Mutation versus All-uses: An Empirical Evaluation of Cost, Strength and Effectiveness

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Abstract

Although mutation has been empirically found to be effective in detecting faults, it often imposes unacceptable demands on computing and human resources because of the large number of mutants that need to be compiled and executed on one or more test cases. We designed a case study to explore two alternatives of mutation to reduce its cost without significantly deteriorating its strength and effectiveness. The alternatives are (1) constrained *abs/ror* mutation which examines only the *abs* and *ror* mutants and ignores the others, and (2) randomly selected 10% mutation which examines only 10% of the randomly selected mutants of each mutation operator in *Mothra*. Data collected during experimentation have shown that both alternatives provide a significant *cost* reduction in terms of the number of test cases required to satisfy an adequacy criterion and the number of mutants to be examined. Such gain is accompanied by a small *strength* loss in the ability to distinguish non-equivalent mutants and cover feasible all-uses. In terms of decreasing order of fault detection effectiveness the ranking is mutation, constrained *abs/ror* mutation, all-uses, and randomly selected 10% mutation. These data suggest that examining only a small percentage of the mutants may be a useful heuristic for evaluating and constructing test sets in practice.

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1 Introduction

Although mutation testing has been empirically found to be effective in detecting faults [3, 7], it suffers from a problem of performance. The complexity of mutation is $O(n^2)$, where n is the number of variable references in the program. The number of mutants generated can be prohibitively large even for programs that are less than 100K lines of code. These mutants have to be compiled, executed, and often examined by the tester to determine equivalence, which makes mutation testing too expensive to be used in practice. Different algorithms were proposed to reduce the time to execute all mutants on a parallel [9] and a sequential [11] machine. These algorithms suffer either a conversion between different operating environments or extra memory requirement to store the program state, which limits their usability. As a significant portion of the computational cost of mutation testing is incurred in executing mutants against test cases, this cost can be reduced significantly by reducing the number of mutants to be

examined. We, therefore, propose the randomly selected 10% mutation and the constrained *abs/ror* mutation criteria described below. The major difference between our approach and the algorithms discussed above is that those algorithms do not reduce the number of mutants to be examined; it is the time to execute the mutants that is targeted for reduction whereas both of them are reduced in our approach.

Cost, difficulty of satisfaction, and fault detection effectiveness [12] are three meaningful bases against which test adequacy criteria should be compared. Cost refers to the *work* necessary to satisfy it. Difficulty of satisfaction is also known as the subsumption relationship [5] and strength [10]. Fault detection effectiveness refers to the fault detection capability of a criterion. We conducted experiments to explore the two alternatives of mutation described above with respect to the all-uses and mutation criteria in terms of these three factors. Data collected during experimentation will help us to answer the questions: Will reducing the number of mutants to be examined be a cost-effective alternative to the mutation testing? Will examining only a small percentage of the mutants be a useful heuristic for evaluating and constructing test sets in practice?

The remainder of this paper is organized as follows. Section 2 provides a brief overview of mutation and data flow based adequacy criteria used in the remainder of this paper. In Section 3, we explain how we compared the cost, strength, and effectiveness of various test adequacy criteria. Our experimental methodology is described in detail in Section 4. Data collected from experiments and its analysis appear in Section 5. Our conclusions appear in Section 6.

2 All-uses and mutation based test adequacy criteria

In this section we provide an overview of all-uses and mutation based test adequacy criteria by presenting only the information required for an understanding of the rest of the paper. More details can be found in [5, 7]. Let P denote the program under test with $\mathcal{D}$ as its input domain. Test cases are selected from the input domain. A test set $T \subseteq \mathcal{D}$ consists of one or more test cases.

