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ROCS: an object-oriented class-level testing system based on the Relevant Observable ContextS technique[1]

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Abstract
Given an algebraic specification of a class of objects, we define a fundamental pair as two equivalent terms generated by substituting all the variables on both sides of an axiom by normal forms. For any implementation error in the class, if it can be revealed by two equivalent terms in general, it can also be revealed by a fundamental pair. Hence, we need only select test cases from the set of fundamental pairs instead of equivalent pairs in general. We highlight an algorithm for selecting a finite set of fundamental pairs as test cases. Further, by using the relevant observable contexts technique, we highlight another algorithm to determine whether the objects resulting from executing a fundamental pair are observationally equivalent. If not, it reveals an implementation error.

Using these algorithms, we have constructed a system to test object-oriented programs at class-level. We describe in detail the implementation of a prototype system, including the data structure of a Data member Relevant Graph (DRG) for the class, the procedures for the construction and path traversal of the DRG, the generation and execution of relevant observable contexts on the objects under test, and the reporting of implementation errors. The implementation illustrates an innovative idea of embedding testing algorithms into an interpreter to facilitate software testing.

Keywords: Equivalent terms; Fundamental pairs; Class-level testing; Object-oriented testing; Observational equivalence; Relevant observable contexts

1 INTRODUCTION

The object-oriented paradigm enhances the reliability, maintainability, and reusability of resulting software. It is known as a technique for improving the productivity, quality, and innovation in software development [1]. However, software testing becomes more complex and difficult than that for conventional programming. It contains four levels: algorithmic level, class level, cluster level, and system level [2]. In this paper, we will only discuss the most fundamental and yet very important level, namely the class level.

There are many possible combinations when methods in a class are invoked. Hence, test cases for object-oriented software at the class level involves not only individual operations but various sequences

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of operations, which are known formally as "ground terms". If two ground terms are equivalent according to the specification, but their implemented method sequences generate observationally non-equivalent objects, then there is an error in the implementation. Using this concept, pairs of equivalent ground terms should be selected as test cases for any given class. This recommendation cannot be directly applied in practice, however, because the set of all equivalent pairs is infinite in most circumstances.

Various authors have proposed black-box techniques for selecting class-level test cases from equivalent ground terms [3-8]. Others have proposed white-box techniques for test case selection [2, 9-14]. We have proved that it is impossible to determine whether two objects are observationally equivalent using a pure black-box technique [15]. On the other hand, when part of the specification is missing in an implementation, there is no way of revealing this problem using a pure white-box technique.

In order (*a*) to overcome the shortcomings of the black-box and white-box techniques and (*b*) to reduce the domain of selection of test cases while keeping the test coverage unchanged, we propose an improved methodology for class-level testing that integrates the black and white approaches. This method covers the selection of test cases from the set of fundamental (equivalent) pairs and the generation of a relevant finite subset of the set of observable contexts for determining the observational equivalence of the objects resulting from the execution of a test case.

We will first of all outline our black-and-white integrated approach, and then focus our discussions on the implementation of a prototype system based on the "**R**elevant **O**bservable **C**ontext**S**" (ROCS) technique.[3] The implementation illustrates an innovative idea of embedding testing algorithms into an interpreter to facilitate software testing.

Section 2 introduces the basic concepts to be used in this paper. In Section 3, we outline our black and white integrated approach. In Section 4, we present the implementation and experiment of a prototype system based on the ROCS technique, including the representation, the construction and path traversal of a data member relevance graph for a given class, the generation and execution of relevant observable contexts on the objects under test, and the determination of implementation errors. Finally, Section 5 concludes the paper.

2 BASIC CONCEPTS

Among formal methods for the specification of object-oriented programs, algebraic specifications are one of the more popular approaches [16-19]. A syntax declaration and a semantic specification compose an *algebraic specification* for a class. The syntax declaration declares the *operations* involved, plus their domains and co-domains, corresponding to the input parameters and output of the operations. The semantic specification contains equational *axioms* that specify the behavioral properties of the operations.

Example 1

An algebraic specification for the class of integer stack.

> **module** *INTSTACK is*
> **classes** *Int Bool IntStack*
> **inheriting** *INT*
> **operations**
> *new*: $\rightarrow$ *IntStack*
> *_.empty*: *IntStack* $\rightarrow$ *Bool*
> *_.push(_)*: *IntStack Int* $\rightarrow$ *IntStack*
> *_.pop*: *IntStack* $\rightarrow$ *IntStack*
> *_.top*: *IntStack* $\rightarrow$ *Int* $\cup$ *{NIL}*
> **variables**
> *S*: *IntStack*
> *N*: *Int*

[3] If we regard "Black and White" as a Scotch Whiskey, it will be nice to have it "on the ROCS".

axioms

a_1: *new.empty = true*
a_2: *S.push(N).empty = false*
a_3: *new.pop = new*
a_4: *S.push(N).pop = S*
a_5: *S.top = NIL if S.empty*
a_6: *S.push(N).top = N* ■

A *term* is a sequence of operations in an algebraic specification satisfying its syntactic requirements. For example, *new.push*(1).*push*(2).*pop* is a term in the class of integer stacks above. A term may be transformed into another using the equational axioms of the specification as progressive *left-to-right rewriting rules*. It is in *normal form* if and only if it cannot be further transformed by any axiom in the specification. For example, *new.push*(1).*push*(2) is in normal form but *new.push*(1).*push*(2).*pop* is not, since the latter can be transformed into *new.push*(1) using axiom a_4 as a rewriting rule.

