the accessing methods for the properties referenced by the predicates of materialized virtual classes. The accessing methods then serve as *update triggers*.

- Data in RDBs exists as values in tables. Thus when virtual tables in RDBs are materialized, the materialized tables typically contain *copies of data values* from the base tables [2]. On the other hand, data in OODBs exists as objects that can be uniquely identified and then accessed using unique object identifiers (oids). Thus when virtual classes in OODBs are materialized, the materialized classes can contain references to the relevant objects rather than value duplicates (copies) of the original objects. This not only saves space, but also significantly simplifies the view update problem. Furthermore, regardless of which properties are "hidden" by a "project" query, objects belonging to a virtual class can be easily associated with their base incarnations. In fact, this provides us with a basis for the arbitrary restructuring of an object's look and feel without compromising its identity.

Only a few published papers address issues of view materialization in OODBs. [10] provide a view materialization model in which updates are propagated by use of change files, representing histories of design sessions. However, [10] duplicate objects (including identifiers) for virtual classes rather than merely storing references to objects. [14] address maintaining consistency for a particular type of join class formed along an existing path in the aggregation graph. Our work instead focuses on the exploitation of the structure of the schema hierarchy and derivation dependency graph in order to reduce update propagations. Our research is also unique in studying incremental updates in the context of the object-slicing paradigm.

Although the object-slicing techniques underlying the current implementation of *MultiView* can be compared to mechanisms used in *role modeling* approaches [28, 21, 8], no other research in the literature discusses

[2]Note that some materialized RDB views may be implemented using techniques such as view indices that resemble membership materialization.

the application of the object-slicing paradigm regarding the support of object-oriented views. The role system proposed by Gottlob et al. was implemented using techniques similar to object-slicing [8]. This system, like ours, is implemented in Smalltalk. The difference between [8] and our implementation is that [8] is a role system, whereas we are developing a view system. Role systems strive to increase the flexibility of objects by enabling them to dynamically change types and class membership. View systems, on the other hand, enable users to restructure the types and class membership of complete classes—based on content-based queries. For example, unlike [8], we do not permit entities to occur several times in the same type of role. Also, the [8] system does not permit the derivation of new virtual classes, and thus does not address issues related to view management.

3 The *MultiView* Model and System

In this section, we review the basic object model principles of the *MultiView* system and outline the architectural model underlying our implementation.

3.1 Basic *MultiView* Object Model

Let O be an infinite set of object instances. Each object $O_i \in O$ consists of state (the **instance variables** or attributes), behavior (the **methods** to which the object can respond), and a unique object identifier. Because our model is object-oriented and assumes full encapsulation, access to the state of an object is only through **accessing methods** (an accessing method modifies or retrieves the value of an instance variable). Together, the **methods** and **instance variables** of an object are referred to as its **properties.**

Objects that share a common structure and behavior are grouped into sets, denoted **classes**. We use the term **type** to indicate the set of applicable property functions shared by all object-instances of the class. Let C be the set of all classes in a database. A **class** $C_i \in C$ has a unique class name, a **type**, and a set membership denoted by **localExtent**(C_i) or short, **extent**(C_i) [3]. The instance variables of a class's type can be **constrained** to a specific class.

For two classes C_i and $C_j \in C$, C_i is a **subtype** of C_j, denoted $C_i \preceq C_j$ if and only if (iff) (**properties**(C_i) $\supseteq$ **properties**(C_j)). C_j is a **supertype** of C_i iff C_i is a subtype of C_j. All properties defined for a supertype are **inherited** by its subtypes. Similarly, C_i is a **subset** of C_j, denoted $C_i \subseteq C_j$, iff $(\forall o \in O)((o \in C_i) \Rightarrow (o \in C_j))$. Thus **globalExtent**($C_i$) $= \bigcup$ **localExtent**(C_j) $\forall C_j \subseteq C_i$. C_j is a **superset** of C_i, denoted $C_j \supseteq C_i$, iff $C_i \subseteq C_j$. C_i is a **subclass** of C_j, denoted C_i *is-a* C_j, iff $(C_i \subseteq C_j)$ and $(C_i \preceq C_j)$. C_i is a **direct subclass** of C_j if $\nexists C_k \in C$ s.t. $k \neq i \neq j$, C_i *is-a* of C_k, and C_k *is-a* of C_j.

An **object schema** is a rooted directed acyclic graph $G = (V, E)$, where V, the finite set of vertices, corresponds to classes $C_i \in C$ and E, the finite set of directed edges, corresponds to a binary relation on $V \times V$ that represents all direct *is-a* relationships. Each directed edge $e \in E$ from V_1 to V_2 represents the relationship C_1 *is-a* C_2. Two classes $C_i, C_j \in C$ share a common property iff they inherit it from the same superclass. The designated root node, **Object**, has a global extent equal to all database instances and an empty type description.

3.2 Object-Oriented Views

We now extend our basic model to include views. The set of all classes, C, is partitioned into two sets—BC is the set of all base classes, and VC is the set of all virtual classes in the database. **Base** classes are defined during the initial schema definition. **Virtual** classes are defined by the application of a query operator to a **source class(es)** that restructures the source's type and/or extent membership. They can be added dynamically to the schema throughout the lifetime of the database. The virtual-class-forming operations supported by the current implementation include the following algebra operators: hide, refine, select, union, intersect, join, and difference. These queries determine the methods, instance variables, and extent of the virtual classes. The join operator is *object-generating*; all other operators are *object-preserving.*

We identify two types of predicates used in virtual-class defining queries. **Class membership predicates**, inherent in hide, union, intersect, refine, and difference queries, are predicate terms that depend upon the classes to which an instance belongs [4]. **Value predicates**, used by select queries, are predicate terms

[3] Although there is no general agreement on whether classes in OODBs should incorporate their own extents or require users to maintain their own collections of class-instances, several systems follow this philosophy, including [13, 12]. Furthermore, the proposed ODMG standard [2] recently formulated by several key OODB vendors also follows this approach.

[4] Set operations are the most typical type of queries using class membership predicates, because they function by using the presence of objects in source classes rather than by checking value-based predicates.

constraining instances based on the values of their local instance variables. The **membership-dependent** and **value-dependent** dependencies between classes follow from these predicates. For example, a virtual class formed by applying a *hide* query to a source class is **membership-dependent** upon that source class. Similarly, a virtual class formed by applying a *select* query that uses some instance variable's value is **value-dependent** upon that property (and hence the class that defines that property). We later use these definitions of dependencies to identify the classes that are affected by an update.

Each virtual class $VC_i \in VC$ maintains the query that initially defined it. In addition, each class C_i maintains a set of all virtual classes $VC_j \in VC$ directly derived from it. We use the notation VC_j **derived-from** C_i to indicate that a class C_i is a source class of a virtual class VC_j. We use the term **Derived-from-Sub-Graph** of V_i to refer to the schema $DS(V_i) = (DV, DE)$ containing all the classes either directly or indirectly derived from V_i.

We define a **materialized virtual class** as a virtual class that caches its extent rather than computing it upon access. We do not replicate objects that belong to materialized virtual classes, but instead store references to them [5]. We refer to this feature as **membership materialization**. As it depends upon oid support, membership materialization is unique to the object-oriented model. This feature reduces the storage overhead of materialization as well as the time and effort required for view update propagation (demonstrated in Sections 4 and 5).

We define a **global schema** as a database schema containing all database classes, both base and virtual, and a **view schema** as containing a user-selected subset of the classes from the global schema. These schemata each have an integrated generalization hierarchy. In our model, virtual classes function as first-class citizens in the global hierarchy, i.e., they inherit and provide properties for inheritance just like base classes. In order to maintain this global class hierarchy, our view management system supports a flexible classification mechanism that is able to make dynamic changes to the class hierarchy, e.g., inserting a new class between two existing classes. We have proposed elsewhere [16, 26] algorithms and techniques to automatically maintain the global class hierarchy. Classification offers unique opportunities for optimizing update propagation to materialized views, as will be discussed in Section 4.

3.3 Object-Slicing Representation

Introducing virtual classes and schemata requires the underlying data model to support the following features:

multiple classification If an object instance qualifies for membership in two virtual classes, then it should belong to both even if no subsumption relationship exists between the virtual classes.

dynamic reclassification Furthermore, an object instance should dynamically gain (or lose) the type of a *virtual class* (e.g., select or join view) if its data values change so that it fulfills (or ceases to fulfill) the class's selection predicate.

dynamic restructuring Objects must be able to flexibly gain and lose types (e.g., select views) during their lifetimes, including both the data stored in their state as well as the set of methods to which they can respond.

multiple inheritance Certain virtual classes, such as those formed by *intersect* queries, must inherit properties from both their source class types.

With the exception of the IRIS functional DBMS [7], which uses a relational database as storage structure, storing data from single objects across many relations, most commercial OODB systems represent each database object as a chunk of contiguous storage determined at object creation time and do not support the features identified as required for view support. We thus could not directly use existing OODB technology to implement *MultiView* . As described elsewhere [22, 19], we adopt an *object-slicing* technique to provide a means of supporting these required features [20]. In object-slicing, a real-world object corresponds to a hierarchy of **implementation objects** (one for each class whose type the object possesses) linked to a **conceptual object** (used to represent the object-itself) rather than associating one implementation with each conceptual object as is commonly assumed in OODBs. This technique of using implementation objects to represent an object's membership in multiple classes is extremely flexible, and provides a solution that extends an OODB system to support all requirements needed to implement our view model.

