Establishing Theoretical Minimal Sets of Mutants

Paul Ammann*, Marcio E. Delamaro†, and Jeff Offutt*
*Software Engineering, George Mason University, Fairfax, VA, USA
†Instituto de Ciências Matemáticas e de Computação, Universidade de São Paulo, São Carlos, SP, Brazil
Emails: {pammann,offutt}@gmu.edu
Email: delamaro@icmc.usp.br

Abstract—Mutation analysis generates tests that distinguish variations, or mutants, of an artifact from the original. Mutation analysis is widely considered to be a powerful approach to testing, and hence is often used to evaluate other test criteria in terms of mutation score, which is the fraction of mutants that are killed by a test set. But mutation analysis is also known to provide large numbers of redundant mutants, and these mutants can inflate the mutation score. While mutation approaches broadly characterized as reduced mutation try to eliminate redundant mutants, the literature lacks a theoretical result that articulates just how many mutants are needed in any given situation. Hence, there is, at present, no way to characterize the contribution of, for example, a particular approach to reduced mutation with respect to any theoretical minimal set of mutants. This paper’s contribution is to provide such a theoretical foundation for mutant set minimization. The central theoretical result of the paper shows how to minimize efficiently mutant sets with respect to a set of test cases. We evaluate our method with a widely-used benchmark.

Keywords - Mutation testing, minimal mutant sets, dynamic subsumption

I. INTRODUCTION

Mutation analysis [5] is an approach to generating tests that distinguish all of a set of variants, or mutants, from some artifact. Mutation analysis is widely considered to be a powerful approach, so much so that other approaches to test generation are commonly evaluated on the basis of mutation score. One long-standing problem with using mutation score to evaluate other approaches is the presence of “redundant” mutants that do not contribute in any material way to the quality of a test set. For example, some mutants are killed by almost any test. Hence, eliminating such mutants from consideration does not affect which tests are chosen, but does result in a different mutation score. In other words, mutation scores can be inflated by redundant mutants, and this can make the mutation score harder to interpret.

The research area of reduced mutation has focused on achieving high quality test sets with fewer mutants [20], [23], [27], [29], [22], [21], [26], [6]. Selective mutation is a reduced mutation approach that limits the set of mutation operators to a subset of the available operators [20], [23], [27], [29], [22], [21], [26], [6]. Some approaches to reduced mutation limit the number of mutants considered to a random subset of mutants generated [19], [24]. Other approaches analyze relationships between specific mutants and remove redundant mutants [13], [11], [14]. Still others engineer higher-order-mutants (HOMs) that subsume one or more first-order mutants (FOMs)†. While these approaches clearly reduce the number of mutants under consideration, there is still a significant research gap. Specifically, there is no way to measure how close reduction techniques get to the goal of minimizing the number of mutants created while maintaining the quality of the corresponding test set.

This paper addresses exactly that research gap. We develop a theoretical framework for determining minimal sets of mutants. In particular, we show that, given a test set, a particular type of subsumption, called dynamic subsumption, enables efficient computation of minimal sets of mutants. We evaluate our approach against a benchmark set of programs and tests.

It is important to appreciate the role of the test set in our approach. Computing minimal mutant sets for all possible test sets is clearly undecidable; it is the fact that we limit attention to a particular test set that makes our approach computable. One way to think of our approach is that it approximates a limit: If one were able to run every possible test, then determining minimal sets of mutants with dynamic subsumption would, in fact, be both sound and complete. That is, any computed minimal mutant set would be, in fact, a “real” minimal mutant set. A corollary of this observation is that the more comprehensive the test set used in the analysis, the more accurate the resulting computation of minimal mutant sets.

Existing approaches to reduced mutation that use subsumption, such as the HOM approach, rely on detailed white-box analysis of the artifact under consideration. If a HOM is engineered to subsume several other mutants, then a test that kills that HOM will, of course, kill the subsumed mutants. However, equivalent mutants, that is, mutants that computes the same function as the original artifact, complicate the situation. If a HOM happens to be equivalent, or if the test engineer simply fails to find a test that kills the HOM, then the subsumption relationship does not help, since there may be tests that kill one or more of the subsumed mutants.

In contrast to the HOM approach to subsumption, our model takes a black-box perspective. We consider only the behavior of some fixed artifact in the context of a specific set of mutants and a specific set of test cases. In particular, our notion of subsumption is only assumed to hold with respect to the specific set of test cases under consideration, and it is possible*

†In the development of Jia et al. [10], one mutant subsumes a second mutant if every test that kills the first mutant is guaranteed also to kill the second. The same notion of subsumption is used to reduce the number of logic mutants generated for DNF predicates [12].
that the subsumption relation would not hold for a different set of tests. Essentially, we replace the risk of equivalent mutants, which affects the HOM approach to subsumption, with the risk of incomplete test sets\footnote{Both the problem of determining whether a mutant is equivalent and the problem of finding a test case that kills a mutant are, of course, undecidable.}.

Our approach to modeling has two advantages. First, it frees us from the details of any particular programming language or artifact and lets us model the problem in a very general way. Second, it allows us to provide a precise definition for what constitutes a minimal set of mutants. While the definition itself is not constructive; the main result of the paper shows that a different notion of subsumption, called dynamic subsumption, completely characterizes mutant set minimality.

