What do all these Buttons do?  
Statically Mining Android User Interfaces at Scale

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ABSTRACT
We introduce FRONTMATTER: a tool to automatically mine both user interface models and behavior of Android apps at a large scale with high precision. Given an app, FRONTMATTER statically extracts all declared screens, the user interface elements, their textual and graphical features, as well as Android APIs invoked by interacting with them. Executed on tens of thousands of real-world apps, FRONTMATTER opens the door for comprehensive mining of mobile user interfaces, jumpstarting empirical research at a large scale, addressing questions such as “How many travel apps require registration?”, “Which apps do not follow accessibility guidelines?”, “Does the user interface correspond to the description?”, and many more. FRONTMATTER and the mined dataset are available under an open-source license.

KEYWORDS
App mining, user interfaces, Android, app stores, static analysis

1 INTRODUCTION
When designing a user interface, a good practice is to follow the conventions as set by other user interfaces. But what are these conventions exactly? While there are myriads of different user interfaces around us, automated empirical analysis of these UIs is a surprisingly difficult task.

The Web, for instance, sports billions of Web pages. Yet, those Web sites that actually are accessible for empirical analysis only form the “surface Web”, with the much larger “deep Web” requiring specific user inputs (such as passwords) to be accessible. To analyze all pages of a Web application, an automated analysis thus has to synthesize such inputs, which brings all the problems of test generation. To automatically reach and explore millions of Web applications, one would have to synthesize interactions for all of these, which is hard—and in many cases (passwords, internal web pages) simply impossible.

The advent of app stores opens an opportunity to mine millions of apps for user interfaces and their properties. Apps can be analyzed dynamically by executing them. However, this approach raises the test generation problem, namely to synthesize appropriate interactions in order to reach and cover the entire user interface. Addressing this problem can be quite expensive. For instance, the developers of the Rico dataset [11] spent $19,200 for crowdsourcing user traces to analyze 9,7K applications. However, the executable code of apps is also available for static analysis. This opens the opportunity to analyze millions of apps for the way they interact with users—and thus jumpstarting empirical research on user interfaces at a large scale. Which apps require a password? How many of these allow for simple password recovery? Which apps allow to contact the vendor, and how? Is the concept of a “shopping cart” universally adopted? How do these things change over time?

Many of these questions could be answered by statically mining app user interfaces. Alas, static analysis of apps and their user interfaces is not exactly easy either. The challenges are manifold:

- A user interface analysis should be complete, that is, take the entire user interface into account. Yet, parts of the user interface may be constructed programmatically, which requires the analysis to identify (and interpret) the constructing code.
- A user interface analysis should be precise, that is, properly identify user interface elements, correctly associate them with each other as well as related code locations. An imprecise analysis (say, simply extracting all fixed strings from an executable and its resources) may retrieve all user interface labels (among many other things), but will not be able to properly group and organize them.
- A user interface analysis should scale, that is, be applicable to the large majority of apps as found in app stores. Scalability is an issue because a precise and complete analysis typically takes time—possibly too much time for the analysis of hundreds of thousands of apps.
In this paper, we present Frontmatter, a complete, precise, and scalable tool to extract user interface information from Android apps. Given an Android app, Frontmatter statically identifies all screens reachable within the app; for every such screen, it extracts the GUI hierarchy of UI elements on the screen, together with their identifiers, types, user-facing values such as displayed text and icons, and Android APIs invoked while interacting with them. This data is extracted from the app manifest and resource files (a description of all screens and their layout) as well as from the app code itself, in particular for dynamically defined content.

To make the analysis precise, we adapted the state-of-the-art static analysis technique by Späth et al. [25] to work on Android apps. Thanks to its flow-, field-, and context-sensitivity, the Frontmatter static analysis avoids unnecessary over-approximations: each UI element is placed at the proper screen and matched with a correct label and a list of triggered API methods. Our implementation also reduces the number of points-to queries needed to resolve particular UI elements.

To accomplish completeness, we propose a lightweight procedure to augment the code so that the resulting call graph contains more feasible edges, which are missing otherwise. At the same time, the respective inter-component control flow graph (ICFG) is kept concise, which contributes to scalability, as the alias and points-to analyses may be expensive on large ICFGs.

As an example of the data Frontmatter provides, consider the well-known VLC video player app. Figure 1 shows its video-playing screen. For each UI element, we show an excerpt of the data extracted by Frontmatter. We see that there are three title elements (title, battery, systime) at the top, a seek bar with time indicators and control buttons at the bottom. Most prominently located in the middle is the big player_overlay_info text label (showing Center in the screenshot), which displays various status messages such as the current aspect of the video shown. Figure 1 shows only a subset of the data extracted from the screen. VLC has nine more screens, in total Frontmatter extracts 214 GUI elements with 100 attached labels and 16 dialogs from the app.

Frontmatter is not the first tool to analyze Android apps; and it also is not the first to do so with a focus on user interfaces. Gator [28] and Backstage [3] take an app, statically analyze it, and extract its user interface information, including the association of UI elements and related code. However, as we show in this paper, their underlying analysis is not always precise enough to scale to real-world programs. In Figure 1, for instance, Frontmatter identifies 16 possible labels for the central player_overlay_info UI element; these are aspect values such as "Center", "4:3", "16:9", or status values such as "Locked" or "Unlocked". Gator also identifies these 16 labels, which is good; however, due to its context-insensitive nature it also reports six more possible values: "/.nomedia", ".nomedia", ".nomedia", ".nomedia", and "/.nomedia". These six additional values all are file paths or parts thereof (a ".nomedia" file in a folder indicates that this folder should not be indexed by VLC), but never user-facing on a screen; hence, they are false positives. While Gator over-approximates on this label, Backstage under-approximates; applied to player_overlay_info, Backstage identifies only one possible center label "4:3". Likewise, a dynamic execution might not be able to explore all possible labels, though reporting only feasible ones.

