# Reuse of Off-the-Shelf Constraint Solvers in C2-Style Architectures

Nenad Medvidovic and Richard N. Taylor

Technical Report UCI-ICS-96-28
Department of Information and Computer Science
University of California, Irvine
Irvine, California 92697-3425

{neno,taylor}@ics.uci.edu

July 1996

**Abstract --** Reuse of large-grain software components offers the potential for significant savings in application development cost and time. Successful reuse of components and component substitutability depends both on qualities of the components reused as well as the software context in which the reuse is attempted. Disciplined approaches to the structure and design of software applications offers the potential of providing a hospitable setting for such reuse. We present the results of a series of experiments designed to determine how well "off-the-shelf" constraint solvers could be reused in applications designed in accordance with the C2 software architectural style. The experiments involved the reuse of SkyBlue and Amulet's one-way formula constraint solver. We constructed numerous variations of a single application (thus an application family). The paper summarizes the style and presents the results from the experiments. The experiments were successful in a variety of dimensions; one conclusion is that the C2 style offers significant potential to application developers and that wider trials are warranted.

***Index Terms* --** architectural styles, message-based architectures, graphical user interfaces (GUIs), constraint management, component-based development, SkyBlue, Amulet.

## I. Introduction

Software architecture research is directed at reducing costs of developing applications and increasing the potential for commonality between different members of a closely related product family. One aspect of this research is development of software architectural styles, canonical ways of organizing the components in a product family [GS93, PW92]. Typically, styles reflect and leverage from key properties of the application domain. C2, a component- and message-based style for development of applications with a significant graphical user interface (GUI) aspect, is a relatively new style [TMA+95, TMA+96]. The practical utility of the style has been initially assessed through the development of a wide variety of small applications. The experimental evaluations to date have not, however, seriously evaluated the potential of the style for supporting reuse of preexisting components. Rather, experience has been limited to reuse of different graphics toolkits, such as Xlib [SG87]. Since the ability to effectively reuse components is essential if a style is to deliver the desired improvements in development costs, further investigation is required.

The focus of this paper, therefore, is a set of experiments conducted to determine how well C2 supports reuse of externally produced components, and in particular constraint solvers. Since C2 focuses on GUI applications, a constraint maintenance system seemed a natural choice. (The earlier experiments with toolkits focused on components at the bottom of a C2 architecture and their integration presented a specialized solution. Since constraint solvers naturally lie within an architecture, neither at the top nor the very bottom, reusing them would examine the more interesting case of communication with other components both above and below.)

In addition to enabling us to investigate the degree of difficulty of encapsulating an off-the-shelf (OTS) component into a C2 architecture, our choice of constraint solvers was based on several other factors:

- in case of success, it will give us a high powered UI component to reuse across C2 applications;
- constraint managers provide significant functionality that we currently do not support;
- this kind of functionality is generally not reused across applications, but is custom coded into UI software.

The application in the C2 style that we decided to use for this exercise was a version of the video game KLAX.[1] While the conceptual architecture contained a component whose purpose was layout and global constraint maintenance, KLAX constraints were implemented locally with in-line code. The two constraint managers we selected for this exercise were SkyBlue [San94] and Amulet's one-way formula constraint solver [MM95]. The main reasons they were selected were availability of the source code and the fact that implementations for both existed in C/C++, the primary language of implementation in KLAX.

1. KLAX is trademarked 1991 by Atari Games.

Initially, a variation of the original KLAX architecture involved incorporating SkyBlue into the application. Constraint-management code, which was dispersed throughout the original application, was replaced with SkyBlue constraints. Furthermore, SkyBlue was adapted to communicate with other KLAX components via C2 messages. A constraint management component in the C2 style was thus created. Following this, SkyBlue was replaced with Amulet's formula constraint solver. This exercise was intended to explore any potential global (architecture-wide) effects of substituting one constraint manager for another, as well as the possibility of multiple constraint managers being active in the same application. These two major experiments were followed by several smaller ones. While the internal architecture varied (deliberately) across experiments, it is worthwhile to note that the look and feel of the application remained unchanged.

The purpose of this initial exercise was not necessarily to exploit all of C2's potential benefits, such as providing a C2 wrapper for executable versions of OTS components implemented in different languages, or integrating components with their own distributed, multi-user, or soft real-time aspects with which a C2 application could interact. Instead, we chose to focus on the following:

- requirements for incorporating an external component into an architecture;
- issues in substituting a C2 component with another one providing the same or similar functionality;
- partial utilization of the services a component provides, as a byproduct of using legacy components in new, unforeseen contexts;
- ramifications of having multiple constraint managers in the same architecture, both within a single component and across components.

