Unit-Level Test Adequacy Criteria for Visual Dataflow Languages and a Testing Methodology

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Visual dataflow languages (VDFLs), which include commercial and research systems, have had a substantial impact on end-user programming. Like any other programming languages, whether visual or textual, VDFLs often contain faults. A desire to provide programmers of these languages with some of the benefits of traditional testing methodologies has been the driving force behind our effort in this work. In this article we introduce, in the context of prograph, a testing methodology for VDFLs based on structural test adequacy criteria and coverage. This article also reports on the results of two empirical studies. The first study was conducted to obtain meaningful information about, in particular, the effectiveness of our all-Dus criteria in detecting a reasonable percentage of faults in VDFLs. The second study was conducted to evaluate, under the same criterion, the effectiveness of our methodology in assisting users to visually localize faults by reducing their search space. Both studies were conducted using a testing system that we have implemented in Prograph's IDE.

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1. INTRODUCTION

Visual dataflow languages (VDFLs) provide meaningful visual representations for the creation, modification, execution and examination of programs. In VDFLs, users code by creating icons (operations) and linking them together. In this article, we refer to this activity as *visual coding*. The icons, or visual constructs, are the source code, rather than merely visual representations of a textual code that lies beneath the icons. In VDFLs, the order of execution, when not explicitly defined by the user, is determined by the visual language's editing engine. That is, the computation is governed by the dataflow firing rule, which states that a computational element can execute as soon as sufficient incoming data has arrived to begin the computation. This model of execution, known as the *dataflow computational model*, has inspired several visual programming languages (Bernini and Mosconi [1994], Kimura et al. [1990], and Fisk [2003]). It is, in general, conceptualized as a kind of fluid that flows through linkages between computational elements. The elements can be thought of as filters or processors that use the incoming data to produce a new stream of outgoing data. In a pure dataflow computational model, control constructs are not explicitly specified by the programmer; rather, the order of execution is implied by the operations' data interdependencies. To allow the user to explicitly add control constructs such as those found in imperative languages, VDFLs [Shafer 1994; Marten 2005] extended the pure computational dataflow model to include the necessary control constructs. This extension, as some researchers believe, is necessary for a dataflow language to have any practical use in developing traditional software. Thus a visual program that is based on the dataflow computational model can be characterized by both its data and control dependencies.

VDFLs are widely used, by researchers and end-users alike for a variety of research and development tasks. For example, there is research into steering scientific visualization [Burnett et al. 1994], using VDFLs for writing functional programs [Kelso 2002], writing and evaluating XML and XPath queries [Boulos et al. 2006; Karam et al. 2006], developing general-purpose applications [Shafer 1994], building domain-specific applications such as those used for laboratory instrumentations [Paton 1998], and buffering of intermediate results in dataflow diagrams [Woodruff and Stonebraker 1995]. In general, researchers feel that it is in these directions that visual dataflow programming languages show the most promise.

Despite claims that the use of graphics in VDFLs allows direct and concrete representations of problem-domain entities, and that the direct representations can simplify the programming task of researchers and developers alike, we found that many informal investigations into VDFLs reveal that, like any other languages, they contain faults. A possible factor in the existence of these

faults, as argued by Meyer and Masterson [2000], is most likely related to incorrect control annotations and datalinks. In spite of this evidence, we have found no related discussions in the research literature of techniques for testing or evaluating a testing methodology that can reveal faults and assist in fault localization in VDFLs. In fact, there has been some work on testing in other paradigms. For example, in the domain of form-based languages, recent work has focused on testing visual form-based languages [Rothermel et al. 2001]. Although the visual dataflow paradigm is similar to the visual form-based paradigm in that they are both visual, several characteristics of the form-based paradigm, such as the dependency-driven nature of its evaluation engine and the responsiveness of its editing environment, suggest a different approach when testing dataflow languages. There has also been work on specification-based testing for imperative languages [Kuhn and Frank 1997; Ouabdesselam and Parissis 1995]. Since most VDFLs are intended for use by a variety of researchers and professional end-users alike, few of these users are likely to create specifications for their programs [Wing and Zaremski 1991]. Moreover, even when specifications exist, evidence suggests that code-based testing techniques can provide an effective mechanism for detecting faults [Hutchins et al. 1994; Wong et al. 1995] and increasing software reliability [Del Frate 1995]. Other research (e.g., Azem et al. [1993], Belli and Jack [1993], and Luo et al. [1992]) considered problems of testing and reliability determination for logic programs written in Prolog. Although VDFLs are comparable to logic-based programs in that both are declarative (i.e., declaring data and control dependencies between operations), several features of the logic paradigm, such as the bidirectional nature of unification, and backtracking after failure, are so different from VDFLs that the testing techniques developed for Prolog cannot be applied to VDFLs.

On the other hand, there has been extensive research on testing imperative programs (e.g., Clarke et al. [1989], Frankl and Weiss [1993], Frankl and Weyuker [1988], Harrold and Soffa [1988], Hutchins et al. [1994], Korel and Laski [1983], Ntafos [1984], Offutt et al. [1996], Perry and Kaiser [1990], Rapps and Weyuker [1985], Rothermel and Harrold [1997], Weyuker [1986, 1993], and Wong et al. [1995]). In fact, the family of testing criteria we present for VDFLs in this article is rooted in the body of the aforementioned work on imperative testing. There are significant differences between VDFLs and imperative languages, and these differences have ramifications for testing strategies of VDFLs. These differences can be divided into three classes, as described next.

The first class pertains to the evaluation or execution order. The order of execution of nonpredicate operations or statements is not predetermined by the programmer, but is simply based on data dependencies. If we were to construct, as with imperative languages, a control flow graph (CFG) that represents the flow of control in VDFLs, taking into consideration all possible execution orders, it would be extremely large and complex. It would also most likely be impossible to satisfy any criteria using this graph, since most dataflow language implementations choose a specific execution ordering for non-predicate operations, and use it for every execution. This is, in fact, the execution behavior of VDFLs. The execution order is maintained by a topological sort that is performed on

all operations during the phases of visual coding and modification of the code. Since we are not considering, for the purpose of our current work, operations, that can have side-effects (object-oriented features such as the *get* and *set* operations that read and respectively write objects' data, and global variables), any execution order of a sequence of non-predicate operations will yield the same result. Thus we need only consider one order—the one determined by the editing engine of the language. In future work we intend to address the side effects issues.

The second class of differences pertains to performing static source code analysis in VDFLs. With imperative languages, a wide range of techniques for computing source code (control-flow and dataflow) analysis in individual procedures and programs are well known [Aho et al. 1986] and have been used in various tools, including data-flow testers (e.g., Korel and Laski [1985], Frankl et al. [1985], and Harrold and Soffa [1988]). With VDFLs, however, the variable declaration process and the visual constructs' characteristics have impact on how precisely and efficiently source code analysis can be done. First, in general, variables in VDFLs cannot be explicitly defined; that is, users write programs by creating icons that are connected via datalinks. In general, a datalink is created between an *outgoing* port on one icon, and an *incoming port* on another. In VDFLs such as the one we are considering in this work, outgoing ports are known as *roots*, and incoming ports are known as *terminals*. One way to deal with the implicit declaration of variables is to think of roots as variable definitions, and terminals connected to those roots as variable uses. Second, although formal grammars for pictures [Zhang and Zhang 1997] and parsing algorithms for pictorially represented programs have been investigated [Chang et al. 1989], none of these techniques is applicable to VDFLs for the purpose of efficiently performing source code analysis. One of the solutions to overcome this difference is to take advantage of the control-flow and data-flow information that can be obtained from the data structures maintained by the editing engine of VDFLs.

The third class of differences pertains to the reporting mechanisms of test results. With imperative languages, the use of textual logs as a way to view test results, albeit difficult to read and interpret, is practically impossible in VDFLs. Test results of VDFLs should be reported in a way that complements the visual constructs, given their unique characteristics and properties. For example, some indication should be given to the tester when a datalink connecting a variable definition to its use is not exercised. Therefore, the reporting mechanism should be visual and well incorporated within the integrated development environment (IDE) that supports the implementation of the VDFL.

In Section 2 of this article, we present Prograph's syntax and its formal semantics. In Section 3, we present a family of structural unit-based test adequacy criteria for VDFLs. In Section 4, we examine the applicability of several code-based data-flow applicability criteria for testing VDFLs. In Section 5, we introduce our a methodology that takes advantage of the aforementioned classes of differences to achieve efficient and precise control-flow and dataflow analyses in VDFLs, and provides a testing environment that implements, in particular, the all-Dus. The testing environment accommodates the user base of VDFLs

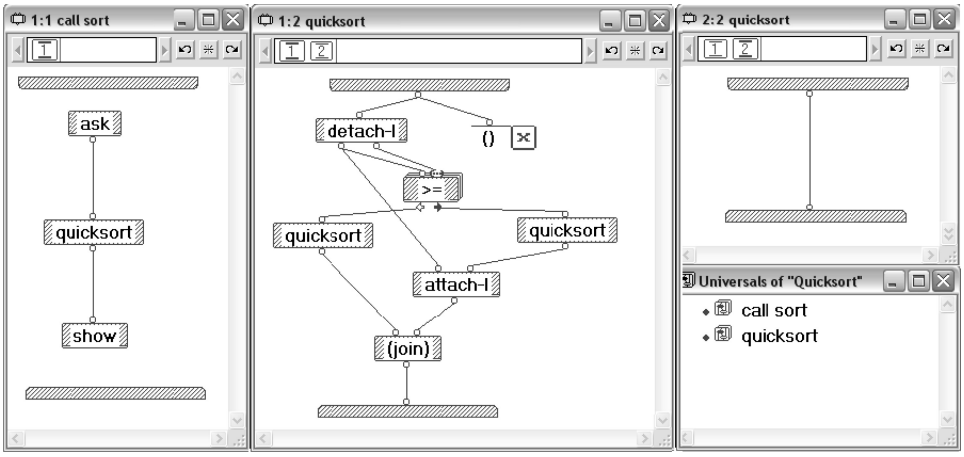


Fig. 1. A Prograph program for quicksort.

with a visual interface that is augmented with a color mapping scheme [Jones et al. 2002] that facilitates the task of localizing faults by reducing their search space without requiring a formal testing theoretical background. In Section 6, we describe the design of our experiments and present the empirical results obtained. Section 7 concludes the article with a summary of our contributions and an outline of planned directions of future work.

2. VISUAL DATAFLOW LANGUAGES

Since much of our work is based on the visual programming environment of Prograph [Shafer 1994], we will next informally introduce its syntax and semantics using the example that is depicted in Figure 1.

2.1 Prograph

Figure 1 shows a Prograph implementation of the well known algorithm *quicksort* for sorting a list into ascending order. The bottom right window entitled Universals of "Quicksort" in this figure, depicts two icons for the methods, call sort and quicksort. Note that Prograph is an object-oriented language; hence the term *method* or *universal* is used to refer to entities known as *procedures* in imperative programming languages.

The left side window, entitled 1:1 call sort in Figure 1, shows the details of the method call sort, a dataflow diagram in which three operations are connected and scheduled to execute sequentially. The first operation in this diagram, ask, is a primitive that calls system-supplied code to produce a dialogue box requesting data input from the user (or a list of numbers typed into the dialogue box). Once the ask primitive has been executed, the data entered by the user flows down the datalink to the operation quicksort, invoking the method quicksort. This method expects to receive a list, which it sorts as explained below, outputting the sorted list, which flows down the datalink to the show operation. The show produces a dialogue displaying the sorted list. The small circle icons on the top and bottom of an operation, representing inputs and outputs, are

called terminals and roots, respectively. Note that the 1:1 in the window entitled 1:1 call sort, indicates that the method call sort has only one case associated with it. In general, a method consists of a sequence of cases. More on what a case is and how it executes can be found next.

The method quicksort consists of two cases, each represented by a dataflow diagram as shown in the windows entitled 1:2 quicksort and 2:2 quicksort of Figure 1, respectively. The first case, 1:2 quicksort, implements the recursive case of the algorithm, while the second, 2:2 quicksort, implements the base case. The thin bar-like operation at the top of a case, where parameters are copied into the case, is called an *input-bar*, while the one at the bottom, where results are passed out, is called an *output-bar*. In the first case of quicksort, the first operation to be executed is the match operation, which tests to see if the incoming data on the root of the input-bar is the empty list. The check mark icon attached to the right end of the match is a *next-case on success control*, which is triggered by success of the match, immediately terminating the execution of the first case and initiating execution of the second case. If this occurs, the empty list is simply passed through from the input-bar of the second case to its output-bar, and execution of quicksort finishes, producing the empty list.

If the input list is not empty, the control on the match operation in the first case is not triggered, and the first case is executed. Here, the *primitive* operation detach-l (or detach left) outputs the first element of the list and the remainder of the list on its left and right roots respectively. Next, the operation, , is executed. This operation is an example of a *multiplex*, illustrating several features of the language. First, the three-dimensional representation of the operation indicates that the primitive operation >= will be applied repeatedly. Second, the terminal annotated as is a *list-terminal*, indicating that a list is expected as data, one element of which will be consumed by each execution of the operation. In this example, when the multiplex is executed, the first element of the list input to the case will be compared with each of the remaining elements. Finally, the special roots and indicate that this particular multiplex is a *partition*, which divides the list of items arriving on the list annotated terminal into two lists items for which the comparison is successful, and those for which it is not. These two lists appear on the and roots, respectively.

The lists produced by the partition multiplex are sorted by recursive calls to the quicksort method. The final sorted list is then assembled using two primitive operations: attach-l, which attaches an element to the left end of a list, and (join), which concatenates two lists.

The execution mechanism of Prograph is data-driven dataflow. That is, an operation executes when all its input data is available. In practice, a linear execution order for the operations in a case is predetermined by topologically sorting the directed acyclic graph of operations and subject to certain constraints. For example, an operation with a control should be executed as early as possible.

