

Beyond Object-Oriented Technology: Where Current Object-Oriented Approaches Fall Short

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ABSTRACT

Object-oriented (OO) technology has been heralded as a solution to the problems of software engineering. The claims are that OO technology promotes understandability, extensibility, evolvability, reusability, and maintainability of systems, and that OO systems are easy to understand and use. However, this technology has not been as successful as expected. An analysis of experiences and empirical studies reveals that the problem is not the technology per se, but rather that the technology provides no support to software developers in performing the processes the technology requires. We present a cognitive model of software development that details the challenges software developers face in using OO technology. The model focuses on three aspects of software development: evolution, reuse and redesign, and domain orientation. We motivate this model with a variety of first-hand experiences and use it to assess current OO technology. Further, we present tools and evaluations that substantiate parts of this model. The model and tools indicate directions for future software development environments, looking beyond the technological possibilities of OO languages and beyond the context of individual developers and projects.

TABLE OF CONTENTS

1. INTRODUCTION	1
2. A COGNITIVE MODEL OF OBJECT-ORIENTED DEVELOPMENT	2
3. EVOLUTION IN OO SOFTWARE DEVELOPMENT	6
3.1. WHERE CURRENT OO TECHNOLOGY FALLS SHORT	6
3.2. BEYOND OBJECT-ORIENTATION.....	8
3.3. REFERENCE AND HIERARCHY FACTORS: METRICS TO SUPPORT EVOLUTION	9
4. REUSE AND REDESIGN	12
4.1. WHERE CURRENT OO TECHNOLOGY FALLS SHORT	12
4.2. BEYOND OBJECT-ORIENTATION.....	14
4.3. EXPLAINER: A TOOL TO SUPPORT REUSE AND REDESIGN	15
5. DOMAIN ORIENTATION	18
5.1. WHERE OO TECHNOLOGY FALLS SHORT	18
5.2. BEYOND OBJECT-ORIENTATION.....	20
5.3. KID: A TOOL TO SUPPORT DOMAIN-ORIENTATION.....	23
6. CONCLUSIONS	25
NOTES	26
ACKNOWLEDGEMENTS	26
AUTHORS' ADDRESSES	26
REFERENCES	26
FIGURES	32

1. INTRODUCTION

Object-oriented (OO) technology has been heralded as a way to make software development easier, faster, and more reliable (CACM, 1990, 1992). Among the claimed software benefits of OO technology are understandability, extensibility, evolvability, reusability, and maintainability, all of which are technically well motivated. The basic OO principle of encapsulating data and procedures into a single unit, the “object,” with a well-defined interface facilitates many of the above objectives (Meyer, 1987). Object libraries can evolve and be made available to designers, allowing designers to build new applications from proven constructs in the library. Languages such as C++, Smalltalk, and CLOS are at the forefront of such work today. Furthermore, object libraries can build upon one another to support a layered architecture and thus reduce the conceptual distance between a problem and its solution (Fischer & Lemke, 1988). OO technology allows software developers to choose objects that directly model problem domain concepts, resulting in systems whose structures more nearly correspond to that of problem domains (Rosson & Alpert, 1990). This has led to what is termed a “seamless” approach to OO development: the structures that are identified during analysis are often carried through into design and implementation (Henderson-Sellers, 1992).

Despite these claims, the collective experience of the authors (as well as that of others) has revealed that current OO technology fails in practice to achieve all its claimed benefits. Central to understanding this shortfall is Brooks’s well-stated observation that software technologies have focused too much on the “accidents” (or software artifacts) and not enough on the “essence” (or human creative resource) of software engineering (Brooks, 1987). Software technologies support the downstream activities (e.g., translation of specification and programming languages) but not the upstream activities (e.g., problem analysis and selection of abstractions) (Swartout & Balzer, 1982). These introductory observations indicate the need for an analysis of OO technology that focuses on the needs of the *human* software developers (Fischer 1987) more than on the formal properties of classes, instances, and inheritance (Stefik & Bobrow 1986). We present such an analysis based on a human-centered model of software development that has grown out of our diverse academic and industrial experiences. The specific model we describe incorporates elements of evolutionary design, reuse and redesign, and domain orientation. The model is a cognitive theory of software development in the sense that it focuses not on the technical accommodation of software objects but on the accommodation of the human developers in their interaction with the software objects. This point of view leads us to address questions such as: (1) What processes of software development are difficult for people? (2) Which processes can be supported by tools, and how? (3) What evidence supports

this particular model? (4) How do existing OO technologies compare? (5) How do prototype tools we have developed perform?

In developing our model, we relied in part on our varied academic and industrial experience and case studies that span many years, projects, and settings. Although such evidence lacks the rigor of highly structured experiments, it also lacks the experiments' artificiality. The use of anecdotal evidence, although uncommon in cognitive psychology, is common in engineering disciplines. An example is the use of critical incidents for product safety and the use of design failures in civil engineering (Petroski, 1985). The reader should also bear in mind that some of the analysis is from areas outside of software development, and the model is more one of general design than one of OO programming. OO technology presents not simply a new way to program, but a new way for people to think about problem domains. The gravest cognitive challenges are not in the downstream activities of programming but in the upstream activities of analysis and abstraction, as noted above. Analogies to other areas in which objects have long been a medium of problem solving should not be overlooked (Simon, 1981, pp. 200-203).

The experiential evidence is used to motivate our model. Together with the model, it provides a framework for assessing where current OO technology falls short of its promise. Our assessment of OO technology may seem negative at times, especially with the subtitle "where current approaches fall short." This emphasizes our belief that much can be learned by analyzing failures. We believe that OO technology is an enabling technology and have argued so in the past (Aoki, 1993; Ward & Williams, 1990b; Fischer, Lemke, & Rathke, 1987). Addressing its shortcomings widens the scope of problem situations in which the technology may be applied.

The remainder of the paper is organized as follows. Section 2 presents a model of OO development that emphasizes evolution, reuse and redesign, and domain orientation. Sections 3, 4, and 5 explore in detail how OO technology addresses each of these concepts, respectively. Each section presents the rationale behind the claim, summarizes empirical and experiential evidence bearing on it, and assesses where current OO technology is with respect to meeting its promise. Each section concludes with a description of our approach and a prototype method or tool that moves us beyond the current technology. Section 6 presents a summary and draws some general conclusions.

2. A COGNITIVE MODEL OF OBJECT-ORIENTED DEVELOPMENT

Software development requires a developer to transform a general, informal understanding of a goal into a formal model using operators and components interpretable by the computer. Many cognitive models focus on this process from the perspective of the cognitive processes internal to a developer. For example, they focus on models of how software

developers might retrieve and apply plans and schemas (Adelson & Soloway, 1985; Rist, 1989) or bring to bear other knowledge for software comprehension (Pennington, 1987). Although these models make an important contribution to our understanding of individuals, the process of software development is a cooperative process among many individuals and different kinds of artifacts. With respect to reuse, we have recognized that this cooperation can span long time intervals as well, raising many issues related to the evolution of software objects (Fischer et al., 1993a). This point of view gives rise to a cognitive model that emphasizes a longer period of time and focuses on the interaction of the human players with the artifacts involved (Hutchins 1993; Norman 1993).

Design methodologists (Rittel, 1984; Schoen, 1983) have emphasized the need for *integrating problem framing and problem solving*. They have argued convincingly that one cannot gather information meaningfully unless one has understood a problem, but one cannot understand a problem without information about it. For instance, Curtis and colleagues observed that the predominant activity in designing complex systems is the participants' teaching and instructing each other--that *understanding the problem is the problem* (Curtis, Krasner, & Iscoe, 1988). Because complex problems require more knowledge than any one person possesses, communication and collaboration among all the involved stakeholders are necessary (Ehn, 1988; Greenbaum & Kyng, 1991). Professional practice has at least as much to do with defining a problem as with solving a problem. New requirements emerge during development because they cannot be identified until portions of the system have been designed or implemented (Fischer & Reeves, 1992). The conceptual structures underlying complex software systems are too complicated to be specified accurately in advance, and too complex to be built faultlessly (Brooks, 1987). Specification and implementation have to co-evolve (Swartout & Balzer, 1982), requiring a tighter integration of the frequently separated stages of software development (analysis, design, specification, and implementation). Thus, evolution occurs as feedback from partial solutions improves the developers' understanding of the problem.

The above considerations on cognitive processes and design theories have led us to develop a cognitive model of OO development. The model focuses on three aspects of object-oriented development: (1) *evolution*, (2) *reuse and redesign*, and (3) *domain-orientation*. Figure 1 is used as a basis to explain this focus. The diagram includes three types of object-oriented software components: (1) *specific projects* that are composed of instances of objects; (2) libraries of object *classes* from which instances are made; and (3) *frameworks* that define recurring patterns of interaction between classes of objects, potentially classes from different libraries (see Deutsch (1983) and Johnson and Foote (1988) for descriptions of these terms).

Figure 1 illustrates that, in our model, evolution is driven by software developers reusing and redesigning software components in the context of successive software development efforts.

The arrows are transformations initiated by software developers. Solid-tip arrows represent the creation of new software components and hollow-tip arrows represent reuse and redesign. It is in examining the software developers' involvement in these processes that the model becomes a cognitive model.

INSERT FIGURE 1 ABOUT HERE

For purposes of illustration, we use an adaptation of the problem of developing a temperature sensing system. This example was introduced by Young (1982) and further developed by Ward and Williams (1990a). The problem situation is that a temperature sensor measures the temperature of a number of furnaces and reports those measurements to a host computer. The temperature of each furnace is obtained by periodically reading a digital thermometer. A framework of the example is diagrammed in Figure 2.

INSERT FIGURE 2 ABOUT HERE

In our model, illustrated in Figure 1, *evolution* implies that software components are expected to change over time; that is, class definitions may be refined with respect to their attributes and methods, and libraries may be repartitioned to contain different classes. Our model stresses that these changes are driven by successive software development projects; the evolutionary scale in Figure 1 is measured by a progression of projects (see also Berard, 1993). A successive project could be a revision of an earlier one or a new development in the same domain. For instance, in Figure 1, Project A might be the development of a system for the temperature sensor problem illustrated in Figure 2. The classes Digital Thermometer and the Sensor would be developed; Digital Thermometer would have instance methods for reporting temperature and Sensor would have instance methods for requesting and interpreting temperature readings from thermometers. With this one project, all the classes might be placed in a single class library, such as Classes A in Figure 1. A new project might be to adapt the sensing system to work with analog thermometers. (Strictly speaking, the digital thermometer device would also have an analog component. However, we will use the digital-analog distinction for simplicity in denoting two thermometer device types requiring different software interfaces.) The software developers might choose to generalize the framework to have a Thermometer class with subclasses Digital Thermometer and Analog Thermometer; the two thermometers might have, for instance, different communications requirements, and hence need different attributes for buffers and methods for reading. Although a single project is not always sufficient for generalizing patterns of class interaction, together Projects A and B yield a common framework illustrated in Figure 2 and corresponding to Framework B in Figure 1.

