Finding the Effectiveness of ADFD and ADFD+

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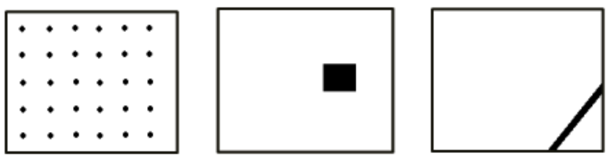
Abstract. The achievement of up-to 50% better results by Adaptive Random Testing (ART) verses Random Testing (RT) ensures that the pass and fail domains in the input domain are useful and need due consideration during selection of test inputs. The Automated Discovery of Failure Domain (ADFD) and its successor Automated Discovery of Failure Domain+ (ADFD+) techniques, automatically find failures and their domains in a specified range and provides their visualisation.
We performed an extensive experimental analysis of Java projects contained in Qualitas Corpus for finding the effectiveness of automated techniques (ADFD and ADFD+). The results obtained were analysed and cross-checked using manual testing. The impact of nature, location, size, type and complexity of failure-domains on the testing techniques were studied. The results provide insights into the effectiveness of automated techniques and a number of lessons for testing researchers and practitioners.

Keywords: software testing, automated random testing, manual testing, ADFD, Daikon

1 Introduction

The input-domain of a given SUT can be divided into two sub-domains. The pass-domain comprises of the values for which the software behaves correctly and the failure-domain comprises of the values for which the software behaves incorrectly. Chan et al. [1] observed that input inducing failures are contiguous and form certain geometrical shapes. They divided these into point, block and strip failure-domains as shown in Figure 1. Adaptive Random Testing achieved up to 50% better performance than random testing by taking into consideration the presence of failure-domains while selecting the test input [2].



(a) Point domain (b) Block domain (c) Strip domain

Fig. 1. Failure domains across input domain [1]

The cost of software testing constitute about half of the total cost of software development. Software testing is an expensive but essential process which is particularly time consuming, laborious and error-prone when performed manually. Alternatively, automated software testing may involve higher initial cost but brings the key benefits of lower cost of production, higher productivity, maximum availability, greater reliability, better performance and ultimately proves highly beneficial for any organisation [3]. A case study conducted by Pacheco et al. reveals that the 150 hours of automated testing found more faults in complex .NET code than a test engineer finds in one year by manual testing [4].

We have developed two fully automated techniques ADFD [5] and ADFD+ [6], which effectively find failures and their domains in a specified range and also provide visualisation of the pass and fail domains. The process is accomplished in two steps. In the first step, an upgraded random testing is used to find the failure. In the second step, exhaustive testing is performed in a limited region around the detected failure in order to identify the domains. The ADFD searches in one-dimension and covers longer range than ADFD+ which is more effective in multi-dimension and covers shorter range.

Three separate tools including YETI, Daikon and JFreeChart have been used in combination to develop ADFD and ADFD+ techniques. The York Extensible Testing Infrastructure [7] is used to test the program automatically with ADFD or ADFD+ strategy. The Daikon [8] checks all test executions and automatically generates invariants to present failure-domains quantitatively. The JFreeChart [9] facilitates graphical representation of the pass and fail domains.

The rest of the paper is organized as follows: Section II presents an overview of ADFD+ technique. Section III evaluates and compares ADFD+ technique with Randoop. Section IV reveals results of the experiments. Section V discusses the results. Section VI presents the threats to validity. Section VII presents related work. Finally, Section VIII concludes the study.

2 Extension of ADFD and ADFD+ technique

The ADFD and ADFD+ techniques were extended before performing any experiments, to increase the code coverage, provide information about the identified failure and generate the invariants of the detected failure-domains. This is achieved in the following way.

1. To increase coverage, the ADFD and ADFD+ techniques were extended to support the testing of methods with byte, short, long, double and float arguments beside the int type arguments.
2. To get details of the failure identified by YETI, the test case generated by YETI is added into the GUI of ADFD and ADFD+ techniques. The test case provides the name of the failing method, the value or values causing the failure and the complete stack trace of the failure.
3. To auto-generate the invariants of a failure domain, we integrated the tool Daikon in ADFD and ADFD+. Daikon is an automated invariant detector

that detect likely invariants in a program [8]. The generated invariants are displayed in the GUI of ADFD and ADFD+ after the test is finished.

