

Finding the Effectiveness of ADFD and ADFD+

Mian Asbat Ahmad and Manuel Oriol

University of York, Department of Computer Science,
Deramore Lane, YO10 5GH YORK, United Kingdom

Abstract. The achievement of up-to 50% better results by Adaptive Random Testing (ART) versus 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].

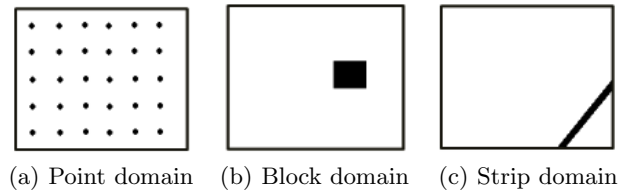


Fig. 1. Failure domains across input domain [1]

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 Enhancement of the techniques

Prior to conducting the experiments for comparative evaluation, the ADFD and ADFD+ techniques were enhanced to increase the code coverage, provide information about the identified failure and generate invariants of the detected failure-domains as stated below.

1. Code coverage was increased by extending the techniques to support the testing of methods with byte, short, long, double and float arguments while it was restricted to int type arguments only in the original techniques.
2. Additional information was facilitated by adding the YETI generated test case to the GUI of the two techniques. Test case includes the name of the failing method, values that caused the failure and stack trace of the failure.
3. Invariants of the detected failure-domains were automatically generated by integrating the tool Daikon in the two techniques. Daikon is an automated

invariant detector that detects likely invariants in the program [8]. The generated invariants are displayed in the GUI of the techniques after completion of the test.

3 Difference in working mechanism of the two techniques

The difference with respect to the identification of failure-domains is illustrated by testing a simple Java program (given below) with ADFD and ADFD+ techniques.

```
/**
 * 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;}
    }
}
```

As evident from the program code that an *ArithmeticException* failure (division by zero) is generated when the value of variable x one of {4, 5, 6, 7, 8} and the corresponding value of variable y one of {2, 3, 4}. The values form a block failure-domain in the input domain.

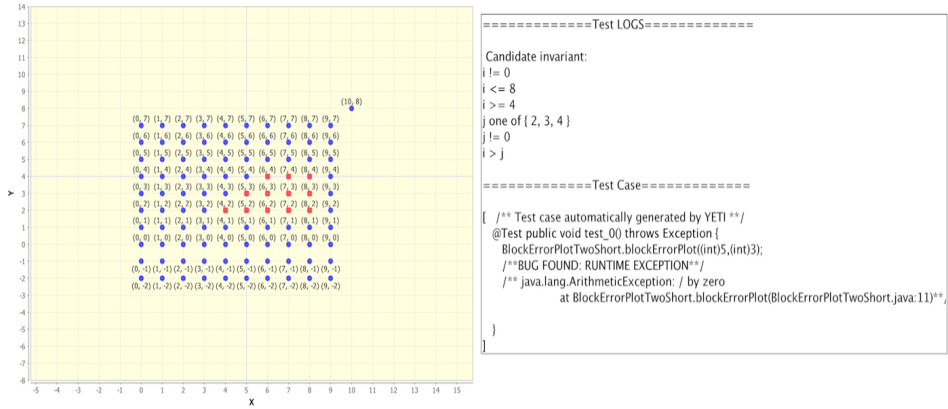


Fig. 2. Graph, Invariants and Test case generated by ADFD+

The test output generated by ADFD+ technique is presented in Figure 2. The labelled graph correctly shows all the 12/12 available failing values in red whereas the passing values are shown in blue. The invariants correctly represent the failure-domain. The test case shows the type of failure, the values causing the first failure and the stack trace of the failure.

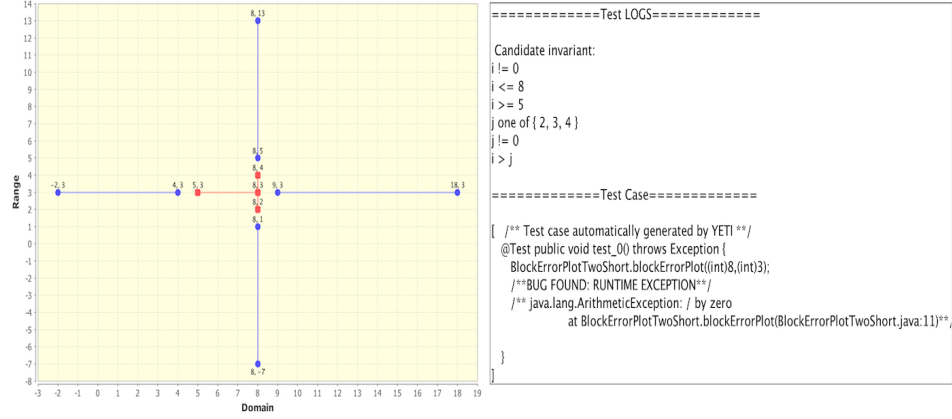


Fig. 3. Graph, Invariants and test case generated by ADFD

The test output generated by ADFD technique is presented in Figure 3. The labelled graph correctly shows the 4/12 available failing values in red whereas the passing values are shown in blue. The invariants identify all but one failing values ($x = 4$). This is due to the fact that ADFD scans the values in one dimension around the failure. The test case shows the type of failure, the values causing the first failure and the stack trace of the failure.