In this paper, we evaluate Frontmatter against Gator and Backstage showing that the above observations are not isolated, but actually common—and while we cannot say that Frontmatter achieves 100% precision1, our experiments confirm that it is sufficiently precise to allow for large scale analysis of user interfaces.

What can one do with Frontmatter? We have applied Frontmatter on almost 250,000 apps from the AndroZoo database (Google Play apps from 2018, 2019, and the first half of 2020) and were able to extract user interface data of 70% of apps.

The reason why a fraction of the apps from the dataset is considered has to do with their nature rather than to the faults of our tool: a lot of apps are games, cross-platform apps with their own UI builders, and apps with side code loading. Around half of the initial dataset of 500K apps consists of games, based on Unity platform, and cross-platform apps (e.g., created with Xamarin). As such, they cannot be analyzed with common static analysis approaches, but only explored dynamically and are therefore filtered out in our study.

This corpus allows us to answer all the questions listed above using simple database queries. For instance, the query about Login functionality reveals that only 35% apps in our dataset that have a "login" label suggesting to reset the password. Frontmatter and the extracted data set are available under open source licenses.

In summary, this paper makes the following contributions:

1. **Context-sensitive reconstruction of user interface hierarchies.** Frontmatter is designed from scratch to allow for flow-, field-, and context-sensitive extraction of user interface data from Android apps. Frontmatter achieves this by integrating the points-to analysis technique by Späth et al. [25] to work with the Android framework; and through a lightweight procedure to construct the elaborate call graph, preserving the context of callbacks.

2. **Associating UI elements and API calls.** The resulting models contain not only UI hierarchies, but also API calls—reactions of UI elements to user interaction, facilitating the analysis of the app’s behavior.

The remainder of the paper is organized as follows. After discussing the existing approaches (Section 2) and the background on Android, its apps, and their user interfaces (Section 3), we introduce and discuss the analysis techniques of Frontmatter (Section 4). In our evaluation (Section 5), we compare it to existing approaches [3, 28]. Section 7 concludes and presents perspectives for future work.

2 RELATED WORK

2.1 Static Analysis of Android Apps

Gator [28] is a popular program analysis toolkit for Android. Gator enables and supports static analysis of Android apps, notably in conjunction with user interaction. Gator uses static analysis to model and extract GUI-related Android objects, their flow through the application, and their interactions with each other via the Android abstractions. Its focus and main uses are classical domains of static analysis, including static error checking, security analysis, and code optimization.
GATOR is able to extract static models of the user interface from an app [22]. While its analysis of callback methods to model window transition graphs is context-sensitive, the reconstruction of window content is context-insensitive, which leads to some imprecision mentioned in a couple of subsequent papers [27–29]. As we will show, GATOR’s precision is not sufficient for extracting models with accurate label assignment.

The BACKSTAGE tool [3] is related to FRONTMATTER and GATOR in that it also aims to analyze apps in conjunction with their user interface, associating user interface elements with handler and generator functions. As the name suggests, the aim of BACKSTAGE is to identify what happens “behind the scenes”, i.e. which API calls are triggered when a user interface element is interacted with. As we show in this work, however, BACKSTAGE frequently fails to reconstruct a full UI hierarchy of an app, missing numerous UI elements and labels. This is in contrast to FRONTMATTER, set to reconstruct the complete GUI model of an app.

GoalExplorer by Lai et al. [14] statically models UI screens and screen transitions in order to guide the dynamic exploration of an app. Although the authors do not cite BACKSTAGE, the analysis of the source code of the tool showed that it uses BACKSTAGE to build an initial UI model. Moreover, they rely on FlowDroid to build call graphs of all component’s entry points, whose limitations will be discussed later. GoalExplorer focuses on the reconstruction of screen transition graphs, while FRONTMATTER aims at screen content.

GUIFetch [7] searches for apps that are as similar as possible to the provided sketch of an app. It builds models of app’s screens and screen transitions using a combination of static and dynamic analysis. In contrast to FRONTMATTER, though, GUIFetch requires the app source code for its analysis.

2.2 Dynamic Exploration of Android UIs

On the Android platform, a number of tools exist to systematically explore dynamic app behavior. Azim et al. [4] introduced Targeted Exploration, a novel technique that leverages static taint analysis to facilitate fast yet effective exploration of Android app activities and Depth-first Exploration, a technique that does not use static analysis, but instead performs a thorough GUI exploration which results in increased method coverage. Bhoraskar et al. [8] presented Brahmatra, an app automation tool addressing the problem that third-party code is usually beyond the reach of traditional GUI testing tools. It uses static analysis to construct a page transition graph and discover execution paths to invoke third-party code, and then performs binary rewriting to “jump start” them efficiently. In contrast to these approaches, FRONTMATTER uses static analysis,
which avoids the problem of test generation having to cover all functionality.

2.3 Android UI Datasets

As for Android UI analysis at scale, Shirazi et al. [23] collected 400 apps from Google Play Store and analyzed the common design patterns of these apps. They estimated the complexity of each app design by counting the numbers of activities, layout files, and images and computed descriptive statistics such as the most frequent interface elements and the most common combinations of widgets.

Alharbi et al. [1] applied a data-mining approach to analyze design pattern changes in Android apps. They tracked 24,436 apps and collected their versions. After extracting UI elements from these apps, they conducted differential analyses regarding design pattern changes.