We used the Siemens suite \cite{9}, \cite{7}, to show the impact of our model. The Siemens suite includes a large number of tests. The evaluation shows that the size of the minimal mutant sets is much smaller than current approaches to reduced mutation achieve. The evaluation further shows that high mutation scores from different approaches to reduced mutation on a given test set are potentially misleading; once redundant mutants are removed, the scores are lower, sometimes much lower. In other words, there is substantial room for improvement in choosing mutants. Correspondingly, users of mutation scores should be cautious; large numbers of redundant mutants may make such scores misleading.

Again, it is important to appreciate the role of the chosen test set in the analysis of minimal mutants: generating a different test set might result in a different set of minimal mutants. That being said, most applications of mutation analysis end up with exactly one test set–namely the first set that kills enough mutants. From a practical perspective, our algorithms can be applied at any stage of testing. The richer the test set \(T\) is, the more mutants a minimal mutant set requires to capture the behavior exhibited by the artifact with respect to that test set.

In terms of the score function, if \(T\) is not mutation adequate, then there will be at least one mutant \(m\) in \(M\) that is live, which means that no test \(t \in T\) kills \(m\). A live mutant \(m\) may be equivalent, or \(T\) may rather be missing a suitable test that kills \(m\). Each live mutant has a column in the score function without any \(true\) entries. Instead of insisting on mutation adequacy, we constrain our minimization procedures to maintain the effectiveness of mutation, evaluated by which mutants are killed by a given test set. Formally, a subset of \(T\), denoted \(T_{\text{maintain}}\), maintains the mutation score with respect to \(M\) (and \(T\)) if for every mutant \(m\) in \(M\), if \(T\) kills \(m\) then \(T_{\text{maintain}}\) kills \(m\).

The score function captures all of the information about the mutants and tests of interest in this paper. If two tests kill precisely the same set of mutants, we consider the tests to be indistinguished, even though, in terms of the domain of \(P\), the tests may have different input values. Similarly, if two mutants are killed by precisely the same set of tests, we consider the mutants to be indistinguished (thus far), even though the mutants may involve different syntactic changes to the underlying artifact. Indeed, indistinguished mutants may well cause different semantic changes to the underlying artifact, but these semantics are simply not captured by the test set \(T\), and hence are not reflected in the score function \(S\). Put another way, if \(T\) were augmented with additional tests, these additional tests might distinguish previously indistinguished mutants.

Below we show a score function for an example with five tests and four mutants: \(T = \{t_1, t_2, t_3, t_4, t_5\}\) and \(M = \{m_1, m_2, m_3, m_4\}\). \(T\) is mutation-adequate, all tests in \(T\) are distinguished, and all mutants in \(M\) are also distinguished. We use this score function as a running example through the rest of this section.

\[
\begin{array}{ccccc}
T & m_1 & m_2 & m_3 & m_4 \\
\hline
\hline
t_1 & t & t & t & t \\
t_2 & t & t & t & t \\
t_3 & t & t & t & t \\
t_4 & t & t & t & t \\
t_5 & t & t & t & t \\
\end{array}
\]
Observation 1: Score Function Boundedness.
The score function has, at most, \(2^{|M|}\) distinguished rows. The reason is that each distinguished test kills some specific subset of \(M\) and there are exactly \(2^{|M|}\) such subsets.

Observation 1 is important because it makes clear that although the domain of \(P\) may be large or unbounded, the number of distinguished rows in the score function is bounded. Put another way, the score function can identify every possible input in the domain of \(P\) with one of \(2^{|M|}\) equivalence classes, depending on which mutants that input kills.

B. Minimal Sets of Tests

The key theoretical contribution of this paper is describing sensible minimizations to the score function. The motivation for minimizing tests is straightforward: if killing mutants is the goal, why run tests that do not increase the mutation score? Minimal test sets directly help the practicing test engineer.

The motivation for minimizing mutants has less to do with the practicing test engineer than with mutation testing researchers. The motivation for minimizing mutants is identifying the theoretical boundary of just how many mutants are required, and comparing existing mutation analysis methods against this boundary to see whether they can be improved, and, if so, potentially how much. While this theoretical lower bound may never be reached, it gives testing researchers an important tool. By knowing what’s possible, we can objectively evaluate the effectiveness of our current engineering techniques to reduce the number of mutants. That is, this analysis gives us a firm bound against which to measure.

First we address test set minimization, a well-understood process that we include here for completeness.

Definition 1: Minimal test sets.

A test set \(\bar{T}\) is \emph{minimal} iff for any test \(t_i \in \bar{T}\), \(\bar{T} - \{t_i\}\) does not maintain the mutation score with respect to \(M\) and \(T\).

Note that \(\bar{T}\) depends on exactly which mutants are used.

There may be multiple minimal test sets, possibly of varying cardinalities, for any given test set \(T\). Let \(\bar{T}_M = \{T_1, T_2, \ldots\}\) denote the set of \emph{all} possible minimal test sets with respect to mutant set \(M\). Any element of \(\bar{T}_M\) with the smallest cardinality is not only minimal, but also \emph{minimum}.

In the example, \(\bar{T}_M\) contains three minimal test sets:

\[
\bar{T}_M = \{\{t_4\}, \{t_1, t_2\}, \{t_1, t_3\}\}
\]

Note that a given test need not be part of any minimal test set. In the example, \(t_5\) is not in any minimal test set. Of the three minimal test sets, one, namely \(\{t_4\}\), has least cardinality (equal to 1), and hence is minimum.