The remainder of the paper is organized as follows: Section II describes the rules and intended goals of C2. The material in this section is condensed from a more detailed exposition on the style, given in [TMA+95]. Section III presents a detailed overview of the architecture and implementation of KLAX. Section IV motivates the need for a constraint manager in KLAX and describes the particular KLAX constraints we decided to maintain in an external constraint solver. Section V discusses the design and implementation issues encountered in integrating SkyBlue with the architecture, while Section VI discusses replacing SkyBlue with Amulet's constraint manager. The library of KLAX components created in the process of including SkyBlue and Amulet is described in Section VII. A discussion of several "interesting" variations of the KLAX architecture built with the components from the library is given in Section VIII. Finally, our conclusions round out the paper.

## II. Overview of C2

C2 is an architectural style designed to support the particular needs of applications that have a graphical user interface aspect. The style supports a paradigm in which UI components, such as dialogs, structured graphics models (of various levels of abstraction), and, as this paper will show, constraint managers, can more readily be reused. A variety of other goals are potentially supported as well. These goals include the ability to compose systems in which: components may be written in different programming languages, components may be running in a distributed, heterogeneous environment without shared address spaces, architectures may be changed dynamically, multiple users may be interacting with the system, multiple toolkits may be employed, multiple dialogs may be active, and multiple media types may be involved.

The C2 style can be informally summarized as a network of concurrent components hooked together by connectors, i.e., message routing devices. Components and connectors both have a defined top and bottom. The top of a component may be connected to the bottom of a single connector and the bottom of a component may be connected to the top of a single connector. There is no bound on the number of components or connectors that may be attached to a single connector. When two connectors are attached to each other, it must be from the bottom of one to the top of the other (see Fig. 1).

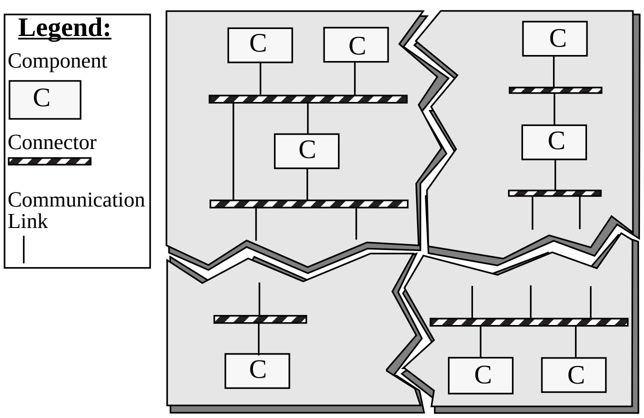


Fig. 1. A sample C2 architecture. Jagged lines represent the parts of the architecture not shown.

Each component has a top and bottom domain. The top domain specifies the set of notifications to which a component responds, and the set of requests that the component emits up an architecture. The bottom domain specifies the set of notifications that this component emits down an architecture and the set of requests to which it responds. All communication between components is achieved by exchanging messages. This requirement is suggested by the asynchronous nature of component-based architectures, and, in particular, of applications that have a GUI aspect, where both users and the application perform actions concurrently and at arbitrary times and where various components in the architecture must be notified of those actions. Message-based communication is extensively used in distributed environments for which this architectural style is suited.

Central to the architectural style is a principle of limited visibility or *substrate independence*: a component within the hierarchy can only be aware of components "above" it and completely unaware of components which reside "beneath" it. Notions of above and below are used in this paper to support an intuitive understanding of the architectural style. As is typical with virtual machine diagrams found in operating systems textbooks, in this discussion the application code is (arbitrarily) regarded as being at the top while user interface toolkits, windowing systems, and physical devices are at the bottom. The human user is thus at the very bottom, interacting with the physical devices of keyboard, mouse, microphone, and so forth.

Substrate independence has a clear potential for fostering substitutability and reusability of components across architectures. One issue that must be addressed, however, is the apparent dependence of a given component on its "superstrate," i.e., the components above it. If each component is built so that its top domain closely corresponds to the bottom domains of those components with which it is specifically intended to interact in the given architecture, its reusability value is greatly diminished and it can only be substituted by components with similarly constrained top domains. For that reason, the C2 style introduces the notion of event translation. Domain translation is a transformation of the requests issued by a component into the specific form understood by the recipient of the request, as well as the transformation of notifications received by a component into a form it understands. The C2 design environment [RR96] is intended, among other things, to provide support for accomplishing this task.

