A Cost-Effective Random Testing Method for Programs with Non-Numeric Inputs

Arlinta C. Barus, Tsong Yueh Chen, *Member, IEEE*, Fei-Ching Kuo, *Member, IEEE*,
Huai Liu, *Member, IEEE*, Robert Merkel, and Gregg Rothermel, *Member, IEEE*

Abstract—Random testing (RT) has been widely used in the testing of various software and hardware systems. Adaptive random testing (ART) is a family of random testing techniques that aim to enhance the failure-detection effectiveness of RT by spreading random test cases evenly throughout the input domain. ART has been empirically shown to be effective on software with numeric inputs. However, there are two aspects of ART that need to be addressed to render its adoption more widespread—applicability to programs with non-numeric inputs, and the high computation overhead of many ART algorithms. We present a linear-order ART algorithm for software with non-numeric inputs. The key requirement for using ART with non-numeric inputs is an appropriate "distance" measure. We use the concepts of categories and choices from category-partition testing to formulate such a measure. We investigate the failure-detection effectiveness of our technique by performing an empirical study on 14 object programs, using two standard metrics—F-measure and P-measure. Our ART algorithm statistically significantly outperforms RT on 10 of the 14 programs studied, and exhibits performance similar to RT on three of the four remaining programs. The selection overhead of our ART algorithm is close to that of RT.

Index Terms—Random testing, adaptive random testing, category-partition method

✦

1 INTRODUCTION

Rᴀɴᴅᴏᴍ Testing (RT) [1]—that is, testing software by randomly generating inputs—is a standard testing approach. RT is also a mainstream approach for reliability estimation; for example, RT can help calculate the *failure rate*, which refers to the probability of an input causing failure of the software under test. Arcuri et al. [5, pg. 258] observe that RT is "one of the most used automated testing techniques in practice". RT has been widely applied to the testing of various systems [4], [17]. Considerable research has also been conducted to propose methodologies for generating random test cases [15], [30].

Adaptive Random Testing (ART) [9] is a class of random testing techniques designed to improve the failure-detection effectiveness of RT by increasing the diversity across a program's input domain of the test cases executed. The Fixed-Size Candidate Set ART technique (FSCS-ART), was the first ART technique, and is also the most widely studied. To generate an additional test case using FSCS-ART, a number of candidate test cases are randomly generated. The candidate that is the most "distant" from previously executed test cases, according to a criterion known as the *max-min criterion*, is selected as the next test case. The *Cartesian distance* measure is used to determine the distance between numeric inputs.

Various studies using programs with numeric inputs [9], [21] have shown that ART requires substantially fewer test cases than RT to reveal failures. However, as Ciupa et al. [11] observe, test case selection overhead can result in FSCS-ART having poorer overall cost-effectiveness than RT. The reduction in test cases required to reveal failures was, in their experiments, outweighed by selection overhead. Arcuri and Briand [3] argue that the high selection overhead of FSCS-ART renders it unsuitable for practical use. They also observe that the effectiveness of FSCS-ART on programs with very low failure rates has not been studied – a fact that, itself, can be attributed to high selection overhead. A number of techniques, such as mirroring [8] and forgetting [6], were proposed to reduce the overhead of various ART algorithms. More recently, Shahbazi et al. [25] proposed a new ART approach, Random Border Centroidal Voronoi Tessellations (RBCVT), which takes advantage of the properties of the Voronoi tessellation to achieve test case diversity. The authors developed a novel algorithm (RBCVT-Fast) that has an $O(n)$ selection overhead (that is, the process of generating n test cases takes $O(n)$ time). However, RBCVT-Fast, as presented, is only directly applicable to simple input domains representable as a d-dimensional real space.

This paper presents an ART algorithm for software with non-numeric, structured input formats, which retains FSCS-ART's failure-revealing effectiveness, and has an $O(n)$ selection overhead. We provide an approach that relies on the concepts of *categories* and *choices*, originally proposed as part of the *category-partition* testing technique [24], to form the basis of a new "distance measure". We evaluate the

- A.C. Barus is with the Institut Teknologi Del, Kab Toba Samosir 22381, Sumatera Utara, Indonesia. E-mail: arlinta@del.ac.id.
- T.Y. Chen and F.-C. Kuo are with the Swinburne University of Technology, Hawthorn 3122, VIC, Australia. E-mail: {tychen, dkuo}@swin.edu.au.
- H. Liu is with the Australia-India Research Centre for Automation Software Engineering, RMIT University, Melbourne 3001, VIC, Australia. E-mail: huai.liu@rmit.edu.au.
- R. Merkel is with Monash University, Clayton 3800, VIC, Australia. E-mail: robert.merkel@monash.edu.
- G. Rothermel is with the Department of Computer Science and Engineering, University of Nebraska - Lincoln, Lincoln, NC 68588-0115, NE. E-mail: E-mail: grother@cse.unl.edu..

effectiveness of this ART algorithm on 14 object programs that have non-trivial input formats, using two standard effectiveness metrics, the *F-measure* and *P-measure*, as well as test case generation time.

The remainder of this article is organized as follows. Section 2 provides essential background on ART, categories and choices. Section 3 describes the theoretical framework for applying ART to non-numeric software, and our linear-order ART algorithm. Section 4 presents our empirical study, including details on the study setup. Section 5 presents our experiment results, including quantitative statistical analysis of those results. Section 6 presents further interpretation and discussion of the results. Section 7 discusses related work. Some concluding thoughts, including recommendations for future study, are offered in Section 8.

2 PRELIMINARIES AND BACKGROUND

2.1 ART

Chen et al. [9] proposed ART as an enhancement to RT. Their approach was based on the intuition of "even spread". A number of studies [2], [27] have found evidence that faults tend to cause erroneous behavior to occur in contiguous regions of the input domain. Thus, Chen et al. [9] argued that two test cases whose inputs were "close" to each other in the input domain were more likely to have similar execution behaviors than two test cases that were more "widely separated". Hence, they reasoned that a method that spreads test cases more evenly would identify failures using fewer test cases.

To implement this idea, Chen et al. [9] introduced a distance-based ART algorithm, also known as Fixed-Size Candidate Set ART (FSCS-ART). In FSCS-ART, two sets of test cases are considered: the *executed set*, **E**, which records those test cases that have already been executed, and the *candidate set*. To select a new test case, a set of k candidates $(c_1, c_2, \ldots, c_k)$ is first "generated randomly" as the candidate set. From these, the best candidate c_o is selected according to a criterion, and testing is conducted with c_o, which is then added to **E**. Testing continues until a pre-specified stopping criterion is met, such as the detection of failures, the execution of the required number of test cases.

The original FSCS-ART used the *max-min* criterion. For each candidate c_i, the Cartesian distance to each member of **E** is calculated, and the smallest distance for c_i is recorded as d_i. The candidate c_o with the largest d_i is selected (i.e., $d_o \geq d_i \forall i, 1 \leq i \leq k$). An alternative selection criterion is the *max-sum* criterion. In this case, for each candidate, the *sum* of the distances to each member of **E** is calculated, and the candidate for which this sum is the largest is chosen.

ART algorithms may consider the entire set of previously executed test cases when selecting the best candidate. However, as Chan et al. [6] show, it is possible to greatly reduce the selection overhead of ART techniques, while retaining much or all of their failure-revealing effectiveness, by evaluating only a subset of **E** when selecting the best candidate. They call this technique *forgetting*.

2.2 Categories and Choices

To test software with non-numeric input formats using FSCS-ART, two things are required:

- A method for randomly sampling inputs from the software's input domain.
- A way of measuring the "distance" between elements of the software's input domain.

The first requirement is common to all RT techniques, while the second is unique to ART; hence, the latter is our focus.

To understand our new distance measure, we need to know why the Cartesian distance is an effective distance measure for ART on software with numeric inputs. Most numerical software consists primarily of compositions of continuous functions. Given two inputs close to each other, as measured by the Cartesian distance, it is likely that their execution patterns will be similar, and thus that their failure behaviors will also be similar. It is this similarity in execution patterns that we seek to measure in a broader range of software.

To achieve this, we have developed an approach based on the concepts of *categories* and *choices* from the *category-partition method* [24]. In this method, the tester must identify input parameters or environmental conditions that affect the execution of the functional unit under test, which are characterized as *categories*. Each category is then partitioned into disjoint partitions, called *choices*, which cover values the category may take. Each choice represents "a set of similar values that can be assumed by the type of information in the category". For instance, consider a transaction processing system handling a large range of monetary and non-monetary quantities (for instance, it may deal with cash and credit transactions, and the transfer of items from a stock inventory); here, an appropriate category may be "unit type", with choices "cash", "credit", and "inventory item". Here, a transaction involving a cash amount of $123.45 would have a unit type of "cash", while a transaction involving the transfer of 10 widgets would have a unit type of "inventory item". In the category-partition method, constraints (stated within the software specification) are used to identify which combinations of categories and choices are valid, and which are not. Then, all valid combinations of categories and choices are generated as *test frames*. Each test frame is then fleshed out into a concrete test case using representative data for each choice in the frame. In our present work, we simply use the concepts of categories and choices to formulate a distance measure for ART. Our approach is presented in detail in Section 3.1.