Although finding a \emph{minimum} test set is, like many optimization problems, computationally hard\(^3\), generating a minimal test set is straightforward. Algorithm 1 generates a minimal test set with time complexity \(|T|\ast|M|\). Note that Algorithm 1 selects tests for removal in an arbitrary order. If Algorithm 1 is applied to all possible permutations of tests in \(T\), then it will generate all possible minimal test sets.

Algorithm 1: Test set minimization

// Input: Mutant set \(M\) and test set \(T\)
// Output: A minimal test set

\[
\text{minSet} = T
\]

for each \(t\) in minSet {
    // Note: \(t\) selected arbitrarily
    if (minSet-(t) maintains reduction mutant score wrt \(M\) and \(T\))
        minSet = minSet - \{t\}
}

return minSet

C. Minimal Sets of Mutants

We now turn to the problem of minimizing \(M\), a topic that, to our knowledge, has not been previously addressed in the literature. We propose the following informal rationale for declaring mutants to be “unnecessary”:

\emph{Testing \(P\) without considering unnecessary mutants should yield the exact same “results” as testing \(P\) with the full set of mutants \(M\).}

Building on this rationale, the only tests that a given set of mutants can “force” to be in a test set are those in some minimal test set. Hence, we define unnecessary mutants in terms of minimal test sets. We require that \(M\) generate precisely the same set of minimal test sets both with and without a redundant mutant. Recall that \(\bar{T}_M\) denotes the set of minimal test sets of \(T\) with respect to some particular set of mutants \(M\). The key part of the definition is the equality at the end:

Definition 2: Redundant mutants.

Let \(M_j = M - \{m_j\}\) for some mutant \(m_j \in M\). We say that \(m_j\) is \emph{redundant} with respect to mutant set \(M\) and test set \(T\) iff \(\bar{T}_M = \bar{T}_{M_j}\).

Again, note that this definition of redundant mutants is in the context of a particular test set \(T\). Computing \(\bar{T}\) for various mutant sets in the running example, first the full mutant set \(M\), and then \(M\) with each mutant removed in turn, yields:

\[
\bar{T}_M = \{\{t_4\}, \{t_1, t_2\}, \{t_1, t_3\}\}
\]

\[
\bar{T}_{M_1} = \{\{t_4\}, \{t_1, t_2\}, \{t_1, t_3\}\}
\]

\[
\bar{T}_{M_2} = \{\{t_4\}, \{t_1, t_2\}, \{t_1, t_3\}\}
\]

\[
\bar{T}_{M_3} = \{\{t_1\}, \{t_4\}\}
\]

\[
\bar{T}_{M_4} = \{\{t_4\}, \{t_1, t_2\}, \{t_1, t_3\}, \{t_2, t_5\}, \{t_3, t_5\}\}
\]
Note that $\tilde{T}_M$, $\tilde{T}_{M_1}$, and $\tilde{T}_{M_2}$ are identical. This means that both $m_1$ and $m_2$ are redundant with respect to $M$. If a pair of redundant mutants, $m_1$ and $m_2$, are indistinguishable, it is possible that we might only be able to remove one of the mutants safely. Consider the case where mutant $m_1$ is not redundant with respect to $M$. If some additional mutant $m_2$ is indistinguishable from $m_1$ and we form $M \cup \{m_2\}$ then only one of $m_1$ or $m_2$ can be removed from $M \cup \{m_2\}$ without altering the associated minimal test sets. Algorithm 2, based on the dynamic subsumption relation developed later in the paper, clarifies precisely which mutants can be removed safely. In particular, only one mutant from each set of indistinguishable mutants is (possibly) needed; beyond that, all redundant mutants can be safely removed.

Since $m_1$ and $m_2$ are distinguished and redundant, both can safely be removed from $M$ without altering the resulting minimal test sets, thereby yielding a minimal mutant set of $\{m_3, m_4\}$. In this example, there is only one minimal mutant set.

When a redundant mutant $m$ is removed, it is possible that tests that were distinguished with respect to $M$ are no longer distinguished with respect to $M - \{m\}$. From the practical perspective, this means that the test engineer has a choice about which test to use when constructing a minimal test set. In the example above, for the minimal set of mutants $\{m_3, m_4\}$, tests $t_2$ and $t_3$ are indistinguishable.

**Definition 3: Minimal mutant sets.**

Mutant set $M$ is *minimal* if it contains no redundant mutants.

We show the score function after minimization for our running example.

<table>
<thead>
<tr>
<th>$m_3$</th>
<th>$m_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$</td>
<td>$t$</td>
</tr>
<tr>
<td>$t_2$</td>
<td>$t$</td>
</tr>
<tr>
<td>$t_3$</td>
<td>$t$</td>
</tr>
<tr>
<td>$t_4$</td>
<td>$t$</td>
</tr>
<tr>
<td>$t_5$</td>
<td>$t$</td>
</tr>
</tbody>
</table>

Although this example has only one minimal mutant set, there are potentially many minimal mutant sets.