2.1 All-uses criterion

Let s_i and s_j , $1 \leq i, j \leq n$ be two statements in P at which variable x is defined, $d_i(x)$, and used, $u_j(x)$, respectively. The pair $(d_i(x), u_j(x))$ is a def-use pair. A def-use pair is a *p-use* or a *c-use* pair depending on whether s_j is a predicate or not, respectively. We say that any such pair is *feasible* if there exists a test case $t \in \mathcal{D}$ such that the execution of P on t causes control to transfer from s_i to s_j , traversing one or more statements, without defining x at any statement other than at s_i . Such a path is also considered a *definition clear path* with respect to x . A test case $t \in T$ covers a c-use pair $(d_i(x), u_j(x))$ if the execution of P on t causes the execution of a definition clear path with respect to x from s_i to s_j . A p-use pair $(d_i(x), u_j(x))$ is considered covered if a definition clear path with respect to x from s_i to s_j to s_k is executed for each successor s_k of s_j . We refer to the set of all c-uses and p-uses as *all-uses* [5]. A test set T may be evaluated against the all-uses criterion by computing the ratio of the total number of all-uses covered to the total number of feasible all-uses. A ratio of unity implies that T is adequate with respect to the all-uses criterion.

2.2 Mutation criterion

Let m be a syntactically correct program obtained by making a syntactic change in P ; m is known as a *mutant* of P . Let r be a rule according to which P is changed; r is known as a *mutant operator*. There could potentially be an infinite number of mutant operators. To keep mutation testing practical, the set of mutant operators is kept small and consists of simple mutant operators [4]. The application of a set of mutant operators MO to P results in a set

of mutants $m_1, m_2, \dots, m_n, n \geq 0$. Mutant m_i is considered *equivalent* to P if for all $t \in \mathcal{D}$, $P(t) = m_i(t)$. When executed against a test case t , mutant m_i is considered *distinguished* from P if $P(t) \neq m_i(t)$. Unless distinguished, a non-equivalent mutant is considered *live*. One can obtain a variety of mutation based criteria by varying MO . Hereafter, we refer to the mutation based criterion with respect to the set of all 22 mutant operators in Mothra [4] as the *mutation* criterion. A test set T may be evaluated against the mutation criterion by executing each mutant against elements of T . The ratio of the number of mutants distinguished to the number of non-equivalent mutants is the *mutation score* of T for P . T is considered adequate with respect to the mutation criterion if the mutation score is unity.

One mechanism for reducing the cost of mutation testing is to examine a small percentage, say 10%, of randomly selected mutants of each mutant type and ignore the others. Earlier empirical investigations by Acree [1], Sayward, and Budd [3] have shown that even with test cases generated using only 10% of the mutants, no more than 1% of the non-equivalent mutants were overlooked. In this paper we present results not only to verify this aspect but also to investigate the cost and effectiveness of the randomly selected 10% mutation. Hereafter, we refer to such alternate mutation as 10% mutation.

Another mechanism for reducing the cost of mutation testing is constrained mutation. Using constrained mutation, one examines only a few specified types of mutants and ignores the others. For example, the constrained *abs/ror* mutation studied in this paper examines only the *abs* and *ror* mutants. The *abs* mutant operator generates mutants by replacing each use of x by $abs(x)$, $-abs(x)$, and $zpush(x)$ wherever possible. The terms, $abs(x)$ and $-abs(x)$ represent the absolute value and the negative absolute value of x , respectively. A mutant containing $zpush(x)$ is considered distinguished if a test case causes the value of x to be zero when execution reaches the mutated expression. When applied to a program containing an assignment statement $z := x + 1$, the *abs* operator generates six mutants obtained by replacing this assignment by $z := abs(x) + 1$, $z := -abs(x) + 1$, $z := zpush(x) + 1$, $z := abs(x + 1)$, $z := -abs(x + 1)$, and $z := zpush(x + 1)$. The *ror* mutant operator generates mutants by replacing each relational operator by other relational operators. In addition, it also replaces each condition consisting of at least one relational operator by the boolean constants *true* and *false*. For example, when applied to a program containing a predicate "if ($x = 0$) then", this mutant operator generates the following seven conditions: "if ($x < 0$) then", "if ($x \leq 0$) then", "if ($x \neq 0$) then", "if ($x > 0$) then", "if ($x \geq 0$) then", "if (*true*) then", and "if (*false*) then". A detailed rationale of such selection can be found in [14]. Hereafter, we refer to the constrained mutation using *abs* and *ror* mutation operators as *abs/ror* mutation.