The internal architecture of a component shown in Fig. 2 is targeted to the user interface domain. While issues concerning composition of an architecture are independent of a component's internal structure, for purposes of exposition below, this internal architecture is assumed.

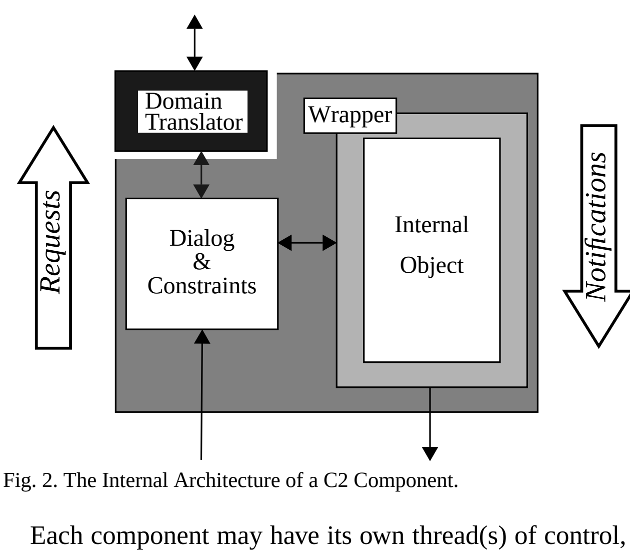


Fig. 2. The Internal Architecture of a C2 Component.

Each component may have its own thread(s) of control, a property also suggested by the asynchronous nature of tasks in the GUI domain. It simplifies modeling and programming of multi-component, multi-user, and concurrent applications and enables exploitation of distributed platforms. A proposed conceptual architecture is distinct from an implementation architecture, so that it is indeed possible for components to share threads of control.

Finally, there is no assumption of a shared address space among components. Any premise of a shared address space would be unreasonable in an architectural style that allows composition of heterogeneous, highly distributed components, developed in different languages, with their own threads of control, internal structures, and domains of discourse.

## III. Overview of KLAX

The architecture into which an externally developed constraint solver was to be integrated is a version of the video game KLAX. A description of the game is given in Fig. 3. This particular application was chosen as a useful test of the C2 style concepts in that the game is based on common computer science data structures and the game layout maps naturally to modular artists. Also, the game play imposes some real-time constraints on the application, bringing performance issues to the forefront.

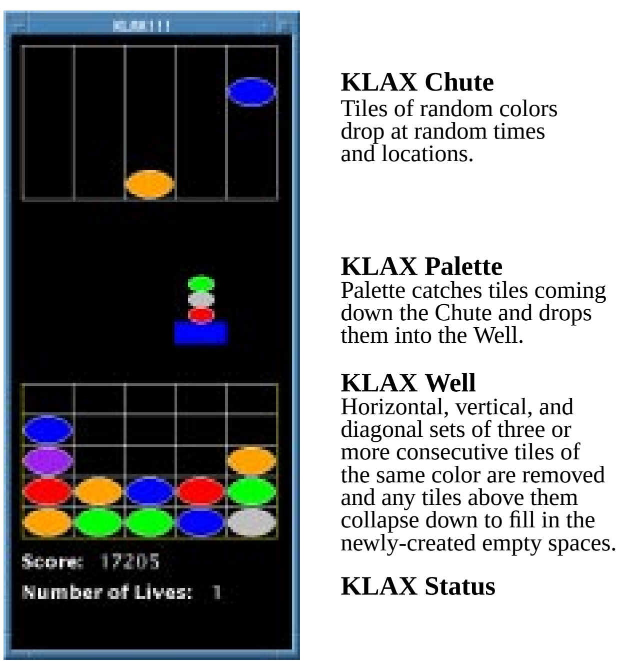


Fig. 3. A screenshot and description of our implementation of the KLAX video game.

The design of the system is given in Fig. 4. The components that make up the KLAX game can be divided into three logical groups. At the top of the architecture are the components which encapsulate the game's state. These components are placed at the top since game state is vital for the functioning of the other two groups of components. The game state components receive no notifications, but respond to requests and emit notifications of internal state changes. Notifications are directed to the next level where they are received by both the game logic components and the artists components.