Reuse means that existing software components can be incorporated into the solutions of new problems, and *redesign* means that some existing components might be adapted to fit new problems (Fischer, Lemke, & Rathke, 1987). In Figure 1, the downward arrow pointing to Project B is used to illustrate that some classes from the previous project may be reused. In our example, the Sensor class was reused and did not change. The upward arrow leading from Project B is used to illustrate a synthesis of new classes such as Analog Thermometer and Thermometer and the redesign of the former class Digital Thermometer to be a subclass of the new class Thermometer. A further redesign might be that all the Thermometer classes are partitioned into their own class library, Classes B, leaving the modified class library, Classes A'. Reuse and redesign go hand in hand with evolution: components evolve so that they may be reused in other contexts, and the reuse and redesign of those components leads to further evolutionary changes, which in turn, support continued reuse.

Finally, *domain orientation* means that all of the software components--frameworks, classes, and instances in projects--are grounded in specific problem areas. In our model, completed projects yield a conceptualization of a domain; they provide the basic abstractions of a domain in terms of classes and frameworks. As more projects are implemented and the coverage of a domain increases, software developers have the sense that they are interacting with the domain itself rather than with low-level computer abstractions. An ideal is that problem experts can manipulate software components directly, bypassing computer software developers who heretofore have acted as middle-men; systems become *end-user modifiable* (Fischer & Girgensohn, 1990). In the example, managers in a steel mill would be able to configure the complete monitoring systems themselves, selecting among concepts (classes) such as Analog Thermometer or Digital Thermometer. This kind of human-computer interaction is termed *human problem-domain communication* (Fischer & Lemke, 1988). A perspective of domain-orientation also clarifies the relationship among software components: there may be project- or problem-independent components but there are no domain-independent components, classes and frameworks exist to serve different designs.

This general model of software development using OO technology provides a context for the discussion that follows, and allows us to explore human cognitive requirements with respect to evolution, reuse and redesign, and domain-orientation. Current OO development technologies have made claims related to these three concepts including: (1) OO systems support software evolution, extension, and/or modification; (2) OO systems are reusable and easily constructed from existing components; and (3) OO systems are understandable to domain experts (users) and developers. The following three sections explore each of these concepts and claims in turn. Figure 3 provides an overview of these sections.

INSERT FIGURE 3 ABOUT HERE

The model aspects and corresponding prototypes are not related in a simple orthogonal relationship. Instead, we see that evolution subsumes reuse and redesign in the sense that the latter two processes make sense only over the development of several projects, and at the same time, reuse and redesign drive evolution. Finally, domain-orientation permeates all activities because software components cannot be understood or developed independent of the problem they are designed to solve.

3. EVOLUTION IN OO SOFTWARE DEVELOPMENT

The first claim in Figure 3 concerns the extensibility and evolvability of OO systems. Several points indicate that OO systems can evolve to support changes in requirements and business environments. First, class definitions can be easily extended through inheritance (specialization). For instance, in the temperature sensor example, suppose the abstract class Thermometer existed with one subclass Digital Thermometer. A subsequent project that needed an Analog Thermometer could easily be accommodated by adding it as another subclass of Thermometer. Second, OO systems are easy to extend or modify due to their understandability. The more understandable OO components are, the easier to change such components for both users and developers. Third, changes can (theoretically) be localized in an OO system without dramatically affecting other parts of the system because objects are loosely coupled encapsulations of data and behavior.

3.1. Where Current OO Technology Falls Short

A case study of the development of an OO Computer-Aided Software Engineering (CASE) tool illustrates the natural evolution of OO components and the lack of support for this evolution. The study is described in more detail elsewhere (Aoki, 1993, 1992). The project involved the development of MEI, a CASE tool in Smalltalk-80 (Goldberg & Robson, 1983). MEI supports various OO analysis and design methods and notations. It also includes object repositories and 3D graphical libraries. The project was undertaken by a large Japanese software company over a two-year period. The project team included ten members with OO experience ranging from one to ten years. The completed program contained 700 classes and 14,000 methods.

Over the course of the development effort, four kinds of changes were identified: (1) refining existing classes, (2) abstracting from existing classes, (3) composing classes from existing components, and (4) decomposing classes into new components. The evolution of components proceeded in a bottom-up fashion. Initially, the development group identified low-level classes. As the number of low-level classes grew, it was common to examine them for

common patterns of structure and behavior, and then to create abstract superclasses that captured the commonalities and reduced redundancies in the subclasses. In addition, as classes became larger and more complex, the developers would often decompose them into smaller classes. These decomposed classes then became candidates for further refinement and abstraction. Of the four modification processes identified in this project, only refinement and, to a lesser extent, composition were directly and easily supported in Smalltalk. Abstraction and decomposition were not. Furthermore, in discussing problems with developing classes, it became apparent that many developers were proceeding in a bottom-up fashion because they had difficulty thinking abstractly. Additional developers who had extensive theoretical mathematics backgrounds were brought in. They were able to help identify classes that should be abstracted for more general library usage.

Other researchers have made similar observations about the evolvability of OO systems and the extent to which current OO environments support evolution. Lubars and colleagues (1992) reported a case study aimed at assessing evolution in an OO system. They developed an OO requirements specification for an automated teller machine and then examined the effects of various types of changes on the specification. Their conclusion was that extensibility is not free. Changes must be anticipated and objects structured accordingly. The simple guidelines provided by current OO methods do not adequately support the task of identifying and building objects that are extensible. Lubars and colleagues pointed out that “reliance on simple guidelines and strategies from methods textbooks may ... cause the analyst to miss reuse opportunities and *make the model more difficult to change*” (Lubars et al., 1992, p. 184, emphasis added).

Opdyke and Johnson (1989) discussed many evolutionary changes that are common in the development of OO application frameworks. They noted that “object-oriented software is harder to change than it should be” because many of the changes involve “changing the abstractions embodied in *existing* object classes and the relationships among those classes” (Opdyke & Johnson, 1989, p. 146). Some of these common changes, which are tedious, difficult, and/or error-prone in OO environments, include: (1) creating an abstract class for one or more existing classes, (2) changing an existing relationship between objects from an inheritance (generalization/specialization) to an aggregation (component) relationship, and (3) moving a class from one inheritance hierarchy to another.

As these observations illustrate, current OO environments support evolution through refinement, but fall short in their support for many other evolutionary processes. There is a need for a better understanding of the processes involved in evolution and tools to better support these processes.

3.2. Beyond Object-Orientation

Our model of OO development (Figure 1) emphasizes the importance of component evolution across multiple projects. In our experience, components evolve through four key processes: *refinement*, *composition*, *abstraction*, and *factorization*. These are illustrated as an on-going cycle in Figure 4 and are explained below.

INSERT FIGURE 4 ABOUT HERE

Software developers can *refine* an existing class by subclassing it and adding to its properties and behaviors, its slots and methods. In our example, the notion of a thermometer was refined by creating a class, Thermometer, with subclasses, Digital Thermometer and Analog Thermometer.

Developers can *compose* a new class from existing classes by referencing other classes. For example, both analog and digital thermometers would contain an analog component but could have different buffering and communications components. In object-oriented languages that support composition, the Analog Thermometer class could be composed of the classes Analog Component and Analog Type Buffer; the Digital Thermometer class could be composed of the classes Analog Component and Digital Type Buffer.

Software developers can *abstract* classes when they identify commonalities in behaviors and properties among existing classes. For instance, had the two classes of thermometers developed independently, a software developer might create the class Thermometer to contain common properties, such as the Analog Component, and pass this property to Digital Thermometer and Analog Thermometer through inheritance. Abstraction aims at reducing redundant coding and improving comprehensibility, reusability, and maintainability.

Finally, developers can *factor* classes by partitioning the properties and methods of an object into simpler, more cohesive (and presumably more reusable) components. The original class behavior and structure are maintained; composition recombines the capabilities. However, the newly derived classes now may be shared among other classes. Proposing the classes Analog Component and Analog Type Buffer as components of thermometers is an illustration of factoring. A class for representing a pressure monitoring device could, for example, reuse the Analog Type Buffer.

We see the support for evolution through the four operations as a critical aspect of OO development that is not adequately supported with current OO programming environments or existing OO analysis and design methods. The following section describes a measurement model developed to help support OO class evolution.

3.3. Reference and Hierarchy Factors: Metrics to Support Evolution

Over the course of a single, long-term project or several projects, software developers can redesign class libraries and frameworks using the four evolution operations described above. A key issue is how developers know when to apply or whether they have appropriately applied these operations. To support software developers with issues of component evolution, we developed two metrics, the reference factor and the hierarchy factor, described below. Roughly, these metrics can classify object classes according to their appropriateness as library or application components. Library components correspond to supporting domains (discussed in Section 5.2). A class library is a repository for abstract classes that provides high reusability across multiple application domains. Application components correspond to dominant domains (discussed in Section 5.2). Applications consist largely of concrete, instance-level objects and can form a basis for reuse by being placed in a catalog of examples.

To support software developers in producing and evolving the two types of object repositories--class library and application catalog--we developed two metrics and constructed a tool that analyzes objects under development. The *reference factor* (RF) measures the degree of composition and decomposition, and the *hierarchy factor* (HF) measures the degree of refinement and abstraction. Figure 5 presents definitions and examples of RF and HF. The values of RF and HF range from 0 to 1. Low RF and HF values indicate that the classes have library-like characteristics with high reusability and should be stored in a class library, and high RF and HF values indicate that the classes have application-specific characteristics and should be stored in a catalog as specific examples.

INSERT FIGURE 5 ABOUT HERE

The reference factor is defined in terms of the total number of classes in reference paths and the rank order of a class in the partially ordered reference sequence (see Figure 5a). Composition and decomposition are interdependent; if a class is better modularized, more classes will use it. Also, better decomposition can be achieved when similar structures or behaviors are found in a large number of classes. Both the composition and decomposition processes deal with “has-a” or “part-of” relationships, which represent the reference structure. The metrics for the composition and decomposition are quantified from this class reference structure. The value of an RF is between 0 and 1, and becomes smaller when the class is referenced by many classes but does not reference other classes.

