An Extensible Query Model and Its Languages for a Uniform Behavioral Object Management System

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Abstract

In this paper, we present an extensible, uniform, behavioral query model and its languages for the TIGUKAT object management system [PÖS92]. The TIGUKAT model is purely behavioral in nature, supports full encapsulation of objects, defines a clear separation between primitive components such as types, classes, collections, behaviors, functions, etc., and incorporates a uniform semantics over objects which makes it a favorable basis for a query model. Queries are modeled as type and behavior extensions to the base object model, thus incorporating queries as an extensible part of the model itself. We present the framework of the complete query model definition that includes the extended types and behaviors, a formal object calculus with safety based on the evaluable class of queries, an equivalent object algebra, an SQL-like ad hoc query language for user-level querying and proof of its completeness.

Keywords: object-oriented systems, object query model, object calculus, object algebra, query language, object model

1 Introduction

To meet data management requirements of new complex applications, object management systems are emerging as the most likely candidates. The general acceptance of this new technology depends on the increased functionality it can provide, and one measurement is the power of its query model. Users of these systems must have a declarative language to formulate queries by focusing on "what" information is required, and leaving it to the system to determine "how" to efficiently retrieve the information. Therefore, the formal query model of these systems should define a declarative calculus that can be used to formulate queries to the object-base and an equivalent procedural or functional algebra to execute them efficiently.

Several research efforts have addressed the problem of formalizing a query model in an object-oriented environment. These have led to the development of design frameworks for object algebras [YO91], object calculi [AB93], and query languages [Blána, ÖS94]. Furthermore, some work is ongoing to extend SQL with object-oriented features [Gale2]. Straube and Özsu [SÖ90] have investigated query processing issues in the domain of object-oriented databases. They specify both an object algebra and calculus definition, and the two are linked with a calculus to algebra translation. However, the reduction is only partial and the algebra lacks object creating operators. The algebra of Shaw and Zdonik [SZ90] consists of an abstract relational algebra with both preserving and creating operators forming a complex object algebra. Osborn [Os88] defines an algebra for an object-oriented model based on atomic objects, strongly typed aggregates (tuples) and both homogeneous and heterogeneous sets. The algebra provides a full range of algebraic operations including the combine operator which is equivalent to cartesian product. However, the integration of the result of a combine with the existing lattice is not specified. Kim [Kim89] defines an algebra that includes object-creating operators for selecting joins on objects, but the integration of these new objects into the existing lattice is not known and so they hang off the root of the lattice.

In this paper, we report our work on a complete object query model and its languages. The query model is developed in a uniform, extensible fashion (using object-oriented techniques) as type and behavior extensions to the base object model. Thus, queries are uniformly modeled as objects and are accessible through behaviors like any other object. This work is conducted within the framework of the TIGUKAT project. TIGUKAT is an extensible uniform, behavioral, object management system. Its object model [PÖS92] is characterized by an abstract behavioral definition and a uniform approach to objects. Everything, including types, classes, behaviors, functions, meta-information and so on, is modeled as a first class object.

The identifying characteristics of the TIGUKAT query model which differentiates it from other proposals are as follows:

1. It incorporates a formal object calculus and object algebra specification with a proven equivalence (see [PŁO93] for theorems and proofs).

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1. We prefer the terms "object-base" and "object management system" over the more popular terms "object-oriented database" and "object-oriented database management system" since not only data in the traditional sense is managed, but objects in general which include things such as code in addition to data.
2. Its safety criterion is based on the *evaluable* class of queries [GT91] which is arguably the largest decidable subclass of domain independent queries [Mak83].

3. It exploits object-oriented features to extend the *evaluable* class by introducing notions of *object generation* which relaxes range specification requirements.

4. It incorporates a complete SQL-like user language called TQL (TIGUKAT Query Language), an object definition language called TDL (TIGUKAT Definition Language) and a control language called TCL (TIGUKAT Control Language) [Lip83]. TQL is proven equivalent to the formal languages making it easy to perform logical transformations and argue about its safety.

5. It uniformly models queries as first-class objects by defining type and behavior extensions to the object model. This makes for an extensible query model with a consistent uniform underlying semantics.

Although our work is within the context of the TIGUKAT project, the results reported here extend to any system based on a uniform behavioral object model where behaviors are implemented as functions.

The remainder of the paper is organized as follows. In Section 2, we give a brief overview of the TIGUKAT object model. This outlines the fundamental features of the model and gives a short specification of the primitive type lattice. In Section 3, an overview of the TIGUKAT query model as an extension to the object model is presented and the concept of queries as objects is described. In Section 4, we present the formal object calculus and discuss its safety. In Section 5, the syntax and semantics of the TIGUKAT Query Language are given. In Section 6, we present the operators of the formal object algebra. In Section 7, we define a Geographic Information System (GIS) as an example objectbase and present several example queries expressed in their equivalent TQL, object calculus and object algebra forms. The reader may want to refer to the examples in this section while reading the earlier parts of the paper. Finally, Section 8 contains concluding remarks and a brief discussion of the ongoing work.

2. Object Model Overview

The TIGUKAT object model [PO92] is defined *behaviorally* with a *uniform* object semantics. The model is behavioral in the sense that all access and manipulation of objects is based on the application of behaviors to objects, and the model is uniform in that every component of information, including its semantics, is uniformly modeled by objects and has the status of a *first-class object*. Thus, an object is a fundamental concept in TIGUKAT, meaning every expressible element incorporates at least the semantics of the primitive notion for "object."

The primitive objects of the model include: atomic entities (reals, integers, strings, etc.); types for defining common features of objects; behaviors for specifying the semantics of operations that may be performed on objects; functions for specifying implementations of behaviors over types; classes for automatic classification of objects based on type; and collections for supporting general heterogeneous groupings of objects. In the remainder of the paper, the prefix $T$- refers to a type, $C$- refers to a class, $L$- refers to a collection, and $B$- refers to a behavior. For example, $T_{person}$ is a type reference, $C_{person}$ a class reference, $L_{seniors}$ a collection reference, $B_{age}$ a behavior reference, and a reference such as $D_{avid}$ without any prefix represents some other application specific reference. Some primitive types and behaviors are elaborated on in this paper. For the complete model definition see [PO92].

