AndroEvolve: Automated Android API Update with Data Flow Analysis and Variable Denormalization

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Abstract—The Android operating system is frequently updated, with each version bringing a new set of APIs. New versions may involve API deprecation; Android apps using deprecated APIs need to be updated to ensure the apps’ compatibility with old and new versions of Android. Updating deprecated APIs is a time-consuming endeavor. Hence, automating the updates of Android APIs can be beneficial for developers. CocciEvolve is the state-of-the-art approach for this automation. However, it has several limitations, including its inability to resolve out-of-method-boundary variables and the low code readability of its update due to the addition of temporary variables. In an attempt to further improve the performance of automated Android API update, we propose an approach named AndroEvolve, which addresses the limitations of CocciEvolve through the addition of data flow analysis and variable name denormalization. Data flow analysis enables AndroEvolve to resolve the value of any variable within the file scope. Variable name denormalization replaces temporary variables that may present in the CocciEvolve update with appropriate values in the target file. We have evaluated the performance of AndroEvolve and the readability of its updates on 360 target files. AndroEvolve produces 26.90% more instances of correct updates compared to CocciEvolve. Moreover, our manual and automated evaluation shows that AndroEvolve updates are more readable than CocciEvolve updates.

Index Terms—Program transformation, Android, data flow analysis, readability, API deprecation, API update

I. INTRODUCTION

Android is currently one of the most prominent operating systems (OS) due to the vast amount of its users. Android OS is frequently updated to add new features or to fix bugs. With each new version, changes and modifications in its APIs are inevitable. Changes to Android APIs may deprecate older versions and render them unusable in the newer version of the OS. To prevent errors caused by such API deprecation, developers need to constantly update deprecated-API usages in their code, while still maintaining backward compatibility with older Android versions. This problem, termed Android fragmentation [6], [24], is a common occurrence. Aside from being cumbersome and time-consuming to mitigate, Android fragmentation also introduces security risks [27].

Due to the nature of Android fragmentation, updating usages of deprecated Android APIs has become a priority. To help developers, several studies have proposed automatic approaches for updating Android API usages [5]. [7]. AppEvolve is a recent approach [5]. It uses both before- and after-update code examples to learn the update automatically. However, while it is able to provide an applicable update for some examples, it was found to have several weaknesses and a replication study by Thung et al. [21] demonstrated that AppEvolve works correctly only when the target file to be updated has a very similar syntax to the code example.

More recently, Haryono et al. [7] presented a new tool for automatic Android API update called CocciEvolve built on Coccinelle4J [11]. CocciEvolve shows better performance than AppEvolve on 112 target files. The main improvements that CocciEvolve provides are: generated update-scripts in the Semantic Patch Language (SmPL) [11], updates generated by using only a single after-update example, and its capability to update multiple instances of deprecated API invocations within a single file. However, the code example used in CocciEvolve must be in the form of an if statement containing the updated API in the “then” statement and the old API in the “else” statement, or vice versa. A sample of such an after-update code example can be seen in Figure 1.

```
if (android.os.Build.VERSION.SDK_INT >=
    android.os.Build.VERSION_CODES.M) {
  minutes = picker.getMinute();
} else {
  minutes = picker.getCurrentMinute();
}
```

Fig. 1: An example of after-update code for getMinutes() API

The major problem of CocciEvolve is its inability to resolve all the values used as API arguments. These values in API method invocations in a method body can be expressions in various forms, such as literal expressions, name expressions, field access expressions, method invocations, and object creations. When the expressions refer to a variable defined outside of the method boundary, CocciEvolve fails to resolve the variable or produce a working update. Another problem in CocciEvolve is about the readability of its update results. During the update process, CocciEvolve introduces temporary variables that refer to other variables in the target file. The temporary variables are used to ease the transformation process...
in CocciEvolve, but they clutter the update results.

In this work, we propose AndroEvolve, an improved automated Android API usages update tool that addresses the limitations of CocciEvolve, with two new features: data flow analysis and variable name denormalization. During the update-script creation, data flow analysis is used to resolve the values used as API arguments, including all variables that are defined outside of the current method containing deprecated API invocations to be updated. Definitions of such out-of-method-boundary variables are located and used to replace the variables in the API invocations. For brevity, we refer to such variables as out-of-method variables in the rest of the paper.

Variable name denormalization is added to improve the readability of the updated code as a post-processing step. As temporary variables can be introduced by CocciEvolve to normalize syntactic differences between update examples and the target file to ease the code update process, the readability of the updated code may be decreased with more temporary variables used. Our denormalization refers to a process that converts the code normalized to use temporary variables back to their original form after updates have been performed and thus improves the readability of the produced updates.