In our example the method quicksort has only one input and one output, and therefore does not illustrate the relationship between the terminals of an operation and the roots of the input-bar in a case of the method it invokes. These terminals and roots must be of equal number, and are matched from

left to right. A similar relationship exists between the roots of an operation and the terminals of the output-bar in a case of a method invoked by the operation.

One important kind of operation not illustrated in the above example is the local operation. A local operation is one that does not call a separately defined method, such as the quicksort method shown above. Instead, it contains its own sequence of *cases* and their operations, and is therefore analogous to a parameterized begin-end block in a standard procedural language. A local operation is often referred to as local method, and can also have roots and terminals attached to it. Roots and terminals on a local operation can be annotated with a loop to create a repeating case or cases. *Terminate on success*, and *Terminate on failure*, as the names indicate, are controls that can be applied to operations in a local operation to stop the iterations during execution. More information on the operations and possible control can be found in Section 3.2.

The formal semantics of Prograph are defined by specifying an *execution function* for each operation in a program. Each execution function maps a list X to a pair (Y, c), where c is a control flag, Y is a list, and the lengths of the lists X and Y are, respectively, equal to the number of terminals and the number of roots of the operation, and the elements X and Y are from a domain Δ containing all values of simple types and instances of classes. Execution functions may produce the special value **error**; for example, if a list terminal receives a value that is not a list. By defining execution functions for operations, the input/output behavior of a program is specified. To find more on the language syntax and semantics, see Shafer [1994].

3. A FAMILY OF TEST ADEQUACY CRITERIA FOR VISUAL DATAFLOW LANGUAGES

As previously mentioned, test adequacy criteria have been well researched for imperative languages. In this section, we explore the appropriate applicability of several of these criteria (e.g., Laski and Korel [1983], Ntafos [1984], and Rapps and Weyuker [1985]) to VDFLs. We argue that an abstract control-flow model, which is common to all these test adequacy criteria, can be appropriately adapted to VDFLs. Moreover, we argue that code-based data-flow test adequacy criteria, which relate test adequacy to interactions between definitions and uses of variables in the source code (definition-use associations), can be highly appropriate for VDFLs; in particular that of Rapps and Weyuker [1985]. There are several reasons for this appropriateness. The first reason involves the types of faults that have been known to occur in VDFLs, the largest percentage of which have been observed to involve errors in incorrect or missing controls, and datalinks [Meyer and Masterson 2000]. Second, the application of [Rapps and Weyuker 1985] criteria, combined with the use of the color mapping scheme of Jones et al. [2002] on the datalink constructs of VDFLs, can be shown to provide significant advantages including a relative ease of applicability to individual datalinks (or, as we show later in Section 4.2 definition-use associations) and an increased ability to localize faults.

3.1 The Abstract Model for Prograph

Test adequacy criteria are often defined on models of programs rather than on the code itself. We have created such a model for VDFLs [Karam and Smedley 2001] that we call the operation case graph (OCG). In this article we augment the *OCG* to represent the complete set of Prograph's operations and their applicable controls. These are: input-bar; output-bar; locals; and universal methods or functions; Constants; match; and primitives or system defined methods. These operations may have the following control annotations: next-case, finish, terminate, fail, continue, or repeat annotation. Roots and terminals on locals or universals may have list or loop annotations. An operation that is control annotated is referred to as a predicate operation otherwise it is a *non-predicate* operation.

Given a Prograph procedure p in a program P, we say that since each procedure consists of one or more cases, we define an abstract graph model for Prograph by constructing an *OCG* for each case c in p or $OCG_{(c)}$. Each $OCG_{(c)}$ has a unique entry and exit nodes n_e, and n_x respectively, and will be assigned the name and label of its corresponding case in Prograph. For example, if a method X has two cases 1:2 *X* and 2:2 *X* denoting X *case one* of *two* and *X case two* of *two*, respectively, the *OCG* graphs will be labeled $OCG_{(1:2X)}$ and $OCG_{(2:2X)}$. A local operation, as previously mentioned, has its own sequence of cases, and each case will also have its own *OCG*. We next describe the building process of the control-flow abstract model of $OCG_{(p)} = \{OCG_{(c1)}, OCG_{(c2)}, \ldots, OCG_{(cn)}\}$ in the context of the example of Figure 2, which is designed to introduce all the control constructs of Prograph.

3.2 The Building Process of the OCGs

Most test adequacy criteria for imperative languages are defined in terms of abstract models of programs, rather than directly on the code itself. This means that the code is translated into a control-flow graph (CFG) and testing is applied to the graph representing the code. This definition reflects explicitly the code constructs, and program execution follows the flow of control in the CFG. In general, to construct a CFG for a function f or $CFG_{(f)}$, f is decomposed into a set of disjoint blocks of statements. A block is a sequence of consecutive statements in which the flow of control enters at the beginning of the block and leaves at the end without halt or the possibility of branching, except at the end. A control transfer from one block to another in $CFG_{(f)}$ is represented by a directed edge between the nodes such that the condition of the control transfer is associated with it.

With VDFLs, the dataflow computational model (control and data dependency) makes grouping several non-predicate operations in one block not very desirable, since the execution order is determined by the editing engine. Therefore, to deal with the first class of differences between imperative languages and VDFLs that we mentioned in Section 1, we represent each procedure $p \in P$ with an $OCG_{(p)}$ that preserves two properties of p's operations: data and control dependencies. With regard to preserving the data dependencies, we say that for each procedure p, there is a sequence of operations,

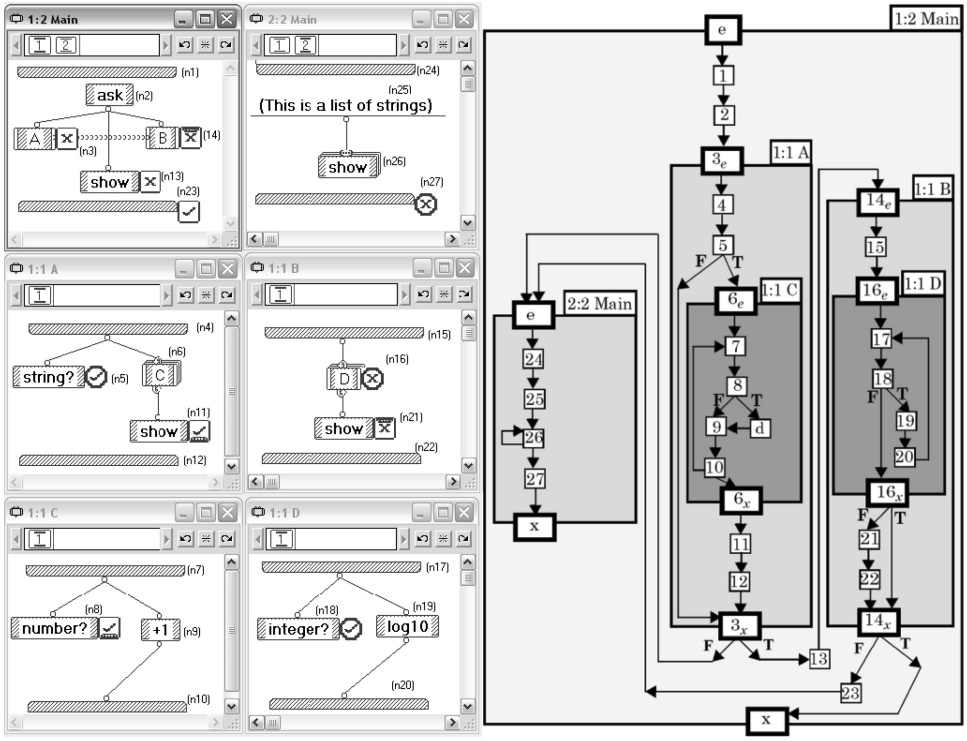


Fig. 2. Universal method *Main*, and *Locals A, B, C*, and *D*.

$O = \{o_1, o_2, o_3, \ldots, o_m\}$, whose order corresponds to a valid execution ordering with respect to the data dependencies in the procedure (in particular, this will be the execution order chosen by the editing engine). Thus, to model the data dependencies in $OCG_{(p)}$ and preserve the execution order, we represent each noncontrol nonlocal operation $o_i \in O$, with a node $n_i \in OCG_{(c)} \in OCG_{(p)}$ linked together with an edge to n_{i+1}, the node representing the next operation $o_{i+1} \in O$, provided that o_{i+1} is a nonlocal operation. If o_{i+1} is a local operation, then we construct the edge to the entry node n_e of the local operation's. For example, as depicted in Figure 2, the operation labeled n_2 is represented with node 2[1] in $OCG_{(Main)}$, and an edge is constructed to node n_{3e}, the entry node of the local operation represented by $OCG_{(1:1A)}$. For each non-control local operation $o_i \in O$, we construct the appropriate $OCG_{(o_i)}$ with n_e and n_x, the entry and exit nodes of $OCG_{(o_i)}$, respectively, and construct an edge from n_x to n_{i+1}, the node representing the next operation $o_{i+1} \in O$, provided that o_{i+1} is not a local operation. If o_{i+1} is a local operation, then we construct an edge to its entry node n_e.

To represent the control dependencies between operations in O, we classify the set of operations O into two subsets, O_s and O_x, where $O_s \in O$ is the

[1]It is assumed that when we say n_k we make reference to an operation in the Prograph code, and when we say node k we make reference to n_k's corresponding node in the OCG.

subset of operations that always succeed by default, and $O_x \in O$ is the subset that do not. This classification is necessary to accurately represent and account for the flow of control in $OCG_{(p)}$, since control annotated operations $\in O_s$ (on failure) do not change the control flow of the program. For example, in Figure 2, the primitive operation show that is labeled n_{13}, which is annotated with a next-case on failure⊠. Since n_{13} succeeds by default, the control flow in $OCG_{(1:2Main)}$ will not be affected. However, had the control been applied (on success) to n_{13}, the flow of control would have been affected, and subsequently, when the operation is evaluated, the control will be transferred to the next case 2:2 Main or $OCG_{(2:2Main)}$. The output-bar, among other operations, belongs to O_s.

Therefore, to represent the control dependencies between operations in O, we perform static analysis on each control annotated operation $o_i \in O$. Next, we present each control and discuss how it is represented in the *OCG*.

Next-Case annotation. An operation o_i with a next-case annotation will be represented as follows: If o_i is a nonlocal operation $\in O_x$, then o_i will be represented by a node n_i with two edges coming from it (*true* and *false*), one connected to n_{i+1}, which is the node representing the next sequential operation o_{i+1} in the current case, and the other to entry node n_e of the next case. If o_i is a nonlocal operation $\in O_s$, we check the type of the control annotation, if it is next-case on failure⊠, we ignore the control; however, if it is a next-case on success☑, we construct an edge to the entry node n_e of the next case. For example, as depicted in Figure 2, the operation labeled n_{23} is annotated with a next-case on success, so we construct an edge from node *23,* its corresponding node in $OCG_{(1:2Main)}$, to the entry node of the $OCG_{(2:2Main)}$. If o_i is a local operation $\in O_x$, we construct the appropriate $OCG_{(o_i)}$, with its n_e and n_x, respectively. We recursively process all of o_i's content, and then construct two edges on n_x of o_i to represent the flow of control (true and false): one to n_{i+1}, the node representing the next sequential operation o_{i+1} in the current case; and the other to n_e, the entry node of the next case. For example, as depicted in Figure 2, since the local operation labeled n_3 is annotated with a next-case on Failure, we represent it with $OCG_{(1:1A)}$, and construct two edges on its n_x, one to the next operation n_{13}, and the other to n_e of $OCG_{(2:2Main)}$.

Finish annotation. An operation o_i with a finish annotation is unique in the sense that, when evaluated/activated in non-repeated or looped case, the flow of control does not change upon the outcome of the finish control. This means that if the outcome is either true or false, the next node that gets evaluated or executed is the same. The same situation occurs when the finish annotated operation happens to be in a repeated or looped case; however, here the true or false outcome may set a flag that will indicate whether successive iterations will take place after finishing the current iteration. Thus, to handle a finish annotated operation, whether in a repeated or nonrepeated case, and represent both its true and false outcomes, an operation o_i with a finish annotation will be represented as follows: if o_i is a nonlocal operation $\in O_s$, we simply ignore the evaluation of its control (on success or failure), and represent o_i with a node

n_i with one edge connected to n_{i+1}, the node representing the next sequential operation o_{i+1}. If o_i is a nonlocal operation $\in O_x$, we represent o_i with a node n_i with two edges coming out from it (*true* and *false*), one edge connected to n_{i+1}, the node representing the next sequential operation o_{i+1} in the current case, and the other edge to a dummy node *d*. From the dummy node *d*, we also construct an edge to n_{i+1}. The reason for constructing this edge is to allow the flow of control to go to n_{i+1} when the outcome of the finish control goes through the dummy node *d*. When *d* exists in a looped-local and is traversed, it sets a flag value that indicates whether the loop edge can be traversed. For example, as depicted in Figure 2, the operation labeled n_8 is annotated with a finish on success☑. We therefore represent n_8 with node 8 in $OCG_{(1:1C)}$, and construct two edges from it, one to the next operation n_9, and the other to *d*, the dummy node. If o_i is a local operation $\in O_x$, we construct the appropriate $OCG_{(o_i)}$, with its n_e and n_x, respectively. We recursively process all of o_i's content, and then construct two edges on n_x of o_i to represent the flow of control (true and false): one to n_{i+1}, the node representing the next sequential operation o_{i+1} in the current case; and the other to dummy node *d*.