Objects are defined as (*identity, state*) pairs where *identity* represents a unique, immutable object identity and *state* represents the information carried by the object. Thus, the model supports *strong object identity* [KC86]. This does not preclude application environments such as object programming languages from having many references (or denotations) to objects which need not be unique. The state of an object encapsulates the information carried by that object. More specifically, the state encapsulates the denotations of objects and hides the structure and implementation of the information carried by that object. Conceptually, every object is a *composite* object, meaning every object has references (not necessarily implemented as pointers) to other objects. For example, integers have behaviors which return objects, but obviously they are not implemented as a series of pointers. This illustrates a strong point of the model in the separation of behaviors from their implementations.

The access and manipulation of an object's state occurs exclusively through the application of behaviors. An important primitive behavior defined on objects is *identity equality* that compares two object references based solely on the identities of the objects they denote. This is the only kind of equality defined in the primitive type system.

The model separates the definition of object characteristics (a type) from the mechanism for maintaining instances of a particular type (a class). A type specifies behaviors and encapsulates behavior implementations and state for objects created using that type as a template. The behaviors defined by a type describe the *interface* to the objects of that type. Types are organized into a lattice structure using the notion of *subtyping* which promotes software reuse and incremental development. Since TIGUKAT supports *multiple subtyping*, the type structure is potentially a directed acyclic graph (DAG). However, this DAG is converted to a lattice by *lifting* with the base type *null*.

A class ties together the notions of type and *object instance*. A class is a supplemental, but distinct, construct responsible for managing all instances created using a specific type as a template. The entire group of objects of a particular type is known as the *extent* of the type. This is separated into the notion of *deep extent* which refers to all objects created from the given type, or one of its subtypes, and the notion of *shallow extent* which refers only to those objects created from the given type without considering its subtypes. In general, we use *extent* in place of *deep extent* and explicitly mention *shallow extent* when required.

Objects of a particular type cannot exist without an associated class and every class is uniquely associated with a single type. Thus, a fundamental notion of TIGUKAT is that objects imply classes which imply types. Another unique feature of classes is that object creation occurs only through a class. Defining object, type and class in this manner introduces a clean separation of these concepts. This separation is important in schema evolution which manipulates type objects into new subtype relationships and need not be concerned with the overhead of classes.

We define a *collection* as a general user-definable grouping construct. A collection is similar to a *class* in that
it groups objects, but it differs in the following respects. First, no object creation may occur through a collection; object creation occurs only through classes. Second, an object may exist in any number of collections, but is a member of the shallow extent of only one class. Third, the management of classes is implicit in that the system automatically maintains classes based on the subtype lattice whereas the management of collections is explicit, meaning the user is responsible for their extents. Finally, the elements of a class are homogeneous up to inclusion polymorphism while a collection may be heterogeneous in the sense that it can contain objects which may be of different types. There is no equivalent of shallow extent for collections.

We define class as a subtype of collection. This introduces a clean semantics between the two and allows the model to utilize both constructs in an effective manner. For example, the targets and results of queries are typed collections of objects. This means targets also include classes because of the specialization of classes on collections. This approach provides great flexibility and expressiveness in formulating queries and gives closure to the query model which is often regarded as an important feature [YOG91].

Two other fundamental notions are behaviors and the functions (known as methods in other models) that implement them. We clearly separate the definition of a behavior from its possible implementations (functions/methods). The benefit of this approach is that common behaviors over different types can have a different implementation for each of the types. This is in direct support for behavior overloading and late binding of implementations to behaviors. These are recognized as major advantages of object-oriented computing.

The semantics of every operation on an object is specified by a behavior defined on its type. A function implements the semantics of a behavior. The implementation of a particular behavior may vary over the types which support it. However, the semantics of the behavior remain consistent over all types supporting that behavior. There are two kinds of implementations for behaviors. A computed function consists of runtime calls to executable code and a stored function is a reference to an existing object in the objectbase. The uniformity of TIGUKAT considers each behavior application as the invocation of a function, regardless of whether the function is stored or computed. Functions are examined more closely in Section 3. We show that queries are specialized functions and therefore carry all the semantics of function objects, meaning they can be used as implementations of behaviors.

3 Query Model Overview

An identifying characteristic of the TIGUKAT query model is that it is a direct extension to the object model. In other words, it is defined by type and behavior extensions to the primitive model. We define a type Tquery as a subtype of Tfunction in the primitive type system as illustrated in Figure 1. This means that queries have the status of first-class objects and inherit all the behaviors and semantics of objects. Moreover, queries are functions and can be used as implementations of behaviors, they can be compiled, they can be executed and so on.

Functions have source code associated with them and the source code for a query is a TQL statement as defined in Section 5. Functions have a behavior B_compile which compiles the code. For a query, this involves translating the query statement into an algebra tree, optimizing it and generating an execution plan. Functions have a behavior B_execute which executes the compiled code. In general, for a query this means submitting the execution plan to the storage manager for processing. Furthermore, queries have specialized behaviors such as B_result which is a reference to the materialized query result (i.e., the actual result collection itself). If this result is made persistent, then the query is said to be stored and in some cases need not be re-evaluated the next time it is called upon B_execute itself. Other behaviors relating to the extensible query optimizer include B_initialPT and B_optimizedPT for accessing the initial and optimized processing trees; B_search_strategy for accessing the search strategy used for optimization; B_trans_transformations for accessing the list of transformation rules used during optimization; B_input-types for accessing the types of the operand collections; B_output-type for accessing the type of the result collection; and several other behaviors for keeping various statistics about queries.

Incorporating queries as a specialization of functions is a very natural and uniform way of extending the object model to include declarative query capabilities. The major benefits of this approach are as follows:

1. Queries are first-class objects, meaning they support the uniform semantics of objects, they are maintained within the objectbase as another kind of object and they are accessible through the behavioral paradigm of the object model.

2. Since queries are objects, they can be queried and can be operated upon by other behaviors. This is useful in generating statistics about the performance of queries and in defining a uniform extensible query optimizer.

3. Queries are uniformly integrated with the operational semantics of the model and thus, queries can be used as implementations of behaviors (i.e., the result of applying a behavior to an object can trigger the execution of a query).