To evaluate the performance of AndroEvolve, we have conducted an experiment using a dataset of 360 target files containing 20 different Android APIs. We have compared the performance of AndroEvolve against CocciEvolve by counting the number of successful updates produced by each tool. AndroEvolve has produced 26.9% more successful updates. For readability, we have compared the update results of AndroEvolve and CocciEvolve through both an automated measurement by using a popular readability scoring tool and a manual measurement by asking the opinions of two experienced Android engineers. The measurements highlight that AndroEvolve produces updates that are about 50% and 83% more readable than CocciEvolve with respect to the automated and manual measurements respectively.

The main contributions of our work are as follows:

1) We propose AndroEvolve, a tool that addresses the limitations of CocciEvolve. AndroEvolve adds data flow analysis to resolve out-of-method variables and introduces variable name denormalization to increase update readability.

2) We evaluate AndroEvolve on a dataset containing 360 target files involving 20 Android APIs and show that it outperforms CocciEvolve in terms of both update success rate and the readability of the updates.

The rest of this paper is organized as follows. Section provides preliminaries on CocciEvolve, data flow analysis, and code readability. Section provides the motivating examples that show the problems present in CocciEvolve. Section discusses our approach in creating AndroEvolve as the upgraded version of CocciEvolve. Section provides the details on the experiments and its results. Section discusses the limitations of our work. Lastly, Section concludes our work and provides a discussion of future plans.

II. PRELIMINARIES

CocciEvolve [7] is the state-of-the-art tool on automatic Android API usage update. It distinguishes itself by only requiring a single after-update example, providing a readable update-script, and introducing code normalization that tolerates some syntactic differences during code updates.

Firstly, using only a single after-update example, CocciEvolve becomes applicable to more cases than its predecessor AppEvolve [5] that requires both before- and after-update example. Secondly, a readable update-script is achieved through the use of Coccinelle4J [10]. Coccinelle4J is a program matching and transformation tool for Java language, ported from Coccinelle [11], [14]. Coccinelle4J describes its transformation using a patch written in Semantic Patch Language (SmPL), which has similar syntax with diff. Having a patch that describes the program transformation helps the developers to better understand the updates and transformations applied. Finally, by doing a normalization on both the after-update example and the target file, CocciEvolve minimizes the syntactic differences that may cause a failed update. Syntactic differences occur when the after-update and the target file API invocation arguments are expressed in different syntax. This was one of the main limitations of AppEvolve, as shown in a replication study by Thung et al. [21].

Data flow analysis, such as def-use analysis, is an analysis of the data within the code based on the control flow paths taken by the program. For each given expression at a point inside a program, data flow analysis can determine the value of the expression. Sample uses of data flow analysis are dead code elimination, variable value prediction, and program slicing. For our work, data flow analysis is mainly used to determine the values of variables used in the arguments for API invocations and to conduct program slicing.

Code readability is a measure of how easy it is to read a piece of code. It is an important code feature that developers look out for, especially for code that needs to be maintained for a long run, or code that is touched by multiple developers. Having readable code makes it easier for developers to understand and modify the code. Studies on code readability have been conducted extensively [4], [18]–[20]. These studies define the metrics and features that are considered as important factors in determining code readability. These features include structural features (e.g. numbers of lines of code, length of each line of code, etc.) and textual features (e.g. name of variables, consistency between comments and variable name, etc.).

III. MOTIVATING EXAMPLE

The two major limitations of CocciEvolve are its inability to resolve variables defined outside of the current method containing invocations to deprecated APIs (so called out-of-method variables) and the presence of temporary variables in the updated code.

Out-of-method variables. An after-update example for the requestAudioFocus(...) API is shown in Figure 2. In this example, the deprecated API that is going to be updated
41 AudioFocusRequestOreo audioFocusRequestOreo = new AudioFocusRequestOreo();
67 public void tryToGetAudioFocus() {
68 OnAudioFocusChangeListener listener = this;
69 int result;
70 int type = AudioManager.STREAM_MUSIC;
71 int duration = AudioManager.AUDIOFOCUS_GAIN;
72 if (android.os.Build.VERSION.SDK_INT >=
73 android.os.Build.VERSION_CODES.O) {
74 AudioFocusRequest request = audioFocusRequestOreo.
75 getAudioFocusRequest();
76 } else {
77 result = audioManager.requestAudioFocus(request);
78 }
79 }
110 private class AudioFocusRequestOreo {
111 public AudioFocusRequest getAudioFocusRequest() {
112 ...
113 }
114 }
Fig. 2: Sample out-of-method argument for an API invocation
requestAudioFocus(...) from the target file is the requestAudioFocus(...) in line 77. The updated API and its argument is shown in line 74–75. In this method, the method invocation argument for the updated API is the request object, shown in line 75. This object needs to be defined through a method invocation of audioFocusRequestOreo.getAudioFocusRequest() (line 74). The variable audioFocusRequestOreo is also defined outside at line 41. This variable and its definition is a new argument that is not yet defined in the deprecated API invocation, thus they are not present in the target file. Since CocciEvolve only performs an intra-procedural analysis of update examples and only considers line 74–75 for the update script creation, the variables related to the request object (line 41, 110–133) cannot be resolved, hence creating a non-working update.