Terminate annotation. An operation o_i with a terminate annotation will be represented as follows: if o_i is a nonlocal operation $\in O_s$, we check the type of the control annotation, if it is terminate on failure☒, we ignore the control. For example, as depicted in Figure 2, the operation labeled n_{21} is annotated with a terminate on success, so we construct an edge from node *21,* its corresponding node in $OCG_{(1:2C)}$, to node n_{i+1} or node *22*. However, if o_i is annotated with a terminate on success☑, we construct an edge to n_x, the exit node of the current case. If o_i is a nonlocal operation $\in O_x$, we represent o_i with a node n_i with two edges coming from it (true and false): one edge connected to n_{i+1}, the node representing the next sequential operation o_{i+1} in the current case; and the other edge to n_x, the exit node of the current case. If o_i is a local operation $\in O_x$, we construct the appropriate $OCG_{(o_i)}$, with its n_e and n_x, respectively. We recursively process all of o_i's content, and then construct two edges on n_x of o_i to represent the flow of control (true and false): one to n_{i+1}, the node representing the next sequential operation o_{i+1} in the current case; and the other to n_x, the exit node of the current case. For example, as depicted in Figure 2, the operation labeled n_{14} is annotated with a terminate on failure, so we construct its $OCG_{(1:1B)}$, and construct on the n_x of $OCG_{(1:1B)}$ or node 14_x two edges, one to node n_{i+1} or node *23,* and the other to the exit node *x* of $OCG_{(1:2Main)}$.

Fail annotation. The evaluation of an operation o_i with a fail annotation is analogous to exception throwing in imperative languages. An operation o_i with a fail annotation will be represented as follows: if o_i is a nonlocal operation $\in O_s$, we check the type of the control and if it is fail on failure☒ we ignore the control. For example, as depicted in Figure 2 the operation labeled n_{27} is annotated with a fail on failure, so we ignore the control, and we just construct an edge from node *27*, to the exit node *x* of $OCG_{(2:2Main)}$. However, if the control is fail on success☑, we construct an edge to the entry node n_e of the next case. If o_i is a nonlocal operation $\in O_x$, o_i will be represented by a node n_i with

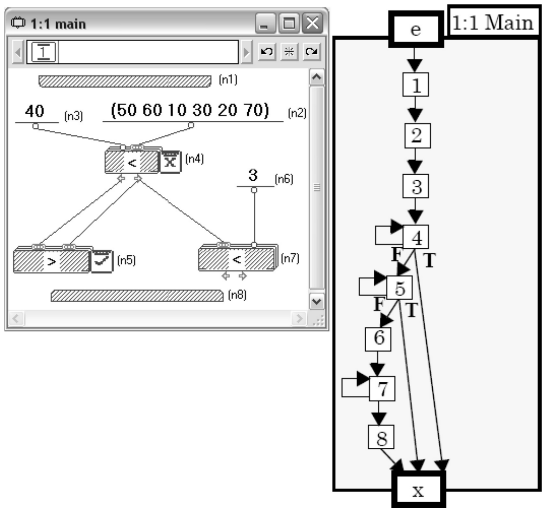


Fig. 3. Illustrating the list and partition control.

two edges coming from it (true and false): one connected to n_{i+1}, which is the node representing the next sequential operation o_{i+1} in the current case; and the other to n_x, the exit node of the current case. If o_i is a local operation $\in O_x$, we construct the appropriate $OCG_{(o_i)}$, with its n_e and n_x, respectively. We recursively process all of o_i's content, and then construct two edges from n_x of o_i, to represent the flow of control (true and false) one to n_{i+1}, the node representing the next sequential operation o_{i+1} in the current case, and the other to n_x, the exit node of the current case. For example, as depicted in Figure 2, the local looped operation labeled n_{16} is annotated with a fail on failure. We therefore represent it with $OCG_{(1:1D)}$, and construct two edges from its exit node 16_x, one to the next operation node *21,* and the other to the exit node of $OCG_{(1:1C)}$ or node 14_x.

List, repeat, partition, or loop annotation. An operation o_i with a list, repeat, partition, or a loop annotation, will be represented according to the type of the operation. If o_i is a nonlocal operation $\in O_s$, we represent it with a node n_i, and construct an edge that goes out of n_i and back into n_i, and construct another edge to n_{i+1}, the next node in the case. For example, as depicted in Figure 2, the operation labeled n_{26} is annotated with a list control, and we therefore represent it with node *26* and construct one edge that goes out of node *26* and back into it, and another edge to node *27*. If o_i is annotated with a second control on success, we construct the appropriate edges; otherwise we simply ignore it because it will not have any effect on the control flow of the program. If o_i is a nonlocal operation $\in O_x$, we represent it with a node n_i, construct an edge that goes out of n_i and back into n_i, and construct another edge to n_{i+1}, the next node in the case. We then check to see if o_i is annotated with a second control. If o_i is annotated with a control annotation, we construct the appropriate edges that represent the control. For example, as depicted in Figure 3, the operation

labeled n_4 is annotated with a partition control, and therefore we represent it with node *4* and construct an edge that goes out of node *4* and back into it. We then construct, as previously described for the terminate control, two edges: one to node *5*, and the other to the exit node. Another example is the list annotated operation n_5 in Figure 3. It should be noted that although the operation labeled n_7 is annotated with a partition control, it does not alter the control flow of the program, and therefore, as depicted in Figure 3, we represent it by constructing node *7*, and an edge that comes out of node *7* and back into it. If o_i is a local operation $\in O_x$, we construct an edge from the node representing the output-bar of $OCG_{(oi)}$ to the node representing the input-bar. For example, in $OCG_{(1:1C)}$ of Figure 2, the *OCG* representing the local operation labeled n_6 that is annotated with a loop control, we construct an edge from the output-bar of $OCG_{(1:1C)}$ or node *10* to its input-bar or node *7*. If o_i is control annotated, as it is the case with the local operation labeled n_{16}, we then construct the appropriate edges, as previously described for the fail control: one to node *21*, and the other to node 14_x.

3.3 Control-flow Test Adequacy Criteria For Visual Dataflow Languages

In imperative languages, a test adequacy criterion fails to be applicable if it requires coverage of nonexecutable code constructs, often referred to as *dead code*. For such code, it is a common practice to render the applicable criterion and redefine it so that it is applicable to executable code only. In VDFLs, a similar approach applies; we next define our applicable node and control test adequacy criteria for VDFLs. Before we do that, however, we need to first define a test case and a test suite for VDFLs. Formally, a test suite can be defined as follows:

Definition 3.1 (A test suite T in VDFLs). We define a test case t for a *universal* method p to be the tuple $(z, i, o_{v/i}, c_n)$, where: z is the test case number; i is a set of input values for t; $o_{v/i}$ is p's output valid/invalid results, and c_n is the set of exercised nodes in $OCG_{(p)}$ that is obtained as the result of executing t on p. We say that t is valid or $t = (z, i, o_v, c_n)$ if the actual output for an execution of p with t is the same as the expected output for t; otherwise, t is invalid or $t = (z, i, o_i, c_n)$. Having defined what a test case is, a test suite T can then be defined as the tuple $(Z, I, O_{V/I}, C_N)$, where: $Z = \{z_1, z_2, \ldots, z_k\}$ is the set of test case numbers; $I = \{i_1, i_2, \ldots, i_k\}$, $O_{V/I}$ $(o_{v/i} \in O_{V/I})$ is p's output valid/invalid set of results of executing p with all test cases $t \in T$; and C_N is the set of covered nodes in $OCG_{(p)}$ that is obtained as the result of executing p with all test cases $t \in T$.

Definition 3.2 (all-nodes criterion for VDFLs). Formally, given a VDFL *universal* method p with an operation case graph $OCG_{(p)}$, a test t exercises a node $n \in OCG_{(p)}$ if t causes the evaluation of p, and traverses a path through $OCG_{(p)}$ that includes n. A test suite T is node-adequate for p and for each dynamically executable node n in $OCG_{(p)}$ if there is at least one $t \in T$ that exercises n.

Definition 3.3 (all-edges criterion for VDFLs). Formally, given a VDFL *universal* method p with an Operation Case Graph $OCG_{(p)}$, a test t exercises an edge $e = (n_i, n_j) \in OCG_{(p)}$ if it causes the execution of p, and that execution

traverses a path through $OCG_{(p)}$ that includes e. A test suite T is edge-adequate for a p if, for each dynamically executable edge e in $OCG_{(p)}$, there is at least one $t \in$ in T that exercises e.

As with imperative languages, if all edges in $OCG_{(p)}$ are covered, all nodes are necessarily covered. This observation leads to the conclusion that branch coverage in VDFLs is stronger than node coverage. When a testing criterion A is stronger than another testing criterion B, we say that A subsumes B. Thus branch coverage subsumes node coverage, and a test suite T that satisfies branch coverage, must also satisfy node coverage.

3.4 Dataflow Analysis in OCGs

The data interaction model in VDFLs, although visual, is somewhat analogous to that of imperative languages. In imperative languages, data interaction between variables is made by explicitly defining and referencing the names of variables in a procedure. For example, the statement s_1: $x = 3$ explicitly defines x and writes to its memory location, whereas the statement s_2: $y = x + 3$ explicitly uses or references x by reading from its memory location. In VDFLs, variables cannot be explicitly defined, and their interactions are modeled as datalinks connecting operations' roots to other operations' terminals. In this interaction model, roots serve as implicit variable definitions and terminals connected to those roots serve as variable uses. In general, when a root r, on an operation o_i is connected to a terminal t on an operation o_j (i and $j > 1$), we say that t in o_j references r in o_i. In other words, r is used in o_j. For example, as depicted in Figure 4, in 1:1 *C root* r_1 is connected to terminal t_1 on the universal method D.

The basic structure of a Prograph universal method is similar to a procedure in imperative languages. The roots on the input-bar of a universal represent the method's inputs, and correspond to reference parameters in imperative languages. The terminals on the output-bar of a universal represent the method's outputs, and correspond to variables returned in imperative languages. The reader should note that Prograph, unlike imperative languages, allows more than one root on the output-bar. When a universal method has more than one case, roots on the input-bar of each case are essentially the same variables. A similar situation exists for terminals on the output-bar. For example, in Figure 4, the roots on the input-bars of cases 1:2 *A* and 2:2 *A* are the same. Likewise, the terminals on the output-bars of cases 1:2 *A* and 2:2 *A* are also the same.

Operations in the body of a universal that are connected to roots on the universal's input-bar get their values from the roots which are connected to the terminals at the call site. For example, in Figure 4, the reference parameter labeled i_1 in 1:1 *D* gets its value from the root labeled r_1 in 1:1 *C*. As with imperative languages, reference parameters and actual parameters in visual dataflow languages are bound at call sites. Thus we say that the reference parameter or i_1 in 1:1 *D* is bound to the actual parameter or r_1 in 1:1 *C*. Since we are only interested in unit-based data-flow analysis in *VDFLs*, a call site is considered a primitive operation. Work is underway to deal with inter-procedural dataflow analysis and testing for interactive units in VDFLs.

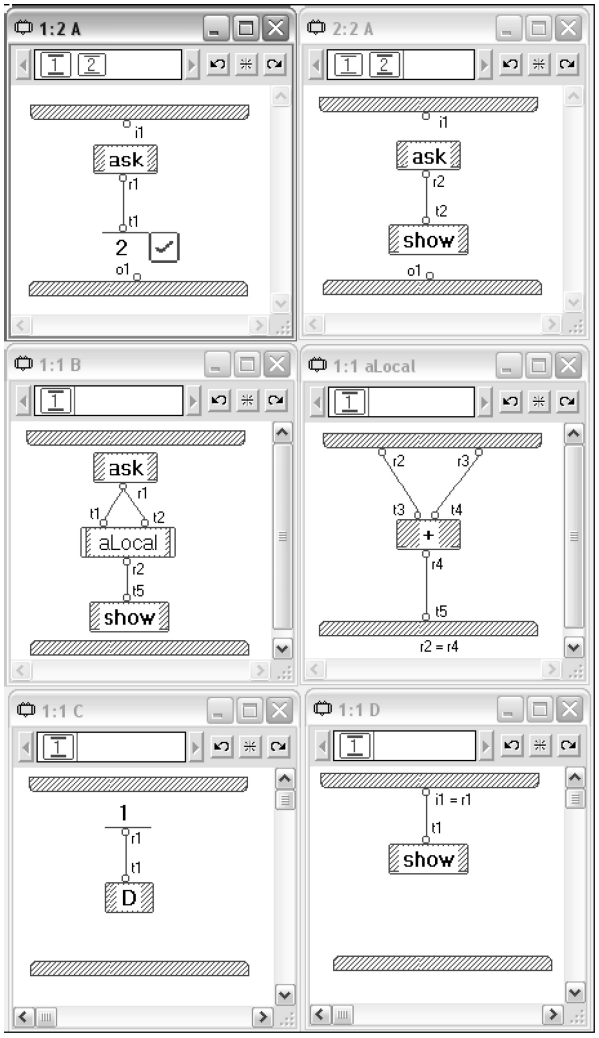


Fig. 4. Universal method *A, B, C*, and *D*.

A local operation is similar in structure to a universal method; however, the roots on the local's input-bar are not considered reference parameters; rather, they correspond to the roots to which the local operation's terminals are connected to. For example, as depicted in Figure 4, roots r_2 and r_3 on the input-bar of case 1:1 *aLocal* corresponds to the root labeled r_1 on the ask primitive in method 1:1 *B*. Therefore, r_2, and r_3 in 1:1 *aLocal* can be considered as references to r_1 in 1:1 *B*.