The hierarchy factor is a metric for the refinement and abstraction of a class, and is defined in terms of the number of its superclasses and subclasses (see Figure 5b). Refinement and abstraction are interdependent; the better a class is abstracted, the easier it is to refine to a

concrete class. Both the refinement and abstraction processes deal with “is-a” and “is-kind-of” relationships, which represent the class hierarchy. The metrics for the refinement and abstraction are quantified from this class hierarchy. The value of an HF is between 0 and 1, and becomes smaller as the class becomes more abstract.

A tool was built that graphically presents the results of applying the metrics to Smalltalk-80 classes (Goldberg, 1984). The metrics were also applied to the project for developing a CASE tool in the Smalltalk-80 environment, called MEI, discussed earlier (Aoki, 1992). Figure 6 shows the results of applying the metrics to the principal classes of Smalltalk-80: HFs, RFs, the rank orders of topological sort, and names of classes that refer each class. Figure 7 illustrates the correlation between HF and RF; the horizontal axis represents HF and the vertical axis represents RF. Figure 7a shows the distribution of the standard Smalltalk-80 classes plotted according to their HF and RF values. Figure 7b shows the distribution of classes in the MEI project plotted according to their HF and RF values. Average RF and HF values for both situations are also shown.

INSERT FIGURE 6 ABOUT HERE

INSERT FIGURE 7 ABOUT HERE

In the graphs of Figure 7, dots that appear in the top left corner represent classes that have high abstraction with high reusability, and dots that appear in the bottom right corner represent classes that are relatively concrete and application-specific. As this figure clearly illustrates, the standard Smalltalk-80 classes (Figure 7a) have stronger characteristics as a library, whereas classes created during the MEI project have stronger characteristics as an application (Figure 7b). Classes plotted outside of the shadowed area in Figure 7b are those that have been created during the MEI project and will be stored in a class library in the future because they have high-level abstraction.

Two general findings from an analysis of the MEI project data are that: (1) there are several types of object evolution paths, and (2) there are two general types of programmers. Figure 8 illustrates six types of class evolution paths that were identified. The metric values for example classes are provided in Figure 6.

INSERT FIGURE 8 ABOUT HERE

1. **A (Initial Stage):** Newly created classes usually belong to the area A in Figure 8 because they have no subclasses.

2. **A to B:** Classes such as Array, Byte String, and Point have become equipped with basic behaviors or structures, and thereby are not divided into subclasses, but are used by other classes. Their HFs have remained large and their RFs have become smaller, shifting them toward area B in Figure 8. Classes in this area are basic library classes, containing well-refined concrete classes.
3. **A to D:** The class Collection has become equipped with abstract behaviors and a large number of subclasses created through refinement. Because the abstract class does not have its own instance variables, it does not use other classes as components and other classes do not use it as a component. Thus, both its HF and RF have become smaller, shifting it toward area D in Figure 8.
4. **A to F, D to F:** The class BitBlt references other classes as components by deeply nesting them and has a high degree of abstraction. It has many subclasses such as Pen, and reference components such as Form and Path, which in turn further reference other objects. Thus, its HF has become smaller and its RF has stayed relatively large. The class is regarded as an abstract application library class.
5. **D to E:** The class Object initially had no instance variables and was a typical abstract class with a quite small HF and a relatively small RF, such as Collection contained in D. Through the development processes, the abstraction of its behaviors has progressed, it has started to reference many other classes as components, and its RF has become larger.
6. **A to C:** Classes such as SystemDictionary, CodeController, and CodeView were application-specific complex objects, with a high degree of refinement and composition. Their HFs have stayed very large and their RFs have gotten larger, shifting to area C.

In addition to these evolution paths, we plotted the classes in the Figure 7b using different colors (not shown) for the different project members authoring the classes. This analysis identified that each project member has typical patterns in creating and evolving classes. Project members were divided into two main types: class-library-developers and catalog-developers. Figure 9 illustrates the two types.

INSERT FIGURE 9 ABOUT HERE

Classes created by class-library-developers include many abstract classes (Figure 9a). The project members in this group were interested in models, paradigms, methodologies, and

theories, and were good at creating highly abstract meta-level systems. They were more interested in creating classes for a general library than in creating classes specific to a particular problem domain. Classes developed by catalog-developers (Figure 9b), in contrast, were mainly concrete classes. The members in this group were interested in styles, modes, and look-and-feel paradigms. They were interested in creating a number of application examples using class libraries and in improving and expanding basic classes created by others.

This early analysis of the metrics tool suggests that the metrics can be used to distinguish library from application-specific classes, to plot the evolution of classes over time, and to distinguish library component developers versus application component developers.

4. REUSE AND REDESIGN

One of the biggest claims of OO proponents is that OO components and systems are highly reusable (see Figure 3). The promise of reuse is that we can achieve "plug-compatible" systems, reduced development time, and improved quality. Current OO programming languages, such as Smalltalk, provide a library of reusable classes, which can drastically reduce programming time. In addition, off-the-shelf OO frameworks can be purchased that support OO design and programming in particular problem domains. Specific features of OO languages also promote reusability, albeit at a lower level of detail (Stefik & Bobrow, 1986). Inheritance makes it possible for a subclass to share, or reuse, methods and variables defined in its superclass. Polymorphism makes it possible for objects of different classes to respond to the same message. Being able to send the same message to objects of different classes means that a given class will be usable in several different contexts. Meyer (1987) has argued that OO design promotes reuse because the categories of objects the system deals with are relatively stable even though the functionality required may change over time. Thus, in a system whose organization is based on objects, a change in functionality will not necessitate a major reorganization of the software as it might in a system based on functional decomposition. Typically, any changes will be localized to a few classes.

4.1. Where Current OO Technology Falls Short

An analogy can be made between software component reuse in a high functionality programming environment and hardware component reuse in a large hardware store. One study investigated a large hardware store with more than 300,000 "components" (Fischer & Reeves, 1992). The store provides customer assistance for locating items in the following manner: as customers enter the store, they are helped by floor managers who direct them to specialty aisles and once in a particular area the customers are aided by specialty assistants. For example, the plumbing supplies are attended by assistants experienced as plumbers. The managers and

assistants, through background knowledge and experience, are able to anticipate and support customers in defining problems and working out solutions. The components themselves are part of the problem-solving effort, with customers and assistants using them in positive and negative deictic references. Problems are solved through cooperative refinement by the application of problem- and domain-specific knowledge and plans, and through the media of the components involved. Potentially this cooperation can be established between a problem solver and a computer system.

The strategy of employing specialized domain experts (e.g., in plumbing, lighting, etc. in the hardware store) is successful for several reasons: (1) the experts provide location support and are able to help customers find the right item(s); (2) the experts provide comprehension support and allow the customers to focus on describing their problems, and then they provide and explain the solution; and (3) this focus on the problem and communication with the assistants reduces the likelihood that a customer will be overwhelmed by the abundance of available items. This is a very different strategy than that employed by other high-volume stores, where there is an abundance of "components" and only limited support for locating and understanding which components are needed for the task at hand.

Other researchers have studied reuse in high-functionality systems. Smalltalk-80, for example, has 670 classes and more than 6000 methods. Empirical studies (Draper, 1984; Fischer, 1987; Nielsen & Richards, 1989) have shown that developers do not exploit the power of such high functionality systems. Lange and Moher (1989) performed an intensive one-week field study of a professional software engineer with considerable experience in OO development. The researchers found that the engineer's dominant reuse strategies were to reuse by inheritance and to reuse by copying source code from a sibling class as a template. The engineer was very familiar with the class library and consequently was often able to recall the name of a particular class a priori and locate it in the hierarchy easily. However, even when the engineer could name a class a priori, she did not often remember method names, leading to a more ad-hoc search within classes for reusable methods. The researchers also observed "comprehension avoidance" strategies in which the engineer tried to avoid getting into the details of methods, and instead tried to modify and test methods to assess their reusability for her task.

Despite the promise of reuse in OO development, systematic reuse on a large scale is not being realized (Krueger, 1992). Part of the problem is that the *existence* of high functionality (i.e., reusable components) does not guarantee the *use* of that functionality. This may be because developers do not know what reusable components exist, how to access them, how to understand them; and/or how to combine, adapt, and modify them to meet current needs (Fischer, 1987). Current OO programming languages provide only simple tools such as Smalltalk's Class Hierarchy Browser (Goldberg & Robson, 1983) for locating reusable classes and methods. As

Nierstrasz and colleagues have noted, "effective reuse of software presupposes the existence of tools to support the organization and retrieval of components according to application requirements, and the interactive construction of running applications from components" (Nierstrasz, Gibbs, & Tsichritzis, 1992, p. 160).

Another problem is that current OO analysis and design methods do not adequately support reuse within the software development process. The reuse process involves two steps: (1) composing new systems from existing components, and (2) developing components that can be reused in future systems. However, the current OO methods often assume that new systems are developed from scratch (Nierstrasz, Gibbs, & Tsichritzis, 1992), and reuse happens sometime during implementation. Although some OO researchers (e.g., Johnson & Foote, 1988) emphasize that classes must be designed for reuse and offer guidelines to promote reusability, none of the popular OO methods emphasizes this point. Reuse is not something "tacked on" at the end of software development; it must be integrated throughout the evolutionary development process (Fischer & Girgensohn, 1990).

4.2. Beyond Object-Oriented

Reuse and redesign are key aspects of our model of OO development (Figure 1). The observations of the preceding section illustrate several difficulties with respect to reuse. First, locating reusable components in a high-functionality environment (computer-based or not) can be challenging, even when the user is familiar with much of the existing functionality. Retrieval mechanisms that demand that the name of the component and/or its place in the class hierarchy be known a priori are insufficient for the location task. Second, users are reluctant to invest the time to thoroughly understand components once they are located. In the hardware example, the store assistants provided a buffer for the customer. Customers could talk about the desired functionality (in problem-oriented terms) and assistants would provide a component or alternative components that could meet the need. In Lange and Moher's (1989) study, the engineer did not attempt to understand everything that the component did and how it accomplished tasks. Instead, she ran various tests on the component to see if it would perform the needed functionality. Third, as components are reused, they are often modified (redesigned), that leads to further component evolution. But as described earlier, many types of modification are not easily supported in existing OO environments. These three aspects of reuse and redesign--location, comprehension, and modification--are illustrated in Figure 10 (Fischer, Henninger, & Redmiles, 1991; Biggerstaff & Richter, 1987).