3 Example to explain ADFD and ADFD+ techniques

To illustrate the difference between the working of ADFD and ADFD+ techniques, we take a simple Java program and test it with the two techniques. It has only one method which receives two integer data types as arguments. It is evident from the program code that an *ArithmeticException* (divison by zero) failure is generated when the value of variable $x\ is\ one\ of\ \{4, 5, 6, 7, 8\}$ and the corresponding value of $y\ is\ one\ of\ \{2, 3, 4\}$. The values form a block failure-domain in the input domain.

```
/**
* A program with block failure-domain.
* @author (Mian and Manuel)
*/
public class BlockErrorPlotTwoShort {
    public static void blockErrorPlot (int x, int y){
        int z;
        if ((x >= 4) && (x <= 8) && (y == 2))
            { z = 50/0;}
        if ((x >= 5) && (x <= 8) && (y == 3))
            { z = 50/0;}
        if ((x >= 6) && (x <= 8) && (y == 4))
            { z = 50/0;}
    }
}
```

The test output generated by ADFD+ technique is presented in Figure 2. The labelled graph correctly shows all the failing values in red whereas the passing values are shown in blue. The invariants are correct indicating that failing values. The test case shows the type of failure, the values causing the first failure and the stack trace of the failure.

The test output generated by ADFD technique is presented in Figure 3. The labelled graph shows the correct failing values, however, it scans only in one-dimension therefore both the graph and the invariants failed to identify one of the failing values i.e. when the values of variable $x = 4$.

Having said this both have their advantages and disadvantage. The ADFD+ uses more resources and not feasible for large range. The ADFD uses very less resources as compared to ADFD and can easily cover long ranges around the failure. It may also be mentioned that both the techniques perform equally well for one-dimensional programs.

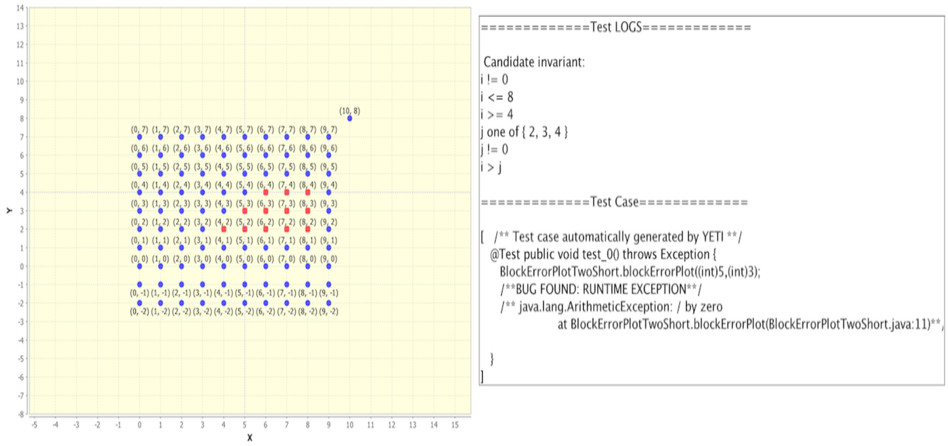


Fig. 2. Graph, Invariants and Test case generated by ADFD+

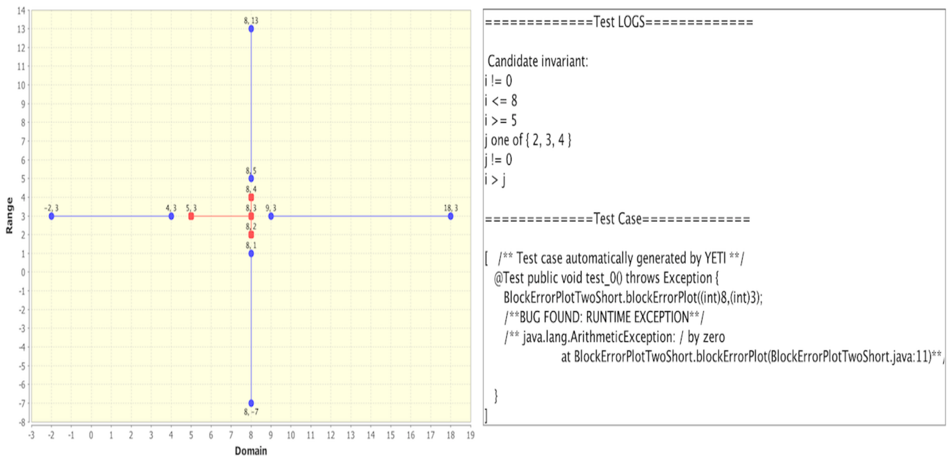


Fig. 3. Graph, Invariants and test case generated by ADFD

4 Evaluation

To evaluate the presence, nature and type of failure-domains in production software we tested the main ".jar" files of all the 106 projects in Qualitas Corpus []. The source code of the programs containing failure-domains were also evaluated manually to verify the conformance of automated results. Only one and two dimensional numerical programs were selected for evaluation. Every program was tested independently by ADFD, ADFD+ and manual testing. All the programs in which failure-domains were identified are presented in Table ??. Due to the absence of contracts and assertions in the code under test, undeclared exceptions were taken as failures in accordance with the previous studies [5, ?].