Our proposed solution is the addition of data flow analysis as a variable value resolver. We use data flow analysis on the after-update example’s code to find the definitions of the variables used in the API invocation’s arguments in a file scope. To further improve the functionality of this data flow analysis across files and Java classes, we also copy method and class definitions. If a variable’s value is resolved as a method invocation or an object creation, its method or class definition is needed to create a working update. AndroEvolve copies such definitions into the updated file, allowing the uses of those method invocations or object creations.

**Temporary variables in update results.** Temporary variables are used in CocciEvolve to ease the process of code update. However, these variables remain in the updated code, affecting its readability. Furthermore, these variables only refer to other variables that are already in the actual target file. Consider the sample updated code in Figure 3, there exist two temporary variables, parameterVariable0 (line 2) and classNameVariable (line 3). These variables refer to other parameters of the setTimeH method, and can be removed and replaced by their definitions. To resolve this problem, our proposed solution is to add variable name denormalization. This denormalization removes the declarations and definitions of the temporary variables, and replace uses of such temporary variables with the original variables that are referred to by those temporary variables. For example, line 2 in Figure 3 will be removed and parameterVariable0 in line 5 and 7 will be replaced by hour.

1 public void setTimeH(TimePicker tp, int hour) {
2 int parameterVariable0 = hour;
3 TimePicker classNameVariable = tp;
4 if (Build.VERSION.SDK_INT >= Build.VERSION_CODES.M) {
5 classNameVariable.setCurrentHour(parameterVariable0);
6 } else {
7 classNameVariable.setCurrentHour(parameterVariable0);
8 }
9 }
Fig. 3: An example of temporary variables in the output of CocciEvolve after updating the setCurrentHour(...) API invocation.

**IV. APPROACH**

**A. AndroEvolve Overview**

The workflow of AndroEvolve is comprised of two main functionalities, update-script creation, and update-script application. Figure 4 provides a graphical description of this workflow. Update script creation takes as input the API update mapping and the after-update example of the API to create the update script. The API update mapping defines the mapping between the deprecated API and the updated API. Within the update script creation process, several components are at work. First, data flow analysis is used to resolve any out-of-method variables used by the updated API arguments in the after-update example. This data flow analysis also locates the definitions of any method invocations or object creations used as API arguments. Following the data flow analysis, source file normalization is done on the code block containing the API invocation. Variable normalization introduces temporary variables as replacements for the API invocation arguments to facilitate the update process. Finally, an update script is created based on this modified example code.

This update script, along with the API update mapping and the target file, is the input for the update application process. Within the update application process, there are also several steps that are applied. First, source file normalization is also used in the target file to ease the update process. The update script is then applied to the normalized code. After the update is done, we copy the methods and class definitions that are used by the method invocation or object creations that are used in the updated API arguments. Finally, we apply variable name denormalization to remove temporary variables introduced by the variable normalization and replace their usage with the original expressions used as the API arguments. Details of each functionality are provided below.

**B. Data Flow Analysis**

API method invocations may include arguments that are syntactically different but semantically equivalent. Figure 5 shows an example of different forms of arguments for setAudioAttributes method invocations. In the first
Fig. 4: Summary of AndroEvolve workflow

example, the argument is first instantiated and assigned into a variable (line 2, 3) before being used as the argument for the first `setAudioAttributes` method invocation (line 10). The `builder` variable (line 3) in this example can be a free out-of-method variable (only defined in line 2 outside of the method containing lines 9 and not passed as an argument). The second example shows a code fragment where a complex expression is directly put as an argument of the second `setAudioAttributes(...)` method invocation (line 26). Contrary to the first example, the argument used in this example is bound (i.e., a variable locally defined or passed in via a method parameter).

Suppose that CocciEvolve is given an after-update example as shown in the first example in Figure 5. Part of the code containing the API invocation and its argument is first normalized, resulting in the normalized first example code (line 30–44). Slice of the normalized code that is used to create the update script is the part contained within the if statement, shown in line 40–42. Using this normalized code slice, CocciEvolve will produce an incorrect update, as shown in Figure 6. This update script is incorrect since based on the code slice, `newParameterVariable0` is only resolved to the bound variable, `attributes` (line 40). This is because CocciEvolve cannot resolve the correct value of the expression used as the API invocation argument and only uses the bound variable found within the slice, which is `attributes`. Due to this reason, CocciEvolve can generate a correct update script for the second example (as shown in Figure 7), but not for the first example.

Fig. 5: An example of different forms of argument for `setAudioAttributes` method invocation

This problem severely limits the coding styles that are acceptable as examples for CocciEvolve, which subsequently limits its effectiveness. This problem also prevents CocciEvolve from being able to produce a working update script for examples which contain free variables.