Deka et al. [11] created the Rico dataset dynamically mining apps and captured view hierarchies, screenshots, and user interactions with help of crowdsourcing. The Rico dataset contains design data from more than 9.7k Android apps spanning 27 categories. It exposes visual, textual, structural, and interactive design properties of more than 72k unique UI screens. Based on the Rico dataset, Micallef et al. [17] investigated whether smartphone apps use login features, and what relationships exist between login features and apps popularity. Liu et al. [16] proposed an automatic approach for annotating mobile UI elements with both structural semantics such as buttons and functional semantics such as add or search, and computed semantic annotations for the 72k unique UIs in the Rico dataset. The ReDraw data set [19] is obtained via dynamic analysis, like Rico; it was successfully used to prototype GUIs for mobile apps using machine learning techniques.

Being purely dynamic, both the Rico and ReDraw data sets capture any kind of GUI including dynamic content and are very precise—for the executions that have been considered. However, by construction, their models cannot be complete; it is hard to cover UI elements that are visible only under certain conditions; and exploration of an app takes time. Also, neither records API usage.

In contrast to these approaches, FRONTMATTER is set to be applied automatically (i.e., without human intervention), statically (i.e., without executing the app) to the totality of Android app binaries.

2.4 Mining Web User Interfaces

FRONTMATTER is not the first approach to mine UI data. For the Web platform, Webzeitgeist [13] is a platform for large-scale design mining comprising a repository of over 100k Web pages and 100 million design elements, capturing and combining the visual and structural representations of web pages to compute design features that were used to power a number of data-driven design tools. FRONTMATTER focuses on the Android domain instead, which allows to take the entire application into account—in contrast to mining Web applications, where the large majority of pages is inaccessible for the public.

2.5 Visual User Interface Mining

A number of approaches analyze user interfaces visually, i.e. from screen shots and recordings. Pu et al. [21] combined visual analysis with code mining, increased performance of web page segmentation and allowed extraction of textual content without the "costly" recognition stage.

Bakaev et al. [6] applied a vision-based machine learning approach and built a Web User Interface Visual Analyzer, using image and text recognition to identify UI elements and labels. In contrast, FRONTMATTER can extract the type and labels of visual elements directly from the Android application.

2.6 Optimizing Android App analysis

Besides GATOR and BACKSTAGE, recent approaches have been suggested to further improve static analysis of Android apps. Mirzaei et al. [18] employed static techniques to identify interaction between GUI widgets and significantly reduced the number of tests by avoiding the generation of tests for widgets that do not interact. Zhang et al. [30] introduced a launch mode analysis for distinguishing launched instances of an activity class on the launch mode specified and employed a launch-mode-aware context-sensitive activity transition analysis to track activity transitions context-sensitively, together with an object-sensitive pointer analysis. Both these optimizations could further improve the precision of FRONTMATTER, as well.

3 BACKGROUND

We now provide some background on the Android GUI, i.e. how UI elements are declared and how they can be arranged in the layout.

In the Android framework, a single screen containing several graphical user interface (GUI) elements, such as buttons and text fields, referred to as widgets, is represented by an activity object. Each app typically contains multiple activities. The layout of the activity is usually declared in an XML file. This XML file describes the hierarchical structure of the GUI.

All building blocks of Android GUI can be divided into two groups: views and layouts. View elements represent specific UI widgets like buttons, text fields, and images. They are terminal nodes in a GUI tree. Layout elements serve as containers, which help to organize views in a particular manner, for instance within a grid or as a scrollable list. Each XML node corresponds to a certain Android class, either provided by the platform or implemented by a developer. Thus, the Android framework uses layout files as a template to create UI objects at runtime.

As an example of a layout file, consider Listing 1. This layout contains a TextView widget which displays text to the user; an ImageButton—a button with an icon; a ListView used to show a list of other widgets; a fragment container, which will be substituted with a layout of SampleFragment during the runtime; and a RelativeLayout container, which is empty now, but can be utilized as an inflation point for additional UI elements, instantiated in the code.

Each UI element usually has an identifier (such as @+id/info) that allows the code to refer to it to activate it or update its content. UI elements also may have text which typically comes as a symbolic label (such as @string/info) that would be replaced by a string according to the user’s language. Finally, UI elements are tied to callbacks—functions that are invoked when the UI element is activated. For the @+id/btn button, the onClick callback is xmlDefinedOnClickListener: This means that when the button is clicked,
the method void xmlDefinedOnClick(View v) is invoked, with v being that button.

All activities which are available in an application should be declared in the app’s manifest file. Android manages activity instances by invoking specific callback methods that correspond to particular stages of their life cycle. When the system creates an activity, it invokes the corresponding onCreate callback, which should be implemented by the developer.

Listing 2 shows an example code of this method. It is used to define the layout for the activity’s user interface, create and initialize additional widgets, and bind data to lists. By calling the setContentView(layoutFileId) method (Line 4) the system retrieves a UI hierarchy from the layout xml file and instantiates necessary Java classes. Here, R.layout.sample is a unique integer identifier referring to layout.xml, generated by the compiler. Internally, the setContentView method fetches a special LayoutInflater object which takes care of transforming an XML template into a widget instance. This object is also widely used within the application code to manipulate layouts and their parts. In Line 10, the LayoutInflater inflates new_layout to the GUI hierarchy taking container as an attachment point. Depending on the signature, the inflate method can perform various actions. Normally, it returns the root View of the created hierarchy. If the third boolean attachToRoot parameter is provided and true, the inflater attaches new widgets to a container. Otherwise, the view remains dangling and can be manually attached via an addView call. Calls to inflater can occur in any place of the application code, where the context is available (either propagated through method calls or obtained via a system call). Thus, it is important to resolve inflate invocations in the whole program code.