INSERT FIGURE 10 ABOUT HERE

The reuse and redesign model in Figure 10 applies to various kinds of software components or artifacts, such as subroutines in a structured programming environment, classes in an OO environment, and/or existing design examples. In some of our studies, we explored the reuse of examples of previous design solutions (Fischer, Henninger, & Redmiles, 1991). After finding a potentially useful example, a software developer is expected to explore it more carefully to build an analogy between the example task and the current task or design goals. The location, comprehension, modification cycle would be applied to a catalog of completed projects and not just the classes implemented on one project. For instance, a software developer might study the temperature sensing system as an example to develop a system to monitor pressure. A hypothesis is that the designer learns by analogy from the example how to develop a system for the current task. The model of Figure 10 helps identify where in the reuse and redesign process tools can add support to software developers.

Current OO environments provide little support for these reuse processes. What is needed is an approach analogous to that of the high-functionality hardware store described earlier - tools more explicitly support the problems of location, comprehension, and modification (Neighbors, 1984; Prieto-Diaz, 1991; Rosson, Carroll, & Sweeney, 1991). The next section discusses EXPLAINER, a tool that specifically supports the comprehension of reusable objects.

4.3. EXPLAINER: A Tool to Support Reuse and Redesign

Reuse and redesign require software developers to locate, comprehend, and sometimes modify software components, as illustrated in Figure 11. Comprehension is central in this cycle as it provides a basis for judging the relevance of components during the location step and, later, for modifying a retrieved component. In studying reuse and redesign, we developed the EXPLAINER tool for helping software developers understand software components through examples (see Figure 11).

INSERT FIGURE 11 ABOUT HERE

The domain of EXPLAINER is a Lisp library of graphics functions. Although the LISP example code is not object-oriented, it does rely heavily on modules imported from the graphics library. What can be learned from the evaluation of EXPLAINER is how software developers can be helped in understanding software components through the use of examples. In principle, this is the same problem software developers face when attempting to understand classes and frameworks developed by others. Although previous work has evaluated the usefulness of examples generally in helping people learn programming concepts (Pirolli & Anderson, 1985; Kessler & Anderson, 1986), EXPLAINER focuses on specific principles of explanation using multiple perspectives and programming plans.

A programmer would engage the EXPLAINER tool after a relevant example is identified. Tool support for locating and modifying examples has been explored in previous work (Fischer et al., 1993a; Fischer, Henniger, & Redmiles, 1991). The EXPLAINER interface is implemented as a hypermedia tool (see Figure 11). This implementation allows minimal information about an example to be initially presented (Fischer et al., 1990; Black, Carroll, & McGuigan, 1987). The programmers can then decide which specific features of the example they want to explore, presumably choosing those most relevant to their current task. Information is accessed and expanded through the command menu (middle of Figure 11).

The interface presents multiple presentation views of the information comprising an example: code listing, sample execution, component diagrams, and text. These views are initially selected for EXPLAINER due to their popularity in existing computer-aided software engineering (CASE) tools (Sodhi, 1991). Unique to EXPLAINER is the characteristic that the same information is presentable in different views. Within each view, the programmer can access information from different representation perspectives. For instance, text has been presented from Lisp, Program Features, and Cyclic Operations perspectives (lower right of Figure 11).

The EXPLAINER interface allows programmers to access information about the programming plans (Pennington, 1987; Soloway et al., 1988) behind the example through different views and from different perspectives. Highlighting and textual descriptions allow programmers to understand the relationships between elements of programming plans and system components. This specific information enabled the test programmer to identify the Lisp function called to draw the label, the assignment function that calculated the position, and what variables the position calculation depended on. The programmer could then apply the same functions in a solution to a new task.

The empirical evaluation of EXPLAINER tested three conditions under which subjects solved the programming task of drawing a clock face (see Figure 12). In all three conditions, programmers were given the same example, a program illustrating operations in a cyclic group (see Figure 11). The conditions varied the programming tool that the three groups of subjects worked with to help them understand the example. In the first condition, subjects worked with the EXPLAINER tool as described above. In the second condition, subjects also worked with the EXPLAINER tool but the interactive menu was deactivated (the example information was fully expanded when subjects began the test). In the third condition, subjects worked with a commercially available, searchable on-line manual that contained descriptions of all the functions used in the example. The purpose of the intermediary second condition was to determine if only the difference in information content between EXPLAINER and the on-line manual affected the results.

INSERT FIGURE 12 ABOUT HERE

The evaluation measured the performance of programmers with respect to variability in two senses. First, a notion of "directness" was defined as the number of different variations programmers would try in solving a task. The rationale was that the more support the programmers had from the example and tool in solving the task, the lower the number of trial and error variations would be. The observed measures are defined below, and these are compared across groups. Second, within each group the variance in the observed measures is calculated and then compared across groups. The rationale with this test was that the more support the example and tool combination provided, the more uniform (smaller variance) the programmers' behavior as measured would be within a condition.

Eight subjects were tested for each condition and were randomly assigned to conditions. The subjects all had roughly the same background knowledge in LISP programming (being recruited from masters-level artificial intelligence classes in computer science) and little familiarity with the graphics functions required by the task.

Detailed values and comparisons of the results are available elsewhere (Redmiles, 1992). We present a brief summary of the results here. As a group, the subjects using EXPLAINER performed the programming task more directly and with less inter-subject variability than the subjects using the on-line documentation tool. The latter group proceeded in a trial-and-error fashion and, not surprisingly, exhibited great inter-subject variability. It is important to note that the reduction in variance was not at the cost of performance. The "better" values for the various measures were similar across conditions--good performers were about the same in all conditions. The reduction in variance derives from the "worse" values coming closer to the "better" in the condition that used the Explainer tool--otherwise poor performers were helped by EXPLAINER.

The variability of the programmers' performance in the on-line documentation group is consistent with other studies of programmers (see the survey by Egan, 1991). Furthermore, the provision of an example by itself was insufficient to prevent this variability, as also observed by Kessler and Anderson (1986) and noted earlier. However, the provision of an example, supplemented by information constituting a representation of a programming plan and with a means of exploring the relationship of the programming plan to a specific example solution, did stem the variability. Programmers who needed to compensate for variation in background knowledge, skill, or other predispositions, were supported by the EXPLAINER tool and approach.

The kind of support that the EXPLAINER tool provides is critical to supporting software reuse and redesign. Increasingly, software developers are called upon to apply software

components they did not author. Comprehension tools support collaboration between developers who never meet.

5. DOMAIN ORIENTATION

The third claim of OO technology that we examine in this paper is that OO systems are understandable (see Figure 3). This claim is well motivated on the surface. The metaphor of communicating objects is a powerful one (Rosson & Alpert, 1990), which exploits our "natural" tendency to anthropomorphize (Wirfs-Brock, Wilkerson, & Wiener, 1990) and to categorize things into generalization structures. The understandability claim assumes that it is "natural" for developers and users (who are experts in the problem domain) to think in OO terms (at least as compared to more traditional structured languages). In other words, it should be natural for developers and users to map their "worlds" into autonomous, communicating objects with data and behavior and into generalization or inheritance structures. This implies: (1) a clearer relationship between the problem and solution, and (2) improved communication between users and developers.

The first implication is realized if the computational structures in the solution directly model problem domain concepts, so that the resulting systems' structures more closely correspond to that of the problem domain. This correspondence between the structure of the problem and the structure of the solution reduces the conceptual distance between a developer's mental model of the problem and his or her mental model of the solution (Rosson & Alpert, 1990). This has been referred to as the "seamless integration" of analysis, design, and implementation (Henderson-Sellers, 1992), which supports *human problem-domain communication* (Fischer & Lemke, 1988).

The second implication results from the first. A closer mapping for the designer between problem and solution should also reduce the conceptual distance between the users' and the developers' mental models of the problem. Objects in the problem domain will have computational counterparts in the solution (Fischer, 1987). This correspondence should improve the communication between users and developers and presumably promote the development of systems that meet the users' needs.

5.1. Where OO Technology Falls Short

Some of the authors have been involved in teaching the OO approach for many years. In one graduate-level course on OO development, students are required to analyze, design, and implement a small system in Smalltalk/V Windows (Digitalk, 1991). One semester, the project was a shopping system for a gourmet food shop. None of the students had any previous experience with OO methods or programming languages, although most had some previous

analysis, design, and/or programming experience (primarily COBOL). The students were given a textual description of the problem and requirements of the system to be developed. Requirements included (among other things) that customers be able to browse items in the store and make purchases based on previous purchases, pre-specified recipes and/or menus, or personalized shopping lists.

Several techniques were used to gain insights into their progress during the semester: (1) anonymous journals were turned in biweekly, so that students could ask questions, make comments and suggestions, and vent frustrations without fear of reprisal; (2) students were able (but not forced) to present/discuss their progress-to-date, which often led to intense class discussions of various design issues and implications; (3) lab sessions were provided in which students worked through a tutorial and were able to explore the Smalltalk systems with assistance from classmates and teaching assistants; and (4) in their final project reports, the students were required to reflect on their learning experience. From these sources, and an examination of their design diagrams and code, several observations were made.

The students varied considerably in terms of which abstractions they viewed as "essential." The only classes agreed upon by all students were *customer*, *item*, and *menu*. There was a great deal of variability in the number and labels for other classes (although there were many other "things" described in the requirements specification). In addition, the generalization (inheritance) structures that were identified varied considerably. Some students did not specialize or generalize the class *item* at all; others created two subclasses, *food* and *non-food*; others had several layers of subclasses below *item*; and still others conceptualized *item* and *service* (e.g., recycling, cooking classes/tips) as subclasses of an abstract class called *product*. There was some confusion over whether a shopping cart should be included as a class (to model the purchase-in-progress), and if so, if this was separate from the abstraction of a purchase. In general, even though the domain was familiar to all students, it was difficult in many cases for them to identify what abstractions were relevant to the problem and whether or to what extent they should be generalized or specialized. This implies two problems: (1) a vocabulary problem in naming concepts, and (2) a conceptualization problem, whereby different analyses of the problem led to different solution frameworks.

Other researchers have investigated and commented on these vocabulary and conceptualization problems (e.g., Furnas et al., 1987). These problems reflect difficulties in modeling and communication, which are not resolved simply by adopting an OO approach. There are many OO analysis and design methods that mention the problem of finding the objects in a domain (Monarchi & Puhr, 1992). Some methods provide weak, overly simplistic guidelines such as "pick the nouns" in the problem description (e.g., Booch, 1991; Rumbaugh et al., 1991; Wirfs-Brock, Wilkerson, & Wiener, 1990). Other methods provide slightly more help

by suggesting a look at devices, things, events, roles, sites, organizational units, etc. (e.g., Coad & Yourdon, 1991; Shlaer & Mellor, 1988). More recently, techniques such as use-cases (Jacobson et al., 1992) and scripts (Rubin & Goldberg, 1992) are being suggested to help structure the developer/analyst's thinking about the problem, which in turn should facilitate identification of objects, but further research in this area is still necessary.