To alleviate this problem, AndroEvolve uses Data Flow Analysis (DFA) to resolve the values of expressions used as arguments in an API method invocation. This resolver should handle all possible forms of Java expressions. This data flow analysis is built to gather and predict a set of possible values.
private int duration = 9;
private int frequency = 3;
public int amplitude = duration / frequency;
public VibrationEffect createVibration(int time, int amplitude) {
    return VibrationEffect.createOneShot(time, amplitude);
}

public void onCreate() {
    if (android.os.Build.VERSION.SDK_INT >=
        android.os.Build.VERSION_CODES.O) {
        vibrator.vibrate(createVibration(3, amplitude));
    } else {
        vibrator.vibrate(50);
    }
}

43 private int duration = 9;
44 private int frequency = 3;
45 public int amplitude = duration / frequency;
46 public VibrationEffect createVibration(int time, int amplitude) {
    return VibrationEffect.createOneShot(time, amplitude);
}
48 }
69 public void onCreate() {
    if (android.os.Build.VERSION.SDK_INT >=
        android.os.Build.VERSION_CODES.O) {
        vibrator.vibrate(createVibration(3, amplitude));
    } else {
        vibrator.vibrate(50);
    }
}

43 private int duration = 9;
44 private int frequency = 3;
45 public int amplitude = duration / frequency;
46 public VibrationEffect createVibration(int time, int amplitude) {
    return VibrationEffect.createOneShot(time, amplitude);
}
48 }
69 public void onCreate() {
    if (android.os.Build.VERSION.SDK_INT >=
        android.os.Build.VERSION_CODES.O) {
        vibrator.vibrate(createVibration(3, amplitude));
    } else {
        vibrator.vibrate(50);
    }
}

at any given point inside the code. Hence, this functionality is able to predict and resolve the correct replacement values for any expressions used in the API invocation arguments.

We made a custom lightweight DFA for this purpose by using the symbol resolver from Java Symbol Solver that is a part of Javaparser [22]. This DFA conducts a bottom-up search from the bound variables or expressions used as the API method invocation arguments and expands the search scope until it finds the value or the method definition referred by the expressions, or until it explores the entire file. Using this approach, we can predict the value of free variables that are referred by the bound variables. Values and method invocations that are found by this analysis are used to replace the original expressions. These replacements are done to ensure that the expressions used as API invocation arguments are in the form of literal expressions, static class members, method invocations, or object creations.

The workflow for this DFA is shown in Figure 8. The DFA receives as an input the expression to be resolved. This expression is used as API invocation argument and can be in the form of a method invocation expression, name expression, field access expression, and literal expression. Each form of expression will require a specific processing as given in the workflow diagram. To give a better understanding of this workflow, assume an example code provided in Figure 9.

In this update example, we can see that the updated vibrate API used a method invocation expression as its argument (line 71). According to the workflow, we resolved the method definition, createVibration(...), and processed it using the copy method and class definition.

Then, we resolve the scope of the method. However, since createVibration(...) method is a public method that can be referenced directly, no object or class is used in its invocation, thus resulting in no scope to resolve. Next, we resolve the arguments of the method invocation. The first argument, 3 is an integer literal expression, thus no replacement is needed. However, the second argument, amplitude is a name expression, so we need to resolve its definition. Resolving this argument results in its definition which is duration / frequency (line 45). Since this definition still contains expressions in the form of name expression, we further resolve their values recursively. From this process, we found the literal expressions of 9 (line 43) for duration and 3 (line 44) for frequency. These expressions are used to replace their values in the amplitude variable definition in line 45 definition resulting in:

45 public int amplitude = 9 / 3;

In the end, we replace this definition of amplitude variable into the value used as the API invocation argument in line 71, resulting in this updated API:

71 vibrator.vibrate(createVibration(3, 9 / 3));

This data flow analysis is built for AndroEvolve as an upgrade from CocciEvolve. Therefore, the DFA is run as a preprocessing step before the update script creation. As a
preprocessing step, this feature does not change the internal working behavior of the CocciEvolve but instead adds a layer of functionality that modifies the input code.

### C. Source File Normalization

Following the approach taken by CocciEvolve, AndroEvolve also uses source file normalization in its workflow. Source file normalization is used to mitigate the problem of semantically-equivalent code being expressed in different forms, which can cause a failed API update. Variable normalization in AndroEvolve is focused on the part of the file that contains the API invocations defined in the API update mapping, along with their arguments. Given an API invocation, source file normalization normalizes the code in three steps:

1. **AndroEvolve is the first Python API usage search tool that**

2. **AndroEvolve uses source file normalization in its workflow.**

3. **Extract the returned value of the API invocation into variable assignment.**

Consider a code fragment containing a `fromHtml(String)` API invocation as shown in the first example of Figure 10. Source file normalization will convert the code given in the first example into the normalized form given in the second example. First, all arguments, including the class or object used in the API invocation, are extracted. This extraction introduces the variables `classNameVariable` (line 2), containing the class used in the API invocation, and `parameterVariable0` (line 3), containing the argument of the API invocation. Next, the return value of the API invocation is also extracted, resulting in the `tempFunctionReturnValue` variable (line 4–5).