The terminals on a local's output-bar carry the values of the roots to which they are connected to, and through an assignment at the output-bar assign those values to the local operations' roots. To illustrate, consider the local operation 1:1 *alocal* in Figure 4, where, the terminal labeled t_5 carries the value of the root labeled r_4, and through the $r_2 = r_4$ assignment at the output-bar,

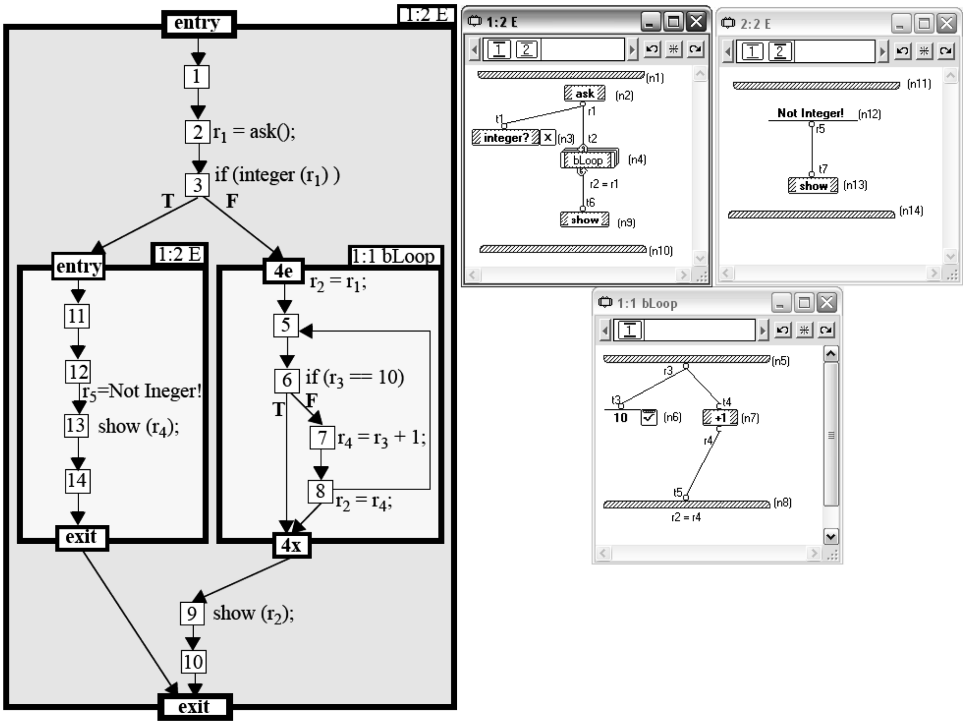


Fig. 5. Method E and its looped-*Local* bLoop.

assigns the value of r_4 to r_2 in 1:1 B. Roots corresponding to actual parameters can be redefined only when they are used as loop roots. To illustrate, consider the looped-local operation 1:1 *bLoop* in Figure 5, where the assignments $r_2 = r_1$ and $r_2 = r_4$ occur at the at the loop root in 1:1 E and output-bar of the 1:1 *bLoop*, respectively. The first assignment $r_2 = r_1$ is necessary to carry the flow of data in case the flow of execution breaks before it reaches the output-bar of 1:1 *bLoop*. The second assignment is necessary to increment the index of the loop or r_2. In this work, we make no distinction between atomic data such as a root representing an integer and aggregate data such as a root representing a list or root-list. Thus a datalink connecting a root-list or partition control list *root* as it is the case on the left or right *root* on the operation that is labeled n_4 in Figure 3, to a *list-terminal* (the left or right *list-terminal* on the operation that is labeled n_5 in Figure 3), is regarded as definition-use association on the whole list datum.

4. APPLICABLE DATAFLOW TEST ADEQUACY CRITERIA FOR VDFLS

Most code-based dataflow test adequacy criteria for imperative programs are defined in terms of paths that define and use variables through the control flow graph *of a program*. In this section we examine the applicability of several code-based test adequacy criteria to VDFLs.

4.1 Background: Traditional Dataflow Analysis

In imperative languages, dataflow analysis in a control flow graph of a function f or $CFG_{(f)}$ focuses on how variables are bound to values, and how these variables are to be used. Variable occurrences in a $CFG_{(f)}$ can be either definitions or uses, depending on whether those occurrences store values in, or fetch values from memory, respectively. Two types of uses are of interest to dataflow testing: computational use or *c-use*; and predicate use or *p-use*. Given a definition of a variable x in a block b_i corresponding to a node $n_i \in CFG_{(f)}$, we say that a block b_j corresponding to a node $n_j \in CFG_{(f)}$ contains a computational use or *c-use* of x if there is a statement in b_j that references the value of x. We also say that a node $n_k \in \mathrm{CFG}_{(f)}$ contains a predicate use or *p-use* of x if the last statement in b_k contains a predicate statement where the value of that variable is used to decide whether a predicate is true for selecting execution paths. A conditional transfer statement in a node $n \in CFG_{(f)}$ has two executional successors: n_l; and n_m, such that l is different from m.

Paths in the $CFG_{(f)}$ that trace a definition to all or some of its uses is commonly known as definition-use chains or du-chains.

Dataflow analysis techniques for computing du-chains for individual procedures [Aho et al. 1986] are well known, and dataflow test adequacy criteria have been well researched for imperative languages, and various criteria have been proposed (e.g., Clarke et al. [1989], Frankl and Weyuker [1988], Laski and Korel [1983], Ntafos [1984], Perry and Kaiser [1990], and Rapps and Weyuker [1985]). Dataflow test adequacy criteria can be particularly applicable to VDFLs. There are many reasons for that. The first reason involves the types of faults (missing or erroneous datalinks) that have been observed to occur in VDFLs [Meyer and Masterson 2000]. The second reason involves the relative ease of application to VDFLs. As mentioned in Section 1, the dataflow information maintained by the editing engine of VDFLs languages allow, unlike their imperative counterparts, efficient and more precise algorithms to be used for obtaining dataflow analysis, thus allowing dataflow testing to be realized for VDFLs with less cost than its imperative counterparts—a fact that shall become more clear in Section 4.3.

4.2 Dataflow Associations for VDFLs

Dataflow test adequacy concentrates, on interactions between definitions and uses of variables in the source code. These are called *definition-use* associations or simply *DUs*. *DUs* can be appropriately modeled in VDFLs as datalinks. There are several reasons for this appropriateness. First, as with imperative languages, we recognize two types of variable uses in *VDFLs*: *c-use* or computational use; and *p-use* or predicate use. A c-use occurs when a datalink connects a root r on one operation o_i to a terminal t that exists on a noncontrol annotated operation o_j $(j > i)$. For example, as depicted in Figure 4, the root labeled r_2 in method 2:2 A is c-used in the Primitive operation show. A p-use occurs when a datalink connects a root r on an operation o_k to a terminal t that exists on a control annotated operation o_l $(k > l)$. For example, as depicted in Figure 4, the root labeled r_1 in case 1:2 A, is p-used in the control annotated *Match* 2. In

VDFLs we consider two types of *DUs*: definition-c-use (def-c-use) association; and definition-p-use (def-p-use) association. Given a universal method *p,* let $O = \{o_1, o_2, \ldots, o_n\}$ be the set of operations in p, and N be the set of blocks or nodes in an $OCG_{(p)}$, representing p. Let $R = \{r_1, r_2, \ldots, r_x\}$ be the set of roots on an operation o_i, where $1 < i < n$, and let $T = \{t_1, t_2, \ldots, t_y\}$ be the set of terminals on an operation o_j, where $1 < i < j < n$, we have the following definitions:

Definition 4.1 (def-c-use association for VDFLs). A def-c-use association is a triple $(n_i, n_j, (r, t))$, such that, n_i and n_j are nodes $\in OCG_{(p)}$ representing operations $o_i \in O$ and $o_j \in O$ respectively, $r \in R$ in o_i, $t \in T$ in o_j, there is a datalink between r and t, o_j is a noncontrol annotated operation, and there exists an assignment of values to p's input, in which n_i reaches n_j. For example, the def-c-use with respect to r_5 at n_{12} and its c-use at t_7 in n_{13} in 2:2 E of Figure 5 is $(n_{12}, n_{13}, (r_5, t_7))$.

Definition 4.2 (def-p-use association). A definition-p-use association is a triple $(n_i, (n_j, n_k), (r, t))$, such that, n_i, n_j, and n_k are nodes or blocks in $\in OCG_{(p)}$ representing the subset of operations $\{o_i, o_j, o_k\} \in O$, $r \in R$ in o_i, $t \in T$ in o_j, there is a datalink between r and t, o_j is a control annotated operation, and there exists an assignment of values to p's input, in which n_i reaches n_j, and causes the predicate associated with n_j to be evaluated such that n_k is the next node to be reached. For example, the def-p-use with respect to r_1 at n_2 and its p-use at n_3 in 1:2 E of Figure 5 is: $\{(n_2, (n_3, n_{4e}), (r_1, t_1)), (n_2, (n_3, e_{(2:2E)}), (r_1, t_1))\}$.

There are three points to consider about these definitions.

—We make a distinction between p-uses and c-uses, and that lets us track whether a test suite T that exercises all du-associations in $OCG_{(p)}$, also exercises both outcomes of each control annotated operation that has a datalink connecting the root of some other operation to one of its terminals. This distinction, as we shall see, has consequences in the visual reflection technique we use in our color mapping scheme to show exercised du-associations or datalinks.

—In the absence of Persistents or global variables, the redefinition of a variable or root r does not arise, except on the output-bar of a case that has been annotated with loop control, and thus will not interfere with any other definition or redefinition of r along any particular path in $OCG_{(p)}$. To illustrate, consider the example that is depicted in Figure 5; r_2 is defined at the entry node of the loop (n_{4e}), and always redefined at the output-bar (n_8) of every case belonging to the loop operation. Therefore, any du-chains that are applicable to r_2 in n_{4e} are also applicable to r_2 in n_8. This fact is one factor that facilitates more efficient dataflow analysis in VDFLs. Aside from extracting non-*Loop-roots* related du-associations from the editing engine, accounting for the *Loop-root* related ones, is a simple exercise of knowing where the definition is (node) and associating that definition with the same uses as those of the original definition, since it is not possible to have a redefinition on any path in the $OCG_{(p)}$.

—Analogous to the definition of du-associations for imperative programs in (Clarke et al. [1989], Frankl and Weyuker [1983], Korel and Laski [1983], Ntafos [1984], Perry and Kaiser [1990], and Rapps and Weyuker [1985]

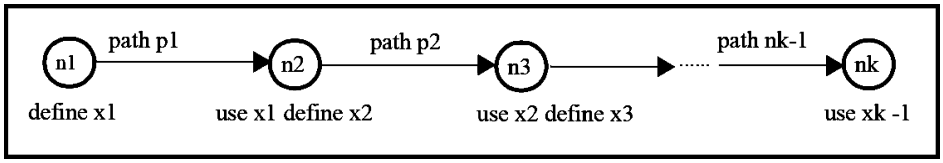


Fig. 6. k-dr interactions.

our du-associations, which can be determined statically may not all be executable. There may be no assignment of input values to a program that will cause a definition of a root r to reach a particular use on a terminal t. Determining whether such du-associations are executable is shown to be impossible in general and often infeasible in practice [Frankl and Weyuker 1988; Weyuker 1983]; thus, dataflow test adequacy criteria typically require that test data exercise (cover) only executable du-associations. In this respect, our criterion (as we shall show) is no exception and can indeed contain nonexecutable du-associations. In the rest of this article, to distinguish the subset of the static du-associations in a VDFLs that are executable, we refer to them as executable du-associations.

The second reason for the appropriateness of modeling datalinks as *DUs* in *VDFLs* can be attributed to the visual reflection of tested or exercised *DUs* that are associated with a datalink during testing or after a test suite has been exercised. In general, there is visually, a one-to-one mapping between every datalink and its associated *DUs*. A more detailed description of our color mapping technique to datalinks is found in Section 5.1.

4.3 Applicable Dataflow Testing Criteria

Having introduced the definition and use associations in VDFLs, we next briefly examine the applicability of three major dataflow testing criteria: Ntafos [1984]; Laski and Korel [1983]; and Rapps and Weyuker [1985].

Ntafos [1984] proposed a family of test adequacy criteria called the *required k-tuples*, where k is a natural number > 1. The required k-tuples require that a path set $P = \{p_1, p_2, \ldots, p_n\}$ covers chains of alternating definitions and uses, or definition-reference interactions called *k-dr* interactions (k > 1). An example of k-dr interactions is depicted in Figure 6. In n_1, there is a definition of a variable x_1, that is used to define variable x_2 in n_2 such that $x_1 \in n_1$ reaches n_2 via path p_1. Therefore, the information assigned to variable $x_1 \in n_1$ is propagated to variable $x_2 \in n_2$. This information is further propagated to another variable, say, $x_3 \in n_3$ such that $x_2 \in n_2$ reaches n_3 via path p_2. This information propagation process continues until it reaches n_k. Thus the set of paths $\{p_1, p_2, \ldots, p_{k-1}\}$ form k-dr interactions. The required k-tuples requires some subpath propagating each k-dr interaction such that (1) if the last use is a predicate the propagation should consider both outcome (true and false), and (2) if the first definition or the last use is in a loop, the propagation should consider either a minimal or some larger number of loop iterations. The required k-tuple coverage criterion, or k-dr interaction chain coverage criterion, then requires that all feasible k-dr-interaction chains should be tested.

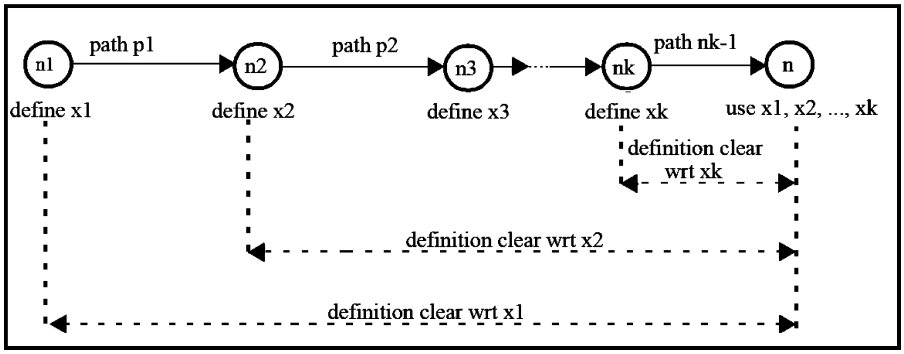


Fig. 7. Paths that are definition-clear with regard to x_1, x_2,,, x_k.