A widget object provides a number of methods to manipulate its properties and associate it with text, listeners, or add it to other widget groups. A reference to an existent View can be obtained with the findViewById method (Line 8). Besides using XML files, one can create particular widgets or the entire layout dynamically in the app code (like in Line 11). Usually, listeners of interaction events are tied to UI elements programatically. For instance, in Line 13 the EditText object is additionally assigned an onLongClick callback by calling View.setOnLongClickListener(1) method. These listeners are commonly implemented as anonymous classes, which may capture the outer variables (in our example, labels). We model callback associations to capture the propagation of views and control flow.

Listing 2: onCreate method example

```
1 class SampleActivity extends Activity {
2     @Override
3     void onCreate(Bundle bundle){
4         this setContentView(R.layout.sample);
5         View info = getActivity().findViewById(R.id.info);
6         info.setText("Info");
7         List<String> labels = helper.getLabels();
8         LinearLayout c = (LinearLayout) this.findViewById(R.id.container);
9         LayoutInflater inflater = LayoutInflater.from(this);
10        View container = inflater.inflate(R.layout.new_layout, c, true);
11        EditText et = new EditText(this);
12        container.addView(et);
13        et.setOnLongClickListener(new View.OnLongClickListener{
14            @Override
15            public void onLongClick(View v) {
16                v.setHint(labels.get(0));
17            }
18        });
19    }
20 }
```

Listing 3: ListAdapter handling example

```
1 class SampleActivity extends Activity {
2     void onCreate(Bundle bundle){
3         ... 
4         List<String> items = db.getItems();
5         ListView l=(ListView) this.findViewById(R.id.list);
6         l.setAdapter(new SearchAdapter(this, items, containerId));
7     }
8 }
9 class SampleAdapter extendsListAdapter {
10    @Override
11    public View getView(int position,
12        View convertView, ViewGroup parent) {
13        View convertView = LayoutInflator.from(context);
14        inflate(R.layout.row_items, convertView, false);
15    }
16    }
17 }
18 }
19 }
```

There are Android objects which require special handling of their layouts. The most frequently used are:

**AdapterView** is a view that displays items loaded into an adapter from a data-source. For each item to show on a screen, the Android platform generates a sublayer with the getView method, (Listing 3), which should be implemented for each adapter assigned to the view. Thus, the association of a
view element and an adapter, established by setAdapter
call, (Line 6), and adapter layout generation (Line 12) should
be modeled correctly.

**Fragment** is a portion of the user interface that can combine a
single activity to build a multi-pane UI or reuse a module in
multiple activities. There are two different ways to include a
fragment into an activity: (1) Declare it in the layout file of
the activity directly (see Line 9 in Listing 1 for an example);
(2) Dynamically attach the fragment in the code by means of
the FragmentManager class (Line 14in Listing 4).

As with adapters, the layout of the fragment is initialized in a
special **onCreateView** callback method—its return statement
should reference a root view container object with an inflated
UI tree. Moreover, it can fetch the execution context and
update other widgets (as in Line 4).

### Listing 4: Fragment handling example

```java
class SampleFragment extends Fragment{

    @Override
    View onCreateView(LayoutInflater li, ViewGroup vg, Bundle b){
        View info = getActivity().findViewById(R.id.info);
        info.setText("Fragment added");
        View view = li.inflate(R.layout.fragment, vg, false);
        return view;
    }
}
```

In summary, in order to construct a precise GUI model of an app,
one needs to correctly identify creation, inflation, and attachment
of UI components (like activities, views, adapters, and fragments) by
determining the control and data flow through respective methods.

### 4 ANLYZING ANDROID USER INTERFACES

To properly resolve the several variables involved in assembling
the GUI, one requires a highly precise **pointer analysis**. To this end,
**Frontmatter** implements a static analysis built on top of the SOOT
framework [26], FlowDroid [2], and especially Boomerang [24, 25].

Boomerang is a demand-driven, flow-, field-, and context-sensitive
pointer analysis for Java programs. It computes not only the possible
allocation sites of a given pointer (points-to information), but also all pointers that can point to those allocation sites (alias information).

#### 4.1 Constructing the Call Graph

Boomerang’s pointer analysis requires an **inter-procedural control
flow graph** based on a corresponding call graph. Rather than having a
single entry-point method from which to start the call graph
construction, Android apps combine a large set of entry callbacks, invoked by the system. Hence, it is necessary to start the analysis
by producing a dummy main method, which models the invocation
of these callbacks.

First, **Frontmatter** generates an entry point for the analyzed
app, suitable for call graph generation. Then it uses the entry point
to build a control-flow graph, which is used to initialize a context-
sensitive points-to analysis. Finally, **Frontmatter** identifies points-
of-interest involved in GUI construction, and performs resolution
of all variables involved.

We utilize a customized **main** method generator from Flowdroid.
The generator aims to accurately model the life-cycle of Android
components and the execution order of related callbacks. However,
for our purposes, it still is incomplete. For instance, it only con-
siders fragments defined in XML layout templates, thus missing the
ones attached dynamically in the code. Hence, the call graph,
generated then by Soot with the SPARK [15] constructor, lacks edges, rendering parts of the actually executable code effectively
unreachable. To obtain a higher recall along with proper handling
of fragments, we implemented a number of extensions to enrich
the final call graph with additional edges.

The call graph assembly procedure encompasses four steps, dis-
cussed in the following subsections.