### D. Copying Method and Class Definition

To provide a correct update, substituting the expressions into the resolved value is insufficient if the expressions are in the form of method invocation or object instantiation. This is because these expressions require their definitions to be used. Accordingly, we must copy method and class definitions from the resolved expression.

There are several important points to be considered for this feature. First, the copied class or method should be defined within the file containing the after-update example. This is due to AndroEvolve limitation as a tool that works on a file scope. Therefore, if the class or method is defined outside of the after-update example file, AndroEvolve will not be able to resolve them. Second, the copied class or method must be given an unique name, as required by Java. Lastly, the class or method that is copied must be in a scope that is accessible by the API invocation in the target file.

The workflow of this feature can be seen in Figure 11. First we extract the definitions of the methods and classes referenced by the expression from the code. Then, we make sure that in the target file, there are no class nor method with the same name as the extracted class and method. If a duplicate name is detected, the copied class or method name that is a duplicate is modified by adding number to the name. After validating the name, we then modify the access modifier of the class and method to public to make sure that the API invocation in the target file can access them. After all these process, we then copy the class and method definition into the end of the target file.

Figure 12 illustrates this task. Lines 1–7 show an example for `requestAudioFocus(...)`. The updated API uses an `AudioFocusRequestOreo` object (line 3–4) as an argument but it is not resolved. To correct the update, we must resolve and copy the relevant class definition, and instantiate the `AudioFocusRequestOreo` object. Lines 10–51 show the results of this process. The `AudioFocusRequestOreo` object is instantiated (line 11) and the relevant class is added into the updated code (line 30–51).

### E. Variable Name Denormalization

Another problem of CocciEvolve is the temporary variables that are added during the update process. These temporary variables add multiple lines of code to the updated file which can be considered harmful since it makes the code less readable and understandable. Typically, most of the added lines just reference other variables in the code – thus they are unnecessary. An example of the temporary variables created by CocciEvolve can be seen in Figure 13. In this figure, we can see that the temporary variables named `parameterVariable` (line 11–16) and `classNameVariable` (line 17) only refer to other variables that already exist in the file (method parameter in line 10).

Addressing this problem will be beneficial towards the readability and ease of understanding of the updated code. It will also make the code closer to developer-written code and less artificial. Variable name denormalization is our proposed approach for this purpose. Through the use of this denormalization, we aim to remove all unnecessary temporary variables and replace them with their values or referred variables. An example of the denormalized code based on the example from Figure 13 can be seen in Figure 14. In Figure 14 temporary variables are removed and the relevant values are used directly in the method invocations. This results in a shorter,
Fig. 13: Sample CocciEvolve update result for deprecated API `saveLayer`.

```java
if (android.os.Build.VERSION.SDK_INT >=
2) android.os.Build.VERSION_CODES.O) { 
  AudioFocusRequest request = audioFocusRequestOreo.getAudioFocusRequest(); 
  result = audioManager.requestAudioFocus(request); } 
else { 
  result = audioManager.requestAudioFocus(listener, 
  int saveFlags) { 
    float parameterVariable0 = left; 
    float parameterVariable1 = top; 
    float parameterVariable2 = right; 
    float parameterVariable3 = bottom; 
    if (VERSION.SDK_INT >= 21) { 
      tempFunctionReturnValue = mCanvas.saveLayer(left, 
      top, right, bottom, paint); } 
    } else { 
      tempFunctionReturnValue = mCanvas.saveLayer(left, 
      top, right, bottom, paint, saveFlags); }
```

Fig. 12: Sample updates for `requestAudioFocus()` deprecated API.

```java
... 
public AudioFocusRequest getAudioFocusRequest() { ... }
```

Fig. 14: Denormalized code of the one shown in Figure 13.

![Denormalization workflow](image)

Fig. 15: Overview of the variable denormalization workflow.

V. EXPERIMENT

A. Dataset

Our dataset contains 360 target files containing 20 Android deprecated-APIs, extended from the APIs that were used to evaluate CocciEvolve. The dataset is obtained from a randomly selected GitHub projects obtained using AUSearch, a tool to search Github repositories for API usages. Using this tool, we collected public GitHub repositories that contain invocations of the deprecated APIs and their replacement APIs in our dataset. Our dataset comprises after-update examples, target files to update that contains usages of the APIs, and one-to-one mappings from the deprecated APIs to the replacement APIs. Detailed statistics of the target files are shown in Table I.

As shown in Table I, there are no target files for the API `shouldOverrideUrlLoading(...)`. During the search, we did not find any after-update example nor target file for it.