These observations highlight several problems underlying the claim that OO is understandable or natural. First, the mapping from problem to solution is not yet seamless. Although the mapping from problem to solution is smoother in OO development than in structured development, not all OO structures identified in the problem have a one-to-one correspondence in the solution (Henderson-Sellers, 1992). For example, generalization relationships, such as the fact that a car is a kind of automobile, can be directly mapped into a subclass *car*, which inherits structure and behavior from its superclass *automobile*. However, aggregation (part-whole or composition) relationships, such as the fact that an engine is a part of a car, are not as directly implementable. The semantics of part-whole relationships (e.g., the fact that if the car moves, its parts move also) must be implemented by the developer, whereas the semantics of generalization relationships are built in via inheritance. Thus, although OO development does improve the smoothness of transitioning from analysis to design to implementation, there is not always a one-to-one relationship between problem and solution.

This leads to a second limitation of the understandability claim: users and developers may both be thinking in terms of objects but not in terms of the *same* objects. Not all objects that the users conceptualize in the problem domain will necessarily be objects in the solution, and there will likely be other objects added to the solution that users do not see as relevant to their problem. Even if we assume that the users and developers can agree on the key abstractions or objects in the users' domain (in other words, we reduce the gap between their mental models of the problem domain to an "acceptable" level), there still needs to be a transition from the problem domain model to the solution.

A third limitation is that it is not necessarily easy to find the "right" abstractions or object in a given domain. Reading various OO analysis and design methodology texts tends to lead one to assume that recognizing or identifying the appropriate objects in a domain is straightforward--that the objects are "just there for the picking" (Meyer, 1989). In our experience, identifying the "right" abstractions for a domain can be the most difficult part of development.

5.2. Beyond Object-Orientation

In a conventional (domain-independent) software environment, developers starting a new project typically have to work with low-level programming constructs and methodologies. This forces them to focus on the raw material to implement a solution rather than to try to understand

the problem. This contrast has been characterized as a mismatch between the *system model* provided by the software environment and the *situation model* of the software developer (van Dijk & Kintsch, 1983; Pennington, 1987; Fischer, 1987). We have studied domain-orientation in a software environment to bridge this gap by allowing domain-oriented concepts to evolve and thus allow developers to focus on abstractions in their problem domain and not on programming language concepts. We call the class of software environments that support problem-domain communication, *domain-oriented design environments*, and we have studied the application of these environments in several domains (Lemke & Fischer, 1990; Fischer, Henniger, & Redmiles, 1991; Fischer, 1994). Each of these environments relies on a domain model.

A domain model is generally recognized in software engineering as the end product of a domain analysis process that is either "synthetic" or "evidentiary" (Prieto-Diaz, 1987). In synthetic domain analysis, a software developer starts with an informal description of one or more systems within an application domain, identifies aspects common across the systems, and models these with object classes and frameworks. In evidentiary domain analysis, a software developer starts with existing systems and attempts to identify common components through reverse engineering or "design recovery" (Biggerstaff, 1989). Our model portrays domain analysis as a combination of these two processes by emphasizing the aspect of evolution. In our model, evolution corresponds to the belief that domains are open-ended; future needs cannot be completely anticipated and some problems are by nature ill-structured and require trial and error exploration (Rittel, 1984; Simon, 1981). In the example, some classes and methods were postulated based on Project A in Figure 1. The new requirement in Project B to accommodate a different kind of thermometer resulted in a redesign of the domain model, and a class *Thermometer* was introduced to capture the commonalties between *Digital Thermometer* and *Analog Thermometer*.

In a software development project, developers may separate components into different domains; any single project may involve components from several domains. Some of the components are project-specific; they belong to the primary or *dominant domain*. Others are project-independent; they belong to *supporting domains*. Supporting domains can be valid application (dominant) domains in their own right. The distinction is that they can also be used in constructing systems from different dominant domains. These domains form a hierarchy in which components from higher domains can be implemented using components from lower ones. The basic concepts behind domain separation have been expressed as domain networks (Arango, 1988) and horizontal versus vertical domains. Figure 13 illustrates a separation of dominant and supporting domains for the temperature sensing example. In this project, all of the classes and frameworks could be classified as dealing with this temperature sensing. However, as related projects are implemented, classes begin to develop to support different kinds of

thermometers, potentially different sensor interfaces, and communications among the thermometers, sensors, and host devices.

INSERT FIGURE 13 ABOUT HERE

The creation of a domain-oriented software environment is, of course, also a software development project. We have developed such environments for several dominant domains, including graphics software design, kitchen floor plan design, and local-area network design. In so doing, we identified frameworks and classes in supporting domains, including mechanisms for locating, comprehending, and modifying design components and knowledge.

This adds another dimension to the concept of dominant and supporting domains (see Figure 14). Namely, once separated, these supporting domains are available to assist end-users. For example, a tool for modifying object classes in a software design environment may be incorporated in the system for temperature sensing. End-users of the system could use the capability to further modify the thermometer classes. The distinction between development environment and application project begins to fade along with the gap between system and situation models.

INSERT FIGURE 14 ABOUT HERE

These observations have motivated the evolutionary model of OO development (Figure 1) in several ways. We do not claim to know how to find the appropriate abstractions, but we recognize that it is a difficult process and encourage the analysis of both dominant and supporting domains (see Figure 13). Domain orientation combined with evolution support across multiple applications will help to flush out the key abstractions in a domain. Current OO programming environments are domain-independent, and include mostly low-level components (e.g., sets, arrays, strings, characters, integers) and supporting domain components (e.g., graphical user interface objects) that are still far-removed from the problem domain. Design environments that are domain-oriented can further help to reduce the gap between users and developers by providing both with the environment whose elements are domain-oriented abstractions (thus forcing a somewhat restricted vocabulary and not providing low-level abstractions for the developer to "drop down into"). Domain-oriented environments also hide the lower levels of detail from the developer, so that the mapping between problem and solution should be smoother. Section 5.3 describes the KID design environment, which instantiates this approach.

5.3. KID: A Tool to Support Domain-Orientation

During the past five years, we have developed and evaluated various prototype systems of domain-oriented design environments to study issues of problem-domain communication and the integration of problem framing and problem solving (Fischer, McCall, & Morch, 1989; Lemke & Fischer, 1990; Fischer, Henniger, & Redmiles, 1991). Design environments support users in applying domain knowledge and provide them with various feedback mechanisms. The KID design environment supports kitchen designers in the development of floor plans (Nakakoji, 1993; Nakakoji & Fischer, 1995). KID consists of several subsystems. KID-Construction, shown in Figure 15, supports construction of a kitchen floor plan. The palette of KID-Construction contains domain-oriented building blocks such as sinks, stoves, and refrigerators. The designer can create a design by applying parts from this palette, that supports design by composition. The palette elements are instances of classes, and users can apply components stored in a class library without worrying about the underlying programming substrate. Another way users can create designs is through design by modification or redesign of existing catalog examples.

INSERT FIGURE 15 ABOUT HERE

KID-Specification is another subsystem of KID, that allows kitchen designers to specify their abstract design requirements and design intentions (see Figure 16). Designers can select answers presented in the *Questions* window. Such questions, answers, and associated arguments are structured based on IBIS (Issue-Based Information Systems) (Conklin & Begeman, 1988), and are gradually accumulated by users through actual design tasks. The summary of currently selected answers appears in the *Current Specification* window. Each answer is accompanied by a slider that allows designers to assign a weight representing the relative importance of the answer (1-10 scale where 10 indicates most importance). The mechanisms are further described by Nakakoji (1993).

INSERT FIGURE 16 ABOUT HERE

A unique feature of KID is its ability to deliver information to users relevant to their current task in terms of the domain semantics. *Critics* (see message pane in Figure 15) identify potential problems in a design (Fischer et al., 1993b). Their knowledge about kitchen design includes design principles based on building codes, safety standards, and functional preferences specified through KID-Specification. If a design principle or heuristic (such as "if you are a single-person household, you may need a simple single-bowl sink") is violated, a critic will fire

and display a critique in the message pane, identify a possibly problematic situation, and prompt the user to reflect on it.

Another rule-based information delivery mechanism suggests catalog examples for the user to consider. KID automatically orders catalog examples according to the specified requirements in KID-Specification and presents them to users for reuse and redesign (see the Catalog window in Figure 15). KID uses critiquing rules to compute the appropriateness of each catalog example and provides mechanisms to describe why a particular catalog example is inferred to be appropriate to the requirements (Nakakoji, 1994).

In one study (Nakakoji, 1993), eight novices and one expert in kitchen design used KID to develop a design for a kitchen to fit the following task situation: both husband and wife have jobs; during weekdays, the wife does most of the cooking; and during weekends, the couple cooks meals together. Subjects were encouraged to think aloud (Ericsson & Simon, 1980) by making statements to the experimenter and, in three trials, subjects were observed through constructive interaction (Miyake, 1986) in which they were paired to encourage verbalization. A post-experiment interview collected additional comments, and the protocols and comments were analyzed to evaluate the benefit of KID.

Overall, the study indicated that KID augmented the users' design process. The novices unanimously acknowledged that KID provided them with useful information about kitchen design, and although the expert responded that her final design was not affected by using KID, she noted that the KID made her reflect on information she might not otherwise have considered (Nakakoji & Fischer, 1995). More specifically, KID supported the integration of problem framing and problem solving and the incremental understanding of a task. The unexpected appearance of critic messages caused subjects to reflect on their task and attend to the associated explanation (Figure 16). Moreover, subjects often argued against a design principle that was used to deliver information, and modified the associated rules (arguments). Not only the delivered knowledge itself, but also the inferred relevance by the system, that provided information about dependencies between the specification and construction, helped give subjects direction in reframing their partial construction and specification.

KID demonstrates many of the goals for domain-orientation presented in our model, namely, the analysis of dominant and supporting domains into abstractions that users can access in developing a new project. The classes in this domain are represented by the elements of the palette. Completed designs captured as catalog entries represent instantiations of a kitchen floor plan framework. The less obvious, supporting domains include components that can be useful across a spectrum of design domains, for example, mechanisms for supporting rule-based critics, catalog suggestion, explanation, and end-user modification.

6. CONCLUSIONS

The problems software developers face in applying OO technology can be understood only by looking beyond the technological possibilities and beyond the context of individual developers and projects. OO technology makes possible software evolution, reuse and redesign, and domain orientation. However, these goals cannot always be achieved in practice. Software development is a cooperative design process among many individuals and many kinds of artifacts. With respect to reuse and redesign, the cooperation often spans multiple projects and individuals who never meet.