A term without variables is referred to as a *ground term*. We only consider ground terms in this paper because actual test cases in dynamic testing involve ground terms only. An algebraic specification is said to be *canonical* if and only if every sequence of rewrites on the same ground term reaches a unique normal form in a finite number of steps. In other words, every ground term of a canonical specification has a unique normal form. Canonical specifications are terminating and free from confusion, and hence only such specifications will be discussed in this paper. Two ground terms u_1 and u_2 are said to be *equivalent* (denoted by $u_1 \sim u_2$), if and only if both of them can be transformed into the same normal form by some axioms in the algebraic specification as left-to-right rewriting rules.

Let *C* be a class in a given specification. An observer of *C* is an operation or method that returns attribute values of an object in *C* without affecting any observable attributes. A creator of *C* is an operation or method that returns initial objects of *C*. The *state* of an object in *C* is the combination of all the attribute values of this object. A *constructor* or *transformer* of *C* is an operation or method that transforms the state of an object in *C*. In other words, when a constructor or transformer acts on an object, it changes at least one attribute value of the object. The difference between a constructor and a transformer is that the former can appear in a normal form but the latter cannot. In Example 1, for instance, the operation *new* is a creator, *_.push*(*N*) is a constructor, *_.pop* is a transformer, and *_.empty* and *_.top* are observers.

An *observable context* on *C* is either (*a*) an observer in *C* or (*b*) a sequence of operations or methods satisfying the syntactic requirements in *C*, that starts with a constructor or transformer but ends with an observer.

Given a canonical specification and its implementation in a class *C*, two objects O_1 and O_2 in *C* are said to be *observationally equivalent* (denoted by $O_1 \approx O_2$) if and only if, for any observable context *oc* on *C*, O_1.*oc* and O_2.*oc* produce either identical results or observationally equivalent objects in the output class of *oc* [15].

3 SUMMARY OF OUR APPROACH

There are two important theoretical aspects in our approach.

One is the concept of a *fundamental pair*, which is obtained by replacing all the variables on both sides of an axiom by normal forms. In example 1, for instance, the pair of equivalent ground terms *new.push*(2).*push*(6).*pop* ~ *new.push*(2) is a fundamental pair, since it can be formed by replacing the variables *S* and *N* in axiom a_4 by the normal forms *new.push*(2) and "6", respectively. However, *new.push*(8).*pop.push*(6).*push*(7).*pop* ~ *new.push*(6) is not a fundamental pair, since it cannot be formed directly from any of the axioms.

The other theoretical aspect in our approach is the formulation of a theorem, which states that an implementation of a canonical specification is consistent with respect to all equivalent terms if and only if it is consistent with respect to all fundamental pairs. In this way, although the set of fundamental pairs is a proper subset of the set of general equivalent ground terms, the testing coverage of fundamental pairs remains identical to that of general equivalent ground terms, and hence we need only concentrate on the testing of fundamental pairs. For example, we need only select test cases such as the fundamental pair *new.push*(2).*push*(6).*pop* ~ *new.push*(2), and need not consider more general equivalent ground terms such as *new.push*(8).*pop.push*(6).*push*(7).*pop* ~ *new.push*(6).

Unfortunately, an axiom may induce an infinite number of fundamental pairs by assigning different normal forms to its variables. We need some means of selecting a finite number of representative test cases from this infinite number of cases. Assuming the regularity hypothesis and uniformity hypothesis [3], we have proposed an algorithm GFT for **G**enerating a **F**inite number of **T**est cases. It consists of the following main steps:

(1) Replace each variable of a non-observable type in an axiom *ax* by a number of normal form patterns with lengths no greater than a given positive integer *k*, thereby unfolding *ax* into several new equations. Repeat the process until all the variables in the new equations are of observable types. The integer *k* may be determined by a white-box technique, such as by referring to the maximum sizes of arrays or the boundary values of variables declared in the implemented code.

(2) Partition the input domain of the operation in each derived equation in (1) into sub-domains using the conditions in the set of the axioms defining the operation.

(3) Randomly select an element from each sub-domain obtained above. Use these elements to replace all occurrences of the corresponding variables in the new equation to obtain a group of fundamental pairs for the axiom *ax*.

On the other hand, in spite of the theorem above, an infinite set of observable contexts may be required to check the observational equivalence of objects resulting from the fundamental pairs. We have proved that this problem cannot be solved by any black-box technique. Based on white-box techniques, therefore, we have constructed a heuristic algorithm to select a finite subset of the set of relevant observable contexts. It is known as DOE for **D**etermining **O**bservational **E**quivalence. The basic idea is as follows:

Suppose we want to decide whether the objects O_1 and O_2 resulting from the execution of a test case are observationally equivalent. Suppose, further, that O_1 and O_2 have different values for the same data member d_x of the implemented class. Such different values may or may not have an effect on the observable attributes of O_1 and O_2. If no observable attribute is affected, d_x need not be considered. If some observable attribute is affected, d_x must have affected the attribute through some series of methods in the implemented class. Such a series of methods is called a *relevant observable context*. We need only use the relevant observable contexts to decide whether O_1 and O_2 are observationally equivalent. We can ignore any other observable contexts for this decision. The relevant observable contexts are constructed from a **D**ata member **R**elevance **G**raph (DRG), which is an abstraction of the given implementation of a given specification.