3 THEORETICAL FRAMEWORK

3.1 A Distance Measure for Non-Numeric Inputs

The distance measure, originally developed by several of the authors of this paper [20], [22], makes use of the concepts of categories and choices from the category-partition method described in Section 2.2.

In the category-partition method, categories and choices are used to obtain test frames, from which concrete test cases are generated. In our approach, we work in the opposite manner: for a given concrete input, we identify its relevant test frame. Categories and choices are still defined as described above. However, rather than simply generating all valid test frames from the defined categories and choices, we take two program inputs, determine their categories and choices, and use this information to calculate the distance between them, with a greater distance representing more

TABLE 1
An Example of Categories and Choices

Category	Choice
Unit type	Cheque Credit Inventory item
Customer type	Business Personal Government Other
Status	Accepted Rejected

dissimilar inputs. Technically speaking, given two program inputs x and y, our distance measure is a count of the number of categories in which x and y have different choices.

More formally, let us denote the set of categories by $\mathbf{A} = \{A_1, A_2, \ldots, A_g\}$, where g denotes the total number of categories. For each A_i, its choices are denoted by $\mathbf{P}_i = \{p_1^i, p_2^i, \ldots, p_h^i\}$, where h denotes the number of choices for A_i. Note that the choices for a single category are disjoint, and that any input is a combination of input values chosen such that the inputs correspond to choices from a non-empty subset of $\mathbf{A}$. For input x, let us denote the corresponding non-empty subset by $\mathbf{A}(x) = \{A_1^x, A_2^x, \ldots, A_q^x\}$, where q refers to the number of categories associated with x. Since categories are distinct and their choices are disjoint, input x in fact consists of values chosen from a non-empty subset of choices, denoted as $P(x) = \{p_1^x, p_2^x, \ldots, p_q^x\}$, where p_i^x ($i = 1, 2, \ldots, q$) is the choice of the category A_i^x for x.

For any two inputs x and y, we define $DP(x, y)$ as the set that contains elements in either $P(x)$ or $P(y)$ but not both. That is, $DP(x, y) = (P(x) \bigcup P(y)) \setminus (P(x) \bigcap P(y))$, where "$\setminus$" is the set difference operator. Now, we define $DA(x, y) = \{A_m | A_i$ if $\exists p_j^i \in DP(x, y)\}$. In other words, $DA(x, y)$ is the set of categories in which inputs x and y have different choices. Then, the distance measure between x and y is defined as $|DA(x, y)|$ (the size of $DA(x, y)$); that is, the *number* of categories that appear in either x or y but not both, or in which the choices in x and y differ.

TABLE 2
Three Example Inputs

Input	Processed Transaction	Category and Choice
x	A cleared cheque payment of $123.45 from Anycorp, a business customer.	Unit type:Cheque Customer type:Business Status:Accepted
y	A credit card payment of $543.21 from Mr. Fred Phisher, a personal customer whose dubious identity leads to the payment being rejected.	Unit type:Credit Customer type:Personal Status:Rejected
z	The dispatch of 12 widgets from stock to Othercorp, a business customer. The order is accepted.	Unit type:Inventory item Customer type:Business Status:Accepted

TABLE 3
Calculation of Distances among x, y, and z

Between the pair of	DP	DA	|DA|
(x, y)	Unit type:Cheque Unit type:Credit	Unit type	3
	Customer type:Business Customer type:Personal	Customer type	
	Status:Accepted Status:Rejected	Status	
(x, z)	Unit type:Cheque Unit type:Inventory Item	Unit type	1
(y, z)	Unit type:Credit Unit type:Inventory Item	Unit type	3
	Customer type:Personal Customer type:Business	Customer type	
	Status:Rejected Status:accepted	Status	

For example, consider again the transaction processing system in Section 2.2 with the categories and choices shown in Table 1. Assume that we have three inputs, x, y, and z, the processed transactions and relevant categories/choices of which are given in Table 2. We can calculate DP, DA, and $|DA|$ for each pair of these three inputs as shown in Table 3. By our measure, x and y have a distance of 3, x and z have a distance of 1, and y and z have a distance of 3.

Obviously, categories and choices are not suitable for all non-numeric programs or all types of inputs. However, they have been popularly applied to many non-numeric applications in various fields, so the proposed distance measure should have wide applicability in the testing of various programs with non-numeric inputs.

3.2 A Linear-Time ART Algorithm

We now present an ART algorithm for structured inputs using the category-choice distance measure to achieve a linear test case selection time (i.e., selecting n test cases takes $O(n)$ time). Compared to FSCS-ART, our algorithm also requires a candidate set, but uses the max-sum criterion in an innovative way that calculates the sum of the distance between each candidate and all previously executed test cases. We call this algorithm "*ARTsum*".

Before presenting *ARTsum*, let us briefly recall the naive implementation of the max-sum criterion as follows. Suppose that n test cases have been selected and executed, denoted by $\mathbf{E} = \{e_1, e_2, \ldots, e_n\}$. Each test case e_j ($j = 1, 2, \ldots, n$) is associated with a set of choices $P(e_j) = \{p_1^{e_j}, p_2^{e_j}, \ldots, p_q^{e_j}, \}$. $P(e_j)$ can be rewritten as a tuple $R(e_j) = (r_1^{e_j}, r_2^{e_j}, \ldots, r_g^{e_j})$, where g is the total number of categories, $r_i^{e_j} = 0$ means that e_j is not associated with category A_i, and $r_i^{e_j} = l$ ($l \geq 1$) means that e_j is associated with the lth choice of A_i. Similarly, a candidate c can also be associated with the tuple $R(c) = (r_1^c, r_2^c, \ldots, r_g^c)$.

Define a function as follows:

$$D(i, j) = \begin{cases} 0 & \text{if } r_i^c = r_i^{e_j}, \\ 1 & \text{if } r_i^c \neq r_i^{e_j}, \end{cases} \quad (1)$$

where $i = 1, 2, \ldots, g$ and $j = 1, 2, \ldots, n$. The distance between c and e_j can then be calculated as $\text{dist}(c, e_j) = \sum_{i=1}^{g} D(i, j)$. Note that $\text{dist}(c, e_j)$ is effectively equal to $|DA(c, e_j)|$. Therefore, the sum of the distances from c to all executed test cases can be calculated as:

$$\text{sum\_dist}\,(c, \mathbf{E}) = \sum_{j=1}^{n} \left(\sum_{i=1}^{g} D(i, j) \right). \qquad (2)$$

Clearly, if we calculate the sum of the distances according to Equation (2), the selection of the next test case requires $O(n)$ time (note that g is a constant). Therefore, a naive implementation of max-sum using Equation (2) has a computation overhead of $O(n^2)$ for selecting n test cases.

Recall the three example test cases x, y, and z shown in Table 2. Suppose that $\mathbf{E} = \{x, y\}$ and z is the candidate. We have $R(x) = (1, 1, 1)$, $R(y) = (2, 2, 2)$, and $R(z) = (3, 1, 1)$. Then, we can calculate $\text{dist}(x, z) = 1 + 0 + 0 = 1$ and $\text{dist}(y, z) = 1 + 1 + 1 = 3$ (as also given in Table 3). Hence, we finally get $\text{sum\_dist}(z, \mathbf{E}) = 1 + 3 = 4$.

Our linear-order *ARTsum* is based on Theorem 1.

Theorem 1. *Define a tuple of integers* $\mathbf{S} = (s_1^0, s_1^1, \ldots, s_1^{h_1}, s_2^0, s_2^1, \ldots, s_2^{h_2}, \ldots, s_g^0, s_g^1, \ldots, s_g^{h_g})$, *where g is the total number of categories, h_i is the total number of choices for the ith category A_i $(i = 1, 2, \ldots, g)$, s_i^0 denotes the number of previously executed test cases that are not associated with the ith category A_i, $s_i^{l_i}$ $(l_i = 1, 2, \ldots, h_i)$ denotes the number of previously executed test cases associated with the l_ith choice of A_i. Let n denote the number of previously executed test cases, that is, $n = |\mathbf{E}|$. By definition, $\sum_{v=0}^{h_i} s_i^v = n$ $\forall i, 1 \leq i \leq g$. For a candidate c associated with $R(c) = (r_1^c, r_2^c, \ldots, r_g^c)$, the sum distance between c and $\mathbf{E}$ is:*

$$\text{sum\_dist}(c, \mathbf{E}) = \sum_{i=1}^{g} \left(n - s_i^{r_i^c} \right). \qquad (3)$$