3 Comparison methodology

The cost of the alternative mutation testing is measured by two metrics. One is the number of test cases required to satisfy it [10]. The other is the number of mutants to be examined [14]. We use Equations (1) and (2) to compute the cost reduction in terms of the number of test cases required with respect to the mutation or all-uses adequacy criteria, respectively, and the cost reduction in terms of the number of mutants examined with respect to the mutation adequacy criterion.

$$(1 - \frac{\text{average size of test sets adequate with respect to alternate mutation}}{\text{average size of mutation (or all-uses) adequate test sets}}) * 100\% \quad (1)$$

$$(1 - \frac{\text{total number of mutants examined when using alternate mutation}}{\text{total number of mutants examined in mutation}}) * 100\% \quad (2)$$

Two measures were selected for the strength of the alternative mutation testing. In one, the strength is measured in terms of the mutation scores by Equation (3). In the other, the strength is measured in terms of the all-uses scores by Equation (4).

$$\frac{\text{number of mutants distinguished by a test set}}{\text{total number of non-equivalent mutants}} * 100\% \quad (3)$$

$$\frac{\text{number of all-uses covered by a test set}}{\text{total number of feasible all-uses}} * 100\% \quad (4)$$

Given a program P , a specification S , and a test set T adequate with respect to a criterion C , T is said to be able to expose faults in P if there exists a test case $t \in T$ which makes P behave differently from S . As long as T detects at least one fault in P , T is counted as a fault-revealing test set. Equation (5), defined below, is used to compute the percentage of C fault-revealing adequate test sets.

$$\frac{\text{number of } C \text{ adequate test sets which expose at least one fault}}{\text{number of } C \text{ adequate test sets generated}} * 100\% \quad (5)$$

4 Experimental methodology

4.1 Subject programs

For cost and strength comparison, we used a suite of the four programs described below. Faults discovered while preparing the programs were removed. This was done as the goal of our experiments was to investigate which one of the adequacy criteria is more expensive and difficult to satisfy and not to investigate their fault detection capability. A source listing of each of these programs and removed faults can be found in [13].

- **FIND:** This program takes two inputs, an array a and an index f , and permutes the elements of a so that elements to the right of position f are greater than or equal to $a[f]$ and elements to the left of position f are less than or equal to $a[f]$.
- **STRMAT1 and STRMAT2:** Each program takes a text and a pattern of zero or more characters. If the pattern appears in the text then the position of the first occurrence of the pattern in the text is returned, otherwise a zero is returned.
- **TEXTFMT:** This program takes a text as input and formats it.

For effectiveness comparison, we used another suite of four programs with naturally occurring faults described below. A source listing of each of these programs and their faults can also be found in [13].

- **SORT:** This program takes an array and sorts it in descending order.
- **STRMAT3:** This program is similar to STRMAT1 and STRMAT2 with faults not removed.
- **POSITION:** This program takes two inputs, an array a and a value max , and sums the elements of a until the sum meets or exceeds max . If such an element exists, its position is returned, otherwise, a zero is returned.
- **STAT:** This program takes an array a and computes its sum, minimum, and maximum.

4.2 Experiments & testing tools

We generated mutants in our experiments using all 22 mutant operators in *Mothra* except the *goto*. Two testing tools, *Mothra* and ATAC [8] were used. *Mothra* is a mutation testing tool for testing Fortran 77 programs. Given a program and a test set, *Mothra* generates a set of mutants, executes them against test cases in the test set, and computes the mutation score. ATAC is a data flow coverage measurement tool for C programs. Given a program and a test set, ATAC computes the block, decision, c-use, p-use, and all-uses coverage. While using these tools, it is the tester's responsibility to determine equivalent mutants and infeasible data flow attributes.