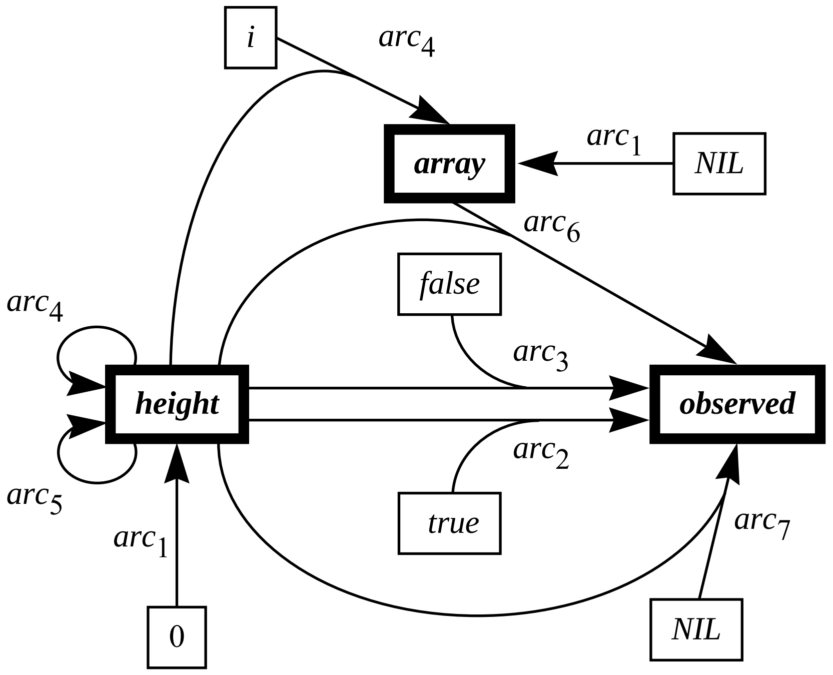
In the DRG of an implemented class, a bold rectangular ***node*** denotes a data member and a thin rectangular *node* represents some constant coming from the program under test. If a data member d_2 directly affects another data member d_1 in the method m_1 under a condition $p(...)$, we draw an *arc* from d_2 to d_1 and label it as (p, m_1). We call $[d_2, (p, m_1), d_1]$ a *segment* of the DRG, d_2 a *start node* of the segment, d_1 an *end node* of the segment, (p, m_1) an *output arc* of d_2, and (p, m_1) an *input arc* of d_1. If d_2 is identical to d_1, the segment is said to be a *cycle*. Otherwise it is said to be *acyclic*. If m_1 is an observer, the segment is called an *observable segment*. Each DRG contains a special *node* called *observed*, which is the end node of an observable segment. An arc with *observed* as an end node is call an *observer arc*.

Example 2
Consider the specification in Example 1. Suppose the implementation of the specification is as follows.

```
#include <iostream.h>
#define SIZE 100
#define NIL 0
enum bool { false, true };
```

```
class intStack
    {
    /*  intStack consists of 2 data members:  */
    int array[SIZE];
    int height;
    public:
        void newStack( );
        bool empty( );
        void push(int i);
        void pop( );
        int top( );
    };

void intStack :: newStack( )
    {
    height = 0;
    for (int j = 1;  j <= 100;  j++)
        array[j] = NIL;
    }

bool intStack :: empty( )
    {
    if (height = = 0)
        return true;
    else return false;
    }

void intStack :: push(int i)
    {
    if (height = = SIZE)
        cout << "Stack is full";
    else
        {
        height = height + 1;
        array[height] = i;
        }
    }

void intStack :: pop( )
    {
    if (height > 6)                    /*  Error: The condition should be height > 0  */
        height = height – 1;
    }

int intStack :: top( ) {
    if (height > 1)                    /*  Error: The condition should be height > 0  */
        return array[height];
    else  return  NIL;
    }
```

The DRG of the implementation is shown in Figure 1.



arc$_1$: (*true*, *newStack*);
arc$_2$: (*height* = 0, *empty*);
arc$_3$: (*height* ≠ 0, *empty*);
arc$_4$: (*height* ≠ *size*, *push*(*i*));
arc$_5$: (*height* > 6, *pop*);
arc$_6$: (*height* > 1, *top*);
arc$_7$: (*height* ≤ 1, *top*);

Figure 1. DRG of Integer Stacks Implemented in Example 1

Suppose d_x is a data member of an implemented class C, and O_1 and O_2 are two objects of C. If (*a*) $O_1.d_x \neq O_2.d_x$, (*b*) there is a path P from the node d_x to the node *observed* in the DRG of class C, and (*c*) the methods in the labels of the arcs in path P are op_1, op_2, ..., op_t, and *obs*, then $op_1.op_2...op_t.obs$ will be a relevant observable context induced from the path P with respect to O_1 and O_2.

The benefits of our integrated approach are as follows.

(*a*) We reduce the selection domain of test cases but the test coverage remains identical.

