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**Believable Specifications:
Organizing and Describing Object Interfaces
Using Protocol Conformance**

by
David G. Thomson, B.C.S.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of
Master of Computer Science

School of Computer Science
Carleton University
Ottawa, Ontario
March 1993

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**Believable Specifications:
Organizing and Describing Object Interfaces
Using Protocol Conformance**

submitted by David G. Thomson, B.C.S.

in partial fulfillment of
the requirements for the degree of
Master of Computer Science

Thesis Supervisor

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Dave Thomson, March 1993

Abstract

We examine the problem of organizing and describing the behavior of objects in a Smalltalk system, and present a model based on protocol conformance and refinement. Protocol conformance is based on a subtype relationship that includes object behavior and aliasing information for parameter and return values. As an illustration of the model, the Smalltalk Collection classes are factored and discussed using the approach.

Keywords: protocol, interface, type, subtype, object oriented programming, Smalltalk, specification

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Chapter 1

1 Introduction

A major factor in the ability to realize truly reusable and pluggable components [Cox 86] is the ability to clearly, concisely and unambiguously specify the external services which the components provide, and how these services are to be used by clients. These interface specifications establish the rules under which the service user and service provider agree to operate. However, it is important that the interface specifications provide only the minimum amount of information necessary to correctly use the component — providing too much information limits implementation flexibility and makes maintenance more difficult. An interface designer should specify the information required to properly make use of a component but no more. This is known as the *principle of least commitment*. We investigate this problem in the context of the object-oriented language Smalltalk.

1.1 Overview

Smalltalk is a dynamically typed, pure object-oriented language. Objects are instances of classes, and all instances of a class share the same methods. A method contains code which is invoked in response to a message sent by another object. Classes are arranged in a hierarchy which allows subclasses to inherit state and behavior (methods) from superclasses, resulting in a powerful code sharing mechanism.

Objects provide *encapsulation* of data, in that their state variables are accessible only from methods implemented in the object's class, or one of its subclasses. A

a result, the externally visible behavior of an object consists solely of its response to messages. In addition, Smalltalk includes a rich class library and interactive development environment.

Historically, most specifications for Smalltalk systems have been incomplete and/or based on source code.¹ Despite this, Smalltalk the language, and Smalltalk the environment, have been very successful. However, most Smalltalk applications have been developed by individuals or small teams where the details of how interfaces work are well known to the team, or are discovered by reading the code. There has been limited success in shipping Smalltalk components [Digitalk 86], but access to the source code has been essential to understanding how the component interfaces are to be used. Access to the source code is an advantage in that components can be customized by the application programmer. However, it is a disadvantage to the extent that it results in a weaker form of reuse than black box component reuse, which is, at present, virtually impossible due to the lack of workable Smalltalk interface specifications.

The language definition for Smalltalk is minimal, and basic data types that are normally included in the definition of traditional languages are provided by a base class library. However, the composition of this class library varies between Smalltalk systems. With the availability of commercial Smalltalk systems from several vendors² [Digitalk 90] [Digitalk 89] [PPS 92] [OTI 92] there is a growing movement to establish standards [OMG 92] [IBM 92] [ANSI 93] for the base library in order to allow, at least at a certain level, the development of portable application code. A recurring problem in these efforts is that of adequately specifying what the interfaces are, and what they do, without overspecification and unnecessary bias towards a particular implementation. The flexibility provided by dynamic typing and polymorphism³ makes the problem more complex than with traditional

¹We review several such specification approaches in chapter 2

²Programming environments which are Smalltalk-like are also available from other vendors.

³*Polymorphism* is the name given to the property of object-oriented systems which allows different

languages.

In practice, many classes (e.g. Object, Booleans, Magnitudes, Collections, Streams) in the base libraries of modern Smalltalk systems are similar, as a result of their common origins in the research community [Goldberg 85]. However, in many cases the details are sufficiently different that it is difficult to write portable code. Methods often operate identically for a wide range of cases, but differ in less frequently used cases. The problem facing the application developer is that of knowing what is portable and to what extent, since there is no Smalltalk standard.

The idea that routines should be clearly separated into procedures which change their environment, and side effect free functions which do not, is now firmly established in the programming community [Hogg 91] [Wikstrom 87]. In Smalltalk systems from different vendors, methods which are procedural in nature may have equivalent side effects, but return a different value. Since *all* methods in Smalltalk return a value, in such cases the choice of return value is sometimes arbitrary. In fact, due to such differences Smalltalk programmers often adopt informal rules to prohibit the use of return values of methods which are procedural [Barry 92].

It is usually possible to produce a specification for such problematic interfaces which is both useful to the application programmer, and allows existing implementations to comply without any changes. This is achieved by clearly distinguishing the common, guaranteed behavior from the different, incidental behavior. Such an approach that minimizes the impact on existing implementations is clearly desirable (especially from the perspective of Smalltalk vendors) in working towards a *de jure* standard specification. A practical and effective way to document Smalltalk interfaces is a prerequisite for both the standardization of the base Smalltalk system, and the success of third party value-added components.

This thesis examines the problem of documenting Smalltalk interfaces in a manner which meets the needs of the application programmer who uses the interfaces, classes to provide different implementations for the same message.

and the Smalltalk component developer who must implement such interfaces. We focus on capturing the relationships between classes of objects which exhibit common behavior, in order to facilitate interface specifications that are independent of inheritance.⁴

1.2 Interface Specifications

“The most important recent development in programming languages is the introduction of the explicit notion of interface to stand between the implementation of an abstraction and its clients.”

Burstall and Lampson [Burstall 84]

The idea of separating specification from implementation is well accepted in the software engineering community [Liskov 86]. This approach allows the continual refinement and enhancement of systems while maintaining backward interface compatibility with previous implementations, and facilitates portability by allowing different implementations of the same interfaces.

Services provided by a software component are typically documented in terms of the following characteristics:

- Service name.
- Type and meaning of the parameters.
- Description of the behavior of the service i.e. its function and externally visible side effects.
- Type and meaning of the return value (if any).

An interface specification acts as a “contract” [Meyer 90] between a service provider and a service user. It outlines the services provided, the conditions of service, and the guarantees the service provider is willing to make. At the same

⁴The idea that inheritance is an implementation mechanism that should be separated from specification issues is a widely held view [Snyder 86] [America 87] [Porter 92] [Lalonde 91] [Cook 90]. However, some strongly typed object-oriented languages (e.g. Trellis/Owl [Shaffert 86] and C++ [Stroustrup 86]) combine them

time, it hides information on one side concerning how the service is provided, and on the other side concerning how the services are being used. This establishes an agreement under which service providers and service users can be independently developed and maintained.

1.2.1 Verification vs. Testing

There are generally two approaches to judging how closely an implementation complies with a specification. The first is by formal verification which proves correct implementation of a specification. Although this is intuitively appealing, there are practical problems. Among other things, provable specifications typically require people to have specialized training in formal methods in order to read and write them. This results in a communication problem, and in particular makes it difficult for service users to determine whether or not the specification actually describes the desired behavior of the system. [Holt 92] notes that “Although formal methods hold great promise for improving the process of software development, up to now these methods have had limited impact on the actual development of software.”, and gives an overview of the problems that must be solved in order for the situation to change. Many researchers believe that informal methods which are loosely based on formal principles will continue to dominate for the foreseeable future [de Champeaux 91].

The second approach to judging compliance to a specification is through testing, which is by far the most commonly used approach. Testing is either done manually, or by automated test systems. Test code is developed to exercise a system under test in accordance with the specification. Of course, the test code is itself an implementation developed from the same specification, and so the system under test and the automated test system are both suspect. They in effect test each other, ultimately increasing the confidence in the correctness of both (but never proving it), as errors appear and are corrected. Regardless of whether testing is manual or automated, these approaches require human readable specification .

1.2.2 Interfaces that ‘Usually’ Work

Interface specifications of one form or another have been used to achieve a separation between client and implementation in many systems, both hardware and software. A notable hardware example is the Intel 8086 family of microprocessors [Intel 90], which has achieved virtually complete upward compatibility in the 80286, 80386, and 80486 processors. A prominent software example is the Unix operating system C programming interface [Unix 83]. Most Unix C interfaces are now standardized in the IEEE POSIX specification [IEEE 90], allowing implementations as varying as QNX, SunOS, Unix System V, and OSF/1 to support C applications with *identical* source code on all platforms.

As simple as they are, the Unix manual pages are an example of a very successful interface specification. One of the main reasons for this success is the fact that they are simple, concise, and readily available to programmers. They are sufficiently precise to allow programmers to develop applications that use the interfaces without the need to examine the source code to understand what a call really does. Of course they do have limitations, and trial and error experimentation with an interface is still occasionally required to fill in missing details.

1.3 The Problem

Interface specifications have not been used as successfully with Smalltalk systems. Ironically, this is partly due to the fact that Smalltalk code tends to be much simpler and more concise than C code. The *de facto* form of Smalltalk interface documentation is the *method comment*, which is a short, informal description of what the method does [Goldberg 85].⁵ Smalltalk programmers frequently examine the implementation of a method in order to resolve ambiguities or missing information in the method comment [Skublies 91] [Meyer 90] [Gold 91]. The implementation is the

⁵Most vendors also provide a user guide which explains the purpose and general function of each class, illustrated with the help of examples.

final word concerning the behavior. In fact, many Smalltalk programmers ignore or do not trust the method comments because such comments are notorious for being incomplete or incorrect [Barry 92].

1.3.1 Inheritance and Polymorphism

Smalltalk also introduces new problems. Objects which are instances of different classes, or even unrelated by inheritance, may implement methods with compatible behavior, allowing them to be substituted for each other under certain conditions (polymorphism). On the other hand, classes that are related by inheritance may be partially or totally *incompatible*. Since a subclass may add behavior, cancel inherited behavior, or change inherited behavior in arbitrary ways, the inheritance relationship alone guarantees *virtually nothing* about an object's externally visible behavior. Inheritance is used primarily as a code sharing mechanism, and subclassing may or may not reflect behavioral similarities.

In the interest of reuse, the dynamic nature of Smalltalk allows components to be built that will work with classes that are not yet implemented (or are partially implemented), provided they eventually implement the required behavior. These complications make it difficult to describe the behavioral requirements (the types) of parameters and return values.

1.3.2 Aliasing

An important but often ignored issue is object aliasing. In simple terms, an object is aliased if it is referenced from two or more variables. The pass-by-reference⁶ mechanism of Smalltalk results in a heavily aliased environment, and yet method comments rarely provide information concerning whether parameters or return values are aliased. There is considerable potential for unexpected side effects from otherwise unrelated code. On the other hand, aliasing is fundamental to the way

⁶In Smalltalk this is also referred to as pass-by identity.

tightly coupled systems of objects cooperate to do useful work [Hogg 91]. The problem is that normally no distinction is made between *essential aliasing*, which is fundamental to the behavior of the interface, and *incidental aliasing*, which is a side effect of the implementation that should not be relied upon.

1.3.3 Encapsulation

It is ironic that while Smalltalk is touted for its support of encapsulation through objects, in reality the level of implementation encapsulation that is actually achieved at both the object and component⁷ level is quite low. This is in part due to the language itself [Snyder 86], but also due to the way Smalltalk systems are (not) specified, distributed, and used, since Smalltalk component reuse typically requires access to the implementation. From this perspective, a C library often does a much better job of encapsulating behavior. [Hogg 91] states "...the big lie of object-oriented programming is that objects provide encapsulation". In a pass by reference model such as Smalltalk where pointers are passed as parameters and return values, it is a complex problem to localize the potential for affecting the state (and subsequent behavior) of an object. Encapsulation can be somewhat improved through disciplined software engineering approaches [Lieberherr 88] which limit the ability of client code to send messages to objects which comprise the *state* of other objects which are service providers. However, the problem of describing the encapsulated behavior remains.

1.3.4 "Is it really a problem?"

The poorly documented nature of Smalltalk interfaces is often downplayed by the Smalltalk community since the source code is normally available for inspection as required. However, this aspect of Smalltalk systems has created a barrier to entry

⁷A Smalltalk component is normally considered to be a set of new classes and/or enhancements to existing classes.

for new Smalltalk programmers. A new Smalltalk programmer quickly discovers he must spend long hours studying source code in order to become proficient in this powerful new environment. Recognizing this problem, some organizations institute formal or informal mentoring programs which give new programmers access to a Smalltalk “wizard” so they can learn all of the subtle intricacies of the system by “osmosis”. This is currently the most effective way to learn Smalltalk.

1.3.5 “What can I rely on?”

Application programmers can (and often do) rely on obscure behavior that can only be discerned from reading the source code. Any change to the code is potentially a change to the specified behavior, since effectively the code *is* the specification.

Major problems soon become apparent when a Smalltalk vendor or component supplier attempts to improve or change the implementation of a base class or component, or if an application developer attempts to build a system for simultaneous deployment on Smalltalk systems from different vendors. A problem with many Smalltalk components currently in use is that the scope of what can be done to improve them (e.g. for performance or maintenance reasons) is very limited. Frequently, the implementations can not be safely changed in anything but trivial ways because of the potential for breaking client application code.

The problem is that there is no distinction between the guaranteed behavior that was the intent of the implementor,⁸ and behavior that is purely incidental to the particular implementation. A relatively innocuous example due to [Wills 91] is a sorting algorithm which happens to leave items that are equal in their original order. Is this a side effect of the particular sort algorithm, or is it specified behavior? In real world applications the practical effects can be much more serious.

The need for the distinction between specified and incidental behavior becomes painfully obvious in the context of object sharing and aliasing issues. An application

⁸This spelling (*implementor*) is the one in common usage in the Smalltalk community.

programmer may rely on the fact that the private state of an object happens to be returned as the result of a method, and that state modifications to the return value will effectively change the state of the original object. Conversely, the programmer might rely on the fact that state is *not* returned. The rules regarding who can modify the state of an object must somehow be reflected in the “contracts” between the service providers and service users, without unduly exposing the implementation. An implementation change which returns an object that is equal but has different aliasing properties may break working, “correct” application code.

1.3.6 “The Spec is the Code”

While Smalltalk code serves as a concise specification for simple operations, as complexity increases it becomes more difficult to deduce what a method does from its code. The effects of inheritance make matters even worse [Snyder 86], both for the application programmer and for the implementor. Many methods in the base library are difficult to understand due to deep hierarchies, differing implementations among classes, and method overriding and cancellation⁹ [Lalonde 91] [Lalonde 86] [Wegner 88]. It is not unusual for a new Smalltalk programmer to have to trace execution with a debugger in order to understand the actual behavior. The combination of polymorphism and method overriding makes it very difficult to understand the behavior of classes deep in a hierarchy, and how they are implemented. In particular, a message send to *self*¹⁰ may actually invoke a method in the same class, a subclass, or a superclass. This is described as the *Yoyo Problem* by [Taenzer 89] because one gets the feeling of riding a yoyo tracing message sends to *self*, up and down a hierarchy.

In some cases methods are “accidentally” inherited¹¹ and either do not work or violate representation invariants of the superclass [Cook 92]. Methods which

⁹Method *overriding* and *cancellation* in Smalltalk are illustrated in section 2.5.1.

¹⁰*self* is the special variable representing the receiver of the message.

¹¹This happens when the programmer neglected to cancel an inherited method

initially appear to be supported may in fact produce errors or simply operate in unexpected ways. The implementor of a class may not even realize or intend that some of these interfaces be supported. In fact, the implications of re-implementing a method (in a subclass) on the behavior of inherited methods can be very difficult to trace or understand, and specification and implementation are either in conflict, or hopelessly intertwined.

1.4 Motivation

Approximately six variants of the Smalltalk base library are now commercially available ([Digitalk 88] [Digitalk 88b] [Digitalk 90] [Digitalk 89] [PPS 92] [OTI 92]) on a total of over fifteen different hardware and operating system combinations, ranging from embedded real-time systems, to Microsoft Windows and IBM OS/2, to Unix systems supporting X/Windows based user interfaces.

The recent explosion of platforms supporting graphical user interfaces has caused software suppliers to scramble to provide their applications on as many platforms as possible, with simultaneous deployment wherever possible. One shot porting is not a viable option, since maintenance becomes very difficult if multi platform applications can not be at least partially, if not totally, single sourced.

The programming interfaces available across Smalltalk systems can be divided into two sets: common interfaces, and platform dependent interfaces. The approach used in specifying these interfaces significantly affects how the distinction is made. In particular, an approach that is closely linked to implementation will result in a smaller set of common interfaces than one that is not. The larger the set of common interfaces, the more application code can be single sourced.

From certain perspectives, the set of common interfaces is large, but this set can be difficult to determine due to implementation differences. To date there has been only one significant attempt to define a set of common interfaces in a manner independent of the implementation [IBM 92]. However, as we shall discuss

in chapter 2, it has several important weaknesses. In particular, the approach does not describe behavior in sufficient detail to eliminate¹² the need for access to source code.

Source code inspection *may* be an acceptable requirement for a developer working with a single Smalltalk implementation. However, its suitability diminishes quickly when a programmer must inspect multiple implementations and generalize their common properties in order to write portable code.

1.5 Contribution

"Even if the actual specifications used are not (completely) formal, formal techniques could help us to develop a framework for specifying components independently of the code that implements them."

OOPLSA '91 Formal Methods Panel [de Champeaux 91]

We present a descriptive model for specifying and grouping the behavior of Smalltalk objects into units called *protocols*. Protocols are independent of implementation inheritance relationships, and describe essential aspects of behavior while leaving incidental aspects unspecified (the fact that something is unspecified is important information to a diligent application programmer).

Protocols are in turn used to describe the properties of message parameters and return values. We then establish *conformance* and *refinement* substitutability relationships which arrange protocols in a lattice, providing a complete picture of the behavioral relationships of a set of classes. Conformance provides the flexibility to describe parameters and return values without naming particular classes.

We draw from recent work on object-oriented type systems, and aliasing prevention. Although such approaches are primarily focused on implementation issues, many of the problems are the same. In particular, we show that while the parameter contravariance¹³ rule (required for substitutability) limits flexibility in strongly typed object oriented implementation systems, the same problem does not occur

¹²Or at least *virtually* eliminate.

¹³Contravariance, covariance, and the *contravariance problem* are discussed in chapter 2.

with a specification system.

The protocol model is intended to provide a client's view¹⁴ of Smalltalk component interfaces, independently of implementation. This provides improved encapsulation, and facilitates the development of applications which will work with different implementations of the same interfaces.

We illustrate our ideas by presenting a factoring of the Smalltalk Collection classes based on portable behavior across several commercially available Smalltalk systems. We have chosen the Collection classes because they are representative of the issues involved in specifying Smalltalk systems, and because many other researchers illustrate their ideas with these classes. By choosing examples from the Collections, we can compare our approach with other work.

1.6 Organization of the Thesis

In chapter 2 we establish a framework in which to review approaches for organizing and describing the behavior of objects in a Smalltalk system. We then review several approaches to specifying Smalltalk interfaces, and present related work in object oriented type systems. In chapter 3 we present our descriptive model which organizes object behavior into sets of messages called *protocols*, and describes message behavior, parameters, and return values. Chapter 4 establishes the conformance and refinement relations and their implications for describing behavior. In chapter 5 we show how the model is applied and present a factoring of the Smalltalk Collection classes in order to illustrate the approach and explore the important issues. In Chapter 6 we summarize the work and suggest directions for future research.

¹⁴As opposed to a service provider's view which describes implementation detail required to subclass existing classes.

Chapter 2

2 Background and Related Work

In this chapter we establish a framework in which to characterize approaches to the problem of describing the behavior of objects in Smalltalk. We then examine a number of representative approaches in the context of this framework. We define our use of terminology where there is the potential for confusion over different usages, but we assume the reader is familiar with the general principles behind object oriented languages, and Smalltalk in particular.

2.1 The Smalltalk Object-Message Model

An *object* is an instance of a particular *class*. A *method* contains code which is invoked when a *message* is sent to an object. A method is identified uniquely by the class of the object receiving the message and a *message selector*. A message consists of a message selector and message parameters.

Smalltalk is a pass-by-reference system. Objects have a unique *identity* – that is, it is possible to ask if two variables reference the same object, independent of any notion of equality of values.

Polymorphism is the name given to the property of object-oriented systems which allows different objects to respond to the same message in different (or similar) ways, since different classes may have methods which can be invoked by a given message.

All objects in the same class share the same methods, and the same representa-

tion. Classes are arranged in an inheritance hierarchy — a tree.¹⁵ A subclass inherits both code and state variables from its superclass. When a message is sent to an object, method lookup searches upward through the inheritance hierarchy until a matching method is found, allowing classes of objects to inherit behavior. We will use the term *inheritance* to refer only to implementation inheritance as described above.¹⁶

Inheritance is a powerful implementation mechanism, supporting a style of programming where a new class is programmed in terms of its differences from an existing class. A subclass may cancel inherited methods, add new methods, and override inherited methods in order to change behavior. As a result of this flexibility, inheritance alone provides no guarantee concerning the behavioral relationships of classes, since the behavior of a class may differ from its superclass in arbitrary ways.

2.2 A Framework for Characterizing Approaches

The problem of capturing the behavioral properties of (classes of) objects can be divided into the following three subproblems, the second of which is particularly important for object-oriented systems.

- **Group Membership** — establishing the conditions which define membership in a group of objects having common behavioral properties.
- **Relationships Between Groups** — defining relations between groups of objects having common behavioral properties.
- **Description of Behavior** — defining the behavioral properties implied by group membership.

¹⁵It is possible to introduce multiple inheritance into Smalltalk. However, commercial Smalltalk systems use only single inheritance.

¹⁶Some researchers use the term *inheritance* when describing behavioral (or specification) relationships.

Despite the fact that we have identified these as separate problems, in fact they are interrelated. Nonetheless, it is still useful to distinguish them in this way for discussion purposes.

Note that we are concerned with establishing groups of objects which have common behavioral properties. We are not interested in how an object is implemented, but rather in how it can be used.¹⁷ In particular we are interested in establishing groupings of objects which have some intrinsic property in common which is externally visible. The result is that our groupings establish a static view of the externally visible behavior of a set of classes, showing the relationships between (objects of) classes having similar intrinsic properties. This is in contrast to work which attempts to capture information concerning how objects *interact* to accomplish work [Helm 90] [Adams 92] [Wirfs-Brock 90].

2.2.1 Group Membership

A group of objects exhibiting common interfaces or behavior is commonly referred to as a *type*. A type can be thought of as defining a predicate on objects such that an object x has type T whenever x satisfies the predicate corresponding to T .

There is a wide range of views in the object-oriented community concerning how such a predicate defines membership in a type, some emphasizing the implementation of behavior, and others the specification. All of these views are motivated by the need to establish groupings of objects with common behavioral properties. In this section we present an overview of the various approaches used to establish membership in a group of objects exhibiting common behavior.

Figure 1 shows a spectrum of types (adapted from [Palsberg 92]) with points indicating commonly used notions of the type predicate, in order of increasing expressiveness from left to right. By increasing expressiveness we mean roughly that the groupings describe the behavior of objects more precisely.

¹⁷See also [America 90], upon which we base our description of this idea

Figure 1: Spectrum of types

Moving from left to right across the spectrum, membership of an object in a type is characterized as follows:

- **Class and Arbitrary Subclasses** The object is an instance of a particular class or one of its subclasses. By arbitrary subclasses, we mean that a subclass can add methods, change the behavior of inherited methods, or cancel inherited methods.
- **Method Names** The object implements a certain set of methods identified only by their message selectors.
- **Signatures** The object implements a certain set of methods (identified by their message selectors), and the types of the parameters and return values are also specified. A *signature* is a set of message selectors and associated parameter and return type information.
- **Class and Monotone Subclasses** The object is an instance of a particular class or one of its subclasses, and subclasses may only add methods or override methods (no method cancellation).
- **Behavior** The functionality provided by a method is described in some way, typically in a manner independent of its implementation.

- **Class and Strictly Monotone Subclasses** – The object is an instance of a particular class or one of its subclasses, and subclasses may only add methods.
- **Set of Classes** – The object is an instance of one of a set of classes.

Allowing arbitrary subclasses is not a very useful definition of behavior, since subclass behavior may differ from superclass behavior in arbitrary ways. The method names approach is somewhat of an improvement since it guarantees that an object will at least respond to a set of messages. However the action taken in response to a message is left unspecified, and there is no guarantee that the parameters will be appropriate, since their behavioral requirements are not described.

Since signatures impose restrictions on parameters and return values, they can be used to guarantee *type safety*, in the sense that all messages sent will be understood.¹⁸ However, signatures have limitations, as shown by the following example [Palsberg 92]. Consider two classes, Cowboy with methods `#draw`, `#move`, and `#shoot`, and Rectangle which implements `#draw` and `#move`, but in completely different ways. Signatures fail to capture this difference. A Cowboy substituted for a Rectangle may be type safe, but will certainly result in run-time errors.

Monotone subclasses provide signature compatibility, but still may change the behavior of inherited methods in incompatible ways. Behavioral descriptions *usually* include signatures and behaviorally relate parameters and return values independently of any particular implementation. Strictly monotone subclasses include full behavior, and even require that the behavior have a particular implementation.

Sets of classes are the most limiting, in the sense that they can only describe objects in existence at the time the type is defined, since each acceptable class must be listed.

