Detecting Sensitive Data Disclosure via Bi-directional Text Correlation Analysis

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ABSTRACT

Traditional sensitive data disclosure analysis faces two challenges: to identify sensitive data that is not generated by specific API calls, and to report the potential disclosures when the disclosed data is recognized as sensitive only after the sink operations. We address these issues by developing BiDiTEXT, a novel static technique to detect sensitive data disclosures. BiDiTEXT formulates the problem as a type system, in which variables are typed with the text labels that they encounter (e.g., during key-value pair operations). The type system features a novel bi-directional propagation technique that propagates the variable label sets through forward and backward data-flow. A data disclosure is reported if a parameter at a sink point is typed with a sensitive text label. BiDiTEXT is evaluated on 10,000 Android apps. It reports 4,406 apps that have sensitive data disclosures, with 4,263 apps having log based disclosures and 1,688 having disclosures due to other sinks such as HTTP requests. Existing techniques can only report 64.0% of what BiDiTEXT reports. And manual inspection shows that the false positive rate for BiDiTEXT is 10%.

CCS Concepts

- Software and its engineering → Software testing and debugging; Security and privacy → Software security engineering;

Keywords

Sensitive Data Disclosure, Bi-directional Text Correlation, Android apps

1. INTRODUCTION

Sensitive data disclosure has been a long-standing challenge for data security. By accessing the disclosed sensitive information, adversaries can learn about the system and then conduct attack [28, 25]. A prominent example is the OpenSSL Heartbleed vulnerability disclosed in 2014. The OpenSSL versions with such a flaw allow remote attackers to retrieve sensitive data, for example, user authentication credentials and secret keys [12, 38]. Attackers can then compromise the target systems with the disclosed sensitive information.

The proliferation of mobile devices [13, 33] makes the situation even worse since mobile devices process a lot of sensitive user data. Previous studies showed that it is common that mobile apps undesirably disclose sensitive user information [26, 39, 10]. Many techniques have been proposed that work at the system level or the application level, static or dynamic [21, 9, 14, 8]. Haris et al. provide a comprehensive list of the approaches to detecting sensitive information disclosures in mobile computing [16]. All these approaches require definition of the sensitive data sources, usually certain APIs whose return value is sensitive. With the definition, if forward data flow is observed between taint sources and sinks, disclosure defects are reported. Later, researchers realized that some generic APIs may return sensitive values, depending on the context, although they may return insensitive values in many cases. SUPOR [17] and UIPicker [27] aimed to identify which user inputs on the user interfaces can be sensitive. Then the sensitive inputs are associated with the variables in the code such that static or dynamic forward data flow analysis can be applied to detect the potential sensitive user inputs disclosures. Sensitive user inputs are identified in the context of the user interfaces which contain text or graphical information to instruct what the users should enter.

However, the above solutions still have limitations. Sensitive data may come from generic API methods not related to UI (e.g., loading data from some file or receiving data from network). In these cases, most existing approaches would not work properly. We cannot simply treat the generic APIs as the taint sources as that will lead to a large number of false warnings. In addition, forward data flow analysis is insufficient. In many cases, a piece of data may be first emitted through a sink and then later typed as sensitive. There may not be any forward data flow from the type revelation point to the sink point.

In this paper, we develop BiDiTEXT, a technique to detect data disclosures by examining the text labels correlated with variables. The text labels, either from the code (e.g., the textual keys in key-value pairs) or the UI, provide rich information about the data contained in the variables. BiDiTEXT extracts these labels, and leverages a novel type system to propagate these labels through both backward and forward data flow. Data disclosures are reported when a parameter at a sink point is typed with a sensitive textual label. The bi-directional propagation scheme is unique and different from the traditional unification based type inference systems. It features the capability of avoiding undesirable unification of text labels, enabling a low false positive rate. Backward propagation allows BiDiTEXT to capture cases in which data sensitiveness is revealed after the data is sent through some sink.