We have presented a detailed model of software development that focuses on the three aspects of evolution, reuse and redesign, and domain orientation. In its detail, the model is based on OO technology, but more generally it has elements of a model of long-term cooperative design. The model represents a cognitive model by being developed from the perspective of software developers and the problems they face. We have examined first-hand observations that have motivated the model as well as studies by other researchers.

The scale and scope of the model and the number of hypotheses in it make it difficult to evaluate in a conventional empirical study. In particular, no single software development environment exists that embodies all the technical and organizational aspects of the model. However, evidence observed in unstructured settings as well as an assessment of the current state of software engineering indicates not only the need for but a movement toward environments that support this model.

The varied experience and prototype tools contributed by the different authors have proven helpful in corroborating the model. Many specific hypotheses have been verified in prototype systems. Metrics help less theoretical developers identify good abstractions. Design examples with perspective explanations reduce variability of performance in sample groups. Techniques of domain orientation make software accessible to non-computer professionals and make a class of problems accessible to novices.

OO technology is not a "silver bullet" (Brooks, 1987) that will eliminate the "software crisis." It is an enabling technology that provides a foundation for the next generation of paradigms in support of complex computation. Successes today come from the talents and dedication of people practicing good design with the tools at their disposal. The model and tools we have presented push the technology in a direction that is more inclusive, of people as well as of problem domains.

NOTES

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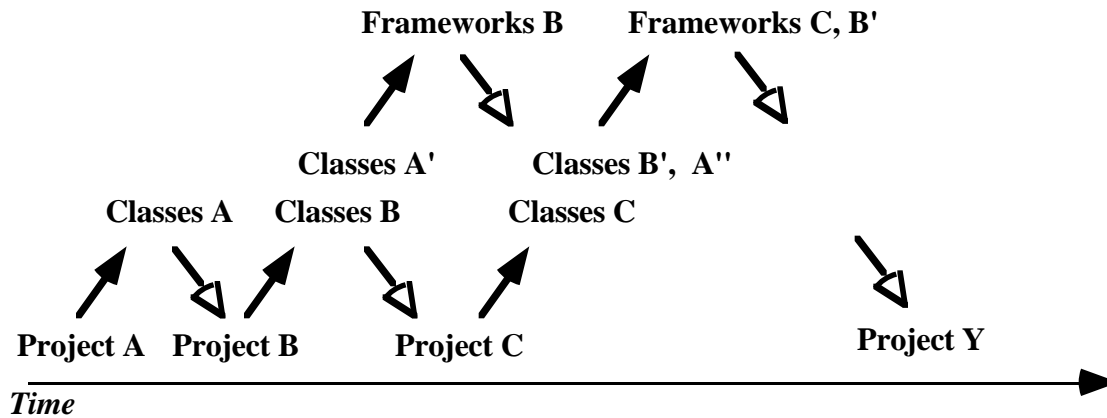
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FIGURES

Figure 1: An evolutionary model of OO development



A progression of software development projects delineate time and provide a long-term context in which the fundamental claims of OO technology, including domain-orientation and reuse, may be studied. The solid-tip arrows are primarily associated with evolution, driven by software developers creating new software objects to accommodate new projects. Hollow-tip arrows indicate software developers reusing components, although reuse at times leads to redesign. Stable structures of class libraries and frameworks emerge over multiple projects. Domain-orientation permeates the model as all of the creation, reuse, and redesign of components is driven by problems arising in the development of specific projects.

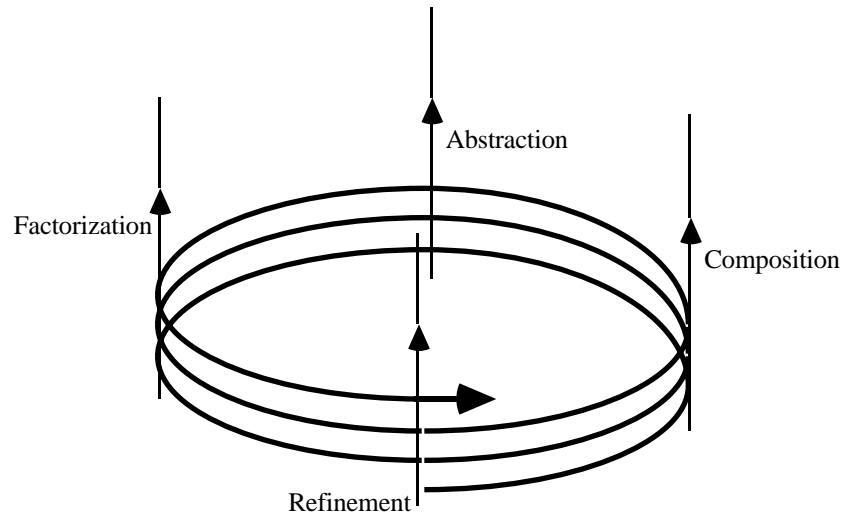
Figure 2: Framework for a temperature sensing system



This example illustrates parts of the cognitive model proposed in Figure 1. A temperature sensor measures the temperature of a number of furnaces and reports those measurements to a host computer. The temperature of each furnace is obtained by periodically reading a digital thermometer. The temperature sensor system is likely to be part of a larger project for which monitoring (and, most likely, control) of the temperatures of a set of furnaces is important. This application might be, for example, process control in a steel mill.

INSERT FIGURE 3 HERE

Figure 4. Evolving components



Development of software components involves an evolutionary cycle of subprocesses.

Figure 5: Definitions of reference factor (RF) and hierarchy factor (HF)

$$RF_A = \frac{\text{ranking number of class A in topological sort}}{\text{total number of classes (total number of elements in topological sort)}}$$

Example:

- A refers to (B, C)
- B refers to (D, F)
- C refers to (D, E, F)
- D refers to ()
- E refers to ()
- F refers to (D)

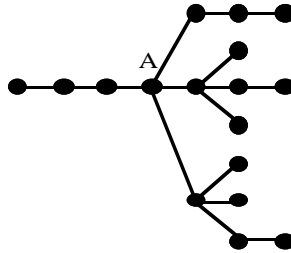
Ranking Topological Sort : D, F, B, E, C, A

$$RF = 6 / 6 = 1$$

(a) Reference factor

$$HF_A = \frac{\text{number of superclasses of class A}}{\text{number of superclasses of class A} + 1 + \text{number of subclasses of class A}}$$

Example:



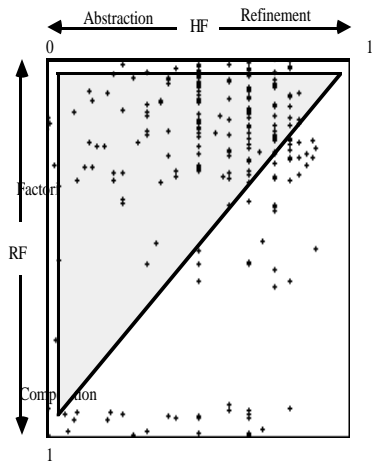
$$HF = 3 / (3 + 1 + 13) = 0.176$$

(b) Hierarchy factor

Figure 6: HF and RF values of principal classes provided in Smalltalk-80

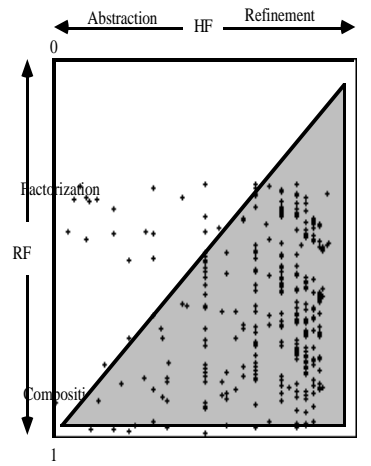
Class Name	HF	RF	Sequence	Referred to By
Array	0.571	0.000	0	
BitBlt	0.100	0.649	218	Form, Pen
ByteString	0.833	0.003	1	Character
Collection	0.027	0.312	105	Bag, OrderedCollection, Set, SortedCollection
CodeController	0.700	0.631	212	Character, Cursor, Explainer, ReadStream, String
CodeView	0.600	0.634	213	CodeController
Dictionary	0.300	0.152	51	Association, Bag, Cursor, OrderedCollection
Object	0.000	0.997	335	Array, Association, Browser, Context
Point	0.750	0.045	15	Array, Cursor, Form, OrderedCollection
Rectangle	0.250	0.042	14	Array, Cursor, Form, OrderedCollection
SystemDictionary	0.800	0.860	229	Array, Association, Browser, BrowserView
View	0.038	0.994	334	Controller, DisplayScreen, Form, Inspector

Figure 7: Comparison between the results of applying metrics



Average HF = 0.552
Average RF = 0.288

(a) Classes in Smalltalk-80 Library



Average HF = 0.699
Average RF = 0.653

(b) Classes Created in MEI Project

Figure 8: Evolution of objects during the project lifetime

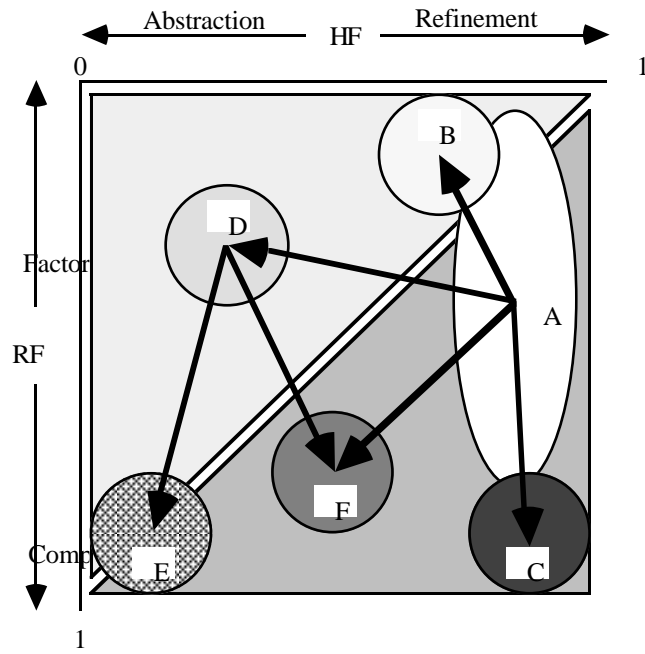
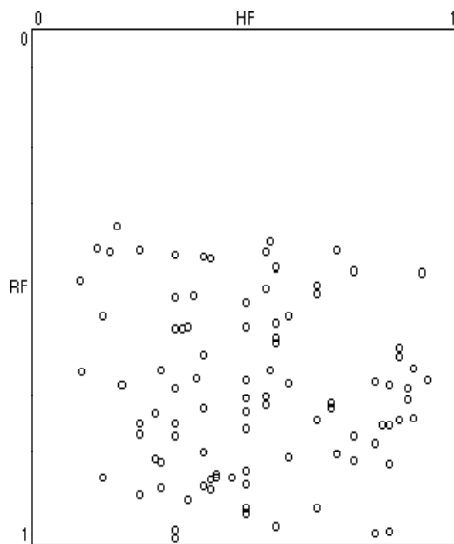
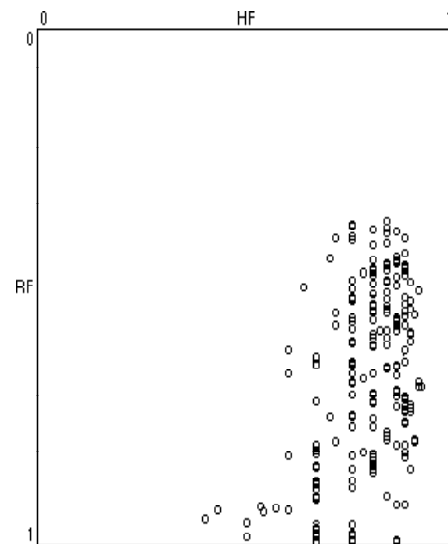