It should be noted that type membership criteria need not be related to implementation classes or inheritance at all. Some systems define types as sets of

¹⁸A message is “understood” by an object if the object implements or inherits a method having the same message selector as the message.

classes [Johnson 86] [Oxhoj 92] [Palsberg 91] or make use of class information to define types [Borning 82]. However, method names, signatures, and behavior based models can be defined *independently of classes*, and classes can be thought of as implementing types. In fact, a type may describe only certain aspects of the behavior of a class, and thus a class may implement several types simultaneously. The term *protocol* is normally used to refer to groupings defined by method names, signatures, or behavior. In this context the terms *type* and *protocol* can be used somewhat interchangeably.

Behavioral type models provide a mechanism for defining object behavior abstractly in terms of interfaces, without reference to inheritance or other implementation details. Of course, in order to be practical, behavioral models need to be associated with the classes that implement the behavior through some sort of relationship.

2.2.2 Relationships Between Groups

The ability to establish relationships between groups of objects having common behavior is of critical importance in object-oriented systems. Polymorphism allows different objects to respond to the same messages. If the behavior of these messages is compatible then objects of one type may be substitutable for objects of another type under certain conditions.

Components can be built that will operate on parameters which are instances of classes that *may not even have been defined* when the component was compiled, providing they are behaviorally substitutable for parameters the component was *designed* to work with. This is an important form of reuse. In particular it allows large systems to be extended without modifications to existing code. In order to properly describe the parameters and return values of such components, it is necessary to establish a relationship between groups of objects, so that we can say whether one object is substitutable for another in such contexts.

The criteria established for group membership may be based on properties such as class membership and inheritance (*implementation types*), or specification properties such as externally visible behavior (*specification types*). Depending on the particular criteria used, the corresponding relationship between groups may be *inheritance*, *subsetting*, or *conformance* (also referred to as *subtyping*), and these relationships may characterize substitutability to varying degrees. Inheritance is an implementation relationship which relates classes through *subclassing*. Sets of classes are related through *subsetting* which establishes both an implementation (class membership) and a specification (externally visible behavior) relationship. Conformance and subtyping are not as consistently defined in the literature.

Conformance is typically a specification relationship used with specification types, (or protocols), when describing behavioral interfaces. Subtyping normally refers to a substitutability relationship between either specification or implementation types. A type *S* is a subtype of a type *T* if all (possible) objects of type *S* are substitutable for parameters of methods written to accept objects of type *T*. The equivalent relationship when using *protocol* terminology is conformance.¹⁹ Whether discussing subtyping or conformance, it is important to identify whether or not a substitutability relationship is implied.

In order to guarantee substitutability [Wegner 88], subtype operations must accept *at least* all parameters accepted by the supertype, return a subset²⁰ of the return values of the supertype, and the interface specifications for the supertype must hold in the subtype. In other words, a type *S* is a subtype of a type *T* if:

- *S* provides at least the operations of *T*.
- For each operation in *T*, the corresponding operation in *S* has the same number of parameters, and either both return a value or neither return a value.
- The types of the parameters of *S*'s operations are the same or *supertypes* of

¹⁹Some definitions of conformance provide a weaker relationship than substitutability.

²⁰A proper subset is not required – it may return the same return values

the corresponding parameters of the operations in T . This is known as the *contravariance* rule for parameters [Cardelli 84].

- The types of the return values of the operations in S are the same or *subtypes* of the results of the corresponding operations in T . This is known as the *covariance* rule for return values [Cardelli 84].
- The externally visible behavior of each operation in S is as specified for the corresponding operation in T .

If only the first four hold, then S is *signature substitutable* for T . This is the basis for type safety.

The parameter relationship is said to be *contravariant* because the relationship between corresponding parameters is *opposite* to the relationship of the two types being compared. The return value relationship is said to be *covariant* because the relationship between corresponding return values *parallels* the relationship for the types being compared. Some researchers [Cook 89] [Palsberg 92] [Dodani 92] have pointed out that the contravariance rule for parameters may be too restrictive since a programmer typically wants to specialize rather than generalize parameters in subtypes. This is referred to as the *contravariance problem*.

Requiring parameter contravariance in implementation type systems limits flexibility since it precludes specializations involving restricted cases. Figure 2 shows an example of a specialization hierarchy. String is a specialization of Array, which holds only characters. An instance of String is substitutable for an Array *under certain conditions*, providing no attempt is made to store a non-character into it. However, in general a String is not substitutable for an Array, since a method expecting an Array may try to store an arbitrary object into the String.

Some type systems, such as Eiffel [Meyer 88] allow covariant parameter redefinition, and recognizing that this can lead to run time errors, provide mechanisms such as dynamic type checks to handle the problem at run time.

Figure 2: A Specialization Hierarchy

For completeness, most type systems [Palsberg 92] define two special types: *NONE* and *ANY*. *NONE* is the subtype of all other types, and is defined such that there are no classes which implement the type. *ANY* is the exact opposite, in that it is the supertype of all types. Any object of type *NONE* has *all possible behavior*, and is substitutable for all other objects. Since there may be incompatible operation name collisions between different types, such an object is, in general, impossible to implement. Thus it is convenient to define *NONE* such that there are no objects of that type. In other words, *NONE* has *maximal* behavior, and *no* objects implement the type. *ANY* has *minimal* behavior, and *all* objects implement the type.

Sets of classes are a form of type *union*. A type union is a logical OR of types such that an object is a member of the type if it is a member of one or more types in the disjunction. For example, consider a union of three types, T1, T2, and T3, written as $T1 \mid T2 \mid T3$. An object x is a member of the type union if it is a member of *either* T1, T2, or T3, or *any combination*. This can be a somewhat confusing concept, because the union really describes distinct kinds of objects, which may have little behavior in common. The difficulty concerns conclusions that can be drawn concerning the behavior of an object which satisfies a union type. The only assured behavior is that of the nearest common supertype,²¹ and this property is used in

²¹ The *nearest common supertype* of a set of types is the supertype of all types in the set, which itself has no subtype that is also a supertype of all types in the set.

lieu of union types by [Borning 82] in one of the first type systems for Smalltalk. However, union types can provide more specific information (than the nearest common supertype) through the use of *type casing* — run time testing of an object's behavior. The types in the union are the possible cases. [Johnson 86] also uses static analysis of control flow to identify the individual cases during compilation.

Establishing a relationship between groups of objects having common behavior serves two different roles in a specification. First, it is fundamental to being able to describe the properties of parameters and return values in a polymorphic system. Second, it allows information sharing, in that the behavior of one group may be defined in terms of one or more other groups by *composition* and/or *refinement*. Using *composition*, behavior is described as conformance to previously described behaviors, and *refinement* describes new behavior in terms of increasingly precise statements concerning previously described behavior.

Figure 3: Composition and Refinement

Figure 3 illustrates the concepts of composition and refinement. The arrows indicate a composition relationship; dark lines are used to show where refinement also occurs. The types T1, T2, T3, and T4 define the behavior of a set of messages, numbered 0 through 7. Through composition T2, T3, and T4 include the behavior of `message0`. Additionally, T4 includes the behavior of `message1` through `message5` (inclusive) through composition of T2 and T3. The definition of `message6` from T1 is refined by T3 (to provide additional information), and this refinement is included

in T4 through composition. Finally, T4 refines `message1` and `message4` from T3 and T2 respectively.

Approaches that support refinement of behavior, as opposed to *just* composition (through conformance), are more powerful since subtypes or conformant protocols provide additional information concerning aspects of behavior that have been left unspecified by the supertype (or conformed-to protocol). In addition to allowing behavior to be described in more detail, refinement also allows generalization and specialization of parameter and return values according to the substitutability rule. The use of composition alone would result in the parameter and return value definitions being exactly the same.

2.2.3 Description of Behavior

One of the most important advances in software engineering is the use of *abstractions*. An abstraction encapsulates the details of how a particular service is implemented, reducing the amount of detail that must be understood at one time, and allowing the programmer to concentrate on higher level problems. [Liskov 86] provides an excellent discussion of the principles of abstraction in software development, and the role of specifications in describing the externally visible behavior of abstractions.

Abstraction by specification focuses on the behavior that a client can depend on from a service provider without exposing the details concerning how the behavior is implemented. Two important advantages of this approach are [Liskov 86]:

- **Locality** The implementation of one abstraction can be read or written without the requirement to examine the implementation of any other abstraction. To write a program that uses an abstraction, a programmer need only understand the abstraction's behavior — not the details of its implementation.

- **Modifiability** Abstraction by specification helps to bound the effects of program modification and maintenance. If the implementation of an abstraction changes but its specification does not, the rest of the program will not be affected by the change.

An *interface* is the point where the service provider and client meet. It is that part of a component implementation which is made visible to the client by the service provider. An *interface specification* defines the conditions under which the service provider agrees to provide the service, and the promises the service provider is willing to make. An interface specification defines the boundary of an *abstraction* - only the information required to use the service should be provided by the interface specification, and no more. In this way, the interface *encapsulates* the implementation.

Attributes of Specifications

Three attributes which are important for specifications are as follows [Liskov 86]:

Restrictiveness The specification should be restrictive enough to rule out implementations that are unacceptable to its abstraction's users.

Generality The specification should be general enough to rule out few, if any acceptable implementations.

Clarity A good specification should facilitate communication among people.

The first two attributes concisely describe what is known as the *principle of least commitment* [Wikstrom 87]. The *restrictiveness* and *generality* attributes mean that the specification should provide sufficient information to properly describe the required functionality and the conditions under which it is provided, but it must not overspecify. Overspecification limits implementation flexibility and maintainability, and can preclude important optimizations. Underspecification may allow implementations with undesirable properties.

A good check for generality is to examine every property of a specification and ask whether it is really needed. If not, it should be eliminated or weakened. An important factor in achieving generality is making a distinction between *essential* and *incidental* behavior, and ensuring that only essential behavior forms a part of the specification. *Essential* behavior is that which is fundamental to the service being provided — and presumably the utility of the interface would be severely limited if it were omitted. *Incidental* behavior is a side effect of implementation choices or the specification approach. Essential behavior is intended as part of the service commitment, while incidental behavior is not. The distinction is up to the interface designer.

The *clarity* attribute requires that a specification be easy to read and understand. A specification may be sufficiently restrictive and sufficiently general and may have exactly the right meaning, but this is not enough. If the meaning is difficult for readers to discover, the specification's utility is severely limited. Clarity is difficult to characterize. According to [Liskov 86], *conciseness*, *redundancy*, and *structure* are the most important factors in achieving clarity. The most concise presentation may not be the best specification, but is often a good starting point. Redundancy plays an important role because it reduces the likelihood that an important point will be missed. Presenting the same information in different ways gives readers a benchmark against which they can double check their understanding. Additionally, while redundancy does not reduce the number of errors in a specification, it makes them more evident and provides the reader with an opportunity to notice them.

Structure serves two roles. First, it acts as a categorization mechanism to make things easier to find. Second, structure can provide information itself as a result of properties associated with the structuring mechanism. A strong structuring relationship makes definite statements concerning the implications of the structure. For example, in our society the parent/child relationship provides information con-

cerning both genetics and legal obligations for support. A weaker structuring relationship, such as “friend” provides information with less certainty. The stronger the properties associated with a structuring relationship, the more significant the information provided by structure alone. In particular we are interested in the structure provided by defining relationships between groups of objects having similar behavior.

Definitional vs. Operational

Specifications can be characterized as being either *definitional* or *operational* [Liskov 86]. A *definitional* specification indicates a set of properties that a correct implementation will exhibit, whereas an *operational* specification gives a recipe for how the results should be computed. In some cases, a definitional specification can be much more concise than an operational one, for example a specification for square root which can simply state that the relationship between the answer and the parameter is such that the answer squared is equal to the parameter. An operational specification for square root would be much more complicated. However, in other cases it is much simpler to use an operational specification, such as for a program which calculates an income tax return, because the problem itself is normally stated operationally.

An inherent risk in operational specifications is overspecification, since it is often possible to deduce information from the description and sequencing of the steps which, at least in the mind of the interface designer, is incidental to the primary functionality. For this reason definitional specifications are preferred wherever possible.

A common way of providing definitional specifications is through the use of pre and post-conditions [Wills 91] [America 90] [Cook 92]. Pre conditions state axioms that must be true in order for the operation to be invoked, and post conditions describe the effects of the operation. Pre- and post conditions are typically described

using some sort of notation based on a model of the object's state.

Aliasing Information

"Both programmers and formalists could benefit from constructs that enhance the locality of analysis by annotating methods in terms of their resulting aliasing properties."

Geneva Convention On The Treatment of Object Aliasing [Hogg 92]

An important aspect of behavior is *aliasing*. [Hogg 92] provides an excellent overview of the problem of aliasing in object-oriented systems.

An object is aliased if there are references to it from two or more variables.²² Unless managed carefully, aliases can result in mysterious bugs as variables "seem to change their values on their own". An example from procedural languages is as follows [Hogg 92]. Consider a call-by-reference matrix multiply procedure `mult(left, right, result)` which multiplies the first two matrices and puts the result in the third. This may work fine until a programmer calls it as `mult(a, b, a)`. If the implementor of the multiply procedure did not consider the possibility that a parameter may be aliased with the result, the result is likely to be a meaningless jumble of numbers. Even worse, no error is reported.

Aliasing is also a problem for formal approaches since it can make even the simplest expressions difficult to prove. Consider the simple Hoare expression:

$$\{x = \text{true}\} \ y := \text{false} \ \{x = \text{true}\}$$

If `x` and `y` refer to the same boolean variable (i.e. are aliased) then the formula will not be valid, and proving that aliasing can not occur can be difficult.

While the aliasing problem is considered to be "under control" in traditional languages [Hogg 92], the approaches to the problem have for the most part proven to be incompatible with the dynamic environment of languages such as Smalltalk, which are also heavily aliased.

²²Any of global, local, parameter, or object state variables

The treatment of aliasing can be categorized as follows [Hogg 92]:

Detection Static or dynamic (run time) diagnosis of potential or actual aliasing.

Advertisement Annotations that help modularize detection: by declaring aliasing properties of methods.

Prevention Constructs that disallow aliasing in a statically checkable fashion.

Control Approaches that isolate the effects of aliasing.

[Hogg 91] is the most significant work on aliasing in object oriented systems, and focuses on the problem of aliasing *prevention*. An important consideration in specifications for a language such as Smalltalk is whether or not the specification includes aliasing *advertisement* information. The most important aliasing cases for such specifications involve whether or not an object retains a reference to a parameter (i.e. it is *captured*), and whether or not returned objects are newly created (unaliased).

Parameters and Return Values

A fundamental problem in specifying interfaces for dynamically typed systems such as Smalltalk is describing the requirements of parameters, and the attributes of return values. A simple approach that lists all of the classes that are acceptable is limited to the classes in existence at the time the interface is specified. This introduces a serious reuse problem since subsequently defined classes, which are otherwise acceptable as parameters, are precluded.

In order to provide enough flexibility to describe classes which may not yet be defined, it is necessary to use group membership and the properties of the relationships between groups to describe parameters and return values. However, in order to ensure that parameters and return values are sufficiently described, substitutability must be implied by such relationships. An approach that describes parameters with

a group relationship which is weaker than substitutability will allow parameters that are unacceptable and cause run-time errors.

Figure 4: The importance of substitutability

The power of a substitutability relationship is illustrated by figure 4. In this example, the Widget hierarchy implements a set of user interface classes, and the UIBuilder class is designed to work with the external interface defined by Widget in order to support the interactive design of user interfaces. The UIBuilder makes no assumptions about widgets except those defined by class Widget. Assume UIBuilder places widgets on a canvas, and allows a user to move them about to create the desired layout. Since UIBuilder relies only on the externally visible behavior of Widget, Buttons and ListWidgets can also be layed out if they exhibit the same external behavior. It is inconsequential whether they add additional behavior or not — the operation of the UIBuilder will not be affected. In other words, other widgets will work with the UIBuilder if they are *substitutable* for objects of class Widget. More importantly, new widgets can be *subsequently* developed, and if they are substitutable for instances of Widgets they too can be used with the UIBuilder *without requiring any modifications to UIBuilder*.

Thus an important aspect of interface specifications for polymorphic systems is whether or not parameters and return values are described using behavioral group membership, and whether or not substitutability is implied. Such an approach contributes greatly to both the restrictiveness and the clarity of the specification since the behavioral requirements are more precisely and concisely described, in contrast

to approaches where parameter and return value attributes must be discerned from context or method comments. Most researchers agree that such type information improves readability [Palsberg 92]. It also provides improved generality over approaches that implicitly indicate parameter and return value attributes by exposing the implementation, since this may commit the interface to incidental behavior.

Signatures describe parameter and return value information in this way, but not all behavioral approaches do. For this reason we treat the description of parameters and return values as a separate issue.

2.3 Areas of Focus – Object-Oriented Type Systems

[Cardelli 85] provides a theoretical basis for understanding object-oriented type systems, and a survey of object-oriented type systems can be found in [Danforth 88]. A discussion of the relationship of object-oriented types to implementation inheritance can be found in [Lalonde 91], and [Wegner 88].

Most practical work on object-oriented type systems can be categorized into the following areas of focus:

Type Inference Given some information (or possibly none) concerning the types of variables in a system, infer the types of other variables and expressions. [Milner 78] [Suzuki 81] [Borning 82] [Oxhoj 92] [Palsberg 91]

Type Safety Compile time (or at least pre-run time) checking can be used to ensure that all messages sent will be understood. If the types of all parameters and return values are known (or can be inferred from a base set) the type of intermediate variables and expressions can be inferred. A type checker can determine that a situation exists which could result in a message being sent to an object for which there is no implementation. The result is a *conservative approximation* of real type safety – some type safe programs may be rejected [Johnson 86] [Oxhoj 92] [Palsberg 91] [America 90].

Compiler Optimizations If a variable can be identified at compile time as representing an instance of one or more classes with identical representation, then certain compiler optimizations such as inlining and pre-loop range checking can be used. This is particularly useful for array operations, which are notoriously slow in Smalltalk since range checking (and a message send) is done on every access. In addition, if a variable can be identified at compile time as representing an instance of a particular class, then run time method lookup can be avoided and the implementation of the method can be identified at compile time. [Johnson 86]

Verification The substitutability relationship can be used to deal with polymorphism in formal verification systems [Leavens 90]. [Wills 91] also uses a type system with a combination of formal and informal techniques to show that two different implementations have equivalent behavior and thus that substituting one for the other can not break working, correctly written code.

Interface Documentation Since types make a statement concerning behavior, they are ideal for both organizing object behavior through subtyping, and for describing the requirements of parameters and return values. This approach has been used recently by [Cook 92] to describe the Smalltalk Collection classes, and in a weaker form, by [IBM 92] to specify Smalltalk base image behavior.²⁴ Several researchers [Snyder 86] [Leavens 90] have noted that Smalltalk programmers work with an informal type model, even though Smalltalk does not support any type system. This suggests that a type (or protocol) based approach may be a natural way to present specifications of object oriented systems.

Each of these areas of research seeks to capture a description of object behavior

²⁴In fact, the terminology used in these works is that of *protocols* and *conformance* (rather than *type* and *subtyping*) but as discussed earlier the concepts are basically the same

in a polymorphic system. While the motivations are different, the central issues are the same.

2.4 Overview Of Related Work

In the next sections, we use our framework to review several approaches to the problem of establishing behavioral group membership, defining relationships between groups, and describing object behavior in Smalltalk systems.

We begin by reviewing the *de facto* standard approach to specifying Smalltalk interfaces, the "Blue Book" [Goldberg 85]. The Blue Book contains two approaches, one based on method comments (*protocol descriptions*), and one based on source code (*implementation descriptions*). We discuss these separately.

Next we review a recent approach by IBM, published in an attempt to establish a specification of a common base for the development of portable Smalltalk applications. This was motivated by the need to simultaneously deploy applications on Smalltalk systems from several vendors. Largely as a result of this effort, an ANSI committee has been formed to establish a Smalltalk base image standard.

Next we examine three Smalltalk type systems. [Borning 82] describes one of the first type systems for Smalltalk, and seeks to improve program readability and perform type safety checks through the addition of type annotations to Smalltalk methods. [Johnson 86] has established a type system for Smalltalk in order to allow certain compile time optimizations. Johnson uses two distinct notions of types, one based on classes, and the other based on signatures. [Wills 91] has developed a type system for Smalltalk with behavior described using a pre- and post-condition notation loosely based on VDM [VDM 90] for the *Fresco* programming environment, with a focus on proving equivalence of behavior.

Finally, we examine recent research on behavioral factoring of the Smalltalk 80 Collection classes by [Cook 92]. Cook uses pre- and post-condition axioms to define behavior, and transfer functions in order to establish conformance. However, the

	Goldberg (proto.)	Goldberg (impl.)	IBM	Borning	Johnson (class)	Johnson (signature)	Wills	Cook
Focus	doc.	doc.	doc.	doc./safe.	optimiz.	optimiz.	verif.	doc.
Group	arbitrary	arbitrary	behavior	signature	set of	signature	behavior	behavior
Membership	subclass	subclass			classes			
Inter-Group Relationship	inherit.	inherit.	conform.	conform.	subset	conform.	conform.	conform.
Refinement	no	no	no	limited	no	yes	yes	no
Substitutability	no	no	no	no	yes	no	yes	no
Behavioral Description	comment	code	comment	none	code	none	pre/post cond.	pre/post cond.
Op./Def	mixed	op.	mixed	N/A	N/A	N/A	def.	def.
Aliasing info	some	code	no	N/A	code	N/A	no	no
Param./Ret	some	some	some	yes	yes	yes	yes	no
Restrictiveness	low	high	low	low	high	low	high	average
Generality	average	low	high	high	low	high	high	high
Clarity	low	average	average	average	N/A	N/A	average	average

Figure 5: Comparison of approaches

approach does not support substitutability since parameter and return types are not addressed.

Figure 5 summarizes the approaches, evaluated using the framework. While the restrictiveness, generality, and clarity evaluations are relative, they are necessarily somewhat subjective; however we explain the rationale in our review.

2.5 Goldberg (Blue Book)

Smalltalk-80 The Language And Its Implementation, commonly referred to as the “Blue Book”²⁴ [Goldberg 85], is the original specification of the classes in the Smalltalk-80 system.

The Blue Book describes the behavior of classes using two different approaches: method comments, and source code.²⁵ In both cases the information is structured according to the implementation inheritance hierarchy. Today, commercial Smalltalk systems continue to use these same approaches for specifying interfaces.

2.5.1 Group Membership

The grouping mechanism is class and arbitrary subclasses — there are no restrictions on overriding or cancellation of inherited methods. To override a method means to reimplement it in a subclass. The subclass may or may not invoke the superclass method from the subclass method. In Smalltalk, cancellation of an inherited method is performed by overriding it with an implementation that signals an error²⁶ if the method is invoked. Figure 6 shows the cancellation of the `#at:put:` message in `Set`, which is otherwise inherited from `Object`.

```
at: index put: anObject
    "Provide an error notification that elements of a Set can not be
    accessed by external keys "

    ^self notKeyedError
```

Figure 6: Method cancellation in Smalltalk

²⁴Due to the color of its cover.

²⁵Class and method categories are used to partition classes in the system, and methods, within a class. However, this categorization is used as a navigational tool with no direct behavioral implications.

²⁶In Smalltalk a debugger window normally pops up when an error is signalled, although, some Smalltalk systems have exception handling capabilities which allow such condition to be trapped by the application.

Membership in a particular class makes a definitive statement about behavior. However, due to subclass overriding and cancellation of methods, membership in a subclass makes a very weak statement concerning adherence to behavior defined by the superclass.

2.5.2 Relationships Between Groups

Inheritance is the mechanism used to relate classes to each other. The reader is presented with an inheritance hierarchy, such as that shown in figure 7.

Figure 7: The inheritance hierarchy for Collections

The structuring mechanism is inheritance, and is therefore not a substitutability relationship. This has two implications for the specification. The first relates to how well parameters and return values can be described. The second relates to how clearly the methods supported by a particular class can be described. These issues are discussed in the next section.

2.5.3 Description of Behavior

Two approaches are used to describe object behavior, *protocol descriptions*, and *implementation descriptions*. A protocol description consists of the method comments for a class, and an implementation description is the source code.

Since these two approaches have very different properties, we consider them separately. Both protocol descriptions and implementation descriptions correspond

directly to methods in classes, and thus the structure is implementation based.

Protocol Descriptions

A *protocol description* lists the messages implemented by a class. Each message is accompanied by a comment describing the operation an instance of the class will perform when it receives that message. Within a class, methods are partitioned into method categories, which are also called interfaces.

testing	
includes: anObject	Answer whether the argument, anObject, is equal to one of the receiver's elements
isEmpty	Answer whether the receiver contains any elements
occurrencesOf: anObject	Answer how many of the receiver's elements are equal to the argument, anObject

Figure 8: Protocol description for the Collection “testing” interface

Figure 8 shows the protocol description for the “testing” interface of Collection. The intent is that the comments describe the operation in a definitional style—that is, *what* not *how*. In practice, a mixture of operational and definitional styles are used.

Despite the fact the Smalltalk environment is heavily aliased, aliasing is not addressed in the method comments, except in rare cases. The comments do not indicate whether or not parameters are captured, and information concerning the aliasing of return values is usually not provided.²⁷ Where information is provided, aliasing properties must be inferred by the reader. For example, statements such as “Answer a copy...” indicate that a new object is returned, and the reader must decide if there are likely to be other references to the copy through context.