B. Research Questions

1) **RQ1: How many updates can AndroEvolve apply correctly?**

We assess update performance by counting the number of correct updates produced. A correct update is an update that contains the deprecated and replacement API method in the form of an `if` code block, alongside with all the methods and classes needed by the replacement API method. We compare the update performance of AndroEvolve and CocciEvolve. We also ask an experienced Java and Android engineer to check the measured update performance and verify their correctness.

2) **RQ2: How readable is the updated code produced by CocciEvolve and AndroEvolve?**

We measured the readability of the updated code produced by AndroEvolve and CocciEvolve. In order to get a better insight on the readability aspect of the update, we conduct an automatic and a manual measurement.

In the automatic measurement, we utilized a state-of-the-art code readability scoring tool proposed by Scalabrino et al. [20]. The tool outputs a code readability score in a scale of 0.0 to 1.0 with the higher score being a measure of better readability. As the readability score is affected by the length of the source code file, we performed a static slicing to obtain parts of the code that are affected by the update. The static
targets. Specifically, we measure the time to perform update
AndroEvolve. The developers are also asked to determine
each pair of updated code produced by CocciEvolve and
that the code resembles the one produced by human. For
readability of the code, and the naturalness of the code. A
were asked to give score in the Likert scale of 1-5 for the
3 years of experience. For each updated code, the developers
as a sample size to represent the variation in the syntax of the
code slicing is done using JavaParser [22] by first locating
the deprecated and updated Android APIs based on their
description. After these APIs are found, we slice the API
method invocations and all the variables that are used in the
invocations. The sliced code is then put into a template class
and method to allow readability measurement using the tool.
An example of the sliced code file is shown in Figure 16.
In the manual measurement, we asked two experienced
Android developers to score 60 updated code, with 30 updated
code each from CocciEvolve and AndroEvolve. We choose 30
as a sample size to represent the variation in the syntax of the
updated code. The developers were not told about which tool
is used to produce the updated code. The first developer has 5
years experience in Android, while the second developer has 3
years of experience. For each updated code, the developers
were asked to give score in the Likert scale of 1-5 for the
readability of the code, and the naturalness of the code. A
higher score indicates higher readability and higher confidence
that the code resembles the one produced by human. For
each pair of updated code produced by CocciEvolve and
AndroEvolve, the developers are also asked to determine
which code that they prefer.

3) RQ3: How efficient is AndroEvolve in producing updates?
We measured the time needed for AndroEvolve to update the
target file. Specifically, we measure the time to perform update
code slicing and update application. The measurement is
conducted in a Macbook Pro with a 2.3 GHz Intel Core i5
processor, and 8 GB 2133 MHz random access memory. The
system ran Java SE 11, with OpenJDK version 11.0.6.

C. Results

1) RQ1: Code Update Accuracy: In total, AndroEvolve
and CocciEvolve managed to correctly update 316 and 249
out of the 360 target files, respectively. AndroEvolve out-
performs CocciEvolve by 26.90%. Analysis on the results
shows that the inclusion of data flow analysis improves
the update result of AndroEvolve significantly, specifically
in the vibrate(long), vibrate(long[], int), and
requestAudioFocus(...) APIs. After-update examples
for these APIs include usages of out-of-method variables that
are not handled by CocciEvolve. AndroEvolve has similar
performance as CocciEvolve for APIs that do not use out-
of-method variables in the after-update example.
Despite the big improvement when compared to Coc-
ciEvolve, AndroEvolve still has several problems. One of
these problems affects addGpsStatusListener(...) and
removeGpsStatusListener(...) APIs. These
APIs utilize out-of-file variables for their method invocation.
Out-of-file variables are variables that are defined outside of a
file scope. These variables can be a class member or a method
invocation argument that are defined in other files. Since
AndroEvolve works only in a file scope, these out-of-method
variables are unresolved, causing an incomplete update. An
example of the updated code that carries this problem is shown
in Figure [17] In this example, the callback object (line 2, 6)
is a class member whose value is defined in another file.
AndroEvolve cannot handle complex updates that involve an
update of a single API into multiple APIs, such as updating
getAllNetworkInfo() API to getAllNetworks() and
getNetworkInfo(...) APIs. Unlike the usual An-
droid API update that replaces an API with a newer API,
the case of getAllNetworkInfo() is different. Updating
this API involves the addition of a new control flow in the
form of a loop that iterates the Network object returned
by getAllNetworks() to receive their NetworkInfo
object by using getNetworkInfo(...) method.
AndroEvolve also cannot update multiple invocations of an
API method written in a single line of code. While uncommon,
1 int tempFunctionReturnValue;
2 if (android.os.Build.VERSION.SDK_INT >= 23) {
3     tempFunctionReturnValue = timePickerBegin.getHour();
4 } else {
5     tempFunctionReturnValue = timePickerBegin.getMinute();
6 }
7 dateTime = tempFunctionReturnValue + ":" +
8     timePickerBegin.getMinute() + ":" +
9     timePickerEnd.getHour() + ":";

