DMMPP: Constructing Dummy Main Methods for Android Apps with Path-Sensitive Predicates

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Abstract

Android is based on an event-driven model, which hides the main method, and is driven by the lifecycle methods and listeners from user interaction. `FlowDroid`, constructs a dummy main method statically emulating the lifecycle methods. The dummy main method has been widely used by `FlowDroid` and also other Android analyzers as their entry points. However, the existing dummy main method is not designed for path-sensitive analysis, whose paths may be unsatisfiable. Thus, when using original dummy main methods, path-sensitive analysis, e.g., symbolic execution, may suffer from infeasible paths. In this paper, we present `DMMPP`, the first dummy main method generator for Android applications with path-sensitive predicates, and the corresponding path condition is satisfiable. `DMMPP` constructs dummy main methods for the four types of components in an application with a more realistic simulation for the lifecycle methods. The experiment demonstrates the benefits of our tool for path-sensitive analyzers, improving 28.5 times more explored paths with a low time overhead.

CCS Concepts

• **Theory of computation → Program analysis**.

Keywords

Android, Dummy Main, Entry Point, Predicate, Path-sensitive

ACM Reference Format:

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1 Introduction

Over the past decade, Android smart devices have become an indispensable part of our lives. The Android system and its applications are widely used in smartphones, tablets, TVs, robots, cars and other devices due to its open source nature, rich application ecosystem, hardware compatibility and user customizability.

In recent years, researchers have conducted extensive and in-depth research on Android applications in various aspects. Unlike Java programs, an Android application does not have a main method, and the application is driven by various events, such as lifecycle methods and callbacks of user operations, from the Android operating system and framework. `FlowDroid`, a precise context, flow, field, object-sensitive and lifecycle-aware taint analysis framework for Android apps [3], constructs a dummy main method as the entry point for analysis, providing infrastructure for many works [17]. The dummy main method simulates multiple entry points statically, such as Activity, Service, BroadcastReceiver, ContentProvider and Fragment, asynchronously executing components and callbacks from user operations.

Since `FlowDroid` uses the IFDS algorithm, a path-insensitive approach, the dummy main method generated by `FlowDroid` does not consider whether the path condition is satisfied. However, for path-sensitive analysis [12, 16], it can affect the analysis accuracy, resulting in false positives and false negatives. For example, predicates generated by `FlowDroid` for a dummy main method are $p_1(i == 0), p_2(i == 1)$, and $p_3(i == 2)$, whose satisfiability depends on the same variable i, which is path-insensitive. When a path condition in the method is $p_1 \wedge p_2 \wedge p_3$, it is obviously unsatisfiable, causing the lifecycle method unreachable.

In this paper, we propose `DMMPP` to construct the dummy main method for Android applications with path-sensitive predicates, which can form a satisfiable path condition. It takes an APK and the lifecycle specifications of components as inputs, built on the top of `FlowDroid`. It models the lifecycle of components with a unified lifecycle graph. For each component, `DMMPP` constructs the dummy main method with path-sensitive predicates after the lifecycle method complementing, according to its lifecycle graph, the instrumentation syntax and the generation algorithm. `DMMPP` can be used by analyzers with both path-sensitive approaches and path-insensitive ones, intrusively via an API invocation or non-intrusively via the APK output after a command line call.

2 Background

We will introduce the dummy main method and use an example to show the path-insensitive predicates generated by `FlowDroid` and how `DMMPP` refines the predicates for path-sensitive analyzers.

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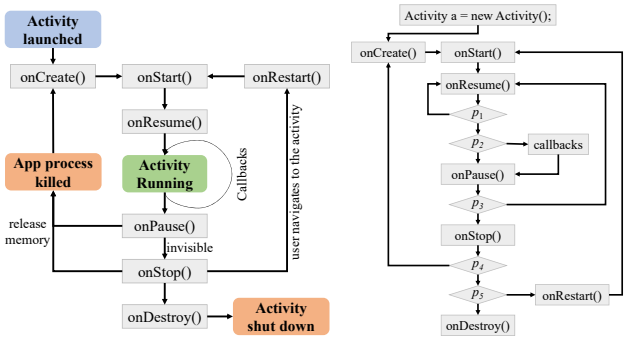