²⁷In practice programmers must generally assume that aliasing is involved and take a conservative approach when dealing with return values. Coding rules such as the Law of Demeter [Eichberg, 88] support this style of programming. However, in some cases the programmer must make use of aliasing properties of parameters or return values, and these usually can only be determined through inspection of the implementation.

```

adding
add newObject          Include the argument, newObject, as one of
                        the receiver's elements. Answer newObject.

```

Figure 9: The #add: protocol description

Figure 9 shows the description of the `add:` method for `Collection`. Knowledge of the paradigms of the Smalltalk system allow the reader to discern that “Include” means that the argument is captured, and not just that subsequent traversals of the collection will make available an equal object (as opposed to the identical object).

```

accessing
associationAt key ifAbsent aBlock
    Answer the association named by the argument,
    key. If key is not found, answer the result
    of evaluating aBlock.

```

Figure 10: The #associationAt:ifAbsent: protocol descriptions

More serious aliasing confusion occurs with descriptions for methods such as `associationAt:ifAbsent:` in `Dictionary`, shown in figure 10. There are two kinds of dictionaries in the Smalltalk system, `Dictionary` and `IdentityDictionary`. Both kinds of dictionaries maintain $\{key, value\}$ mappings. `Dictionary` uses *equality* for key lookup and is implemented as a collection of `Associations`, which are objects having key and value fields. `IdentityDictionary` uses *identity* for key lookup and is implemented by storing keys and values at odd and even offsets in a collection, respectively. The wording of the method comment seems to indicate that stored state is returned, although the fact that “association” is used instead of “Association” may leave doubt in the minds of *some* readers.²⁸

A critical problem is that some readers may not even see the ambiguity. In fact, stored state *is* returned by `Dictionary`, but a new `Association` is returned by

²⁸It is common practice to use capitalized words in Smalltalk method comments when talking about instances of classes, in order to distinguish them from normal English language usage (as in “a Dictionary”).

IdentityDictionary, yet the method comment is the same for both. This particular example has the additional problem that there is no explanation of what "named" means. The reader is expected to infer that for Dictionary, it means "key lookup match on equality", and for IdentityDictionary it means "key lookup match on identity".

Parameters and return values are not consistently described using the grouping mechanism, classes. The information is sometimes encoded in the parameter name, as in the example in figure 9, and sometimes not. However, what such an encoding actually means is not clear. It certainly means that the object may be an instance of the named class, but it also effectively means *any subclass is acceptable unless it won't work*.

The inheritance relationship does not imply substitutability. Since subclasses may be incompatible with superclasses in arbitrary ways, the grouping mechanism of class and arbitrary subclasses makes a very poor tool for describing parameters and return values. For example, SequenceableCollection supports the `atAllPut:` message which stores an object at all indices in a collection. The class Interval implements a compact representation of collections containing intervals of integers, and is read-only. Not only is Interval a subclass of SequenceableCollection, but the specification even states "All messages appropriate to SequenceableCollections can be sent to an Interval". However, an attempt to send `atAllPut:` to an Interval results in an error because `atAllPut:` is implemented using `at:put:`, which is canceled by Interval. The fact that inheritance is implicitly used to describe parameters and return values is the most significant weakness of this approach.

An additional problem with using only classes to describe parameters is that it is difficult to describe cases of polymorphism where the parameters are not related by inheritance. For example, a WriteStream and a TextWindow might both respond appropriately to a `nextPutAll:` message, and either might be an acceptable parameter to a `printOn:` method which writes a String to its parameter. If

`WriteStream` and `TextWindow` do not have a common superclass which supports `nextPutAll:`, there is no class which can describe the parameter. This kind of situation is usually not addressed by the protocol descriptions, although it is sometimes handled with parameter names like `aWriteStreamOrTextWindow` if the opportunity to accept both is recognized.

When a class encoding is not used to describe parameters, a semantic name such as `key` is usually used as in figure 10. The reader must infer class information from context. Similarly the reader is expected to infer the behavioral attributes of a return value, as in the `isEmpty` message in figure 8. The phrase “Answer whether...” tells the reader that the result must be a Boolean. Similarly phrases such as “Answer how many...” or “Answer the position...” typically indicate an integer value, although the latter may also indicate a point in cartesian coordinates.

Finally, because the protocol descriptions parallel the implementation, it can be difficult to determine exactly what messages are supported by a particular class, and how the behavior differs from the superclass.

As an example of the former, it is not initially obvious that `#at:` and `#at:put:` are supported by `Dictionary`, since these are defined in `Object`, and the description says the messages are only supported for objects with *indexed instance variables*. The reader must understand the representation of `Dictionary` in order to deduce that these messages are supported. However, even this may not be enough, since both `Set` and `Dictionary` have indexed instance variables, but `#at:` and `#at:put:` are canceled by `Set`.

As an example of the latter, the Blue Book does not make it clear whether or not the `select:` message is supported for `Dictionaries`, and there is no indication that the result is a new `Dictionary` which preserves $\{key, value\}$ mappings. In other cases refinement of behavior is very indirect, such as with the `#do:` message. It requires almost a “leap of deduction” to figure out that `#do:` traverses the elements of a `SequenceableCollection` in sequenced order, since this is not stated. In short,

there is no mechanism to capture refinements of behavior by subclasses.

Protocol descriptions make easy reading, but have significant problems as specifications. Since group membership is based on classes, parameters can only be loosely described. Intimate knowledge of the paradigms and implementation of the classes is a prerequisite to judging whether or not an instance of a particular class is a suitable parameter. And even then there is the occasional surprise. The following quote sums up this problem quite succinctly:

“Each protocol described in this chapter is understood by any kind of collection, unless that collection specifically disallows it”

Smalltalk-80 The Language And Its Implementation [Goldberg 85]

However, even this is a simplification, since subclasses not only cancel but also *change* behavior in incompatible ways.

Implementation Descriptions

An *implementation description* shows how the behavior described in the corresponding protocol description is implemented. It describes the instances' state variables, and the set of methods that describe how instances perform their operations. Since the description is source code, the specification is *operational*.

Aliasing is exposed²⁹ by the source code, so it is possible to determine when parameters are captured, and when new objects or state is being returned. For example, consider the `#associationAt:ifAbsent:` methods for Dictionary and IdentityDictionary shown in figure 11.³⁰

The fact that stored state is always returned in the case of Dictionary, and that a new Association is always returned for IdentityDictionary is made clear by the implementation. Compare this with the corresponding protocol description

²⁹Although it is possible to determine potential aliasing situations through static analysis of the source code, in some cases it can be very difficult.

³⁰Although a protocol description is given, no implementation description is provided in the Blue Book for these methods, so we have used the source code from the Smalltalk-80 implementation.

```

Dictionary
  associationAt: key ifAbsent: aBlock
  | index |
  index = self findKey: key ifAbsent: [^aBlock value].
  ^self basicAt: index

IdentityDictionary
  associationAt: key ifAbsent: aBlock
  | index storedKey |
  index = self findKeyOrNil: key
  ^((storedKey := self basicAt: index) == nil
    ifTrue: [aBlock value]
    ifFalse:
      [Association
        key: storedKey
        value: (valueArray at: index)])

```

Figure 11: The `#associationAt:ifAbsent:` implementation description

in figure 10. An examination of the implementations of `findKey:ifAbsent:` and `findKeyOrNil:` would reveal the differences in key lookup.

Implementation descriptions suffer from the same problems with parameter descriptions that protocol descriptions do, although the situation is somewhat improved by access to the source code. An examination of the implementation reveals which messages are sent to parameters and implicitly, the expected behavior. However, if parameters are captured for later use, or are passed through several levels of message sends, it can be difficult to understand exactly what behavior is expected, since the behavior is the union of the behavior expected by each method in the call chain. Similarly, if the return value is a result of a chain of message sends it can be difficult to discern what exactly is being returned, especially if objects with distinct behavior are returned for different cases.

Finally, the *Yogo problem* [Taenzer 89] makes execution difficult to trace without the assistance of debugging tools. Message sends to self may actually invoke methods in the same class, a superclass, or a subclass. This combined with method overriding and cancellation makes it difficult to understand which methods are actually run.

2.5.4 Summary

The Blue Book was the first significant attempt to describe the behavior of a large class library, and has been instrumental in moving Smalltalk from the research lab into the main stream. Several Smalltalk implementations have been built based on the descriptions it provides. However, the Blue Book presents more of an implementor's than a client's perspective, and this is reflected in the approaches used.

For protocol descriptions, restrictiveness is low because parameters and return values are not sufficiently described, and aliasing is not consistently addressed. Generality is only average because the protocol descriptions for the most part contain very little detail, but on the other hand, the specification requires a particular inheritance hierarchy. Given the problems with parameters and return values, it is difficult to characterize clarity. The protocol descriptions are concise. However, since there is virtually no redundancy, some ambiguities and errors may pass by unnoticed. Structure is provided by inheritance, but since it is such a flexible mechanism, it provides very little information. It is difficult to understand what methods are supported by a particular class, and how they actually behave. For these reasons we say that clarity is low.

In contrast, implementation descriptions provide *maximum* restrictiveness and *minimum* generality, since they require a particular implementation. Every aspect of the source code forms a part of the specification and may be relied upon by clients. In terms of clarity, implementation descriptions are not especially concise in general, primarily due to the fact that they are totally operational. There is no redundancy, so there is increased opportunity for the reader to miss a critical aspect of the specification. However, there can be no ambiguity with an implementation description. As with protocol descriptions, inheritance-based structure is better than no structure, but introduces problems of its own. Due to the increased precision of implementation descriptions over protocol descriptions, we say that clarity is average.

2.6 IBM Red Book

Smalltalk Portability: A Common Base is an IBM International Technical Support Center Red Book⁴ intended to help IBM engineers and customers develop portable applications using Smalltalk. It was motivated by the need to establish a common base for portability across the different variants of Smalltalk offered by different vendors, and between platform specific variants offered by the same vendor. It is important because it is the first published specification general enough to resolve the differences between existing Smalltalk implementations without requiring (major) changes to the implementations.

Because of the need to describe different implementations with differing inheritance hierarchies, the Red Book differs significantly from the Blue Book in that the information is not structured according to inheritance, and in fact is independent of it. Only the behavior of objects is described, not their subclassing relationships. This factor contributes greatly to the generality of this approach. Otherwise, the approach is similar to the Blue Book in that the same type of comments are used to describe the operation of methods.

2.6.1 Group Membership

In contrast to the Blue Book, group membership is based on behavior rather than classes and arbitrary subclasses. Unlike the Blue Book, descriptions do not correspond directly to methods — it is not specified whether a class implements a particular message or it is inherited. For this reason we will call the descriptions *message comments* instead of method comments. Behavior is grouped by sets of messages and their corresponding comments. There are two kinds of groupings:

- **Protocols** — Named sets of message comments used to capture behavior common to multiple classes.

⁴ These publications are commonly referred to as “Red Books”, due to the red color of the cover.

- **Classes** — A set of protocols which describe the behavior of a class, and any additional message comments specific to the class.

Protocols form a *partition* of the messages, in that no comment for a given message selector appears in more than one protocol. Figure 12 shows the descriptions for the “Expandable” protocol for Collections, and the class String.

```

Behavior Common to Expandable Collections
The following methods are available for expandable collections
add: argument      Add argument to the receiver  Return argument

addAll: argument   Add all of the elements of argument to the
                  receiver (using do )
                  Return argument

String
A String is an Indexable, Updatable, Ordered, CopyReplaceable, Array Like
collection whose elements are characters. It is an error attempting to
insert anything other than Characters into a String

asNumber           Return a number represented by the receiver
                  nil if the receiver is not a valid representation
                  of a number.

asSymbol           Return a Symbol whose characters are the same as
                  the characters of the receiver

```

Figure 12: The “Expandable” protocol and class String.

2.6.2 Relationships Between Groups

Classes are related to protocols through an informal conformance notion, which although not actually defined, seems to mean that a class *C* conforms to a protocol *P* if *P* is a true description of the behavior implemented by *C*. The protocols to which a class conforms are listed with each class, and the classes which conform to each protocol are shown in table format, as in figure 13.

In addition to the protocols shown in the table, two other protocols are defined to which all Collections conform — a “Protocol for All Objects” and a “Protocol for All Collections”.

Protocols are a specification sharing technique which, through composition, are

Protocol	Classes
Expandable	Set, SortedCollection, OrderedCollection
Ordered	SortedCollection, OrderedCollection, Interval, Array, String
Copy-Replaceable	Interval, Array, OrderedCollection, String
Array-Like	Array, OrderedCollection, String
Indexable	SortedCollection, OrderedCollection, Interval, Array, String, Dictionary, IdentityDictionary
Updatable	OrderedCollection, Array, String, Dictionary, IdentityDictionary
Contractible	Set, SortedCollection, OrderedCollection
Insertable-From-Ends	OrderedCollection
Removable-From-Ends	SortedCollection, OrderedCollection

Figure 13: Collection classes grouped by protocol

used to describe common behavior among classes. However, the principle is not recursively applied — protocols are not described in terms of composition of *other* protocols. This results in only a single level of relationships, and no refinement capability.

We illustrate this graphically for three of the collection classes (Set, SortedCollection, and Interval) in figure 14. Classes are shown in bold type. The arrows show conformance of classes to protocols, which (except for the “all Objects” and “all Collections” protocols) are also shown in figure 13. Each of these protocols defines a set of message comments which describes the behavior of individual messages. The implication of conformance of a class to a protocol is that the class understands all of the messages in the protocol and they operate as described in the protocol’s message comments.

Since protocols are not related to each other through conformance, there is no refinement capability between protocols, nor do classes refine behavior described in protocols. The relationship of classes to protocols does not characterize substitutability because, as we discuss in the next section, the parameters and return value descriptions are not described using the grouping mechanism.

Figure 14: Relating Classes To Protocols

2.6.3 Description of Behavior

The message comments in the Red Book do not differ significantly in style from the method comments in the Blue Book. Compare the message comment for `#add:` in figure 12 with corresponding Blue Book method comment shown in figure 9. Again, a mixture of definitional and operational styles are used.

The same aliasing confusion exists as in the Blue Book. Like the Blue Book, `Dictionary` and `IdentityDictionary` share the same message comment for `associationAt:ifAbsent:`, with similar confusion over return value aliasing. The Red Book message comment revises the Blue Book method comment (figure 10) by changing “association” to “Association” in an apparent attempt to correct an error, but the confusion still exists due to differences in implementation between the two kinds of Dictionaries.

The Red Book *rarely* encodes parameter and return value behavioral information and normally uses formal parameter names of the form *argument1*, *argument2*.

This is an improvement, if one considers *no* information to be preferable to *incorrect*

information. Return value behavior must be interpreted from context in the same way as for Blue Book method comments.

Since parameters and return values are not described using the grouping mechanisms of protocols and classes, no substitutability relationship can be established. Note that, as shown in figure 12, String appears to restrict the parameters of messages described in the protocols to which it conforms by stating that only Characters can be stored. However, since the behavioral attributes of the parameters are not described in the protocols to which String conforms, it is not *necessarily* a restriction. If the protocols were defined such that *no* objects were allowed, allowing Characters would be a *relaxation* of a restriction. We will further explain how this property can be used in chapter 5.

One important difference from the Blue Book is that there is no cancellation of messages. Messages described in a protocol are not cancelled by classes. This results in a stronger relation between groups than inheritance, which may add, remove, or change behavior. In fact, the relation between classes and protocols can only add behavior.⁴² A concrete example of this difference is that Interval is described *correctly*. While the Blue Book erroneously indicates that Interval supports `atAllPut:`, the Red Book correctly describes that fact that Interval's are not modifiable.

There is also no ambiguity with respect to deciding which messages are supported, since the conformance relationship is straightforward. If a class conforms to a protocol, then all messages described by that protocol are supported in the described manner.

However, due to the lack of a refinement mechanism, the Red Book still does not capture compatible, but different behavior. For example, OrderedCollection conforms to the "Expandable" protocol shown in figure 12, which in turn describes

⁴² There are minor anomalies noted in the text which are arguably behavior changes. However, these are rare.

the `#add:` message. Since it must apply to all collections that support `#add:`, the description is minimal and does not capture the fact that the element is added to the end of an `OrderedCollection`.

This illustrates a general problem with approaches that do not support refinement. A behavioral description which is general enough to be correct for all conformant classes may not provide enough information in order to be useful as a description for a particular class. For example, in some contexts it may be unimportant that `#add:` adds to the end of an `OrderedCollection`, and either an ordered or unordered kind of collection is suitable. However, in other contexts it is critical that the relationship between `#add:` and the element order be established. Without refinement, it is impossible to simultaneously capture the similarities between ordered and unordered collections, and also the effects of ordering on the behavior of messages supported by both.

2.6.4 Summary

The IBM Red Book differs from the Blue Book primarily in that it describes behavior independently of inheritance. This has two benefits. The first is that the approach can describe implementations with differing inheritance hierarchies — one of its intended goals. The second is that the conformance relation is free of cancellation and overriding, two attributes of inheritance that make it more difficult to understand. The biggest weaknesses are the lack of a refinement mechanism, and the fact that the grouping mechanism is not used to describe parameter and return values.

Like the Blue Book, restrictiveness is low due to the lack of behavioral information concerning parameters and return values, and the fact that aliasing is not addressed. In contrast to the Blue Book, generality is high since no inheritance hierarchy is specified. This comes as no surprise since generality is a central goal of the approach. The message comments are virtually the same as those of the Blue Book.

and have similar weaknesses, but since protocols do not allow message cancellation, protocol conformance is a much better structuring tool than inheritance — even if it only allows a single level. Since protocol conformance does not allow cancellation or arbitrary changes to behavior, clarity is improved over the Blue book method comment. For this reason we say that clarity is average (as opposed to low).

2.7 Borning and Ingalls

[Borning 82] proposed the first type system for Smalltalk that captured information about object behavior through type annotations. Earlier work by [Suzuki 81] was based solely on type inference. The authors identify two reasons for augmenting Smalltalk with a type system.

The first is to provide machine checkable documentation, motivated as follows. Smalltalk affords greater flexibility over typed languages such as Pascal since the user supplies no type declarations. However, in most cases the programmer knows what sort of objects are expected as arguments to the message, and what sort of object will be returned. Since at present one must glean this information from method comments, external documentation, or by inspecting the code, a type declaration system would provide a valuable form of documentation.

The second reason is to support type safety checks. Although the authors note that Smalltalk is type safe in the sense that the worst that can happen is that a "message not understood" run time error will occur, it would be advantageous for the programmer to be informed of such an error when the code is being compiled rather than when it is being used.

2.7.1 Group Membership

Group membership criteria is based on class signatures, as follows. Types are defined as the signatures of *existing* classes in the system. An object is a member of the type if it implements the signature. Types can also be parameterized with other types, and these type parameters can be used as type declarations in defining signatures. Figure 15 shows example signature definition for type `Object`.


```

Object
  supertype none
  "Object is the supertype of all other types"

  ~ x <Object>
    "am I equal to x?"
    ^ <Boolean>

  copy
    "return a copy of myself"
    ^ <self>

  printOn strm <Stream of Character>
    "print myself on strm"
    ^ <self>

```

Figure 15: Example signature definitions for type Object

2.7.2 Relationships Between Groups

Class signatures are related by subtyping as follows. A subtype “inherits” all of the signatures of its supertype, and may add additional declarations of its own. Additionally, the subtype may refine a signature by indicating that a result is a subtype of what is declared in the supertype. Parameter types must be the same.

In other words, a type $\langle A \rangle$ is a subtype of a type $\langle B \rangle$ if all of the following are true:

- $\langle A \rangle$ contains a signature definition for all signatures in $\langle B \rangle$.
- The corresponding parameter types are the *same* for all signatures in $\langle A \rangle$ and $\langle B \rangle$.
- The return values of signatures in $\langle A \rangle$ are the same or subtypes of the corresponding return values in $\langle B \rangle$.

There are two special types, $\langle \text{self} \rangle$ and $\langle \text{UndefinedObject} \rangle$. The type $\langle \text{self} \rangle$ refers to the type of the object receiving the message. $\langle \text{UndefinedObject} \rangle$ is defined specially, to be a subtype of all other types (equivalent to the special type *NONE*). This is somewhat curious, since it violates the subtyping rule described

above. The class `UndefinedObject` does *not* have all of the signatures of all other classes in the system, and in fact responds to relatively few messages. This appears to be motivated by the need to account for the fact that all variables in Smalltalk are initialized to `nil`, the single instance of `UndefinedObject`. Defining `<UndefinedObject>` as a subtype of all other types means that the assignment of `nil` to any variable is type correct.

Methods that return different objects with distinct types on a case-specific basis are *not* described through type unions. Rather, a *nearest common supertype* approach is used. For example, a method which returns an `Integer` or a `String` would be described with a return type of `<Object>`. This captures the common behavior, but much information is lost. More strangely, due to the unusual definition of `<UndefinedObject>`, a method which returns `nil` or an `Integer` would be described with a return value of `<Integer>`, which is of dubious value.

The nearest common supertype rule also applies to parameterized types, as follows. If `t1` and `t2` are types, and `s` is the nearest common supertype (ignoring parameterization), then the parameterization of `s` is determined as follows. If `s` has parameters, the value of each parameter of the nearest common supertype is found by computing the nearest common supertype of the corresponding parameter from `t1` and `t2`.

However, this introduces a problem. Consider two types: `<Array of: Integer>` and `<Array of: Object>`. Following the above rule, we obtain a nearest common supertype of `<Array of: Object>`. This means that `<Array of: Integer>` is a subtype of `<Array of: Object>`. However, this violates the subtyping rule defined above—in particular the requirement that the corresponding *free* parameters have the same type. Consider the `#at:put:` definition shown in figure 16. Since the parameter `x` is declared using the `elementType` type parameter, it will be declared differently in the two parameterized types. In fact, the situation is *Worse* because an `<Integer>` parameterization of `Array` restricts the type of `x`, and thus *is not*

signature substitutable for an `<Object>` parameterization (since contravariance is violated).

```

Array
  supertype SequenceableCollection
  parameters 'elementType'
  "elementType is the type of the elements of the Array.
  Elements of the Array may be subtypes of elementType."

  at index <Integer> put x <elementType>
  "Store x at the specified index."
  ^<elementType>

```

Figure 16: Example parameterized signature definition

It should be noted that the type hierarchy is independent of the implementation hierarchy. A substitutability relationship is not established, since behavior is not considered. Neither is a signature substitutability relationship established due to the problems with parameterized types.

2.7.3 Description of Behavior

The types are just signatures and do not include any description of behavior. Parameters and return values are described using types, as previously discussed. However, there are problems with the subtyping relationship for parameterized types.

An interesting issue is that since the choice of signatures is based on existing classes, common behavior can only be captured by the type system if a suitable class exists which describes this behavior. This is quite limiting because the arrangement of messages into classes in the existing Smalltalk system is based primarily on implementation requirements. This is the same problem the Blue Book has, in that cases of partial common behavior by otherwise unrelated classes can not in general be captured, since the granularity of the behavioral grouping is fixed to be that of the classes being described.

Another interesting point is the fact that the types are arranged in a *hierarchy*, rather than a lattice, since a type may only have a single supertype. This severely

limits the ability of the type system to capture common behavior across different inheritance hierarchies,³³ since such a situation necessitates having multiple supertypes. In such a case, the nearest common supertype reflects only the minimum common behavior.

2.7.4 Summary

The work by [Borning 82] was the first attempt to attach type annotations to a Smalltalk system. Types are based on the signatures of existing classes. The subtyping rule establishes signature substitutability, but this is violated by the special definition of `<UndefinedObject>`, and the common supertype rule for parameterized types. Subtyping is independent of inheritance. Distinct parameter and return values are described by the nearest common supertype.

Since the approach does not describe behavior, restrictiveness is low. For the same reason, and since a particular inheritance hierarchy is not required, generality is high. Although behavior is not included in the subtyping relationship and there is a problem relating parameterized types, when used in conjunction with method comments, the type annotations do improve readability. Additionally, the separation of the type hierarchy from the implementation hierarchy eliminates the problems the Blue Book has with method cancellation and overriding. For these reasons we say that clarity is average.

³³Such as with the `WriteStream` and `TextWindow` example discussed on page 39.

2.8 Johnson et al

The *Typed Smalltalk* project [Johnson 86] [Graver 90] is concerned with investigating approaches to improving the performance of Smalltalk through compiler optimizations. Johnson suggests that major performance improvements in Smalltalk require a type system that will allow traditional kinds of compiler optimizations to be applied. Because Smalltalk is dynamically typed, a compiler has no way to determine the method that will run when a message is sent, and cannot tell whether an operation has side effects or will affect control flow. Thus common subexpression elimination, dead code removal, and other strategies used in traditional languages can not be used. If the method can be determined at compile time, inlining is also possible, reducing relatively expensive context creation to simple operations like branching.

2.8.1 Group Membership

Johnson defines three grouping mechanisms, two based on classes, and one based on signatures:

Object Types A type is a (possibly) parameterized class.

Union Types A type is a set of (possibly) parameterized classes.

Signatures A type is a set of message types, where a message type describes the parameter and return types for a message.

Object types are classes which are parameterized with union types to describe the possible objects that the state variables of instances of a class may hold. For example, an Array of Integers is described as *Array of: Integer*. Classes which do not have (externally visible) state variables, such as Integer, are not parameterized. An Array of Arrays of Integer is described *Array of: (Array of: Integer)*.