Proof. For each r_i^c $(i = 1, 2, \ldots, g)$, we can find a corresponding value $s_i^{r_i^c}$ from $\mathbf{S}$, where $s_i^{r_i^c}$ effectively means the number of executed test cases that satisfy $r_i^c = r_i^{e_j}$. Therefore, $(n - s_i^{r_i^c})$ is equal to the number of executed test cases that satisfy $r_i^c \neq r_i^{e_j}$. According to Equation (1), $(n - s_i^{r_i^c}) = \sum_{j=1}^{n} D(i, j)$. Following Equation (2):

$$\text{sum\_dist}(c, \mathbf{E}) = \sum_{j=1}^{n} \left(\sum_{i=1}^{g} D(i, j) \right) = \sum_{i=1}^{g} \left(\sum_{j=1}^{n} D(i, j) \right)$$
$$= \sum_{i=1}^{g} \left(n - s_i^{r_i^c} \right).$$

Thus, Theorem 1 holds; that is, Equation (3) gives exactly the same results as Equation (2). □

Consider x, y, and z in Table 2 again. Given that $\mathbf{E} = \{x, y\}$, we can let $\mathbf{S} = (0, 1, 1, 0, 0, 1, 1, 0, 0, 0, 1, 1)$, where $s_1^0 = 0$ because both x and y contain a choice for the first category, $s_1^1 = 1$ because only x contains the first choice of the first category, $\ldots$, $s_3^2 = 1$ because only y contains the second choice of the third category. Since $R(z) = (3, 1, 1)$, we can

use Equation (3) to calculate $\text{sum\_dist}(z, \mathbf{E}) = (n - s_1^3) + (n - s_2^1) + (n - s_3^1) = (2 - 0) + (2 - 1) + (2 - 1) = 4$.

Theorem 1 implies that if Equation (3) is used, the selection of a next test case requires a constant time. Now, we present our Algorithm *ARTsum*, in which $\mathbf{S}$ is dynamically updated during the testing process. Once the candidate c_o with the largest sum distance is selected as the new test case e_n (refer to Line 13 in the Algorithm), we update $\mathbf{S}$ accordingly by incrementing each $s_i^{r_i^{e_n}}$ $(i = 1, 2, \ldots, g)$ by 1 (refer to Line 16). Note that both updating $\mathbf{S}$ after executing a test case and the distance calculation for the candidate using Equation (3) are independent of the number of test cases; therefore selecting a single test case takes constant time. Thus, selecting a set of n test cases takes $O(n)$ time.

Algorithm 1. *ARTsum*
___

1: Initialize $\mathbf{S}$ (as defined in Theorem 1) by setting each $s_i^{l_i}$ as 0, where $i = 1, 2, \ldots, g$ (g denotes the total number of categories)
2: Set $n = 0$ and $\mathbf{E} = \{\}$
3: Define an integer $k > 0$ as the number of candidates to be generated
4: **while** Termination condition is not satisfied **do**
5:     Increment n by 1
6:     **if** $n = 1$ **then**
7:         Randomly generate a test case e_n
8:     **else**
9:         Randomly generate k candidates $c_1, c_2, \ldots, c_k$
10:         **for all** c_u $(u = 1, 2, \ldots, k)$ **do**
11:             Calculate $\text{sum\_dist}(c_u, \mathbf{E})$ according to Equation (3)
12:         **end for**
13:     Set $e_n = c_o$, where $\forall u, \text{sum\_dist}(c_o, \mathbf{E}) \geq \text{sum\_dist}(c_u, \mathbf{E})$
14:     **end if**
15:     Add e_n into $\mathbf{E}$
16:     Update $\mathbf{S}$ by incrementing each $s_i^{r_i^{e_n}}$ by 1, where $i = 1, 2, \ldots, g$
17: **end while**

---

4 EMPIRICAL STUDY

4.1 Research Questions

As proven in Section 3.2, *ARTsum* generates test cases in linear time. However, we also wish to evaluate the approach's failure-detection effectiveness, and empirically assess its computational overhead. Thus, we conducted an empirical study examining the following research questions:

RQ1   How effective is *ARTsum* at revealing failures?

RQ2   How does the actual selection overhead of the *ARTsum* algorithm compare to its overhead calculated via theoretical complexity analysis, and to the overhead of alternative techniques?

4.2 Object Programs

To address our research questions, we chose to study three sets of object programs: seven programs from the Software-artifact Infrastructure Repository (SIR) [13], six small Unix utilities, and the regular expression processor component of

TABLE 4
14 C Programs as Experimental Objects

Name	Source	Brief description	LOC	# Faults
printtokens	SIR	lexical analyzer	483	7
printtokens2	SIR	lexical analyzer	402	10
replace	SIR	search and replace tool	516	31
schedule	SIR	scheduler	299	9
schedule2	SIR	scheduler	297	9
tcas	SIR	collision alarm logic	138	41
totinfo	SIR	basic statistics	346	23
cal	SunOS	calendar display	163	11
comm	SunOS	file comparator	144	27
look	SunOS	file searcher	135	29
sort	SunOS	file sorter	842	48
spline	SunOS	curve interpolation	289	16
uniq	SunOS	file comparator	125	29
grep	GNU	regular expression processor	3,161	20
Total			7,340	310

the larger utility program GNU grep. The 14 programs, all implemented in C, are summarized in Table 4.

These three sets of programs present complementary strengths and weaknesses as experiment objects. The SIR repository provides object programs, including a number of pre-existing versions with seeded faults, as well as a pool of test cases that can be further fuzzed to provide test cases for RT and candidates for ART. However, these programs are small and there are only a limited number of faulty versions available for each program. The Unix utilities that we use are also relatively small and simple, but they are provided with sets of faults in the form of mutants. The grep program (even when restricting attention to its regular expression processor component) is a much larger system for which mutation faults could be generated. We provide further details on each of these sets of object programs.

4.2.1 Program Set 1: SIR Programs

We selected seven object programs (printtokens, printtokens2, replace, schedule, schedule2, tcas, and totinfo) from SIR [13] for several reasons:

- The programs are of manageable size and complexity for an initial study.
- The input format of the programs is non-trivial, but manageable.
- Faulty versions of the programs are available.
- All programs and related materials are available from the SIR, facilitating replication of our studies.

Note that two of the SIR programs (tcas and totinfo) accept numbers as inputs. However, the random test case generation for them is not as straightforward as that for typical programs with pure numeric inputs: We could not simply generate random numbers according to a uniform distribution. In our experiments, we generated more structured inputs based on the analysis of the input domain (by identifying categories and choices).

For the SIR programs, we used the existing faulty versions present in the repository for comparison. While these were seeded faults rather than actual ones, they were created by multiple persons based on their own experiences with faults. Table 4 lists the numbers of faults utilized for

each of the programs. replace and schedule2 both had one faulty version which was not killed by any existing test cases from the pool, so we excluded these two faulty versions from our study.

4.2.2 Program Set 2: Unix Utilities

The second set of object programs is a set of Unix utilities, cal, comm, look, sort, spline, and uniq, which were distributed as part of SunOS 5.8 and are part of BSD 4.3. For these Unix utilities, faults in the form of mutants had previously been generated by the automated C mutation tool, Proteum [12], which applied a total of 71 mutation operators to create mutants from these programs. Not all generated mutants were used, as some failed on virtually every test case, whereas others produced behavior equivalent to that of the original program. In this study, we filtered the initial set of mutants provided with the program as follows.

- Determine the failure rates of the mutants using RT with a sample size of 100,000.
- Discard mutants that are not killed by any of the 100,000 random test cases.
- Discard mutants with failure rates greater than 0.1.
- Identify mutants that have exactly the same set of failure-revealing inputs. For each such set of mutants, randomly select one for use in the study.

4.2.3 Program Set 3: GNU grep

Our final program is version 2.5.1a of the GNU grep [26] program, which is described by its "man" page as follows:

The grep command searches one or more input files for lines containing a match to a specified pattern. By default, grep prints the matching lines.

We chose grep for our study for several reasons:

- As a GNU project, current and historical versions are freely available including source code and a partial, but still useful, change history.
- The grep program is in wide use, providing an opportunity to demonstrate the real world relevance of our techniques.
- The grep program, and its input format, are of greater complexity than the programs in the other test sets, but still manageable as a target for automated test case generation.

grep's large size meant that constructing test infrastructure for the entire program would have been infeasible for this study. Thus, we focused on grep's regular expression analyzer, which was still much larger than other programs studied, consisting of 3,161 lines of code and 1,423 branches.

We also had to take a different approach to providing faulty versions of grep for our experiments. grep's software change log showed that most faults found and fixed in grep were either platform-specific, or manifest so rarely that they render experimental comparisons of failure-detection effectiveness impractical.

However, one reported grep fault in the public version history for the program was suitable for our use. The fault relates to incorrect handling of range expressions (such as [a-e], which matches the characters from the set {a, b, c, d, e} if the default Unix locale is used) with non-default locales,

which may define their own character ordering. As a consequence, with some locale settings [a-e] should match the set {a, A, b, B, ..., e}, for instance, but did not. To expose the fault, we changed the locale setting to "en_US.UTF-8" for our experiments.