Fig. 18: An example of multiple invocations of getCurrentHour() method in a single line

TABLE II: Updated code automated readability scores

| API                  | # Code | Average Score | AndroEvolve | CocciEvolve |
|----------------------|--------|---------------|-------------|-------------|
| addAction(...)       | 0      | 0             | 0           | 0           |
| getAllNetworkInfo(...) | 11     | 0             | 0           | 0           |
| getCurrentHour(...)  | 60     | 0.6009        | 0.5071      | 0.5996      |
| getCurrentMinute(...) | 60     | 0.5996        | 0.5172      | 0.5071      |
| setCurrentHour(...)  | 32     | 0.6006        | 0.3904      | 0.5762      |
| setCurrentMinute(...) | 15     | 0.5762        | 0.3962      | 0.5762      |
| setTextAppearance(...) | 10     | 0.3945        | 0.2307      | 0.3945      |
| fromHtml(...)        | 15     | 0.4143        | 0.2593      | 0.4143      |
| startActivity(...)    | 11     | 0.8311        | 0.6890      | 0.8311      |
| shouldOverrideUrlLoading(...) | 5     | 0.4006        | 0.2287      | 0.4006      |
| startDrag(...)       | 4      | 0.4516        | 0.1440      | 0.4516      |
| abandonAudioFocus(...) | 0      | 0             | 0           | 0           |
| getDeviceId(...)     | 29     | 0.4545        | 0.3974      | 0.4545      |
| requestAudioFocus(...) | 53     | 0.2413        | 0.2290      | 0.2413      |
| saveLayer(...)       | 21     | 0.4115        | 0.1011      | 0.4115      |
| setAudioStreamType(...) | 0      | 0             | 0           | 0           |
| vibrate(long)        | 8      | 0.5284        | 0.3629      | 0.5284      |
| vibrate(long)[] int  | 6      | 0.4437        | 0.2631      | 0.4437      |

2) RQ2: Code Readability: In automatic readability measurement, we compute the scores of all 355 updated code and average the scores for the APIs. The detailed scores are shown in Table II. Based on this result, code updated by AndroEvolve has higher scores for all APIs. Further analysis of the updated code shows that a bigger improvement is observed for APIs with multiple arguments (e.g. saveLayer(...), startDrag(...), etc.).

The manual readability measurement strengthens the above findings. The average readability score given by the developers for code updated by AndroEvolve is 4.817. Meanwhile, the average readability score for code updated by CocciEvolve is 2.433. Improvement can also be seen in the scores for code naturalness: AndroEvolve’s code was given an average score of 4.917, while CocciEvolve’s only received an average score of 2.433 for the naturalness aspect of their code.

3) RQ3: Update time: The update time of AndroEvolve is shown in Table III.

Both update-script creation and update-script application steps in AndroEvolve took an average of less than 15 seconds to execute. Given an after-update code example, a target file, and an API update mapping, AndroEvolve can update the API usages in the target file in less than a minute.

Further analysis yields several observations. First, aside from API complexities, the number of API invocations in the target file also affects the update time. Second, when processing multiple files containing the same API usage, the time can be shortened by using the same update script.

VI. DISCUSSION

Based on the results provided in Section V-C, it is evident that AndroEvolve achieves a better performance than CocciEvolve. Our approach solves the problem of out-of-method variables by using data flow analysis to resolve their values. Moreover, variable name denormalization also improves the readability of the updated code, as demonstrated by our automatic and manual readability measurements.

Despite this achievement, AndroEvolve still fails to update some target files, as described in Section V-C1. Some failures are caused by multiple invocations of the same API within a single line of code. A possible solution for this problem is to temporarily separate the same API invocations that exist in the same line of code into multiple statements to be updated independently. Other failures occur due to usages of out-of-file-boundary variables in the after-update example. To mitigate this problem, we need to improve the data flow analysis to make it work in a project scope, and change the input of AndroEvolve from a file into a project. Projects also occur in the case of APIs with complex updates that convert a single API invocation into multiple API invocations. Solving this problem will require an overall change in AndroEvolve, by allowing it to accept a non-one-to-one API update mapping. Another problem occurs when the after-update example makes use of an inner class constructor. This problem occurs due to a limitation of CocciEvolve4J, which AndroEvolve inherits. CocciEvolve4J only supports middleware Java, which only includes a subset of the Java grammar. This subset does not include the inner class constructor. As a consequence, AndroEvolve cannot handle an
1. public ChromeNotificationBuilder addAction(int icon, 
CharSequence title, PendingIntent intent) {
2. if (Build.VERSION.SDK_INT >= Build.VERSION_CODES.M) {
3. Notification.Action action = new Notification.Action.Builder()
4. (mContext, icon).title(title).build();
5. mBuilder.addAction(action);
6. } else {
7. mBuilder.addAction(icon, title, intent);
8. }
9. return this;
}

Fig. 19: Code example for API that use inner class constructor

after-update example that contains inner class constructors. Such an example is shown in Figure 19. In this example, the creation of the action object (line 3) uses an inner class constructor Notification.Action.Builder. This problem affects the update of several APIs, including addAction(...), abandonAudioFocus(...), and setAudioStreamType(...).