(a) Lifecycle of Activity (b) CFG for Dummy Main Method

Figure 1: Activity's Lifecycle and CFG of Its Dummy Main Method Modelled by FlowDroid

2.1 Dummy Main Method

Android is based on an event-driven model, which hides the main method, and is driven by the lifecycle methods and listeners from user interaction. FlowDroid statically models the lifecycle of the component in the Android framework with the dummy main method as the entry point for its taint analysis and also for other analyzers. Figure 1 shows the lifecycle of an Activity and the control flow graph (CFG) of its dummy main method modelled by FlowDroid. During the construction of the dummy main method, FlowDroid proposes opaque predicates to represent the branches in the method, denoted as p_i, where $i \in \{1,2,3,4,5\}$.

2.2 Motivating Example

The opaque predicate, p_i, represents whether the integer variable *intCounterVar* equals to an integer *conditionCounter*. Each time an opaque predicate is inserted by FlowDroid, the *conditionCounter* is incremented by 1, *i.e.*, *conditionCounter*++ [1]. Figure 2 shows the simplified code snippet with predicates in the dummy main method generated by FlowDroid (lines 2-8), which is path-insensitive. All predicates share a single variable i, then a path condition consisting of them will be unsatisfiable. When collecting a path with the constraint, $p_1(i == 0) \wedge p_2(i == 1) \wedge p_3(i == 2)$, a path-sensitive analyzer will discard this path since the constraint is unsatisfiable. This modelling is invalid for the path-sensitive analysis since lifecycle methods are reachable definitely.

```
1  // Path-insensitive Predicates modelled by FlowDroid
2  void dummyMain(){
3      int i = 0;
4      if(i == 0){ // p1 : i == 0
5          if(i == 1){ // p2 : i == 1
6              if(i == 2){ // p3 : i == 2
7                  ...
8  }}}}
9  // Path-sensitive Predicates
10 void dummyMain(boolean[] bArr)
11     if(bArr[0]){ // p1 : bArr[0]
12         if(bArr[1]){ // p2 : bArr[1]
13             if(bArr[2]){ // p3 : bArr[2]
14                 ...
15 }}}}
```

Figure 2: Predicates in Dummy Main Method

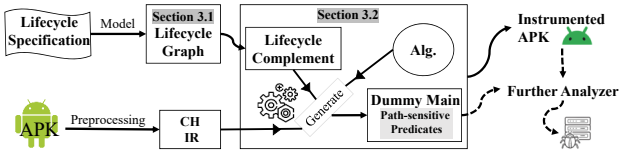

Figure 3: Overview of DMMPP

The goal of DMMPP in this paper is to construct the crystal predicates for the dummy main method to refine the path-insensitive ones introduced by FlowDroid for the path-sensitive analyzers. DMMPP uses the boolean variables from parameters representing the predicates. To reduce the number of parameters, DMMPP wraps the parameters with an array container. The dummy main method with path-sensitive predicates generated by DMMPP is shown in Figure 2 (lines 10-15). Whether the path condition, $p_1 \wedge p_2 \wedge p_3$, is satisfiable will depend on the elements in the input boolean array *bArr*. The path-sensitive predicates will navigate the path exploration in the lifecycle of a component to benefit static analysis.

3 DMMPP

Figure 3 shows the architecture of DMMPP. It is built on the top of FlowDroid and its intermediate representation (IR) Jimple, and requires an APK and the lifecycle specifications of components as inputs. It models the lifecycle of components with a unified lifecycle graph. With the IR and the class hierarchy (CH), DMMPP can recognize the components in the APK. For each component, DMMPP complements its non-explicitly inherited lifecycle method to explicitly indicate component state and constructs the dummy main method with path-sensitive predicates after the complement, according to its lifecycle graph, the syntax and the generation algorithm. A path-sensitive analyzer can use the dummy main method generated by DMMPP directly or use the APK after the persistence indirectly.

3.1 Model

For the convenience of expression, we formalize a component lifecycle graph with corresponding methods, and then show how to use it as input to generate the dummy main method with the instrumentation syntax.