(*b*) We skip the testing of many irrelevant observable contexts when deciding whether the objects O_1 and O_2 resulting from the execution of a test case are observationally equivalent.

(*c*) We have overcome the problem of "missing paths" in pure white-box techniques.

(*d*) When compared with the work of Doong and Frankl [6, 7], we need not require the specifier to add a special-purpose axiom *eqn* to each class in order to define the operational semantics of the equivalence of objects. Nor do we require the designer and programmer to implement a special-purpose recursive method for the respective *eqn* axiom in each class. Thus, we can avoid rejecting a correct implementation of the original class having a problematic *eqn* axiom or implementation.[4]

[4] The situation is acceptable only if the *eqn* function happens to be part of the original class under test.

4 IMPLEMENTATION OF THE ROCS SYSTEM

The main objective of our previous paper [15] was to present the theoretical details of our approach. It only provided an outline of the algorithms involved. We are presenting in this paper the implementation details of the ROCS system so that readers may have a better insight on the working of the methodology.

A special feature of our implementation of the ROCS system is that the test algorithm DOE has been embedded into a C++ interpreter, which is an extension of the interpreter for *Little C* [20]. Thus, ROCS can be regarded as an interpreter that has been enhanced to include testing functions. It covers the construction and path traversal of DRG, the execution of relevant observable contexts, and the determination of implementation errors. In general, testing techniques should scan the program code under test, and hence it is natural and effective to consider embedding them into a compiler or interpreter. Our implementation of the ROCS prototype provides a successful experience in this aspect.

The prototype of ROCS has been implemented using Borland *C++*. It consists of five modules: *parser.c*, *drg.c*, *pigeonC.h*, *subLib.c*, and *pigeonC.c*. The module *pigeonC.h* defines the main data structure, and *subLib.c* defines the interfaces to internal library functions. The module *parser.c* consists of a lexical analyzer and a recursive descent parser. The lexical analyzer can also be called by *drg.c* and other modules. The module *drg.c* constructs the DRG, traverses executable paths by backtracking, and generates and executes the corresponding relevant observable contexts for any two given objects. Finally, *pigeonC.c* serves as the main module of the prototype. It reads the *C++* program code for a given class under test, allocates memory for the program, pre-scans it, and calls and coordinates other modules to perform the tasks.

Let O_1 be an object of the implemented class C, and let $d_1, d_2, ..., d_n$ be the data members. A path P in the DRG of C is said to be *executable for* O_1 if $O_1.d_i$ satisfies all the conditions on the labels of the arcs in P as initial data. Otherwise P is said to be *inexecutable for* O_1.

The tasks of the ROCS system are as follows.

(1) Read the code of the class C under test.

(2) Read a given fundamental pair as a test case generated by Algorithm GFT from the specification of C.

(3) Scan the code of C and draw all the arcs from the code.

(4) Generate the segments from the arcs and obtain the data structure of the DRG.

(5) Execute the method sequences corresponding to the given fundamental pair.

(6) Let O_1 and O_2 be two objects resulting from the execution.

```
For each data member $d_x$ such that $O_1.d_x \neq O_2.d_x$,
    traverse some executable paths from the node $d_x$ to the node observed in the DRG
        (with backtracking if necessary) and
    obtain some relevant observable contexts $oc_j$ induced from these paths.
```

(7) Execute $O_1.oc_j$ and $O_2.oc_j$ in the program under test.

```
If some execution result shows that $O_1.oc_j \neq O_2.oc_j$, then
    report an implementation error.
```

In order to implement these tasks, we should first of all consider the data structure of the DRG. The data structure will affect significantly the space efficiency of the system.

4.1 Data Structure of DRG

A DRG consists of three kinds of basic elements, namely nodes, arc labels, and segments. A segment denotes the connection between two nodes as well as the arc label involved. The module *pigeonC.h* defines three data structures to represent the arc labels, segments, and nodes as follows:

```
struct arcLabel
    {                                    /*  The representation of arc label (p, m)  */
    char condition[STATEMENT_LEN];   /*  Condition p  */
    char method[ID_LEN];             /*  Method m  */
    };

struct segment
    {                       /*  The representation of a segment starting from a given node  */
    int arcLabelIndex;      /*  The index of the arc label of the segment  */
    int endNodeIndex;       /*  The index of the end node of the segment  */
    int iterationNumb       /*  For the case of cycles, the number of iterations required
                                when backtracking  */
    };
```

Since a number of segments may have the same arc label and since the number of segments is much more than that of nodes, we use indices rather than real entities in the fields of the *struct segment*. In this way, the space for storing segments will be reduced. We will explain later why there is no need to include a field in *struct segment* to denote its start node.

```
struct node
    {                     /*  The representation of a data member  */
    char dataMembName[ID_LEN];   /*  Name of the data member  */
    int dataMembType;     /*  Type of the data member  */
    int value;            /*  Value of the data member, if the data member is of
                              a simple type  */
    int arraySize;        /*  Array size if this data member is an array; otherwise it is 0  */
    struct segment acycSegList[LIST_LEN];
                          /*  The list of acyclic segments starting from the node  */
    int acycSegsSize;     /*  The size of acycSegList  */
    int acycSegsIndex;    /*  The current position of acycSegList  */
    struct segment obsSegList[LIST_LEN];
                          /*  The list of observable segments starting from the node  */
    int obsSegsSize;      /*  The size of obsSegList  */
    int obsSegsIndex;     /*  The current position of obsSegList  */
    struct segment cycSegList[LIST_LEN];
                          /*  The list of cycle segments starting from the node  */
    int cycSegsSize;      /*  The size of cycSegList  */
    int cycSegsIndex;     /*  The current position of cycSegList  */
    }
```