Because there are a large number of minimal test sets for any given set of mutants, the definition of minimal mutant sets, which relies on comparing the associated minimal test sets, does not lend itself directly to an efficient algorithm. Hence, the next challenge is identify a way to compute efficiently which mutants are redundant.

**D. Efficiently Computing Minimal Sets of Mutants**

We turn to the notion of subsumption. Traditionally, one mutant is defined to subsume another for all possible executions based on internal reasoning about the artifact being mutated or the mutation operator in question. For example, mutants that negate a term in a Disjunctive Normal Form (DNF) predicate subsume mutants that negate the entire DNF formula. A variety of these relationships are shown in the fault hierarchy of Lau and Yu [18]. The proof of subsumption relies on properties of predicates expressed in DNF.

In this paper, we define a different notion of subsumption strictly in terms of black-box behavior of mutants $M$ on a test set $T$ as captured by the score function. Crucially, this new notion of subsumption does not necessary hold for all possible executions. Rather it is only guaranteed to hold for executions in the set $T$. Specifically, consider two mutants $m_x$ and $m_y$ where every test in $T$ that kills $m_x$ also kills $m_y$.

**Definition 4: Dynamic subsumption.**

If mutant $x$ is not live and $S(i, x) \rightarrow S(i, y), i = 1..|T|$, we say that $m_x$ dynamically subsumes $m_y$ with respect to $T$.

Dynamic subsumption differs from the notion used in white-box mutation analysis in a crucial respect: Not only are tests that kill $x$ also required to kill $y$, but $T$ also has to have at least one test that kills $x$. In other words, dynamic subsumption disallows “vacuous” subsumption, which would be possible if we did not have a test that killed $x$. For example, it is possible, through white-box analysis, to design a HOM $m$ that subsumes several other mutants, but it is (usually) not be possible to tell if $m$ is equivalent. Since we work in the black-box context of a specific set of test cases $T$, the score function can distinguish among live mutants.

In any set $M$ that contains both $m_x$ and $m_y$, if $m_x$ dynamically subsumes $m_y$, then $m_y$ is redundant, and hence may be safely discarded, a fact we prove in the first part of Theorem 1 below.

Perhaps surprisingly, dynamic subsumption completely captures the notion of redundant mutants. That is, the only way in which a mutant becomes redundant is for it to be dynamically subsumed by some other mutant in $M$, a fact we prove in the second part of Theorem 1 below. The main result of this paper formalizes these two properties:

**Theorem 1: Dynamic subsumption and minimal test sets.**

Mutant set $M$ is minimal with respect to test set $T$ if and only if for $\exists x, y \subset M$ such that $m_x$ dynamically subsumes $m_y$.

**Proof:**

**Step 1:** If $M$ is minimal, then there does not exist a distinct pair $m_x, m_y \in M$ such that $m_x$ dynamically subsumes $m_y$.

We proceed by contradiction. Suppose there exist $m_x$ and $m_y$ such that $m_x$ dynamically subsumes $m_y$. Consider the process of producing a minimal test set for either $M$ or $M - \{m_y\}$ by applying Algorithm 1. If Algorithm 1 produces the same minimal test set in each case, then Algorithm 1 produces the same minimal test set in both $M$ and $M - \{m_y\}$. Since this would happen for all possible orders of choosing tests, it means that $\tilde{T}_M = \tilde{T}_{M_2}$. But this would mean that $M$ is not minimal—a contradiction.

Hence, the proof comes down to considering whether, at some stage of Algorithm 1, the **if** test evaluates differently for
some test \( t \) with respect to \( M \) and \( M - \{ m_y \} \). We proceed by case analysis:

- **Case 1:** \( t \) can be removed during the minimization with respect to \( M \), but not the corresponding minimization with respect to \( M - \{ m_y \} \). Dynamic subsumption has nothing to do with this case. Rather, if a test is not needed for a particular set of mutants, it is clearly not needed for any subset either. Hence, Case 1 is impossible.
- **Case 2:** \( t \) can be removed during the minimization with respect to \( M - \{ m_y \} \), but not the corresponding minimization with respect to \( M \). In algorithm 1, the variable \( \text{minSet} \) must have some test that kills \( m_x \), and thus, by dynamic subsumption, \( m_y \) as well. Hence, \( m_y \) cannot be the reason that \( t \) must be kept for set \( M \). In other words, the if decision must be the same for both \( M \) and \( M - \{ m_y \} \). Hence, Case 2 is impossible.

**Step 2:** If there does not exist a distinct pair \( m_x, m_y \in M \) such that \( m_x \) dynamically subsumes \( m_y \), then \( M \) is minimal.

To show this part, for each \( m_x \in M \), we incrementally construct a test set \( T_x \) around \( m_x \). We show that this test set is minimal with respect to \( M - \{ m_x \} \), but does not maintain the mutation score with respect to \( M \). Hence \( m_x \) is not redundant, and cannot be removed from the mutant set. Since we show this for each mutant in the set, the set \( M \) must be minimal.

To construct \( T_x \), consider each other mutant \( m_y \in M \). There must be some test in \( T \) that kills \( m_y \) but does not kill \( m_x \), or else \( m_y \) would dynamically subsume \( m_x \). Include this test in \( T_x \). Note that \( T_x \) kills every mutant except for \( m_x \). Choose some minimal set \( \hat{T}_x \) subseq \( T_x \) using algorithm 1. Note that \( \hat{T}_x \) is minimal with respect to \( M - \{ m_x \} \) but does not maintain the mutation score with respect to \( M \). Hence no \( m_x \in M \) is redundant, and so \( M \) is minimal with respect to \( T \).