#### 4.1.1 Step One: Allocation Points of View Objects

The call graph generated by the SPARK algorithm sometimes misses edges based on the context of the invoking expression. It is a well known limitation which happens because there is no object allocation point for SPARK to use as the starting point for its type propagation3. In order to get these missing edges, one may, for instance, employ the
CHA [10] or RTA [5] call graph construction algorithms, but they are
less precise.

This issue of imprecision affects very common code statements.
For instance, consider the statement

```java
Button button = (Button) findViewById(id);
```

which fetches a UI widget by its id. Although the findViewById method returns a View reference, it follows the proxy pattern
and does not explicitly create and return an instance of the View
object. As SPARK cannot identify an object allocation point for
this statement, all subsequent method calls on that object like
button.setText(text) are not expanded in the call graph, thus
having no outgoing edges. Hence, all overridden methods (common
especially in custom widgets that extend the View class) become
unreachable and thus are excluded from the analysis.

To overcome this problem, we patch the code with **object instantia-
tion statements**. At first, we search the code for findViewById
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for SPARK to use as the starting point for its type propagation3. In
order to get these missing edges, one may, for instance, employ the
CHA [10] or RTA [5] call graph construction algorithms, but they are
less precise.

This issue of imprecision affects very common code statements. For
instance, consider the statement

```java
Button button = (Button) findViewById(id);
```

which fetches a UI widget by its id. Although the findViewById method returns a View reference, it follows the proxy pattern
and does not explicitly create and return an instance of the View
object. As SPARK cannot identify an object allocation point for
this statement, all subsequent method calls on that object like
button.setText(text) are not expanded in the call graph, thus
having no outgoing edges. Hence, all overridden methods (common
especially in custom widgets that extend the View class) become
unreachable and thus are excluded from the analysis.

To overcome this problem, we patch the code with **object instantia-
tion statements**. At first, we search the code for findViewById
invocations. Next, we reassign a local variable which stores the re-
tiation which happens because there is no object allocation point
for SPARK to use as the starting point for its type propagation3. In
order to get these missing edges, one may, for instance, employ the
CHA [10] or RTA [5] call graph construction algorithms, but they are
less precise.
is then usually cast to the correct type (e.g. Button). Where available, instead of insertion we substitute this cast statement with a new expression. For custom widgets we also insert their constructor invocation. Later on in our analysis, we distinguish this case from the standard object allocation.

4.1.2 Step Two: Asynchronous Execution. The Android platform provides a couple of classes to perform background operations asynchronously and publish results on the UI thread. The most commonly utilized are AsyncTask and Handler.

AsyncTask provides a simple method to handle background threads in order to update the UI without blocking it by time consuming operations. Methods of AsyncTask run the code in a separate thread and then may update the GUI with the results of the execution. However, they will be not reachable from the main method, since they are called from the main UI thread by the system. We model this interaction by transforming asynchronous callback invocations into \textit{sequential method calls}. To this end, we substitute the \texttt{execute} call, which activates the task, with four methods, carrying out the actual work: (1) \texttt{onPreExecute()}, which is invoked on the UI thread right before the execution; (2) the main function \texttt{doInBackground(Params...)}, invoked afterwards on the background thread; (3) invoked on the UI thread to display the \texttt{progress onProgressUpdate(Progress...)}; and finally (4) \texttt{onPostExecute(Result)}, invoked on the UI thread after the background computation finishes publishing the result.

In the case of custom workers, a \texttt{Handler} allows communicating back with the main UI thread from any other background thread. The message can be sent through the message queue by calling the \texttt{send\_Message(Message)} method. When the system receives a message for a UI thread, it invokes \texttt{handle\_Message}, which should be overridden in the app’s code. To bind two threads, we identify \texttt{send\_Message} statements and insert \texttt{handle\_Message} calls afterwards.

4.1.3 Step Three: Widget Callbacks. During the construction of the dummy main method, FlowDroid tries to add invocations of all callbacks recognized within an Android component (e.g., an activity). However, this approach has some limitations. First, listeners defined outside of activities (such as listeners assigned in custom methods of the app’s classes) are not considered, thus missing some executed code. More critical, though, is that the identified callbacks are then invoked inside the dummy main method, so that most of the parameters required in constructors of the callbacks’ objects are set to null. Hence, FlowDroid does not allow to automatically associate the call with the specific context, propagate values of particular variables, and bind them with external fields, which reduces both precision and recall of the analysis.

To improve callback integration, we patch the code by \textit{injecting the corresponding callback invoke statements} right after the particular listener is assigned. For instance, in Listing 2, Line 13 the \texttt{EditText} widget is attached a long click listener created in-place as an anonymous class. The Jimple representation of this statement is \texttt{et.setOnLongClickListener(r1)}, where the variable \texttt{r1} references previously instantiated \texttt{View.OnLongClickListener}. We insert \texttt{r1.onLongClick(et)} statement right after, so that the \texttt{onLongClick} method receives a) a proper \texttt{View} object \texttt{et} and b) a variable \texttt{labels}, captured from the outer class.

All in all, we handle 185 Android callbacks (and listeners), of which 75 are from various UI widgets.

4.1.4 Step Four: Adapter Callbacks. In Android, Adapter objects provide a special kind of callbacks which should be handled especially. Adapters function as bridge between the data and special AdapterView widgets, intended to show this data. They are responsible for making a View for each item in the data set. Therefore, we should also model construction of UI elements for at least one item, inflated into the AdapterView container. This View is composed inside an \texttt{Adapter::getView(position, View convertView, ViewGroup parent)} method, which should be implemented by the developer.

To preserve the context, we inject the adapter’s \texttt{getView} calls right after statements with setAdapter method invocation. (see Line 6 in Listing 3). After that, all variables are correctly propagated through the callback.