4. The query model is extensible in a uniform way since the type Tquery can be further specialized by subtyping. This can be used to dichotomize the class of queries into additional subclasses, each with its own unique characteristics, and to incrementally develop the characteristics of new kinds of queries as they are discovered. For example, we can subtype Tquery into TAdhocQuery and TProductionQuery and then define different evaluation strategies for both. Ad hoc queries may be interpreted without incurring high compile-time optimization strategies while production queries are usually compiled once and then executed many times.

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The languages for the query model include a complete object calculus, and equivalent object algebra and an SQL-like user language.

The user query language (TQL) has syntax based on the SQL select-from-where structure, and formal semantics defined by the object calculus. Thus, it combines the power of the relational query languages with object-oriented features.

The calculus has a logical foundation and its expressive power is outlined by the following characteristics. It defines predicates on collections (essentially sets) of objects and returns collections of objects as results which gives the language closure. It incorporates the behavioral paradigm of the object model and allows the retrieval of objects using nested behavior applications, sometimes referred to as path expressions or implicit joins. It supports both existential and universal quantification over collections. It has rigorous definitions of safety (based on the evaluative class of queries) and typing which are compile time checkable. It supports controlled creation and integration of new collections, types and objects into the existing schema.

Like the calculus, the algebra is closed on collections. Algebraic operators are modeled as behaviors on the primitive type T-collection. They operate on collections and return a collection as a result. Thus, the algebra has a behavioral/functionality basis as opposed to the logical foundation of the calculus. The composition over these behaviors brings closure to the algebra.

A desirable property of an object query model is that the algebra and calculus be equivalent in expressive power, meaning that all queries expressed in one language can also be expressed in the other. Space limitations do not allow us to include them here, but in [PLOS93] we prove the equivalence of our object calculus and algebra in both directions and present the reduction of the user query language to the calculus. Moreover, the safety of our languages is proven in that report as well.

4 The Object Calculus

It is well recognized that a declarative query facility is an essential component of any database management system; object-oriented systems are no exception. In this section, we present a high-level object calculus with first-order semantics. In order to maintain the uniformity of the behavioral object model within the query model, the behavioral abstraction is carried through into the calculus.

The logical foundation of the calculus includes a function symbol to incorporate the behavioral nature of the object model. This allows the use of very general path expressions in the calculus. The safety of our calculus is based on the evaluable class of queries [GT91] which is arguably the largest decidable subclass of the domain independent class [Mak83]. We extend this class by making use of object generators in queries which alleviates the need for explicit range expressions for each variable. For a complete discussion of safety in TIGUKAT see [PLOS93].

The alphabet of the calculus consists of object constants \( a, b, c, d \), object variables \( o, p, q, u, v, x, y, z \), monadic predicates \( C, P, Q \), dyadic predicates \( =, \neq, \leq, \geq \), an \( n \)-ary predicate \( E(x,y) \), logical connectives \( \lor, \land, \lnot, \exists \), a function symbol \( \beta \) and delimiters \( ( \ ) \). The object constants, object variables, monadic predicates and function symbol may be subscripted (e.g., \( a_1, a_2, a_n \)). In addition, we adopt a vector notation \( \bar{s} \) to denote a countably infinite list of symbols \( s_1, s_2, \ldots, s_n \) where \( n \geq 0 \).

From object constants and object variables we develop the syntax and semantics of the function symbol \( \beta \) called a behavioral specification (Bspec). A term is an object constant, an object variable or a Bspec. A Bspec is an \( n+2 \)-ary function \( \beta(s, b, \bar{t}) \) where \( s \) and each \( t_i \) denote terms and where \( b \) is an object constant. For \( n = 0 \) we use \( \beta(s, b) \) without loss of generality. A ground term is a term consisting of an object constant or any term formed from ground terms. From now on, any symbol defined as denoting an object constant, including symbols \( a, b, c, d \) denote ground terms as well. Any term that is not a ground term is called a variable term.

The ordered list of terms \( s, b, \bar{t} \) is considered to be behaviorally consistent if and only if \( b \) is an object constant denoting a behavior, the type of the object denoted by \( s \) defines behavior \( b \) as part of its interface, \( \bar{t} \) is compatible with the arity of behavior \( b \), and the types of the objects denoted by \( \bar{t} \) are compatible with the argument types of behavior \( b \). A Bspec \( \beta(s, b, \bar{t}) \) is consistent if and only if \( s, b, \bar{t} \) is behaviorally consistent.

The "evaluation" of a consistent Bspec involves applying the behavior \( b \) to the object denoted by term \( s \) using objects denoted by terms \( \bar{t} \) as arguments. The "result" of Bspec evaluation denotes an object in the objectbase. Since Bspecs denote objects, they have a type (and a class) that are in the objectbase as well.

Bspecs have the following logical foundation. We introduce the \( n+3 \)-ary predicate \( Eval(R, s, b, \bar{t}) \) as an axiom in the language such that \( Eval(R, s, b, \bar{t}) \) is true if and only if \( R \) denotes the "result" of applying behavior \( b \) to the object denoted by term \( s \) using terms \( \bar{t} \) as arguments. The function symbol \( \beta(s, b, \bar{t}) \) is a logical representation of \( R \). The \( Eval \) predicate also serves as an enforcement of the consistency property of Bspecs. From now on we consider only those Bspecs that are consistent.

Bspecs may be composed. This provides the capability of building path expressions in queries. For example, given object constants David, B_worksFor and B_budget where David is an employee, B_worksFor is defined for employees and B_budget is defined for departments, we can compose the Bspec \( \beta(\beta(David, B_worksFor), B_budget) \) which denotes the object representing the annual budget of the department that David works for.

For brevity, we recast the syntax of Bspecs into the dot notation as \( s.b(\bar{t}) \) which we intend as being semantically equivalent to the original specification. If behavior \( b \) does not require any arguments, then the notation simplifies to \( s.b \). The previous example can then be represented as David.B_worksFor.B_budget assuming left-associativity of behavior applications. Parenthesis may be used to change the order of precedence. Some other equivalent syntax, such as function application \( b(s, \bar{t}) \) which is popular in other languages, could have been chosen instead.