**QED**

Algorithm 2 uses Theorem 1 to efficiently compute minimal mutant sets. First, live mutants are removed. Next, indistinct mutants are removed. Finally, dynamically subsumed mutants are removed.

### Algorithm 2: Mutant set minimization

```plaintext
// Input: Mutant set M; Score function S
// Output: A minimal mutant set

remove live mutants from S
remove duplicate columns from S
minSet = remaining columns in S
subsumed = dynamically subsumed mutants in minSet
return (minSet - subsumed);
```

We now apply Algorithm 2 to our running example. There are no live mutants or duplicate columns in the score function, so the variable \( \text{minSet} \) in the algorithm starts with all four mutants, \( m_1, m_2, m_3, \) and \( m_4 \). Mutants \( m_1 \) and \( m_2 \) are dynamically subsumed by mutant \( m_4 \). Removing these two mutants from \( \text{minSet} \) yields exactly the same minimal set of mutants, namely \( \{ m_3, m_4 \} \), identified in the previous section by considering minimal test sets.

### E. Some Properties of Minimal Mutant Sets

Since a representative from each set of indistinguished mutants is chosen arbitrarily in the first step of Algorithm 2, where duplicate columns in \( S \) are removed, minimal mutant sets need not contain exactly the same mutants. However, somewhat surprisingly, minimal mutant sets do all have the same cardinality.

**Theorem 2: Mutant set cardinality**

Every minimal mutant set has the same cardinality.

**Proof.**

The key observation is that dynamic subsumption is just logical implication, and hence is transitive. This means that if one removes a dynamically subsumed mutant from a set of mutants, that removal does not affect which of the remaining mutants are dynamically subsumed. Hence, dynamically subsumed mutants may be removed in an arbitrary order, which is why the second part of Algorithm 2 is structured the way it is, as opposed to being an explicit loop that iteratively checks for dynamic subsumption. Put another way, a minimal mutant set is simply a mutant set with indistinguished mutants collapsed to single representatives and the remaining dynamically subsumed mutants removed—operations that always produce a result of the same cardinality.

**QED**

The appeal of Theorem 2 is that in states that, for a given test set \( T \), a specific number of mutants (selected from \( M \)) are both necessary and sufficient to generate all possible minimal test sets (selected from \( T \)).

**Observation 2. Minimal mutant sets for minimal test sets.**

If \( T \) happens to be a minimal test set, then every corresponding minimal set of mutants has exactly \( |T| \) elements. The resulting score function is square. Every row has exactly one true value, and every column has exactly one true value.

In particular, if \( T \) has exactly one element, so does every minimal \( M \). This extreme example illustrates the idea that \( M \) simply generates tests with respect to some underlying set of tests \( T \). If that test set is already minimal, all \( M \) can do is generate exactly that set. If \( T \) is not minimal, then \( M \) can potentially generate more than one minimal test set.

### III. Assessment

We now use Algorithm 2, to compute minimal sets of mutants with respect to a given test set. This section applies Algorithm 2 to a standard benchmark for testing research, namely the Siemens suite [9], [7], which consists of seven C programs and associated test sets. We have two goals:
1) Examine the relationship between total mutants generated by traditional approaches and minimal mutant sets.
2) Highlight the effect on mutation score of measuring against traditional mutant sets vs. minimal mutant sets.

This section is not a formal experiment. Hence, we do not enumerate research questions, results, threats, etc. Rather, we simply apply our definitions and report facts about test set minimization, mutant set minimization, and reduced mutation.

For each program in the Siemens suite, the Proteum tool [4] was used to generate mutants and the score function was collected for 512 tests randomly taken from the Siemens suite.4

A. Minimal Test Sets

Table I presents characteristics about the test sets used in the study. The column labeled Program lists the programs. The column labeled Total Tests shows how many tests are available in the Siemens suite for each program. The column labeled Used Tests shows how many tests were used in this evaluation—512 for each program. The column labeled Distinguished Tests shows how many of the 512 tests are distinguished. Recall that two tests are indistinguished if they kill exactly the same subset of mutants. The table shows that for each of the seven programs, very few tests were indistinguished.

<table>
<thead>
<tr>
<th>Program</th>
<th>Total Tests</th>
<th>Used Tests</th>
<th>Distinguished Tests</th>
<th>Minimal Tests</th>
<th>Union : Intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td>print_tokens</td>
<td>4073</td>
<td>512</td>
<td>499</td>
<td>12.4</td>
<td>161 : 3</td>
</tr>
<tr>
<td>print_tokens2</td>
<td>4058</td>
<td>512</td>
<td>479</td>
<td>12.1</td>
<td>160 : 1</td>
</tr>
<tr>
<td>replace</td>
<td>5542</td>
<td>512</td>
<td>510</td>
<td>44.4</td>
<td>218 : 19</td>
</tr>
<tr>
<td>schedule</td>
<td>2650</td>
<td>512</td>
<td>482</td>
<td>14.5</td>
<td>158 : 2</td>
</tr>
<tr>
<td>schedule2</td>
<td>1052</td>
<td>512</td>
<td>479</td>
<td>17.1</td>
<td>131 : 4</td>
</tr>
<tr>
<td>ticas</td>
<td>1600</td>
<td>512</td>
<td>408</td>
<td>41.4</td>
<td>207 : 10</td>
</tr>
<tr>
<td>totinfo</td>
<td>4073</td>
<td>512</td>
<td>452</td>
<td>13.3</td>
<td>134 : 4</td>
</tr>
</tbody>
</table>