VII. RELATED WORK

API deprecation. Studies about API deprecation have been done frequently [2], [3], [7], [8], [12], [15], [17], [25], [26]. Li et al. [12] proposed a tool called CDA to characterize deprecated Android APIs. They found inconsistent annotation and documentation on deprecated APIs, and that most deprecated APIs are used in popular libraries. Zhou et al. [26] examined the usages of deprecated APIs in 26 open-source Java frameworks and libraries and found that many of these APIs were never updated. They proposed Deprecation Watcher, a tool to detect deprecated Android API usages from code examples on the web. Brito et al. [2] conducted a large scale analysis on Java systems to measure the usages of deprecation messages. Their analysis showed that a number of deprecated APIs did not use these replacement messages. Yang et al. [25] investigated the impact of Android OS updates on Android apps. They presented an automatic approach to detect parts of Android apps affected by an OS update.

Some studies focus on the effect of API deprecation. [8], [15], [17]. Robbes et al. [15] conducted a case study on the Smalltalk ecosystem and found that API deprecation messages are not always helpful. Hora et al. [8] conducted a case study on the Pharo ecosystem on the impact of API evolution, resulting in similar findings that API changes can have a large impact in the client systems, methods, and developers. They also found that API replacements can not be resolved uniformly. Sawant et al. [17] replicated the study on Java. They found that only a small fraction of developers react to API deprecation and most of these developers prefer to remove usages of deprecated APIs.

Our study also deals with API deprecation. It focuses on automatically updating the usages of deprecated Android APIs. Similar studies on this topic have been done recently. AppEvolve [5] is one of the first tools proposed for this purpose. It performs API updates by learning from both before- and after-update example. CocciEvolve [7] is the current state-of-the-art tool for automated update of deprecated Android API usage. CocciEvolve improves on AppEvolve by only using a single after-update example to perform API update and providing a highly readable and configurable update API update script in the form of semantic patches. CocciEvolve also solves the problem of failure to update code with different form or syntax that occurs in AppEvolve, as highlighted by the replication study by Thung et al. [21]. CocciEvolve utilizes parameter variable normalization to mitigate this problem.

Program transformation. Program transformations have been studied extensively [8], [9], [11], [13], [16], [23]. Stratego [23] is a language for program transformation based on the paradigm of rewriting strategies. Stratego performed transformation following the written transformation rules. LASE [9], [13] is an example based program transformation tool that is capable of locating and applying systematic edits. LASE provides users with a view of the syntactic edit and its corresponding contexts, allowing users to review and correct the edit suggestions. Rolim et al. [16] proposed REFAZER, a technique for automatically learn program transformations by observing code edits performed by developers.

Coccinelle [3], [11] is a C-based program matching and transformation tool that has been utilized for the automated evolution of Linux kernel. Coccinelle allows developers to write their transformation rules using Semantic Patch Language (SmPL). Recently, Kang et al. [10] proposed Coccinelle4J, a port of Coccinelle for Java language. Coccinelle4J allows the transformation of Java program using the same method as Coccinelle, through the use of semantic patch written in Semantic Patch Language.

In our work, AndroEvolve applies program transformation to update deprecated Android API usages. It uses SmPL to write the transformation and Coccinelle4J to apply it.

VIII. CONCLUSION AND FUTURE WORK

Updating the usages of deprecated Android APIs is a priority to ensure the functionality of Android apps in the current and previous versions of Android OS. However, performing such updates is time-consuming and labor-intensive. In this work, we proposed AndroEvolve, an automated Android API usage update tool. AndroEvolve uses data flow analysis to resolve the values of out-of-method variables, allowing AndroEvolve to work on the file scope. AndroEvolve also performs variable denormalization to produce updated code with good readability. We evaluated AndroEvolve using a dataset of 360 target files from which it managed to produce 316 successful updates. On the same dataset, CocciEvolve, the previous state-of-the-art tool, only managed to produce 249 successful updates. We also evaluate the updated code readability using both manual and automatic measurements. In the manual measurement, we asked the opinions of two developers on the readability of the updated code, while in the automatic measurement, we used a code readability scoring tool. In both measurements, AndroEvolve outperforms CocciEvolve by 49.89% and 82.94% respectively.

For future work, we plan to increase the capability of AndroEvolve. First, we plan to improve the data flow analysis to
allow resolving values that are located in other files within the same project. This addition will make AndroEvolve capable of handling out-of-file variables. Second, we also plan to handle more complex Android API updates, especially for cases where a single API is updated into several different APIs. While such a case is uncommon, this improvement would increase the overall effectiveness of AndroEvolve.

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