The object-slicing paradigm can be formalized as follows. Let $O_i \in O$ be a user-defined object. In the object-slicing model, O_i is represented using two kinds of objects: a single conceptual object, $O_{i_{conc}}$ and one implementation object for each class $C_j \in C$ to which the object belongs, $O_{i_{impl_{C_j}}}$. A **conceptual object**

[5] In fact, as we will describe in the following sub-section, we employ an object-slicing technique for object materialization.

consists of a tuple, <***implObjects, OID***>, where OID is the unique, system-generated object-identifier of the conceptual object, and *implObjects* is the set of **implementation objects** that are linked to the conceptual object. An **implementation object** is a tuple <***OID,oid,class,state***> where OID is the object-identifier of the linked conceptual object, *oid* is the object-identifier of the implementation object itself [6], *class* is the class of which the implementation object is a direct instance, and *state* corresponds to the values of the local instance variables stored for the given object. Each implementation object $O_{i_{impl_{C_j}}}$ is an object instance of the database class $C_j \in C$ it represents. Conceptual objects are object instances of a special system class, *ConceptualObject*, rather than of a user-defined class.

For example, Figure 1 depicts a schema composed of two base classes, *Cat* and *HouseCat*, and two virtual classes, *LightCat* (derived from a selection query upon the *Cat* class) and *NamedLightCat* (derived by refining *LightCat* to add a new instance variable, `name`). The right-hand side of the figure illustrates a single instance of the *HouseCat* class with instance variables `height = 9"`, `weight = 7lbs`, and `owner = Fred`. Because the instance fulfills the membership requirements of *LightCat* (weight < 9 lbs), it belongs to both virtual classes. Note that the state of the object is maintained by the implementation objects of the classes defining each property.

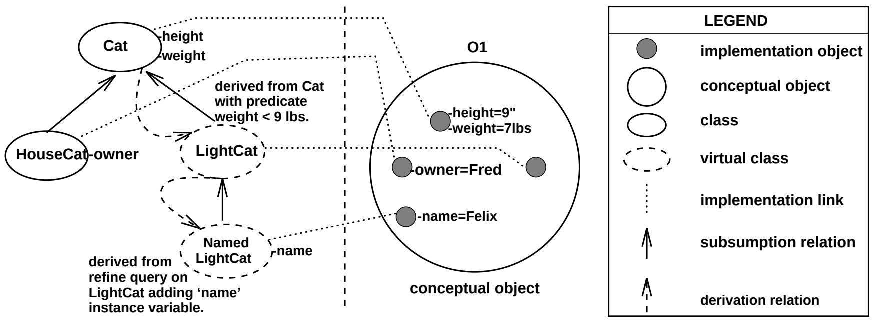


Figure 1: Example of object-slicing.

Because a single real-world object is now represented using multiple database objects, we define a number of functions to operate on objects in the model, including object creation, equality comparison, etc. For example, we say that two objects are *equal* iff they are linked to the same conceptual object. Similarly, given an object $O_i \in O$ and a class $C_j \in C$, we define functions **MakeImpl(**$O_{i_{conc}}$,C_j**)** and **DeleteImpl(**$O_{i_{conc}}$,C_j**)** to create and destroy implementation objects of class C_j for object $O_{i_{conc}}$.

Classification of virtual classes, as shown in Figure 1, may lead to the problem of select upwards and downwards inheritance [1]. In contrast to previous work in this area, we have explored a unique solution for the preservation of uniform upwards inheritance—we **promote** methods and/or attributes from a subclass to a new superclass during the classification of a new virtual class into the global schema in order to ensure that the property will be located above all the classes that inherit that property [7]. This promotion, called **property migration**, ensures a single point of inheritance for both instance variables and methods. Instance variable values are thus shared by both base and virtual classes without duplication. The existence of a **single point of inheritance** combined with the object-slicing approach guarantees that no more than two classes (the original class where the properties currently reside, and the new class to which they are being moved) will ever be involved in such a migration [19].

The object-slicing technique, combined with the characteristic of **single point of inheritance** and **classification**, lends itself well to materialization, because (1) it elegantly avoids the need to duplicate data for materialized classes and (2) any update to an object will take place at a unique location determined by the property involved regardless of the source of the update request. For example, the *LightCat* virtual class in Figure 1 directly shares the `height` attribute with the *Cat* class—without duplicating its value. Consequently, regardless of whether the update is specified via the *Cat* or the *LightCat* class, the same copy

[6] Each implementation object by default possesses its own object identifier. However, because the implementation object serves as an interface for a specific conceptual object, the object-identifier of the conceptual object supersedes that of the implementation object for most practical purposes, such as determining object-equality.

[7] The methods used to set or retrieve an instance variable's value are called **accessing methods**. Accessing methods are always located at the same class as the instance variables for which they are defined, and thus when an instance variable migrates from one class to another, that instance variable's accessing methods must make the same migration.

of the `height` attribute will be modified. Since object-slicing requires an object to possess implementation objects for any class to which it belongs, an object-slicing view implementation is effectively materialized in that the implementation objects representing an object's membership in virtual classes are actual object-instances of those virtual classes. The object-slicing technique is thus subject to the intrinsic problem of view materialization – how to update materialized views so as to keep their extents consistent with the rest of the database. Details on implementation issues in our model such as method resolution, inheritance mechanisms, etc., can be found elsewhere [15, 22].

Object-slicing overhead. As would be expected, extending an existing system with object-slicing techniques involves a certain amount of overhead, including additional data structures, maintenance costs, and processing time. In a separate paper [15], we describe our experimental results evaluating the relative costs and benefits of adopting the object-slicing technique, including an analytical assessment of the storage overhead of the object-slicing representation and its comparison against the conventional representational models. This work was done in the context of regular base classes only [15]. In the current paper we strive to isolate the impact of our propagation techniques for views from the effects of the object-slicing architecture. We thus tailor our experimental models to minimize the impact of the object-slicing implementation.

4 Minimizing Update Propagation for Object-Oriented Views

4.1 General Goals

MultiView supports the following update operations: creation, deletion, addition of a type, removal of a type, and modification of an instance variable. The first four operations alter the set-membership of a target class; the modification operation changes the value of a single object's instance variable. Once the update has taken place, the change must be propagated to the classes affected by it. For example, if an object gains the type of a class that has a union class derived from it, then one direct effect of that update might be that the object gains the type of the union class (i.e., a new implementation object of the union class is created and linked to the updated object).

We use the term **directly-affected** to denote classes whose set-membership changes as a direct result of the update. We distinguish between two causes for such direct effects. One, a set-membership operation (e.g., the removal of a type) potentially directly affects classes that are **derived-from** the updated class. Two, an operation that modifies the value of an object's instance variable potentially directly-affects classes that are value-dependent upon a given instance variable.

For example, given the schema shown in Figure 1, suppose that we were to update an instance of the *Cat* class, changing its weight from 10 lbs to 12 lbs. Because the *LightCat* class is derived from the *Cat* class using a predicate involving `weight`, the *LightCat* class is potentially **directly-affected** by the update. However, because the updated object's membership in the *LightCat* class will not change as a result of the update, the *LightCat* class is not **directly-affected**. If the *LightCat* class were actually **directly-affected** by the update, then the *NamedLightCat* class would be indirectly affected by the update because the latter is set-membership dependent upon the *LightCat* class.

We identify two invariants that define the consistency requirements of conceptual object instances under our data model. Together, these invariants provide the basis for the specification of the semantics of update propagation. The invariants are conditions that hold true at the time of the update, and they must still be true after our update propagation procedures have completed.

- **Invariant 1:** An object possesses the type of a class $C_i \in C$ iff it also possesses the types of all superclasses of C_i. This invariant assures that an object's class membership concurs with the class generalization relationships, which both guarantees the consistency of class extents and enables inheritance in our object-slicing model.

- **Invariant 2:** An object is a member of a virtual class $VC_i \in VC$ iff it fulfills the conditions of **query**(VC_i).

The naive way to propagate an update correctly would be to completely rematerialize all virtual classes in order of derivation upon completion of the update. However, assuming random access or clustering of (implementation) objects by class, each time an object's membership in a given class is evaluated could lead to a random block access. Our goal is thus to minimize the number of times an updated object is evaluated to determine if the object should be a member of a virtual class. An initial propagation strategy is indicated by Proposition 1.

Proposition 1 *An update that is propagated to all* ***directly-affected*** *classes and to the classes in the* ***Derived-from-Sub-Graphs*** *of the* ***directly-affected*** *classes will result in a correctly materialized database.*

Proof. Suppose, contrary to fact, that there were a class C_j that is not **directly-affected** by the update itself, is not derived from any class that is **directly-affected** by the update, but should be affected by the propagation of the update. Because none of the values of a modified object's instance variables can change during the propagation of an update, the membership of C_j must be *membership-dependent* upon some class C_k whose set membership changed during the update propagation. In order for one class to be *membership-dependent* upon another, a derivation relationship must exist between them. Thus C_j must be in C_k's **Derived-from-Sub-Graph**. Similarly, C_k in turn is derived from some other class C_{k+1} whose set membership changed during the update propagation. By transitivity, C_j must have been derived from some **directly-affected** class C_l. Contradiction. □

We can thus correctly propagate an update to an object by propagating to all classes **directly-affected** by the update, and all classes derived from the **directly-affected** classes. A number of problems are associated with this strategy. First, we need an efficient method to reduce the set of potentially **directly-affected** classes to those that are actually **directly-affected**. Furthermore, not all of the classes in the **Derived-from-Sub-Graphs** of **directly-affected** classes will be affected by the update, thus we want to calculate in an efficient manner the branches that can be discarded. Finally, there may be some overlap among the classes in the **Derived-from-Sub-Graphs** of **directly-affected** classes, and we must avoid *self-cancelling update propagation.*

Our update optimization process addresses these problems in four steps:

1. First, we identify the set of classes that are potentially **directly-affected** by the update.

2. Utilizing information contained in the generalization hierarchy, relevance registration, etc., we eliminate from this set those classes that are not **directly-affected** by the update.

3. We propagate to the classes derived from the **directly-affected** classes in an optimized manner, so as to avoid both propagating to classes that are not affected by the update and self-cancelling update propagation.

4.2 Identifying Directly-Affected Classes

In this subsection, we describe how we isolate the set of classes that are **directly-affected** by the update from the set of classes that are potentially **directly-affected** by the update. The type of the update operation (e.g., modify v.s. add-type) determines the nature of the classes that are potentially **directly-affected** by the update.