The column labeled Minimal Tests shows how many tests are in a minimal test set produced by Algorithm 1 applied to the 512 selected tests. Since there are many possible minimal test sets, this final number is the average of 100 minimal test sets generated by choosing tests to remove at random in the if statement of Algorithm 1. Note that the minimal test sets are relatively small compared to the number of distinguished tests. The column labeled Union: Intersection gives the number of tests (taken from 512) that appeared in the union and intersection of the 100 randomly selected minimal test sets. It is clear that even though minimal test sets are relatively small, many different tests can be used to construct a minimal test set. Conversely, there are very few tests that appeared in all 100 trials. This suggests that there are few, if any, “necessary” tests in the set of 512.

4The number 512 is an artifact of the Proteum tool, which processes tests in batches of size up to 512. Since minimal mutants are calculated with respect to a specific test set, as opposed to all possible inputs, it is sensible to carry out the analysis with any test set. For the same reason, we don’t sample different test sets; instead we model a testing process where a particular test set is chosen, and then redundant mutants are identified.

B. Minimal Mutant Sets

Table II captures relevant facts about the mutants used in the study with respect to the test sets (of size 512) described above. Again, the column labeled Program lists the programs. The column labeled Total Mutants reports the total number of mutants. The column labeled Live Mutants reports the number of mutants live after execution of the complete Siemens test suite, and Y is the number of mutants live after execution of the chosen 512 tests. The column labeled Difference (Ratio) reports the difference between these two values in absolute form and also their ratio. By either measure, relatively few mutants are killed by the full suite, but not by the set of 512 tests. In terms of mutation score (not shown in the table), the 512-sized test sets exceeds 99% for all of the programs.

<table>
<thead>
<tr>
<th>Program</th>
<th>Total Mutants</th>
<th>Live Mutants</th>
<th>Difference (Ratio)</th>
<th>Distinguished : Minimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>print_tokens</td>
<td>4336</td>
<td>597 : 625</td>
<td>28 (0.96)</td>
<td>437 : 28</td>
</tr>
<tr>
<td>print_tokens2</td>
<td>4746</td>
<td>692 : 704</td>
<td>12 (0.98)</td>
<td>439 : 30</td>
</tr>
<tr>
<td>replace</td>
<td>11101</td>
<td>2195 : 2318</td>
<td>77 (0.95)</td>
<td>2309 : 58</td>
</tr>
<tr>
<td>schedule</td>
<td>2109</td>
<td>267 : 271</td>
<td>4 (0.99)</td>
<td>520 : 42</td>
</tr>
<tr>
<td>schedule2</td>
<td>2627</td>
<td>488 : 495</td>
<td>7 (0.99)</td>
<td>461 : 46</td>
</tr>
<tr>
<td>ticas</td>
<td>2384</td>
<td>418 : 427</td>
<td>9 (0.98)</td>
<td>596 : 61</td>
</tr>
<tr>
<td>totinfo</td>
<td>6698</td>
<td>877 : 877</td>
<td>0 (1.00)</td>
<td>835 : 19</td>
</tr>
</tbody>
</table>

The first entry in the column labeled Distinguished : Minimal reports the number of distinguished mutants. Recall that two mutants are indistinguished if they are killed by exactly the same subset of tests. The number of mutants that are distinguished is much smaller than the total number of mutants. This suggests that many mutants are not only redundant, they also exhibit identical behavior with respect to the test set. Further, the fraction of mutants that are distinguished (17%) is much smaller than the fraction of tests that are distinguished (93%). In terms of distinguished entries, the score function exhibits different behavior when viewed from the row perspective than it does when viewed from the column perspective.

The second entry in the column labeled Distinguished: Minimal reports the number of minimal mutants in a minimal mutant set.5

Not only is the number of minimal mutants much smaller than the total number of mutants (on average, only 1.2% of mutants are in a minimal set), it is also much smaller than the total number of distinguished mutants (on average, only 6.6% of distinguished mutants are in a minimal set). In other words, the dynamic subsumption relation eliminates a large fraction of the distinguished mutants.

For example, in the case of totinfo (last row in the tables), Proteum generated 6698 mutants, \((6698 - 877) = 5811\) of which were killed by both the full Siemens test suite and

5As Theorem 2 showed, there may be many minimal mutant sets for a given test \(T\), but all are of the same size. Hence, there is no reason to run multiple trials and average the results, as was the case for minimal test sets.
also the set of 512 tests. Of these 6698 mutants, 835 were distinguished. Of the 5811 killed mutants only 19 mutants, or 0.3\%, are needed for a minimal test set. Of the 834 distinguished killed mutants\(^6\), only 19 mutants, or 2.3\%, are needed for a minimal test set. By any measure, the number of generated mutants far exceeds the number necessary.

The two tables given so far give the dimensions of the score function for each program. For example, print	okens has a score function with 512 rows, of which 499 are distinguished, and 4336 columns, of which 437 are distinguished.