As shown by the above example, many path expression formalisms often include a sequence of behaviors with the semantics that the result of the first behavior be used as the input to the second and so on. We call such a sequence of multiple operations a map [S90] which is a Bspec. We introduce the multi-operation dot notation \( s \Rightarrow b_1, b_2, \ldots, b_m \) to denote a multi-operation resulting in the application of behavior object constants \( b_1, b_2, \ldots, b_m \) using objects denoted by terms \( \bar{s} \) as arguments. Furthermore, \( s \Rightarrow b \) is used as a shorthand to denote a multi-operation where the number and ordering of the behaviors are immaterial.

The atoms of the calculus consist of the following:

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The atoms of the calculus consist of the following:
Range Atom: $C(o)$ is a range atom for $o$ where $C$ corresponds to a unary predicate representing a collection and $o$ denotes an object variable. A range atom asserts true if and only if $o$ denotes an object in collection $C$. When $C$ defines a class, it denotes the deep extent of the class and we extend the notation to include $C^+(o)$ which asserts true if and only if $o$ denotes an object in the shallow extent of the class. One may think of $C^+$ as a separate monadic predicate for specifying the shallow range of $o$.

Equality Atom: $s = t$ is a built-in predicate called an equality atom where $s$ and $t$ are terms. The predicate asserts that the object denoted by $s$ is object identity equal to the object denoted by $t$. As a syntactical convenience, we simplify the equality atom specification $s = t$ where $s$ is boolean, to just $s$ and $s = \neg s$. The built-in predicate $s \neq t$ is the complement of equality.

Membership Atom: $s \in t$ is a built-in predicate called a membership atom where $s$ and $t$ are terms and $t$ is a term denoting a collection. The predicate asserts true if and only if the object denoted by $s$ is an element of the collection denoted by $t$. The built-in predicate $s \notin t$ is the complement of membership.

Generating Atom: An equality atom of the form $a = t$ or a membership atom $o \in t$, where $o$ is an object variable and $t$ is an appropriate term for the atom in which $o$ does not appear, are called generating atoms for $o$. They are so named because the object denotations for $o$ can be generated from $t$.

A ground atom is an atom that contains only ground terms. A literal is either an atom or a negated atom. A ground literal is a literal whose atom is a ground atom.

The choice of atoms may seem restrictive when compared to other calculi such as the tuple relational calculus which allows a greater variety of comparison predicates including $=, <, \leq, >$, and $\geq$. An identifying characteristic of our calculus is that it is strictly behavioral and does not allow explicit value based comparisons of objects or their subcomponents. Thus, operations such as $<, >, \geq, \leq$ must be defined as behaviors on the respective types of objects that are to be compared. The only comparison predicate defined is that of object identity equality. However, type implementors can specialize this behavior for their types in order to define a form of equality (including value based comparisons) that is of most utility to them. For example, we define a form of "structural equality" on cartesian product types that compares two product objects based on the isomorphic mappings of their respective component objects.

From atoms, first-order well-formed formula or simply formula (abbreviated WFF) are defined in the usual way using logical connectives $\forall, \land, \lor$ and $\neg$. The concepts of free and bound object variables are also defined in the usual way.

Several variations of queries may be formed. One class of queries deals only with behaviors that are without side-effects. A behavior is said to be side-effect free if it does not modify the state of any object or create new objects during its execution. This property is too restrictive in the context of our model since all operations (including the algebraic operators) are uniformly managed as behaviors. At minimum, a query will always return a new collection as a result and in certain cases will generate a new type for the collection as well. Thus, a small set of predefined behaviors, labelled as algebraic operators, will manage the controlled creation of collection and type objects as their side effects. It is a requirement of our calculus that all user-defined behaviors be side-effect free.

A distinction is commonly made [SS90] between object preserving and object creating operations. An object-preserving operator produces results containing only existing objects from an objectbase. That is, it does not create or modify objects in any way. The query formalism of Straupe and Ozsu [SO90] only considered operations of the object-preserving kind. On the other hand, object creating operators allow for the "taking apart" and "putting together" of objects into various new structures, with new identity. The objects created (especially persistent objects) must be integrated into the underlying type system, including any derived types or classes necessary for the consistent existence of these new objects.

The terms object-preserving and object-creating require further clarification in the context of a uniform object model like TIGUKAT. Queries (at minimum) always create and return a new collection of objects. Furthermore, a query may create a new type object to go along with the collection if a proper type does not already exist. Therefore, all queries are object-creating in one sense. We make the following distinction between queries: if the result collection is formed from existing objects in the objectbase, the query is called target-preserving; otherwise the query is called target-creating.

A target-preserving query is an object calculus expression of the form $\{ t \mid \psi \}$ where $t$ is a target term consisting of a single variable, say $o$, possibly indexed by a set of behaviors, $\psi$ is a WFF with $o$ as the only free variable, and all behavior denotations in the expression are side-effect free.

Indexed variables are of the form $o[B]$ where $B$ is a set of object constants denoting behaviors defined on the type of $o$. The semantics of indexed terms is to project over the behaviors in $B$ for $o$ (possibly) creating a new type. Following a projection, only the behaviors given in $B$ are applicable to objects in the result collection of the query.

Target-preserving queries may seem, at first glance, to be somewhat simplistic and too restrictive, but this form supports a wide variety of useful queries. For example, assume finite classes $C_{\text{dept}}$ and $C_{\text{emp}}$ where $C_{\text{emp}}$ objects have behaviors $B_{\text{dept}}$ and $B_{\text{age}}$ defined on them. The following target-preserving query returns a collection of department objects that have senior citizens working for them:

$$\{ o \mid C_{\text{dept}}(o) \land \exists p(C_{\text{emp}}(p) \land o = p.B_{\text{dept}} \land <p, 65> . B_{\text{age}} . B_{\text{greaterThan}} \} \}
$$

A target-creating query is an object calculus expression of the form $\{ t_1, \ldots, t_k \mid \psi \}$ where the set of variables appearing in (possibly indexed) target terms $t_1, \ldots, t_k$ is precisely the set of free variables, say $\delta$, in the WFF $\psi$. This form is a generalization of the target-preserving kind by allowing $k \geq 2$ target terms over $\delta$ distinct object variables. The result of such a query is a collection of product objects. Say in the previous example we wanted to return (department, employee) pairs instead of just departments and that the returned employee objects project over behavior $B_{\text{age}}$. The target-creating query that produces this result is as follows:

$$\{ o, p[B_{\text{age}}] \mid C_{\text{dept}}(o) \land C_{\text{emp}}(p) \land o = p.B_{\text{dept}} \land <p, 65> . B_{\text{age}} . B_{\text{greaterThan}} \} \}
$$