Here, the field *acycSegList*, *obsSegList*, or *cycSegList* in *struct node* is called a *segmentList* field. The data elements *acycSegsIndex*, *obsSegsIndex*, and *cycSegsIndex* are used to mark the first untraversed segment for backtracking in the traversal of the executable paths of a given object. Their initial values are 1.

A natural representation of a segment is $[d_2, (p, m_1), d_1]$, where d_2 is the start node of the segment. We need not, however, define a field in *struct segment* to denote d_2. It is because *struct segment* is used only in the *segmentList* fields of *struct node*, and hence the start node of *struct segment* is just the *struct node* self. By omitting the obvious start node, the space for storing *struct segment* can also be reduced.

The module *pigeonC.h* uses the following data structures for representing a DRG for a given class under test:

(1) An array known as *arcLabelList*, containing all the arc labels of the DRG. It is declared by the statement

    struct arcLabel arcLabelList[*NUM_ARCS*].

(2) A *struct node* for each data member of the class. All of these *struct node*s make up an array known as *nodeList*, which is declared by the statement

struct node nodeList[*NUM_DATA_MEMBERS*].

4.2 Construction of DRG

The process of constructing a DRG is as follows.

(1) The module *pigeonC.c* pre-scans the program code for the given class under test, finds the locations of all the functions, methods, and global variables in the program, and sets up corresponding tables for future use, such as *functionsTable*, *methodsTable*, and *globalVarsTable*.

(2) The module *pigeonC.c* calls another module *parser.c* to perform lexical analysis and recursive descent parsing. The module *parser.c* also conducts the initialization for *drg.c* and other modules, including the supply of information to the appropriate fields in the *struct node*s in *nodeList*, such as *dataMembName* and *dataMembType*.

(3) Based on the tables and the information above, the function *constructDRG*( ) in the module *drg.c* creates the *arcLabelList* of the DRG for the implemented class under test. It also completes the remaining fields of the *struct node*s in *nodeList*, such as *struct segment acycSegList*[ ] and *int acycSegsSize*, by means of a function *scanBlock*( ), which is a variant of the function *interp_block*( ) in an interpreter [20].

(4) Suppose d_1 and d_2 are two data members in the implemented class. Let p be a predicate and c be a constant. In order to construct the DRG, the function *scanBlock*( ) performs the following tasks for each method m_i. The generated segments corresponding to the scanned statements in this step is listed in Table 1.

(*a*) Scan the code of m_i.

(*b*) When a statement of the form "$d_1 = c$" or "$d_1 = f(..., d_2, ...)$" is found,
put the *arcLabel* (*true*, m_i) into the *arcLabelList*, and
put the segment [index of *arcLabel* (*true*, m_i), index of d_1]
into a *segmentList* field of the node c or the node d_2.

(*c*) When a statement such as "if (p) {...; $d_1 = c$; ...}" or "if (p) {...; $d_1 = f(..., d_2, ...)$; ...}" is found,
put the *arcLabel* (p, m_i) into the *arcLabelList*,
put the segment [index of *arcLabel* (p, m_i), index of d_1]
into a *segmentList* field of the node c or the node d_2,
if $p = p(..., d_3, ...)$, d_3 is a data member different from d_2,
put the segment [index of *arcLabel* (p, m_i), index of d_1]
into a *segmentList* field of the node d_3.

(*d*) If the statement also contains "*else* {...; $d_4 = c_0$; ...}" or "*else* {...; $d_4 = g(..., d_5, ...)$; ...}",
put the *arcLabel* ($\neg p$, m_i) into the *arcLabelList*, and
put the segment [index of *arcLabel* ($\neg p$, m_i), index of d_4]
into a *segmentList* field of the node c_0 or the node d_5.

(e) Skip the other statements in the method m_i.

The time complexity for constructing the DRG of the class has been analyzed in [15].

Scanned Statement	**Corresponding Generated Segment**
$d_1 = c$	$c \xrightarrow{(true,\ m_i)} d_1$
$d_1 = f(..., d_2, ...)$	$d_2 \xrightarrow{(true,\ m_i)} d_1$
if (p) {...; $d_1 = c$; ...}	$c \xrightarrow{(p,\ m_i)} d_1$
if (p) {...; $d_1 = f(..., d_2, ...)$; ...}	$d_2 \xrightarrow{(p,\ m_i)} d_1$
if ($p(\ldots, d_3, \ldots)$) {...; $d_1 = f(..., d_2, ...)$; ...}, [where $d_3 \neq d_2$]	$d_3 \xrightarrow{(p,\ m_i)} d_1$
else {...; $d_4 = c_0$; ...}	$c_0 \xrightarrow{(\neg p,\ m_i)} d_4$
else {...; $d_4 = g(..., d_5, ...)$; ...}	$d_5 \xrightarrow{(\neg p,\ m_i)} d_4$