C. Reduced and Selective Mutation

We turn next to analyzing reduced mutation, the idea that using fewer mutants is nearly as effective as the complete set of mutants. We consider five reduced mutation approaches, one random and four selective. The notion of selective mutation was first suggested by Mathur [20], developed by Offutt et al. [23], and studied extensively thereafter for both FORTRAN [22], [21] and C [1].

We use the Proteum mutation tool suite. We use generic labels for the approaches, and provide the Proteum names in parentheses.

1) STMT: Statement Deletion (Proteum SSDL)
2) ROR: Relational Operator Replacement (Proteum ORRN)
3) CON: Replace Scalars with Constants (Proteum CCSR)
4) 5RND: 5\% random selection of all mutants
5) SELECT: An approximation of selective mutation (Proteum: OOAN+OLLN+ORRN+OLNG)

STMT has been studied as a stand-alone, cost-effective approach to mutation [6], [3], [26]. While ROR and CON have not been studied specifically as proposals for stand-alone operators, they are plausible candidates. A random percentage of all mutants has been widely used to reduce the number of mutants that need to be considered [19], [24]. We chose 5\% of random mutants because the number of mutants selected approximated the mutants created by the SELECT strategy.

The SELECT strategy approximates the original selective mutation definition from the Mothra system [22]. The Mothra approach to selective mutation had five operators:

1) ABS: Absolute Value
2) AOR: Arithmetic Operator Replacement (Proteum: OAAN)
3) LCR: Logical Connector Replacement (AND and OR) (Proteum: OLLN)
4) ROR: Relational Operator Replacement (Proteum: ORRN, but this does not include using the constants true and false)
5) UOI: Unary Operator Insertion (Proteum, logic only: OLNG)

Of these five operators, Proteum has corresponding match for two and a partial match for two more. These matches are indicated in parentheses in the list above.

Table III shows the results of analyzing these five approaches to reduced mutation in the context of the chosen 512 test cases. The rows in the tables are again the programs from the Siemens suite. Each column of data represents one of the five approaches to reduced mutation. Table entries are designed to show the difference between traditional mutation scores and a mutation score measured against the minimal mutant set.

Each entry in the table is of the form X:Y. X is the mutation score, as a percentage, obtained by a test set adequate to the corresponding reduction strategy, against all mutants that are killed by the chosen 512 test cases. Y is the mutation score, again as a percentage, obtained by the same test set against a minimal set of mutants, again in the context of the 512 test cases.

The noteworthy aspect of this table is that although the traditional mutation scores generally seem excellent, the mutation scores against the minimal mutant set are not nearly as good, ranging from a low 27\% to a high of 82\%. One lesson from this evaluation, consistent with other recent studies [11], is that a mutation score measured over a large number of redundant mutants is inflated—possibly to the point of being meaningless.

Figure 1 shows the data from the STMT column of Table III in chart form. For each program, the left bar shows the mutation score with respect to all mutants, and the right bar shows the mutation score with respect to a minimal set of mutants. The basic observation from the chart is that the redundancy in the full set of mutants makes it difficult to interpret mutations scores computed using the full set of mutants.

To take a specific case, consider tcas. The STMT approach appears to achieve a respectable score of 88\% mutation coverage. However, in terms of a minimal set of mutants, statement deletion mutation only kills about one in four.

Next, we present some data about tests in the minimal test sets. Table IV continues the analysis of reduced mutation. This time the table shows how many mutants killed by the 512 test cases are generated by the technique, along with the corresponding test size. Each value should be compared to the reference value in the column labeled Minimal, which (again) shows the number of mutants in the minimal set, along with the corresponding test size. The average number of tests required for the minimal mutant set is often larger than the number of tests required by a reduced approach. The reason is that the test sets for the reduced approaches are missing key tests. Specifically, they are missing tests that kill mutants in

\(^6\)Of the 835 distinguished mutants, 834 are killed by the test set, and one is live.
a minimal mutant set. Put another way, the reduced mutation approaches set omits key mutants; mutants that could lead to very good tests.

TABLE IV

REDUCED MUTATION: MUTANTS GENERATED VS. TESTS

<table>
<thead>
<tr>
<th>Program</th>
<th>STMT</th>
<th>ROR</th>
<th>CON</th>
<th>5RND</th>
<th>SELECT</th>
<th>Minimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>print_tokens</td>
<td>196:11</td>
<td>98:9</td>
<td>358:10</td>
<td>190:11</td>
<td>138:10</td>
<td>28:12.4</td>
</tr>
<tr>
<td>print_tokens2</td>
<td>203:5</td>
<td>192:8</td>
<td>445:8</td>
<td>198:9</td>
<td>244:9</td>
<td>30:12.1</td>
</tr>
<tr>
<td>replace</td>
<td>219:23</td>
<td>264:27</td>
<td>1053:44</td>
<td>443:39</td>
<td>499:35</td>
<td>58:44.4</td>
</tr>
<tr>
<td>tcas</td>
<td>42:12</td>
<td>45:14</td>
<td>66:14</td>
<td>99:24</td>
<td>113:18</td>
<td>61:41.4</td>
</tr>
</tbody>
</table>

For example, consider tcas again. The STMT approach generated 42 mutants that were killed by the 512 test cases, which is in the neighborhood of the 61 mutants in the minimal mutant set. Unfortunately, the choice of these 42 mutants is far from optimal. A test set that kills these 42 mutants has only 12 tests, compared to the average of 41.4 tests needed to kill the minimal set of mutants. In other words, STMT is generating about 1/3 the number of required tests, a fact that was reflected in Table III in the poor STMT mutation score of 27% against the minimal mutant set.