Additional examples are presented in Section 7.
5 The User Language

The main function of the TIGUKAT language is to support the definition, manipulation and retrieval of objects in an objectbase. The language consists of three parts: the TIGUKAT Definition Language (TDL) which supports the definition of metaobjects (types, classes, collections, behaviors and functions), the TIGUKAT Query Language (TQL) which is used to manipulate and retrieve objects, and the TIGUKAT Control Language (TCL) which supports the session specific operations (open, close, save, etc.). Only TQL is presented in this paper; the complete specification of all languages is given in [Lip93, PLO93].

TQL is based on the SQL paradigm. We adopt this paradigm for various reasons. Most importantly, SQL is accepted as a standard query language in relational databases, and current work on SQL3 attempts to extend its syntax and semantics to fulfill requirements of object-oriented systems [Geb92]. The semantics of TQL is defined in terms of the object calculus. In fact, there is a complete reduction from TQL to the object calculus. In addition, TQL accepts path expressions (implicit joins [KBC+89]) in the select, from and where clauses. Object equality is defined on the primitive type T_object, thus explicit joins are also supported by TQL. The results of queries are queryable, since queries operate on collections and always return finite collections as results. Query results can also be used in the from and where clauses of other queries (nested queries). Finally, objects can be queried regardless of whether they are persistent or transient.

We note that the syntax for the application of aggregate functions is not explicitly supported in the current implementation of TQL. However, as the underlying model is purely behavioral, these functions are defined as behaviors on the T_collection primitive type and can be applied to any collection including those returned as a result of a query.

There are four basic TQL operations: select, insert, delete, and update, and three binary operations: union, minus, and intersect. In this paper, we only discuss the select, union, minus, and intersect statements.

The basic query statement of TQL is the select statement which has the following syntax\footnote{The notation used throughout this section is as follows: all hold words and characters correspond to terminal symbols of the language (keywords, special characters, etc.); nonterminal symbols are enclosed between ‘<’ and ‘>’; a vertical bar ‘|’ separates alternatives; and the square brackets ‘[ ]’ enclose optional material which consists of one or more items separated by vertical bars.}:

\[
\begin{align*}
\text{select} & \; <\text{object variable list}> \\
& \quad \text{[into [persistent [all]] <collection name>]}
\end{align*}
\]
\[
\begin{align*}
\text{from} & \; <\text{range variable list}> \\
\text{where} & \; <\text{boolean formula}>.
\end{align*}
\]

The select clause in this statement identifies objects that are to be returned in a new collection. There can be one or more object variables of different formats (constant, variables, path expressions or index variables) in this clause. They correspond to free variables in object calculus formulas. The into clause declares a reference to a new collection which may be made persistent. If the into clause is not specified, a new transient collection is created, but there is no reference to it. The from clause declares the ranges of object variables in the select and where clauses. Every object variable can range over an existing collection or a collection returned as a result of a subquery where a subquery can either be given as a select statement or as a reference to a query object. Thus, a range variable in the from clause is of the form:

\[
<\text{range variable}> : <\text{id list}> \; \text{in} \; <\text{collection reference}> [+]\]
\[
<\text{collection reference}> : <\text{term}> | ( <\text{subquery}> )
\]

Note that the collection reference in the range variable definition can be followed by a plus ‘+’ which refers to the shallow extent when the collection reference is a class. The default is deep extent for classes. The id list is a list of object variables appearing in the select clause and the term is either a constant reference, a variable reference or a path expression.

The where clause defines a boolean formula which must be satisfied by objects returned by a query. Boolean formulas have the following syntax:

\[
<\text{boolean formula}> : <\text{atom}> \\
\text{not} <\text{boolean formula}> \\
<\text{boolean formula}> \; \text{and} \; <\text{boolean formula}> \\
<\text{boolean formula}> \; \text{or} \; <\text{boolean formula}> \\
( <\text{boolean formula}> ) \\
<\text{exists predicate}> \\
<\text{forAll predicate}> \\
<\text{boolean path expression}>
\]

where an atom is defined as:

\[
<\text{atom}> : <\text{term}> = <\text{term}> \\
| <\text{term}> \; \text{in} \; <\text{collection reference}> [+] \\
\]

and term is a variable reference, a constant reference or a path expression.

Two special predicates are added to TQL boolean formulas to represent existential and universal quantification. The existential quantifier is expressed by the exists predicate which is of the form:

\[
<\text{exists} <\text{collection reference}>
\]

The exists predicate is true if the referenced collection is not empty. The universal quantifier is expressed by the forAll predicate which has the structure:

\[
<\text{forAll} <\text{range variable list}> <\text{boolean formula}>
\]

The syntax of the range variable list is the same as in the from clause of the select statement. It defines variables which range over specified collections. The boolean formula is evaluated for every possible binding of the variables in this list. Thus, the entire forAll predicate is true, if for every element in every collection in the range variable list, the boolean formula is satisfied.

The last part of the boolean formula definition is the boolean path expression which is equivalent to:

\[
<\text{path expression}> = \text{TRUE}|\text{FALSE}
\]

where the path expression is the TQL equivalent of a Bspec. However, to avoid such an artificial construct, we include a boolean path expression in the definition of a TQL formula under two conditions. First, all behaviors in the expression must be side-effect-free and second, the result type of the path expression must be boolean.