The game logic components request changes of game state in accordance with game rules and interpret game state change notifications to determine the state of the game in progress. For example, if a tile is dropped from the well, the *RelativePositioningLogic* determines if the palette is in a position to catch the tile. If so, a request is sent to *PaletteADT* to catch the tile. Otherwise, a notification is sent that a tile has been dropped. This notification is detected by the *StatusLogic*, causing the number of lives to be decremented.

The artist components also receive notifications of game state changes, causing them to update their depictions. Each artist maintains the state of a set of abstract graphical objects which, when modified, send state change notifications in hope that a lower-level graphics component will render them. *TileArtist* provides a flexible presentation for tiles. Artists maintain information about the placement of abstract tile objects. *TileArtist* intercepts any notifications about tile objects and recasts them to notifications about more concrete drawable objects. For example, a "Tile-Created" notification might be translated into a "Rectangle-Created" notification. The *LayoutManager* component receives all notifications from the artists and offsets any coordinates to ensure that the game elements are drawn in the correct juxtaposition.

The *GraphicsBinding* component receives all notifications about the state of the artists' graphical objects and translates them into calls to a window system. User events, such as a key press, are translated into requests to the artist components.

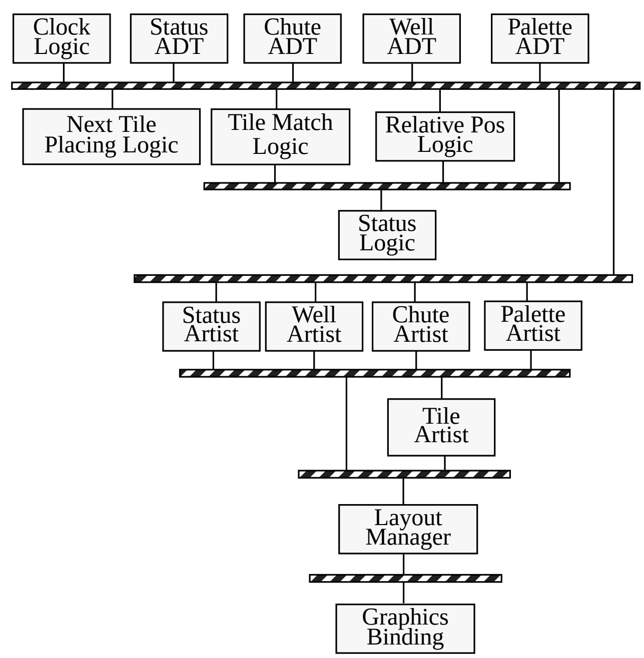


Fig. 4. Conceptual C2 architecture for KLAX. Note that the Logic and Artist layers do not communicate directly and are in fact siblings. The Artist layer is shown below the Logic layer since the components in the Artist layer perform functions closer to the user.

The KLAX architecture is intended to support a family of "falling-tile" games. The components were designed as reusable building blocks to support different game variations. One such variation is described in [TMA+96].

To support the implementation of the KLAX architecture, a C++ framework consisting of classes for C2 concepts such as components, connectors, and messages was developed. The size of this reusable framework is approximately 3100 commented lines of C++ code and it supports a variety of implementations, discussed in [TMA+96], for a single conceptual architecture. This framework is also useful since it allowed us to integrate the Xlib toolkit, by wrapping it to become the C2 *GraphicsBinding* component. The KLAX implementation built using the framework consists of approximately 8100 additional lines of commented C++ code.

Performance of the implementations was good on a Sun Sparc2 workstation, easily exceeding human reaction time if the *ClockLogic* component was set to use short time intervals. Although we have not yet tried to optimize performance, benchmarks indicated our current framework can send 1200 simple messages per second when sending and receiving components are in the same process. In the KLAX system, a keystroke typically caused 10 to 30 message sends, and a tick of the clock typically caused 3 to 20.

## IV. KLAX Constraints

In its form as described above, KLAX does not necessarily need a constraint solver. Its constraint management needs would certainly not exploit the full power of a solver such as SkyBlue, e.g., handling constraint hierarchies. On the other hand, we think it should be possible to use a powerful constraint manager for maintaining a small number of simple constraints. Additionally, the main purpose of this effort was to explore the architectural issues in integrating OTS components into a C2 architecture. We therefore opted not to unnecessarily expend resources to artificially create a situation where a number of complex constraints needed to be managed. Instead, we decided to integrate SkyBlue with KLAX in its present form. If we were unable to do so, there would be at least three possible sources of problems: (1) the C2 style, (2) the KLAX architecture, and (3) SkyBlue. In any case, we would learn a useful lesson.