4.1.5 Effect of these steps. All the above steps are performed not on the call graph, but on \textit{the code right before call graph construction}. Hence, after these steps, we can let Soot build the call graph as usual, so that it automatically integrates these updates handling all the peculiarities of method resolution. Finally, we construct an inter-component control flow graph that we use for variable resolution in the next step. According to our preliminary study, the extended call graph contains \textit{25\% more edges on average} than the one built originally by FlowDroid.

There are also other approaches that address complexities of callback transition in the Android framework, like EdgeMiner [9] or Lithium [20]. While they produce comprehensive callback summaries, it may overcomplicate the call graph and significantly increase the analysis time without substantial recall growth. We may consider them in the future work.

4.2 Constructing the GUI Model
From the call graph, we can now generate the GUI model. At first, we analyze methods reachable from activity callbacks to identify which layouts are associated with that activity.

For each point-of-interest to analyze, we create a set of backward search queries for Boomerang to resolve variable values. For example, for this \texttt{.setContentView(id)} we search backwards in the ICFG for an allocation site of the \texttt{id} variable to identify which layout resource is retrieved here. Since we restrict this search with methods reachable from the activity, we do not need to additionally resolve the variable \texttt{this}. At the same time, it allows us to correctly process methods of superclasses.

As we want to analyze an application, but not the Android platform, we updated Boomerang to skip platform calls. Each time the search process encounters a method invocation from Android, it jumps over it.

As the next step, we proceed with the resolution of all fragments used in the app. To this end, we analyze the \texttt{onCreateView} method of each fragment and reconstruct the UI hierarchy generated there. We apply pointer analysis to the return statement of this method which contains the reference to the root view of a layout. Afterwards, Frontmatter identifies which fragments can be added
to a particular activity by tracking add and replace methods of a FragmentTransaction.

In the same way, Frontmatter resolves adapters, starting from setAdapter point-of-interest and analyzing getView methods.

A View object can be either instantiated with the new-expression statement, or come as a result of an inflation. For this reason, we extended allocation site definitions of Boomerang to include not only ordinary basic type constants, final fields, and new-expression statements, but also specific method invocations such as inflate of LayoutInflator. When Boomerang gives back a points-to sets with a call, Frontmatter makes another query to determine properties of inflated view.

We also adapted the Boomerang propagation of data-flow facts. In order to minimize the number of queries per search, we combine queries and force Boomerang to transfer facts through invocation statements regardless of reference types. For instance, while performing binding fragments to activities, Frontmatter begins the resolution with searching for FragmentTransaction::add(container, fragment) call sites (see Line 17 of Listing 4). At this point, we aim to identify both the fragment object, which will be added to an activity, its container, and the target activity. Normally, we would take this call site as a starting point and query Boomerang for an allocation statement which was a FragmentManager::beginTransaction invocation. Next, we would continue propagation with another query which should have returned a getSupportFragmentManager statement and finally identified the context of that call. Instead, we tell Boomerang to pass through the beginTransaction unit and assume that a data-flow fact is transparently transferred from the FragmentTransaction to the FragmentManager within one query (although object types are incompatible).

The same strategy applies to the resolution of strings. The updated Boomerang consumes the toString method of a StringBuilder and automatically determines strings from StringBuilder::add(s) calls.

As Boomerang strives to find all allocations and aliases, its execution time can be quite high. In order to be able to complete the whole analysis (though, missing some resolutions) we had to set a timeout of 20 seconds for each query. (We plan to extend Boomerang to extract partial results.) Finally, Frontmatter aggregates all findings and generates the full GUI model of the application.

While constructing the GUI hierarchy, Frontmatter also analyzes application behavior—the reaction of the Android framework triggered in response to a user interaction with certain UI elements. To this end, Frontmatter collects all Android APIs which are called by a callback method attached to each UI element.

It is quite common for developers (for instance, for handling options menus) to assign a single event listener to multiple UI elements, and make it call different methods depending on the id of the view that triggered the callback (Listing 5). Thus, to properly analyze the behavior of a UI element, it is necessary not only to correctly associate it with a callback, but also to accurately trace the execution depending on the view ids involved. Otherwise, the analysis would over-approximate a lot. Therefore, Frontmatter accounts for the context and prunes infeasible edges. It walks along the call graph starting from the callback and takes only proper edges, inspecting whether a condition of if and switch statements contains a view id constant or a variable initialized with getId or getItemId methods. The context-sensitivity of Boomerang and the call graph ensures that the list of collected APIs is correct.

4.3 Limitations

Like any approach for software analysis, Frontmatter has inherent limitations. As a static analysis tool, it is fundamentally limited by the halting problem; whether an app will ever show a particular behavior cannot be decided automatically in all generality, and this of course includes any GUI features. Frontmatter thus can over-approximate, reporting GUI features that are infeasible in actual executions.

On the other hand, Frontmatter can also underapproximate, notably when code is loaded or generated only when the app executes; such code is not available at static analysis time. This is the case for apps that embed Web pages; the Web GUI elements can neither be retrieved nor analyzed or reported by Frontmatter.

Finally, Frontmatter assumes that the app uses standard Android user interface elements and concepts. If an app implements its own user interface library, using only low-level Android input and output primitives, Frontmatter will not be able to identify or report user interface elements. This is frequently the case for games as well as for some cross-platform UI libraries; for the latter, Frontmatter could be adapted to incorporate their concepts.

5 EVALUATION

We now turn to the evaluation of Frontmatter, focusing on its precision and usefulness compared to the state of the art, as exemplified by Backstage and Gator. We proceed in four rounds, starting with a single app (VLC) in great detail, and continuing with growing numbers of apps in lesser detail, until we reach the totality of apps in AndroZoo.