One real fault is insufficient to support a comprehensive study, so we also used program mutation to generate additional faulty versions of `grep` for our experiment. Due to limitations in the ability to restrict Proteum to creating mutants for a specific part of `grep` (the regular expression analyzer), it was impractical to use it to generate sufficient mutants for `grep`. Thus, we developed a custom tool that applied two types of mutation operators – *statement mutation* and *operator mutation*. One statement mutation operator that we applied replaced *continue* statements with *break* statements and *vice versa* – these statements are common in the regular expression analyzer in `grep`. Another statement mutation operator replaced labels on *goto* statements. The operator mutation replaced a single arithmetic or logical operator with another. Each mutant had only one mutation operation applied to it. We generated a total of 19 mutants, resulting in a total of 20 faulty versions of `grep`.

4.3 Variables and Measures

4.3.1 Independent Variable

The independent variable in our experiment is the test case selection strategy. As choices for this variable, we include, of course, an implementation of the *ARTsum* algorithm. As baseline techniques for use in comparison, we selected two additional techniques, RT and *ARTmif*.

RT (*random testing with replacement*) is a natural baseline choice, because *ARTsum* is designed as an enhancement to RT, and assessing whether *ARTsum* is more cost-effective than RT is important. In general, an automated oracle is assumed when RT is applied. In our experiments, the base programs (for which seeded faults already existed or were generated) were used to simulate the automated oracles.

ARTmif is an enhanced linear-order ART approach that combines the max-min criterion with forgetting. FSCS-ART can be implemented straightforwardly using the category-choice distance metric and the max-min selection criterion. However, selecting n test cases has an overhead of $O(n^2)$, which may lead to inferior cost-effectiveness, depending on the failure rate and the execution time of the program under test. A "forgetting" technique can be used to reduce the overhead of the approach to $O(n)$ if an ART algorithm considers only a fixed-sized subset of the previously executed test cases when selecting the best candidate. However, prior studies [6] on forgetting always arbitrarily define the size of the subset. In this study, we used a more precise heuristic for conducting the forgetting process:

- During each round of test case selection, count how many candidates have the same minimum nearest neighbor distance d_o.
- When the following two conditions are both satisfied, forget all already executed test cases and then perform max-min FSCS-ART from scratch.
  - Over 90 percent of the candidates have the same d_o.

  - d_o is less than or equal to the number of categories divided by 10.

Given the finite number of categories, if candidates are selected randomly, the probability that most candidates have the same small nearest neighbor distance to previously executed test cases asymptotically approaches one as the number of previously executed test cases increases. In other words, there is an upper bound on the size of the subset of previously executed test cases that satisfy the above conditions. Thus, *ARTmif* has a computational overhead of $O(n)$ for generating n test cases.

There exist some techniques, such as quasi-random testing (QRT) [10] and RBCVT-Fast [25], that can achieve a computation overhead as low as $O(n)$. However, they can be applied only to test software with an exclusively numeric input domain, and therefore could not be compared to *ARTsum* and *ARTmif* in our study.

4.3.2 Dependent Variables

The choice of a metric to use in comparing the effectiveness of testing techniques is non-trivial.

For RQ1, to best characterize the failure-detection effectiveness of the methods, we use two standard metrics: the *F-measure* and the *P-measure* [7]. The F-measure is defined as the mean number of test cases required by a method to reveal the first failure. We define *F-count* as the number of test cases needed to detect a failure in a specific test run. The F-measure is the expected F-count for a testing method:

$$\text{F-measure} = \overline{\text{F-count}}. \quad (4)$$

A smaller F-measure reflects better effectiveness.

The F-measure is particularly appropriate for measuring the failure-detection effectiveness of adaptive testing methods, such as ART, in which the generation of new test cases depends on the previously executed test cases. However, evaluation of the F-measure requires an automated oracle (because testing must be stopped after failure detection), which may not always be available. Thus, we also used the P-measure, which can characterize the testing process without an automated oracle. Suppose that a particular method is used to generate a test suite with n test cases $\{t_1, t_2, \ldots, t_n\}$, the P-measure is defined as the probability of *at least one failure* being detected by the test suite:

$$\text{P-measure}(n) = Prob \, (\exists t_i \text{ that reveals a failure}), \quad (5)$$

where $i = 1, 2, \ldots, n$. A larger P-measure reflects better failure-detection effectiveness. Besides providing a complementary evaluation to the F-measure, the P-measure is also more appropriate than another standard metric, the E-measure (the *expected number of failures*): as observed by Shahbazi et al. [25], multiple failures may be associated with the same software fault.

For RQ2, our dependent variable is simply the time required for the testing techniques to generate test cases.

4.4 Generation of Categories and Choices for Object Programs

The categories and choices used for the object programs considered in this study were designed by the authors. In large part, the selection of appropriate categories and

choices is at a tester's discretion; we chose what we regarded as simple approaches for emulating that process.

For the programs taken from the SIR, and the Unix utilities, limited documentation was available, so we inferred the behavior of each program by examining the test inputs and outputs, as well as the source code. To avoid a possible source of bias, while designing categories and choices, we did not examine the faults. As noted previously, our categories and choices for `grep` were designed to test its regular expression analyzer. To obtain these, we consulted the user documentation.

Precise details on the categories and choices used in our study are provided in Tables A4 to A15 in the Appendices, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TC.2016.2547380.

4.5 Generation of Test Cases for Object Programs

Each of the SIR programs had an existing pool of test cases, but these pools were not large enough (having a few thousand test cases per program) to ensure sufficient randomness. Thus, rather than sampling test cases from the existing pools, we used a number of techniques to dynamically generate test cases on demand. Our approach has some similarities to fuzz testing. We first analyzed the existing test pools to obtain the probability distributions of certain parameters. Then, according to the probability distributions, the concrete values of these parameters could be randomly chosen. The detailed procedure for test case generation for each object program can be found in Appendix A, available in the online supplemental material.

For the Unix utilities, Wong et al. [29] developed a random test case generator, which we used in our study.

For `grep`, we used a generator that was itself based on the categories and choices devised for ART selection. We systematically generated random candidate test cases, which were collectively guaranteed to cover each category and choice. Our test generator does not randomly sample from the entire input domain of `grep`; rather, it samples a small subset of the input space, as our purpose is to test the regular expression analyzer of `grep`. We further filtered the randomly generated pool to remove duplicate entries. The final pool contained 171,634 elements. Readers can refer to Appendix B, available in the online supplemental material, for more technical details on the random test case generation process for `grep`.

4.6 Experiment Environment

All experiments were conducted on a cluster of 64-bit Intel Clovertown systems running CentOS 5. The large number of experimental trials required to collect data with sufficiently narrow confidence intervals consumed a great deal of computer time, making the use of the cluster essential to obtain results in a reasonable time. The object programs were written in standard C and did not require any modifications to compile and run on the nodes in the cluster.

4.7 Experiment Design and Analysis Strategy

4.7.1 Number of Candidates

The parameter k—the size of the candidate set used by FSCS-ART—is at the tester's discretion. Previous work [9] has shown—at least for numeric programs—that failure-

detection effectiveness improves as k increases up to about 10, and then does not improve much further. Thus, our experiments were all conducted with k set to 10.

4.7.2 F-Measure

For an experiment run, a test case was generated (using RT or ART) and executed on both an unmodified version of the object program under test and a version containing the fault of interest. A failure was indicated by a difference between the outputs of the faulty and original versions. For each fault, 2,000 runs were performed for the RT, *ARTmif*, and *ARTsum* strategies, and the F-measure was calculated as the mean value of F-counts (refer to Equation (4)) across all the experiment runs. This large number of runs is desirable due to the statistical properties of the F-count. Typically, the population distribution of the F-count is geometric for RT and near-geometric for most ART variants [7]; therefore, the standard deviation is very high and obtaining acceptably narrow confidence intervals requires large samples.

Being intended as an enhancement to RT, we calculated the ratio of the F-measure for each ART technique compared to the F-measure for RT for each fault. We refer to this as the *F-ratio*. The F-measures for RT on different faults in the same object program vary by orders of magnitude, and these F-measures are not normally distributed. Therefore, to concisely summarize the differences in performance between the methods, we present the relative performance using RT as the baseline – the F-ratio.

4.7.3 P-Measure

Raw data to calculate P-measures was recorded in the same experiments. For each fault in each object program, 2,000 runs of 1,000 test cases were conducted, and failures were recorded. P-measures were calculated according to Equation (5) when the number of test cases $n = 1, 2, \ldots, 10, 20, \ldots, 100, 200, \ldots, 1,000$.