Definition 3.1.1. ***Component Lifecycle Graph (CLG).*** *A component lifecycle graph is a directed graph, denoted as*

$$CLG = \langle N, E, \top, \bot \rangle$$

where

- *N is a set of nodes and a node represents a lifecycle method or a nop instruction;*
- *$E \subseteq N \times N$, E is a set of edges;*
- *$\top \in N$, $\top$ is the start node;*
- *$\bot \in N$, $\bot$ is the end node.*

We assume that CLG contains a unique $\top$ node and a unique $\bot$ node, and for any node N_i in CLG, there exist directed paths from $\top$ node to N_i and from N_i to $\bot$. We call a node a join node if it has more than one predecessor and a branch node if it has more than one successor. We also assume that a branch node has only two successors. If a lifecycle graph has a node with more than two

Name:	$\frac{A \in (a...zA...Z\$<>)*}{\textbf{name}(A)}$	**Type:**	$\frac{\textbf{name}(T)}{\textbf{type}(T)}$
Variable:	$\frac{\textbf{type}(T) \quad \textbf{name}(V)}{\textbf{var}(T, V)}$	**ArrayType:**	$\frac{\textbf{type}(T)}{\textbf{arrayType}(T)}$
Expression:	$\frac{\textbf{instruction}(E)}{\textbf{instruction}(\textbf{exp}(E))}$	**Return:**	$\frac{-}{\textbf{instruction}(\textbf{returnVoid}())}$
Program:	$\frac{\textbf{instruction}(I) \quad \textbf{program}(P)}{\textbf{program}(I,P)}$	**New:**	$\frac{\textbf{type}(T)}{\textbf{instruction}(\textbf{new}(T))}$
IfStmt:	$\frac{\textbf{exp}(E) \quad \textbf{type}(B)\ is\ boolean}{\textbf{instruction}(\textbf{ifStmt}(B,E))}$	**Goto:**	$\frac{\textbf{exp}(E)}{\textbf{instruction}(\textbf{Goto}(E))}$
Load:	$\frac{\textbf{var}(Index, ARR, Ret) \quad \textbf{ArrayType}(Arr) \quad \textbf{type}(Index)\ is\ integer}{\textbf{instruction}(\textbf{load}(Arr,Index,Ret))}$		
Class:	$\frac{\textbf{name}(Name) \quad \textbf{type}(Super) \quad \textbf{var}(Field) \quad \textbf{fun}(Sign)}{\textbf{class}(Name,Super,Field,Sign)}$		
Function:	$\frac{\textbf{name}(Sign) \quad \textbf{var}(Arg) \quad \textbf{program}(Body)}{\textbf{fun}(Sign,Arg,Body)}$		
Invocation:	$\frac{\textbf{var}(Base) \quad \textbf{name}(Sign) \quad \textbf{var}(Arg) \quad \textbf{var}(Ret)}{\textbf{instruction}(\textbf{call}(Base,Sign,Arg,Ret))}$		
InsertExpr:	$\frac{\textbf{exp}(E_1) \quad \textbf{fun}(Sign) \quad \textbf{exp}(E_2)}{\textbf{insertExpr}(Sign,E_1,[after],\textbf{site}(E_2))}$		

Figure 4: Syntax for Generation.

successors, a nop instruction node is introduced and inserted to split the node. For example, the node *onStop()* in Figure 1(a) has three successors, when constructing the CLG, it should be split with a nop instruction node to ensure that each branch node has two successors like the node *onStop()* in Figure 1(b).

3.2 Generation

With the CLG, the lifecycle of each component, such as Activity, Service, BroadcastReceiver, Content Provider and even Fragment, can be expressed uniformly. Since the lifecycle methods of a component are closely related to its state [11], and some bug detection depends on its state [6, 9, 15], if a lifecycle method is not explicitly inherited, DMMPP will complement the method with the parent method invocation, such as `void onDestroy(){super.onDestroy();}`. DMMPP obtains the components and callbacks based on FlowDroid by parsing the XML resource files from the APK.

Syntax. DMMPP uses the syntax shown in Figure 4 to process the dummy main method. For each rule in it, the part below the horizontal line is the operation command and the above one is the restriction. The basic rules, such as **Name, Type, ArrayType, Return, Program, Expression, New, Class, Function, Invocation** and **InsertExpr**, are easy to understand. DMMPP uses the instructions **IfStmt** and **Goto** to express the branch and the loop in the CLG. In particular, for the path-sensitive predicates, DMMPP needs the operation **Load** to obtain the *i*-th element of the predicate array.