Figure 9: Comparison of metrics applied to programmer types

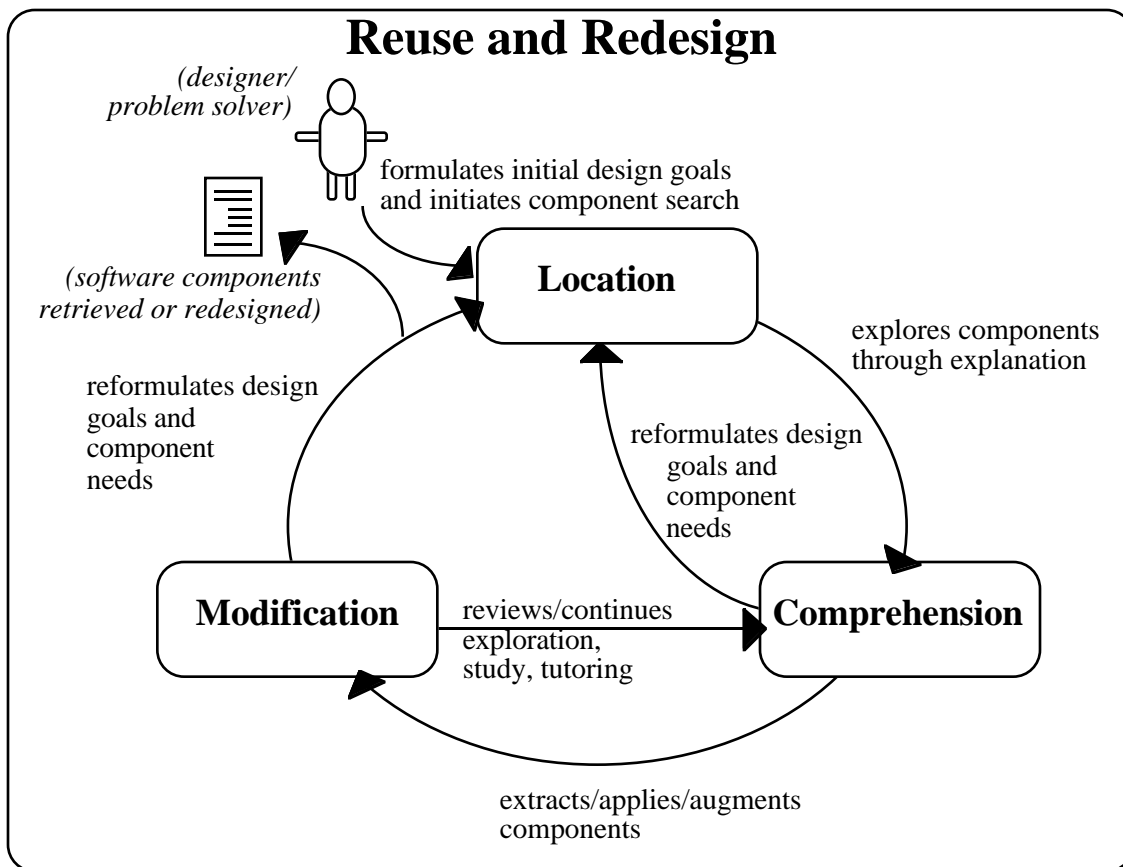


(a) Class-Library-Developers



(b) Catalog-Developers

Figure 10. Reuse and redesign of components



Reuse and redesign requires a software developer to locate components relevant to a task, comprehend them with respect to relevance and modifiability, and, in some cases modify the located components. These stages are intertwined, each providing feedback to the other: comprehension may lead directly to further retrieval, and modification may require further comprehension or additional retrieval.

Figure 11: Comprehension of software components

Explainer

Code

```

(x-attachment))
((null theta-list) nil)
(setq x (* radius (cos (- theta pi/2))))
  y (* radius (sin (- theta pi/2))))
(graphics:draw-string "x"
  x
  y
  :attachment-x
  :center
  :attachment-y
  :center)
(setq x (* (+ radius 5) (cos (- theta pi/2))))
  y (* (+ radius 5) (sin (- theta pi/2))))
(setq x-attachment (cond ((< x 0) :right)
  ((= (floor x) 0) :center
  (t :left)))
(graphics:draw-string label
  x
  y
  :attachment-x

```

Diagram

Example Output

Explanation Dialog

This plot is a visualization of addition modulo 100. ... (more)

Story - (Tell-Story) - Cyclic-Operations Perspective
This plot is a good way to visualize operations in a cyclic group. ... (more)

Position - (Tell-Story) - Program-Features Perspective
The coordinates for labeling are thought about in terms of radians. Values in radians are converted to rectangular coordinates for the plotting functions. The conversions and computations use the constants 2pi (360 degrees), and pi/2 (90 degrees). pi (180 degrees) is a system constant. ... (less)

Position - (Tell-How) - Lisp Concept Perspective
The position consists of a value assignment. The value assignment consists of a special form name, a variable name, a function call, a variable name, and a function call. ... (less)

Typein Commands

Command: Stop Recording

Command:

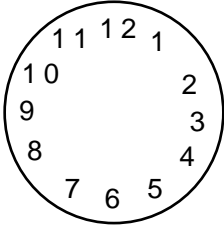
Command:

The above screen shows the actual state of the EXPLAINER interface at the end of one programmer's test session. The interface is based on the principle of making examples accessible through multiple presentation views (e.g., code, sample output, text, and diagram) and multiple representation perspectives (e.g., LISP, program features, and, in this example, cyclic group operations). The hypertext interface allows information to be accessed through selection and use of the command menu (bottom left of screen).

Figure 12: Clock task as described to programmer subjects

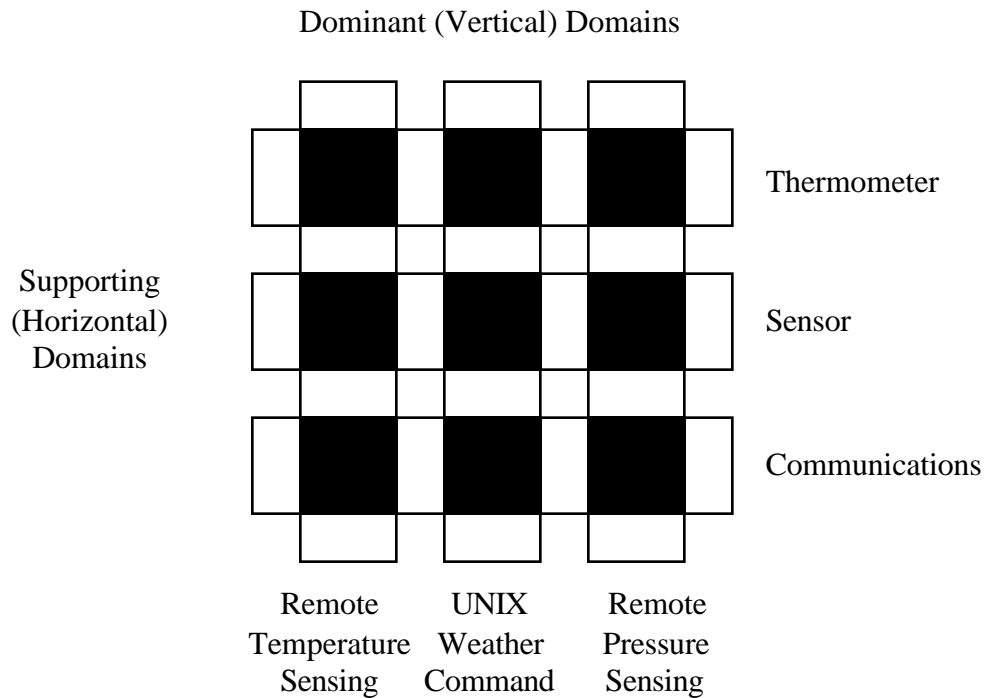
Clock Programming Task

Write a program to draw a clock face (without the hands) that shows the hour numerals, 1 - 12. Your solution should look like the picture below.



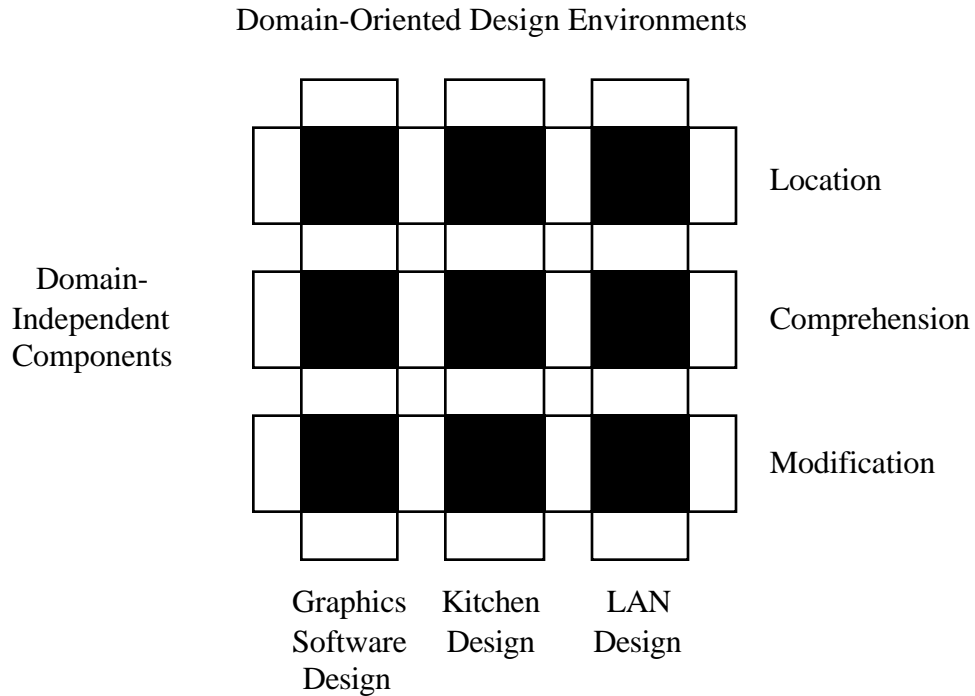
The image shows a circular clock face with a black outline. Inside the circle, the numerals 1 through 12 are arranged in a circular pattern. The numerals are: 1 at the top, 2 at the top-right, 3 at the right, 4 at the bottom-right, 5 at the bottom, 6 at the bottom, 7 at the bottom-left, 8 at the left, 9 at the left, 10 at the top-left, 11 at the top-left, and 12 at the top. The numerals are arranged in a way that they are slightly offset from the circle's edge, creating a ring of numbers.