5.1 Case Study: VLC Media Player

In order to determine if Frontmatter can correctly generate a GUI model of an app, we examined its performance in detail on a sample application. As a test subject, we use the VLC media player app introduced in Section 1, which has been also used to evaluate Gator and Backstage.5 To obtain a ground truth, we downloaded the source code of this application and thoroughly manually investigated the parts responsible for the composition of its UI layouts.

5

Listing 5: One listener for many buttons

1 public void onClick(View v) {
2     Integer vid = v.getId();
3     if (R.id.home_button == vid){
4         resetState();
5         homeButtonClick(v);
6     } else if (R.id.next_button == vid){
7         nextButtonClick(v);
8     }
9 }
Additionally, we ran it in an emulator and recorded each screen state using the UIAutomatorViewer tool from the Android development toolkit.

Comparing FRONTMATTER and GATOR against this ground truth, we made two central observations:

- **On VLC, both GATOR and FRONTMATTER provide a good approximation of the widget set, with FRONTMATTER being more precise.** FRONTMATTER identified the exact set of widgets from the ground truth, while GATOR inserted 6 copies of widgets in the wrong place of the hierarchy. Besides, it recognized a custom view object, but failed to correctly embed it into the hierarchy, again over-approximating with superfluous UI elements. Since GATOR does not support fragments, it missed 7 fragments correctly retrieved by FRONTMATTER.

- **FRONTMATTER is more precise than GATOR as it comes to precisely assigning textual labels to UI elements, an observation already discussed in Section 1.** Both FRONTMATTER and GATOR identified most of the labels used in the app. Even though GATOR additionally extracted few error messages, it suffered from the notable over-approximation and assigned the same set of labels (consisting of 9 elements in one case, and of 18 in the other) to each encountered TextView widget; among them were three strings that are code artifacts and not declared as UI labels. In contrast, FRONTMATTER accurately assigned single labels to the corresponding views, as well as correctly identified 14 labels dynamically assigned to the player_overlay_info TextView.

These two observations are not limited to VLC alone; as we will see, they apply again and again for Android apps.

### 5.2 GATOR/AndroidBench Dataset

In this section, we compare FRONTMATTER against two contenders, GATOR and BACKSTAGE. For this comparison, we use the AndroidBench benchmark of 19 apps built by the GATOR authors for the assessment of their tool [22] and used in follow-up papers; the benchmark is also used to evaluate BACKSTAGE. As in the VLC case study, we also determined the ground truth manually for all applications in the data set.

We manually inspected applications in the same way as we assessed VLC; we downloaded their source code and reconstructed the ground truth. We also used UIautomator to confirm the layout hierarchy and different properties of a UI element. To obtain ground truth, for eight out of 16 apps, we fully analyzed the source code of all activities To compare hierarchies, we associated each UI node with its materialized path in the tree and then matched these paths. We ran all three tools on a machine with 64 cores and gave each of them 10GB of memory. We did not specifically restrict the execution time; still, GATOR could not complete the analysis of Astrid. Since we used the most recent version of GATOR 3.8, its results are different from those reported in [22].

Our results are summarized in Table 1. In the column ‘Identified Views: correct/incorrect/missing’ we report the results of our manual analysis: the number of correctly identified UIs, the number of incorrectly inserted Views, and the number of missed UI elements (in compared to the ground truth).

We also report the following statistics: the number of activities with recognized/undetected layout; the number of UI elements among which we distinguish view containers (i.e. view groups) and...
widgets; the total number of widgets with an id and the number of unique widgets; the number of widgets with at least one label and the total number of labels; the average number of captions per widget.

The observations we made for VLC generalize to this set. **Frontmatter** correctly models the UI hierarchy, sometimes missing the content of custom widgets. It precisely associates widget labels, both of elements with one caption (i.e. buttons) and of text views that store multiple strings, like status messages. Occasionally, **Gator** can find more strings, but almost always it overapproximates and assigns labels to every text widget, with the label-per-widget ratio ranging from 1.18 in TippyTipper to enormous (and highly unrealistic) 202 in K9. (It is hard to conceive a text label that would display more than 200 different strings encoded in the program code.) Our analysis of the ground truth supports this observation. Besides, **Gator** sometimes inserts a lot of duplicate views into the wrong place.

Moreover, labels returned by **Gator** can contain field and method names, and even SQL queries. These strings are used internally in the code, rather than displayed to the user. **Backstage** in general produces more narrow models, but in turn misses elements and text items, sometimes failing to bind an identified layout to an activity.

For four applications, two tools produced almost the same hierarchies with similar label sets. **Frontmatter** did not find status messages in the BarcodeScanner app that **Gator** detected. However, **Gator** assigned these strings incorrectly. For OpenSudoku, **Frontmatter** could not reconstruct the content of a custom widget. On the other hand, **Frontmatter** was able to properly process the SipDroid and SuperGenpass apps, for which **Gator** produced very overapproximated model. A manual investigation of the K9, NPR, and XBMC applications showed that while **Frontmatter** underapproximated and missed widgets sporadically, **Gator** overapproximated and duplicated a significant portion of elements several times.

**Frontmatter** offers precision at the cost of running time: it is significantly slower than **Gator** (on average 8x slower on Android-Bench).

**5.4 Mining at Scale**

Finally, we apply **Frontmatter** on a large scale and construct a database containing tens of thousands of UI models. To this end, we crawled AndroZoo for all latest versions of applications downloaded from the Google Play Store in the first half of 2019. In total we got 72,450 apks. We limit the running time for each app to 10 minutes. Besides, we set a timeout for each **Boomerang** query to 20 seconds.