- Set-membership operators, e.g., add-type, potentially **directly-affect** all classes derived from the updated class.

- Instance-variable-modification operators potentially **directly-affect** only classes formed using queries that actually involve the modified property.

4.2.1 Classes Directly-Affected by Set-Membership Updates

If the update is an operation upon the set-membership of a class (e.g., the addition or removal of a type), then the set of potentially **directly-affected** classes contains all classes directly derived from the target class, along with all superclasses of the target class if the operation is a type addition or all subclasses of the target class if the operation is a type removal. The set of classes directly derived from the target class is easy to obtain because, as stated in Section 3, each class maintains a set of all the virtual classes that are directly derived from it.

Not all of these classes are actually **directly-affected**. However, our generalization hierarchy structure makes the subsumption relationships between classes readily apparent. We can use this information to identify and eliminate classes that are not **directly-affected**.

1. Add all of the potentially **directly-affected** (directly derived) classes to an ordered set, *Directly-Affected* in breadth-first order of their level in the generalization hierarchy. The schema is assumed to be maintained in main-memory for the sake of the efficiency of this algorithm.

2. For each class $C_i \in$ *Directly-Affected*, do:

(a) Evaluate the updated object's membership status regarding C_i.

(b) If the update is a type addition and there is no change in the object's status regarding C_i, then remove all C_j s.t. C_i *is-a* C_j from *Directly-Affected.*

(c) If the update is a type removal and there is no change in the object's status regarding C_i, then remove all C_j s.t. C_j *is-a* C_i from *Directly-Affected.*

The classes remaining in *Directly-Affected* are exactly the set of classes **directly-affected** by the update. By placing the classes into the set of *Directly-Affected* classes in order of their subsumption relationships, we can prune the set efficiently by avoiding the evaluation of the updated object's membership regarding any class whose super or subclasses has already been evaluated without change. For example, suppose that an object belongs to some class C_i. This means that the object must also belong to all superclasses of C_i (i.e., all C_j s.t. C_i *is-a* C_j). If the object now gains the type of some subclass C_k s.t. C_k *is-a* C_i, then the object must belong or be added to all superclasses of C_k. Because object's type memberships were consistent before the update, we know that if the object belongs to C_i then we do not have to evaluate its membership in any class C_j s.t. C_i *is-a* C_j.

4.2.2 Instance-Variable Value Updates

In order to be able to efficiently identify the set of classes **directly-affected** by modification updates, we introduce a **registration** service by which virtual classes can register their interest in specific properties and be notified upon modification of those properties. We are aided to this end by our data model's injunction that each property must reside at a single class that defines the property and acts as its point of inheritance. All classes whose membership may be affected by modifications to an attribute are thus registered with the attribute's **point of inheritance**. We associate *triggers* with the accessing methods to propagate updates to the registered classes if and only if the relevant property's value is modified.

For example, Figure 3 represents a schema where an object of type *Cat* should possess the type of class *SmallCat* if the value of its `weight` instance variable is less than eleven pounds and the value of its `height` instance variable is less than ten inches. Similarly, an object of type *Cat* should possess the type of class *LightCat* if the value of its `weight` instance variable is less than nine pounds. The *DenseCat* class is derived using a difference query between the *SmallCat* and *LightCat* classes. Because the *SmallCat* class's predicate involves the `weight` and `height` properties, the class is registered with the *Cat* class, which defines both of these properties. Similarly, the *LightCat* class is also registered with the *Cat* class for the `weight` property.

Suppose that an object of type *Cat* had the value of its `height` instance variable updated to eleven inches. An inefficient algorithm might evaluate the modified object's membership status in the *LightCat* class even though the value of the object's `weight` instance variable will not have changed. Figure 3(b) illustrates how in the absence of registration an update to the `height` of an instance of *Cat* could be evaluated in terms of classes that are completely independent from that property. If, however, registration is used (Figure 3(c)), then we can readily identify exactly which simple selection classes are immediately affected by the update.

When a modification to an instance variable occurs, not all of the classes that have registered an interest in the modified property will be **directly-affected** by the update. Using the example in Figure 2, suppose that the `weight` of an instance of *Cat* were updated from 10 to 8 lbs. In that case, only the *LightCat* class is **directly-affected** by the update. Because all classes in our model are arranged in a generalization hierarchy, we can optimize our registration process to take advantage of subsumption relationships. We now propose the optimization of the registration process using the notion of *distributed registration.* When a class C_i receives a registration for a class/property pair $< VC_j/p_i >$, it first searches its existing class/property registrations. If a previous registration for the given property $< VC_k/p_i >$ exists such that the registered class VC_k either subsumes or is subsumed by the new class VC_j, the registrations are re-arranged so that the class that defines the property possesses the registration for the superior class, say VC_k and that class possesses the registration for the subclass (e.g., VC_j).

The *registration* structures shown in Figure 3 can thus be distributed along the generalization hierarchy, as illustrated in Figure 2. Figure 2(a) depicts the registration of the *SmallCat*, *LightCat*, and the *VeryLight* classes, all defined by selection queries. The *LightCat* class is registered with the *Cat* class for the `weight` property. However, because the *LightCat* class subsumes the *VeryLightCat* class and the former is registered with the *Cat* class, the latter's registration for the `weight` property is located with the *LightCat* class instead of the *Cat* class. Figure 2(b) illustrates how with just simple registration, an update to a *Cat*'s `weight` from 12 to 14 lbs could be evaluated in terms of both the *LightCat* and *VeryLightCat* classes. If, however, distributed registration is used (as illustrated in Figure 2(c)), then we can readily identify exactly which simple selection classes are immediately affected by the update. Based on the registrations associated with the `weight` attribute, we would evaluate the updated object in terms of the *LightCat* class. Because the

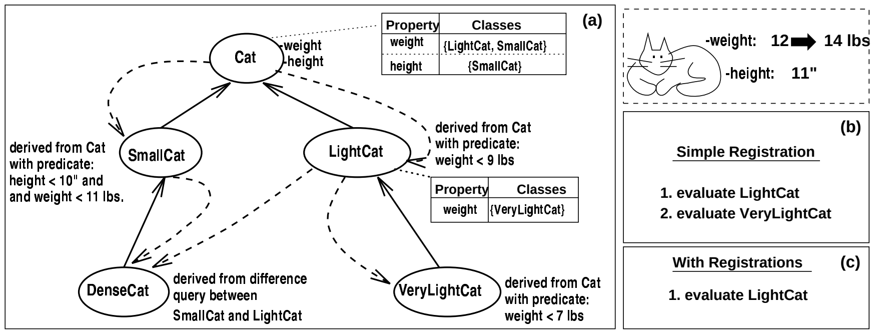


Figure 2: Registrations use both point of inheritance and subsumption.

object does not gain the type of *LightCat*, the propagation would terminate and the *VeryLightCat* class would not be processed.

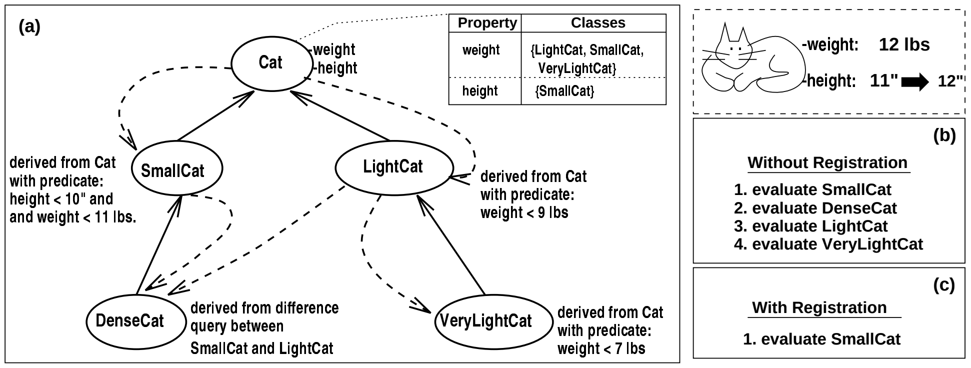


Figure 3: Registrations at the point of inheritance.

In summary, the principles of our registration strategy are:

- When a virtual class is created, its predicate is parsed and the class is *registered* with each property involved in the query specification. Each registration is sent to the class that serves as the point of inheritance for the property involved. Because all classes in our model are arranged in a generalization hierarchy, we optimize our registration process to take advantage of subsumption relationships. The *registration* structures can thus be distributed along the generalization hierarchy. Distributing the *registration* structures allows us to avoid evaluating the update in terms of classes that are obviously unaffected by the update (i.e., classes derived from classes to which the object did not belong either before or after the update).
- When an object is updated, the update method [8] triggers a *notification* function that propagates the update to all virtual classes that have *registered* an interest in the value of the updated property.
- When a virtual class has been informed, via the *notification* class method, that an object in which it has a potential interest has been modified, it then evaluates the update. Should the update warrant that the object gain, keep, or lose the type of the class, then the class will send a message notifying those dependent upon it of the change. Otherwise it does not propagate the change across its derivation hierarchy and the update propagation terminates.

Proposition 2 *The distribution of registration over the generalization hierarchy ensures that we will identify exactly the set of simple select classes that are* ***directly-affected*** *by the modification of an instance variable.*

[8] For the sake of simplicity, we currently make the assumption that instance variables reside at the same location as their update methods.

Proof. Suppose, contrary to fact, that there were a simple select class that is **directly-affected** by the modification but not identified. Any simple select class that is **directly-affected** by the modification of a property must refer to that property within the query defining the class. In that case, the class would have registered its interest in the property at the time of its creation. The only way the class would not be notified of the modification would be if its registration were located with a superclass that was not affected by the modification and whose query the object does not fulfill. If the object does not possess the type of the superclass, it cannot possibly belong to the subclass. Similarly, if the object does not gain the type of the superclass during the update, then it cannot possibly gain the type of the subclass. In that case, the class is not **directly-affected** by the modification. Contradiction.