Sets of classes are union types. For example, an array that can hold either Integers or Characters is described as *Array of: (Integer + Character)*, where *(Integer + Character)* is a type union. Sets of classes can only describe classes already in existence in the system. Additionally they do not deal with polymorphism very cleanly, since common behavior among different classes must be described with a union type, which does not capture the common properties of the classes. The major advantage of object types is that they allow a compiler to determine that a variable or expression is an instance of a particular class, or one of a known set of classes. Both situations facilitate various optimizations, since a variable declared with a union type can often be identified as having a particular object type at various points in a method, through static analysis of program type casing.

Signature types are used to describe parameter and return type expectations without referring to classes. A signature type is an *unnamed* set of message types, which are message names with parameter and return value type information. For example, the signature type *<understands: #(+ <Integer> ^ <Integer>) >* describes an object which implements a *#+* message that takes an Integer as parameter, and returns another Integer. Signature types can describe classes that have not yet been defined, and thus deal with polymorphism better than class types. However, this additional flexibility means that they are much less useful for performing compiler optimizations, since they do not identify a particular class.

2.8.2 Relationships Between Groups

The subtyping relationships are shown in figure 17. Subtyping is defined on union types as subsetting. This means that individual object types are only trivially related, in that subtyping is equality. This is done because in general, parameterized types are not comparable in terms of a subtype relationship. To see this, consider the types *Array of: Integer* and *Array of: Object* shown in figure 18. *Array of Object* can not be a subtype of *Array of: Integer* because return value covariance r

Figure 17: Subtype Relationships in Typed Smalltalk

violated by the definitions of the `#at:` message. Similarly, the opposite arrangement does not work since parameter contravariance would be violated by the definitions of the `#at:put:` message. If we were to specify the return value of `#at:` for *Array of: Integer* in more general terms as being of type *Object* then *Array of: Object* is in fact a subtype of *Array of: Integer*. However, Johnson uses the type parameter to specify such values, since this provides more detailed information for optimization.

```

Array of: Integer
  at: index put: anInteger
    "Store anInteger at the specified index."

  at: index
    "Answer the Integer at the specified index."
  ^anInteger

Array of: Object
  at: index put: anObject
    "Store anObject at the specified index."

  at: index
    "Answer the Object at the specified index."
  ^anObject

```

Figure 18: Ordering of parameterized types

Subtyping is also defined between object types and signature types. An object type *t* is included in a signature type *s* if for each message type *m* in *s*, a message

of type m sent to an object in type t is type correct. The message is type correct in this context if the method invoked accepts at least the parameters of the message type and returns a subset of the return values (signature substitutability). No relationship is defined between signature types and union types, or between signature types, although conceivably signature types could be related through message type subsetting.

2.8.3 Description of Behavior

Since the focus is compiler optimization, the behavior is described by the implementation. However, there are some interesting points.

Aliasing is not addressed explicitly by the approach, but given the goals of the project, this not really necessary. Parameters and return values are described using the three grouping mechanisms: object types, union types, and signatures. Object types describe the behavior of a class exactly, and in fact in *more detail* than the code alone. This is due to the additional information provided by parameterization of the object's state variables. In contrast, signature types provide *no* behavioral information — they are just message type templates.

2.8.4 Summary

An interesting aspect of this approach is that it combines a grouping mechanism that specifies behavior (object types) with one that does not (signature). Object types provide maximum restrictiveness and minimum generality, and signatures provide high generality with low restrictiveness. Given that the intent is to capture the behavior of an implementation for the purpose of compiler optimization, we do not evaluate clarity.

Signatures are required for completeness, to describe cases where polymorphism is *actually used*, but these are exactly the cases that John can not optimize. In effect *Typed Smalltalk* seeks to achieve optimization by eliminating the performance

penalty for polymorphism in cases where the feature is not required. A drawback with the approach is that in order to achieve these optimizations, parameters and return values must be specified with a type system based on classes, rather than a behavioral approach. This means that only classes in existence at the time the type declarations are specified can be used with those interfaces. If an interface is specified using object types, then reuse is severely limited. If signatures are used, the code cannot be optimized.

2.9 Wills

Fresco [Wills 91] is an interactive development environment based on Smalltalk. Smalltalk is extended by *Fresco* in the following two ways:

- *Fresco* systems are composed of units of software called *capsules*.
- *Fresco* extends Smalltalk with a notation for specifying behavior.

Wills notes that the units of reuse in Smalltalk are not classes or even sets of classes, but a combination of new classes and modifications to existing classes. *Fresco* calls these units of reuse *capsules*.

A serious collision problem is potentially introduced when an attempt is made to incorporate components (capsules) from different sources. The introduction of a component into a system may break pre-existing, working code as a result of subtle (or significant) modifications to the behavior of existing classes.

Fresco is designed to allow specification of interfaces using axioms which contain pre- and post-condition expressions, and verification of implementations through a combination formal and informal ("John says it's OK.") "proofs" with the assistance of an interactive theorem prover. The result is that *Fresco* attempts to guarantee that no mutual interference will occur between components. It should be possible for a new component to extend or modify an existing class (to improve performance or add functionality) while ensuring that pre-existing components are not broken by the change.

2.9.1 Group Membership

Classes and types are distinct ideas in *Fresco*. Types describe behavior, and classes implement types. An object is an instance of only *one* class, but it may belong to many types. An object is in a type if it behaves in accordance with the pre- and post-condition axioms for the type. For convenience, and to allow better integration

with the development environment, types and classes are interwoven into a single unit called a Type/Class Definition (TCD). There are two kinds of TCD's:

- TCD's which describe types.
- TCD's which both implement and describe a type (the home type of the class).

2.9.2 Relationships Between Groups

TCD's are related through conformance. Conformance is defined by substitutability as follows. A type C conforms to type A if and only if all objects of type C are also of type A. Since TCD's are mixtures of implementation and specification, they are related both by conformance and inheritance. Inheritance arranges the TCD's in a tree, and conformance arranges them in a lattice. Fresco allows only certain combinations of inheritance and conformance:

- *Refication* — conformance claimed between otherwise unrelated TCD's.
- *Nonconformant inheritance* — in which the state variables and methods of a TCD may be inherited without inheriting the specification.
- *Conformant inheritance* — in which a TCD is claimed to conform to its parent, which has a specification, and may or may not have an implementation.

This precludes cases such as where a TCD claims conformance to an ancestor and not the immediate parent. Figure 19 illustrates the above three combinations of conformance and inheritance.

Conformance is a substitutability relationship and supports refinement of specifications, since conformant TCD's may add more axioms, provided they do not contradict the axioms in the TCD to which they conform.

Figure 19: Valid Conformance and inheritance combinations

2.9.3 Description of Behavior

Behavior is described definitionally in TCD's through the use of theorems. Theorems are used for specifying behavioral axioms, for annotations within code, and in proof steps. The general form of a theorem is shown in figure 20. All parts of a theorem may be omitted except the postcondition.

$$\{ \mid vars \mid theorems \vdash precondition : postcondition \} \mid code \mid$$

Figure 20: General form of a theorem in Fresco

Vars are metavariables, with scope throughout the theorem. Initial theorems preceding $\vdash$ are hypotheses — the rest of the theorem is valid iff the hypotheses can be proved true. Theorems which include hypotheses function as proof rules.

If the precondition is true before execution of the code then the postcondition will be true after it. If "*precondition* : " is missing then the theorem is an invariant, true after the code if it is true before it. If code is missing it is a universal invariant, true all the time. An overlined variable in a postcondition expression represents the same copy of the variable as it was before execution. The copy is guaranteed not to be subject to the side effects of the code — the variables are assumed to be unaliased.

There are two kinds of theorems: *axioms* and *derived theorems*. The behavior

of a TCD is described by axioms. Each operation may be described by one or more axioms, but an axiom applies to at most one operation. The operation of TCD's is described using a model, which may or may not reflect the implementation. Wills notes that an algebraic specification, which simply interrelates the behavior of externally visible operations without using an object state model, is difficult to use for anything but simple types.

SymbolTable

{ s ∈ (Stack of (Dictionary from Symbol to Ref)) }

Every member of SymbolTable has a component s (a model variable). $x \in (\text{Stack of } T)$ is defined elsewhere to be equivalent to $(x \in \text{Stack}) \wedge ((x_i \text{ in } x) \Rightarrow (x_i \in T))$, and similarly for Dictionary. There are four operations: for entering and leaving nesting levels, for adding an identifier at the current level of nesting, and for finding the most deeply nested current declaration of an identifier. Each of these 'advertised' operations is mentioned in the code part of one or more axioms (as opposed to model components like s which only occur within the braces). To give two axioms, as examples:

{ id ∈ Symbol : (s.top.at(id) = ref) } [self declare id with ref]
 { (s.size > 0) : s = s.tail } [self leave]

Figure 21: A SymbolTable TCD example

Figure 21 shows an example of how a TCD is specified. The operation **#declare:with:** is not guaranteed to work unless its first argument is a Symbol (or a subtype). Its result is that the Dictionary at the top of the stack is now such that it maps **id** to **ref**. The operation **#leave** works only if the stack is not empty, and its result is to reduce the stack to its former tail.

The choice of a specification model is up to the interface designer. In practice the implementation may be much more complicated than the model in the specification. The argument is that the most efficient implementation may not be the best way to present the behavior to the user. This implementation of one model using another is called *data reification*. Wills uses this notion of reification to show how conformance can be proven between TCD's with different models. This is done simply by writing

axioms that establish the relationship between the representation of the two models.

The *Fresco* system does not address aliasing, and in fact the notation assumes an aliasing-free system. However, Wills recognizes this issue, and in particular the problem of *framing*, how to scope what part of a system's state may be altered by the execution of a method. Wills notes that the approach typically used in model based specifications, where the frame is a set of variables, will not work for the following reasons:

- The heavy aliasing of Smalltalk means that it isn't so easy to divide up the world into subcomponents, some of which may be modified and some which are not: two subcomponents you thought were different might turn out to be the same, accessed through different strings of pointers.
- In a modular system, what is changed by an operation is partly the responsibility of the service provider, so it is insufficient to just name a given part of the whole state.

Wills proposes an approach to aliasing *control* based on *demesnes*. A demesne is a set of objects which participate in the representation of a given value. The programmer defines for each class a demesne function which answers a set containing the receiver, and the demesnes of some or all of the instance variables. Some variables may be omitted, for example back pointers kept for efficiency, and other type of cached information. This allows reasoning about the aliasing of the program, such as whether the demesnes of parameters are allowed to intersect. This approach has the advantage that it preserves encapsulation, since the demesne definitions are localized with their own classes.

Parameters and return values are described by the axioms, but not explicitly as with most type systems. The type information concerning parameter i is treated like any other precondition, such as those restricting the value of the parameter or model state. Additionally, type membership preconditions are not mandatory

and may be omitted. In such cases the assumption is that any object is acceptable. This approach has the advantage of consistency, but results in the parameter type information being hidden in the set of axioms describing the behavior of a method.

Since return value type information can usually be inferred from the relationship of the return value to parameters or the model used to describe the TCD, it would generally be redundant to provide it. However, this can make return type information difficult to discern, especially with complex descriptions involving many axioms.

2.9.4 Summary

The *Fresco* system is concerned with verification, and seeks to describe behavior in a way that is compatible with automated theorem provers. The programmer supplies formal or informal proofs that the code implements the axioms, and it is checked by the theorem prover. Since the approach can only check certain aspects of the code against the axioms, the implementation can not be fully verified. However, as noted by Wills, the framework of axioms and the obligation to provide even informal proofs brings about a measureable increase in reliability.

Since parameters and return values can be described, and the notation is checked for consistency with automated tools, we say that restrictiveness is high. Additionally, the behavioral specifications are definitional and are independent of any particular inheritance hierarchy. However, generality is somewhat affected by the choice of the model used to describe a TCD. Since the models are based on composition of other TCD's, incidental behavior may implicitly form a part of the specification unless the designer is very careful to use only very simple models. However, since there is some doubt, we say generality is high. The notation seems concise, but the examples shown are quite simple. The specifications lack redundancy, since the formality of the notation does not require it. However, this reduces clarity since it is easier for the reader to miss an important aspect of the specification. Parameter

type information is treated like any other pre condition, not explicitly. Neither are return value types explicitly described. For these reasons we say that clarity is average.

2.10 Cook

[Cook 92] is the most recent work in applying a type system to Smalltalk. The focus is to provide a tool for reviewing the design of a class library through an understanding of the behavioral relationships of a set of classes, as opposed to their implementation relationships.

The protocols supported by the Smalltalk 80 Collection classes are extracted from the implementation by analyzing method cancellation and overriding. The result is sets of message names which can be related to the classes that support them. Through subsetting, a relationship between sets of message names is established.

Behavior is associated with the message names by using pre- and post-conditions which describe properties of an abstract state model. The notation is based on [America 90], and results in alternative view of the Smalltalk-80 Collection classes (figure 24) which shows how the inheritance relationships differ from the behavioral relationships. Figure 22 shows the protocol description for class Bag. A primed function (e.g. F') indicates the value of the representation before the operation, and ρ represents the return value.

Bags are collections that allow repeated elements but don't have any notion of ordering. Bags are represented as functions from values to Natural numbers, indicating how many times the value occurs in the bag. The notation $F \equiv_{f,x} G$ means that the functions F and G are equal at all points but x .

Bag representation $F: V \rightarrow \text{Nat}$

<i>Pre-condition</i>	<i>Message Name</i>	<i>Post-condition</i>
	<i>isEmpty</i>	$\rho = (\forall x F(x) = 0)$
	<i>size</i>	$\rho = \sum_x F(x)$
	<i>includes? x</i>	$\rho = (F(x) > 0)$
	<i>occurencesOf? x</i>	$\rho = F(x)$
	<i>add? x</i>	$F(x) = F'(x) + 1$ and $F \equiv_{f,x} F'$
$F(x) > 0$	<i>remove? x</i>	$F(x) = F'(x) - 1$ and $F \equiv_{f,x} F'$

Figure 22: The Bag protocol

2.10.1 Group Membership

The grouping mechanism is behavioral, with the behavior of messages specified using pre- and post-conditions. The groups of behavior are called *protocols*. Protocols may be based on classes, or they may be abstract. Abstract protocols are used to capture partial behavior that is common to classes not directly related through inheritance.

2.10.2 Relationships Between Groups

Protocols are related through conformance, which is based on two criteria: message name subsetting, and the existence of a transfer function which converts between abstract representations and preserves pre- and post conditions.

A protocol **<A>** conforms to a protocol **** if both of the following are true:

- The message names in **<A>** are a subset¹¹ of the message names in ****
- There exists a transfer function which maps the abstract representation of **<A>** to the abstract representation of ****, and the preconditions in **** imply the pre-conditions in **<A>**, and the post conditions in **<A>** imply the post conditions in ****.

For example, consider the partial descriptions of the Bag and Set classes shown in figure 22 and figure 23 respectively. The transfer function $S = \{c | F(c) > 0\}$ converts the abstract representation of a Bag to a Set and preserves the required pre- and post-conditions.

Cook notes that the specifications reveal a basic problem with using only message names as the basis for conformance and classification. The problem is that the **#add:** and **#remove:** methods for Sets have different behavior than for other collections, since Sets do not admit duplicate elements. The **#add:** message for Set is weaker

¹¹A proper subset is not required — they may be equal.

Sets are represented as subsets S of the set of all values V . This specification also defines the behavior of the abstract protocols *ExtensibleCollection* and *RemovableCollection*.

Set representation $S \subseteq V$

<i>Precondition</i>	<i>Message Name</i>	<i>Postcondition</i>
	<i>isEmpty</i>	$\rho \models (S = \epsilon)$
	<i>size</i>	$\rho \models \rho \vdash \#S$
	<i>includes : x</i>	$\rho \models (x \in S)$
	<i>include : x</i> [<i>add : x</i>]	$S \models S' \cup x$
$x \in S$	<i>removeEvery : x</i> [<i>remove : x</i>]	$S \models S' - x$

Figure 23: The Set protocol

since it only ensures that the element is present. Cook also argues that **#remove:** for Sets is stronger, since it eliminates the element completely. However, the latter may be a side effect of the notation, since regardless of the type of collection if there is only one element, **#remove:** eliminates it completely.

In order to address the problem where messages with the same name have incompatible behavior, Cook proposes message renaming where appropriate. In the case of Set, **#add:** has been renamed to **#include:**, and **#remove:** has been renamed to **#removeEvery:**, as reflected in figure 23.

The pre- and post-condition implication requirements for conformance mean conformant protocols may weaken the pre-conditions and strengthen post-conditions. This parallels the contravariance and covariance rules for substitutability, and provides a mechanism for refinement of behavior.

However, an important consideration is that parameter and return types are described only implicitly in the abstract representations, and are not considered in establishing the conformance relationship. For this reason, a substitutability relationship is not established. For example, Cook shows String as conforming to Array, and Array and Dictionary both conforming to an IndexedCollection protocol

which allows arbitrary keys. In the former case, Strings are not substitutable for Arrays since they can only store Characters. In the latter case, Array's require Integer keys, and are not acceptable where an object supporting arbitrary keys is required.

Conformance arranges the protocols in a lattice, which can be superimposed on the inheritance hierarchy to show how the implementation relationships differ from the specification, or behavioral relationships. An illustration of Cock's factoring of the Smalltalk-80 Collection classes is shown in figure 24. The dashed lines show the conformance relationships, and the curved lines show inheritance.

Figure 24: Interfaces vs. Inheritance

Protocols shown in the diagram which do not participate in the implementation inheritance relationships are abstract — they have been introduced to capture common behavior between classes which are not directly related through inheritance.

2.10.3 Description of Behavior

Behavior is described definitionally using the pre- and post-condition notation with an abstract state model. As with most such notations, aliasing is not addressed, and in fact an aliasing free environment is implicitly assumed.

Parameter and return values are not described using the behavioral groupings, and this is the major weakness of the approach. If parameter and return values were to be considered in establishing a conformance relationship based on substitutability, the arrangement presented would be invalid.

An important aspect of the notation is its ability to leave return values unspecified, as is the case with the `#add:` message (e.g. figure 23). Interestingly, the return value of the `#remove:` message is also left unspecified.

2.10.4 Summary

The behavioral factoring shows an interesting contrast between the inheritance and specification relationships of the Collection classes. Cook notes that the protocol relationships represent a *clients* view, whereas the implementation relationships represent an *implementors* view. Even though the inheritance relationships form a tree, the actual behavioral relationships they implement form a lattice, with multiple sharing of the interfaces described by protocols.

Cook observes that the protocol factoring turns up several kinds of omissions and implementation problems in the Smalltalk 80 Collection class library. These are:

- In some cases, inherited methods violate the representation invariants of a subclass and should be cancelled (e.g. `#addFirst:` in `SortedCollection`).
- In some cases, the same method name is used for distinct behavior, for which no common specification can be found.
- Two different messages occasionally have the same specification, and should be

unified. The `indexOf:` and `#keyAtValue:` message are shown as an example of this situation, and Cook recommends that the latter be renamed to the former.

The pre- and post-condition notation of [America 90] is used to describe behavior, and conformance is defined through the existence of a transfer function. In the presentation of the notation, America initially assumes that parameters and return types *are the same* when establishing conformance through the transfer function. The notation is then extended to add the contravariance and covariance rules for parameters and return types, respectively. In this way, America *does* establish a substitutability relationship. However, since Cook does not require parameter and return value types to be the same, and does not establish contravariance and covariance rules, protocol conformance does not establish substitutability. However, if parameter and return types happen to be the same, conformance *does* imply substitutability.

The behavior is described concisely using the pre- and post-condition notation. However, parameter and return values are not described using the grouping mechanism. For these reasons, restrictiveness is only average. Conversely, generality is high due to the definitional specification approach, and the fact that no inheritance hierarchy is required. The protocol structuring of behavior contributes significantly to clarity. However, as noted by America, it remains to be seen how well the notation deals with more complex behavior. It also seems too cryptic to serve as reference documentation. Nonetheless, it is a useful design review tool. The biggest weakness is that the information conveyed by the structure is limited because conformance does not imply substitutability. For these reasons we rate clarity as average.

2.11 Summary

We have established a framework for comparing approaches to the problem of organizing and describing object behavior in a Smalltalk system, and have reviewed a number of approaches in this context.

The Blue Book uses two approaches: one based on method comments and the other based on source code. Both approaches are implementation based and specify a particular inheritance hierarchy. The structuring mechanism of inheritance conveys very little information concerning the relationships between classes. As a result, parameters are only loosely described. With protocol descriptions, it is difficult to understand which methods are supported by which classes and in what way, and there is no refinement mechanism. Implementation descriptions eliminate some of these problems, but since the source code is totally exposed, there is no distinction between essential and incidental behavior.

The IBM Red Book improves on the Blue Book by partitioning behavior into sets of message comments called protocols. Classes are described in terms of conformance to protocols. As a result, the specification is independent of any inheritance hierarchy. This eliminates the problems that occur when inheritance is used to structure specifications, and allows the same specification to describe implementation with differing hierarchies. However, parameters and return values are not described using these protocols.

Borning and Ingalls arrange classes in a type hierarchy which can be independent of inheritance. Types are based on the signatures of existing classes but do not include any kind of behavioral description. Types may be parameterized in order to describe the values an object's state variables may hold. Parameters and return values are described using types. A signature substitutability relationship is defined, but it has several problems; in particular the definition is violated by the nearest common supertype rule for parameterized types.

Johnson defines two type mechanisms: one based on parameterized classes (ob-

ject types) and the other based on signatures (signature types). Object types can be combined by a logical OR relationship into union types. Object types describe objects of particular classes — no substitution is allowed. Signature types are unnamed sets of message templates giving parameter and return type information. Object types implicitly describe behavior since there is an associated implementation (the class). Signature types have no associated behavior. Object types are related to union types by set membership; union types are related to each other through subsetting, and object types are related to signature types through signature substitutability. Object types are not related to each other because two parameterizations of the same class are generally incomparable in terms of substitutability.

Wills combines types and classes into units called TCD's. The type relationships may be independent of the inheritance hierarchy subject to some simple rules. Pre- and post-condition axioms implicitly describe both parameter and return type information, and the behavior of messages using an abstract state model. However, the model is itself based on composition of other TCD's, and for this reason there is the potential for "accidentally" specifying incidental behavior. A conformance relationship is defined on TCD's which establishes substitutability. However, the notation is better suited to automated verification than to interface documentation.

Cook presents a factoring of the Smalltalk 80 Collection classes, with behavior grouped into protocols which are described using a pre- and post-condition notation proposed by [America 90]. Protocols are related through conformance, which is independent of inheritance. Conformance is established through the existence of a transfer function which converts between abstract representation and pre- or post- and post conditions. However, since parameter and return type are not considered for conformance, a substitutability relationship is not established. Unfortunately, the information provided by the conformance structure

None of the approaches address *dynamic* in the specification, although *dynamic*

is implicit in the source code provided by Blue Book or in the implementation of Johnson's object types. Some approaches, such as those of Wills and Cook implicitly assume that there is no aliasing. However, Wills identifies the problem and proposes an approach that might be used to incorporate aliasing information. Only the approaches described by Johnson and Wills have a refinement capability, although Johnson's approach is limited to the refinement of signatures by other signatures⁴ or classes. In this sense, only Wills actually refines *behavior*. Additionally, only Johnson and Wills establish substitutability. Finally, only Johnson has the ability to describe objects of particular classes. The other approaches do not have this capability since they (always) implicitly permit substitution by objects of other classes.

Chapter 3

3 The Protocol Model

Our protocol model is designed to support the organization and description of Smalltalk object interfaces in an implementation independent manner. The audience of the resulting documentation is both component users and component implementors. The protocol model is intended to be used in the following ways:

- As a tool for documenting the interfaces provided by existing Smalltalk systems, and in particular for describing common behavior across different implementations.
- As a tool to allow specifications of object behavior to be written which are independent of implementation details such as the choice of inheritance hierarchies or other incidental differences.
- As a tool for understanding behavioral differences and similarities among classes of objects for the purposes of design review or teaching.

The following are the goals of the protocol model, in priority order:

Clarity: It should capture the similarities and differences between classes of objects, in order to reduce the total amount of information required to describe the behavior, and maximize specification sharing. It should be easy for programmers to quickly understand and use, in order to be useful as reference documentation.

Generality: It should not constrain the implementation unnecessarily, in order to allow flexibility in implementation choices, and to capture the essential similarities among different existing implementations while allowing incidental differences. It should not expose the implementation unnecessarily, in order to prevent client applications from making use of incidental behavior which may be subject to change.

Restrictiveness: It should describe the behavior in sufficient detail to allow both the development of useful client programs, compliant implementations, and independent test code.

3.1 Organization of Object Behavior

The organization of object behavior is primarily motivated by the need to make a statement about the behavioral assumptions a method implementation makes concerning its formal parameters, and what behavioral guarantees it is prepared to make concerning its return values. The behavior exhibited by a set of classes can be arranged into behavioral groups in a manner compatible with the way experienced programmers work with objects in a system. These groupings can then be used to advantage to make a statement about the behavioral properties of parameters and return values.

We call these groupings of behavior *protocols*. A protocol P is written $\langle P \rangle$. A protocol consists of a set of messages and corresponding behavioral descriptions which are called *message specifications*. A specification for a particular message may appear in arbitrarily many protocols.