Table 1. Correspondence between Scanned Statements and Generated Segments

A question arises here. If the condition *p* appears in a *for* or *while* statement, how do we deal with it? We note that the DRG technique is concerned with the "directly affects" relations only among the data members and constants coming from the given program, rather than among other local auxiliary variables. If we regard a *for* loop or *while* loop as a function, we can concentrate only on the effects of the input data members of the function to the output data members of the function, and ignore the effects from local auxiliary variables. Suppose, for instance, that the code for operation *push*(*i*) in Example 1 is as follows:

```
void intStack :: push(int i)
    {
    for ( int j = 1; j <= 99; j++ )
        array[j] = array[j+1];
    array[100] = i;
    }
```

Since the condition $j <= 99$ in the *for* statement is related only to a local auxiliary variable *j*, it need not be considered in the construction of the DRG. We can regard this *for* statement as a function through which the data member *array*[ ] affects itself. Since *i* in the statement "*array*[100] = *i*" represents a constant rather than an auxiliary variable, the effect of *i* on the data member *array*[ ] must also be considered. Thus, we obtain two segments [*array*[ ], (*true*, *push*(*i*)), *array*[ ]] and [*i*, (*true*, *push*(*i*)), *array*[ ]] from the code.

4.3 Traversal of Executable Paths in DRG

The construction of a DRG for the given class is independent of the given fundamental pair as a test case. After constructing a DRG, ROCS executes the method sequences corresponding to the given fundamental pair, and produces two objects O_1 and O_2. For each data member d_x such that $O_1.d_x \neq O_2.d_x$, ROCS must traverse the executable paths from the node d_x to the node *observed* in the DRG (with backtracking if necessary) to obtain the corresponding relevant observable contexts oc_j, and then perform oc_j on the current states of O_1 and O_2. These tasks are conducted by the module *drg.c*. The following stack is used for the traversal and backtracking:

```
struct stack
    {
    int topIndex;                      /*  The index of the top of the stack  */
    struct traversedSegment travdSegList[LIST_LEN];
                                       /*  The list of traversed segments  */
    };

struct traversedSegment
    {                                  /*  A traversed segment */
    int arcLabelIndex;                 /*  The index of the arc label of the segment */
    int endNodeIndex;                  /*  The index of the end node of the segment  */
    char preObject1[OBJECT_SIZE];  /*  The state of object O1 before running the method
                                           in the arc label  */
    char preObject2[OBJECT_SIZE];  /*  The state of object O2 before running the method
                                           in the arc label  */
    };
```

Suppose a segment Seg_2 is contiguous to another segment Seg_1 in the *travdSegList*[ ]. The state of object O_i after running the method in the arc label of segment Seg_1 is the same as that of object O_i before running the method in the arc label of segment Seg_2. Hence, there is no need to include a field in *struct traversedSegment* to denote the state of object O_i after running the method in the arc label of the segment. In this way, the space for storing the segments in *travdSegList*[ ] can also be reduced.

For each given data member d_x such that $O_1.d_x \neq O_2.d_x$, the path traversal process starts from the node d_x and consists of the following steps. Readers may also refer to the flowchart in Figure 2 for a better understanding the procedure.

```
(1) Assign data member $d_x$ to a working variable $d$, and
    empty the stack by setting stack.topIndex to 1.

(2) Select an untraversed segment and use it as the value of the working variable thisSeg, as follows:

    (a) If $d.obsSegsIndex \leq d.obsSegsSize$, then
            select the segment d.obsSegList[obsSegsIndex],
            copy it to thisSeg, and
            increase obsSegsIndex by 1.

    (b) Otherwise if $d.acycSegsIndex \leq d.acycSegsSize$, then
            select the segment d.acycSegList [acycSegsIndex],
            copy it to thisSeg, and
            increase acycSegsIndex by 1.

    (c) Otherwise if ($d.cycSegsIndex \leq d.cycSegsSize$)
        and ($d.cycSegList[cycSegsIndex].iterationNumb \leq T$),[5] then
            select the segment d.cycSegList[cycSegsIndex],
            copy it to thisSeg,
            increase d.cycSegList[cycSegsIndex].iterationNumb by 1, and
            if the updated $d.cycSegList[cycSegsIndex].iterationNumb > T$, then
                increase d.cycSegsIndex by 1.

    (d) If ($d.obsSegsIndex > d.obsSegsSize$) and ($d.acycSegsIndex > d.acycSegsSize$)
        and ($d.cycSegsIndex > d.cycSegsSize$), then
                /* there is no untraversed segment in d.obsSegList[obsSegsIndex],
                   d.acycSegList[acycSegsIndex], or $d_i$.cycSegList[cycSegsIndex]  */
            perform backtracking as described below.
```