Similarly, suppose, contrary to fact, that there were a class that is incorrected identified as being **directly-affected** by the modification. In order to be identified in this manner, the class must have registered its interest in the property. In order to be identified as **directly-affected**, the class must have registered interest in the modified property and the object's membership in the class must have been evaluated as changed. In that case, the class is by definition **directly-affected** by the modification. Contradiction. □

4.3 Optimizing Propagation to Classes Derived from Directly-Affected Classes

Once we have identified all classes that are **directly-affected** by an update, it follows from Proposition 1 that we can complete update propagation by propagating the update to the classes derived from the **directly-affected** classes. We optimize propagation of the update to the **directly-affected** classes and the classes derived from them using two techniques:

Identify branch termination conditions. Under certain conditions, propagation to branches of the derivation or generalization hierarchy can be terminated. For example, propagation to a branch of the derivation hierarchy can be terminated if the object does not qualify to belong to any of the entrance points into the branch either before or after the update.

Eliminate self-cancelling update propagation. The propagation process could involve updates that cancel out each other's effects. We call this the *self-cancelling update propagation* problem because it could lead to repetitive evaluations of the object in the context of a single class, sometimes with self-cancelling results.

Branch termination conditions. If the value of an instance variable of the object is modified, we do not need to propagate the update to any class that depends upon the value of that instance if that class is subsumed by another class for which the object does not qualify to belong with either its original or new instance variable values. For example, because the *VeryLightCat* class is subsumed by the *LightCat* class, if an instance of the *Cat* class shown in Figure 4 were to change the value of its *weight* instance variable from 12 to 10 lbs, then our update algorithm should determine that because the instance remains unqualified for membership in the *LightCat* class there is no need to evaluate the instance's status in the *VeryLightCat* class.

Self-cancelling propagation. Figure 4(a) presents a schema vulnerable to the self-cancelling problem. Figure 4(b) illustrates how a decrease of the *weight* of an instance of the *Cat* class could cause it to first gain, then lose, the type of the *DenseCat* class. From this example it follows that a self-cancelling propagation problem could extend to a potentially huge set of classes to the detriment of efficiency.

In order to overcome these two problems, we propose the following solution. First, we assign a unique **derivation number** to each class in the database, indicating its global derivation depth in the schema. A class's derivation number can be calculated once during its lifetime (at class creation time) and because we don't replace existing derivation relationships with new ones, it will never change. All base classes have a derivation number of '0'. All derived classes are assigned the derivation number of the maximum of the derivation numbers of its source classes, plus one. Through transitivity we are guaranteed that if class $C_k \in$ **Derived-from-Sub-Graph**(C_j), then $\mathrm{DerNum}(C_k) > \mathrm{DerNum}(C_j)$. Using this derivation number framework, we propagate changes to affected classes using a breadth-first traversal by order in the derivation hierarchy. Once the traversal reaches a class to which the updated object does not belong either before or after the update, it *terminates update propagation* to that class's branch.

Because a derived class will only be processed after all of its source classes have been processed, we are guaranteed that no class will be processed more than once. (Note that it is possible that one of a class's source classes may not be processed at all.) This solution addresses the first problem (how to identify branch termination conditions) by not examining branches of classes that are immune to the effects of the update, thereby potentially eliminating a large set of dependent materialized classes. Derivation-ordered processing also avoids the second problem of self-cancelling update propagations by ensuring that if $\mathrm{DerNum}(C_k)$

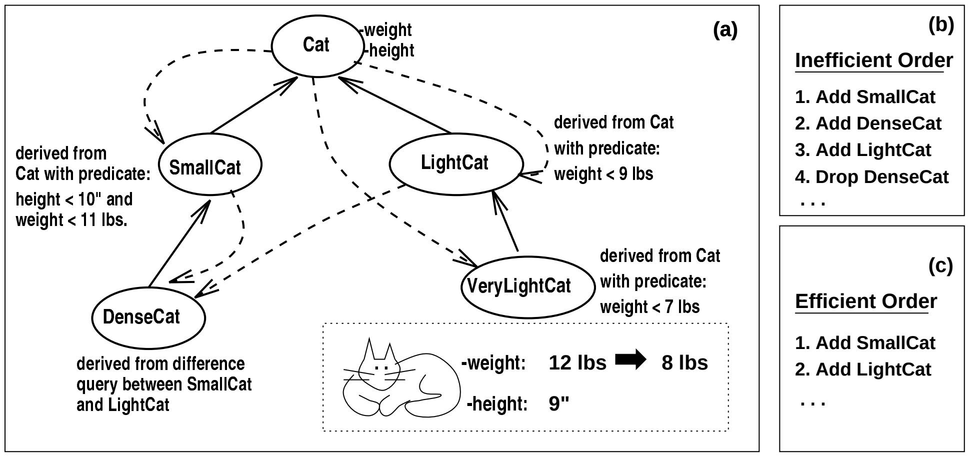


Figure 4: An example schema where propagation order can lead to **self-cancelling propagation**.

$<$ DerNum(C_l), then a modified object's membership in C_k can be evaluated only before the object's membership in C_l has been evaluated.

For example, Figure 4(c) shows how this strategy avoids the pitfall illustrated in Figure 4(b). Because we process the potentially relevant classes in order of derivation number, the status of an instance of *Cat* regarding class *DenseCat* will not be evaluated until after the object's membership status regarding both class *SmallCat* and class *LightCat* has been determined and stabilized.

Proposition 3 *Using the derivation-ordering principle to control update propagation along the derivation hierarchy, an update will be evaluated in terms of any given class at most once.*

Proof. Derivation-ordering ensures that a modified object will never be evaluated in terms of a virtual class C_k before it is evaluated in terms of one of C_k's source classes and, vice-versa, that once a class C_k has been evaluated, none of its source classes will subsequently be evaluated or modified during the propagation process. The state of an object cannot change during the propagation process. Because the only reason an object would be evaluated regarding a given class more than once would be if the object's qualification to be in the class change, the update will be evaluated in terms of any given class at most once. Furthermore, if neither of a class's source classes are affected by the update, then the propagation process will terminate before evaluating that class. □

5 Performance Evaluation

5.1 Experimental Setting

MultiView supports the standard set of view definition operators (project, select, union, intersect, difference, and join) and a full complement of update operations on both base and virtual classes (creation, deletion, type gain, type loss, and modification of the value of an instance variable). Our optimization algorithms are tailored to improve the efficiency of update propagation in the presence of certain types of configurations of classes. For this reason, we chose to use both the traditional simple virtual classes and more complex combinations of virtual classes as representative models for our evaluative experiments. The parameters that our cost models use are summarized in Table 1.

For the sake of simplicity, we limit our experiments to the following basic models.

1. By varying the update probability (P), view predicate selectivity (f), and number of query predicate components ($QComponents(VC_i)$) of an *isolated selection view*, we perform evaluations of the trade-off in basic costs/benefits between materialized and non-materialized views.

2. We combine *multiple select classes* in a single schema to study the effects of our registration strategy, varying the subsumption relationships of the select class predicates.

3. We use a varying number of virtual classes arranged in configurations subject to the *self-cancelling update propagation* problem to demonstrate the cost and benefit of our derivation ordering strategy.

parameter	**definition**
k	# update transactions.
q	# query transactions.
P	Probability that a given operation is an update ($P = k/k + q$).
$f(Query)$	Selectivity of $Query$.
$ExtentCost(class)$	Cost in ms to retrieve the extent of a base or materialized class; or calculate the extent of a non-materialized virtual class.
$PerformCost(Update, obj$	Cost in ms to perform the specified update upon the object.
$size(extent(C_i))$	Number of objects in class C_i's extent.
$AddCost(VirtClass, obj)$	Cost in ms to add the virtual class's type to the object.
$DropCost(VirtClass, obj)$	Cost in ms to drop the virtual class's type from the object.
$ScreenCost(Query, C_i)$	Cost in ms to screen one object from class C_i for $Query$, including cost of retrieving the object from C_i's extent.
$Cost(Query, Class_i)$	Cost of applying $Query$ to the extent of class $Class_i$.
$predComps(VC_i)$	# of predicate components in virtual class VC_i's query.
$extent(Class)$	Set of objects in specified class's extent.
NV	# virtual classes in schema.
NSV	# selection virtual classes in schema.
NR	# of virtual classes registered for the updated property.
NUR	Number of virtual classes registered for the updated property that are subsumed by another registered class that is unaffected by the update. and that does not contain the updated object in its extent.
$PAdd(VC_i, O_j, U_k)$	Probability that the update U_k causes the object O_j to gain the type of virtual class VC_i.
$PDrop(VC_i, O_j, U_k)$	Probability that the update U_k causes the object O_j to lose the type of virtual class VC_i.
$NSupC(C_i)$	# classes in superclass hierarchy of class C_i
$NSubC(C_i)$	# classes in subclass hierarchy of class C_i
$VC_i.Query$	Query that defines virtual class VC_i.

Table 1: Model Parameters.

Experimental environment. We have successfully completed a prototype implementation of the *MultiView* model as described in this paper using the commercial GemStone OODB system [9]. This includes the object-slicing representation, as well as the incremental update propagation algorithms as outlined in this paper. A description of the implementation is, however, beyond the scope of this paper. Instead, the reader is referred to our technical reports on this subject [17, 18, 22]. The experiments described below were carried out using *MultiView* on a Sun4m running SunOS 4.1.3 with 32 megabytes of memory. We employ a 10,000 object implementation of the OO7 benchmark schema for our tests [5]. Figure 5 shows the three class subschema of the OO7 Benchmark's example database that is central to our models.

For our analysis we consider each update operation to be the modification of a single object. Unless stated otherwise, we characterize a query upon a view as selection query on a single property. Each query thus requires an iteration through the view's extent retrieving a property from each object. For non-materialized views, we assume that query optimization will be performed during the query substitution process.