TQL supports three binary operations: union, minus, and intersect. The syntax of these statements is as follows:

\[
<\text{collection reference} > \; \text{union} \; <\text{collection reference} > \\
<\text{collection reference} > \; \text{minus} \; <\text{collection reference} > \\
<\text{collection reference} > \; \text{intersect} \; <\text{collection reference} >
\]

TQL has a proven equivalence to the formal languages making it easy to perform logical transformations and argue about its safety. The theorems and proofs of equivalence can be found in [Lip93, PLO93].
The Object Algebra

The underlying framework of the object algebra and calculus are essentially the same. However, an important difference is that the algebra has a functional basis as opposed to the logical foundation of the calculus. In the algebra, names are used as placeholders for collections of objects with the appropriate types. The predicates $=, \neq, \in, \notin$ and connectives $\land, \lor, \neg$ are handled as boolean functions. There is a small set of well-defined functions (the algebraic operators) that provide meaningful operations over collections and can be composed to form queries (existential and universal quantification are handled by composing these operators). Thus, a query is a functional expression to be evaluated and the algebra is a functional language.

Operands and results of the object algebra operators are typed collections of objects. Thus, the algebra is closed since the result of any operator may be used as the operand of another. Let $\Phi$ represent an operator in the algebra. The notation $P \Phi \langle Q_1, \ldots, Q_n \rangle$ is used for expressions where $P$ and each $Q_i$ are names for typed collections of objects. They represent the arguments to $\Phi$. When $n = 1$ we use $P \Phi Q$ and when $n = 0$ we use $P \Phi$ without loss of generality. The collections represented by $P$ and $Q_i$ may be names for basic collections or the result of an algebraic subexpression.

Since the model supports substitutability, any specialization of collection, including classes, may be used as an operand. Similar to the range predicates of the calculus, we define $P^+$ to denote the shallow extent when $P$ is the name for a class.

Some algebraic operators are qualified by a boolean-valued formula (i.e., a predicate). A predicate $F$ is a boolean-valued functional expression that is composed from Bspecs, mops and the functions for $=, \neq, \in, \notin, \land, \lor, \neg$. The arguments to $F$ are permutations of the members of the operand collections for the algebraic operator that $F$ is defined on. The arguments of predicate $F$ must be type consistent with the operand collections. Predicate qualified operators are written as $P \Phi_F \langle Q_1, \ldots, Q_n \rangle$ where $F$ is a predicate with arguments, say $p, q_1, \ldots, q_n$, that range over the elements of collections $P, Q_1, \ldots, Q_n$ respectively.

The object algebra defines both target-preserving and target-creating operators. The target-preserving operators are as follows:

**Set Operations** The typical set union, difference and intersection operators are defined. In addition, a collapse operator is defined for flattening collections of collections.

**Select** (denoted $P \sigma_F \langle Q_1, \ldots, Q_n \rangle$): Select is a higher order operation accepting a function, the predicate $F$, and the $n+1$ary collections $P, Q_1, \ldots, Q_n$ as arguments. The result collection contains objects from $P$ corresponding to the $p$ component of each permutation $\langle p, q_1, \ldots, q_n \rangle$ that satisfies $F$.

**Map** (denoted $Q_1 \Rightarrow_{\text{map}} \langle Q_2, \ldots, Q_n \rangle$): where $\text{map}$ is a side-effect free behavior application that is type consistent with the membership types of $Q_1, Q_2, \ldots, Q_n$. Map applies the behaviors of map to each permutation of objects $\langle q_1, q_2, \ldots, q_n \rangle$. The results of the application are returned in the result collection.

**Project** (denoted $P \Pi_D$): where $D$ is a collection of behaviors with the restriction that it be a subset of the behaviors defined on the membership type of $P$. The $D$ collection is automatically unioned with the behaviors of type $\text{object}$ in order to ensure consistency.

The result collection contains objects of $P$, but with the membership type coinciding with the behaviors of $D$. The $D$ collection has no impact on which objects appear in the result collection of the query. It is only important during the final type assignment which occurs at type inferencing time after the extent of the query has been produced. This form of project differs from the traditional one in that it does not project over the structure of objects, but rather over their behavioral semantics.

The full object algebra includes target-creating operators in order to provide necessary object formation operations. The result of these operations is a collection of new objects that are object identity distinguishable from the ones in the argument collections. The primary target-creating operator is $\text{product}$:

**Product** (denoted $Q_1 \times \cdots \times Q_n$): where $n \geq 2$. Product produces a collection containing product objects created from each permutation $\langle q_1, \ldots, q_n \rangle$ such that component $q_i$ is an object from $Q_i$. Product may initiate the creation of a new type along with a new class to maintain the product objects.

If the map of a map operator is not side-effect free and creates new objects (e.g., it may contain an algebraic operation), then the map operation is target-creating.

The above collection of operators form the primitive algebra (some refer to this as a physical algebra). They are fundamental in supporting the expressive power of the calculus and other expressions can be defined in terms of them. We add the following operators to the primitive algebra and call it the extended algebra (some call this a logical algebra). These operators provide useful functionality; generalize the expressive power of the algebra and are important for higher-level optimizations [SO90].

**Join** (denoted $P \bowtie_F \langle Q_1, \ldots, Q_n \rangle$): where $n \geq 1$. Join produces a collection of product objects created from each permutation $\langle p, q_1, \ldots, q_n \rangle$ that satisfies $F$.

**Generate Join** (denoted $Q_1 \gamma_{\theta} \langle Q_2, \ldots, Q_n \rangle$): where $g$ is a generating atom of the form $o \theta q \langle q \rangle \hat{b}$ (where $\theta$ is one of $=, \neq$) over the elements of collections $Q_1, Q_2, \ldots, Q_n$. Generate join produces a collection of product objects created from each permutation of the $q_i$'s and extended by an object $o$ in the following way. If $\theta$ is $=$, then the result contains product objects of the form $\langle q_1, q_2, \ldots, q_n, q, o \rangle \hat{b}$ for each permutation of the $q_i$'s (i.e., each product object is a permutation of the $q_i$'s extended by the result of the map for that permutation). If $\theta$ is $\neq$, then the result contains product objects $\langle q_1, q_2, \ldots, q_n, o \rangle$ for each permutation of the $q_i$'s and each $o \in q_1 \cup q_2 \cup \cdots \cup q_n$ (i.e., for a permutation of the $q_i$'s and for each member $o$ of the collection resulting from the map $\langle q_1, q_2, \ldots, q_n \rangle \hat{b}$, a product object $\langle q_1, q_2, \ldots, q_n, o \rangle$ is created as a member of the result collection).