A protocol makes a behavioral statement about an object through a conformance relationship. Protocols are also related to other protocols through *conformance* and *refinement*. Conformance models requirements satisfaction, and refinement is a relationship which allows protocols to make increasingly precise statements concerning behavior described in other protocols to which they conform.

```

addAll: aCollection
  "Include all the elements of aCollection as the receiver's elements
  Answer aCollection "

  aCollection do [ each | self add: each]
  ^aCollection

```

Figure 25: The #addAll: method for class Bag

Messages are grouped into protocols of related behavior that are useful for describing parameters and return values. Consider for example the #addAll: method in class Bag (Figure 25) which, according to its implementation, requires its parameter to respond to the #do: iterator message. Now suppose we group collection messages into protocols such that a protocol named <collection> includes an appropriate message specification for #do:. The #addAll: method can then express the behavioral requirements of the parameter by referring to the <collection> protocol.

Of course, <collection> is a superset of the required behavior, and in fact, any convenient grouping that included an appropriate #do: message specification would suffice. The process of arranging object behavior into these groupings is called *factoring*. A *particular* arrangement is also called a *factoring*.

An important observation is that protocols are recursively defined, in that they group message specifications which in turn make use of protocols to describe parameters and return values. Although the notion of conformance defines a relation on protocols, protocols themselves depend on conformance in order to define the parameters of message specifications. Due to this self-referential nature, we must introduce *conformance* briefly, before revisiting it in more detail in the next chapter.

An object is said to *conform* to a protocol if the implemented behavior of the object is in accordance with all message specification in the protocol. Then the object *implements* the protocol, and the protocol (through its name specification) makes a true statement concerning the object's behavior. Protocols are also *correlated*

to *each other* through conformance. A protocol $\langle A \rangle$ is said to *conform* to protocol $\langle B \rangle$ if all objects which conform to $\langle A \rangle$ also conform to $\langle B \rangle$. The next sections define the composition of protocols in a top-down manner.

3.2 Protocols

A *protocol* $\langle P \rangle$ is a named semantic interface, defined by the following:

- A glossary of terms.
- A set of *message specifications* such that no two message specifications have the same *message selector*.

The *glossary of terms* defines terminology that is used by the message specifications to describe message operation. It is a word-sharing mechanism so that commonly used concepts need not be repeatedly defined in multiple message specifications. The glossary typically defines terms related to an abstract model of behavior for a particular object, and is usually specific to the domain the object is applied to.

```
elements
Collections accept objects from client applications for
safe-keeping, and allow clients to access the objects
in various different ways. The objects held by a particular
collection at any point in time are called its elements.
The elements of a collection may be retrieved in various
different ways for different kinds of collections, but in
all cases, the elements of a collection are defined by
its response to the #do: message, which iterates over
the elements
```

Figure 26: An example glossary entry

For example, conceptually all Collections contain *elements*. Regardless of whether they are implemented with a state variable of that name, elements constitute the abstract state of a Collection. The concept of elements is defined in the glossary for the $\langle \text{collection} \rangle$ protocol so collection operations can be described

in terms of their effects on these elements. Figure 26 shows such a glossary entry. Glossary entries are typically defined in terms of one or more message specifications.

3.3 Message Specifications

A *message specification* describes an individual message in the context of a protocol, and is defined by the following:

- A message selector.
- A set of parameter specifications.
- A set of return value specifications.
- A behavioral description which relates the parameters and return values to each other and to the abstract state of the object receiving the message.

Figure 27: An example message specification

An example of a message specification for the #add: message for the <elementAddableCollection> protocol is shown in figure 27. The symbol % and @ are used to distinguish words which are *not* an *object* or *formal parameter*.

names respectively. These eliminate confusion over normal English usage of a word, and a usage which has a more precise definition. A similar technique is used by [Parnas 86].

A message specification has no semantic meaning outside of the context of a protocol. This is because a message specification typically refers to protocol glossary terms and/or is defined in terms of the behavior of other messages in the same protocol.

A *message selector* names a message, and is denoted as such with a preceding # symbol. For example, #at:put: is a 2-parameter message selector. We distinguish a message, a message send (the application of a message selector), and a method as follows:

- A message selector, together with its formal parameters, is a *message*.
- A message selector, together with a set of *actual* parameters is a *message send*.
- A message selector, together with a receiver object, identifies a unique implementation of the message (a *method*).

Just as a method is uniquely identified by a receiver and message selector, a message specification is uniquely identified by a protocol and message selector pair $\langle P, s \rangle$ where P is a protocol name and s is a message selector. For example, $\langle \text{object}, \# = \rangle$ identifies the specification for the $\# =$ message in the $\langle \text{object} \rangle$ protocol.

3.4 Parameter Specifications

A *parameter specification* is defined by the following:

- A parameter name.
- A textual description.
- A parameter interface definition.
- A parameter aliasing attribute.

A parameter specification places constraints on the parameter in terms of protocol conformance, and provides information concerning how the parameter is used by implementations of the message. An example parameter specification is shown in figure 28.

Figure 28: A parameter specification

The *parameter name* is the name of a formal parameter and is used to identify the parameter with a parameter specification, and to refer to the parameter in textual descriptions.

The *textual description* is used by the interface designer to provide a quick reference to the purpose and use of the parameter.

3.4.1 Parameter Interface Definitions

A *parameter interface definition* is defined as *either* of the following:

- A single protocol name $\langle P \rangle$.
- A logical OR of two or more protocols $\langle P1 \rangle \mid \langle P2 \rangle \mid \dots$.

The parameter interface definition identifies the behavioral assumptions the message makes concerning the parameter. A client must supply an appropriate actual parameter. An OR of protocols means that the parameter must conform to at least one of the protocols in the disjunction. This is required to describe cases where a message accepts objects with diverse behavior and tests their behavior by sending messages in order to determine the action to be taken.³⁵ Note that this is different from the case where a message accepts objects with diverse behavior, but only makes use of behavior which they have in common. In the latter case, the message is not really dealing with diverse cases of behavior.

It is important to notice that when a message specifies that a given formal parameter must conform to a protocol $\langle P \rangle$, the message is making a commitment not to use or attempt to use behavior of a corresponding actual parameter which is not defined in $\langle P \rangle$. In this sense, the conformance statement is a *maximal* behavioral requirement — at most all of the behavior described by $\langle P \rangle$ will be used, and no more.

Figure 29 presents a simple example of an implementation which requires an OR interface definition.³⁶ The method accepts either Points or Integers and answers a new Point which is the result of the subtraction. The interface definition for the parameter is: $\langle \text{point} \rangle \mid \langle \text{integer} \rangle$. Such an interface definition is analogous to the type unions of [Johnson 86].

³⁵ This is sometimes referred to as *type casing*.

³⁶ There are at least two other obvious implementations, both of which avoid an explicit behavioral test of the parameter — one which sends **asPoint** to the parameter to coerce it to a Point, and one which implements **x** and **y** for Integers to return themselves. In any case, the message specification is identical.

```

- delta
  "Answer the result of subtracting the delta from the receiver."

^delta isPoint
  ifTrue: [(self x - delta x) @ (self y - delta y)]
  ifFalse: [(self x - delta) @ (self x - delta)]

```

Figure 29: The `#-` method from class `Point`

3.4.2 Parameter Aliasing Attributes

Specification of aliasing information weakens encapsulation since implementation details necessarily become exposed. However, if information about whether a parameter is stored, or whether a returned value is new or returned state is not explicitly provided, interaction bugs often occur which are difficult to diagnose and fix. In the worst case, it might be impossible to effectively use an interface without information concerning the aliasing of parameters. Alternately, the lack of information might simply require defensive programming techniques which result in unnecessary object creation and copying, incurring a performance penalty.

As an example of the former, consider the `#at:put:` message for `Array`, which is defined to store an object into the `Array` at a given index. It is critical that any description of the interface guarantee that a reference is retained to the exact object being stored, and not some equivalent copy. A client storing an object into an array expects to be able to affect the state of that object through other references, and have those effects be visible when the object is later retrieved.

```

addAll: aCollection
  "Add the elements of aCollection to the receiver."

  aCollection do: [x | self add: x]
  ^aCollection

```

Figure 30: The `#addAll:` method for `Collection`

As an example of the latter, consider the `#addAll:` message for `Collection`.³⁷

³⁷As we shall see later, not all collections actually support this message.

2 OF 2

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

which can be implemented as shown in figure 30. If a specification for this message does not guarantee that the collection parameter is *not* captured³⁸ then the client may have to unnecessarily create new collections since modifying a collection previously used as a parameter to this message could have (possibly undesirable) side effects.

The key to addressing these problems without weakening encapsulation is to separate *incidental* aliasing from *essential* aliasing, both for parameters and for return values. Essential aliasing forms a critical part of the behavior of the interface, and as such it must be specified by the interface designer. Incidental aliasing should not be specified since it is a side effect of the implementation choices, and is not fundamental to the functionality of the interface. The distinction is up to the interface designer.

Of course, incidental aliasing still *occurs*, but armed with a clear statement of guaranteed vs. unspecified behavior, the client programmer is able to write code that will continue to work correctly as long as the guarantees made by the interface hold.

Essential aliasing of parameters is described using a *parameter aliasing attribute*, which is one of the following identifiers:³⁹

captured The receiver *always* retains a reference to the parameter, directly or indirectly, as a result of this message.

uncaptured The receiver *never* retains a reference to the parameter, directly or indirectly, as a result of this message.

unspecified It is unspecified as to whether or not a reference is retained as a result of this message i.e. either case may occur.

³⁸One could envision a version of #addAll which was optimized for adding and was implemented by simply storing the collection parameter.

³⁹The **uncaptured** attribute was suggested by [Hogg, 92].

The captured and uncaptured annotations are self-explanatory. However, the unspecified annotation requires some explanation.

The unspecified annotation is used to describe both *sometimes-aliased* cases and also the case where the interface designer has decided not to expose the information. A sometimes aliased case is when, as a result of conditional expressions, different execution paths of a method result in different aliasing. The implication is that the aliasing can not be predicted without evaluating these conditions.

```

add: anAssociation
    "Include anAssociation as one of the receiver's elements. Answer
    anAssociation "

    | index element key |
    (key := anAssociation key) == nil ifTrue: [~self subscriptBoundsError: key].
    index = self findKey: key.
    element = self basicAt: index
    element == nil
(1)         ifTrue: [self atNewIndex: index put: anAssociation]
(2)         ifFalse: [element value: anAssociation value].
    ~anAssociation

```

Figure 31: The #add: method for Dictionary

An example which illustrates both cases is the #add: method in Dictionary (figure 31). The Association parameter is a {key, value} pair. If the Dictionary already contains an Association with a key equal to the parameter's key, then the Dictionary updates its existing Association with the new value at line (2). Otherwise it is a new key, and the parameter is stored at line (1). Thus the parameter is captured only in the case where it contains a new key i.e. it is sometimes-aliased.

From the perspective of an application programmer, one could argue that it is of limited utility to divulge such case-specific information at the interface, since the application code must check in advance to see if the Dictionary contains the key in order to predict whether the parameter will be captured. From the perspective of the Dictionary's implementor, providing the information totally exposes the implementation — both that the representation is composed of Associations, and that the client's Association is actually stored under specific conditions, and commits

the Dictionary to this behavior.

Of course there may also be non case specific situations where the interface designer decides not to expose the aliasing of the parameter, simply for implementation flexibility. If there is a hierarchy of related behavior, it may be convenient for *some* subclasses to capture the parameter but not others. Such is the case with Dictionary and IdentityDictionary, for example. The behavior of Dictionary and IdentityDictionary is different only in that the former uses equality (`#=`) for key lookup, and the latter uses identity (`#==`). Dictionary is implemented as a collection of Associations containing the keys and values. IdentityDictionary is implemented as an Array such that keys are at odd offsets and values are at even offsets. For this reason, while it is convenient for Dictionary to capture an Association parameter, IdentityDictionary does not make use of this. For the same reasons, a Dictionary can return stored state in response to the `associationAt:` message, while IdentityDictionary must create a new Association each time.

The `unspecified` annotation gives the interface designer the flexibility to avoid making a commitment to capture or not capture a parameter. In such cases, clients must operate under the assumption that the parameter *might* be captured.⁴⁰

It should be noted that the parameter aliasing attribute is somewhat different from the interface definition in that the former is a commitment on the part of the service provider, while the latter is a condition of service. We shall see in the next chapter that this difference has a bearing on how parameter aliasing is related to conformance between message specifications.

3.5 Return Value Specifications

Return values are described in a manner similar to that of parameters. However, the interpretation is slightly different. Whereas the parameter description is *prescriptive*

⁴⁰To properly describe case-specific parameter aliasing requires splitting the method into different execution paths in order to separate the captured cases from the uncaptured case. [Chambers 91] While it may be possible to extend the protocol model to use message specification splitting to describe method-splitting, this has not been explored.

in that it states requirements to which the parameters must conform, the return value information is *descriptive* in that it provides information about the result being returned.

A *return value specification* is defined by the following:

- A textual description.
- A return value protocol.
- A return value aliasing attribute.

Figure 32: A return value specification

An example return value specification is shown in figure 32. The *textual description* is used by the interface designer to provide a quick reference to interpretation of the return value.

Whereas a protocol makes a conformance requirement statement about parameters, it makes a conformance *commitment* concerning the return value. The specification guarantees that the return value will conform to the specified protocol.

A message specification may have multiple distinct return value specifications. Conversely, a single return value specification may describe multiple return *values* if the return value specification applies to all such values. Multiple return value specifications are necessitated by cases where a message is defined to return objects conforming to different protocols, on a case-specific basis. These are conveniently described with separate conformance statements, aliasing, and textual annotations.

As an example, consider the `#findElementIndex` method (shown in figure 33) which searches an indexable collection for an object and returns an integer index if

```

findElementIndex: anObject
    "Answer the index position of the element equal
    to anObject in the receiver. If no such element
    is found, answer nil."
    | index size |
    size := self size
    index := 1.
    [index <= size]
        whileTrue: [
            (self at: index) = anObject
                ifTrue: [^index].
            index := index + 1].
    ^nil

```

Figure 33: The #findElementIndex: method for indexed Collections

it is found or `nil` if it is not. This is described using two return value specifications (figure 34): one promising conformance to `<integer>` which describes the success case, and one promising conformance to `<undefinedObject>` which describes the fail case. In order to allow us to establish correspondence between sets of return value specifications, we do not permit two distinct return value specifications which promise conformance to the *same* protocol.

Figure 34: Return value specifications for #findElementIndex:

An important factor of any protocol specification model is the ability to describe undefined return values. If a message specification has no return value specifications, then the return value is undefined. This can be used to separate procedural messages from functional messages, and to allow for inconsequential difference in component implementations. For example, the Smalltalk 80 implementation of `#removeAssociation:` for Dictionary returns the parameter, while the Smalltalk/V

implementation returns the Dictionary itself. In neither case does the return value provide information that the client did not already have. An interface can be specified to allow such implementations that return different results but are otherwise operationally equivalent. In such cases, the fact that an object is returned is incidental and should not be used to advantage by clients. This is important in the context of developing standard specifications for existing implementations in a way that minimizes code changes.

3.5.1 Return Value Interface Definitions

In order to relate return values through conformance, we define the *return value interface definition* for a message specification to be the single return value protocol, or the logical OR of the protocols in each distinct return value specification. The return value interface definition for the example in figure 33 is:

`<integer> | <undefinedObject>`

These interface definitions are implicit in the descriptions, since such cases are actually described through the use of multiple return value specifications. If a message specification has *no* return value specifications (i.e. it has no defined return value), then it is not prepared to guarantee anything about the behavior of the returned object. However, we require that all objects conform to `<object>` protocol; therefore the default interface definition, which applies to a message specification with no return value specifications, is `<object>`.

3.5.2 Return Value Aliasing Attributes

The return value aliasing attribute is used to provide (or hide) information about the identity of the return value. Many return values are used (or are intended to be used) in a read only manner (i.e. the state of such a return value is intended to be queried but not modified) by clients. For example, consider the `#topRight`

method for Rectangles, which returns a Point representing its top right corner. The implementation of the Rectangle will affect whether a stored Point is returned, or a new Point is created and initialized from stored state. For this reason the Rectangle should probably not be modified by asking for one of its points and destructively modifying the return value. Rather, the Rectangle should be updated explicitly through interfaces designed for that purpose [Lieberherr 88].

The implementor could protect read only return values by always creating and returning new objects, but this imposes an unnecessary performance penalty. It should be inconsequential to the application code whether a returned object is new or returned state (assuming it is not going to be modified). Supplying this information may unnecessarily constrain implementation options or prevent the use of certain optimizations. This is an example of *incidental* aliasing, and the details of such aliasing should be excluded from the interface specification.

Some return values always return a new (unaliased) object, and this should be described by the interface specification in order to allow the client to modify the returned value without unnecessary copying.

In other cases the specification must indicate that a returned object is actually retained state and not just an equivalent value. Consider an Array for example. When a particular element is retrieved from an Array, it is expected that the same object will be returned each time. It is also expected that the effects of state-modifying operations on a retrieved element will be reflected in subsequent retrievals of the same element. This is an example of *essential* aliasing — the service provider is returning state and it is necessary that this be guaranteed by the interface specification.

Information concerning retained references to return values (by the message receiver) are described using a *return value aliasing attribute*, which is one of the following identifiers:

state The receiver retains a reference (direct or indirect)⁴¹ to the returned object after the method returns i.e. the object is returned state.

new The object is newly created in the method invocation and no reference (direct or indirect) is retained by the receiver after the method returns.

unspecified No information is provided as to the origin or retained references to the object.

The **state** attribute indicates that the returned object is guaranteed to be aliased by the receiver. Thus any modifications to the returned object will have side effects on the state of the object which returned the value.

The **new** attribute indicates exactly the opposite, that the return value is not only unreferenced by the object returning it, but it is not referenced by any object whatsoever. The caller of the method holds the sole reference.

The **unspecified** attribute is used to avoid providing information concerning aliasing of the return value. This may be because the interface designer wants to avoid committing to a particular implementation (i.e. it is incidental aliasing), or because the aliasing is not known. The client must treat the returned object accordingly, and not perform destructive operations on it (or in the course of doing so, understand that unsupported and/or nonportable behavior is being used).

This **unspecified** attribute is also used for cases which are not described by any of the other attributes, such as when the receiver itself is returned.

There are other interesting situations, but they are more complicated than they initially appear. For example, it may be useful to distinguish the case where a return value *was* state but is no longer referenced (directly or indirectly) by the receiver after the method returns. Such a case is demonstrated by the **remove:** method for Sets shown in figure 35.⁴² The object to be removed is located in the

⁴¹ There exists some reference path to the object from the receiver's state variables

⁴² The **#remove:** method is normally implemented in terms of the **#remove.ifAbsent:** method

```

remove: anObject
    "Answer anObject. Remove the element anObject from
    the receiver collection. If anObject is not an
    element of the receiver, raise an error."
    [ index ]
(1)    index := self findElementIndex: anObject
        (contents at: index) == nil
        ifTrue: ["self errorAbsentElement]
(2)    contents at: index put: nil.
        elementCount := elementCount - 1.
        self rehashFrom: index.
(3)    ^anObject

```

Figure 35: The #remove: method for Set

representation at line (1), and the reference is removed at line (2). Since Sets do not admit duplicates, we know that the Set could not possibly contain another element which is the same. However, in general the Set does not know whether or not it has an indirect reference to the returned object through one of its remaining elements.⁴³ There is a subtle distinction between these two types of references, since in one case the reference is created by the client, and in the other it is created by the Set. However, it is unclear how a return value annotation can be used to reflect this distinction. For these reasons we do not attempt to distinguish such cases, and they are described using the `unspecified` annotation.

We do not describe the aliasing of the state variables of the return value itself: the attribute applies only to the first level returned object. The implication is that second and subsequent level aliasing of the return value is *always* unspecified. The notation would quickly become unwieldy if an attempt were made to describe aliasing of second and subsequent levels, and for encapsulation reasons, such information should not even be known (or divulged) at this point in the specification.

In addition, there are good software engineering reasons why second level

which allows the client to supply a block of arbitrary code to execute in the fail case. The method have been merged here for clarity.

⁴³It is certainly possible for the Set to check for indirect references by walking all objects that are reachable from its state variables, but it may be unreasonable to expect this kind of behavior from a Set. It would make the complexity of element removal a function of the inter-reference structure of the elements, and other objects which they reference.

state¹¹ of returned values should typically not be destructively modified by clients [Lieberherr 88] — rather if such capability is required then an interface should be supported by the service provider to update the state on the client's behalf. In order to maintain consistency, the service provider may need to update other state variables when a particular state variable is modified, and this becomes difficult if a client may directly modify the state of returned objects.

An exception occurs in the case where the returned state is an object which the client originally gave the service provider for safekeeping. This occurs with element retrieval in Collections (for example). In such cases only the client knows the implications of modifying second level state of the return value.

The fact that aliasing of second (and subsequent) level state is **unspecified** (from the perspective of the service provider) is consistent with both of the above cases. In the first case, the service provider is *unwilling* to divulge the aliasing of second level state. In the second case, the service provider does not *know* the aliasing of second level state, since the object was created and initialized by the client. In the former case, the client must not destructively modify second level state under any conditions, and in the latter case, the client knows the exact identity of the object and assumes responsibility for using the returned object in an appropriate manner.

Consistent with the two cases described above, we use an **unspecified** annotation as opposed to **read** as [Hogg 91] does. Our approach puts the onus on the client to draw the appropriate conclusion based on the promises made by the service provider.

The aliasing cases we describe are slightly different from those of [Hogg 91] due to the fact that we are interested in aliasing *advertisement* rather than aliasing *prevention*. Our aliasing distinctions are motivated by the need to disclose (and

¹¹First level state is the object's state variables. Second level state is the state variables of objects referenced by first level state.

hide) aliasing in varying degrees of detail, while aliasing prevention attempts to guarantee that aliasing can not occur in particular contexts, in a way that can be statically checked.

3.5.3 Behavioral Descriptions

The behavior of a message is described using English text, using two techniques. We attempt to use a definitional style wherever possible.

A small set of basic operations are described in terms of their effects on the abstract state of the object (which is described in the glossary). These form the building blocks for specifying the behavior of more complex messages. For example, messages such as **#add:** and **#remove:** for Collections can be described in terms of their effect on the abstract state i.e. how they affect the *elements*.

The remaining messages are described in terms of the basic messages. For example, while the **#addAll:** message for Collections could be described in terms of its effect on the elements, it is more convenient to describe it in terms of a series of applications of the **#add:** message (figure 36). This is a useful technique which serves to minimize the amount of specification text and reduces inconsistencies.

addAll: newElements

DEFINITION. <elementAddableCollection>

This %message is used to add each %element of a given collection to the receiver's %elements. The operation is defined to be exactly equivalent to adding each %element of @newElements to the receiver using the #add message with the %element as parameter

The @newElements are added in the order specified by the #do %message for @newElements.

newElements <collection> (uncaptured)

The collection of objects to be added to the receiver

RETURN VALUE

<collection> : (unspecified)

The @newElements parameter is returned

Figure 36: The **#addAll:** message specification

In the same way that an `#addAll:` method implemented in this way is independent of the implementation of the `Collection`, a message specified in this way is independent of the abstract model. This is analogous to code-sharing of implementations and results in extensive description-sharing.

In many cases there are several different sets of messages which can be used to describe all the others. It is up to the interface designer to conveniently partition the messages into basic and non-basic messages. The set need not be minimal, but for conciseness it is preferable that it be kept small.

Rather than attempting to define general concepts such as *equality* of objects in terms of an abstract state model, equality is instead defined in terms of the `#=` message. The `#=` message can then be defined in terms of the abstract state model for *particular* classes of objects. In other words, two objects are equal if and only if `#=` message returns `true` when the two objects are compared. This is actually more correct than attempting to do it the other way around, since it is the response of an object to the `#=` message that defines what equality means for any particular object.

English text is, of course, prone to ambiguities. In order to completely, and unambiguously describe the behavior of a message, a formal specification language would be required. Such a specification must include information concerning when the message can be sent, conditions on the values of the parameters, the value of the result, possibly the messages the object sends during processing of the message, and perhaps even the time allowed (or required) to perform the computation [America 87]. However, there are some obstacles to the practical application of formal techniques.

[America 87] notes that “Unfortunately, formal specification technology is not yet in a position that formal specifications of this kind can be included in a practical programming language.” According to [America 90], there is also the problem that a specification technique with enough power to sufficiently describe such behavior

results in a description which is not feasible to check with a compiler.¹⁵ Nonetheless, [America 87] argues that "...lacking a suitable formalism to express the behavior of objects in a type, we should at least associate with each type an informal description of this behavior," and describes an informal annotation approach to describing behavior [America 90], which relies on programmer discipline. [Wills 91] proposes a mixture of formal and informal techniques. [Leavens 90] argues for careful informal specifications when formal specifications are not practical.

From our perspective, while an easily understandable formal description would be ideal, we find that currently applicable techniques are not suitable as a tool for communicating object behavior to most application programmers. Some researchers [Gentleman 92] [Barry 93] note that formal descriptions are not necessarily correct nor are they often very readable, and documentation must still accompany formal specifications. However, [de Champeaux 91] notes that "Formal techniques can support the development of methods for software development, which can then be taught to programmers in a less formal, but nevertheless rigorous way." While our behaviora' descriptions are informal, our notions of conformance and substitutability are based on formal principles of object oriented type systems [Cardelli 84] [America 90].