The P-measure does not, by itself, provide enough information to assess a testing strategy if the resulting test suites are of different sizes; thus, a further metric is required. In this study, we used the aggregation of P-measures across various test suite sizes, as measured by the total area under the P-measure graph, namely the "P-measure area", (abbreviated as "PMA"). Suppose that P-measures have been calculated for N_s different test suite sizes $\{n_1, n_2, \ldots, n_{N_s}\}$, where $n_1 < n_2 < \cdots < n_{N_s}$. PMA is calculated as:

$$\text{PMA} = \frac{\text{P-measure}(n_1)}{2} \times n_1 +$$
$$\sum_{i=2}^{N_s} \frac{\text{P-measure}(n_i) + \text{P-measure}(n_{i-1})}{2} \times (n_i - n_{i-1}).$$
$$(6)$$

As we discuss in Section 5.1.2, a higher PMA was a reliable indicator that a particular parameterized test strategy was more effective, regardless of test suite size.

4.8 Threats to Validity

4.8.1 Internal Validity

There are relatively few threats to the internal validity of this study. Experimental conditions were identical in all respects, except for the independent variable of the testing method, for

each experiment treatment. Where testing methods were concerned, one possible issue involves our implementations of methods, or of testing oracles. It is possible that these implementations contain errors; however, the amount of programming required to implement each specific testing method was small, and the implementations were checked by various authors. The oracle is computationally trivial, involving a simple string comparison. Furthermore, the implementations were all created by the same individuals, helping ensure that differences in programming abilities would not bias results. In terms of the execution time comparisons, given that the authors implemented both *ARTsum* and *ARTmif*, it was possible that the implementation of one was more optimized than the other, affecting their relative computational overhead. The implementations were reviewed for obvious inefficiencies and none were found.

4.8.2   External Validity

The most obvious threat to external validity is that we consider only 14 object programs. We cannot say whether the studied methods will exhibit similar results on other software systems without further study. The selection of appropriate categories and choices is a subjective process relying on the knowledge and experience of the testers (which were the authors). Our study considered only one set of categories and choices for each object program. We cannot be sure that other testers, presented with the same software under test, would choose a set of categories and choices that would achieve similar results. The particular faults we used, almost all of which were the result of fault seeding by programmers or randomly applying mutation operators, may not be representative of real faults and fault distributions encountered in industrial practice. A further threat to external validity involves our considering the detection of a single fault at a time. There is no reason why the same intuition that explains why ART detects single faults more quickly than RT should not also hold when multiple faults are present; however, this needs to be assessed empirically.

4.8.3   Construct Validity

As discussed in Section 4.3.2, none of the metrics used here give a full picture of the fault-finding effectiveness of a testing technique. They all measure failure-detection capability, but do not directly measure the ability of a technique to detect multiple faults in the software under test.

4.8.4   Conclusion Validity

Given the large number of experiment runs conducted for each fault, we believe that our tests had sufficient statistical power to draw conclusions about the F-measures and P-measures of each testing strategy at the individual fault level. However, the use of weaker nonparametric tests for statistical significance has limited our ability to show significant differences where they may exist.

5   DATA AND ANALYSIS

5.1   RQ1: Failure-Detection Effectiveness

5.1.1   F-Measure

For each object program, we present a boxplot and a table summarizing the results. The boxplot for each program

(Fig. 1) graphically displays the range of F-ratios through their quartiles for each of the two ART methods, for all faulty versions of the program under test. Smaller F-ratios indicate better performance for ART, and an F-ratio smaller than 1 indicates that ART outperformed RT. The boxplot is non-parametric, that is, there is no underlying assumption of statistical distributions. The lower and upper sides of the box denote the lower and upper quartiles respectively. The line inside the box indicates the median F-ratio. The whiskers represent the smallest and largest data within a range $\pm 1.58 \times IQR$, where IQR is the interquartile range. Small circles represent outliers outside this range. Full results are given in Tables A16 to A29 in the Appendices, available in the online supplemental material.

Table 5 presents direct pairwise comparisons of the F-measures of RT, *ARTsum*, and *ARTmif* for each object program. Each cell in the table represents the number of faults on which the technique listed *above* the cell outperformed the technique listed to the *left*. For instance, in Table 5a, the entry in the top right-hand corner of the table shows that *ARTmif* had a *smaller* F-measure than RT on all 11 of the faults. Similarly, the entry in the bottom left-hand corner shows that RT outperformed *ARTsum* on 0 of the 11 faults.

Because the number of faults for each object program was small and their F-measures were not normally distributed, conventional parametric hypothesis testing (such as T-tests or ANOVAs) is not suitable for analyzing our results [16]. Thus, to test whether the performance differences were statistically significant, we conducted a Friedman test for each method. The Friedman test [14] examines whether the rankings of the methods across trials (faults, in this case) are as would be expected if they were sampled from the same population. To use an overall α (probability of a non-significant difference being incorrectly classified as significant) of 0.05 across the entire paper, we used the Holm-Bonferroni method [19] to determine which programs exhibited statistically significant differences. Note that in the nonparametric statistical test, it is irrelevant whether we use the F-ratio or the unadjusted F-measure, as the ranking is unaffected. On all programs except schedule, the testing methods exhibited failure-detection results that were statistically significantly different. To determine which methods performed significantly differently for each fault, post-hoc comparisons using the Wilcoxon signed-rank test [28] with corrections for multiplicity were used. A *bold* number in the tables indicates that the differences between methods was statistically significant. For instance, the fact that *ARTmif* outperformed RT on 17 of the 20 grep faults is statistically significant, whereas the fact that *ARTsum* outperformed *ARTmif* on 11 of the 20 grep faults is not.

ARTsum significantly outperformed RT in terms of the F-measure on 10 of the 14 object programs. For three of the remaining four programs, replace, schedule, and totinfo, there was no statistically significant difference in the performance of *ARTsum* and RT. On only one program, tcas, did RT significantly outperform *ARTsum*.

ARTmif displayed similar but not identical performances. *ARTmif* outperformed RT on 10 of the 14 object programs. There were no statistically significant differences in performance on three programs, replace, schedule, and schedule2. Again, only on tcas did RT outperform

(a) cal   (b) comm   (c) grep   (d) look

(e) printtokens   (f) printtokens2   (g) replace   (h) schedule

(i) schedule2   (j) sort   (k) spline   (l) tcas

(m) totinfo   (n) uniq

Fig. 1. Boxplots of F-ratio distributions for ART techniques for each object program.

ARTmif. The magnitude of the performance improvement varied between programs. The differences in effectiveness between *ARTsum* and *ARTmif* were small. There was a slight preponderance of results indicating that *ARTsum* may marginally outperform *ARTmif*, but these did not achieve statistical significance.

5.1.2 P-Measure

Fig. 2 shows the P-measure for the three techniques for selected faults to illustrate general trends in the results.

Note the use of logarithmic scales on the *x*-axis in Fig. 2 to enable the three techniques to be distinguished for small test suite sizes.

The values of P-measures depend not only on the program under test and the testing method, but also on the size of the test suite. Thus, simply examining individual P-measures on some specific test suite sizes may not provide a complete picture. To enable the statistical analysis of the P-measure results, we used PMA (as defined in Section 4.7.3) to aggregate results enabling us to compare

TABLE 5
Number of Faults for Which the Technique on the Top Row Has a Lower (Better) F-Measure Than the Technique on the Left

(a) cal

	RT	ARTmif	ARTsum
RT	N/A	**11**	**11**
ARTmif	0	N/A	8
ARTsum	0	3	N/A

(b) comm

	RT	ARTmif	ARTsum
RT	N/A	**27**	**27**
ARTmif	0	N/A	13
ARTsum	0	14	N/A

(c) grep

	RT	ARTmif	ARTsum
RT	N/A	**17**	**20**
ARTmif	3	N/A	11
ARTsum	0	9	N/A

(d) look

	RT	ARTmif	ARTsum
RT	N/A	**22**	**21**
ARTmif	7	N/A	13
ARTsum	8	16	N/A

(e) printtokens

	RT	ARTmif	ARTsum
RT	N/A	**7**	**7**
ARTmif	0	N/A	5
ARTsum	0	2	N/A

(f) printtokens2

	RT	ARTmif	ARTsum
RT	N/A	**10**	**9**
ARTmif	0	N/A	3
ARTsum	1	7	N/A

(g) replace

	RT	ARTmif	ARTsum
RT	N/A	18	14
ARTmif	13	N/A	**6**
ARTsum	17	**25**	N/A

(h) schedule

	RT	ARTmif	ARTsum
RT	N/A	4	4
ARTmif	5	N/A	8
ARTsum	5	1	N/A

(i) schedule2

	RT	ARTmif	ARTsum
RT	N/A	6	8
ARTmif	3	N/A	8
ARTsum	1	1	N/A

(j) sort

	RT	ARTmif	ARTsum
RT	N/A	**41**	**47**
ARTmif	7	N/A	31
ARTsum	1	17	N/A

(k) spline

	RT	ARTmif	ARTsum
RT	N/A	**14**	**13**
ARTmif	2	N/A	6
ARTsum	3	10	N/A

(l) tcas

	RT	ARTmif	ARTsum
RT	N/A	8	7
ARTmif	33	N/A	21
ARTsum	34	20	N/A

(m) totinfo

	RT	ARTmif	ARTsum
RT	N/A	**18**	17
ARTmif	5	N/A	3
ARTsum	6	**20**	N/A

(n) uniq

	RT	ARTmif	ARTsum
RT	N/A	**28**	**24**
ARTmif	1	N/A	12
ARTsum	5	17	N/A

the effectiveness of testing methods. For a given fault, if PMA is larger for a method α than for another method β, the performance of α is superior to that of β. Fig. 2 clearly shows that for the selected faults, if one method has a higher P-measure and is therefore more effective than another for a given test suite size, then it will be equal to or superior than the other for other test suite sizes. This pattern holds for all faults.