We defined the following 4 constraints for management by SkyBlue:

- *Palette Boundary:* The palette cannot move beyond the chute and well's left and right boundaries.
- *Palette Location:* Palette's coordinates are a function of its location and are updated every time the location changes.[2]
- *Tile Location:* The tiles which are on the palette move with the palette. In other words, the x coordinate of the center of the tile always equals the x coordinate of the center of the palette.
- *Resizing:* Each game element (chute, well, palette, and tiles), is maintained in an abstract coordinate system by its artist. This constraint transforms those abstract coordinate systems, resizing the game elements to have the relative dimensions depicted in Fig. 3 before they are rendered on the screen. This constraint would be essential in a case where the application is composed from preexisting components supplied by different vendors. A similar constraint could also be used to accommodate resizing of the game window, and hence of the game elements within it.

2. Location is an integer between 1 and 5.

## V. Integrating SkyBlue with KLAX

The four constraints were defined based on the needs of the overall application. Further thought was still needed to decide the location of the constraint manager in the KLAX architecture. There clearly were several possibilities. One solution would have been to include SkyBlue within the appropriate components for the *Palette Boundary*, *Palette Location*, and *Tile Location* constraints, since they are local constraints. The *Resizing* constraint pertains to several game elements, and would thus belong in a separate component.

We initially opted for another solution: define all four constraints in a centralized constraint manager component. The *LayoutManager* component was intended to serve as a constraint manager in the original design of KLAX shown in Fig. 4. However, in the initial implementation, the constraints were solved with in-line code locally in the *PaletteADT* and *PaletteArtist* and the sole purpose of the *LayoutManager* was to properly line up game elements on the screen. The implemented version of the *LayoutManager* also placed the burden of ensuring that the game elements have the same relative dimensions on the developers of the *PaletteArtist*, *ChuteArtist*, and *WellArtist* components. Incorporating constraint management functionality into the *LayoutManager* therefore rendered its implementation more faithful to its original design.

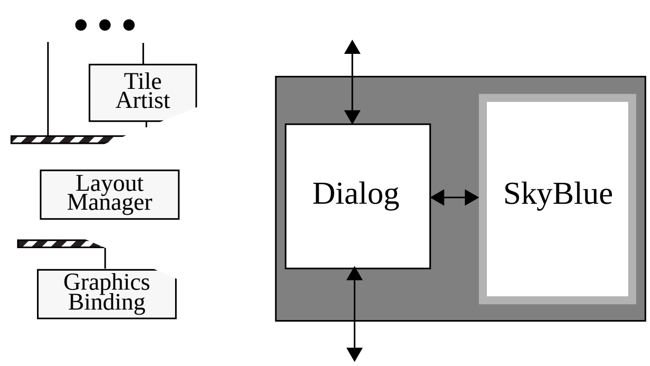


Fig. 5. The SkyBlue constraint management system is incorporated into KLAX by placing it inside the *LayoutManager* component. *LayoutManager*'s dialog handles all the C2 message traffic.

The constraints were defined in the "dialog and constraints" part of the *LayoutManager* component (see Fig. 2), while SkyBlue became the component's internal object. As such, SkyBlue has no knowledge of the architecture of which it is now a part. It maintains the constraints, while all the request and notification traffic is handled by *LayoutManager*'s dialog, as shown in Fig. 5. *LayoutManager* thus became a constraint management component in the C2 style that can be reused in other applications by only modifying its dialog to include new constraints.[3]

*PaletteADT, PaletteArtist, ChuteArtist,* and *WellArtist* also needed to be modified. Their local constraint management code was removed. Furthermore, their dialogs and message interfaces were expanded to notify the *LayoutManager* of changes in constraint variables and to handle requests from the *LayoutManager* to update them. Only 11 new messages were added to handle this modification of the original application and there was no perceptible performance degradation. The entire experiment was completed by one developer in approximately 45 hours.

## VI. Integrating Amulet with KLAX

C2 supports reuse through component-based development, substrate independence, and domain translation. These features also support component substitutability and localization of change. We claim that, in general, two behaviorally equivalent components can always be substituted for one another [MORT96]. Furthermore, behavior preserving modifications to a component's implementation in an architecture have no architecture-wide effects.

In the example discussed in the previous section, this would mean that SkyBlue may be replaced with another constraint manager by only having to modify the "dialog and constraints" portion of the *LayoutManager* to define constraints as required by the new solver. The set of messages in *LayoutManager*'s interface and the rest of the KLAX architecture would remain unchanged.