Construction. With the syntax, DMMPP constructs the dummy main method for each component according to the generation algorithm shown in Algorithm 1 based on the IR Jimple. It takes a component and its CLG as inputs. Firstly, DMMPP instantiates the component, which is the caller of the lifecycle methods in the CLG (line 4). Then, it traverses the CLG in depth-first order with a stack, generating an invocation statement for each node with the lifecycle method (lines 6-20). The actual arguments required in the invocation statement are also taken from the formal parameters of the dummy main method, simplified as *getArgsFromParameters(...)* (line 14). Thirdly, DMMPP generates the branch statement and the goto statement according to the CLG and inserts them at the corresponding position (lines 24-40). For the branch statement, DMMPP loads the predicate from the parameter array with an index, which can be assigned the value true or false by a path-sensitive analyzer to

Algorithm 1: Dummy Main Method Generation

```
   Input: component, clg
1  fun ← NULL, args ← ∅, body ← ∅, node ← clg.⊤, stack ← ∅;
2  caller ← NULL, map ← ∅; // map⟨Node, Expression⟩
3  stack.push(node);
4  caller ← instruction(new(type(component)));
5  // generate method invocations
6  while stack is not empty do
7      node ← stack.pop();
8      stmt ← NULL;
9      if node is ⊥ then
10         stmt ← instruction(returnVoid);
11     else if node is not ⊤ then
12         if node.m is nop instruction then
13             stmt = instruction("nop");
14         list ← getArgsFromParameters(node.m, args);
15         stmt ← instruction(call(caller,node.m,list,NULL));
16         map.put(node, call);
17     body.add(stmt);
18     map.put(node, stmt);
19     successors ← clg.successorOf(node);
20     stack.push(successors);
21 // insert if- and goto- statements
22 predicateIndex ← 0;
23 predicates ← getPredicatesFromParameters(args);
24 for node ∈ clg.N do
25     current ← map.get(node);
26     next ← body.getNext(current);
27     if node is branch node then
28         // crystal predicate
29         load(predicates, predicateIndex, predicate);
30         predicateIndex ++;
31         for succ ∈ clg.successorOf(node) do
32             if next is not succ then
33                 next ← succ;
34         ifStmt ← instruction(ifStmt(predicate, next));
35         insertExpr(body, ifStmt, "after", current);
36     succ ← clg.successorOf(node);
37     next ← map.get(succ);
38     if current is not ⊥ ∧ next is not NULL then
39         gotoStmt ← instruction(Goto(next));
40         insertExpr(body, gotoStmt, "after", current);
41 fun ← fun("dummyMainMethod",args,body);
42 return fun;
```

control the exploration along the different branches or paths. Finally, it returns the dummy main method, which will be added into the component class as an entry method for the analyzer directly (lines 41-42). DMMPP also instruments the callbacks declared in the component into the dummy main method, such as click listeners, key event listeners and so on. In addition, DMMPP can also write the generated IR back to the APK with the support of FlowDroid as its output, benefiting the path-sensitive static analyzer indirectly.

Table 1: Benefits for Analyzer

	App	#C	Explored Paths			Construction Time (ms)		
			FL	D	Δ	FL	D	Δ
F-Droid	app.fedila	6	6	12	**+6**	235	2960	2725
	ch.bailu.a	17	17	37	**+20**	414	2,038	1,624
	com.asdoi.	6	6	12	**+6**	72	2,262	2,190
	com.gimran	13	13	30	**+17**	199	421	222
	com.mobile	14	14	153	**+139**	1,111	516	-595
	com.tuyafe	5	5	10	**+5**	30	1,724	1,694
	com.ubersp	1	1	13	**+12**	40	5	-35
	jp.takke.c	7	7	14	**+7**	42	1,932	1,890
	net.gitsai	8	8	2,104	**+2,096**	2,775	534	-2,241
	xyz.myachi	8	8	1,588	**+1,580**	6,991	2,377	-4,614
Google Play	appnewness	7	7	35	**+28**	191	554	363
	com.alb.pl	1	1	5	**+4**	12	4	-8
	com.e.ulil	5	5	10	**+5**	32	460	428
	com.pinayr	11	11	293	**+282**	2,094	187	-1,907
	f.fajrak.b	9	9	46	**+37**	278	517	239
	it.discors	9	9	49	**+40**	306	998	692
	kick.wpapp	8	8	40	**+32**	240	486	246
	kr.ieodo.a	5	5	10	**+5**	27	530	503
	net.easyjo	7	7	14	**+7**	42	1,427	1,385
	usd.aleavt	3	3	99	**+96**	459	59	-400
	Total	150	150	4,574	**+4,424**	15,590	19,991	4,401