4.1 Research questions

The following research questions have been addressed in the study:

1. *If ADFD and ADFD+ techniques capable of correctly identifying and presenting the failure-domains in production software?*
2. *What are the types and frequency of identified failure-domains?*
3. *If the nature of identified failure-domains is simple or complex and does it make any difference in its identification by manual and automated techniques?*
4. *If obtained results consistent with previous theoretical and practical results presented?*

5 Experimental setup

We tested all the 4500 classes included in the main jar files of each of the 106 open-source packages contained in Qualitas Corpus [11] using ADFD and ADFD+ technique. The Qualitas Corpus is selected for two reasons: (1) It is a database of open-source Java programs that spans across the whole set of Java applications. (2) It is specially built for empirical research which takes into account a large number of developmental models and programming styles. Each test on average took 40 seconds to complete. The YETI ran for 5 seconds while the remaining time is used for finding failure-domains, generating invariants and drawing graph. The machine took approximately 100 hours to process the experiments. Only the failing one and two dimensional methods with arguments (int, long, float, double and short) were taken in to consideration. This is because at the moment ADFD and ADFD+ are not capable of drawing/handling more than two dimensions. All experiments were conducted with a 64-bit Mac OS X Mountain lion version 10.8.5 running on 2.7 GHz Intel Core i7 with 16 GB (1600 MHz DDR3) of RAM. YETI runs on top of the Java^{TM}SE Runtime Environment [version 1.7.0_45]. The ADFD and ADFD+ executable files are available at `https://code.google.com/p/yeti-test/downloads/list/`.

6 Results

We found 57 faulty classes spread across 25 different packages. Results of the experiments are given in Table 1, 2, 3 and 4. All those failure-domains were declared as strip failure-domains in which 100 or more contagious failures were discovered. Accordingly, in 48 out of 57 classes strip failure-domain is detected as shown in Table 1. The failure-domains in which 10 or more contagious failures were discovered. The failure-domains in which 5 or less contagious failures were discovered are termed as point failure-domains.There are 4 classes which contain point failure-domain as shown in Table 2. The 2 classes contain block failure domain as shown in Table 3. The 2 classes contain two types of failure-domains i.e. AnnotationValue with both point and block failure-domain and Token with point and Strip failure-domain as shown in Table 4.

The source code of all the 57 classes were analysed manually.

7 Threats to validity

As in the case of any experimental study, the results are considered conclusive only if the programs tested represent general behaviour. We have tried to minimize this threat by choosing all the classes from all the projects included in the purpose built repository of Qualitas Corpus.

YETI with ADFD and ADFD+ strategies selected is executed only for 5 seconds to find a failure in the SUT. Since both the test strategies are based on random+ strategies which have high precedence for boundary values therefore most of the failures detected are boundary failures. Despite the fact that the failure-domains remained the same for a specific failure detected, It is likely possible that increasing the test duration may lead to the discovery of new failures exhibiting different behaviour.

Another threat to validity may be related to hardware and software resources. For example the OutOfMemoryError occured at the value of 6980000 on the machine executing the test. On another machine the failure revealing value can increase or decrease depending on the hardware specifications and system load.