We believe that behavioral descriptions are critical to the notion of conformance, and like [America 87] we believe that an informal but disciplined description of behavior is better than none. While it may be possible to substitute more formal behavioral descriptions such as those of [America 90] and [Cook 92] in place of our informal textual descriptions, the use of annotated text better meet our goals of acceptance and ease of use by programmers, since special training in formal method is not required to read or write the specifications.

¹⁵[America 90] proposes a formal specification approach based on pre- and post-conditions, but because of the problems described, instead chooses to use an approach based on informal annotation which describe behavioral properties.

3.6 Summary

We have described the components and sub-components of protocols and how they are assembled to describe behavior. In the next chapter we explain how protocols establish the criteria for membership in a group of objects having common behavior, and how protocols are related to each other through conformance and refinement.

Chapter 4

4 Conformance and Refinement

We now revisit conformance, and introduce the concept of refinement. *Conformance* allows a protocol to be defined through composition of other protocols. *Refinement* allows a protocol to make more precise statements concerning behavior defined in protocols to which it conforms. These two techniques result in extensive information sharing, and establish a strong structuring mechanism.

4.1 Conformance

Conformance is defined on objects and protocols. Additionally, in the context of protocols, conformance is defined on message specifications. Finally, in the context of message specifications, conformance is defined on interface definitions, abstracting attributes and behavioral descriptions. We now define these relationships.

4.1.1 Object Conformance

In general terms, conformance is satisfaction of a predicate. For example, a protocol $\langle P \rangle$ establishes a predicate $P(x)$ on objects x by defining a set of behavior. An object x satisfies the predicate if it implements this set of behavior. Of course, such an object may have additional behavior, or it may be possible to specify the object's behavior in more detail. Thus a protocol may describe only a subset of an object's behavior, or it may leave certain aspects of the behavior unspecified. Conformance of an object x to a protocol $\langle P \rangle$ is written $x \leq \langle P \rangle$.

Since we are concerned with describing intrinsic properties of behavior, we require that all objects of the same class necessarily conform to the same protocols, since they have the same implementation. All objects of the same class have the same intrinsic properties when they are created, and these properties can not change over the lifetime of the object. This is the same relationship between classes and behavior established by most practical object-oriented type systems (e.g., [America 90] [Oxhoj 92] [Johnson 86]) and allows us to establish a straightforward relationship between classes and protocols.

Note that in Smalltalk, *classes are also objects*, which conform to protocols that describe behavior common to objects which happen to be classes. For this reason we talk about the behavior of *objects*, and classes are the mechanism by which the behavior is implemented.

4.1.2 Protocol Conformance

Protocols are also related to *each other* through conformance. If all⁴⁶ objects that conform to a protocol $\langle P \rangle$ also conform to a protocol $\langle Q \rangle$, then $\langle P \rangle$ is defined to conform to $\langle Q \rangle$, written $\langle P \rangle \leq \langle Q \rangle$. It follows from this that if $\langle P \rangle \leq \langle Q \rangle$ then for any object x , if $x \leq \langle P \rangle$ then $x \leq \langle Q \rangle$. If both $\langle P \rangle \leq \langle Q \rangle$ and $\langle Q \rangle \leq \langle P \rangle$ then necessarily $\langle P \rangle$ and $\langle Q \rangle$ define the same behavior i.e. $\langle Q \rangle = \langle P \rangle$. We define these relationships in terms of predicate satisfaction in figure 37.

$\langle P \rangle \leq \langle Q \rangle$	iff $\forall x. P(x) \implies Q(x)$
$\langle P \rangle = \langle Q \rangle$	iff $\forall x. P(x) \iff Q(x)$

Figure 37: Conformance vs. predicate satisfaction

We now establish necessary and sufficient conditions for protocol conformance. A protocol $\langle P \rangle$ conforms to a protocol $\langle Q \rangle$ if and only if both of the following are

⁴⁶ All *possible* objects, not just those that are currently defined or existing in a system.

true:

- Every message specification in $\langle Q \rangle$ has a corresponding message specification in $\langle P \rangle$ with the same message selector.
- Every message specification in $\langle P \rangle$ conforms to its corresponding message specification in $\langle Q \rangle$.

This means that in order for $\langle P \rangle$ to conform to $\langle Q \rangle$, $\langle P \rangle$ must define message specifications for at least all of the message selectors in $\langle Q \rangle$, and these specifications must specify compatible behavior.

Conformance is transitive. If $\langle A \rangle \leq \langle B \rangle$ and $\langle B \rangle \leq \langle C \rangle$ then $\langle A \rangle \leq \langle C \rangle$. Similarly any object which conforms to $\langle A \rangle$ conforms to $\langle C \rangle$. If an object or a protocol conforms to a protocol through transitivity we say that it *implicitly* conforms.

4.1.3 Message Specification Conformance

In the context of protocols, message specifications are related through conformance. A message specification s in a protocol P is identified by a protocol and selector pair $\langle P, s \rangle$. A message specification $\langle P, s \rangle$ conforms to a message specification $\langle Q, t \rangle$ where P, Q are protocols and s, t are message selectors if and only if all of the following are true:

- s and t are the same message selector.
- $\langle P, s \rangle$ and $\langle Q, t \rangle$ have the same formal parameters (the same names in the same positions).
- the parameter interface definitions of $\langle Q, t \rangle$ conform to the corresponding⁴⁷ parameter interface definitions of $\langle P, s \rangle$ (contravariance).
- the parameter aliasing attributes of $\langle P, s \rangle$ conform to the corresponding parameter aliasing attributes of $\langle Q, t \rangle$ (covariance)

⁴⁷Parameter correspondence is by formal parameter name

- the return value interface definition of $\langle P, s \rangle$ conforms to the return value interface definition of $\langle Q, t \rangle$ (covariance).
- the return value aliasing attributes of $\langle P, s \rangle$ conforms to the corresponding⁴⁸ return value aliasing attributes of $\langle Q, t \rangle$ (covariance).
- the behavioral description of $\langle P, s \rangle$ conforms to the behavioral description of $\langle Q, t \rangle$ (covariance).

4.1.4 Interface Definition Conformance

Recall that an interface definition is either a single protocol, or a logical OR of two or more protocols. We define interface definition conformance as follows. The protocol set for an interface definition is the set of protocols in the disjunction (or the set consisting of the single protocol). An interface definition I conforms to an interface definition J if and only if the protocol set for I is a *subset* of the protocol set for J .⁴⁹ Figure 38 shows some example conformance relationships for interface definitions.

$\langle \text{integer} \rangle \mid \langle \text{undefinedObject} \rangle$	conforms to	$\langle \text{integer} \rangle \mid \langle \text{undefinedObject} \rangle$
$\langle \text{undefinedObject} \rangle \mid \langle \text{integer} \rangle$	conforms to	$\langle \text{integer} \rangle \mid \langle \text{undefinedObject} \rangle$
$\langle \text{integer} \rangle$	conforms to	$\langle \text{integer} \rangle \mid \langle \text{undefinedObject} \rangle$
$\langle \text{undefinedObject} \rangle$	conforms to	$\langle \text{integer} \rangle \mid \langle \text{undefinedObject} \rangle$
$\langle \text{integer} \rangle \mid \langle \text{undefinedObject} \rangle$	does NOT conform to	$\langle \text{integer} \rangle$
$\langle \text{integer} \rangle \mid \langle \text{undefinedObject} \rangle$	does NOT conform to	$\langle \text{undefinedObject} \rangle$

Figure 38: Interface Definition conformance examples

Note that interface definition conformance is defined by a *subset* relationship, since an interface definition is defined to require an object conforming to one or more protocols in the corresponding disjunction. The subset relationship follows directly from this definition.

⁴⁸Return value correspondence is by return value protocol.

⁴⁹Note that we do not require a proper subset i.e. the sets may be equal.

4.1.5 Parameter Aliasing Conformance

Parameter aliasing attributes that are the same conform to each other. We define the following additional conformance relationships among the parameter aliasing attributes:

- **captured** conforms to **unspecified**.
- **uncaptured** conforms to **unspecified**.

These follow trivially since both **captured** and **uncaptured** satisfy the conformance predicate implied by **unspecified**, since **unspecified** imposes no restrictions.

4.1.6 Return Value Aliasing Attribute Conformance

Return value aliasing attributes that are the same conform to each other. We define the following additional conformance relationships among the return value aliasing attributes:

- **state** conforms to **unspecified**.
- **new** conforms to **unspecified**.

Again, these follow trivially since any aliasing attribute satisfies the predicate implied by **unspecified**, since **unspecified** imposes no constraints whatsoever.

4.1.7 Behavioral Description Conformance

A behavioral description D2 conforms to a behavioral description D1, if the behavior described by D1 is implied by D2. We define the following rules for behavioral descriptions.

- D2 includes the text of D1, and may only add additional text

- D1 may leave certain aspects of behavior unspecified. These aspects can be specified by D2.
- D2 may not contradict D1.

Given that D2 includes the text of D1, it is more difficult for a designer to accidentally violate conformance in a message specification when conformance between protocols has been asserted. In most cases, contradictions are readily apparent.

The conformance rules for behavioral descriptions reflect the fact that substitutability requires that behavior be strictly *additive*. Conformant protocols may only define new messages, or provide more precise statements concerning the behavior of existing messages.

4.2 Refinement

The refinement relation can be applied wherever we have defined conformance, and is defined as follows. Given any A and B such that there is a conformance relation defined on A and B, then A is a refinement of B if A conforms to B but B does not conform to A. Refinement applies to protocols, message specifications, interface definitions, and aliasing attributes. It is also convenient to say that if A is a refinement of B, then A refines B.⁵⁰

Refinement makes a stronger statement than conformance. Refinement describes the property which relates protocols in a way that allows them to make progressively more and more precise statements concerning object behavior, while still satisfying conformance.

We call a message specification in a protocol <P> a *definition* if it is not included in any protocol to which <P> conforms. Otherwise it is a refinement. The protocol

⁵⁰Strictly speaking, it follows from this definition that an object *x* which conforms to a protocol <P> is said to be a refinement of that protocol. Regardless of whether this seems to make sense or not, it is of no practical consequence, so for simplicity we omit any such special case from the definition.

conformance relationship defines a directed, acyclic graph.⁵¹ For any given message specification $\langle P, s \rangle$ in a protocol $\langle P \rangle$ there exists a *path* through refinements (if any) to the *definition* $\langle P', s' \rangle$ of the message specification. The set of all paths from $\langle P \rangle$ establishes message specification *visibility*. A message specification $\langle Q, t \rangle$ is *visible* from a protocol $\langle P \rangle$ if either $\langle P \rangle = \langle Q \rangle$ or there exists a path from $\langle P \rangle$ to $\langle Q \rangle$. We say that the *implicit specification* of a message in a protocol $\langle P \rangle$ is the closest⁵² message specification visible from $\langle P \rangle$ through the conformance graph. Thus the implicit specification may be either in $\langle P \rangle$ or in some protocol to which $\langle P \rangle$ conforms. Note that we use the *closest* visible message specification in order to ensure we obtain all refinements in the refinement path, not to resolve potential conflicts caused by visibility through *different* paths. In section 4.3.4 we discuss resolution of the case where there are message specifications for the same message selector visible through different paths.

Figure 39 shows a segment of a conformance graph tracing the visibility of the `#add:` message for the `<orderedCollection>` protocol.

Figure 39: Visibility path for the `#add:` message

The full text of the behavioral description of a message specification is obtained

⁵¹In particular, it forms a *lattice*.

⁵²Involving the fewest number of arcs in the graph.

by concatenating the behavioral description from the definition together with the text *added* by behavioral refinements in the visibility path, in reverse order.⁵³ The message specification for the `add:` message as traced in the graph in figure 39 is shown in figure 40.

```

add: newElement

DEFINITION: <elementAddableCollection>
  This %message is used to add an %element to the receiver. The position
  of the new %element in the element traversal order is unspecified. The
  number of %elements in the receiver (as defined by the #size message) is
  increased by 1.

  The behavior of this message when @newElement is the special value %nil,
  is unspecified

REFINEMENT: <dequeue>
  The @newElement is added to the end of the receiver's %elements so that
  it becomes the last %element in the traversal order. This %message is
  defined to be equivalent to #addLast: for this receiver.

REFINEMENT: <orderedCollection>
  This message is defined to work correctly for all values of @newElement,
  including the special value %nil

  newElement <object> : (captured)
    The object to be added to the receiver.

RETURN VALUE
  <object> : (state)
    @newElement

```

Figure 40: The `#add:` message for `OrderedCollection`

In this example, `<elementAddableCollection>` defines the adding of an element to a collection, but does not specify where in the collection the element is added. Additionally, since some collections use the value `nil` specially in their representation, in general this value must be excluded. For this reason, `<elementAddableCollection>` disallows the value. The `<dequeue>` protocol defines the ability to add and remove from both ends of a collection, and refines the `#add:` message to indicate that elements are added to the end of the collection. Fi-

⁵³In practice, editing tools are used to manage the specifications so that there is only one copy of the text for a given definition or refinement entry. The tools assemble the full text for viewing on demand.

nally, the `<orderedCollection>` protocol adds a refinement to relax the restriction on `nil` valued parameters.

4.3 Properties of Conformance and Refinement

We now characterize refinement by describing how a refinement of a message specification can and can not differ from a message specification to which it conforms:

- The behavior described by the implicit specification holds true for the refinement (conformance).
- Refinement of the behavioral description can only occur where information is missing from the implicit specification. A specification may also identify situations of unspecified behavior, which permits a refinement to describe the behavior in more detail, provided a contradiction is not caused.
- The refinement must accept at least all the parameters that the implicit specification allows, and may accept parameters that, according to the implicit specification, would be invalid. That is, a refinement may *relax* restrictions on parameters. The behavioral description may not restrict parameter *values*. (parameter contravariance)
- A refinement may be more specific about the conformance of return value: possibly returning a subset of the return values described by the implicit specification. The behavioral description may also restrict the *values* returned (return value covariance)

A message specification may form a part of the behavior described by a protocol `<P>` in the following ways:

Definition the message specification visible to `<P>` is a definition and it is not visible in any protocol to which `<P>` conforms. (In other words, `<P>` contains the definition).

Refinement $\langle P \rangle$ contains a refinement of an implicit specification of the message.

Conformance an implicit message specification is visible and there is no refinement in $\langle P \rangle$.

4.3.1 Conflict Resolution

Since protocol conformance forms a directed acyclic graph, there can be multiple conformance paths to the same message specification. Consider the example conformance graph shown in figure 41.

Figure 41: The potential for specification conflicts

Note that $\langle \text{bag} \rangle$ implicitly conforms to $\langle \text{collection} \rangle$ and $\langle \text{object} \rangle$ through transitivity. A protocol or object could conform to $\langle \text{elementAddableCollection} \rangle$, $\langle \text{elementRemovableCollection} \rangle$, or both simultaneously. There is the potential for an inconsistency if, for example, $\langle \text{elementAddableCollection} \rangle$ and $\langle \text{elementRemovableCollection} \rangle$ both defined or refined the same message. This is analogous to the problems encountered with multiple inheritance strategies where a method implementation is inherited from two or more superclasses. We resolve this as follows.

If a message specification for a given message forms a part of the behavior described by a protocol (in any of the above ways), we say that the protocol *supports*

the message. Given a protocol and message which is *supported* either by definition, refinement, or conformance, the implicit specification is found by searching for the first refinement or definition in the conformance path from the protocol. Using the above example, the source of the specification for the `#=` message for the `<bag>` protocol, is `<collection,#=>`. The specification for the `#add:` message is `<elementAddableCollection,#add:>`. In order to prevent ambiguity and contradiction, we require the implicit specification for any message supported by a protocol to be the same `<protocol,selector>` pair regardless of which path is used. That is, all paths must yield the same result.⁵⁴ This is analogous to the graph oriented solution for resolving multiple inheritance [Snyder 86].

4.3.2 Substitutability

Given two protocols `<A>` and `<B>` such that `<A>` refines `<B>`, objects which conform to `<A>` are substitutable⁵⁵ for objects which conform to `<B>` for the following reasons.

1. Due to the properties of the object message model, all a method can do to a parameter is send messages to it.⁵⁶ Thus the responses an object makes to these messages fully describes its externally visible behavior.
2. Objects conforming to `<A>` respond to all messages responded to by objects conforming to `<B>`.
3. Due to the parameter contravariance rule, objects conforming to `<A>` accept all parameters accepted by the corresponding messages to objects conforming to `<B>`.

⁵⁴In fact, it may be sufficient to simply require that the conformance relationships for all visible refinements form a *total ordering* of the refinements. That is, there is one path to the *definition* which contains all visible refinements. However, the implications of this have not been explored.

⁵⁵As parameters to methods which are written to use them in accordance with the message specifications in `<B>`.

⁵⁶We ignore, for the moment, the case where the method is a virtual machine primitive and can access the representation of an object without sending messages to it.

4. Due to the return value covariance rule, objects conforming to $\langle A \rangle$ return a subset of the values returned by the corresponding messages to objects conforming to $\langle B \rangle$.
5. Due to the aliasing conformance rules, the substitution of objects conforming to $\langle A \rangle$ can not cause (new) unexpected side-effects, and essential aliasing specified by $\langle B \rangle$ is identical in $\langle A \rangle$.
6. The behavioral descriptions ensure that all behavioral assertions made in $\langle B \rangle$ hold in $\langle A \rangle$.

4.4 Summary

In this chapter we have explained how protocols define membership in a group of objects having common behavior, and how protocols are related to each other. We have discussed the properties of conformance and refinement, and how they establish substitutability. Since protocols do not form a partition of message selectors, we have explained how we resolve conflicts caused by conformance to different protocols having message specifications with the same message selector.

In the next chapter, we address practical issues involved in applying the approach, and present our factoring of the Collection classes, contrasting it to that of [Cook 92].

Chapter 5

5 Applying the Model

In this chapter we discuss practical issues involved in applying the model, and present a protocol factoring of the Collection classes to illustrate the approach. We compare our factoring with that of [Cook 92]. Several issues arise in the factoring of these classes, and in particular we revisit the contravariance problem, and show how it does not limit specification flexibility as it does for implementation type systems.

5.1 Abstract and Concrete Protocols

Through conformance and refinement, protocols establish relationships between sets of objects having common behavior which allows specification sharing and contributes to understanding of the differences and similarities in the behavior of conforming objects. However, in order to be useful to programmers, protocols must be related to real Smalltalk classes. There are several reasons for this.

First, programmers must be able to easily determine which protocol a given class conforms to and all classes that conform to a given protocol. Programmers often create new objects by sending messages directly to classes,⁵⁷ so the relationship between protocols and classes must be established. If a specification requires a parameter which conforms to a particular protocol, it must be possible to determine which classes implement objects which are suitable. Additionally, Smalltalk environment tools are currently class based, and present the programmer with cla-

⁵⁷As opposed to through the use of compiler literals, or by sending messages to other globally known objects.

names which must be related to specifications involving protocols.

Secondly, due to representational assumptions made by virtual machine *primitives*,³⁸ the parameters or return values for some methods must be instances of particular classes. The object message model breaks down at the interface to virtual machine primitives, which may directly access an object's representation. Primitives may access the state variables of a parameter *without sending messages* to it.

Figure 42: Object representation

For example, figure 42 illustrates how an object of class Point (with value (47,103)) appears to a primitive in a typical Smalltalk system. Primitives operate on an object's memory representation directly. A primitive reference to the Point is a pointer to an area of storage consisting of an object header, and fixed sized slots for the object's state variables. The *x* and *y* state variables for Point objects are shown. Primitives access these state variables by *position* e.g. *x* is known to be the first slot after the header. Since primitives are highly dependent on object representation, a behavioral description is insufficient in such cases. In addition, for reasons of implementation efficiency some classes of objects are "special", and not only must they have a particular representation but must actually be instances of a specific class which is known to the virtual machine.

Thirdly, relating the protocols to classes provides the capability to optionally provide a more precise parameter or return value specification than is possible by

³⁸Primitives are low level operations normally written in C or Assembler

simply working with behavioral properties. This allows a message specification to state that it returns or requires instances of a particular class, rather than an instance of some unknown class that behaves in a compatible way.

We address these problems by partitioning protocols into *abstract protocols* and *concrete protocols*. Classes are related to abstract protocols through concrete protocols which map one-to-one to classes. Concrete protocols have only outedges in the protocol conformance graph (i.e. they conform to abstract protocols). Each concrete protocol *represents* a class in the system which is visible to clients. In this manner, concrete protocols effectively impose an additional requirement for conformance that of membership in a particular class.

Abstract protocols are used as a tool to factor the similarities and differences between concrete protocols in a manageable way, much as abstract classes are used to factor implementation. Just as a Smalltalk programmer factors a system to maximize code reuse and minimize code bulk, protocols are used to factor specifications to maximize information reuse and minimize specification bulk. The conformance graph clearly shows the behavioral relationships between different classes in the system. It becomes clear which classes and protocols are related and in what way. Additionally, maintenance of specifications is an important factor in establishing the reusability of a component. If its specification is not up to date, the component is difficult to reuse. Abstract protocols provide a powerful *information sharing* mechanism which leads to concise and easily maintainable specifications.

Concrete protocols establish a correspondence between the conformance graph and the inheritance tree of a set of classes. Classes in the inheritance tree can be related to their corresponding concrete protocols in the protocol conformance graph. Figure 43 shows the relationship between classes and protocol , and conformance and inheritance, for Dictionary and IdentityDictionary. Note that the Dictionary and IdentityDictionary classes do not *conform* to the corresponding protocol , but rather *instances* of these classes do. The concrete protocol *represent* the behavior

described by the corresponding classes in the protocol graph — the classes are shown here only to make the correspondence clear.

Figure 43: Protocols and Classes

For convenience, we normally choose concrete protocol names that are the same as their corresponding class names, but it is important to note that this need not be the case. The actual mapping between concrete protocols and classes may be platform specific. For example, while the `<string>` protocol describes instances of `String` in Smalltalk/V [Digitalk 90], it describes instances of `ByteString` in Smalltalk-80 [PPS 92]. A `String` class exists in Smalltalk-80, but it serves as an abstract superclass for several subclasses of `String`. This illustrates the importance of separating the concepts of concrete protocol and class — different implementations of the same concrete protocols may actually use different class names, and the actual mapping is platform dependent.

Relating protocols to classes allows questions about the relationship between protocols and classes to be answered. Given any class in a system, the set of all protocols to which it conforms can be determined from the conformance graph. In a similar manner, given a protocol, the set of all conforming classes (currently existing

in the system) can be determined.

The new conformance requirement imposed by concrete protocols does not affect the substitutability relationship we have established for protocols. Consider three protocols, $\langle C \rangle$, $\langle C' \rangle$, and $\langle B \rangle$ such that $\langle C \rangle \leq \langle C' \rangle \leq \langle B \rangle$ but $\langle C \rangle$ is concrete and contains no message specifications. Now all objects that conform to $\langle C' \rangle$ are substitutable for objects that conform to $\langle B \rangle$. The protocol $\langle C \rangle$ is exactly the same as $\langle C' \rangle$ except that it imposes the additional constraint⁵⁹ of membership in a particular class. Thus the objects that conform to $\langle C \rangle$ are necessarily a subset of the objects that conform to $\langle C' \rangle$, and thus they are substitutable for objects which conform to $\langle B \rangle$. There is no substitution for conformance to a concrete protocol, since the class is specified exactly.

There are similarities between the signature and object types of [Johnson 86] and our abstract and concrete protocols. Abstract protocols correspond to named signature types which also describe behavior. Concrete protocols correspond to object types in that they map one-to-one to classes.⁶⁰ Just as concrete protocols form the leaves of our protocol graph, Johnson's object types can not have subtypes.

While the motivation is different, in both cases there is the need to uniquely identify instances of particular classes. Object types allow Johnson to describe instances of exact classes in order to perform optimizations that would not be possible if only behavior were considered. Concrete protocols allow us to describe exact classes when a behavioral description is not sufficiently restrictive to properly describe parameter constraints or return value guarantees. Johnson's signature types are more flexible than object types, in that they describe a potentially infinite number of classes purely in terms of message names and parameter/return types, but they preclude the compiler optimizations allowed by object types. However, signa

⁵⁹From the client's perspective it is a constraint; from the service provider's perspective, it provides *additional information*.

⁶⁰The union types of [Johnson 86] correspond to our logical OR of protocols used to describe parameters and return values.

ture types permit methods to be typed in a way that allows parameters which are instances of classes that are not yet implemented. Our abstract protocols allow the same flexibility as signature types, and they also provide implementation flexibility when used to describe return values. Additionally, through conformance and refinement, abstract protocols serve as a factoring mechanism to capture common behavior among concrete protocols.

Note that in addition to our protocol model, [Johnson 86] is the only approach reviewed which has the ability to unambiguously restrict parameters and/or return values to instances of *particular* classes. All the other approaches permit substitution of instances of different classes, provided they are behaviorally substitutable. Such approaches can not describe situations where such substitutions are not acceptable.

5.2 Special Protocols

We define three special protocols as follows:

<object> A protocol to which all other protocols conform.

<NONE> A protocol conforming to all other protocols.

<RECEIVER> A notational convenience which represents the protocol to which the receiver of the message conforms.

All objects are defined to conform to the **<object>** protocol. Although the **<object>** protocol may define behavior, it essentially places no restrictions on a parameter definition since it allows all possible parameters. This is equivalent to the special type *ANY* in type systems.