[5] Here, T is a global ceiling allowed by the system for the number of iterations of any cycle segment.

```
(3) If the condition thisSeg.arcLabelIndex$\uparrow$.condition is satisfied by the current states of $O_1$ and $O_2$,
    then
        copy the values of arcLabelIndex and endNodeIndex in thisSeg
            to the corresponding fields of stack.travdSegList[topIndex].
        copy the current state of $O_1$ to the field preObject1 of stack.travdSegList[topIndex],
        copy the current state of $O_2$ to the field preObject2 of stack.travdSegList[topIndex],
        execute the method thisSeg.arcLabelIndex$\uparrow$.method on $O_1$ and $O_2$,[6]
        increase stack.topIndex by 1, and
        conduct the following:

    (a) If thisSeg.endNodeIndex$\uparrow$ is the special node observed, then
                /*  thisSeg.arcLabelIndex$\uparrow$.method should in fact be an observer  */
            if the values resulting from the executions of step (3) are not identical, then
                report that an implementation error has been found
                    because the original $O_1$and $O_2$ are not observationally equivalent, and
                exit from the process;
            otherwise perform bcktracking as described below.

    (b) If thisSeg.endNodeIndex$\uparrow$ is not the special node observed, then
            update the working variable d to thisSeg.endNodeIndex$\uparrow$, and
            go to step (2) above.

(4) If the current states of $O_1$ and $O_2$ do not satisfy the condition thisSeg.arcLabelIndex$\uparrow$.condition,
    then backtrack to step (2) to select another untraversed segment.
```

When backtracking is required, the following will be conducted:

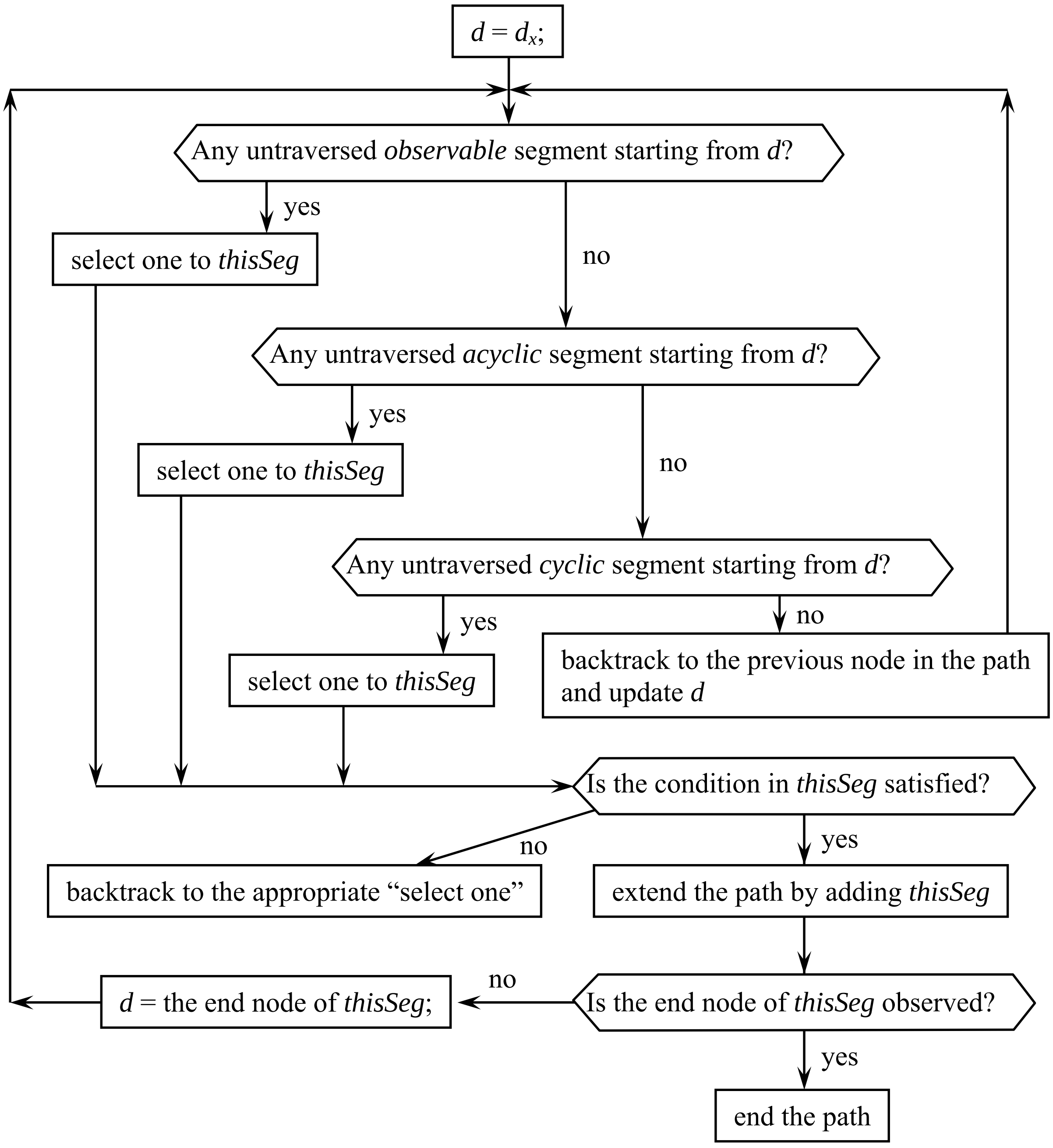
```
(i)    If stack.topIndex = 1, that is, if stack is empty,
           report that the given data member $d_x$ has successfully passed the check, and
           exit from the process.

(ii)   If stack.topIndex > 1, decrease stack.topIndex by 1.

(iii)  Restore $O_1$ to stack.travdSegList[topIndex].preObject1[ ] and
           $O_2$ to stack.travdSegList[topIndex].preObject2[ ].

(iv)   Update the working variable d to stack.travdSegList[topIndex – 1].endNodeIndex$\uparrow$.

(v)    Go to step (2) to update thisSeg by selecting an untraversed segment from
           d.obsSegList[obsSegsIndex], d.acycSegList[acycSegsIndex], or d.cycSegList[cycSegsIndex].
```