Materialized Query Costs. If the view is materialized, then we do not need to compute the extent of the view in order to query it. Accessing an object from the extent of a materialized view involves only the cost of retrieving an object from GemStone (independently from object-slicing). Thus the cost of performing the query upon the view extent does not involve any costs additional to the cost of performing the actual query. The time to query a materialized virtual class VC_i's extent, regardless of the number of classes from which it is derived, is thus:

[9]More specifically, we use GemStone version 4.0.1, using the Opal interface.

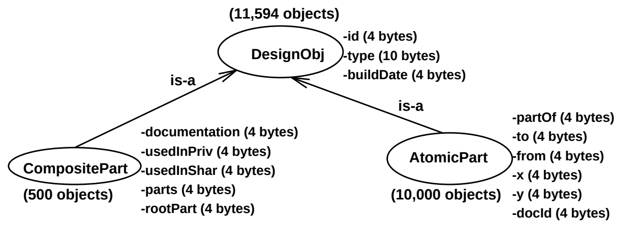


Figure 5: Subschema of OO7 Database.

$$\boxed{Cost(Query, VC_i) := ScreenCost(Query, VC_i) \times size(extent(VC_i)).} \tag{1}$$

Non-Materialized Query Cost. If the view is not materialized, then the cost of querying the view includes the cost of computing the view's extent in addition to the cost of performing the query. Thus each query upon a virtual class's extent can incur significant storage and computation costs. The cost of querying the extent of a non-materialized virtual class VC_i that is derived from a single source class SRC is roughly (discounting query optimization):

$$\boxed{\begin{aligned} Cost(Query, VC_i) :=\ & ScreenCost(VC_i.Query, SRC) \times size(extent(SRC)) \\ & + ScreenCost(Query, VC_i) \times f(VC_i.Query) \times size(extent(SRC)) \end{aligned}} \tag{2}$$

If the queried class is derived from other non-materialized virtual classes, then either each of the source classes in the queried class's derivation chain must be re-materialized or else the query must be modified (and optimized) so as to take the class's derivation history into account. Discounting query optimization, the cost of computing the extent of a class VC_i derived from a source class SRC_i (possibly itself a non-materialized virtual class) can be expressed recursively:

$$\boxed{ExtentCost(VC_i) = \begin{cases} ScreenCost(VC_i.Query, SRC_i) \times size(extent(SRC_i)) & \text{if } SRC_i \text{ is base class} \\ ExtentCost(SRC_i) + & \text{otherwise} \\ ScreenCost(VC_i.Query, SRC_i) \times size(extent(SRC_i)) & \end{cases}} \tag{3}$$

Materialized Update Costs. When a view is materialized, then we must propagate all relevant updates to the view. After the update, all database objects' class memberships must concur with the class generalization relationships, and each database object should be a member of exactly those virtual classes whose queries it fulfills. The cost of an update to an object thus includes the cost of propagating the update to all affected materialized virtual classes, in addition to the cost of accessing the updated property. Because our update optimizations are tailored to combinations of classes, we focus on models with a varying number of virtual classes. The cost of performing an update and propagating it to all affected materialized virtual classes is at a *minimum* (meaning with all possible optimizations):

$$\boxed{\begin{aligned} Cost(Update, obj) :=\ & PerformCost(Update, obj) + \textstyle\sum_{i=1}^{NV}(PAdd(C_i, obj, Update) \times AddCost(C_i, obj) \\ & + PDrop(C_i, obj, Update) \times DropCost(C_i, obj)). \end{aligned}} \tag{4}$$

Without optimization, the cost of performing an update and propagating it to all affected materialized views is in the worst-case:

$$\boxed{\begin{aligned} Cost(Update, obj) :=\ & PerformCost(Update, obj) + \textstyle\sum_{i=1}^{NSV}(ScreenCost(VC_i.Query) \\ & + (PAdd(VC_i, obj, Update) \times NSupC(VC_i) \times AddCost(VC_i, obj)) \\ & + (PDrop(VC_i, obj, Update) \times NSubC(VC_i) \times DropCost(VC_i, obj))). \end{aligned}} \tag{5}$$

With both derivation ordering and distributed registrations, we can avoid evaluating the update's affect on any virtual classes registered for the updated property that are subsumed by another registered class that is unaffected by the update and that does not contain the updated object in its extent. With this optimization, the cost performing and propagating the update becomes:

$$\boxed{\begin{aligned} Cost(Update, obj) := \quad & PerformCost(Update, obj) + \bigcup_{i=1}^{NR-NUR}[(PAdd(VC_i, obj, Update) \\ & \times Add(VC_i, obj) \times NSupC(VC_i)) + (PDrop(VC_i, obj, Update) \\ & \times Drop(VC_i, obj) \times NSubC(VC_i)) + ScreenCost(VC_i.Query, SRC_i)] \end{aligned}} \tag{6}$$

Non-Materialized Update Costs. If a view is not materialized, then we do not need to propagate an update to an object's type or instance variable values to the view. The cost of an update to an object is thus simply the cost of accessing and modifying the updated property, namely

$$\boxed{Cost(Update, obj) := \quad PerformCost(Update, obj)} \tag{7}$$

5.2 Model 1–Trade-off between Materialization and Non-Materialization

Our first model concerns an isolated selection view *Select*1 directly derived from the base class *AtomicPart*, as shown in Figure 6:

$$\boxed{\text{AtomicPart createSelectClass: \#Select1 query: [:ap | (ap x) < 435696658],}}$$

where approximately 1,000 of the 10,000 *AtomicPart* instances have randomly-generated values for x that fulfill this query's predicate. For this model, we perform three series of tests, varying the parameters $predComps(VC_i)$ (number of components in the view predicate), k (number of update operations), and f (view selectivity).

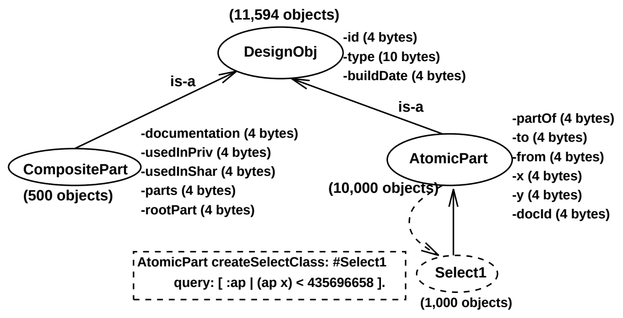


Figure 6: The Select1 virtual class is derived from AtomicPart.

Varying view predicate components ($predComps(Select1)$). The first experiment demonstrates the basic benefit of materialization. Figure 7 compares the cost of an aggregation query that computes the size of the extents of materialized and non-materialized *Select* virtual classes, each derived from a source class with a 10,000 object extent. The figure compares the cost of computing the size of the extent of a virtual class 1,000 times while varying the complexity of the virtual class's selection predicate. In this experiment we isolate the cost of the retrieval from the cost of any queries we might perform upon the retrieved extent. We chose this aggregate query because it allows us to ignore the cost associated with accessing and returning the result objects. This graph shows that we can compute the size of the extent of a materialized virtual class in constant time (near zero milliseconds), independent of the complexity of the query defining the class [10].

Varying number of updates (k). In order to test the effects of update probability upon materialization, we measured the time to perform k updates and 1 query where $0 \leq k \leq 10000$, on a schema with the isolated view *Select1* with fixed selectivity $f(query(Select1)) = 0.1$. The query and update we used are listed below.

[10] Because a materialized virtual class's extent is maintained as a single instance of type Set, accessing the class's extent only needs to retrieve this single Set object. Of course the time needed to perform iterative operations upon the content of the extent set depends upon the number of objects in the set.

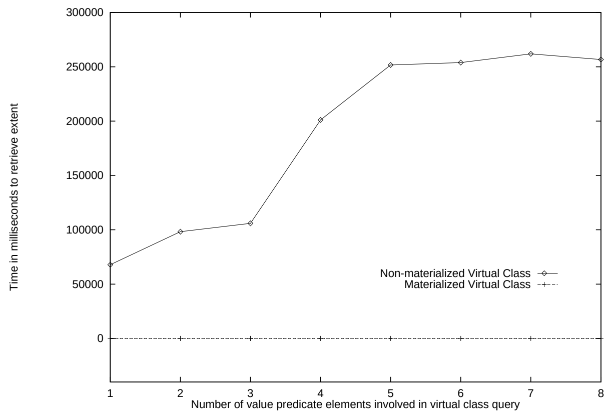


Figure 7: Retrieval costs for materialized and non-materialized virtual class extents.

- $\boxed{\textbf{Update1:}\quad ((AtomicPart\text{ extent})\text{ at: }(aRandomNumber))\text{ x: }aNumber}$ where $aRandomNumber$ is a random number between 1 and 10,000, and $aNumber$ is either 1 or 2081201866, depending on the previous value of the object's x property. In this way we guarantee that every update results in a change in the *Select1* class's extent.

- $\boxed{\textbf{Query1:}\quad Select1\text{ select: [:s1 | s1 id} < 1088092823]}$ For our database, this query results in the selection of approximately 500 objects from the 1,000 objects in the extent of *Select1* (the variance is because each update changes the extent of *Select1*). In order to minimize the affect of our object-slicing architecture, we are querying upon a property that is inherited by both that *AtomicPart* and *Select1* classes, namely *id* (as opposed to x) from Figure 8.

For our first test, we ran $Update1$ k times and $Query1$ once for values of k from 0 to 10000. Figure 8 shows the average number of milliseconds to perform transactions while varying k. The results of this test indicate that with an isolated selection view of view selectivity $f(Select1) := 0.1$, an update impact probability of 1, and a query selectivity of $f(Query1) := 0.05$, the cost of performing a single query on the non-materialized view is counter-balanced by the cost of propagating approximately 3000 updates to the materialized view.