Laski and Korel [1983] defined and studied another kind of testing path selection criteria based on dataflow information. They observed that a given node may contain uses of several variables. Each variable may be defined at more than one node. Different combinations of the definitions constitute different contexts of the computation at the node. Figure 7 depicts one of their strongest criteria; ordered context coverage.

In an $OCG_{(f)}$, it is possible to apply either the Ntafos [1984] or the Laski and Korel [1983] criteria; however, there are two main reasons why these criteria would not be feasible in VDFLs. First, accounting for the dataflow information required by these criteria requires complex and costly dataflow analysis necessitating backward propagation of variables and their uses, which, as we shall show, is more expensive then the chosen [Rapps and Weyuker 1985] criteria. Second, required paths in k-dr interactions and ordered context paths, do not have a direct one-to-one mapping with datalinks in VDFLs—a strategy that makes it possible to color an exercised datalink when the path that is associated with it has been traversed—and would be too complex and overcrowding for the tester to have to deal with, both visually and theoretically.

Therefore, our approach to defining a dataflow test adequacy criterion for VDFLs adapts the all-dus dataflow test adequacy criterion defined for imperative programs in Rapps and Weyuker [1985]. The all-dus, is concerned with tracing all definition-clear subpaths that are cycle-free or simple-cycles from each definition of a variable x to each use reached by that definition and each successor node of the use. Thus, adapting the all-dus testing criterion of Rapps and Weyuker [1985], the all-Dus for VDFLs can be defined as follows:

Definition 4.3 (all-dus). Given a VDFL universal method p with its $OCG_{(p)}$, the set of complete feasible paths M in $OCG_{(p)}$, a set of execution paths $Q \subset M$, and a test suite T for p, we say that T satisfies this criterion iff for each feasible definition-use association $= \{(n_i, n_j, (r, t)), (n_i, (n_j, n_k), (r_m, t_n))$ or $(n_i, (n_j, n_l), (r_m, t_n))\}$, there is some test case t in T such that, when p is executed on t, there exists at least one path q in Q on which every DU in $OCG_{(p)}$ is exercised.

There are several advantages associated with the applicability of the all-dus criterion to VDFLs. First, since variables in VDFLs cannot be redefined,

accounting for the all-dus can be obtained from the editing engine, and accounting for the redefinition of loop-associated variable definitions (loop-root) can be easily calculated since they always occur at the same place (output-bar of a case). A second advantage is the ease of visually mapping every path corresponding to a du-association to a datalink. The du-associations corresponding to the redefinition of a loop-root on an output-bar of a case are constructed during a testing session as indirect datalinks. The construction process of the indirect links will be discussed in Task 2 of Section 5.1, in the context of the example in Figure 13. The third advantage is the color mapping scheme that can be applied to each exercised du-associations or datalink. Our color mapping scheme uses a continuous coloring technique to color datalinks that are exercised only during failed executions (incorrect results), passed executions (correct results), or both.

5. A METHODOLOGY FOR TESTING VDFLS

Several algorithms for collecting static control-flow and dataflow analysis techniques [Aho et al. 1986] have been developed for imperative languages. All these algorithms process the program's textual source code to build the flow of control and extract static analysis by propagating variable definitions along control flow paths to conservatively identify executable du-associations. As previously discussed in Section 1, the second class of differences between VDFLs languages and traditional ones (the iconic nature of the VDFLs) makes it impossible to use conventional text scanners to: construct the *OCG;* preserve the control and data dependencies among operations; extract all-Dus; or probe the code for dynamic tracking purposes. To compensate for these fundamental differences, we have augmented a Prograph-to-Java translator in a way that allowed us to extract the topologically sorted operations[2] , and perform LR parsing on them (before they are translated to Java) to accurately build the OCGs, as well as integrate support for our testing methodology into Prograph's environment at a fine granularity, providing functionalities that gave us the ability to:

—Determine the source code static control-flow and dataflow analysis.
—Probe the Java code to automatically track execution traces of every test case t in T, which provide the information necessary to determine the exercised du-associations that is involved in producing valid or invalid output values in a test case.
—Visually communicate, through the use of a coloring scheme, the coverage of datalinks, which in turn play an important role in helping users locate potential faults in the visual code.
—launch a user-accessible test sessions facility—developed through the tools add-on in Prograph—to visually pronounce validations output, and communicate to the user how well exercised a function is.

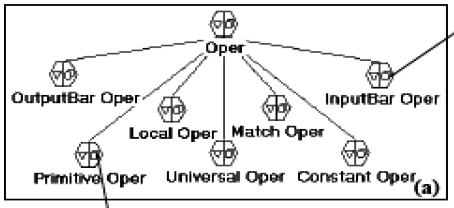
[2]The topological sorted order of operations is performed automatically by the editing engine while editing the program. This sorting preserves both the control and data dependencies in developed programs.

5.1 The Details of the Methodology

The approach we chose to gain access to the set of operations that is stored and maintained by the editing engine, involved the design and implementation of a component that acts as an interface to the editing engine's application programming interface (API). This approach has proven to be very useful in the phases of: (1) constructing the OCG and extracting dataflow analysis, using a one-pass LR parsing technique, (2) probing of the code as it is translated to Java, and (3) coloring and visual validation of datalinks after testing. We next discuss details related to each phase. The code used in all phases in our prototype was mainly written in Prograph, with the exception of a few libraries that were written in C++. We next explain each phase of our methodology in the context of the example that is depicted in Figure 5.

Task 1—constructing the OCG and computing static dataflow analysis.
Using the *API* interface component, we were able to access an indexed set of operations that is stored and maintained by the editing engine of Prograph. This information made it possible to perform a one-pass over the set, building the *OCGs*, and collecting their relevant du-associations. A portion of the design and algorithms of our object-oriented one-pass solution is depicted in Figure 8. Figure 8(a) depicts part of the operation class hierarchy (implemented in Prograph). Each inherited class in the hierarchy has a method *buildOper*()—depicted in Figure 8(c) and Figure 8(d) for primitive and input-bar operation, respectively—that determines the type of operation, its control, and then builds the appropriate node, edge(s), and extract relevant du-associations. The algorithm in Figure 8(a) is invoked on all operations in the set. To illustrate how its main function (*biuldOper*()) works, without getting wrapped up in infinite details, we next describe our one-pass technique in the construction context of the input-bar (n_1), and the primitive operations ask and integer? of Figure 5 that are labeled n_2 and n_3, respectively.

- When the input-bar operation is fetched from the set, the *buildOper*() algorithm in Figure 8(d) is invoked. Line 2 constructs n_1 in the *OCG* of Figure 5. Line 3 creates the edge between n_1 (already fetched) and n_2 the next operation to be fetched. Line 4 records the edge (n_1, n_2), and assign a false value to it. This false value will be true when this edge is traversed.
- When the operation ask is fetched from the set, the *buildOper*() algorithm in Figure 8(c) is invoked. Since the ask primitive is not annotated with any type of control, the first case of the switch statement in the algorithm of Figure 8(c) on line 4 is executed. Line 5 determines O_1 (or n_3) in the *OCG* in Figure 5. Line 6 creates the edge between n_2 (already fetched) and n_3 the next operation to be fetched. Line 7 records the edge (n_2, n_3) in the *OCG* and assigns a *false* value to it. Line 8 makes a call to *extractDUs* (*O, null, null, null*) algorithm of Figure 8. Since n_2 does not have any control annotations, the first switch case on line 2 of the *extractDUs* algorithm is chosen. The for loop however does not execute, since n_2 does not have any terminals. Now consider the integer? primitive. When the operation integer? is fetched from the set, the *buildOper*() algorithm in Figure 8 (c) is invoked. Since the integer? primitive is annotated with next-case control, the fourth case of the switch statement




```
1. algorithm buildOper (Oper O) {
2.  constructNode (O);
3.  e = constructEdge (O, determineNextOper(O);
4.   OCG(f).Edges = OCG(f).Edges U {e, false} }
                                                    (d)
```

```
1. algorithm buildOcg(f)
2. for each function f in F
3.  for each Case C in f
4.    for each operation O in C.
5.      buildOper(O);
                                                    (b)
```

```
1. algorithm buildOper (Oper O) {
2.  constructNode (O);
3.  switch(Oper)
4.    Case !isRepeat(O) && !isControl(O):
5.       O1 = determineNextOper(O);          // Determine the next opertaon in the topologically sorted set.
6.        e  = constructEdge (O, O1);              // e is  the edge built between O and O'
7.       OCG(f).Edges = OCG(f).Edges U {e, false}     // Collect each  edge in teh OCG and assign it to false.
8.        extractDUs (O, null, null, null);              // A call to extract the Def-c-uses of O.
9.    Case isRepeat(O) && isControl(O):
10.       e    = constructEdge (O, O);
11.      O1  = determineNextOper (O);
12.     e1   = constructEdge (O, O1);     // e' is the edge that represents one of the True and False outcome
13.      OT = deternmineType (O);       // OT is the opertaion type = {Os or Ox}
14.    OC = determineControl (O);    // OC is the opertaion control {Fail, Fnish, Terminate, or NectCase }
15.    O2  = determineNThTargetOper (O, OT, OC);   // O2 is the target Oper according to OT and OC
16.       if (O2 == null) {                          // The OT and OC do not allow for 2 edges out of O
17.        OCG(f).Edges = OCG(f).Edges U ( {e, false}, {e1, false});
18.        extractDUs(O, e1, null, e); }
19.       else  {
20.           e2  = constructEdge (O, O2);
21.           OCG(f).Edges = OCG(f).Edges U ( {e, false}, {e1, false}, {e2, false} );
22.           extractDUs(O, e1, e", e); }
23.   Case isRepeat (O):
24.      e = constructEdge (O, O);
25.      e1= constructEdge (O, determineNextOper(O));
26.      OCG(f).Edges = OCG(f).Edges U ( {e, false} ,{e1, false} );
27.      extractDUs (O, e1, null, e);
28.   Case isControl (O):
29.       O1  = determineNextOper (O);
30.        e   = constructEdge (O, O1);
31.       OCG(f).Edges = OCG(f).Edges U ( {e, false});
32.        OT = deternmineType (O);
33.        OC = determineControl (O);     }
34.        O2  = determineNThTargetOper (O, OT, OC);
35.          if (O2 == null)   {
36.            extractDUs(O, e1, null, null); }
37.          else  {
38.           e1  = constructEdge (O, O2);
39.           OCG(f).Edges = OCG(f).Edges U ( {e1, false} );
40.           extractDUs(O, e1, e2, null); } }
                                                    (c)
```

Fig. 8. Algorithms in (b), (c), and (d) for building the *OCG* and extracting dataflow information.

in the algorithm of Figure 8(c) on line 28 is executed. Line 29 determines O_1 (or n_4) in the *OCG* in Figure 5. Line 30 creates the edge between n_3 (already fetched) and n_4 the next operation to be fetched. Line 31 records the edge (n_3, n_4) in the *OCG* and assigns a *false* value to it. Line 32 determines and returns O_T the type of n_3 (O_s or O_x). You may recall from The building process of the

OCGs that $O_s \in O$ is the subset of operations that always succeed by default, and $O_x \in O$ is the subset that does not. Line 33 determines and returns O_C the type of control (i.e. fail, finish, next-case, or terminate} (in this case, it is next-case on failure). Line 34 invokes *determine*N^{Th}*TargetOper*(O, O_T, O_C) which determines O_2 the nth operation to which the other edge of the evaluation of the integer? is built to (in this case its the input-bar or n_{15} in the *OCG*). Line 38 creates the edges between n_3 and n_{15}; (shown in Figure 5 as an edge from n_3 to the Entry node 1:2 E, and from that to n_{11}). Line 39 records the edge (n_3, n_{11}), and finally line 40 makes a call to *extractDUs* (*O,* e_1, e_2, *null*). Since n_3 has a control annotation, the first switch case on line 2 of the *extractDUs* algorithm is chosen.

- As previously mentioned, with the presence of loops in Prograph, roots associated with a loop or loop-roots are first defined at the local's loop-root, and then implicitly redefined at the *Output-Bar* of each *case* in the looped-local. For example, as depicted in Figure 5, the loop-root r_2 is first defined at the looped operation *bLooped*, and subsequently redefined at the operation labeled n_8 with the implicit statement $r_2 = r_4$. Thus the du-associations related to a loop-root lr are divided into two sets. One set that satisfies the du-associations with regard to the definition of lr on the looped-local, and a second set that satisfies the du-associations with regard to the implicit redefinition of lr on the output-bar of the looped-local. The first set is collected by computing the du-associations with regard to the definition of lr that is connected or has uses, via wrap-around datalinks, to operations inside the looped-local. For example, the definition of the loop-root r_2 on node 4_e in Figure 5 has a c-use on the operation labeled n_7, and a *p-use o*n the operation labeled n_6. The second set is collected by computing the du-associations with regard to the implicit redefinition of lr (at the output-bar) that has uses on operations inside the looped-*local*. For example, the implicit redefinition of the loop-root r_2 at n_8 has a c-use on the operation labeled n_7, and a p-use on the operation labeled n_6. Since the implicit redefinition of a loop-root always occurs at the output-bar of the looped *cases*, collecting the du-associations associated with a loop-root before the implicit redefinition can be resolved statically by relying on the automatic collection of the dataflow information provided by the editing engine during the visual coding phase.