Note that the concept of executability of a given path for a given object defined in previous section is very different from the concept of feasibility of a path in other flow graph techniques [21]. An *infeasible path* is usually defined as a path whose conditions cannot be satisfied by *any* input value, and is well-known to be undecidable. However, since the executable and unexecutable paths defined in the previous section are related to a *given object* O_1, their conditions can be determined from the known values $O_1.d_i$ of the data members of the given object O_1. Thus, unlike the concept of feasibility, the executability of a given path for a given object is decidable.

[6] Note that the states of O_1 and O_2 may be changed after the execution of this step.

4.4 Execution of Relevant Observable Contexts

We see from the previous subsection that the execution of a relevant observable context on the given objects O_1 and O_2 should be synchronized with the traversal of the corresponding executable path in the DRG. In the graph traversal process, whenever a path is extended by a segment, the method contained in the arc label of the segment is executed on the current states of O_1 and O_2.



d = d_x;
Any untraversed observable segment starting from d?
yes
select one to thisSeg
no
Any untraversed acyclic segment starting from d?
yes
select one to thisSeg
no
Any untraversed cyclic segment starting from d?
yes
select one to thisSeg
no
backtrack to the previous node in the path and update d
Is the condition in thisSeg satisfied?
no
backtrack to the appropriate "select one"
yes
extend the path by adding thisSeg
no
d = the end node of thisSeg;
Is the end node of thisSeg observed?
yes
end the path

Figure 2. Flowchart on Traversal of Executable Paths in DRG

4.5 Determining Object Equivalence or Implementation Error

During the path traversal process for a given data member d_x such that $O_1.d_x \neq O_2.d_x$, when we reach the special node *observed*, we have completed traversing the entire executable path and executing the corresponding relevant observable context on O_1 and O_2. If the results of the execution on O_1 and O_2 are not identical, ROCS concludes that the original O_1 and O_2 are not observationally equivalent, report an implementation error, and then exit from the task. Otherwise it will trigger backtracking, with a view to traversing another untraversed path. If all the data members d_x such that $O_1.d_x \neq O_2.d_x$ have successfully passed the check, then ROCS reports that $O_1 \approx O_2$ and exit from the system.

4.6 Experimentation and Analysis

We have implemented the system on a *Pentium II* and experimented it with Example 2. All the errors in the example can be exposed. The time for constructing the DRG is 0.038731 s. The respective number of observable contexts generated and the total run time required are shown in Table 2.

Global ceiling supplied by the user for the number of iterations of any cycle	0	1	2	3	4
Number of observable contexts generated by the prototype	5	8	19	25	37
Total run time for all observable contexts	0.083 686 s	0.184 558 s	0.305 763 s	0.576 521 s	0.734 295 s
Run time for the first observable context that reports the error	-	-	0.186 549 s	0.195 764 s	0.274 391 s

Table 2. Run Times for Example 2

We have also experimented with the prototype using other programs that contain various types of error. Some programs contain common typos, such as having a condition *height* > 0 coded as *height* < 0 or *height* > 10. Some refer to non-existent elements of arrays, such as *array*[1000]. Some contain faults caused by placing statements in erroneous positions. Others have errors in the general ideas behind the programs, rather than in individual statements. All types of errors have been exposed by the system. The run times are acceptable.

Let s be the number of statements in the code for a given class C. Since the construction of the DRG for class C is based on scanning and processing each statement in the code, and the time for processing each statement is bounded, the time for constructing the DRG for C is $O(s)$.

Let L be the maximum length of all acyclic paths from any node to the node *observed*. Given any objects O_1 and O_2, let n be the maximum number of output arcs in any node such that the Boolean conditions in the arcs are true for the current values of $O_1.d_i$ and $O_2.d_i$. . Here, L is a constant and n is a variable depending on different objects O_1 and O_2. Since the ceiling for the number of iterations of cycles is a constant, the complexity of traversing executable paths is $O(n^L)$ for the worst case.

5 CONCLUSION

We have proposed an integrated approach for selecting fundamental pairs of equivalent ground terms as class-level test cases for object-oriented programs and applying observable context technique to determine whether the objects resulting from the execution of a test case are observationally equivalent. After outlining the basic idea of the approach, this paper describes in detail the prototype system based on the relevant observable contexts (ROCS) technique, including the representation, construction, and path traversal of a data member relevant graph for a given class, the generation and execution of relevant observable contexts on the objects under test, and the determination of implementation errors. The production of a prototype of the ROCS system provides an innovative experience for embedding testing processes into the language interpreter. A white-box testing technique involves the scanning and parsing of program code, and hence its integration with interpreters or compilers would help to expedite the process. Some experiments have been conducted via the prototype system, and the empirical results agree with the outcome predicted by our framework.

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