The comparative results derived from the execution of the two techniques on the selected program indicate that ADFD+ is more efficient than ADFD in identification of failures in two dimensional program. ADFD and ADFD+ performs equally well in one-dimensional program but ADFD covers more range around the first failure than ADFD+ and is comparatively economical because it uses less resources than ADFD+.

3.1 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 influence in identification by automated and manual techniques?
4. What is the external validity of the obtained results?

4 Evaluation

The effectiveness of ADFD and ADFD+ techniques in identifying failure-domains and the impact of nature, location, size, type and complexity of failure-domains on the testing techniques were experimentally evaluated.

4.1 Experiments

In the experiments we tested 4500 classes selected from all the packages contained in Qualitas Corpus. The Qualitas Corpus is selected for three 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. (3) All the packages are open-source and their code is easily accessible.

The main “.jar” file of each project was extracted to get the “.class” files because YETI tests only the byte code. Each class was tested separately by ADFD and ADFD+ techniques. Each test on average took 40 seconds to complete. The YETI ran for 5 seconds while the remaining time was used for finding failure-domains, drawing graph and generating invariants. 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 dimensional programs. 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][10]. The source code of the programs containing failure-domains were also evaluated manually to verify the results of automated techniques. 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 JavaTMSE 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/>.

4.2 Results

We found 57 classes with various failure-domains from 25 different packages. Results are split into four tables (Table 1, 2, 3, 4) on the basis of the existence of failure-domain type. The tables include detail of the name of failing class and method and the invariants calculated automatically and manually.

The failure-domains were declared as strip failure-domains if 50 or more contagious failures were detected. Accordingly, in 48 out of 57 classes strip failure-domains were detected as shown in Table 1.

The failure-domains were declared as point failure-domains if more than 1 and less than 5 contagious failures were detected. Accordingly, in 4 out of 57 classes point failure-domains were detected as shown in Table 2.

The failure-domains were declared as block failure-domains if more than 5 and less than 50 contagious failures were detected. Accordingly, in 2 out of 57 classes block failure-domains were detected as shown in Table 3.

The remaining 2 classes contained two types of failure-domains i.e one containing both point and block failure-domain and the other containing point and Strip failure-domain as shown in Table 4.

5 Discussion

5.1 Effectiveness of ADFD and ADFD+ techniques

5.2 Type and Frequency of Failure-domains

5.3 Nature of failure-domains

5.4 External validity of Results

6 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 occurred 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.

7 Related Work

8 Conclusion

9 Future Work

Acknowledgments. The authors are thankful to the Department of Computer Science, University of York for physical and financial support. Thanks are also extended to Prof. Richard Paige for his valuable guidance, help and generous support.

10 The References Section

1. Chan, F., Chen, T.Y., Mak, I., Yu, Y.T.: Proportional sampling strategy: guidelines for software testing practitioners. *Information and Software Technology* **38**(12) (1996) 775–782
2. Chen, T.Y.: Adaptive random testing. *Eighth International Conference on Quality Software* **0** (2008) 443
3. Beizer, B.: *Software testing techniques* (2nd ed.). Van Nostrand Reinhold Co., New York, NY, USA (1990)
4. Pacheco, C., Lahiri, S.K., Ball, T.: Finding errors in. net with feedback-directed random testing. In: *Proceedings of the 2008 international symposium on Software testing and analysis*, ACM (2008) 87–96
5. Ahmad, M.A., Oriol, M.: Automated discovery of failure domain. *Lecture Notes on Software Engineering* **02**(4) (2014) 331–336
6. Ahmad, M.A., Oriol, M.: Automated discovery of failure domain. *Lecture Notes on Software Engineering* **03**(1) (2013) 289–294
7. Oriol, M.: *York extensible testing infrastructure* (2011)
8. Ernst, M.D., Perkins, J.H., Guo, P.J., McCamant, S., Pacheco, C., Tschantz, M.S., Xiao, C.: The daikon system for dynamic detection of likely invariants. *Science of Computer Programming* **69**(1) (2007) 35–45
9. Gilbert, D.: The jfreechart class library version 1.0. 9. (2008)
10. Oriol, M.: Random testing: Evaluation of a law describing the number of faults found. In: *Software Testing, Verification and Validation (ICST)*, 2012 IEEE Fifth International Conference on, IEEE (2012) 201–210

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	ToolPalette	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
19	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 > 698000000
22	ObjectCacheHashMap	ObjectCacheHashMap(i)	I <= -2147483641 I >= -2147483648	I >= -518 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	j <= -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 j= 63, I = {65, 69, 71, 72} I >= 75, I j= 82, I >= 84 I <= 89, I >= 92, I j= 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