3.3 Usage

DMMPP is open source, and its latest version and executable JAR file are publicly available [1]. There is also a video demonstrating DMMPP with the YouTube link on Github. DMMPP can be used as an API library intrusively, which will be a precursor of an Android static analyzer based on Soot/FlowDroid. It can also be used as an independent, command line tool non-intrusively to generate the dummy main method with the path-sensitive predicates and output the APK with the dummy main method, which can be used for other Android static analyzers or may be converted to a JAR file as an input of a Java static analyzer. DMMPP has been integrated into Androlic [10], which is an extensible flow, context, object, field, and path-sensitive static analysis framework for Android and DMMPP can also been used for other analyzers.

4 Evaluation

To evaluate the effectiveness of DMMPP, we randomly collect 20 real-world apps, 10 of which are from F-Droid [4] and the other 10 from Google Play [7], which is also publicly available at Github. We choose Androlic to observe the benefits brought by DMMPP, since its approach is path-sensitive. We take the dummy main method for each component generated by FlowDroid (denoted as 'FL' in Table 1) and the one generated by DMMPP (denoted as 'D') as its inputs respectively. The configuration of Androlic contains a maxLoopUnrollNumber with a value of 1 and a timeout threshold of 5 minutes. The experiment is conducted under the environment of JDK-1.8, where the operating system is Windows 11 with 4 cores (Intel (R) Core(TM) i7-10510U) and 32G RAM.

Table 1 shows the number of components (denoted as "#C"), the number of feasible paths and the construction time for dummy main methods, excluding the parsing time of the application. The symbol 'Δ' represents the increase in the number of feasible paths and the time overhead brought by DMMPP.

It can be seen that DMMPP benefits the path-sensitive analyzer with about 28.5 (4,424/150 − 1) times more feasible paths than FlowDroid from the dummy main method with a time overhead of only 4.4 seconds totally. FlowDroid contributes so few feasible paths in its dummy main method because "*We may skip the complete component*" [2],*i.e.*, `if(i==0){ return; }else{ lifecycle method invocations }`. For each component, the construction time of FlowDroid for the dummy main method is about 104 milliseconds, and DMMPP contributes an additional 28.5 (4,424/150 − 1) times feasible paths with a time consumption 29.3 milliseconds on average. DMMPP takes more time because it complements lifecycle methods and constructs a more complete dummy main method.

In summary, the evaluation demonstrates that DMMPP can benefit the path-sensitive analyzer via the dummy main method generated by it with the path-sensitive predicates, providing many feasible paths with a very low time overhead as expected.

5 Related Work

The most related work to the dummy main method generation is FlowDroid. The dummy main method provided by it works for the path-insensitive analysis, such as the flow-sensitive analysis, but hinders the path-sensitive analysis, such as symbolic execution, since the predicates in a path condition can not be satisfied which violates the reachability of lifecycle methods. Compared to FlowDroid, DMMPP complements the non-explicitly inherited lifecyle methods and provides the path-sensitive predicate, which can satisfy the reachability of lifecycle methods as every lifecycle method is reachable declared by Android platform. It works for both path-sensitive analysis approaches and path-insensitive ones. A review has found that analysis approaches for Android applications can be improved with more precise techniques to make them more applicable [14], which path-sensitive analysis can do. Therefore, it can help the path-sensitive work, such as taint analysis of arrays [8], malicious application detection [18], security vulnerability detection [13] and estimation of API calls [5].

6 Conclusion

We have introduced DMMPP, which constructs the dummy main method with path-sensitive predicates for Android application analysis. It provides multiple ways for analyzers to use it. The experiment demonstrates the benefits of DMMPP for path-sensitive analyzers. Directions for future work include using DMMPP for analyzers to find real bugs in APKs and merging the same parameters from different methods/callbacks to reduce the parameter redundancy of the dummy main method.

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