The special protocol **<NONE>** defines no new behavior of its own. It is equivalent to the special type *NONE* and conforms to all other protocols (conceptually, it has all possible behavior). An object conforming to **<NONE>** is substitutable for all other objects. However, except in trivial cases, it is impossible to implement such an

object due to behavioral conflicts among protocols.⁶¹ As with the type *NONE*, we define **<NONE>** such that there are no objects which conform. The **<NONE>** protocol is *completely restrictive* as a parameter definition, and allows *no* actual parameters. However, in accordance with the parameter contravariance rule, a refinement may relax this restriction, while still sharing the behavioral description. We illustrate this property in the next section.

Figure 44 shows the relationship between **<object>** and **<NONE>**. The use of **<NONE>** does not introduce ambiguity with respect to concrete protocols, because by definition it allows no conforming objects.

Figure 44: Defining All and Nothing

The **<RECEIVER>** protocol is a notational convenience that allows a message specification to indicate a return value which conforms to the same protocols as the receiver. This is equivalent to the special type *Self* defined by [Johnson 86] and [Borning 82]. Due to the contravariance requirement for parameter interface definition conformance, **<RECEIVER>** can not be used in a parameter specification since it is necessarily covariant. However, for the same reason, it is valid in a return value specification.

⁶¹There is an additional factor in our system which makes such an object impossible — as a result of the class membership constraint imposed by concrete protocols — such an object would have to simultaneously be an instance of every class in the system.

5.3 A Factoring of The Collection Classes

In this section we present an overview of our factoring of the Collection classes. An important part of the motivation for this work was to develop a behavioral specification that would allow portable applications to be written for several of the major Smalltalk systems. In particular we considered three of the most popular Smalltalk implementations [PPS 92], [Digitalk 90], [Digitalk S9], and the Blue Book [Goldberg 85], as the basis for a specification. The strategy used to define the scope of the behavior was as follows. We started with the behavior described in the Blue Book and added all methods which have become *de facto* standard. We consider a method to be *de facto* standard if it is supported by both vendors in a compatible way.

An initial set of the messages supported by the Collection classes was computed automatically by looking at implemented and inherited methods in a manner similar to that described by [Cook 92], except that three implementations (in addition to the Blue Book) were involved instead of one. Removing methods that are canceled by subclasses does not eliminate all of the problem areas. Each method must be manually inspected and tested as required to determine its actual behavior. The following are the major problems found:

- **Cancellation** — Inherited methods are not supported.
- **Indirect Cancellation** — Inherited methods are implemented using methods which have been cancelled.
- **Coincidental Naming** — Methods with the same name have different behavior and expect different parameters.
- **Subclass Parameter Restriction** — Subclasses accept only a subset of the parameters accepted by the superclass.

- **Incompatible Return Values** Subclasses return values which would not be returned by superclasses.
- **Overriding** Subclasses change the inherited behavior in an incompatible way.
- **Aliasing** Aliasing of parameter and return values may differ among classes in a hierarchy (or across different Smalltalk variants), and in such cases a judgement must be made as to what is incidental and what is essential aliasing.

In addition to the above problems, subtle incompatibilities between implementations were discovered, and these were resolved by making the specification more general if this could be done without significantly reducing the usefulness of the description. If this was not possible, then the behavior exhibited by one of the two implementations was chosen for the specification. In practice this was rarely necessary.

We assigned concrete protocols to classes, and introduced abstract protocols to factor common behavior as the message specifications were written. The process of factoring protocol specifications is very similar to the process of factoring a class hierarchy. In both cases the structure evolves to minimize bulk and capture common behavior in a concise way, in accordance with properties of conformance and inheritance relationships, respectively. An attempt was made to factor the behavior in such a way that methods which actually *implemented* refinements were captured as such in the specification wherever possible.

Figure 45 shows the conformance graph for our factoring of the Smalltalk Collection classes. Note that this is just one possible factoring of the behavior, and like finding an elegant solution to a programming problem, achieving a *good* factoring is somewhat of an art. However there is a difference between the notion of a *good* factoring and a *correct* factoring. The former is a subjective judgement concerning clarity, generality, and restrictiveness. The latter is an objective judgement, since the factoring is correct if it uses the notation correctly and follows the rule for

conformance and refinement.

In the next sections we present an overview of each protocol, and explore the issues that arise in more detail. As an example, the full specification for the `<collection>` protocol is provided in appendix A.

Figure 45: Conformance Graph for the Collection classes

5.3.1 Collection

Figure 46 shows the message selectors for the `<collection>` protocol, which defines the behavior shared by all collections. We identify messages with `>>` which we have found can be used to define all other messages in the protocol.¹² In this case `#do:` is such a message.

```

<collection>
  CONFORMS_TO: <object>
  REFINES:
  DEFINES:
    #asArray          >> #do:
    #asBag             #includes
    #asOrderedCollection #inject:into:
    #asSet             #isEmpty
    #asSortedCollection #notEmpty
    #asSortedCollection: #occurrencesOf
    #collect            #reject
    #detect             #select
    #detect:ifNone:     #size

```

Figure 46: Message selectors in the collection protocol

There are several interesting aspects of this protocol. The protocol does not provide any mechanisms for modifying an object — the object may be manipulated only in a read-only fashion. There is no modification capability that is common to all collections.

A fundamental aspect of the `<collection>` protocol is that it defines what *elements* of a collection are. The elements are defined by the `#do:` message which is the iterator supported by all collections. Instead of defining what elements are and then describing how `#do:` traverses them, we say that for any given object, the elements are the objects *actually traversed* by `#do:` (figure 47). The same message also defines the traversal order, the default order being unspecified. In this way, `#do:` defines what elements are, and *elements* is an abstract concept which interrelates externally visible behavior. Such basic message capture the essential functionality defined by the protocol, since they define the terms by which the other

¹²As noted earlier, there may be several such sets of messages for a given protocol.

```

do: operation

SYNOPSIS
    Iteratively evaluate @operation with each %element of the receiver in
    the receiver's standard traversal order.

DEFINITION <collection>
    This %message defines the receiver's %elements.

    This is one of the mapping operations. For each %element of the
    receiver, @operation is %evaluated with the %element as parameter.

    Unless specifically %refined, the %elements are traversed in no
    particular order. Each %element is visited exactly once. Conformant
    protocols may %refine this message to specify a particular ordering.

    operation <block>
        The object to %evaluate with each of the %elements of the receiver
        as parameter.

RETURN VALUE
    UNDEFINED There is no specified return value.

```

Figure 47: The #do: message specification

messages are defined.

Notice also that many of the other messages in this protocol follow directly from the ability to traverse the elements. In this case all of the other messages *could* be implemented using only the #do: message. Thus the only thing that can be said about collections in general is that they have elements, and these elements can be traversed in some unspecified order.

The analogy between abstract protocols and abstract classes now becomes apparent. Just as an abstract class can implement behavior based on behavior assumed to be provided by a concrete subclass, an abstract protocol can specify behavior by composing and interrelating other externally visible behavior which can then be specified in more detail by a conforming protocol. For example, if a protocol refines the #do: message to specify a particular traversal order, then messages like #select: which are specified to use the traversal order defined by #do: need not be explicitly refined.

Looking at the next level of the conformance graph in figure 45, we see that the

behavior has been partitioned into five groups, corresponding to five different ways of using collections. We now examine these in more detail. Note that there is not necessarily any relationship between the names we have chosen for the protocols, and any names of abstract classes that may exist in a given implementation.

5.3.2 DictionaryAccessCollection

A dictionary implements a mapping between *keys* and *values*. The values can be accessed by looking them up by their key. Given a value, a dictionary will also return the corresponding key. Additionally, there are messages to access the keys and values as pairs. These pairs are instances of class Association. Figure 48 shows the message selectors for the <dictionaryAccessCollection> protocol, which defines the behavior shared by all dictionaries. There are three interesting aspects of the dictionary protocols.

```

<dictionaryAccessCollection>
  CONFORMS_TO: <collection>
  REFINES:
    #collect:
    #reject:
    #select:
  DEFINES:
    #add:                                #includesKey
    #addAll:                             #keyAtValue
    #associationAt:                      #keyAtValue:ifAbsent
    #associationAt:ifAbsent:             >> #keys
    #associationsDo:                     #keysDo
    >> #at:                               #removeKey
    #at:ifAbsent                         #removeKey:ifAbsent
    >> #at:put:                           #values

```

Figure 48: Message selectors common to all Dictionary

First, the elements of a dictionary (as defined by the `#do` message) are its *values*. Dictionaries differ from other collections that support the `#add:` message in that the parameter is a $\{key, value\}$ pair (an Association), not an element. Curiously, although `#add:` takes an Association as parameter, `#addAll:` requires a Dictionary; a collection of Associations will not work. This is because a Dictionary is *not* a

collection of Associations, and the `#addAll:` message is typically implemented for Dictionaries by sending `#associationsDo:` to the parameter, which is not supported by other collections. Conversely, if the method were written by sending `#do:` to the parameter in order to accept a collection of Associations, a Dictionary would not be acceptable since the *values* would be traversed, not the Associations. Dictionaries are described in a somewhat confusing manner by [Goldberg 85] as being collections of Associations, but the behavior of `#do:` shows that the elements of a dictionary are actually its *values*.

Second, the three mapping messages (`#select:`, `#reject:`, and `#collect:`) are refined. These messages are defined in `<collection>` to collect the appropriate results into a collection responding to the same protocols as the receiver (i.e., specified using the `<RECEIVER>` protocol). The `<dictionary>` protocol refines these to further specify that the collected values are associated in the resulting Dictionary with their corresponding keys from the original Dictionary. Thus the definition in `<collection>` applies, but important additional information is provided.

Third, the two concrete dictionary protocols have different criteria for a successful key lookup and are in this sense incompatible. The `<dictionary>` protocol uses the `#=` (equals) message to check for a key match, while the `<identityDictionary>` message uses the `#==` (identity) message. Key lookup is defined by response to the `#at:` message. However, no useful specification for the key lookup criteria can be produced such that one of the criteria conforms to the other. The problem is that if we specify that *either* equality or identity is used for key lookup, then a client might rely on that property and one could not be substituted for the other. On the other hand, if we say for example, that identity is sufficient but not necessary, then we can define a conformance relation based on the fact that equality lookup conforms to identity lookup, since identity implies equality.⁶³ However, while such a specification for the identity case is correct, it is of limited usefulness since a client

⁶³Our definition of the `#=` message requires this

programmer could not tell for certain if a particular key is *not* in the dictionary. This is an example of *underspecification*, in that the specification is correct but does not contain enough information to be useful to clients. For these reasons, we can not establish a conformance relationship between these two types of dictionaries. This makes sense, because neither is substitutable for the other due to the key lookup differences.

Still, we would like to capture the fact that these two dictionaries work the same way except for the key lookup criteria. We solve this by defining key lookup as the response to the `#at:` message, and specifying an `#at:` message in `<dictionaryAccessCollection>` that simply leaves the key lookup criteria undefined. The `#at:` message is then refined by the two concrete dictionaries to define key lookup. In this way, the common behavior is captured, even though in terms of conformance, the two dictionaries are incomparable.⁴ Additionally, an object that conforms only to `<dictionaryAccessCollection>` is not useful as far as key lookup is concerned. However, a message that simply uses the keys and/or the values without requiring lookup can specify parameter conformance to this protocol and thereby accept both kinds of dictionaries.

This simple example illustrates a more general property of any two protocols `<A>` and `<B>` which are not related by conformance, but both conform to a third protocol `<C>`. Such an arrangement describes a situation where `<A>` and `<B>` have either disjoint, or mutually incompatible behavior, and yet these objects are mutually substitutable under limited conditions — those defined by `<C>`.

Unlike [Cook 92] we do not factor the `#at:` and `#at:put:` messages to have a specification with non-dictionary collections. There is a very weak relationship between the behavior of these messages for dictionaries, and for collections with integer indices. It would be possible to factor this into a common protocol, but the common protocol would have to admit either no keys (using the `<NONE>` protocol) or

⁴Neither conforms to the other.

integer index keys, and the dictionaries could then relax this restriction. However, integer index keys are tied closely to the ability to retrieve elements at all indices in the range from 1 to the size of the collection, regardless of whether a value was stored at a particular index using `#at:put:`. This is not the case for dictionaries, which can have holes where retrieval is invalid. For these reasons we have chosen to leave the behavior disjoint. Note that [Cook 92] defines `#at:` in `UpdatableCollection` to admit arbitrary keys, allowing conformance by `Dictionary`. However, the keys are restricted to `Integers` in `SequenceableCollection`, which violates parameter contravariance. Similarly, [Cook 92] defines `#at:put:` in `UpdatableCollection` to admit arbitrary keys, and then restricts the keys to `Integers` in `Array`, resulting in the same problem.

5.3.3 WriteAccessSequencedCollection

This protocol defines the ability to store elements into a collection at integer indices in the range `1..size`, where `size` is the number of elements in the collection. Figure 49 shows the message selectors for the `<writeAccessSequencedCollection>` protocol.

```

<writeAccessSequencedCollection>
  CONFORMS_TO <collection>
  REFINES
  DEFINES
  >>    #at put.
        #atAll put
        #atAllPut
        #replaceFrom to with
        #replaceFrom to with startingAt

```

Figure 49: Messages defining write access to sequenced Collections

The number of elements in a collection is defined for convenience as the response to the `#size` message, but the `#size` and `#do:` messages are mutually interrelated and in fact the `#size` message is itself defined in terms of the `#do:` message. Unlike dictionaries, which are variable size, some sequenced collections are of fixed size and

in such cases all elements are initially set to a default value (nil). The `#at:put:` message defines storage of elements, and all other messages in this protocol can be defined in terms of this message.

Figure 50: Specifying elements allowed by `#at:put:`

An interesting problem arises with the specification of the `#at:put:` message for this protocol. For illustration purposes, figure 50 shows `<writeAccessSequencedCollection>` and the protocols conforming to it. It can be seen from the conformance graph that `<string>`, `<array>`, and `<orderedCollection>` conform to `<writeAccessSequencedCollection>` and yet the first can only contain objects conforming to `<character>`, while the latter two can hold any object. Initially this appears to cause a problem in producing a specification for the `#at:put:` message in a manner which allow conformance by all three. We can not use `<object>` to specify the new element to be stored in the collection, since `<string>` would have to restrict this to `<character>`, and this is disallowed by the contravariance rule for parameters. In other words, if `<writeAccessSequencedCollection>` specified that *any object* could be stored, then an object conforming to `<string>` would not be substitutable, since `string` accept only characters. We could use `<character>`, (and relax the restriction to allow all objects in `<sequencedObjectCollection>`), but this is somewhat confusing, and

would preclude conformance by objects of classes such as `ByteArray` which restrict new elements in other incompatible ways.

In actuality, `<object>` is exactly the *opposite* from what we need. The solution is to use the `<NONE>` protocol, which conforms to all other protocols. Using `<NONE>` in a parameter specification is *totally restrictive* since there are *no objects* which conform.⁶⁵ Since `<writeAccessSequencedCollection>` is an abstract protocol, we can use it to define the behavior for `#at:put:` without making a commitment to allow any *particular* elements to be stored — and in fact we allow *none*. We can then *relax* this restriction in `<sequencedObjectCollection>` to allow *any* object to be stored, by specifying the new element parameter of `#at:put:` using `<object>`. Similarly we can relax the restriction in `<string>` to allow the storage of elements conforming to `<character>`. The solution is also flexible in that we could add other protocols such as `<byteArray>` which relax the restriction in different ways. This approach allows us to capture the similarity between strings and arrays without violating the contravariance rule.

When used in a parameter specification, the `<NONE>` protocol allows us to leave parameter conformance requirements unspecified, and *defer* the specification to conformant protocols. However, we can still capture common aspects of behavior which are independent of the *particular* parameters.⁶⁶ Note that since return values must be *covariant*, we specify the *return values* of the accessing message `#at:` using `<object>`.

Note that [Cook 92] shows `String` as conforming to `Array` (figure 24). In order to ensure substitutability we can not do the same, due to the parameter restrictions `String` places on messages supported by `Array`. Intuitively, a `String` is not

⁶⁵In fact, even if there were objects which did conform to all other protocols, the arrangement is still correct since the contravariance rule for parameters is satisfied.

⁶⁶This is similar to *genericity* in strongly typed languages, where a *generic type* can be defined which, when supplied with a *type parameter T*, results in a type which can operate on objects of type *T*. In actuality the generic type is a *type generator* which defines many types, yet captures the common behavior in one place.

substitutable for an Array, since a client might try to store something other than a Character into it.

There is an interesting conflict between strongly typed object oriented implementations and protocol based specifications which is related to the *contravariance problem*. Recall that the contravariance problem refers to the fact that requiring parameter contravariance limits flexibility because it precludes conformance by specializations which involve restricted cases. While such a specialization does not in general reflect substitutability, it may imply substitutability under certain conditions. For example, a String is substitutable for an Array as long as no attempt is made to store into it. Consider the arrangement of classes shown in figure 51, in which String and ByteArray are restricted cases of ArrayedCollection.

Figure 51: The Contravariance Problem

In this scenario, the ArrayedCollection class provides a default implementation of the `#at:put:` message.⁶⁷ Now assume that the implementation is such that it will work for all of the subclasses, but it is overridden in ByteArray. Suppose that in its implementation of the `#at:put:` method, ByteArray performs a bit wise AND of new integer elements with 255 to ensure that they are byte values. ByteArray then invokes the superclass implementation of `#at:put:` to store the new element. In order to be useful, the ArrayedCollection implementation of `#at:put:` must be typed to allow any elements which can be stored by subclass. However, the

⁶⁷In most Smalltalk implementations this message is actually provided by class Object, even though only it is only valid for classes with indexed instance variables.

same method must be typed in the String and ByteArray subclasses to restrict new element parameters to Character and Integer respectively. As a result, parameter contravariance is violated, and String and ByteArray can not be subtypes⁶⁸ of ArrayedCollection.

Figure 52: Conformance of restricted cases

However, as shown in figure 52, we have no trouble *specifying* the same scenario using protocols. We simply define `#at:put:` in `<arrayedCollection>` to allow *no* parameters (using `<NONE>`) instead of *any*, and then proceed to *relax* the restriction in the subclasses. It makes no sense to do the same in the implementation, because if the implementation of `#at:put:` in `ArrayedCollection` allowed no parameters, it could not be invoked. The `<NONE>` parameter definition allows no parameters, capturing the fact that a String is substitutable for an Array, providing it is not stored into. This approach is different from simply removing the definition of `#at:put:` from `<arrayedCollection>` and defining it in only the conformant protocols. Such an approach would not capture the common behavior which is independent of element restrictions. The use of `<NONE>` in a parameter specification allows us to capture this common behavior while still maintaining a substitutability relationship.

The distinction between *NONE* and *ANY* is subtle and sometimes confusing. The `<NONE>` protocol includes *maximum* possible behavior, but *no* objects. The `<object>` protocol, which corresponds to *ANY*, includes *minimum* behavior, and *all* objects. We make an observation concerning this duality with respect to pro-

⁶⁸If the normal substitutability definition is used

gramming in Smalltalk. Consider the method comment in figure 53 for `#at:put:` taken directly from a commercial Smalltalk implementation [Digitalk 90].

```
at: anInteger put: anObject
"Answer anObject. Replace the object in the receiver
at index position anInteger with anObject. If the
receiver does not have indexed instance variables, or
if anInteger is greater than the number of indexed
instance variables, report an error."
```

Figure 53: The `#at:put:` method comment

We argue that two different things are meant by designating the new element parameter as `anObject`.⁶⁴ In terms of the implementation of *this particular method* any object is acceptable — supporting Object behavior is a *maximum* requirement for the parameter since that is sufficient to implement this method. It is also the most that the programmer can say about the parameter in this context. However, method comments have a second role in specifying the general behavior of a message for a hierarchy — the same notation can mean that supporting Object behavior is a *minimum* requirement, since subclasses may require *more specific* behavior. In general there is a conflict between making a statement for a method in a particular class, and making a statement specifying the behavior of a message for an entire hierarchy. Of course, if the implementation hierarchy is such that subclasses are truly substitutable for superclasses (a subtype hierarchy), then the conflict disappears, since the two statements are the same. However, as we have just shown, forcing inheritance to model substitutability can limit implementation flexibility.

5.3.4 ReadAccessSequencedCollection

This protocol defines the ability to retrieve elements from a collection at integer indices in the range `1..size`, where `size` is the number of elements in the collection.

⁶⁴As discussed in section 2.5.3, it is common practice in Smalltalk to bound type parameters by naming a class in a parameter name. The intent is usually that instances of that class or a subclass are acceptable, but since subclassing is not subtyping this does not work in general.

Figure 54 shows the message selectors for the `<readAccessSequencedCollection>` protocol.

```

<readAccessSequencedCollection>
  CONFORMS_TO <collection>
  REFINES
    #=
    #do
  DEFINES
    #,
    ^> #at:
    #copyFrom to
    #copyReplaceAll:with:
    #copyReplaceFrom to with
    #copyWith:
    #copyWithout
    #findFirst
    #findLast
    #first
    #indexOf:
    #indexOf:ifAbsent:
    #indexOfSubCollection:startingAt:
    #indexOfSubCollection:startingAt:ifAbsent:
    #last
    #reverse
    #reverseDo:
    #with:do:

```

Figure 54: Messages defining read access to sequenced Collections

The `#=` message is refined from `<object>` to indicate that two objects conforming to this protocol are equal if their corresponding elements are equal. The definition of `#=` in object merely states that identity is sufficient but not necessary for equality. A refinement of `#=` can not be provided by `<collection>` because equality for the Set class is implemented as identity. The reasons for this are not clear, but it may be for efficiency. In order to compare two sets for equality, one must test every element of the first for membership in the second, and vice versa. Since a membership test is $O(N)$ in the worst case,⁷⁰ the equality test would be of $O(N^2)$ complexity.

The `#do:` message is refined by `<readAccessSequencedCollection>` to indicate that the elements are traversed in index order. The `#at:` message defines the ability to retrieve an element at an index, and the remaining messages in this protocol can be specified in terms of `#at:`. Note also that `#reverse` is non-destructive, and returns a new object with the elements of the receiver arranged in reverse order.

The `<readAccessSequencedStaticCollection>` describes the behavior common to sequenced collections that do not reorganize their elements, in contrast to

⁷⁰The algorithm normally used involves simple hashing with linear collision resolution.

`<sortedCollection>` which does. The `<readAccessString>` protocol captures the fact that `<symbol>` can be treated like a read only string. The `<interval>` protocol refines the messages that return new collections, in order to indicate that an `<array>` is returned instead of a new `<interval>`. This is valid because these messages specify the return value in terms of the special `<RECEIVER>` protocol, and `<array>` and `<interval>` both conform to `<readAccessSequencedStaticCollection>`.

Both the `<sortedCollection>` and `<orderedCollection>` protocols conform to `<indexRemovableCollection>`, which defines the ability to remove an element by index. This behavior is the same for these two collections because removal of a single element does not cause a `<sortedCollection>` to reorganize — the original ordering is preserved.

5.3.5 ElementRemovableCollection

This protocol defines the ability to remove elements from a collection by providing the element to be removed. Figure 55 shows the message selectors for the `<elementRemovableCollection>` protocol.

```
<elementRemovableCollection>
CONFORMS_TO: <collection>
REFINES:
DEFINES:
  >> #remove.
      #remove.ifAbsent
      #removeAll
```

Figure 55: Messages defining element removal for Collection.

This simple protocol defines element removal through the `#remove:` message. Sets, Sortedcollections, Bags, and OrderedCollections have this capability. Although sets can only contain a single occurrence of a particular object, our definition for element removal is the same. We simply say that the first matching element is removed, where the search order is as defined by the `#do:` message. This allows the same definition to work for all of sets, ordered, and unordered collections such as

Bags, since `#do:` defines an unspecified traversal order in the latter case.

This is in contrast to [Cook 92] which defines `#remove:` for sets to be incompatible with other collections, since after removal there can be no equal element left. We argue that such a strong statement is unnecessary and fails to capture common behavior, since the information is implied by the definition of the `#add:` message for `<set>`, which does not admit duplicates.

5.3.6 ElementAddableCollection

This protocol defines the ability to add elements to a collection without providing a key or index. Figure 56 shows the message selectors for the `<elementAddableCollection>` protocol.

```
<elementAddableCollection>
  CONFORMS_TO: <collection>
  REFINES:
  DEFINES:
    >> #add:
    #addAll:
```

Figure 56: Messages defining element adding for Collections

This protocol defines the ability to add an element to a collection at some unspecified position in its traversal order. The `<bag>` protocol uses this definition directly, and the `<dequeue>` protocol refines it to add ordering information.

The `<dequeue>` protocol defines the ability to add and remove elements from either the beginning or the end of the traversal order, but not anywhere between. It refines the `#add:` message from `<elementAddableCollection>` to define it to add the element to the end.

It is readily apparent from the conformance graph why `OrderedCollection` is the workhorse of the Collections. These versatile collections can be accessed by integer indices and allow adding and removing by element or by index and to both ends.

[Cook 92] shows Bags as being substitutable for Sets, but this is only because

the `#add:` message for `Set` has been renamed to `#include:` to account for the fact that `#add:` for `Set` does not admit duplicates. In the actual implementations, the classes are incomparable in terms of conformance. Since the `#add:` message for `Set` has fundamentally different behavior, `<set>` does not conform to `<elementAddableCollection>` and defines its own `#add:` message.