**Reduce** (denoted $P \Delta_{\hat{o}}$): where $P$ is a collection of product objects and $\hat{o}$ is a list representing symbolic references to the component domains of the product. The reduce operator has the effect of discarding the $\hat{o}$ components of the objects in $P$. That is, product objects of the form $\langle p_1, \ldots, p_i, \hat{o}, p_{i+1}, \ldots, p_n \rangle$ are mapped
to \(<p_1, \ldots, p_i, p_{i+1}, \ldots, p_n>\). This is similar to the relational projection operator except that the specified components are removed. If \(P\) is not a product object, the empty collection is produced.

7 Example Objectbase

In this section, we present some examples on a geographic information system (GIS) objectbase to demonstrate the power of the query model and its languages. This example is selected because it is among the application domains which can potentially benefit from the advanced features offered by object-oriented technology.

A type lattice for a simplified GIS is given in Figure 2. The example includes the root types of the various sublattices from the primitive type system to illustrate their relative position in an extended application lattice. The GIS example defines abstract types for representing information on people and their dwellings. These include the types \(T_{\text{person}}, T_{\text{dwelling}}\) and \(T_{\text{house}}\). Geographic types to store information about the locations of dwellings and their surrounding areas are defined. These include the type \(T_{\text{location}}\), the type \(T_{\text{zone}}\) along with its subtypes which categorize the various zones of a geographic area, and the type \(T_{\text{map}}\) which defines a collection of zones suitable for displaying in a window. Displayable types for presenting information on a graphical device are defined. These include the types \(T_{\text{display}}\) and \(T_{\text{window}}\) which are application independent, along with the type \(T_{\text{map}}\) which is the only GIS application specific object that can be displayed. Finally, the type \(T_{\text{shape}}\) defines the geometric shape of the regions representing the various zones. For our purposes we only use this general type. In more practical applications this type would be specialized into subtypes representing polygons, polygons with holes, rectangles and so on. Table 1 lists the signatures of the behaviors defined on the GIS specific types. The specification \(T_{\text{set}}(T)\) where \(T\) is a type is used to denote a collection type whose members are of type \(T\).

The following examples illustrate possible queries on the GIS. They are first expressed in TQL (T1): followed by the corresponding object calculus expression (C1) and then the equivalent algebraic expression (A1). In the algebraic expressions, we subscript an operand collection by the variable which ranges over it. This variable is used as a symbolic reference to the elements of the collection. We also use symbols \(R1, R2\) as temporary results and “\(~\)” for assignment. Furthermore, we use the arithmetic notation for operations \(o.B\text{greaterThan}(p), o.B\text{elementOf}(p)\), etc., instead of the boolean path expressions.

Example 7.1 Return land zones valued over $100,000 or cover an area over 1000 units.

\begin{align*}
T & : \text{select} \ o \\
& \text{from} \ o \ \text{in} \ C_{\text{land}} \\
& \text{where} \ (o.B\text{value}() > 100000) \ \text{or} \ (o.B\text{area}() > 1000) \\
C & : \{ o \ | \ C_{\text{land}}(o) \ \land \ (o.B\text{value} > 100000 \ \lor \ o.B\text{area} > 1000) \} \\
A & : C_{\text{land}} = \sigma_{o.B\text{value} > 100000 \ \land \ o.B\text{area} > 1000}
\end{align*}

Example 7.2 Return all zones which have people living in them (the zones are generated from person objects).

\begin{align*}
T & : \text{select} \ o \\
& \text{from} \ o \ \text{in} \ C_{\text{person}} \\
& \text{where} \ (o = B\text{Residence}.(B\text{inZone}())) \\
C & : \{ o \ | \ \exists q(C_{\text{person}}(q) \ \land \ o = q.B\text{Residence}.B\text{inZone}()) \}
\end{align*}

Table 1: Signatures of example specific types in Figure 2.

\begin{table}
\begin{tabular}{|l|l|}
\hline
Type & Signatures \\
\hline
\hline
\(T_{\text{location}}\) & \(B\text{Latitude}: T_{\text{real}}\) \\
\(T_{\text{longitude}}: T_{\text{real}}\) \\
\hline
\(T_{\text{display}}\) & \(B\text{Display}: T_{\text{display}}\) \\
\hline
\(T_{\text{window}}\) & \(B\text{Drag}: T_{\text{window}}\) \\
\hline
\(T_{\text{shape}}\) & \(B\text{title}: T_{\text{string}}\) \\
\(B\text{origin}: T_{\text{location}}\) \\
\(B\text{area}: T_{\text{real}}\) \\
\(B\text{proximity}: T_{\text{location}} \rightarrow T_{\text{real}}\) \\
\hline
\(T_{\text{map}}\) & \(B\text{resolution}: T_{\text{real}}\) \\
\(B\text{orientation}: T_{\text{real}}\) \\
\(B\text{zones}: T_{\text{set}}(T_{\text{zone}})\) \\
\hline
\(T_{\text{land}}\) & \(B\text{value}: T_{\text{real}}\) \\
\hline
\(T_{\text{water}}\) & \(B\text{volume}: T_{\text{real}}\) \\
\hline
\(T_{\text{transport}}\) & \(B\text{efficiency}: T_{\text{real}}\) \\
\hline
\(T_{\text{altitude}}\) & \(B\text{low}: T_{\text{integer}}\) \\
\(B\text{high}: T_{\text{integer}}\) \\
\hline
\(T_{\text{person}}\) & \(B\text{name}: T_{\text{string}}\) \\
\(B\text{birthDate}: T_{\text{date}}\) \\
\(B\text{age}: T_{\text{natural}}\) \\
\(B\text{residence}: T_{\text{dwelling}}\) \\
\(B\text{house}: T_{\text{person}}\) \\
\(B\text{children}: T_{\text{person}} \rightarrow T_{\text{set}}(T_{\text{person}})\) \\
\hline
\(T_{\text{dwelling}}\) & \(B\text{address}: T_{\text{string}}\) \\
\(B\text{inZone}: T_{\text{land}}\) \\
\hline
\(T_{\text{house}}\) & \(B\text{inZone}: T_{\text{developed}}\) \\
\(B\text{mortgage}: T_{\text{real}}\) \\
\hline
\end{tabular}
\end{table}

Example 7.3 Return the maps with areas where senior citizens live.