Task 2—tracking execution traces, and visual representation of results.
To track the dynamic execution, we have simply instrumented the Prograph-to-Java translator in a way that allows us to probe each operation/control annotated operation before it is translated. Once the Java textual code has been compiled, test suites are then run on the Java code. The probes allowed our testing environment to record, under each test case t in T, the execution traces and maintain the states (true or false) of each operation, predicate operation, or du-associations, as collected by the algorithms in Figure 8 and Figure 9. To apply our color mapping scheme to exercised datalinks, our testing environment also maintained a set of pointers for each operation, root, and terminal to allow us to effectively color these datalinks after the execution of each test case t in

```
1.  algorithm extractDUs(Oper O, Edge e1, Edge e2, Edge e) {
2.    Case  (e1 = e2 = e = null) :                          // O does not have any controls
3.      for each terminal t ∈ O {                  // for each termninal on the operation being processed
4.        O.use  = O.t(i);
5.        Op.def = O.t(i).connectedRoot( );                  // Op is a predecessor of O.
6.        O.def-c-use = O.def-c-use U ( {Op.def, O.c-use,  false}) }
7.    Case  (e2 = null) && (e1 != e != null) :               // O has a Repeat control
8.      for each terminal t ∈ O {                  // for each termninal on the operation being processed
9.        O.use  = O.t(i);
10.         Op.def = O.t(i).connectedRoot( );
11.       O.def-p-use = O.def-p-use U ( {Op.def, O.p-use, e, false } , {Op.def, O.p-use, e1, false } ); }
12.   Case  (e1 != e2  != e != null) :              // O has a Repeat and another control
13.     for each terminal t ∈ O {
14.       O.use  = O.t(i);
15.       Op.def = O.t(i).connectedRoot( );
16.       O.def-p-use = O.def-p-use U ( {Op.def, O.p-use, {e, false , e1  false}) }
17.     Case  (e2 != null) :
18.      for each terminal t ∈ O {                 // O has a control
19.       O.use  = O.t(i);
20.       Op.def = O.t(i).connectedRoot( );   // Op is a predecessor of O.
21.       O.def-p-use = O.def-p-use U ( {Op.def, O.p-use, {e, false , e1, false}) } }
```

Fig. 9. Collecting the dus.

a test suite T. To illustrate the use concept of these pointers, consider the ask and integer? operations in 1:2 E of Figure 5 and their root r_1 and terminal t_1, respectively. Figure 10 depicts in Window (a) and its related windows (b, c, d, e, and f), a series of connected arrows that starts in the highlighted item of (a) and ends in the highlighted item in (e). The series of arrows shows the various highlighted window items' value, when double clicked in the same order as that of the arrow sequence. The sequence, when followed from (a) to (e), shows the primitive operation integer? in (a); its pointer value in (b) as the first item in the Window; the terminal pointer of t_1 in (d); its connected operation ask in (e); and finally, the pointer value of operation ask in the top item of (f). The various values of operations, terminals, and roots are used in the color mapping scheme during testing.

The visual illustrations and colors we used to represent all-dus coverage reflect two constraints that we believe to be important for the integration of visual testing into VDFLs. We derived these constraints from literature on cognitive aspects of programming (Gren and Petre [1996] and Yang et al. [1997]), and the use of color in fault localization [Agrawal, et al. 1995; Jones et al. 2002]. The constraints we placed on the visual representation and colors of exercised datalinks under test should: (1) be courteous of screen space and maintain consistency of visual constructs; and (2) be accessible and recognizable.

To satisfy the first constraint when reflecting through color the all-dus coverage of datalinks and their associated du-associations, we introduced only one additional artifact to existing datalinks; indirect datalinks. Direct datalinks are of course created by the user at the visual coding phase. Indirect datalinks, however, are constructed, after the user initiates a testing session, from loop-roots to

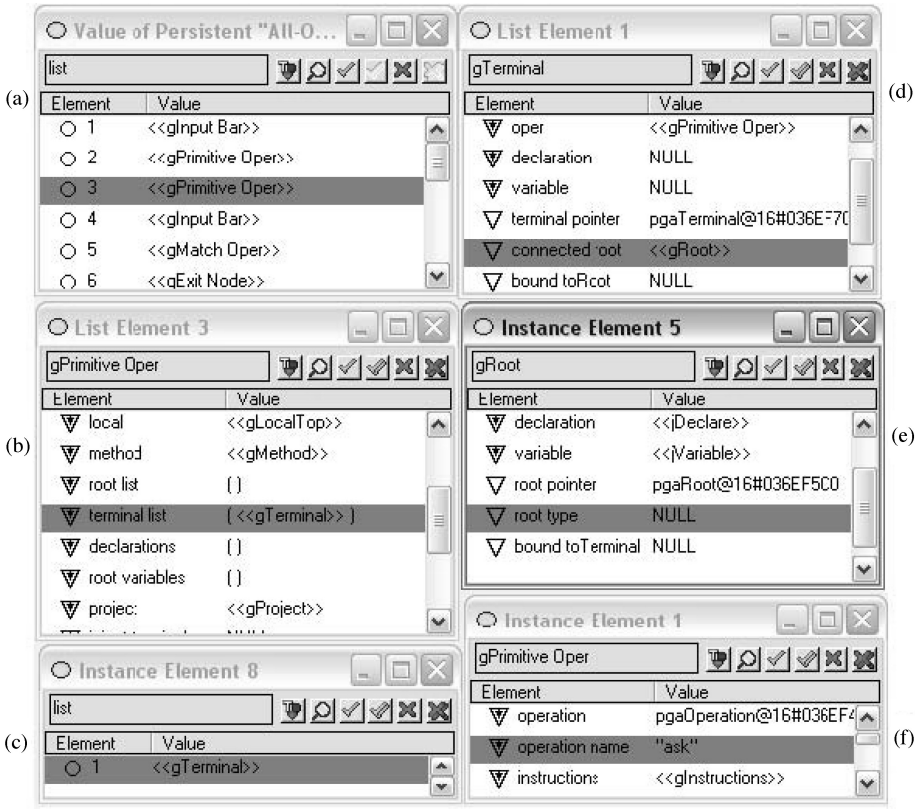


Fig. 10. A fragment tof Prograph's implementation showing the pointers used in tracking and coloring of operations ask and integer, and root r_1 and terminal t_1 in the example of Figure 5.

terminals inside a looped-local operation. For example, as depicted in Figure 13, four indirect datalinks are constructed from the loop-roots on the looped-Local factorial operation to the terminals on operations 0, -1, and * to represent their associated du-associations. While indirect datalinks do introduce additional artifacts to the visual code, their presence is necessary to communicate, through color, their testedness. The indirect datalinks appear and disappear depending on whether the looped-local window that is associated with the use (c-use or p-use) is opened. That is, if the looped-local window is closed/minimized, the indirect datalinks are made to disappear and the loop-roots that are associated with the indirect datalinks are made to blink to indicate that user attention is needed. Once the user double clicks on a blinking loop-root, the looped-local window is opened and the indirect datalinks are made to reappear. The blinking, as a metaphor, has been used commercially in many of today's operating systems and applications to draw a user's attention to a specific area on the screen. For the sake of simplicity, direct and indirect datalinks will be referred to in the rest of this article as datalinks.

To satisfy the second constraint, and assist the analyst in identifying and minimizing the fault search space, we incorporated a color mapping scheme

that uses a continuous level of varying color (hue) to indicate the ways in which the datalinks participate in the passed and failed test cases in a test suite. We selected colors along the red (danger), yellow (cautious), and green (safe), to improve our goal of drawing users' attention to testing results and potential fault locations. A similar approach [Jones et al. 2002; Liblit et al. 2005] that used color to localize faulty statements in imperative languages, found these color combinations to be the most natural and the best for viewing. Other studies found that, due to the physiology of the human eye, red stands out while green recedes [Christ 1975; Murch 1984; Shneiderman 1998]. The color mapping scheme measurements and testing results will be described in Section 6.2.

The testing system we have implemented in Prograph's *IDE* and used to produce Figure 10 and Figure 13 in this article, provide users with the ability to initiate an all-dus testing session, and use the static and dynamic data collected from Task 1 and Task 2 to present the user with testing results in a debug-like window. This approach provides, in Prograph, an integrating environment of testing and debugging. Creating these debug-like windows was made possible through the API and external library that are available to third part developers of Prograph.

6. EXPERIMENTAL DESIGN AND EMPIRICAL RESULTS

To obtain meaningful information about the effectiveness of our all-dus adequate testing methodology in: (a) revealing a reasonable percentage of faults in VDFLs; and (b) assisting users in visually localizing faults by reducing their search space, we designed and conducted two studies. We next describe the design setup, measurements analysis, and empirical results for Study 1. Study 2 is discussed in Section 6.2.

6.1 Study 1

In setting up the design of our first study, we used a set $F = \{f_1, f_2, \ldots, f_8\}$ of 8 programs/functions[3] we called the *base functions* set, and produced, for each $f \in F$ a test pool[4] $tp_{(f)}$. Next, we used $tp_{(f)}$ to create for each $f \in F$ (i) $DUT_{(f)} = \{T_1, T_2, \ldots, T_k\}$ the set of du-adequate test suites with regard to f, and (ii) $RST_{(f)} = \{T'_1, T'_2, \ldots, T'_k\}$ the set of randomly selected test suites for f such that, for each $j < k$, $T_j = \{t_1, t_2, \ldots, t_d\}$ and $T'_j = \{t'_1, t'_2, \ldots, t'_d\}$ are of equal size, and t and t' are test cases in T and T', respectively. We then created $V_{(f)} = \{v_{1(f)}, v_{2(f)}, \ldots, v_{n(f)}\}$ the set of faulty versions for each $f \in F$, where each faulty version $v_{i(f)} \in V_{(f)}$ contained a distinct single fault. Finally, for each faulty version $v_{i(f)} \in V_{(f)} \in F$, we ran on $v_{i(f)}$: (1) every du-adequate test suite $T_j \in DUT_{(f)}$ and recorded its fault detection ability; and (2) every randomly selected test suite $T'_j \in RST_{(f)}$ and recorded its fault detection ability. We say that a fault is detected when: in (1) the output of $v_{i(f)}$ when executed on $t \in T$, produce results that differ from that of f when executed on t; in (2) the output of $v_{i(f)}$ when executed on $t' \in T'$, produce results that differ from that

[3]We use the words program and function interchangeably in the rest of this article.

[4]Details of creating test pools and other experimental steps will be explained later in this section.

of f when executed on t'. Similar studies, design approach, and fault-detecting abilities of several varieties of test suites applied to imperative and form-based programs, have been used in Frankl and Weiss [1993]; Hutchins et al. [1994]; and Rothermel et al. [2001]. We next describe the rest of our study design setup and results.

6.1.1 *Base Programs and Test Suites.* Our base programs' specifications for this study were chosen not to be overly complex. The logic behind this was to allow people involved in this study to seed faults in these programs, create their test pools, and examine their code for infeasible du-associations. The subject programs had to however be complex enough to be considered realistic, and permit for the seeding of many hard-to-find faults. Each function was chosen to be compilable and executable as a stand-alone unit. Since our testing methodology has been implemented in Prograph's *IDE*, we obtained 8 Prograph programs from examples that were shipped with Prograph, and were thus considered to be commercially produced. Table I lists the numbers of operations, control annotated operations, and du-associations for each base program. These base programs provided the oracle to check the results of test cases executed on the faulty versions.

6.1.2 *Base Programs' Test Pools and their Test Suites.* Since it is easy to show that, for *VDFLs*, as well as for imperative programs, dataflow adequacy criteria (*Definition* 4.4) can produce test suites that are stronger then statement (*Definition* 3.2) or decision coverage criteria (*Definition* 3.3), we elected to acquire du-adequate test suites for our base programs to evaluate the effectiveness of our testing methodology. To obtain these, we began by asking one Prograph expert to generate $TP_{(F)} = \{tp_{(f1)}, tp_{(f2)}, \ldots, tp_{(f8)}\}$ the set of test pools containing for each base function $f_i \in F$ its own test pool $tp_{(fi)}$. To populate each $tp_{(fi)} \in TP_{(F)}$, the user first created an initial set of test cases based on his understanding and knowledge of exercising f_i's functionality and special values and boundary points that are easily observable in the visual code. The tester then examined the du-coverage achieved by the initial test cases set, and modified/augmented the initial set of test cases, to ensure that each executable du-association was exercised by at least 7 test cases. The resulting test pools for each $f_i \in F$, as depicted in Table I, ranged in size from 143 to 524 test cases.

To obtain the du-adequate test suite $dut_{(fi)} = \{t_1, t_2, \ldots, t_m\}$ from each $tp_{(fi)}$, we first determined, for each test case $t \in tp_{(fi)}$ it's exercised du-associations, and then created $dut_{(fi)}$ by randomly selecting a test case t from $tp_{(fi)}$, and adding it to $dut_{(fi)}$ only if it incrementally added to the overall cumulative coverage achieved by test cases added to $dut_{(fi)}$. We repeated this process until $dut_{(fi)}$ was du-adequate; yielding, for each $f_i \in F$ a $dut_{(fi)}$ of size m. This process resulted, after discarding duplicate test suites, between 12 and 17 du-adequate test suites for each $f_i \in F$. Finally, to create a randomly selected test suite $rst_{(fi)}$ for each function $f_i \in F$, we performed the random function $t' = \text{ran}\ (tp_{(fi)} = \{t_1, t_2, \ldots, t_m\})$, m times, where m is the size of $dut_{(fi)}$, $= \{t'_1, t'_2, \ldots, t'_m\}$ to randomly select test cases from $tp_{(fi)}$ of the same sizes as that of the latter.

Table I. The Number of Operations, Edges, Du-Associations (Dus), Number of Faulty Versions, and Test Pool Size (Number of Test Cases) for Each Base Program

Programs	Operations	Edges	Dus	Faulty Version	Test pool size for each f
Bubble Sort	54	32	49	11	267
Factorial	27	6	32	15	179
Fibonacci	49	8	50	13	192
Gaussian elimination	88	32	106	19	481
Matrix multiplication	64	28	56	9	318
Replace subtree	31	10	29	16	298
Topological sort	66	28	74	18	143
Word place: *finding the place of a word in a sentence.*	82	31	107	20	524

6.1.3 *Faulty Versions.* Ideally, the most desirable type of faults to study would be real faults that have been recorded in the course of the development of the software; however, due to inadequate information available to us about faults of that type, we created $V_{(f)}$ the set of n faulty versions for each base function $f_i \in F$. To do that, we asked 8 different individuals with different perceptions of fault-related production in Prograph programs (ranging in expertise from intermediate to experts), and mostly without knowledge of each other's work, to introduce in each $v_{i(f)} \in V_{(f)}$, a single fault that reflects, as realistically as possible, their experience with real Prograph development, in an effort to preserve the accuracy of our study. The fault seeding process yielded, as depicted in Table I, between 9 and 20 faulty versions for each $f_i \in F$. The seeded faults were mostly changes to a single feature of the visual code, and took the form of creating erroneous or missing: datalink; control; input; or primitive.