We calculated the PMA for all faults in all programs and ranked the methods for each fault in each program, and conducted Friedman tests (applying a Holm-Bonferroni correction across all hypothesis tests, for both P-measures and F-measures) to check the statistical significance of the rankings. Our results showed that, in virtually all cases, if one method demonstrated a superior (lower) F-measure than another for a specific fault in a program, that method would have a superior (higher) PMA, and that the differences that were statistically significant for the P-measures and F-measures were identical. The rankings of F-measure and P-

measure are almost the same, with a slight difference only for replace as given in Table 6. The complete PMA's rankings are given in Table A30 in the Appendices, available in the online supplemental material.

5.2 RQ2: Test Suite Generation Time

Fig. 3 shows the execution time required to generate test suites of various sizes for three of the 14 object programs using RT, ARTsum, and ARTmif. Consistent with our theoretical analysis, they all require time linear in the size of the generated test suite. The constant factors for ARTsum, however, are consistently lower than those for ARTmif.

Table 7 shows these constant factors by indicating the time required to generate 10,000 test cases using RT for all the input generators. Note that schedule and schedule2 share the same input generator, as do printtokens and printtokens2, so only 12 input generators are listed. We also compare the relative time taken using the three different methods for each input generator. As can be seen, there
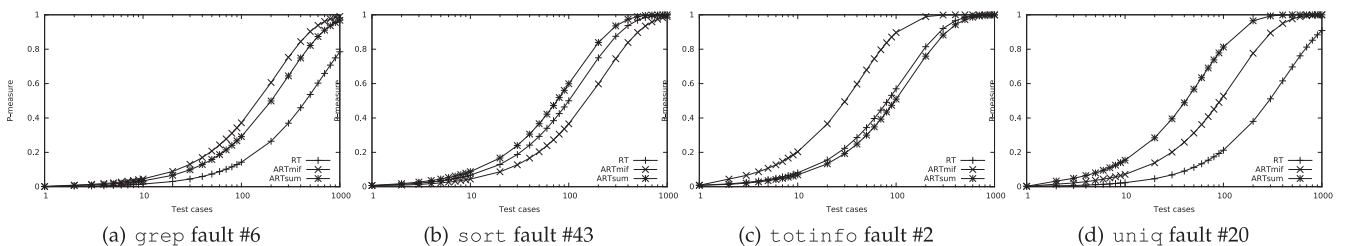

(a) grep fault #6   (b) sort fault #43   (c) totinfo fault #2   (d) uniq fault #20

Fig. 2. P-measure by technique for selected faults.

TABLE 6
Number of Faults for Which the the Technique on the Top Row Has a Higher (Better) PMA than the Technique on the Left for `replace`

	RT	*ARTmif*	*ARTsum*
RT	N/A	18	14
ARTmif	13	N/A	**5**
ARTsum	17	**26**	N/A

TABLE 7
Comparison of Time Required to Generate 10,000 Random Inputs Using RT, *ARTmif* and *ARTsum*

	Generation time (s)			Relative generation time		
	RT	*ARTmif*	*ARTsum*	*ARTmif*/RT	*ARTsum*/RT	*ARTsum*/*ARTmif*
`cal`	0.032	0.15	0.065	4.7	2.0	2.3
`comm`	0.034	0.222	0.117	6.5	3.4	1.9
`grep`	0.011	23.122	0.064	2102.0	5.8	361.3
`look`	0.023	0.368	0.105	16.0	4.6	3.5
`printtokens`	0.421	13.365	3.046	31.7	7.2	4.4
`replace`	0.018	2.264	0.146	125.8	8.1	15.5
`schedule`	0.052	3.637	0.331	69.9	6.4	11.0
`spline`	0.022	0.622	0.116	28.3	5.3	5.4
`sort`	0.011	2.717	0.072	247.0	6.5	37.7
`tcas`	0.018	2.306	0.104	128.1	5.8	22.2
`totinfo`	0.045	1.464	0.3	32.5	6.7	4.9
`uniq`	0.025	0.839	0.1	33.6	4.0	8.4

is wide variation in the relative time costs of input generation depending on the program. The generation time using the *ARTsum* algorithm are within a range of 2.0 to 8.1 times that of RT, whereas *ARTmif* takes 4.7 to 2102.0 times longer than RT and takes 1.9 to 361.3 times longer than *ARTsum*.

6 DISCUSSION

Overall, *ARTsum* and *ARTmif* were clearly each more effective than RT, as measured by both the F-measure and P-measure, on a majority of the object programs considered. *ARTsum* also had a much lower selection overhead than *ARTmif*, and its overhead was close to that of RT.

We examined the cases in which *ARTsum* was not significantly more effective in terms of fault-detection than RT. This occurred on the object programs `replace`, `schedule`, and `totinfo`, where differences between *ARTsum* and RT were not statistically significant, and on `tcas`, where RT was more effective than ART. Our investigation revealed an interesting pattern related to the distribution of failure-revealing inputs in test frames for the different faulty versions of `replace`. We first examined the failure rate within failure-revealing "test frames" – that is, the subsets of the test pool that shared the same categories and choices, and contained at least one failure-causing input. We hypothesized that for faults on which ART performed poorly, the failure rate within the failure-revealing test frame would be lower. There did not appear to be any such systematic effect, so we then examined the distribution of the test frames containing failure-causing input in terms of their average "distance". We found that the "distance" between frames containing failures was *higher* for faults on which ART outperformed RT, and *lower* when RT outperformed ART. The faulty versions of `schedule` and `tcas`, on which ART exhibited comparatively poor performance, have similar distributions of failure-revealing inputs in test frames.

One potential explanation for this is that when a test case is executed in a test frame that contains a failure, but that test case does not reveal a failure, this reduces the chances of selecting nearby test cases. Thus, a technique will perform better if there are other failure-revealing test cases located far away, rather than close by. This suggests that our distance measure and selection criteria could still be improved. One obvious approach for improvement is that to maximize testing effectiveness, non-homogeneous test frames should be avoided, and the best way to do this is to have fine-grained test frames that correspond to distinct program functionalities. Testers are best advised to use a larger number of categories and choices to make as fine-grained a difference measure as possible, and ensure that they align with the functionality of the program under test.

Given that `grep` was our largest program, it is worth considering effectiveness results on that program in some detail. For `grep`, *ARTmif* was inferior to RT for three faults: faults 4, 15, and 17 as listed in Table A18 in the Appendices, available in the online supplemental material. We examined these cases in more detail, and found behavior similar to that occurring in the cases of `replace` and `schedule`. However, we also noted an additional factor: the inferior effectiveness was related to the non-uniform distribution of the test cases selected. Such biases have been observed in previous studies of ART. In fact, biases are almost inevitable; it is difficult to achieve an effective spreading of inputs without inducing *some* bias towards certain inputs. *ARTmif* preferentially selected inputs that had a large number of choices. For each of the three faults in `grep` on which *ARTmif* did not outperform RT, most of the *failure-causing inputs*

(a) `printtokens`
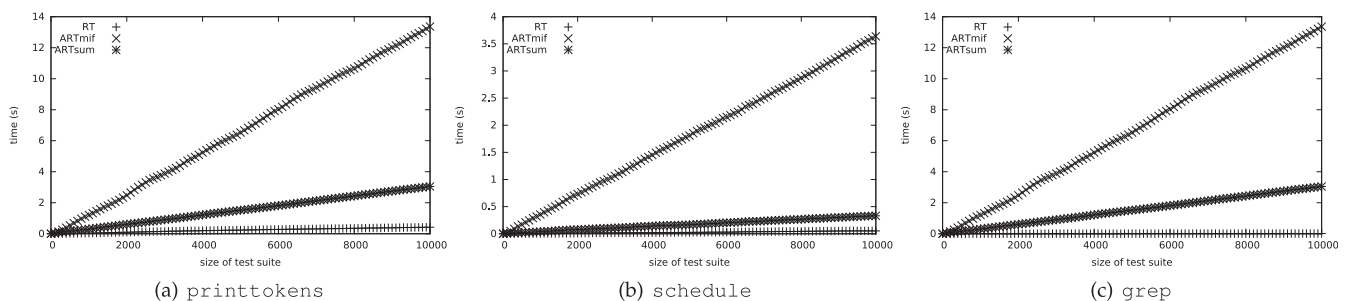

(b) `schedule`

(c) `grep`

Fig. 3. Time required to generate test suites.

had a very small number of choices. Hence, these failure-causing inputs were less likely to be selected by *ARTmif* than by random chance. This is related to the granularity problems of the distance measure as discussed in Section 3.2, but is not strictly the same. The same phenomena affect the results for individual mutants of the same program. This combined with the relatively small number of mutants per program, is probably responsible for a few unusual looking boxplots in Fig. 1.