5.4 Summary

In this chapter we have discussed how we use abstract protocols to factor the behavior of a set of classes in order to facilitate the reuse of specification information. Conformance and refinement allow us to describe behavior in terms of the behavior of more general protocols, contributing to an overall understanding of the relationships between classes. Concrete protocols allow us to unambiguously specify objects of particular classes, addressing practical issues involving virtual machine primitives.

We have presented an overview of our factoring of the `Collection` classes, and have shown how a requirement for substitutability results in differences from the results of [Cook 92]. We have shown how we resolve the contravariance problem in our specifications, and how specification types differ from implementation types in this regard.

In the next chapter we evaluate our work in the context of the framework developed in chapter 2, discuss experience using the approach, and suggest directions for future research.

Chapter 6

6 Conclusions and Future Work

In this chapter we evaluate our approach using the same criteria used to review other approaches in chapter 2, and discuss possibilities for future research. Figure 57 summarizes our results in comparison with the approaches we have previously reviewed.

	Goldberg (proto.)	Goldberg (impl.)	IBM	Borning	Johnson (class)	Johnson (signat.)	Wills	Cook	Protocol model
Focus	doc.	doc.	doc.	doc./safe.	optimiz.	optimiz.	verif.	doc.	doc.
Group Membership	arbitrary subclass	arbitrary subclass	behavior	signature	set of classes	signature	behavior	behavior	behavior
Inter-Group Relationship	inherit.	inherit.	conform.	conform.	subset	conform.	conform.	conform.	conform.
Refinement	no	no	no	limited	no	yes	yes	no	yes
Substitutability	no	no	no	no	yes	no	yes	no	yes
Behavioral Description	comment	code	comment	none	code	none	pre/post cond.	pre/post cond.	annot. text
Op./Def.	mixed	op.	mixed	N/A	N/A	N/A	def.	def.	mixed
Abusing info.	some	code	no	N/A	code	N/A	no	no	yes
Param./Ret.	some	some	some	yes	yes	yes	yes	no	yes
Restrictiveness	low	high	low	low	high	low	high	average	average
Generality	average	low	high	high	low	high	high	high	high
Clarity	low	average	average	average	N/A	N/A	average	average	high

Figure 57: Comparison of approaches

6.1 Evaluation

The protocol model uses a behavioral grouping based on sets of message specifications. Group membership is established through a conformance relationship. Behavioral groups are also related to each other through conformance, which establishes a substitutability relationship. Our approach also provides refinement

capability, since new protocols may specify behavior by adding additional information to message specifications to which they conform. Additionally, refinement may generalize parameters and specialize return values according to the contravariance and covariance rules for substitutability.

Behavior is described using annotated text. In order to reduce the possibility of inconsistencies there are specific rules concerning how refinements may change behavioral descriptions. In particular, text may only be *added*. The actual text of message specifications is *shared* by conforming protocols. The full text of a behavioral description is obtained by concatenating the text from all refinements, to the original definition of the message specification, in reverse order.

The behavioral descriptions use a mixture of definitional and operational styles, with a preference for definitional. Glossary entries describe an abstract state model, which is itself defined in terms of the behavior of a small number of basic messages. For this reason, one might argue that there is actually no model, since behavior is described by interrelating the externally visible behavior of messages, and glossary entries are simply an abstraction used to make this easier. For example, the elements of a collection are defined by the response to the `#do:` message. The remaining messages are defined in terms of the glossary entries and the basic messages.

We address several important aliasing cases. First, we allow the interface designer to specify that a parameter is *always* captured, or is *never* captured by a method. Second, we allow the designer to specify that the receiver retains a reference to a return value after the method returns, or alternately, that the returned value is new and guaranteed to be unaliased. Finally, we achieve this without weakening encapsulation, since in both cases we allow the designer to indicate that the aliasing is *unspecified*. This capability is critical to the ability to handle incidental aliasing which should not be specified. In such cases the client must assume that aliasing may or may not be involved, and operate conservatively.

We describe parameters and return values through *conformance to protocols*. We

provide two kinds of protocols for this purpose. First, abstract protocols provide a behavioral description independent of classes. Objects of any class exhibiting the specified behavior are acceptable. This provides the flexibility to allow objects of classes that may not be defined at the time the interface is specified. It also contributes to generality in the specification of return values. For example, if one implementation returns an `Array`, and another returns an `OrderedCollection`, the interface could be specified to return a `<sequencedObjectCollection>` to which both classes conform. Although the client may not rely on the *class* of the return value, the return value protocol specification defines (and limits) the terms under which the return value may be used.

Second, concrete protocols map one-to-one to classes, although the particular mapping may be implementation-specific due to different naming. Pragmatic issues such as virtual machine primitives or implementation assumptions may require that parameters be limited to objects of a particular *class*. Concrete protocols allow the designer to specify that objects of a particular class are required, and substitutions (compatible or otherwise) are not permitted. Similarly, the interface designer may optionally *commit* the interface to return instances of a particular class, which may be required in certain cases. Concrete protocols identify classes uniquely, and abstract protocols factor behavior among a set of concrete protocols. This results in extensive information sharing.

We establish a substitutability relationship, provide aliasing annotations, describe parameters and return values, and take steps to reduce the potential for inconsistencies in behavioral descriptions. These aspects of the protocol specification increase restrictiveness significantly over Blue Book protocol descriptions. However, the very aspect of the protocol model which makes it suitable as reference documentation also limits its restrictiveness. Since English text is used in the behavioral descriptions, we rate restrictiveness as only average.

We do not require classes to be arranged in a particular inheritance hierarchy, are

not tied to platform class names, and provide flexibility in describing (or hiding) parameter and return value aliasing. In addition, we provide the capability to describe *undefined* return values. For these reasons we say that generality is high.

The structure provided by conformance and refinement contribute significantly to clarity, in the following three ways. First, it reduces the total amount of information required to describe the interfaces through extensive information sharing. Protocols organize behavior into units which once understood, can be directly applied to understanding the behavior of conformant protocols and classes.

Second, since conformance implies substitutability, one need not be concerned with exception cases. Composition of behavior is clearly defined. The conformance relationship clearly shows which kinds of objects are allowable as parameter, and what may be assumed about return values, with no surprises.

Third, refinement allows a style of specification where protocols are specified in terms of increasingly precise statements concerning behavior defined in protocols to which they conform. In other words, if a protocol <A> conforms to a protocol then in <A> "everything you know about still applies, but in *addition* you can also assume the following..."

As a result of method cancellation and overriding, inheritance provides very little information of its own concerning externally visible behavior. However, protocol conformance is a much stronger structuring relationship, and conveys all the information implied by substitutability.

Finally, our annotated text descriptions are easier⁷¹ to read than the more formal notations of [Wills 91] and [Cook 92], and important information is provided by our aliasing attributes. This, together with the structure provided by conformance, results in a high degree of clarity.

⁷¹For our intended readers.

6.1.1 Discussion

It is particularly interesting to compare our approach to those of [Wills 91] and [Cook 92]. We say that both our approach and that of Cook have only average restrictiveness. Cook uses a more formal notation, but does not achieve high restrictiveness since parameters and return values are not addressed and a substitutability relationship is not established. In contrast, we use a less formal notation but *do* describe parameters and return values and establish substitutability. The result is that we rate the restrictiveness of both approximately the same.

In addition, Cook's notation results in lower clarity. Aside from the fact that the notation itself is more difficult to read, it lacks redundancy and the conformance structure is weaker than ours. In addition parameter and return values requirements are not described. Our approach has two aspects of redundancy. First, parameters and return values are described both in the behavioral description of the message and also in parameter and return value descriptions. This ensures that their purpose is always stated. Second, our approach provides the capability to leave aspects of behavior *explicitly* unspecified. When such behavior is subsequently *specified* in refinements, the redundancy makes it easier to understand the differences. In addition, our structure is stronger because it implies substitutability. Thus we have achieved approximately the same generality and restrictiveness as Cook's approach, but improved clarity.

In addition to having a formal notation, Wills' approach *does* establish a substitutability relationship, resulting in higher restrictiveness than Cook's approach. However, it too lacks redundancy and is more difficult to read than annotated text. In addition, parameters and return value conformance is not always explicitly identified by the notation, making the information more difficult to discern. For these reasons we say it has only average clarity.

In comparison with our approach, Wills' descriptions have higher restrictiveness but lower clarity. In essence, our use of annotated text for behavioral descriptions

(as opposed to a more formal notation) has resulted in a tradeoff of restrictiveness for clarity. However, this is consistent with the goals we have identified in chapter 3. This tradeoff seems to reflect the practical issues involved in producing human readable specifications with current technology.

6.2 Conclusions

We have presented an approach for specifying Smalltalk component interfaces through the use of conformance and refinement of protocols. Our conformance relationship establishes substitutability, resulting in a stronger structuring mechanism than inheritance. This, together with our use of annotated text and specification sharing results in improved clarity over other approaches. Since our specifications are independent of inheritance, we have achieved improved generality over traditional approaches such as [Goldberg 85]. Our combination of abstract and concrete protocols provides interface designers with increased flexibility over both class based or purely behavioral approaches while combining the advantages of both. While we provide annotations for describing essential aliasing, we allow incidental aliasing to be left unspecified. We achieve lower restrictiveness than approaches such as [Wills 91] which use a more formal notation. However, we are willing to make this tradeoff in the interests of improved clarity, which we achieve. We make the following observations:

- Formal notations do not *necessarily* increase restrictiveness, as shown by our review of [Cook 92]. *What* is described is just as important as *how* it is described.
- There seems to be a tension between the use of formal notation and clarity. The challenge of specification approaches is to simultaneously achieve a high degree of restrictiveness and clarity.

- Structure can provide important information in a very concise manner, contributing significantly to clarity.
- In order to achieve a high degree of generality, implementation inheritance relationships must not be described.
- Refinement is a powerful tool for describing behavior *additively* in terms of previously described behavior.
- Substitutability is essential for simultaneously achieving high clarity and restrictiveness.
- For practical reasons, any Smalltalk specification approach must be able to describe objects of particular classes in a manner which optionally precludes substitutability.

6.2.1 Experience

The protocol model has been in use for a year now at OTI.⁷² It was developed in response to the need to produce a specification for the Smalltalk base classes independently of implementation, in order to facilitate development of applications for simultaneous deployment on Smalltalk systems from different vendors. We have produced a specification for most of the classes in the base library [OTI 92b]. In addition, we have also used the approach to specify interfaces for subsequent *independent* implementation. The latter work identified the need to resolve aliasing ambiguities through annotations.

We maintain protocol specifications in a Smalltalk object repository, and have developed tools to support editing and typesetting of specifications. We represent the components of the protocol specification with Smalltalk objects. This allows us

⁷²Object Technology International, Inc.

to ensure that specification text is *actually* shared, and facilitates the development of tools to check that the conformance rules are not violated.

Initial user response to reference manuals produced from the protocol specifications has been favorable [Adams 93]. In particular our protocol model is seen as a significant improvement over traditional approaches [Barry 93] [des Rivières 93].

6.3 Future Work

We identify the following possibilities for future work in this area.

The protocol model does not have an effective way to describe parameterization of classes. For example, we can not define a protocol which corresponds to an Array of Integers (for example) unless a class exists which has this restriction. We describe state invariants of this kind *implicitly* through the parameter specifications of messages which can change object state. Currently we must describe the fact that the Array is expected to contain integers in the behavioral description. There are complications to introducing a notion of parameterized protocols. First, a protocol which could be parameterized can not in general be related to other protocols through conformance, since the actual parameterization affects substitutability. It is for this reason that [Johnson 86] does not relate parameterized types (object types) to each other. Second, parameterization is in effect a restriction on the values an object's state variables may contain. In this sense it is a *subclass* of a class of objects. The result is that all objects in a class do not conform to the same protocols, violating an assumption that is critical to our ability to establish a one-to-one relationship between concrete protocols and classes. Nonetheless, it may be useful to find a solution to these problems.

Whether formal or informal, pre- and post-conditions are an effective way to describe the behavior of a message. The challenge is to find a way to integrate such capabilities into the protocol model without overburdening the reader with notation, or introducing too much redundancy.

We have no way to describe aliasing of second (or subsequent) level state of parameters using aliasing annotations. For example, when an Association is added to a Dictionary, the annotations do not describe the fact that only the Association's *value* field is captured by the Dictionary. This must currently be indicated in the behavioral description.

While our conflict resolution scheme (for visibility to multiple specifications for the same message) is simple and straightforward to check, there may be alternate schemes which provide additional flexibility at the expense of some additional complexity.

While we have developed tools to edit and browse specifications in the Smalltalk environment, the specification tools are still separate from the code browsing tools. Better integration with the development environment tools is needed.

A protocol based approach to specifications may lead to changes in the way *type casing* is done in Smalltalk. The currently used approach is to test a parameter for class membership, or check the position of an object's class in the inheritance hierarchy. An approach that allowed a method to test a parameter for protocol conformance is more in keeping with a behavioral specification of parameters.

Finally, our discussion of the contravariance problem with respect to specifications may have applications for implementation type systems. In cases where contravariance is a problem, perhaps *NONE* and *ANY* can be combined for parameters to messages in abstract classes in such a way that the client is told that the parameter type is *NONE* (the specification type), when really it is *ANY* (the implementation type). This would support reuse of the method by subclasses which can generalize the specification type while specializing the implementation type. If abstract classes can not be instantiated then this exception to the contravariance rule may be acceptable. A related result has been achieved by [Dodani 92], who proposes different rules for conformance between concrete classes and a restricted notion of abstract classes, which can not be instantiated.

6.4 The Final Word

Some researchers [de Champeaux 91] have argued that many everyday aspects of the object-oriented paradigm represent *informal* formal methods, and that the paradigm is itself evidence of a progression towards increased formality in software design. Whether or not this is true, software development methods that complement intuitive mental models are more likely to be successful than ones that conflict with them.

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A Appendix A: Sample Protocol Specification

<collection>
 CONFORMS_TO. <object>

Glossary Entries =====

%elements

Collections accept objects from client applications for safe-keeping, and allow clients to access the objects in various different ways. The objects held by a particular collection at any point in time are called its elements. The elements of a collection may be retrieved in various different ways for different kinds of collections, but in all cases, the elements of a collection are defined by its response to the #do message, which iterates over the elements.

Message Specifications =====

asArray

SYNOPSIS

Answer a new array whose %elements are the %elements of the receiver

DEFINITION. <collection>

This is a conversion %message. A new object conforming to <array> is created and initialized with the same %elements as the receiver. The new array has the same size as the receiver, as defined by the #size %message.

The order of the %elements in the new array is the order defined by the #do: %message for the receiver

RETURN VALUE

<array> : (new)

The new array containing the same %elements as the receiver

SEE ALSO: #()

asBag

SYNOPSIS

Answer a new bag whose %elements are the %elements of the receiver

DEFINITION. <collection>

This is a conversion %message. A new object conforming to <bag> is created and initialized with the same %elements as the receiver

The initialization is defined to be equivalent to adding the %elements of the receiver to the new object using the #addAll %message with the receiver as parameter

RETURN VALUE

<bag> : (new)

The new bag containing the same %elements as the receiver

SEE ALSO: #()

asOrderedCollection**SYNOPSIS**

Answer a new `orderedCollection` whose `%elements` are the `%elements` of the receiver

DEFINITION `<collection>`

This is a conversion `%message`. A new object conforming to `<orderedCollection>` is created and initialized with the same `%elements` as the receiver

The initialization is defined to be equivalent to adding the `%elements` of the receiver to the new object using the `#addAll: %message` with the receiver as parameter.

RETURN VALUE

`<orderedCollection>` (new)

The new `orderedCollection` containing the same `%elements` as the receiver

SEE ALSO `#()`**asSet****SYNOPSIS**

Answer a new set constructed by adding each `%element` of the receiver in turn to an empty set

DEFINITION `<collection>`

This is a conversion `%message`. A new object conforming to `<set>` is created and initialized with the same `%elements` as the receiver. Since `<set>` removes duplicate `%equal` objects, the result may have fewer objects than the receiver

The initialization is defined to be equivalent to adding the `%elements` of the receiver to the new object using the `#addAll: %message` with the receiver as parameter.

RETURN VALUE

`<set>` (new)

The new set constructed from the `%elements` of the receiver.

SEE ALSO `#()`**asSortedCollection****SYNOPSIS**

Answer a new `sortedCollection` constructed by adding each `%element` of the receiver in turn to an empty `sortedCollection`. The default `%sortBlock` is used

DEFINITION `<collection>`

This is a conversion `%message`. A new object conforming to `<sortedCollection>` is created and initialized with the same `%elements` as the receiver. No `%sortBlock` is specified. The default `%sortBlock` is used unless another `%sortBlock` is specified in a refinement.

The initialization is defined to be equivalent to adding the `%elements` of the receiver to the new object using the `#addAll: %message` with the receiver as parameter

RETURN VALUE

<sortedCollection> . (new)

The new object containing the same %elements as the receiver

SEE ALSO: # (asSortedCollection: sortBlock)

asSortedCollection discriminator

SYNOPSIS

Answer a new sortedCollection constructed by adding each %element of the receiver in turn to an empty sortedCollection. The @discriminator is used as the %sortBlock for the new sortedCollection.

DEFINITION <collection>

This is a conversion %message. A new object conforming to <sortedCollection> is created and initialized with the same %elements as the receiver. The @discriminator is used as the %sortBlock for the new sortedCollection, and must meet the requirements of a %sortBlock as specified by <sortedCollection>.

The initialization is defined to be equivalent to adding the %element of the receiver to the new object using the #addAll %message with the receiver as parameter.

discriminator <block>

The object to use as the %sortBlock for the new <sortedCollection>.

RETURN VALUE

<sortedCollection> . (new)

The new object containing the same %elements as the receiver, sorted according to the order determined by the @discriminator %sortBlock.

SEE ALSO: # (asSortedCollection sortBlock)

collect: transformer

SYNOPSIS

Answer a new <collection> which is constructed by gathering the results of evaluating @transformer with each %element of the receiver in turn.

DEFINITION <collection>

This is one of the mapping operations. For each %element of the receiver, @transformer is %evaluated with the %element as parameter. The results of these %evaluations are collected into a new collection. The default behaviour for the new collection is to have receiver's %type.

The %elements are traversed in the order specified by the #do %message for this receiver.

NOTE: The @transformer must evaluate to an object acceptable as an %element in a collection of the same type as the receiver. This is defined by the #at put message or the #add message, depending on the particular collection. This definition does not allow any such object, it is essentially abstract.

transformer <block>

The object to %evaluate with each of the %elements of the receiver as parameter.

RETURN VALUE

<RECEIVER> . (new)

An object containing the results of %evaluating @transformer with each of the receiver's %elements.

SEE ALSO `#(do inject into reject select)`

`detect discriminator`

SYNOPSIS

Answer the first %element of the receiver which causes @discriminator to evaluate to %true when the %element is used as the parameter

DEFINITION <collection>

For each %element of the receiver, @discriminator is %evaluated with the %element as parameter. The first element which results in an %evaluation result of %true is returned, and no further %elements are considered

The %elements are traversed in the order specified by the #do %message for this receiver

`discriminator` <block>

The object to %evaluate with each of the %elements of the receiver as parameter

RETURN VALUE

<object> (state)

The first %element of the receiver which causes @discriminator to %evaluate to %true

SEE ALSO `#(detect ifNone)`

`detect discriminator ifNone exceptionHandler`

SYNOPSIS

Answer the first %element of the receiver which causes @discriminator to evaluate to %true when used as the parameter to the %evaluation. If no such %element is found then answer the result of evaluating @exceptionHandler

DEFINITION <collection>

For each %element of the receiver, @discriminator is %evaluated with the %element as parameter. The first %element which results in an %evaluation result of %true is returned, and no further %elements are considered. If no %element causes @discriminator to %evaluate to %true, the result of %evaluating @exceptionHandler with no parameters is returned

The %elements are traversed in the order specified by the #do %message for this receiver

`discriminator` <block>

The object to %evaluate with each of the %elements of the receiver as parameter

`exceptionHandler` <block>

The object to %evaluate if no %element causes @discriminator to %evaluate to %true

RETURN VALUE

<object> (state)

If an %element of the receiver causes @discriminator to %evaluate to %true then the first such %element. Otherwise the result of %evaluating @exceptionHandler

SEE ALSO `#(detect)`

do. operation

SYNOPSIS

Iteratively evaluate @operation with each %element of the receiver in the receiver's standard traversal order

DEFINITION: <collection>

This %message defines the receiver's %elements

This is one of the mapping operations. For each %element of the receiver, @operation is %evaluated with the %element as parameter

Unless specifically %refined, the %elements are traversed in no particular order. Each %element is visited exactly once. Conforming protocols may %refine this message to specify a particular ordering

operation <block>

The object to %evaluate with each of the %elements of the receiver as parameter

RETURN VALUE

UNDEFINED There is no specified return value

SEE ALSO #(<collect: inject into reject select>)

includes target

SYNOPSIS

Answer %true if an %element of the receiver is %equal to @target. Otherwise answer %false.

DEFINITION: <collection>

This %message is used to test an object for inclusion among the receiver's %elements. If at least one of the receiver's %elements is %equal to @target, %true is returned. Otherwise %false is returned.

target <object>

The object to be tested for inclusion

RETURN VALUE

<boolean> (unspecified)
%true, if an %element of the receiver is %equal to @target
Otherwise %false

SEE ALSO #()

inject. initialValue into operation

SYNOPSIS

Answer the final result of iteratively evaluating operation using each element of receiver and the previous evaluation result as argument.

DEFINITION: <collection>

This is one of the mapping operations. The first %evaluation of @operation is performed with @initialValue as the first parameter, and the first %element of the traversal as the second parameter. Subsequent %evaluations are done with the result of the previous %evaluation as the first parameter, and the next %element as the second parameter. The result of the last %evaluation is returned.

The %elements are traversed in the order specified by the #do: %message for this receiver.

initialValue <object>

The object to be passed as the first parameter to the first %evaluation

operation <block>

The object to iteratively %evaluate with the result of the previous %evaluation and the next %element as parameters.

RETURN VALUE

<object> (unspecified)

The result of the last %evaluation of @operation in the traversal

SEE ALSO #(collect do reject select)

isEmpty

SYNOPSIS

Answer %true if the receiver contains no elements. Otherwise answer %false

DEFINITION <collection>

This %message is used to determine if the receiver is empty i.e. it contains no %elements. The receiver is empty if and only if it answers 0 when sent the #size %message

RETURN VALUE

<boolean> (unspecified)

%true if the receiver contains no elements. Otherwise %false

SEE ALSO #(size)

notEmpty

SYNOPSIS

Answer %false if the receiver contains no elements. Otherwise answer %true

DEFINITION <collection>

This %message is used to determine if the receiver is not empty i.e. it contains at least one %element. This %message is equivalent to (receiver size > 0)

RETURN VALUE

<boolean> (unspecified)

%false if the receiver contains no elements. Otherwise %true

SEE ALSO #(size)

occurrencesOf: target

SYNOPSIS

Answer a count of the number of %elements of the receiver which are %equal to @target

DEFINITION <collection>

This %message is used to determine how many %elements of the receiver are %equal to a given object. Note that if the receiver conforms to <set>, then the result is always 0 or 1

target <object>

The object which for which occurrences are to be counted

RETURN VALUE

<integer> (unspecified)

A non-negative value indicating the number of %element: in the receiver

SEE ALSO # (includes)

reject. discriminator

SYNOPSIS

Answer a new object conforming to the same %protocols as the receiver which is comprised of those %elements of the receiver which cause @discriminator to %evaluate to %false

DEFINITION: <collection>

This is one of the mapping operations. For each %element of the receiver, @transformer is %evaluated with the %element as parameter. Each %element which causes @discriminator to %evaluate to %false is added to the new collection.

The %elements are traversed in the order specified by the #do %message for this receiver.

Unless specifically %refined, this %message is defined to return an instance of the same %class as the receiver.

discriminator <block>

The object to %evaluate with each of the %elements of the receiver as parameter.

RETURN VALUE

<RECEIVER> (new)

An object conforming to the same %protocols as the receiver, and containing those %elements which cause @transformer to %evaluate to %false.

SEE ALSO # (collect do inject into reject)

select. discriminator

SYNOPSIS

Answer a new object conforming to the same %protocols as the receiver which is comprised of those %elements of the receiver which cause @discriminator to %evaluate to %true

DEFINITION: <collection>

This is one of the mapping operations. For each %element of the receiver, @discriminator is %evaluated with the %element as parameter. Each %element which causes @discriminator to %evaluate to %true is added to the new collection.

The %elements are traversed in the order specified by the #do %message for this receiver.

Unless specifically %refined, this %message is defined to return an instance of the same %class as the receiver.

discriminator <block>

The object to %evaluate with each of the %element: of the receiver as parameter.

RETURN VALUE

<RECEIVER> (new)

An object conforming to the same %protocols as the receiver, and containing those %elements which cause @transformer to %evaluate to %true

SEE ALSO #collect do inject into reject)

1.6

SYNOPSIS

Answer the number of %elements in the receiver

DEFINITION <collection>

This %message is used to determine the number of %elements in the receiver

RETURN VALUE

<integer> (unspecified)

The non-negative integer count of the number of elements in the receiver

SEE ALSO #(isempty)

END

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FIN