We expect that our analysis is not suitable for some applications: games usually implement GUI via drawing on canvas, and cross-platform apps are based on specific frameworks like Mono or Xamarin, which implement their own way of building an app extensively using reflection. For 37,991 applications **Frontmatter** reported non-empty results. The analysis of 7180 apps could not finish in time. Other 538 applications crashed Soot with various exceptions. The results of 26741 apks contain a list of activities only. In these cases **Frontmatter** could not relate activities to appropriate layouts.

Most of the undetected associations are induced by limitations covered in Section 4.3. For instance, a lot of apps use special libraries to build the GUI, such as the Data Binding Library by Google or Litho by Facebook, which provide custom UI binding procedures. Besides, the high level of precision can become a bottleneck. We found that for complex applications **Boomerang** queries during layout binding were too slow to meet the timeout. With increased running time **Frontmatter** is able to extract the model.

**5.3 AndroZoo Subset**

To test our findings on an even larger set, we ran **Frontmatter** and **Gator** on a random subset of 1,000 apps from the AndroZoo database. After removing Unity based games and apps created with with common cross-platform frameworks, the subset boiled down to 518 apps. As in the previous experiment, we ran both tools on a machine with 64 cores and gave each of them 10GB of memory, but we restricted the timeout to 10 minutes.

**Frontmatter** produced models for 403/518 = 78% of all apps, whereas **Gator** was successful for 385/518 = 74%. The unsuccessful cases produced timeouts, crashes, and empty models for both tools.

Our previous observations also hold for this dataset: **Gator** retrieves more UI elements (see Table 2). However, **Gator** produced two outliers (for the apps com.bibliocommons.mysapl and com.directworks.dualapps) with more than 70,000 elements in the hierarchy. They account for almost half of the total number of detected elements. A brief manual examination showed that these apps are unlikely to have so many widgets. Moreover, we counted UI elements that occur more than once inside a particular activity of an app (column **Duplicated elements**). Even though the Android system does not prohibit widget reuse, certain views are rarely inflated several times, for **Gator** the ratio of the total number of such elements to the unique ones is more than 40. Along with the extreme number of labels per widget (37.55), this evidence confirms that **Gator** considerably overapproximates. In contrast, **Frontmatter** detected fewer widgets, but with higher precision per label.

**6 USE CASES**

We have aggregated all data collected in Section 5.4 in a SQLite database, allowing us to easily query the GUI dataset.

With simple SQL queries one can get insights into various GUI features of the dataset. For instance, the query

```sql
SELECT DISTINCT pkg, version FROM app-widgets
WHERE (label LIKE '%fingerprint%')
```

lists apps which mention a fingerprint login in their interface. Our database contains 31 such applications.
Another related query

```
SELECT COUNT (DISTINCT pkgs FROM apps_with_login_view)
WHERE (label like '%ForgetPassword%')
OR (label like '%ForgotPassword%')
OR (label like '%resetPassword%')
OR (label like '%recoverPassword%')
```

reveals that 45% of apps which have a login button also have a means to request a lost or forgotten password.

One may be interested how many apps actively ask for (positive) user ratings—706 apps ask to ‘rate us’ according to this query:

```
SELECT COUNT (DISTINCT pkg)
FROM appswidgets WHERE (label like '%rate us%')
OR (label like '%rate 5%')
OR (label like '%rate our%') OR (label like '%rate the app%')
OR (label like '%rate this app%') OR (label like '%rate it%')
```

The dataset also contains information about the drawables used in apps, such as the color or an icon name:

```
SELECT drawable, COUNT (drawable) AS v_o FROM pkgs
WHERE d.drawable_type like '%background%'
GROUP BY drawable ORDER BY v_o DESC
```

shows that the most frequently used background colors are white, black, and gray, which is not surprising.

All these basic features can be combined for further refinement, and of course correlated with additional features obtained from app store analysis (“Rating requests are most prominent in app category X”) or program analysis (“Applications that have a label X also use API Y”).

7 CONCLUSION AND FUTURE WORK

We have introduced FRONTMATTER, a tool to automatically extract user interfaces of Android applications at a large scale with high precision. Given an app, FRONTMATTER statically extracts all accessible screens, the user interface elements, as well as their textual and graphical features, increasing precision over the state of the art. Executed on tens of thousands of real-world apps, FRONTMATTER opens the door for comprehensive mining of mobile user interfaces, jumpstarting empirical research at a large scale. Our own work will focus on deeper analysis of the mined FRONTMATTER data:

- Do interface texts correspond to app descriptions? The set of user interface labels form linguistic concepts, as do the set of words in app descriptions [12]; comparing these might reveal mismatches between user interfaces and functionality.
- Which UI features are common for specific categories? Which ones are uncommon? “Travel” apps would typically sport user interfaces to query locations, book rooms, or book trips; for “Music” apps, we would expect interfaces to play, well, music. But would there be apps that sport unique features found nowhere else?

- Are there specific user interface patterns for specific features? Which are the features typically provided by product pages, by registration pages, by query pages? Many applications require passwords to login. Most of these would also offer to recover passwords, or to register as a new user. Are there apps which require login and which do not provide such features? Should they?
- User interfaces and popularity. Would especially popular apps sport user interface elements that others do not? What is it in their user interfaces that makes popular apps special? Would “polished” interfaces manifest themselves, and how?
- Halls of fame, halls of shame. Just like patterns for good user interfaces, would there be anti-patterns, too? What are the most common mistakes to avoid, and can one detect them from the extracted data? What is the worst interface ever?

To foster replication and extension of our research, FRONTMATTER and the mined user interface data are available under open source and open data licenses at https://bit.ly/3knQHe9

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