We have shown that *ARTsum* significantly outperformed RT on 10 of our 14 object programs. Our results showed that *ARTsum* and *ARTmif* had comparable performance, and that *ARTsum* slightly outperformed *ARTmif* particularly when there were a small number of categories. However, this is consistent with our view that the max-sum criterion handles a coarse distance measure better than the max-min criterion.

We have clearly shown that while both *ARTsum* and *ARTmif* are linear-time algorithms, in practice, *ARTsum* can incur a much smaller selection overhead than *ARTmif*. Therefore, given that *ARTsum* and *ARTmif* have comparable failure-detection effectiveness, the lower overhead suggests that *ARTsum* should be considerably more cost-effective overall.

Despite the satisfactory effectiveness demonstrated by the "forgetting" strategies employed in *ARTmif* in this study as well as prior studies, the settings of their parameters seem to be arbitrary and are not rigorously justified. This arbitrariness does not occur for *ARTsum*, which in our view is a further reason to prefer it to *ARTmif*.

Selecting categories and choices for ART may impose an additional burden on the tester, compared to RT. It is true that the selection of appropriate categories and choices may not always be straightforward, and may depend substantially on the tester's expertise and experience. If random test cases could be easily generated, RT might be more cost-effective than ART. Nevertheless, in many practical situations, especially when the software under test involves more complicated inputs (such as those with non-numeric types), it is not straightforward to randomly generate test cases. As noted by Arcuri et al. [5, pg. 261], "[w]hen the input domain consists of numeric inputs, it is easy to uniformly choose random test cases from it. But it is not always clear how to do that when more complex types of test cases are used." To apply RT to a non-numeric input domain, testers may need to perform some analysis of the input domain. One useful method for doing so is by identifying categories and choices, just as has been done in this paper. If such an approach has been taken, the additional effort by testers to apply ART over RT would be small.

Another interesting issue is that while *ARTsum* can generate test cases in linear time, its test case generation time is still several times longer than RT. This implies that RT may be more cost-effective than *ARTsum* under particular conditions, especially when test execution time is negligible. However, the execution of test cases often takes a substantial amount of time, particularly once the time taken for testing infrastructure such as setup, teardown, and result reporting is taken into account. In such a situation, the larger number of test cases required by RT would result in longer overall testing time than *ARTsum*. For example, one of our object programs, `grep`, on average took 2.98×10^{-4}

seconds to execute a test case. On average, RT required 1.1×10^{-6} seconds, and *ARTsum* took 6.4×10^{-6} seconds, to generate one test case. For `grep`, therefore, the cost of performing testing is dominated by the cost of test case execution. The ratio of total testing time taken by ART over RT was thus very similar to the F-ratio. For example, on the first mutant of `grep`, *ARTsum* took 1.33×10^{-2} seconds, whereas RT took 3.10×10^{-2} seconds. There is no "golden method" that always has higher cost-effectiveness than other testing methods for all programs. Indeed, RT can be better than *ARTsum* under some conditions, such as in cases involving high failure rates and short program execution time. In this paper, we intend to provide a testing method for programs that have non-numeric inputs requiring systematic analysis, and that have long execution times. For such situations, it is very likely that *ARTsum* is more cost-effective than RT.

7 RELATED WORK

The extension of ART to non-numeric input domains has been of interest for some time. Ciupa et al. [11] demonstrated the application of ART to unit testing of object-oriented software. There are significant differences between their approach and ours. Ciupa et al.'s distance measure, which was specifically designed for unit testing of object-oriented software, is based on the structure of method inputs, and permits no tester discretion. Our distance measure, in contrast, allows testers to use their knowledge of the specification and/or the program structure to specify appropriate categories and choices. It is not restricted to object-oriented languages, and is applicable beyond unit testing. Ciupa et al.'s implementation uses FSCS-ART as the test case selection technique. This technique's quadratic selection overhead implies that overall, ART might not actually be cost-effective compared to random testing. Our technique, in contrast, takes advantage of the properties of our distance measure to achieve linear-time selection overhead, addressing these cost-effectiveness issues.

There have been a number of attempts to reduce the selection overhead of ART, even before Arcuri and Briand [3] drew attention to the implications of this for the practical use of ART. For instance, Shahbazi et al. [25] devised RBCVT-Fast, a linear-time ART algorithm for d-dimensional real input domains. Our work is complementary to theirs in that it can be applied to non-numeric input domains.

RT is of course not the only way to automatically generate test data; alternatives include model-based, symbolic execution-based, and search-based testing methods. Compared with RT/ART, these "more systematic" methods are guaranteed to detect faults that violate specific properties using, in many situations, fewer test cases. However, they normally incur a very high cost in generating test cases; for example, model checking based algorithms are often exponential-time, which is not comparable to linear time at all. In other words, the savings in the number of test cases (and thus the savings in the test execution time) may not be sufficient compensation for a much longer test case generation time. In addition, no testing method is guaranteed to detect all types of faults. The "systematic" methods may be very effective in detecting certain types of faults, but they may also be very ineffective in the detection of other faults. Random strategies (such as RT

and ART) can be considered to be complementary to them: due to the randomness, random strategies can detect some faults difficult to detect using systematic methods [4], [5], [17]. As mentioned in Section 6, there is no "golden method". Any testing method has its own advantages and disadvantages, dependent on various factors, in particular, the program execution time which can vary enormously. The *ARTsum* method proposed in this paper can be considered as a possible cost-effective enhancement to RT and a good complementary testing method to other systematic ones, when the software under test involves non-numeric and structured inputs. ART is complementary to other systematic testing methods not only because ART and other methods can work independently to detect different types of faults, but also because they can be integrated to provide hybrid techniques. For example, ART has been used to improve the test cases' diversity in model-based testing [18]. It would be worthwhile to systematically compare ART with other state-of-the-art testing techniques, but such an experimental comparison is beyond the scope of this paper (in which we focus on how to improve RT) and is one important direction for the future work.

There are some obvious parallels between some aspects of combinatorial testing [23] and our ART algorithm. But there are some fundamental differences. Combinatorial testing has coverage as its underlying notion, and aims to detect faults that are related to interactions between different parameters. The underlying concepts of ART, in contrast, are randomness and diversity across the input domain. ART does not involve any form of coverage of specific combinations of parameters, and combinatorial testing does not involve randomness and diversity across the input domain. From an operational perspective, ART normally generates test cases in an incremental way, while combinatorial testing fundamentally requires the generation of an entire test suite that satisfies certain coverage criteria, such as t-way combinations. In other words, the combinatorial testing has a lower bound on how many test cases should be generated, while ART can generate any number of test cases until a termination condition is satisfied. The incremental nature of ART is actually an advantage over combinatorial testing, especially when there are many factors that must be considered in testing. For example, a complex system (such as `grep`) can involve n functionalities, each of which may be associated with m options and then p sub-options. Such a hierarchy in inputs can result in a very large input space. In addition, there may be an "explosion" in the input space: The lower bound in test suite size of combinatorial testing will increase exponentially as the values of m, n and p increase. Our work addresses this "explosion" problem by a simple method: The distance measure we proposed treats the input space in two flat layers – the input space is partitioned into different categories and their associated choices. The numbers of categories and choices do not necessarily grow with the increase of m, n, and p, and there are common categories and choices across different functionalities, options, and sub-options. Even if the numbers of categories and choices become larger with the growth of the input domain, due to its incremental nature, ART does not suffer from the input space "explosion" problem: ART imposes no rigid requirements on the test suite size no matter how large the input space is. Such fundamental differences make it extremely difficult, if not impossible, to compare ART and combinatorial testing using the F-measure. The measurement of P-measure had a similar problem: Both RT and ART have high flexibility in test case generation, making it possible to obtain P-measure values with various test suite sizes; by contrast, combinatorial testing imposes fixed test suite sizes.

8 CONCLUSION

ART was proposed to enhance the failure-detection effectiveness of RT. In this work we have presented a linear-order ART algorithm, *ARTsum*, that makes use of a novel distance measure, and takes advantage of the properties of this distance measure to achieve a linear-order test case generation. Our work is complementary to the recent RBCVT-Fast algorithm [25], which is an innovative linear-order ART algorithm for numeric inputs.

We conducted an empirical study using a total of 14 programs, comparing our *ARTsum* algorithm with RT and a baseline ART technique using the max-min criterion and the technique of "forgetting" to reduce selection overhead, namely *ARTmif*. Each of the ART algorithms significantly outperformed RT with respect to the F-measure for 10 of the 14 object programs, was significantly outperformed by RT for only one program, and had performance comparable to that of RT for the remaining three programs. An almost identical pattern was observed for the P-measure. Furthermore, the selection overhead of *ARTsum* was quite close to that of RT, and far lower than that of *ARTmif*.