T: select o
from o in C_{\text{map}}
where exists ( select p
from p in C_{\text{person}}, q in C_{\text{dwelling}}
where (p.B\text{age}() \geq 65 \ \text{and} \ q = p.B\text{residence}(\text{and} \ q.B\text{inZone}() \in o.B\text{zones}())
C: \{ o | C_{\text{map}}(o) \ \land \ 3q(C_{\text{person}}(p) \ \land \ q.B\text{dwelling}() \ \land \ q.B\text{age}() \geq 65 \ \land \ q = p.B\text{residence}() \ \land \ q.B\text{inZone}() \in o.B\text{zones}())\}
A: R1 \leftarrow C_{\text{person}} \sigma_{p.B\text{age}() \geq 65}
\left(C_{\text{map}} \times_{p.q} (C_{\text{dwelling}} \times_{q.R1} p.B\text{inZone}()) \Delta_{p.q}\right)
\quad \text{where} \ q = p.B\text{residence}() \ \land \ q.B\text{inZone}() \in o.B\text{zones}()

Example 7.4 Return all maps that describe areas strictly above 5000 feet.

T: select o
from o in C_{\text{map}}
where forall p in ( select q
from q in C_{\text{altitude}}
where q \in o.B\text{zones}()
\quad p.B\text{low}() > 5000
C: \{ o | C_{\text{map}}(o) \ \land \forall q(C_{\text{altitude}}(p) \ \land \ q.B\text{altitude}() \ \land \ q = p.B\text{inZone}() \in o.B\text{zones}())\}
A: R1 \leftarrow C_{\text{altitude}} \sigma_{p.B\text{low}() \geq 5000}
\left(C_{\text{map}} \times_{p.q} (p.B\text{inZone}() \in o.B\text{zones}) \Delta_{p.q}\right)

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Figure 2: Type lattice for a simple geographic information system.

Example 7.5 Return the dollar values of the zones that people live in.

T: \text{select } q.B_{\text{value}} \text{ from } p \text{ in } C_{\text{person}} \\
C: \{ o \mid \exists p(C_{\text{person}}(p) \\
A: \left( C_{\text{person}} \supset S_{\omega} B_{\text{zone}} \text{ and } B_{\text{value}} \right) \sim p \}

Example 7.6 Return the zones that are part of some map and are within 10 units from water. Project the result over B_{\text{title}} and B_{\text{area}}.

T: \text{select } q.B_{\text{title}}, B_{\text{area}} \text{ from } p \text{ in } C_{\text{map}}, o \text{ in } p.B_{\text{zones}}, q \text{ in } C_{\text{water}} \\
C: \{ o[B_{\text{title}}, B_{\text{area}}] \mid \exists q(C_{\text{map}}(p) \land C_{\text{water}}(q) \\
A: R1 \leftarrow C_{\text{map}} \supset S_{\omega} B_{\text{zones}} \\
R2 \leftarrow \left( R1 \land S_{\omega} B_{\text{proximity}(q)} \sim 10 \right) C_{\text{water}} \sim q \}

Example 7.7 Return pairs consisting of a person and the title of a map such that the person’s dwelling is in the map.

T: \text{select } p, q.B_{\text{title}}(p) \text{ from } p \text{ in } C_{\text{person}}, q \text{ in } C_{\text{map}} \\
C: \{ o, p \mid \exists q(C_{\text{person}}(p) \land C_{\text{map}}(q) \land o = q.B_{\text{title}} (p), q.B_{\text{zone}} \in q.B_{\text{zones}} ) \}

A: \left( C_{\text{person}} \supset S_{\omega} B_{\text{zone}} \text{ and } B_{\text{title}} \right) \sim q

where \( F \) is the predicate:

\( p.B_{\text{residence}} \land o.B_{\text{zone}} \in q.B_{\text{zones}} \)

8 Conclusions and Future Work

The development of an efficient and effective query processor for an object management system requires a formal specification of all its components including the user level language, the object calculus, the object algebra and the completeness of the languages. In this paper, we present the framework of the formalization of the TIGUKAT query model [PLOS93]. This specification is being used as a foundation for implementing the query model.

The query model is defined in a consistent way as type and behavior extensions to the base object model. This is a uniform object-oriented approach to developing an extensible query model that is seamlessly integrated with the object model. This kind of natural extension is possible due to the uniformity built into the TIGUKAT object model which treats everything as a first-class object and allows the consistent abstraction of an object’s “attributes” into the uniform semantics of behaviors.

The TIGUKAT Query Language (TQL) is a user-level language with similarities to the SQL3 standardization efforts [Gal92]. The formal object calculus is a powerful declarative object creating language that incorporates the behavioral paradigm of the object model. Safety is based on the evaluation class of queries [GT91] which is arguably the largest decidable subclass of the domain independent class.
[Mak81] The calculus includes atoms for object restriction and object generation which extend the evaluable class. The object algebra includes a complete set of functional operators that fully support the object-creating nature of the calculus. The novel operators are the behavioral projection which is a form of type generalization and the generate join which extends a join with a mapping of behaviors on the operand collections. The calculus and algebra are equivalent in expressive power and the reduction from TQL to the calculus is complete. Object creating languages require the ability to perform schema evolution because the new objects may not correspond to any type in the lattice. As part of the algebra, we define how the operators relate to the schema in terms of the creation and integration of new types [PLÖS93].

There are a number of ongoing research activities related to this project. A main memory version of the TIGUKAT object model has been implemented. We are coupling this implementation with the EXODUS storage manager [CDV88] to provide persistence. A compiler for the query model and user language presented in this paper is being implemented on top of the object model implementation. Furthermore, we have completed the design of an extensible query optimizer for the algebra and it too is in the implementation stage. The optimizer has been developed as a uniform extension to the object model and will therefore be integrated just like the query model.

Another issue we are addressing is the definition of update semantics for the model. We have defined the syntax and semantics of a TIGUKAT Definition Language (TDL) which allows for the consistent creation of schema such as types, classes and collections. Furthermore, we have also defined TQL statements INSERT, UPDATE and DELETE to perform updates on the objectbase and are currently working out the semantics of these constructs. A related issue involves handling behaviors with side effects and we are hopeful in developing some rules for dealing with these in our languages.

References