8 Related Work

9 Conclusion

10 Future Work

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11 The References Section

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S#	Class	Method	ADFD+	ADFD	Manual
1	LeadPipeInputStream	LeadPipeInputStream(i)	I >= 2147483140 I <= 2147483647	I	I > 698000000
2	BitSet	BitSet.of(i,j)	I <= -1, I >= -18, J <= 7, J >= -12	I one of {-513, -1} J one of {-503, 507}	I <= -1 J != 0
3	ToolPallete	ToolPalette(i,j)	I <= -1, I >= -18	I one of { -515, -1} J one of {-509, 501}	I <= -1, J any value
4	IntMap	idMap(i)	I <= -1, I >= -18	I one of {-1, -512}	I <= -1
5	ExpressionFactory	expressionOfType(i)	I <= 13, I >= -7	I one of {-497, 513}	I >= -2147483648 I <= 2147483647
6	ArrayStack	ArrayStack(i)	I >= 2147483636 I <= 2147483647	I one of {2147483142, 2147483647}	I > 698000000
7	BinaryHeap	BinaryHeap(i)	I <= -2147483637 I >= -2147483648	I one of {-2147483648, -2147483142}	I <= 0
8	BondedFifoBuffer	BoundedFifoBuffer(i)	I <= -2147483639 I >= -2147483648	I one of {-505, 0}	I <= 0
9	FastArrayList	FastArrayList(i)	I <= -2147483641 I >= -2147483648	I one of {-2147483644, -2147483139}	I <= -1
10	StaticBucketMap	StaticBucketMap(i)	I >= 2147483635 I <= 2147483647	I one of {2147483140, 2147483647}	I > 698000000
11	PriorityBuffer	PriorityBuffer(i)	I <= -1, I >= -14	I one of {-2147483647, -2147483142}	I <= 0
12	GenericPermuting	permutation(i,j)	I <= 0, I >= -18	I one of { -498, 0} I one of {2, 512}	I <= 0, I >= 2 J != 0
13	LongArrayList	LongArrayList(i)	I <= -2147483640 I >= -2147483648	I one of {-510, -1}	I <= -1
14	OpenIntDoubleHashMap	OpenIntDoubleHashMap(i)	I <= -1, I >= -17	I one of {-514, -1}	I <= -1
15	ByteVector	ByteVector(i)	I <= -2147483639 I >= -2147483648	I one of {-2147483648, -2147483141}	I <= -1
16	ElementFactory	newConstantCollection(i)	I >= 2147483636 I <= 2147483647	I one of {2147483141, 2147483647}	I > 698000000
17	IntIntMap	IntIntMap(i)	I <= -2147483638 I >= -2147483648	I one of {-2147483644, -2147483139}	I <= -1
18	ObjectIntMap	ObjectIntMap(i)	I >= 2147483640 I <= 2147483647	I one of {2147483591, 2147483647}	I > 698000000
	IntObjectMap	IntObjectMap(i)	I <= -1, I >= -17	I <= -1, I >= -518	I <= -1
19	ArchiveUtils	padTo(i,j)	I >= 2147483641 I <= 2147483647	I one of {-497, 513} J one of {2147483591, 2147483647}	I any value J > 698000000
20	BloomFilter32bit	BloomFilter32bit(i,j)	I <= -1 I >= -18	I one of {-515, -1} J may be any value	I <-1 J <-1
21	IntKeyLongValueHashMap	IntKeyLongValueHashMap(i)	I >= 2147483635 I <= 2147483647	I one of {2147483590, 2147483647} I >= -518	I > 698000000
22	ObjectCacheHashMap	ObjectCacheHashMap(i)	I <= -2147483641 I >= -2147483648	I one of {-512, 0}	I <= 0
23	ObjToIntMap	ObjToIntMap(i)	I <= -2147483636 I >= -2147483648	I one of {-2147483646, -2147483137}	I <= -1
24	PRTokeniser	isDelimiterWhitespace(i)	I <= -2 I >= -18	I one of {-509, -2} I one of {256, 501}	I <= -2 I >= 256
25	PdfAction	PdfAction(i)	I <= -2147483640 I >= -2147483648	I one of {-514, 0} I one of {6, 496}	I <= 0 I >= 6
26	PdfLiteral	PdfLiteral(i)	I <= -1, I >= -14	I one of {-511, -1}	I <= -1
27	PhysicalEnvironment	PhysicalEnvironment(i)	I <= -1, I >= -11	I one of {-2147483646, -2147483137}	I <= -1
28	IntegerArray	IntegerArray(i)	I >= 2147483636 I <= 2147483647	I one of {2147483587, 2147483647}	I > 698000000
29	AttributeMap	AttributeMap(i)	I <= -2147483639 I >= -2147483648	I one of {-514, 0}	I <= 0
30	ByteList	ByteList(i)	I <= -1, I >= -14	I one of {-513, -1}	I <= -1
31	WeakIdentityHashMap	WeakIdentityHashMap(i)	I >= 2147483636 I <= 2147483647	I one of {2147483140, 2147483647}	I >698000000
32	AmmoType	getMunitionsFor(i)	I <= -1 I >= -17	I one of {-514, -1} I one of {93, 496}	I <= -1 I >= 93
33	IntList	IntList(i,j)	I <= -1 I >= -15	I one of {-1, -509} j one of 0	I <= -1 j = 0
34	QMC	halton(i,j)	I <= -1, I >= -12 J <= -1, J >= -15	I <= -1, I >= -508 j <= 499, j >= -511	I <= -1 J any value
35	BenchmarkFramework	BenchmarkFramework(i,j)	I <= -1, I >= -13	I one of {-501, -1}	I <= -1
36	IntArray	IntArray(i)	I <= -1, I >= -16	I one of {-2147483650, -2147483141}	I <= -1
37	TDoubleStack	TDoubleStack(i)	I <= -1, I >= -13	I one of {-511, -1}	I <= -1
38	TIntStack	TIntStack(i)	I <= -1, I >= -12	I one of {-2147483648, -2147483144}	I <= -1
39	TLongArrayList	TLongArrayList(i)	I <= -1, I >= -16	I one of {-2147483648, -2147483141}	I <= -1
40	AlgVector	AlgVector(i)	I <= -1, I >= -15	I one of {-511, -1}	I <= -1
41	BinarySparseInstance	BinarySparseInstance(i)	I <= -1, I >= -15	I one of {-506, -1}	I <= -1
42	SoftReferenceSymbolTable	SoftReferenceSymbolTable(i)	I >= 2147483635 I <= 2147483647	I one of {2147483140, 2147483647}	I > 698000000
43	SymbolHash	SymbolHash(i)	I <= -1, I >= -16	I one of {-2147483648, -2147483592}	I <= -1
44	SynchronizedSymbolTable	SynchronizedSymbolTable(i)	I <= -2147483140 I >= -2147483648	I one of {-2147483648, -2147483592}	I <= -1
45	XMLChar	isSpace(i)	I <= -1, I >= -12	I one of {-510, -1}	I <= -1
46	XMLGrammarPoolImpl	XMLGrammarPoolImpl(i)	I <= -1, I >= -13	I one of {-2147483648, -2147483137}	I <= -1
47	XML11Char	isXML11NCNameStart(i)	I <= -1, I >= -16	I one of { -512, -1}	I <= -1
48	AttributeList	AttributeList(i)	I >= 2147483635 I <= 2147483647	I one of {2147483590, 2147483647}	I > 698000000