6.1.4 *Measuring the Effectiveness of Fault Detection.* Let $T \in DUT_{(f)}$ and $T' \in RST_{(f)}$ be two test suites for $f \in F$, respectively, and $V_{(f)} = \{v_{1(f)}, v_{2(f)}, \ldots, v_{n(f)}\}$ is the set of faulty versions in f each containing a single known fault. We say that if $TS = (T \text{ or } T')$ detects $(e <= n)$ of the faults in $V_{(f)}$, then the effectiveness of TS can then be measured by percentage of faulty versions whose faults are detected by TS, and is given by $(e/k\ ^*100)$. A fault is detected by TS if there exists at least one test case $t = (z, i, o_{v/i}, c_n) \in TS$ (recall *Definition 3.1*) that, when applied to $v_{i(f)}$ and f, causes the production of the tuple (z, i, o_i, c_n) in $v_{i(f)}$, and the tuple (z, i, o_v, c_n) in f. As mentioned earlier, base programs provided the oracle to check the output (o_v for valid or o_i for invalid) of a test case executed on a faulty versions.

6.1.5 *Data Analysis and Overall Results.* Figure 11 contains a separate graph for each of the eight base program $f \in F$. Each graph contains every faulty version $v_{i(f)}$ of f, and each $v_{i(f)}$ occupies a vertical bar position along the x-axis and is represented by an overlapping pair of vertical bars. The two overlapping bars depict the percentage of the du-adequate test suites (black bars) and the percentage of the randomly generated test suites (light grey), respectively, that detected the fault in that faulty version. The legend and information on the X-axis and Y-axis are depicted in the lower part of Figure 11. As

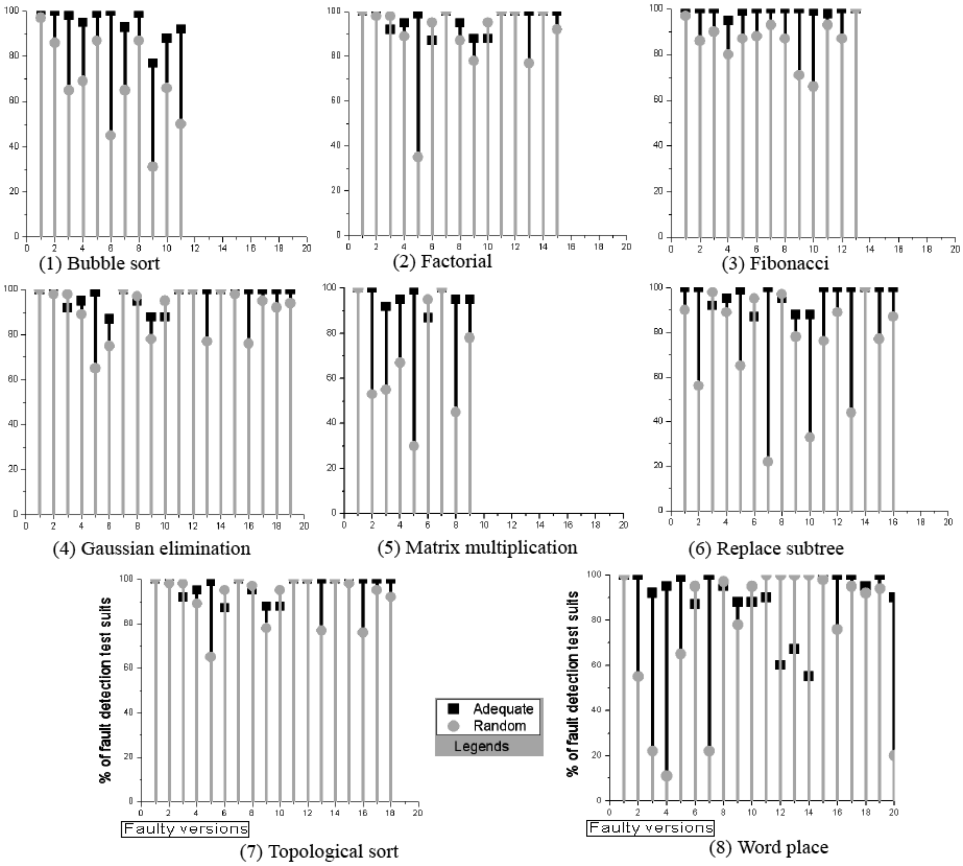


Fig. 11. Percentages of test suites that revealed faulty versions, per program, per version. Black bars depict results for du-adequate test suites; gray bars depict results for randomly generated test suites.

the overlapping bars of each program and its faulty versions indicate in Figure 11, both $DUT_{(f)}$ and $RST_{(f)}$ missed faults in Study 1 which involved 121 faulty versions. Figure 12 indicates three vertical bars on the X-axis: the first bar represents, with the Y-axis, the number of faulty versions in which the $DUT_{(f)}$ was more effective than $RST_{(f)}$; the second bar indicates, with the Y-axis, the number of faulty versions in which the $RST_{(f)}$ was more effective than $DUT_{(f)}$; and the third bar indicates, with the Y-axis, the number of faulty versions in which the $RST_{(f)}$ was as effective as the $DUT_{(f)}$ in detecting the fault. As depicted in Figure 12, there were across the entire study 80 faulty versions in which the $DUT_{(f)}$ were more effective then $RST_{(f)}$, 20 faulty versions in which the $RST_{(f)}$ were more effective then $DUT_{(f)}$, and 21 faulty versions in which $RST_{(f)}$ were as effective as $DUT_{(f)}$. These results clearly indicate that du-adequate test suites are more effective at revealing faults than their randomly generated counterparts. Two similar studies by Hutchins et al. [1994] for imperative languages, and Rothermel et al. [2001] for form-based languages also showed that du-adequate test suites were more successful at detecting faults.

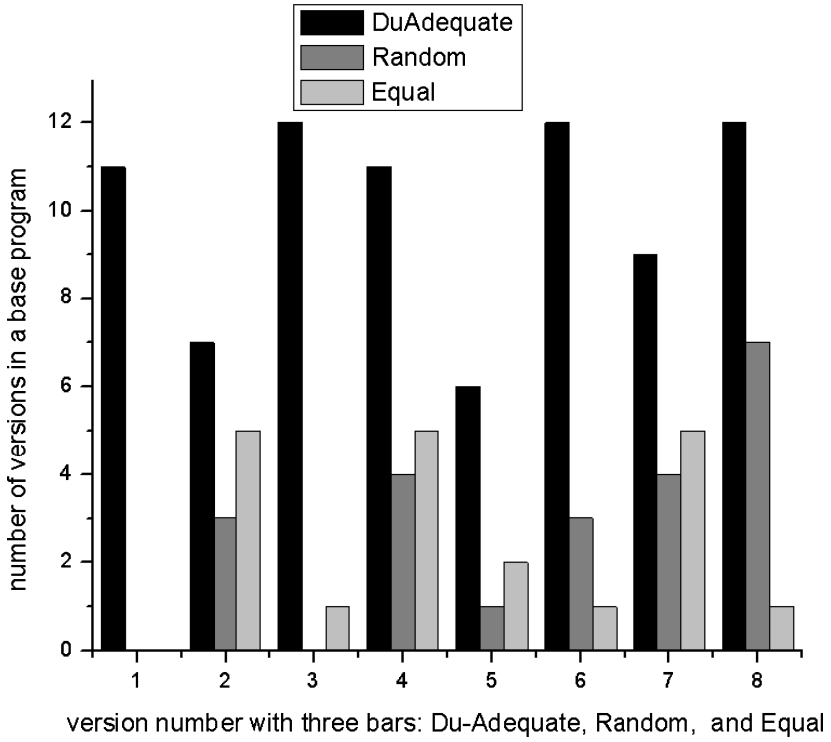


Fig. 12. This graph captures for each program and its versions, three vertical bars on the X-axis containing the numbers of: $DUT_{(f)} > RST_{(f)}$; $DUT_{(f)} < RST_{(f)}$; and $DUT_{(f)} = RST_{(f)}$.

6.1.6 *Study Conclusion.* In this study, we conducted a highly accurate measurement of the test suites ($T \in DUT_{(f)}$ and $T' \in RST_{(f)}$) effectiveness in detecting faults. There are, however, some aspects of this study that would limit our ability to generalize the results pertaining to the capabilities of our test suites. We thus need to make it clear that (*i*) our base programs may not be large enough, and may not unnecessarily capture the program space in VDFLs; (*ii*) our faulty versions creation method may not necessary represent the fault space in VDFLs; and (*iii*) our test pools were generated based on the correct base programs, and it may be worth investigating the effectiveness of our test suites had we included the faulty version in the test pool extraction. Second, we cannot claim any knowledge on different groupings of faults. For example, we were not able to determine, after an exhaustive examination of the faults in our programs, why some faults were easily detected by $DUT_{(f)}$, others easily detected by $RST_{(f)}$, and several other faults were equally well detected by both $RST_{(f)}$ and $DUT_{(f)}$. We did conclude that there is no clear strategy to follow to bring about such groupings.

6.2 Study 2

Thus far, we have not demonstrated that our testing methodology, combined with our color mapping scheme and visual feedback, can assist users in

visually localizing faults by reducing their search space. In Study 2, we use the $DUT_{(f)}$ of Study 1 (since it was proven to be more effective at detecting faults) to measure how effective our color mapping scheme is in helping to locate faults after a test suite set is executed on a faulty version. The procedure in this study was as follows: for every $f \in F$, we executed each $v_{i(f)} \in V_{(f)}$ on each $T \in DUT_{(f)}$, and then applied, for to each ($v_{i(f)}$, T) pair, the continuous color scheme and visual feedback to the datalinks (du-associations: *c-use* and *p-use*). We then calculated for each $v_{i(f)}$, over all test suites $T \in DUT_{(f)}$, the continuous color of each datalink in $v_{i(f)}$. The datalinks' colors were then used in this study to investigate the space faults and the user's ability to localize faults. We next describe our color mapping scheme, empirical results, and study conclusion (see Figure 13).

6.2.1 *Color Mapping Scheme.* The fundamental idea of our color mapping scheme revolves around continuously coloring (red to yellow to green[5]), according to the relevant percentage of test cases that produce valid results when executing the du-associations to the test cases that exercise the du-associations but produce invalid results. As such, the color of a datalink can be anywhere in the continuous spectrum of colors from red to orange to yellow to green. A similar color mapping scheme was used in Agrawal et al. [1995] and Jones et al. [2002] to study the localization of faulty program lines or statements. Other similar studies colored cells for validation in form-based languages [Rothermel et al. 2001].

For every direct and indirect datalink in $v_{i(f)} \in V_{(f)}$, our color mapping scheme[6] is as follows:

- If the percentage of the test cases in $DUT_{(f)}$ that exercise a direct and indirect datalink and produce valid results, when run on $v_{i(f)}$, is much higher than the percentage of test cases that produce incorrect results, then the hot spot appears more green; otherwise it appears more red. The intuition here is that datalinks that are executed primarily by test cases that produce valid results are not likely to be faulty, and thus are colored green to denote a possible safe neighborhood; otherwise, datalinks that are executed primarily by test cases that produce invalid results should be suspected as being faulty, and thus are colored red to denote a possible faulty neighborhood. The notion of neighborhood is necessary in VDFLS since, unlike imperative languages, the code constructs are graph-like, and distributed over many cases. Hence our notion of localizing faults through color mapping differs from that introduced for imperative languages [Agrawal et al. 1995; Jones et al. 2002]. In our study, the fault space is considered to be found if it is located in the neighborhood of one or more datalinks that are colored suspiciously or in the reddish-orangish color range in a case containing the fault. The intuition here is that this can direct a user's attention to a faulty neighborhood, and minimize the search space of faults.

[5]These color combinations were found to be the most natural in [Jones et al. 2002], and they also complement the blue colored program constructs in Prograph.

[6]The reader is encouraged to read the PDF file of this article or print a colored copy.