Thirty adequate test sets with respect to mutation, *abs/ror* mutation, 10% mutation, and all-uses adequacy criteria were randomly generated with the exception that there are only five 10% mutation adequate test sets for FIND, STRMAT1, STRMAT2, and TEXTFMT. Details of test case generation can be found in [13].

Table 1: Program size metrics

		Number of mutants [†]			Number of decisions [‡]	Number of all-uses
		mutation	<i>abs/ror</i> mutation	10% mutation		
Cost & strength comparison	FIND	916	166 (18.12 %) [§]	94 (10.26 %)	17	119
	STRMAT1	627	125 (19.94 %)	65 (10.37 %)	16	63
	STRMAT2	510	99 (19.41 %)	50 (9.80 %)	12	66
	TEXTFMT	938	135 (14.39 %)	103 (10.98 %)	18	53
Effectiveness comparison	SORT	490	90 (18.37 %)	50 (10.20 %)	5	37
	STRMAT3	415	85 (20.48 %)	43 (10.36 %)	8	53
	POSITION	251	37 (14.80 %)	26 (10.36 %)	6	22
	STAT	446	72 (16.14 %)	44 (9.87 %)	8	54

[†] Mutants include both non-equivalent and equivalent.

[‡] Decisions and all-uses include both feasible and infeasible.

[§] % = $\frac{\text{number of mutants examined using alternate mutation}}{\text{number of mutants examined in mutation}} \times 100$

Table 2: Average size of mutation, 10% mutation, *abs/ror* mutation, and all-uses adequate test sets

	FIND	STRMAT1	STRMAT2	TEXTFMT
mutation	24.57	20.23	17.57	16.67
10% mutation	9.20	10.00	8.60	9.60
<i>abs/ror</i> mutation	14.73	12.00	8.27	6.97
all-uses	6.67	6.07	6.40	5.23

5 Experimental results and analysis

Table 1 lists the number of mutants, decisions and all-uses for the programs used. These metrics serve as indicators of the relative complexity of programs considered in our experiments. Table 2 lists the average size of mutation, 10% mutation, *abs/ror* mutation, and all-uses adequate tests, respectively. Tables 3 and 4 contain the average all-uses and mutation scores using mutation, 10% mutation, *abs/ror* mutation, and all-uses adequate test sets, respectively. Scores in the above tables are computed as percentages. Table 5 contains statistics on fault-revealing adequate test sets with respect to mutation, 10% mutation, *abs/ror* mutation, and all-uses criteria.

Cost comparison

From our experimental data and the summary in Table 2 we make the following observations:

- 42% to 63% and 40% to 58% fewer test cases are required to satisfy 10% mutation and *abs/ror* mutation adequacy, respectively, than to satisfy mutation adequacy.
- 35% to 84% and 33% to 121% more test cases are required to satisfy 10% mutation and *abs/ror* mutation adequacy, respectively, than to satisfy all-uses adequacy.
- 175% to 268% more test cases are required to satisfy mutation adequacy than to satisfy all-uses adequacy.
- 89% to 90% and 80% to 85% cost reduction in terms of number of mutants to be examined for 10% mutation and *abs/ror* mutation adequacy, respectively.

Table 3: Average all-uses scores using mutation, 10% mutation, *abs/ror* mutation, and all-uses adequate test sets

	FIND	STRMAT1	STRMAT2	TEXTFMT
mutation	100.00	100.00	100.00	99.39
10% mutation	99.59	97.93	98.62	96.97
<i>abs/ror</i> mutation	99.56	97.13	96.27	95.45
all-uses	100.00	100.00	100.00	100.00

Table 4: Average mutation scores using mutation, 10% mutation, *abs/ror* mutation, and all-uses adequate test sets

	FIND	STRMAT1	STRMAT2	TEXTFMT
mutation	100.00	100.00	100.00	100.00
10% mutation	97.59	97.25	96.37	99.01
<i>abs/ror</i> mutation	98.29	98.84	95.70	95.90
all-uses	92.31	86.01	91.60	92.86