Table 1. classes with strip failure-domains

S#	Class	Method	ADFD+	ADFD	Manual
1	Assert	assertEquals(i,j)	I != J	I != J	I != J
2	Board	getTypeName(i)	I <= -1 I >= -18	I >= -504, I <= -405, I >= -403 I <= -304, I >= -302, I <= -203 I >= -201, I <= -102, I >= -100 I <= -1	I <= -910, I >= -908, I <= -809, I >= -807, I <= -708, I >= -706, I <= -607, I >= -605, I <= -506, I >= -504, I <= -405, I >= -403, I <= -304, I >= -302, I <= -203, I >= -201, I <= -102, I >= -100, I <= -1
3	HTMLEntities	get(i)	I <=- 1 I >= -17	I >= -504, I <= -405, I >= -403 I <= -304, I >= -302, I <= -203 I >= -201, I <= -102, I >= -100 I <= -1	I <= -910, I >= -908, I >= -807, I <= -708, I >= -706, I <= -809, I <= -607, I >= -605, I <= -506, I >= -504, I <= -405, I >= -403, I <= -304, I >= -302, I <= -203, I >= -201, I <= -102, I >= -100, I <= -1
4	Assert	assertEquals(i,j)	I <= 0, I >= 20 J <= 18, j >= -2	I one of {-2147483648, -2147483142} J one of {-501, 509}	I != J

Table 2. Classes with point failure-domains

S#	Class	Method	ADFD+	ADFD	Manual
1	AnnotationValue	whatKindIsThis(i)	I <= 85, I >= 92, I >= 98 I = 100, I >= 102, I <= 104	I ¡= 63, I = {65, 69, 71, 72} I >= 75, I ¡= 82, I >= 84 I <= 89, I >= 92, I ¡= 98 I = 100, I >= 102, I <= 114 I >= 116	I <= 63, I = 65, 69, 71, 72 I >= 75, I <= 82, I >= 84 I <= 89, I >= 92, I <= 98 I = 100, I >= 102, I <= 114 I >= 116
2	Token	typeToName(i)	I <= -2147483641 I >= -2147483648	I one of {-510, -2} I = {73, 156} I one of {162, 500}	I <= -2, I = 73, 156, I >= 162

Table 3. Classes with block failure-domains

S#	Class	Method	ADFD	ADFD+	Manual
1	ClassLoaderResolver	getCallerClass(i)	I >= 2, I <= 18	I >= 500, I <= -2 I >= 2, I <= 505	I <= -2, I >= 2
2	Variant	getVariantLength(i)	I >=0, I <= 12	I >= 0, I <= 14, I >= 16 I <= 31, I >= 64, I <= 72	I >= 0, I <= 14, I >= 16 I <= 31, I >= 64, I <= 72

Table 4. Classes with mix failure-domains