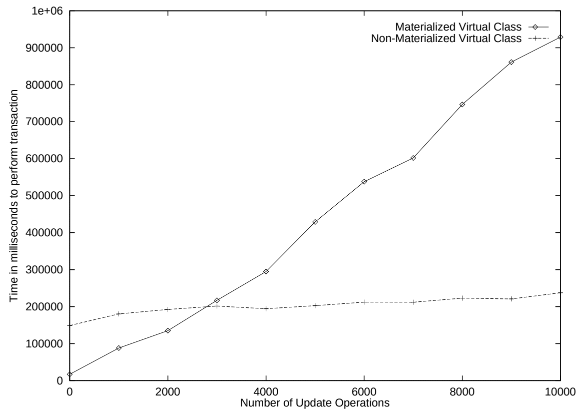


Figure 8: Milliseconds to run k updates and 1 retrieval on an inherited property (varying k).

Varying view predicate selectivity (f). We next focus on the effect of view predicate selectivity by fixing update probability P at 90% and varying the view selectivity factor f from 1 to 100%. Our goal in this experiment was to evaluate the impact of view selectivity upon materialization performance.

Figure 9 shows the results of performing nine random updates and one query upon a simple selection view *Select2* derived from the *AtomicPart* class while varying the selectivity factor of the view from 0 (no objects fulfill the view predicate) to 1 (all 10,000 objects fulfill the view predicate). The selectivity factor of the query is fixed at 1% of the 10,000 objects in *AtomicPart*.

Query2: ((*Select2* extent) select: [:item — (item id) < 2081201856]

As we would expect from Equations 1 and 2, when query optimization is used during the query-rewriting process, the selectivity factor of the view has a greater impact on the cost of querying the materialized view than the non-materialized view. Regardless of the view selectivity factor, querying the non-materialized view involves one iteration upon the extent of the view's source class. The dotted line in the graphs (indicating the time in milliseconds to perform the updates and query on a non-materialized class) reflects this fact by remaining fairly level. If the view is materialized, however, then the query involves only those objects that fulfill the view selection predicate. Thus, as $f(Select2)$ increases, the proportion of the total non-materialized query cost that is derived from the cost of actually querying the virtual class (as opposed to computing its extent) increases. This is reflected by the rise of the solid line in the graphs (indicating the time in milliseconds to perform the updates and query on a materialized class).

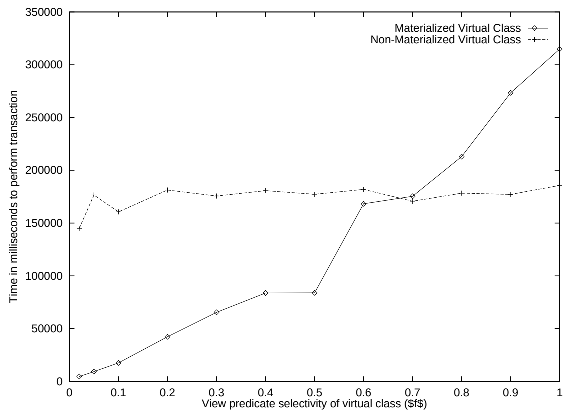


Figure 9: Milliseconds to run 9 updates (k=9) and 1 retrieval (q=1) on a property while varying view selectivity (f).

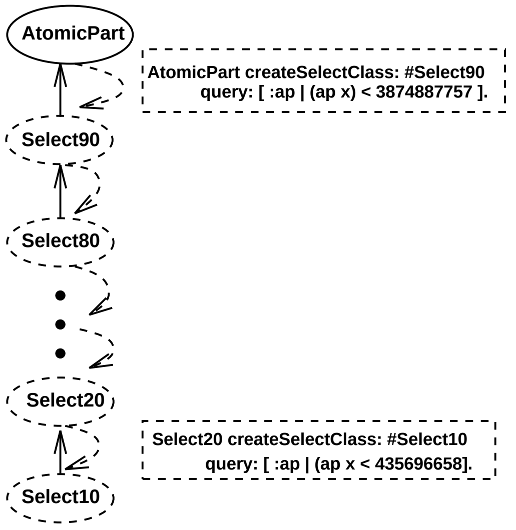
5.3 Model 2–Evaluating the Distributed Registration Service

We next focused our evaluation on the modify operator, which being the most complex can result in an object gaining and losing multiple types. For Model 2 we demonstrate the effects of our hierarchical registration strategy by combining *multiple select classes* in a single schema, varying the subsumption relationships of the select class predicates.

In order to test the impact of the view hierarchy upon materialization propagation performance, we measured the time in milliseconds required to perform 10,000 updates in the presence of an increasing number of selection classes arranged in the subsumption hierarchy depicted in Figure 10. *Select90* is derived from the *AtomicPart* class, *Select80* is derived from the *Select90* class, etc. Because the benefit of the hierarchical ordering optimization lies in avoiding unnecessary evaluations, we fix the selectivity of the update at 0 (meaning that the update does not affect any updated objects' virtual class memberships) and define all virtual classes as dependent upon the updated property (x). Given an object that does not belong to the uppermost selection class, we would expect that any update that does not cause the object to gain the type of the uppermost selection class to be immediately terminated if distributed registrations are employed. Otherwise (if the registrations are not distributed along the subsumption hierarchy), all classes must be evaluated in terms of the update.

Figure 11 shows the time needed in milliseconds to perform 10,000 updates in a schema with a varying number of selection classes, where NUR varies from 0 to 9. When no virtual classes are present, $NUR = 0$, when one virtual class is present, $NUR = 1$, and so on. We compare the performance of our implemented update propagation method that does not distribute registrations across the generalization hierarchy to the performance of one that does.

Even under such a small sample schema, the benefit of distributing registrations is conspicuous. The dotted line in Figure 11 indicates the time in milliseconds needed to perform 10,000 updates when the registrations are not distributed. The solid line indicates the time in milliseconds needed to perform the



AtomicPart
AtomicPart createSelectClass: #Select90
query: [:ap | (ap x) < 3874887757].
Select90
Select80
Select20
Select20 createSelectClass: #Select10
query: [:ap | (ap x < 435696658].
Select10

Figure 10: A chain of selection classes derived from each other.

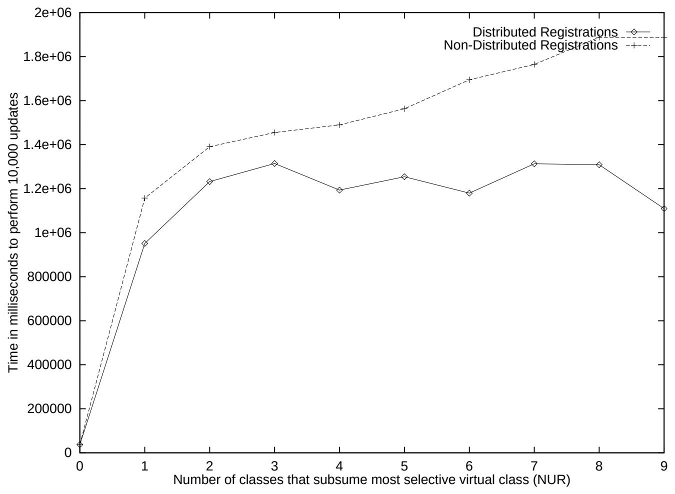


Figure 11: Comparing the performance of distributed and non-distributed registrations while varying NUR.

10,000 updates when the registrations are distributed. As we would expect, when no or only one virtual class exists in the schema, the two algorithms require the same amount of time. However, as the number of virtual classes registered for the updated property increases, the non-distributed algorithm must check the updated instance against each of the virtual class's predicates. The algorithm with distributed registrations only needs to check the updated instance against the topmost virtual class's predicate.

5.4 Model 3–Benefit of Derivation Ordering

In Model 3, we examine the relative impact of registration and derivation level propagation on the self-cancelling update propagation scenario. In order to calculate the relative cost and benefit to algorithms of compensating for this pitfall, we devised a test in which we measured the time to update 1000 objects of the *AtomicPart* in the presence of an increasing number of virtual classes arranged in a manner vulnerable to the self-cancelling update propagation problem. We evaluated the impact of our propagation optimization techniques by implementing four propagation algorithms that employ combinations of our two main optimization techniques as described in Section 4 (derivation-ordered propagation and interest registration).

Figure 12 organizes the four algorithms we implemented in terms of the optimizations they perform. Algorithm *both* and Algorithm *only-reg* use relevance registration to avoid propagating updates to irrelevant derived classes. Algorithm *both* and Algorithm *only-ordering* both update in order of derivation level, so they are not subject to self-cancelling update propagation.

For this test, we implemented the updates so that they alternately incremented and decremented the value of the x instance variables of the updated instances by one. The results of this test, displayed in Figure 13, indicate that in the presence of the self-cancelling update problem, an algorithm using only derivation ordering out-performs one using only registration. In summary, our tests indicate that although registration alone significantly improves the time needed to propagate updates, an algorithm that employs registration and propagates in order of derivation number can significantly outperform one that employs only registration in the presence of even one class that is prone to the self-cancelling update problem. Note that without derivation-ordering, update time increases exponentially with the number of self-cancelling classes present. Because additional selection classes are added in order to create each self-cancelling virtual classes, the algorithm that uses derivation-ordering and without registration suffers a moderate performance loss as the number of self-cancelling classes increases. However, the time of the algorithm using both derivation-ordering and registration is hardly affected at all by the increased number of self-cancelling classes.

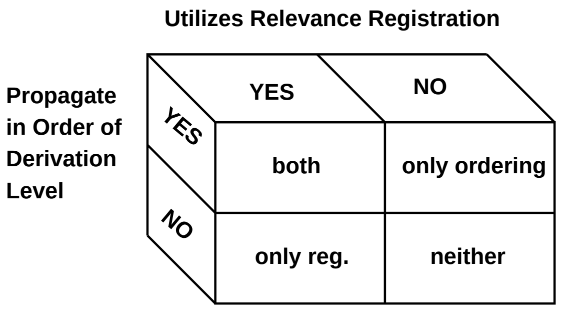

Utilizes Relevance Registration
Propagate in Order of Derivation Level
YES
NO
YES
NO
both
only ordering
only reg.
neither

Figure 12: Optimizations of the Four Algorithms.