Figure 13. Dominant and supporting domains in projects



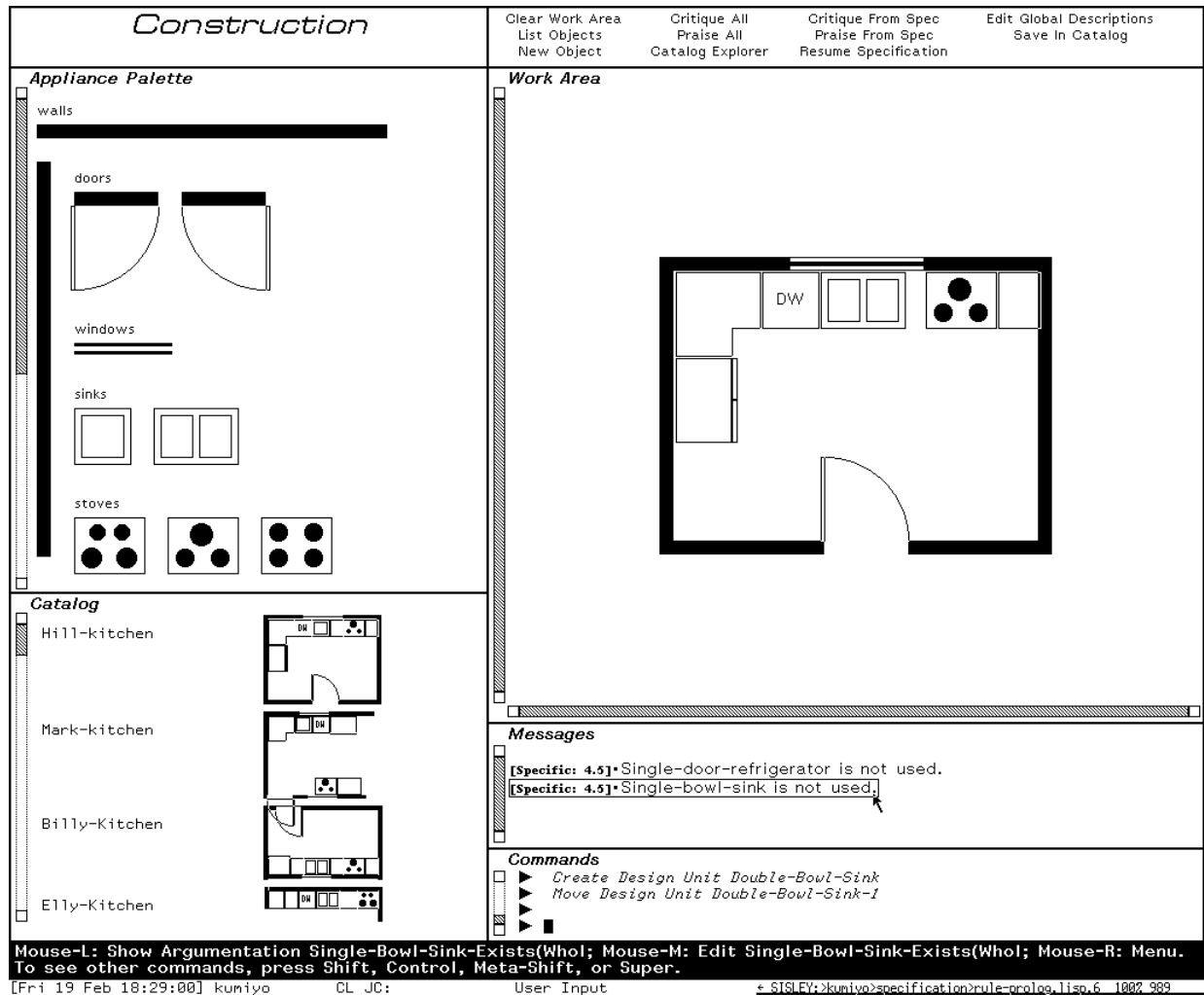
Any single software development project may involve several domains. Software developers must separate components as they develop domain models. This separation leads to dominant domains that are identified with the statement of a project, e.g. temperature sensing, and supporting domains that are reusable in multiple projects. For example, some installations have a command in UNIX that samples an outside thermometer; the basic framework is the same as for sensing temperatures in furnaces.

Figure 14: Supporting domains in domain-oriented design environments



The development of domain-oriented design environments explored dominant domains of graphics software design (Fischer, Henninger & Remiles, 1991), kitchen floor plan design, and local-area network design (Fischer et al. 1994). Domain-independent process support for location, comprehension, and modification of designs evolved as supporting domains.

Figure 15: Domain orientation in KID.



Building blocks (design units) are selected from the Palette and moved to desired locations inside the Work Area. Designers can reuse and redesign complete floor plans from the Catalog. The Messages pane displays critic messages, which are triggered by design changes that violate hard or soft constraints. Users may click on critic messages or catalog entries to access additional explanations (see Figure 16). Catalog examples in the Catalog pane are automatically ordered according to the requirements of the current construction. These requirements are determined either by the elements in the current Work Area or issues selected in a Specification Window (Figure 16).

Figure 16: Specification and explanation to support information delivery

<i>Specification</i>		Save Current Specification Start New Specification Show Suggestions Quick Question	Load Specifications Copy Specification Set Options Quick Answer	Store Base Issues Catalog Explorer Resume Construction Quick Argument									
<p>Catalog</p> <ul style="list-style-type: none"> HILL-KITCHEN MARK-KITCHEN BILLY-KITCHEN ELLY-KITCHEN ISAK-KITCHEN JONES-KITCHEN OSCAR-KITCHEN ANDI-KITCHEN BARB-KITCHEN BOB-KITCHEN CATHY-KITCHEN COLE-KITCHEN COUGER-KITCHEN DOHSON-KITCHEN DREYER-KITCHEN GEORGE-KITCHEN GONZALES-KITCHEN 	<p>Questions</p> <ul style="list-style-type: none"> • Entertainment requirement? <ul style="list-style-type: none"> • Yes • Occasionally • Seldom • Not at all - Methods of Cooking - Do you usually use a microwave? <ul style="list-style-type: none"> • yes • no - Other Kitchen Activities - Children's Hangout? <ul style="list-style-type: none"> • yes • no - Do you need a eating space? <ul style="list-style-type: none"> • yes • no - Preferences - Type of kitchen? <ul style="list-style-type: none"> • contemporary • Traditional • Country - Shape of kitchen? <ul style="list-style-type: none"> • L-shape • U-shape • [answer suggested because how-many-coo • Corridor • Island • [answer suggested because entertainmen • One-wall 	<p>Current Specifications for: Type: kitchen Name: joe-kitchen</p> <ul style="list-style-type: none"> • Size of family? 1 <input type="checkbox"/> One • How many cooks usually use the kitchen at once? 2 <input type="checkbox"/> one • Is the primary cook right-handed or left-handed? 5 <input type="checkbox"/> Left handed • Entertainment requirement? 10 <input type="checkbox"/> Yes 											
<p>Considered Questions</p> <ol style="list-style-type: none"> 1 Entertainment requirement? 2 Which type of sink do you need? 3 Is the primary cook right-handed or left-handed? 4 How many cooks usually use the kitchen at once? 5 Size of family? 6 Kitchen Specification 	<p>Argumentation for</p> <p>Which type of sink do you need?</p> <ul style="list-style-type: none"> • double bowl sink "Double-Bowl-Sink-Exists(Jc::Whole-Design)" (+) If you often entertain, a double bowl sink is preferable. [Nakakoji, Kuniyo; 10/12/91 18:26:48] • single bowl sink "Single-Bowl-Sink-Exists(Jc::Whole-Design)" +(+) If you have a small family, you may need just a single-bowl sink. [Nakakoji, Kuniyo; 												
<p>Suggested:</p> <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;">Issue</th> <th style="text-align: left;">Answer</th> <th style="text-align: left;">Argument</th> </tr> </thead> <tbody> <tr> <td>[4.50] Which type of sink do you need?</td> <td><i>single bowl sink</i></td> <td>If you have a small family, you may need just a single-bowl sink.</td> </tr> <tr> <td>← Size of family?</td> <td>One</td> <td>[Specified]</td> </tr> </tbody> </table>		Issue	Answer	Argument	[4.50] Which type of sink do you need?	<i>single bowl sink</i>	If you have a small family, you may need just a single-bowl sink.	← Size of family?	One	[Specified]	<p>Commands</p> <ul style="list-style-type: none"> ▶ Show Why Suggested single-bowl-sink ▶ Show Arguments type-of-sink ▶ Select Issue From Argument if-you-often-ent ▶ Toggle Answer yes 		
Issue	Answer	Argument											
[4.50] Which type of sink do you need?	<i>single bowl sink</i>	If you have a small family, you may need just a single-bowl sink.											
← Size of family?	One	[Specified]											
<p>Mouse-L: Show Further Argumentation; Mouse-M: Select this question; Mouse-R: Menu. To see other commands, press Shift, Control, Meta-Shift, or Super.</p>													
<p>[Fri 19 Feb 18:32:54] kuniyo CL SPEC: User Input + SISLEY:kuniyo?specification?rule-prolog.ligo.6 1002 389</p>													

KID provides an explanation about interdependency between a design requirement and a critic (such as the critic triggered in Figure 15). Argumentation and issues related to the current design may be reviewed and used to further specify design goals.