We have demonstrated a feasible and computationally efficient scheme of linear order for applying ART to programs with non-numeric input types. We have shown that ART can be used to efficiently perform debug testing on several programs with non-numeric input domains. In doing so, we address the cost-effectiveness issues raised by Arcuri and Briand [3], permitting both practical use and further investigation of the behavior of FSCS-ART for programs with very low failure rates. In this study, the emphasis was on the delivery of a novel linear-order ART algorithm and the demonstration of its practicality, so the question of effectiveness with very low failure rates was not studied. Obviously, further work is now called for to examine this question. There is much scope for more advanced distance measures to take better account of more information about the characteristics of the software under test, to better predict similarity in failure behavior of inputs. Within the general paradigm of categories and choices, there are many potential refinements that could be attempted, such as finer granularity of the distance measure, various weighting schemes for categories and choices, etc. We believe that finding appropriate distance measures for specific domains will prompt much future research.

REFERENCES

[1] V. D. Agrawal, "When to use random testing," *IEEE Trans. Comput.*, vol. 27, no. 11, pp. 1054–1055, Nov. 1978.

[2] P. E. Ammann and J. C. Knight, "Data diversity: An approach to software fault tolerance," *IEEE Trans. Comput.*, vol. 37, no. 4, pp. 418–425, Apr. 1988.

[3] A. Arcuri and L. Briand, "Adaptive random testing: An illusion of effectiveness?" in *Proc. 20th Int. Symp. Softw. Testing Anal.*, 2011, pp. 265–275.

[4] A. Arcuri, M. Z. Iqbal, and L. Briand, "Black-box system testing of real-time embedded systems using random and search-based testing," in *Proc. 22nd IFIP WG 6.1 Int. Conf. Testing Softw. Syst.*, 2010, pp. 95–110.

[5] A. Arcuri, M. Z. Iqbal, and L. Briand, "Random testing: Theoretical results and practical implications," *IEEE Trans. Softw. Eng.*, vol. 38, no. 2, pp. 258–277, Mar./Apr. 2012.

[6] K.-P. Chan, T. Y. Chen, and D. Towey, "Forgetting test cases," in *Proc. 30th Annu. Int. Comput. Softw. Appl. Conf.*, 2006, pp. 485–494.

[7] T. Y. Chen, F.-C. Kuo, and R. Merkel, "On the statistical properties of testing effectiveness measures," *J. Syst. Softw.*, vol. 79, no. 5, pp. 591–601, 2006.

[8] T. Y. Chen, F.-C. Kuo, R. Merkel, and S. P. Ng, "Mirror adaptive random testing," *Inform. Softw. Technol.*, vol. 46, no. 15, pp. 1001–1010, 2004.

[9] T. Y. Chen, H. Leung, and I. K. Mak, "Adaptive random testing," in *Proc. 9th Asian Comput. Sci. Conf.*, 2004, pp. 320–329.

[10] T. Y. Chen and R. Merkel, "Quasi-random testing," *IEEE Trans. Reliability*, vol. 56, no. 3, pp. 562–568, Sep. 2007.

[11] I. Ciupa, A. Leitner, M. Oriol, and B. Meyer, "ARTOO: Adaptive random testing for object-oriented software," in *Proc. 30th Int. Conf. Softw. Eng.*, 2008, pp. 71–80.

[12] M. E. Delamaro and J. C. Maldonado, "Proteum – a tool for the assessment of test adequacy for C programs," in *Proc. Conf. Performability Comput. Syst.*, 1996, pp. 79–95.

[13] H. Do, S. G. Elbaum, and G. Rothermel, "Supporting controlled experimentation with testing techniques: An infrastructure and its potential impact," *Empirical Softw. Eng.: Int. J.*, vol. 10, no. 4, pp. 405–435, 2005.

[14] M. Friedman, "The use of ranks to avoid the assumption of normality implicit in the analysis of variance," *J. Am. Statist. Assoc.*, vol. 32, no. 200, pp. 675–701, 1937.

[15] J. D. Golic, "New methods for digital generation and postprocessing of random data," *IEEE Trans. Comput.*, vol. 55, no. 10, pp. 1217–1229, Oct. 2006.

[16] F. J. Gravetter and L. B. Wallnau., *Statistics for the Behavioral Sciences*. St. Paul, MN, USA: West, 1996.

[17] A. Groce, G. J. Holzmann, and R. Joshi, "Randomized differential testing as a prelude to formal verification," in *Proc. 29th Int. Conf. Softw. Eng.*, 2007, pp. 621–631.

[18] H. Hemmati, A. Arcuri, and L. Briand, "Achieving scalable model-based testing through test case diversity," *ACM Trans. Softw. Eng. Methodol.*, vol. 22, no. 1, pp. 6:1–6:42, 2012.

[19] S. Holm, "A simple sequentially rejective multiple test procedure," *Scandinavian J. Statist.*, vol. 6, pp. 65–70, 1979.

[20] F.-C. Kuo, "On Adaptive Random Testing". PhD thesis, Faculty of Information and Communication Technologies, Swinburne Univ. Technology, Hawthorn, Australia, 2006.

[21] Y. Liu and H. Zhu, "An experimental evaluation of the reliability of adaptive random testing methods," in *Proc. 2nd Int. Conf. Secure Syst. Integration Reliability Improvement*, 2008, pp. 24–31.

[22] R. Merkel. "Analysis and Enhancements of Adaptive Random Testing". PhD thesis, School of Information Technology, Swinburne Univ. Technology, Hawthorn, Australia, 2005.

[23] C. Nie and H. Leung, "A survey of combinatorial testing," *ACM Comput. Surveys*, vol. 43, no. 2, pp. 11:1–11:29, 2011.

[24] T. J. Ostrand and M. J. Balcer, "The category-partition method for specifying and generating functional tests," *Commun. ACM*, vol. 31, no. 6, pp. 676–686, 1988.

[25] A. Shahbazi, A. F. Tappenden, and J. Miller, "Centroidal Voronoi tessellations—a new approach to random testing," *IEEE Trans. Softw. Eng.*, vol. 39, no. 2, pp. 163–183, Feb. 2013.

[26] The GNU Project. Grep home page [Online]. Available: http://www.gnu.org/software/grep

[27] L. J. White and E. I. Cohen, "A domain strategy for computer program testing," *IEEE Trans. Softw. Eng.*, vol. 6, no. 3, pp. 247–257, May 1980.

[28] F. Wilcoxon,"Individual comparisons by ranking methods," *Biometrics Bull.*, vol. 1, no. 6, pp. 80–83, 1945.

[29] W. E. Wong, J. R. Horgan, S. London, and A. P. Mathur, "Effect of test set minimization on fault detection effectiveness," *Softw.: Practice Exp.*, vol. 28, no. 4, pp. 347–369, 1998.

[30] B. Zhou, H. Okamura, and T. Dohi, "Enhancing performance of random testing through Markov chain Monte Carlo methods," *IEEE Trans. Comput.*, vol. 62, no. 1, pp. 186–192, Jan. 2013.

Arlinta C. Barus received the bachelor's degree in informatics engineering from the Bandung Institute of Technology, Indonesia, the master's degree in information communication and technology from the University of Wollongong, and the PhD degree from the Swinburne University of Technology. She is a lecturer at the Del Institute of Technology, Indonesia. Her current research interest is mainly in software testing.

Tsong Yueh Chen received the BSc and MPhil degrees from the University of Hong Kong, the MSc and DIC degrees from the Imperial College of Science and Technology, and the PhD degree in computer science from the University of Melbourne. He is a professor at the Swinburne University of Technology. He taught at The University of Hong Kong and the University of Melbourne. His main research interest is on software testing. He is a member of the IEEE.

Fei-Ching Kuo received the bachelor of science honors degree in computer science and the PhD degree in software engineering, both from the Swinburne University of Technology, Australia. She is a senior lecturer at the Swinburne University of Technology, Australia. She was a lecturer at the University of Wollongong, Australia. Her current research interests include software analysis, testing, and debugging. She is a member of the IEEE.

Huai Liu received the BEng and MEng degrees both from Nankai University, China, and the PhD degree in software engineering from the Swinburne University of Technology, Australia. He is a research fellow at the Australia-India Research Centre for Automation Software Engineering, RMIT University, Australia. His current research interests include software testing, cloud computing, and end-user software engineering. He is a member of the IEEE.

Robert Merkel received the PhD degree from the Swinburne University of Technology. He is a lecturer at Monash University, Melbourne, Australia. His research interests include software testing and software reliability.

Gregg Rothermel received the PhD degree in computer science from Clemson University. He is a professor and Jensen chair of software engineering at the University of Nebraska-Lincoln. His research interests include software engineering and program analysis, with emphases on the application of program analysis techniques to problems in software maintenance and testing, end-user software engineering, and empirical studies. He is a member of the IEEE.

▷ **For more information on this or any other computing topic, please visit our Digital Library at** www.computer.org/publications/dlib.