To demonstrate this claim, we substituted SkyBlue with Amulet's one-way formula constraint solver. This exercise required extracting and recompiling the needed portion of Amulet.[4] Once the solver was extracted from the rest of Amulet, it was successfully substituted for SkyBlue and tested by one developer in 75 minutes. As anticipated, no architecture-wide changes were needed. The look-and-feel of the application remained unchanged. There was again no performance degradation.[5]

## VII. KLAX Component Library

Integrating SkyBlue and Amulet with KLAX provided an opportunity for building multiple versions of *PaletteADT, PaletteArtist*, and *LayoutManager* components. The two integrations described above resulted in three versions of the *LayoutManager*: the original, SkyBlue, and Amulet versions. These are listed as *LayoutManager* versions 1, 2, and 3 in Table 1. Two versions each of the *PaletteADT, PaletteArtist, ChuteArtist*, and *WellArtist* were created as well: original components maintaining local constraints with in-line code (versions 1 of the four components in Table 1) and components whose constraints were managed elsewhere in the architecture (versions 2 of the four components in Table 1).[6]

**Table 1: Implemented Versions of PaletteADT, PaletteArtist, ChuteArtist, WellArtist, and LayoutManager KLAX Components**

| | Version Number | Constraints Maintained | Constraint Managers |
|---|---|---|---|
| Palette ADT | 1 | Palette Boundary | In-Line Code |
| | 2 | None | None |
| | 3 | Palette Boundary | SkyBlue |
| | 4 | Palette Boundary | Amulet |
| Palette Artist | 1 | Palette Location<br>Tile Location<br>Tile Size | In-Line Code |
| | 2 | None | None |
| | 3 | Palette Location<br>Tile Location | SkyBlue |
| | 4 | Palette Location<br>Tile Location | Amulet |
| Chute Artist | 1 | Chute Size | In-Line Code |
| | 2 | None | None |
| Well Artist | 1 | Well Size | In-Line Code |
| | 2 | None | None |
| Layout Manager | 1 | None | None |
| | 2 | All | SkyBlue |
| | 3 | All | Amulet |
| | 4 | Resizing | SkyBlue |
| | 5 | Resizing | Amulet |
| | 6 | All | SkyBlue & Amulet |

The two initial integrations also suggested other variations of these components, such as replacing in-line constraint management code with SkyBlue and Amulet constraints in the *PaletteADT* and *PaletteArtist* (see Footnote 3). Also, a version of the *LayoutManager* was implemented that maintained only the *Resizing* constraint, in anticipation that other components will internally manage their local constraints (this scenario was briefly described at the beginning of Section V). This resulted in a total of 18 implemented versions of the five components, as depicted in Table 1.

## VIII. Plug and Play

The four versions of *PaletteADT* and *PaletteArtist*, two versions of *ChuteArtist* and *WellArtist*, and six versions of the *LayoutManager*, described in Table 1, could potentially

3. In the remainder of the paper, when we state that a constraint solver is "inside" or "internal to" a component, the internal architecture of the component will resemble that of the *LayoutManager* from Fig. 5.
4. This may seem like unnecessary work. However, we were unable to locate implementations of any other constraint solvers, which was the deciding factor in our selection. Furthermore, the availability of Amulet's source code and its implementation language (C++) made it a good candidate for this project.
5. For the purpose of brevity, in the remainder of the paper Amulet's one-way formula constraint manager will be referred to simply as "Amulet."

6. In the remainder of the paper, a particular version of a component will be depicted by the component name followed by the version number (e.g., *PaletteADT*-2).

be used to build 384 different variations of the KLAX architecture. Three such variations were described in Section III (using versions 1 of all five components), Section V (using versions 2 of the five components), and Section VI (replacing *LayoutManager*-2 with *LayoutManager*-3 in the architecture from Section V). In this section, we discuss several additional implemented variations of the architecture that exhibit interesting properties.

### *A. Multiple Instances of a Constraint Manager*

One architecture used *PaletteADT*-3, *PaletteArtist*-3, *ChuteArtist*-2, *WellArtist*-2, and *LayoutManager*-4. In other words, the *Palette Boundary*, *Palette Location*, and *Tile Location* constraints are defined and maintained in SkyBlue inside *PaletteADT* and *PaletteArtist*, while the *Resizing* constraints are maintained globally by the *LayoutManager*. Therefore, multiple instances of SkyBlue maintain the constraints in different KLAX components.