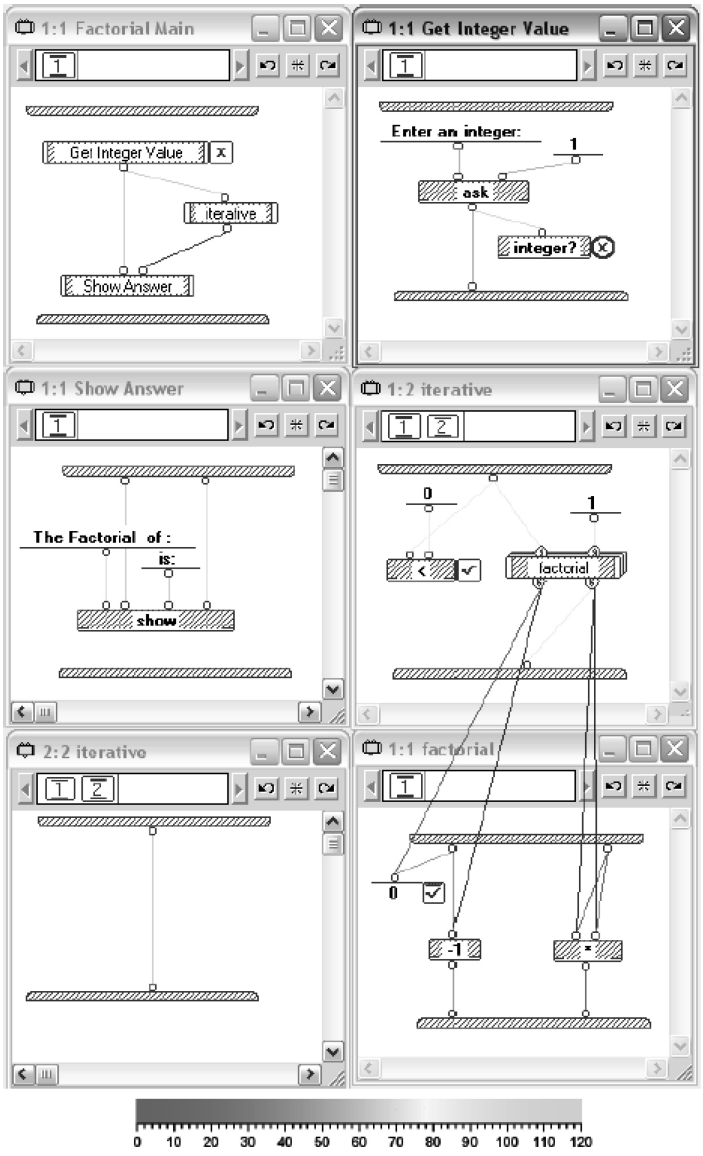


Fig. 13. The *factorial main* under test showing color reflections on datalinks.

- If the percentage of the test cases in $DUT_{(f)}$ that produce valid results, when run on $v_{i(f)}$, is near-equal to the percentage of test cases that produce incorrect results, then the hot spot is colored yellow. The intuition here is that datalinks that are executed by test cases that produce a mixture of valid and invalid results are consider a cautious neighborhood, and are thus colored yellow.
- If 100% of the test cases in $DUT_{(f)}$, run on $v_{i(f)}$, do not exercise a particular hot spot, then that hot spot is not colored, and is left blue (its original color). The intuition here is that if a datalink is never exercised, leaving it in its original

color could give incentive to users to further investigate its neighborhood in case of failure.

6.2.2 *Color Measurements of Datalinks.* Recall *Definition* 3.1 where we defined a test suite $T = (Z, I, O_{V/I}, C_N)$. Using Z, the test case number; I, the set of inputs values; $O_{V/I}$ $v_{i(f)}$'s output valid/invalid set of results of executing $v_{i(f)}$ using T; and C_N, the set of covered nodes in $OCG_{(v_{i(f)})}$ that helped us to determine the exercised datalinks in each $t = (z, i, o_{v/i}, c_n) \in T$, we colored a hot spot or datalink representing a c-use as follows: color = low red + ((%valid()) (*%valid*() + *%invalid*()) * color range). The valid() function returns, as a percentage, the ratio of the number of test cases that executed the hot spot and produced a valid result to the total number of test cases in the test suite. Likewise, the *invalid*() function returns, as a percentage, the ratio of the number of test cases that executed the hot spot and produced an invalid result to the total number of test cases in the test suite. The value for the *low red* is the lower end of the color spectrum, and has a value of 0. The color range corresponds to the high end of the desired color spectrum; green in our case. For example, if a datalink representing a c-use is executed by 50% of test cases that produced invalid results, and 100% of the test cases that produced valid results, its color will be 10/15 * 120 = 80, which renders this as a green-yellowish color, as depicted in the color legend of Figure 14. The color of a hot spot or datalink representing a p-use is computed, using the above formula, as the average color of the du-associations representing the true and false exercised outcome.[7] For example, if a datalink representing a p-use (true) is executed by 50% of test cases that produced invalid results, and 100% of the test cases that produced valid results, and its p-use (false) is executed by 100% of test cases that produced invalid results, and 50% of the test cases that produced valid results, its color will be 1/3 * 120 = 40, thus the datalink will be rendered at (80 + 40)/2 = 60. The indirect datalinks (representing c-use and p-use associations) that are constructed during testing are colored analogously to their direct datalinks counterpart.

6.2.3 *Data Analysis and Overall Results.* To evaluate our color mapping technique, and report how frequently a fault is found in a reddish-oringish neighborhood, we analyzed the color mapping applied to our subject program's faulty versions. To simplify the presentation of faulty versions and their fault space, we decided to represent, as depicted in Figure 14, a separate graph for each of the eight base programs' faulty versions. Each faulty version $v_{i(f)}$ of f occupies a vertical bar (with color spectrum) position along the x-axis and represents the low and high neighborhood color of the fault space where the fault is found. The Y-axis represents the color range (120). The color legend is depicted in the lower part of Figure 11.

Across all versions of the base programs, there were two categories of neighborhood fault space that were found to exceed the danger zone. The first

[7]We initially tried to color datalinks representing def-p-use associations [recall *Definition 4.2:* (n_i, (n_j, n_k), (r_x, t_y)), (n_i, (n_j, n_l), ($r_{x'}$, $t_{y'}$))] by dividing them into two halves and applying the color mapping scheme to each half separately. This approach was found to be difficult to explain to users with regard to the overall color mapping consistency scheme.

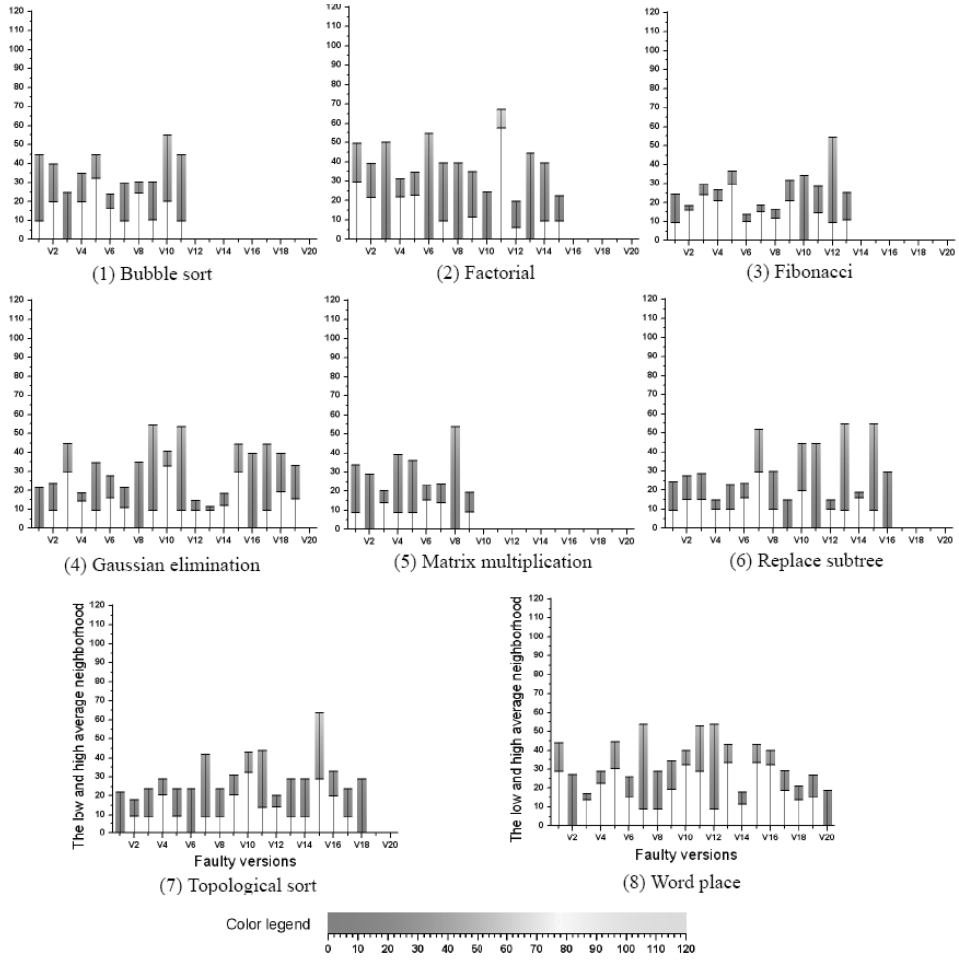


Fig. 14. This graph captures for each base program the color range of the neighborhood where the fault was found.

category had its low color spectrum in the appropriate zone but its high color spectrum in the inappropriate zone. For example, as depicted in Figure 14, versions 3 and 6 of the Factorial base program have their fault space approximately between 53 and 60. In the second category, both the low and high color spectrum were not found in their appropriate zone. For example, as depicted in Figure 14, version 11 of the Factorial base program has its fault space approximately between 60 and 70. Across all faulty versions of the base programs, less than 6% was found to be in category 1, and less than 3% was found in category 2. We were not very concerned with category 1, since the majority of the datalinks in all instances were in the low color spectrum, and were very indicative to the user as to where the fault space is. As for the second category, we examined their versions, and discovered that the fault was in erroneous datalinks that initialize root values that were used in datalink executions by all or most test cases.

Versions 11 and 15 of Factorial and Topological sort, in particular, were found to have more than one faulty space. This is not considered a threat to our testing techniques, since users can use the process of elimination in examining the faulty spaces or neighborhoods.

6.2.4 *Study Conclusion.* One significant problem in Study 2 was the presence of infeasible paths and their related du-associations in the faulty versions. There are two different causes to infeasible paths. The first cause is semantic dependencies that always hold. These dependencies in the single fault versions of our subject programs varied in nature from a du-association on a path that is directly related to conditional statements whose either true or false outcome can never be realized to loops-related du-associations paths that could never be traversed. The presence of these du-associations is usually referred to as dead du-associations. The second cause of infeasible paths is due to the limitation or lack of input data to exercise them.

Not being able to color datalinks was difficult to explain to users. It is our intention to deal with the first cause by trying to detect, using static analysis similar to that of Clarke [1976], and color identified infeasible datalinks green.

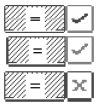
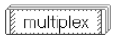
As for the category of the fault space spectrum, we intend to address this situation by using a more advanced visualization technique that could perhaps make use of the dependency analyses and slicing of the code. Computing static output slices can be achieved by either using iterative dataflow equations [Aho et al. 1986; Weiser 1984], or using a dependence graph [Horwitz et al. 1990]. The second approach is particularly applicable to VDFLs, since OCG is already a graph representing both data and control dependencies.

7. CONCLUSIONS

The recently increasing popularity in the visual paradigm in general, and VDFLs in particular, has resulted in many languages that are being used to produce much research and commercial software. Further, this popularity is likely to grow due to the users' anticipation of moving into the visual age of programming. VDFLs are prone to faults that can occur at the visual coding phase. To provide users of this paradigm with some of the benefits that are enjoyed by their imperative counterpart, we have developed a testing methodology that is appropriate for VDFLs. Our methodology and algorithms are compatible with and accommodate all visual languages with a dataflow computational engine. Our algorithms are also efficient, especially when given the fact that our static dataflow analysis is derived from probing the same data structures used to execute the visual code. This article presented an implementation overview of a tool that we have developed that implements our testing methodology, along with the results of two studies that evaluate the effectiveness our fault detection and fault localization technique.

Our empirical results from Study 1 suggest that our testing methodology can achieve fault detection results comparable to those achieved by analogous techniques for testing imperative languages. To investigate the importance of these results and evaluate their potential benefits to VDFLs users, we implemented, for Study 2, a color mapping technique that is based on our *all-DUs*

Table II. Hot Spots of Interest in the Visual Code.

	Hot Spot	Hot spot color scheme
Operation		A non control annotated operation's borders are colored to indicate it's correspondent OCG's node participations in a test suite.
Predicate Operation		The borders and the check/cross marks represent the hot spots of interest, and they are associated with the *True* and *False* edges in the *OCG*, respectively. If the operation $o \in Os$, then both hot spots will be proportionately colored when the edge $e \in OCG$ that is associated with o is exercised. If $o \in Ox$, then the borders are appropriately colored when the when the *true* edge $e \in OCG$ is exercised, and the check/cross mark is appropriately colored when the when the *true* edge $e \in OCG$ is exercised
Loop		The loop arrows are appropriately colored to indicate the "loop back edge" participation in the OCG after a test suite.
Multiplex		The 3-D like lines on the multiplexed operation are colored to indicate the "back edge" participation in the *OCG* after a test suite.

testing methodologies. This coloring technique provided a visual mapping of the participation of datalinks in testing to assist users with no formal testing theory in minimizing the fault search space. The datalinks are colored using a continuous spectrum from red to yellow to green. Our empirical results from Study 2 suggest that our technique is promising for helping locate suspicious constructs in VDFLs and point to some directions for future work. We were encouraged by the fact that, for our subject programs, our technique significantly reduced the search space for the faults in a single fault version. We suspect, however, that users who have programming experience will perform differently using our testing approach than users who do not have such experience. Thus we intend to examine the relative effectiveness of our testing to both of these user populations. To build knowledge of testing skills among less experienced users, one approach we could take wiould be to allow these users to experiment with weaker adequacy criteria, such as *all-Nodes* or *all-Edges*.

Since Study 2 focused on single faulty versions, we are currently conducting additional studies to further evaluate our technique with multiple faults by applying *all-Nodes*, *all-Edges* and *all-Dus* in one testing session, all at once, and evaluate the faults localization detection ability of our system. The color mapping scheme that we are applying to the operations and control annotated operations (hot spots) is depicted in Table II.

One approach that can be beneficial to the user is the ability to modify the source code after locating a fault, and have our testing environment rerun the modified program on the test suite and dynamically update the views. One approach to doing this would be to incorporate regression test selection techniques similar to those found in Gupta et al. [1996].

Finally, the testing methodology presented in this article addresses only one of the important problems in dealing with VDFLs errors. Other testing problems have been examined in the context of imperative languages. These problems include: generating test inputs, validating test outputs, and detecting nonexecutable code. These problems are also important in the context of VDFLs, and in our ongoing work we are investigating them. We are also working on a way to scale up the methodology by taking into account global and dynamic variables.

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