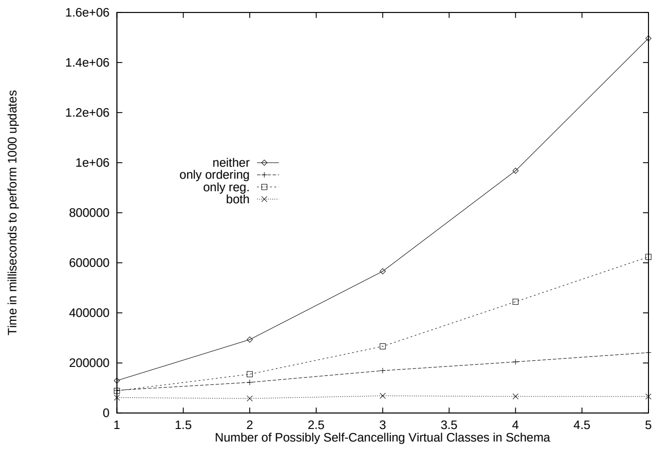


Figure 13: Propagation in Schema with Self-cancelling Updates.

6 Contributions and Future Issues

In this paper, we identify techniques by which we can exploit unique features of the object-oriented paradigm to optimize updatable materialized views. Our update algorithms are incremental, and perform selective notification to the set of classes determined to be **directly-affected** by a given update. We use inherent object-oriented features, such as the integration of classes into a generalization hierarchy, encapsulation, and membership materialization, both to facilitate the identification of the classes that are **directly-affected** by an update and also to optimize the propagation to the classes derived from classes **directly-affected** by the update. New techniques we introduce include distributed registration, subsumption-based propagation termination, and derivation-ordered prevention of the self-cancelling effect.

We have implemented a prototype (version 1.0) of the *MultiView* system [18], which supports updatable materialized object-oriented views. Our system incorporates the incremental update propagation strategies introduced in this paper. We present experimental results that demonstrate the performance gains derived from our proposed view materialization strategies. We have identified two potential inefficiencies to which update propagation algorithms are subject—the propagation of updates to irrelevant derived classes and the propagation of self-cancelling updates. Our evaluation demonstrates that our techniques of *relevance registration* and *derivation-ordered propagation* successfully address these problems.

While object-slicing does have a large effect upon the performance of the *MultiView* system, the experiments presented in this paper are designed to isolate our algorithmic optimizations from the impact of the object-slicing representation. They thus demonstrate the benefit of our strategies independent of object-slicing. In fact, our propagation algorithms should work even more efficiently in the absence of an object-slicing architecture. In a related paper, we explore the use of clustering to ameliorate the overhead of the object-slicing technique employed by our implementation [15].

In the future, we plan to study more powerful query languages for view definition. We also plan to study issues related to the support of deferred updates and multiple (batched) updates for materialized views.

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A Basic Functions

For the purposes of the following algorithms, we employ a number of terms referring to the properties of classes in our system. We list below the functions used to access these properties.

- **DerivationNumber**(C_i) returns the derivation number of the class C_i.
- **SourceClasses**(VC_i) returns the source classes of the query that defines virtual class VC_i.
- **DerivedClasses**(C_i) returns the set of classes derived from class C_i.
- **Extent**(C_i) returns the set of objects belonging to class C_i's extent.
- **DefiningClass**($property_i$) returns the class that serves as the single point of inheritance for property $property_i$.
- **Query**(VC_i) returns the query that defines virtual class VC_i.
- **SelectRegistrations**(C_j) returns the set of select registrations of class C_j (a set of pairs $< p_k, C_l >$, where p_k is a property and C_l is a select class).
- **JoinRegistrations**(C_j) returns the set of join registrations of class C_j (a set of pairs $< p_k, C_l >$, where p_k is a property and C_l is a join class).
- **JoinProperty**($JoinQuery_i$) returns the property on which the natural join query $JoinQuery_i$ is formed.

We describe here the purpose, parameters, and results of functions used within the algorithms presented below.

- **Evaluate**(O_i, VC_j) evaluates O_i's state and type memberships and returns `add, drop,` or `noChange`, depending on whether or not O_i qualifies to be a member of VC_j.
- **AddToExtent**(O_i,C_j) adds object O_i to class C_j's extent. In our object-slicing implementation, this entails the creation and appropriate linking of an implementation object of class C_j's type.
- **DropFromExtent**(O_i,C_j) removes object O_i from class C_j's extent. In our object-slicing implementation, this entails the deletion and appropriate unlinking of the implementation object of class C_j's type.
- **AddRegistration**(*RegistrationSet*, *aRegistration*) adds the given registration structure *aRegistration* to the set of registration structures *RegistrationSet*, indexed by property name.
- **GetRegisteredClasses**(*RegistrationSet*, $property_k$) returns the classes associated with the registration structures in the *RegistrationSet* that have their *property* value set to $property_k$.
- **AddToDerivedClasses**(VC_i, C_j) adds virtual class VC_i to the set of classes associated as being derived from class C_j.
- **AddToArrayOfQueues**($anArrayOfQueues, anItem, n$) will add $anItem$ to the nth queue in $anArrayOfQueues$.
- **JoinObjectSet**(O_i) returns the set of objects generated for join virtual classes that use object O_i as a source object.

B Preparing the Schema for Update Propagation

Each time a new virtual class is created that will depend upon the value of instance variables (e.g., classes created using select or join queries), the schema must be prepared so that updates can be appropriately propagated to the new class. The various types of virtual classes require different information to be kept about them. The `SetUp`(VC_i) function is called at the time of virtual class creation and prepares the schema according to the following principles.

- All virtual classes depend on the extent-membership of their source classes. For example, if an object gains the type of a source class, then it should also gain the type of any hide virtual classes formed from the class. For this reason, every class in the database schema has a `derivedFrom` class instance variable that is used to maintain references to the classes that are directly derived from the class. When a new virtual class is created, its name is added to the `derivedFrom` set of each of its direct source classes.
- Virtual classes formed from join or simple selection queries depend on the values of instance variables of individual objects. In order to maintain the information needed to propagate updates in a structured fashion, we define a `Registration` class. The instances of this class are used to record the registration of select and join classes with the classes that own attributes used in predicates. The class has two instance variables: `className`—the name of the class that is being registered, and `property`—the uniquely-identified property used in the predicate of the registered class. Every class in the database schema is associated with a set of these structures (possibly empty), indexed by property.

Function 1 ***SetUp***(VC_i)

```
begin Setup
    For each class $SRC_j$ in SourceClasses($VC_i$)
        AddToDerivedClasses($VC_i$,$SRC_j$).
        if ($VC_i$ is formed from a simple selection query)
            then
                for each property $property_k$ in properties(query($VC_i$))
                    RegisterSelect($VC_i$,$property_k$,DefiningClass($property_k$)).
                endfor.
        endif.
        if ($VC_i$ is formed from a join query)
            then
                RegisterJoin($VC_i$,joinProperty(query($VC_i$)),DefiningClass($property_k$)).
        endif.
    endfor.
end Setup.
```

The macro functions used by the **SetUp()** function are described below.
The **RegisterSelect(**VC_i,$property_j$,$Class_k$**)** and **RegisterJoin(**VC_i,$property_j$,$Class_k$**)** functions create registration structures for the new class and add them to appropriate registration sets of the classes on which they depend.

Function 2 ***RegisterSelect***$(VC_i,property_j,Class_k)$

```
begin RegisterSelect
    for each class $Class_j$ in GetRegisteredClasses(SelectRegistrations($Class_k$),$property_j$)
        if subsumes($Class_j$,$VC_i$)
            then
                RegisterSelect($VC_i$,$property_j$,$Class_j$).
                exit.
        endif
    endfor.
    AddSelectRegistration($VC_i$,$property_j$,$Class_k$).
end RegisterSelect.
```

Function 3 ***AddSelectRegistration***$(VC_i,property_j,Class_k))$

```
begin AddSelectRegistration
    var tmpReg
    tmpReg := (Registration new).
    tmpReg className: $VC_i$.
    tmpReg property: $property_j$.
    Add(SelectRegistrations($Class_k$),tmpReg).
end AddSelectRegistration.
```

Function 4 ***RegisterJoin***(VC_i,$property_j$,$Class_k$)

```
begin RegisterJoin
    for each class $Class_j$ in GetRegisteredClasses(JoinRegistrations($Class_k$),$property_j$)
        if subsumes($Class_j$,$VC_i$)
            then
                RegisterJoin($VC_i$,$property_j$,$Class_j$).
                exit.
        endif.
    endfor.
AddJoinRegistration($VC_i$,$property_j$,$Class_k$).
end RegisterJoin.
```

Function 5 ***AddJoinRegistration***(VC_i,$property_j$,$Class_k$)

```
begin AddJoinRegistration
    var tmpReg
    tmpReg := (Registration new).
    tmpReg className: $VC_i$.
    tmpReg property: $property_j$.
    Add(JoinRegistrations($Class_k$),tmpReg).
end AddJoinRegistration.
```

C Identifying Directly-Affected Classes

Because the *MultiView* model assumes strict encapsulation, we embed our propagation method into each updating method. When an update takes place in a prepared schema, the *MultiView* update propagation method first identifies the classes directly affected by the update, then propagates the after-effects of the update to the classes derived from the directly-affected classes. By directly-affected, we mean all classes $C_i \in C$ s.t. the modified object's membership in C_i changes as a result of the update, and $\nexists C_k \in C$ s.t. the modified object's membership in C_k changes as a result of the update and C_i is derived from C_k.