What is striking about Table IV is that in many cases, significantly more mutants are generated than in the minimal mutant set, but, in terms of achieving the best coverage, they are not the optimal mutants, and significantly fewer tests than needed for full coverage are generated. This table highlights a research gap: it is clear that a small number of mutants can force the generation of a very high quality test set, but it is not known how to choose these mutants. The best techniques in practice today, selective mutation and SDL-mutation, are a very long way from generating mutant sets that both include the desirable mutants and exclude unnecessary (and, of course, equivalent) mutants. A complete solution is, of course, theoretically impossible. But even modest partial solutions have room to improve matters significantly. A key point is that minimal mutant sets are not a replacement for strategies such as reduced mutation—it is still necessary to execute each mutant to create the set of minimal mutants. Rather, minimal mutant sets give a bound against which to evaluate techniques such as reduced mutation.

IV. RELATED WORK

The subsumption relation has been studied in a variety of contexts for many years. Chusho observed that measuring branch coverage over all branches in a program led to an overestimation of quality, and defined the notion of essential branches as a way of removing redundant branches from coverage measures [2]. In this paper, dynamically subsumed mutants play exactly the same role as non-essential branches do in the Chusho analysis. The difference is that this paper is “black-box,” whereas the Chusho paper considers the actual structure of the code. Hence, the Chusho results hold for all test sets; our results are specific to a particular test set T.

Harman and Jia defined the notion of subsuming Higher Order Mutants (HOMs) [10]. The idea was that a single HOM could stand in for several mutants. Langdon et al. applied subsuming HOMs to relational operators [17]. Lau and Yu identified subsumption relations between faults in Disjunctive Normal Form (DNF) predicates and presented this subsumption relation in a fault hierarchy [18]. Kaminski et al.[12] extended this work by defining special HOMs, which,
though relatively few in number, still subsumed all of the Lau and Yu hierarchy. In terms of the relationship to this work, subsuming HOMs are defined by internal analysis of the artifact under consideration; in contrast, we observe dynamic subsumption with respect to a specific test set.

Kaminski et al. [15] observed that the four of the seven mutants generated by Mothra’s Relational Operator Replacement (ROR) were always subsumed by other mutants. The special treatment here was that the subsumed ROR operators depended on which operator appeared in the original code. Just et al. raised exactly the point that raw mutation scores led to overly optimistic evaluations of quality and defined subsuming mutants in the context of the Conditional Operator Replacement (COR) operator [11]. Again, in terms of the relationship to this work, eliminating mutants in these papers is done at the operator level before test cases are generated. Our approach to subsumption is based on the artifact’s behavior after a specific test set is chosen.

Given that test set minimization is NP-complete, various researchers have developed test set minimization heuristics. Harrold et al. gave an authoritative treatment [8]. Studies have investigated whether minimizing test sets with respect to various coverage criteria has an effect on fault detection of the remaining tests. A positive result [28] reported on a case study in which minimizing test sets with respect to the dataflow “all-uses” coverage did not significantly reduce fault detection ability. A subsequent study [25] on the Siemens suite came to a contradictory conclusion: minimizing test sets with respect to edge (or branch) coverage severely compromised fault detection. The relevance of test set minimization to mutant minimization is that minimal mutant sets are defined in terms of minimal test sets; hence fault-detection bias introduced by minimal test sets potentially affects minimal mutant sets as well. Further research is needed to evaluate this issue.

V. DISCUSSION AND CONCLUSION

This paper has presented a way to identify precisely how many mutants are needed in the context of a given test set. The size of this set is much smaller than delivered by current best-practice approaches to mutation. We conclude that there is considerable scope for new approaches to mutation analysis that consider only relatively few mutants while at the same time thoroughly testing the underlying artifact.

Mutation score is widely used in the literature to evaluate the quality of an approach to generating test cases. As noted in Section IV, this approach has caused some disquiet in the research community due to the presence of redundant mutants. The results of this paper suggest a different methodology for evaluating testing approaches. Rather than evaluating a given approach against all mutants generated by some set of operators, we propose that, in addition, the approach should be evaluated against a minimal set of mutants. Any approach as strong as the chosen mutation operators will achieve 100% in either case. Weaker approaches can still be compared against criteria such as random selection, but using a minimal set of mutants for comparison removes the problem of redundant mutants from the evaluation.

The minimization approach developed in this paper focused on mutation analysis specifically to address the problem of redundant mutants. However, since the approach uses only the black-box score function, the model can also be applied to test requirements from any other coverage criterion, e.g., statement coverage, branch coverage, dataflow coverage, and so on.

The eventual goal of this line of research is to make mutation testing cost-effective enough to use in practice. The dynamic subsumption approach to minimizing the number of mutants demonstrates that it is, indeed, possible to reduce the number of mutants needed to a very small number. We hope the theoretical structure presented in this paper will lead to practical applications to dramatically reduce the number of mutants generated by actual mutation systems.

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