### *B. Partial Communication and Service Utilization*

Particularly interesting are components that are used in an architecture for which they have not been specifically designed, i.e., they can do more or less than they are asked to do. This is an issue of reuse: if we build components a certain way, are their users (designers) always obliged to use them "fully"; furthermore, can meaningful work be done in an architecture if two components communicate only partially, i.e., certain messages are lost? The architectures described below represent a crossection of experiments conducted to better our understanding of partial communication and partial component service utilization.

- A variation of the original architecture was implemented by substituting *LayoutManager*-2 into the original architecture described in Section III. In other words, the architecture was built with *PaletteADT*-1, *PaletteArtist*-1, *ChuteArtist*-1, *WellArtist*-1, and *LayoutManager*-2. *LayoutManager*-2's functionality remains largely unused as no notifications are sent to it to maintain the constraints. The application still behaves as expected and there is no performance penalty. Note that this will not always be the case: if *LayoutManager*-2 was substantially larger than *LayoutManager*-1 or had much greater system resource needs (e.g., its own operating system process), the performance would be affected.
- Another architecture was built using *PaletteADT*-3, *PaletteArtist*-2, *WellArtist*-1, *ChuteArtist*-1, and *LayoutManager*-2. The experiment was intended to explore heterogeneous approaches to constraint maintenance in a single architecture: some components in the architecture maintain their constraints with in-line code (*WellArtist* and *ChuteArtist*), others maintain them internally using SkyBlue (*PaletteADT*), while *PaletteArtist*'s constraints are maintained by an external constraint manager. *LayoutManager*-2 is still partially utilized, but a larger subset of its services is used than in the preceding architecture.
- *PaletteADT*-2, *PaletteArtist*-1, *ChuteArtist*-1, *WellArtist*-1, and *LayoutManager*-1 were used to build another architecture. This version of *PaletteADT* expects that some other component will maintain the *Palette Boundary* constraint. However, *LayoutManager*-1 does not understand and therefore ignores the notifications sent by *PaletteADT* (partial communication). Movement of the palette is thereby not constrained and the application behaves erroneously: the palette disappears when moved beyond its right boundary; the execution aborts when the palette moves beyond the left boundary and the *GraphicsBinding* component (see Section III) attempts to render it at negative screen coordinates.

The above examples seem to imply that partial service utilization generally has no ill effects on a system, while partial communication does. This is not always the case. For example, an additional version of each component from the original architecture was built to enable testing of the application. These components would generate notifications that were needed by both components below them in the architecture and the testing harness. If a "testing" component was inserted into the original architecture, all of its testing-related messages would be ignored by components below it, resulting in partial communication, yet the application would still behave as expected.

### *C. Multiple Constraint Managers in a Single Component*

*LayoutManager*-6 had some of its constraints defined in SkyBlue and others in Amulet. Combining multiple constraint solvers in a single *system* has only recently been identified as a potentially useful approach to constraint management [San94, MM95]. Integrating multiple constraint solvers in a single C2 *component* is certainly at a different level of granularity. However, this exercise sensitized us to several issues intrinsic to the interaction of heterogeneous constraint managers.

Specifying constraints in different solvers over disjoint sets of variables is a trivial task, since there are no dependencies between the solvers. On the other hand, if the two sets of constraint variables intersect, the problem is more complex. In our case, constraint variables in SkyBlue and Amulet are of different types, so that the same variable cannot be used in constraints specified in both solvers. Therefore, each conceptually common variable is implemented by two actual variables (*var_SkyBlue* and *var_Amulet*). Furthermore, additional functionality is needed to monitor the changes in the variables and programmatically update one when the other is changed due to constraint enforcement.

For example, in *LayoutManager*-6, *Palette Boundary*, *Tile Location*, and *Resizing* constraints are defined in SkyBlue, while *Palette Location* is specified in Amulet. Then, every time *location_SkyBlue* changes, its new value is assigned to *location_Amulet* so that Amulet can properly update the *paletteX_Amulet* variable. Then, to propagate its change through the rest of SkyBlue variables, *paletteX_Amulet*'s new value is copied into *paletteX_SkyBlue*.

Our solution to defining SkyBlue and Amulet constraints over overlapping sets of variables, although effective, was not particularly elegant. It had the feel of programming one's own application-specific constraint management functionality. While the purpose of the exercise was to investigate issues pertinent to C2, this problem has broader ramifications. A scenario where both a powerful but complex solver and a simple one are needed in an application is likely. Therefore, we consider the problem of multiple interacting constraint managers an open research issue that requires careful examination.