The following functions identify the classes directly affected by updates. Once these classes have been identified, we propagate the update to the classes derived from them in an efficient manner, as detailed in Section D.

C.1 Identifying Classes Directly-Affected by a Type Change

When an object gains or loses a new type belonging to class C_j, it must also add or lose in an appropriate manner the types of all classes related to C_j through either a derivation or subsumption relationship. Our functions identify classes from the following three hierarchies that are directly-affected by the type change:

- The change must be propagated to all classes derived from C_j as indicated by the **DerivedFrom** relationship associated with C_j.
- If C_j's type is added to an object O_i, then the change must also be propagated to all superclasses of C_j and all classes derived from them.
- If C_j's type is dropped from an object O_i, then the change must also be propagated to all subclasses of C_j and all classes derived from them.

Given an object $O_i \in O$ and a class $C_j \in C$, if O_i is currently not a member of C_j's extent, but now is to be added to C_j's extent, then **IdentifyAffectedByGainType(**O_i, C_j**)** will identify all classes directly-affected by the change, including C_j itself.

Function 6 ***IdentifyAffectedByGainType***(O_i, C_j)

```
begin IdentifyAffectedByGainType
    For each $C_k$ s.t. $C_j$ is-a $C_k$
        if $O_i \notin$ extent($C_k$)
            then
                AddToExtent($O_i$,$C_k$)
                for each $VC_l \in$ DerivedFrom($C_k$)
                    if (Evaluate($O_i, VC_l$) == (add or drop))
                        then
                            mark $VC_l$ as directly-affected
                    endif.
                endfor.
        endif
    endfor.
end IdentifyAffectedByGainType.
```

Given an object $O_i \in O$ and a class $C_j \in C$, if O_i is currently a member of C_j's extent, but is to be dropped from C_j's extent, then **IdentifyAffectedByDropType**(O_i, C_j) will identify all classes directly-affected by the change, including C_j itself.

Function 7 ***IdentifyAffectedByDropType***(O_i, C_j)

```
begin IdentifyAffectedByDropType
    For each $C_k$ s.t. $C_k$ is-a $C_j$
        if $O_i \in$ extent($C_k$)
            then
                DropFromExtent($O_i, C_k$)
                for each $VC_l \in$ DerivedFrom($C_k$)
                    if (Evaluate($O_i, VC_l$) == (add or drop))
                        then
                            mark $VC_l$ as directly-affected
                    endif.
                endfor.
        endif
    endfor.
end IdentifyAffectedByDropType.
```

C.2 Identifying Classes Directly-Affected by Creation or Deletion

When a new object-instance of a class $C_i \in C$ is created for the first time, it is equivalent to creating a new empty conceptual object, then adding the type of C_i. Given a global database schema $G = (C, E)$, the function **create**(C_i) for $C_i \in C$, will create a conceptual object, $O_{i_{conc}}$ for the new object O_i, then perform the following tasks:

Function 8 ***IdentifyAffectedByCreate***(O_i, C_j)

```
begin IdentifyAffectedByCreate
    For each $C_k$ s.t. $C_j$ is-a $C_k$
        mark $C_k$ as directly-affected
    endfor.
end IdentifyAffectedByCreate
```

Our algorithm for the *Delete* operation is straightforward. When an object is deleted, it completely ceases to exist in the context of the database. Thus we can simply delete the object's conceptual object and all of its implementation objects. Since a conceptual object keeps track of all occurrences of the object in both base and virtual classes, it is not necessary to search through the derivation hierarchy [11]. There will now be no references to the original object, so it is now deleted.

Function 9 ***Delete(O_i)***

```
begin Delete
    For each implementation object $O_{i_{impl_{C_i}}} \in O_{i_{conc}}$
        DropFromExtent($O_i$,$C_i$)
    endfor.
    Create a new object $O_{deleted}$ of type DeletedObject.
    Swap the object-identifiers of $O_{i_{conc}}$ and $O_{deleted}$.
    endfor
end Delete.
```

The objects generated for join classes are associated with objects from the source classes of the join query. When an object is deleted, all objects that are associated with it via join queries must also be deleted. The function **DeleteJoinObjects**(O_i) will recursively delete all join virtual class instances that are associated with O_i.

Function 10 ***DeleteJoinObjects(O_i)***

```
begin DeleteJoinObjects
    For each object $O_j \in$ JoinObjectSet($O_i$)
        DeleteJoinObjects($O_j$).
        Delete($O_j$).
    endfor.
end DeleteJoinObjects.
```

C.3 Identifying Classes Directly-Affected by a State Modification

Function 11 *The function* ***TraverseRegistration***(O_i, $property_j$, $value_{new}$, C_k, *type*) *calculates and returns the set of classes that have registered an interest in the modified property and potentially might be affected by the change. The* ***type*** *parameter defines the type of registrations to be traversed (i.e., Select or Join).*

```
begin TraverseRegistration
    Initialize a set, Result, to hold the set of classes that have registered an interest in the modified property
        and potentially might be affected by the change.
    Evaluate $O_i$'s status in $C_k$ in terms of both its current and new state.
        if (type == Select)
            then
                If $O_i$'s status in $C_k$ does not change and $O_i$ is a member of $C_k$
                    then
                    for each $C_l \in$ GetRegisteredClasses(SelectRegistrations($C_k$),$property_j$)
                        Result := Result $\bigcup$ TraverseRegistration($O_i$, $property_j$, $value_{new}$, $C_l$, type).
                    endfor.
                endif.
            else if (type == Join)
                then
                    If $O_i$'s status in $C_k$ does not change and $O_i$ is a member of $C_k$
                        then
                        for each $C_l \in$ GetRegisteredClasses(JoinRegistrations($C_k$),$property_j$)
                            Result := Result $\bigcup$ TraverseRegistration($O_i$, $property_j$, $value_{new}$, $C_l$, type).
                        endfor.
                    endif.
```

[11] Since GemStone provides persistence through reference, any time an object in our database is "deleted," we create a new object of a special *Deleted* type and swap identifiers.

```
            endif.
        If $O_i$'s status in $C_k$ changes and (type = Join)
            then
                Result := Result $\bigcup$ $\{C_k\}$.
                For each $C_l \in$ **GetRegisteredClasses(JoinRegistrations$C_k$,property$_j$)**
                    Result := Result $\bigcup$ **TraverseRegistration**($O_i$, property$_j$, value$_{new}$, $C_l$, type).
                endfor.
        endif.
    If $O_i$'s status in $C_k$ changes and (type = Select)
        then
            Result := Result $\bigcup$ $\{C_k\}$.
            For each $C_l \in$ **GetRegisteredClasses(SelectRegistrations($C_k$),property$_j$)**
                Result := Result $\bigcup$ **TraverseRegistration**($O_i$, property$_j$, value$_{new}$, $C_l$, type).
            endfor.
        endif.
    Return Result.
end TraverseRegistration.
```

Because our model assumes complete encapsulation, when an update is made to the value of an object's instance variable *property*$_j$, the update must be made using the accessing methods for that property. Given an object $O_i \in O$, a property *property*$_j$, and a new value *value*$_{new}$ for O_i's *property*$_j$ instance, the function **IdentifyAffectedByStateModification**(O_i, *property*$_j$, *value*$_{new}$) will identify all classes directly-affected by the change, including C_j itself.

Function 12 ***IdentifyAffectedByStateModification***(O_i, *property*$_j$, *value*$_{new}$)

```
begin IdentifyAffectedByStateModification
    Let $C_j$ be the class that defines property$_j$.
    Initialize the set RegisteredClasses := **TraverseRegistration**($O_i$, property$_j$, value$_{new}$, $C_j$, Select) $\bigcup$ **TraverseRegist
    For each class $RC_k \in$ RegisteredClasses
        mark $RC_k$ as directly-affected.
    endfor.
end IdentifyAffectedByStateModification
```

D Propagating Updates to Derived Classes

The function **SetUpDirectlyAffectedClasses(**O_i,*updateType*) prepares the *QueueArray* to propagate an update of type *updateType* to all classes marked as directly-affected and the classes derived from them. Propagation is performed in order of derivation number.

Function 13 ***SetUpDirectlyAffectedClasses***(O_i,*updateType*)

```
begin SetUpDirectlyAffectedClasses
    For each class $C_k$ marked as Directly-Affected
        Unmark class $C_k$ as Directly-Affected
        if Evaluate($O_i$, $C_k$) == noChange and $O_i \notin$ extent($C_k$)
            then
                break foreach
        endif.
        if updateType == AddType and Evaluate($O_i$, $C_k$) == add
            then
                AddType($O_i$,$C_k$)
            else if updateType == DropType and Evaluate($O_i$, $C_k$) == drop

                then
                    DropType($O_i$,$C_k$)
            endif.
        endif.
        For each class $C_l \in$ derivedFrom($C_k$)
            AddToArrayOfQueues(anArrayOfQueues,$C_l$,derivationNumber($C_l$))
        endfor.
    endfor.
end SetUpDirectlyAffectedClasses.
```

The function **PropagateToDerivedClasses** uses the temporary data structure of an array of queues, *anArrayOfQueues*, to propagate the update to classes in order of derivation number.

Function 14 ***PropagateToDerivedClasses***

```
begin PropagateToDerivedClasses
    While anArrayOfQueues is not empty
        do
            Remove a class $C_k$ from the first non-empty queue in anArrayOfQueues.
            if ((evaluate($O_i, C_k$) == correct) and ($O_i \notin$ extent($C_k$)))
                then
                    break while
            endif.
            if updateType == AddType
                then
                    AddType($O_i$,$C_k$)
                else if updateType == DropType

                    then
                        DropType($O_i$,$C_k$)
                endif.
            endif.
            For each class $C_l \in$ derivedFrom($C_k$)
                AddToArrayOfQueues(anArrayOfQueues,$C_l$,derivationNumber($C_l$))
            endfor.
    endwhile.
end PropagateToDerivedClasses.
```