Strength comparison

From our experimental data and the summary in Tables 3 and 4 we make the following observations:

(1) All-uses scores:

- For FIND: Each mutation, three of the five 10% mutation, and seventeen of the thirty *abs/ror* mutation adequate test sets are all-uses adequate.
- For STRMAT1: Each mutation, two of the five 10% mutation, and eighteen of the thirty *abs/ror* mutation adequate test sets are all-uses adequate.
- For STRMAT2: Each mutation, three of the five 10% mutation, and six of the thirty *abs/ror* mutation adequate test sets are all-uses adequate.
- For TEXTFMT: Twenty-four of the thirty mutation, one of the five 10% mutation, and two of the thirty *abs/ror* mutation adequate test sets are all-uses adequate.

(2) Mutation scores:

- None of the 10% mutation, *abs/ror* mutation, and all-uses adequate test set is mutation adequate.

In summary, 10% and *abs/ror* mutation adequate test sets suffer less than 5% loss on average mutation and all-uses scores when compared with the mutation and all-uses adequate test sets, respectively. Notice that when compared with the all-uses adequacy, both 10% and *abs/ror* mutation provide higher mutation scores.

Effectiveness comparison

From our experimental data and the summary in Table 5, we make the following observations:

- For all four experiments, the mutation criterion is the most effective in exposing program faults.
- The average effectiveness for the mutation, *abs/ror* mutation, 10% mutation and all-uses criteria is 92.50%, 88.33%, 81.66%, and 83.33%, respectively.

The above observations indicate that in our study mutation criterion is the most effective followed, in order, by *abs/ror* mutation, all-uses and 10% mutation.

Table 5: Number of fault-revealing adequate test sets

Program	mutation	<i>abs/ror</i> mutation	10% mutation	All-uses
SORT	30 (100.00 %) [‡]	30 (100.00 %)	29 (96.67 %)	29 (96.67 %)
STRMAT3	21 (70.00 %)	16 (53.33 %)	18 (60.00 %)	12 (40.00 %)
POSITION	30 (100.00 %)	30 (100.00 %)	28 (93.33 %)	30 (100.00 %)
STAT	30 (100.00 %)	30 (100.00 %)	23 (76.67 %)	29 (96.67 %)

[‡]The percentage was computed using Equation (5) in Section 3.

6 Conclusions and future work

In this study we find that compared to the mutation criterion, both the randomly selected 10% mutation and the constrained *abs/ror* mutation provide significant cost reductions in terms of the number of test cases required and the number of mutants examined. This gain is, however, accompanied by a small strength loss in the ability to distinguish non-equivalent mutants and cover feasible all-uses. On the other hand, when compared to the all-uses criterion both alternate mutation criteria require more test cases and suffer a small strength loss in the ability to cover feasible all-uses. However, both of them also show a better effectiveness and a stronger strength in the ability to distinguish non-equivalent mutants than the all-uses criterion. Our overall conclusions are:

- In terms of decreasing order of cost (the number of test cases required) the ranking is mutation, *abs/ror* mutation, 10% mutation, and all-uses.
- In terms of decreasing order of fault detection effectiveness the ranking is mutation, *abs/ror* mutation, all-uses, and 10% mutation.

These data suggest that examining only a small percentage of the mutants may be a useful heuristic for evaluating and constructing test sets in practice. While testing software under time pressure and budget constraints, testers may use mutation testing for the safety-critical parts and leave the other parts to be tested by a cost-effective alternative such as the *abs/ror* mutation or the all-uses criteria.

As discussed in Section 4.2, the tools we used support different programming languages, *Mothra* for Fortran 77 and *ATAC* for C. Although it has been shown that the effect of using different languages is negligible on the conclusions reported here [10], it is certainly desirable to avoid any language translation in the experiments. We are currently using *PROTEUM* [6], a C mutation tool implemented based on [2], to conduct experiments with constrained mutation using different combinations of mutant operators directly on larger size C programs. Such studies have the advantage of eliminating any possible language bias and will shed more light on how to reduce the cost of mutation testing.

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