### *D. Multiple Constraint Managers in an Architecture*

An issue related to using multiple constraint managers inside a single component is using multiple constraint managers in different components, but in a single architecture. Such an architecture was built using PaletteADT-3, PaletteArtist-4, ChuteArtist-2, WellArtist-2, and LayoutManager-3. In this architecture, *Palette Boundary* and *Resizing* constraints are maintained by SkyBlue, and *Palette Location* and *Tile Location* by Amulet. Since the sets of constraint variables managed by the two solvers are disjoint, there are no interdependencies of the kind discussed in the previous example between SkyBlue and Amulet. Hence, this modification to the architecture was a simple one.

## IX. Conclusion

The full potential of component-based software architectural styles cannot be realized unless reusing code developed by others becomes a common practice. A new architectural style can become a standard in its domain only if it makes reuse easier. We believe that C2 is such a style for GUI software.

The series of experiments described in this paper demonstrate that C2 isolates changes inside components and limits any global effects of those changes through message-based communication. Furthermore, C2's principles of substrate independence and domain translation enable component substitutability. Finally, its component- and message-based nature allows partial communication and service utilization of components, which are essential to cost-effective reuse.

In a component-based style, such as C2, the number of possible architectures grows combinatorially as the number of behaviorally related components increases.[7] Thus, the 18 components depicted in Table 1 can generate 384 distinct versions of KLAX. Of course, every possible architecture is neither meaningful (e.g., the third example architecture in Section VIII.B) nor particularly interesting. This exercise fulfilled its purpose nonetheless, since it demonstrated the ease with which a library of components in the C2 style may be created.

Finally, we now have a constraint management component in the C2 style that will be reused across future applications. Beyond this immediate benefit, integrating SkyBlue and Amulet with KLAX has taught us an invaluable lesson on the intricacies of incorporating OTS components into C2 architectures. We will build upon this experience in our exploration of other facets of C2.

7. In [MORT96] we demonstrate how such components, e.g., the different versions of the *LayoutManager*, comprise a type hierarchy.

## X. Acknowledgements

We would like to acknowledge the members of the C2 research group for their contribution on various aspects of C2. We also wish to thank the developers of SkyBlue and Amulet for providing the source code to their systems and adequate documentation to ease our usage of them.

## XI. References

[GS93] D. Garlan and M. Shaw. *An Introduction to Software Architecture: Advances in Software Engineering and Knowledge Engineering*, volume I. World Scientific Publishing, 1993.

[MM95] R. McDaniel and B. A. Myers. Amulet's Dynamic and Flexible Prototype-Instance Object and Constraint System in C++. Technical Report, CMU-CS-95-176, Carnegie Mellon University, Pittsburgh, PA, July 1995.

[MORT96] N. Medvidovic, P. Oreizy, J. E. Robbins, and R. N. Taylor. Using object-oriented typing to support architectural design in the C2 style. Technical Report, UCI-ICS-96-6, February 1996.

[PW92] D. E. Perry and A. L. Wolf. Foundations for the Study of Software Architectures. *ACM SIGSOFT Software Engineering Notes*, pages 40-52, October 1992.

[RR96] J. E. Robbins and D. Redmiles. Software architecture design from the perspective of human cognitive needs. In *Proceedings of the California Software Symposium (CSS'96)*, Los Angeles, CA, USA, April 1996.

[San94] M. Sannella. SkyBlue: A Multi-Way Local Propagation Constraint Solver for User Interface Construction. In *Proceedings of the Seventh Annual ACM Symposium on User Interface Software and Technology*, Marina del Ray, CA, November 1994, pages 137-146.

[SG87] R. W. Scheifler and J. Gettys. The X Window System. *ACM Transactions on Graphics*, June 1987.

[TMA+95] R. N. Taylor, N. Medvidovic, K. M. Anderson, E. J. Whitehead, Jr., and J. E. Robbins. A Component- and Message-Based Architectural Style for GUI Software. In *Proceedings of the 17th International Conference on Software Engineering (ICSE 17)*, Seattle, WA, April 1995, pages 295-304.

[TMA+96] R. N. Taylor, N. Medvidovic, K. M. Anderson, E. J. Whitehead, Jr., J. E. Robbins, K. A. Nies, P. Oreizy, and D. L. Dubrow. A Component- and Message-Based Architectural Style for GUI Software. *IEEE Transactions on Software Engineering*, to appear, 1996.