Our work makes the following contributions:
class CampaignActivity_20 implements Handler.Callback{
    CampaignActivity act;
    CampaignActivity_20(CampaignActivity a) {
        this.act = a;
    }
    public boolean handleMessage(Message msg) {
        Bundle b = msg.getData();
        String dt = b.getString("data");
        Log.d("CampaignActivity", "Got data back: " + dt);
        return false;
    }
}

class CampaignActivity_20_1 implements Runnable{
    CampaignActivity_20_1(String data) {
        jsonString = data;
    }
    public void run() {
        JSONArray jsonArray = new JSONArray(jsonString);
        int len = jsonArray.length();
        for (int i = 0; i < len; i++) {
            JSONObject json = jsonArray.getJSONObject(i);
            String url = json.getString("avatar_url");
            displayImage(url, iv);
        }
    }
}

Figure 1: Motivating example from app com.buybo.t.android.

- We propose BidText, a novel method to detect sensitive data disclosures. BidText leverages constant text labels and features a novel type system that performs bi-directional text label propagation.
- We implement a prototype of BidText for Android apps, and evaluate it on 10,000 apps. BidText reports 4,406 apps that have sensitive data disclosures, with 4,263 apps having log based disclosures and 1,688 having disclosures due to other sinks such as HTTP requests. Existing techniques [7, 17] can only report 64.0% of what BidText reports. And manual inspection shows that the false positive rate for BidText is 10%.
- BidText is available at https://bitbucket.org/hjandy/toydroid.

Figure 2: Data flow (solid arrows) and type propagation (dashed arrows) for Fig. 1.

is retrieved from the Message object. Then the data string of the message is obtained from the mapping at line 8. Right after that, the data string is written to the log file at line 9. Note that writing to a log file is usually considered as a sink for data disclosures [7, 17, 22] because log files can be accessed by malware. After the logging operation, the app instantiates a Runnable object with the data string at line 10, which runs in the UI thread (line 11) to allow interactions with UI elements.

The data string is transmitted to the Runnable instance via the instantiation at line 10. Inside the constructor at line 17, the data is stored in a field variable jsonString at line 18. When the UI thread is running, the run() method at line 20 is invoked. The data string is converted to a JSONArray object at line 21 which is then iterated. Every element in the array is a JSONObject object with ordered key-value pairs (dashed arrows) for Fig. 1.

Now let’s consider the potential sensitive data disclosure in this running example. Based on the above description, the data falling into the sink at line 9 comes from the Web server. We later know that the data contains some sensitive user account information. In other words, the app retrieves the sensitive user account information from the server and writes it to the local log file without any encryption. This is a typical kind of undesirable information disclosure [24, 40] that emits sensitive information from server such as user account, balance in bank account, and employee salary to local files.

Traditional sensitive data disclosure analysis inspects the data flow between some sensitive source point, for example, an API call whose return value can be easily recognized as sensitive (e.g., TelephonyManager.getDeviceId() in Android), and a sink point (e.g., a file write or a socket send). If forward data flow can be discovered from the source point to the sink point, a disclosure problem is reported. In this example, while we do have data flow from the Web server response to the logging operation but we cannot determine whether the response contains sensitive data from the operations along the data flow. If we treat all data from server sensitive, a lot of false alarms will be produced; but if we simply ignore them, we miss true disclosures as in this example.

Different from the traditional disclosure analysis, our technique

The recent version of Android has substantially mitigated this problem by limiting access to log files. But there are still a large number of devices running old versions of Android. Note that BidText is general to support various configurations of sink points.
relies on the observation that the sensitiveness of data used in applications can be recognized through examining the textual information involved in the operations. Such texts are constant strings in either the code or the user interfaces. We randomly sampled 2,000 Android apps and found that on average each app contains 76.7 constant strings in layout files (i.e., XML files used to statically define UIs) and 151 constant strings in app code. These constant strings often provide rich information about what is being held by the corresponding variables. For example, in Fig. 1, method call json.getString("username") at line 28 uses a constant string "username". We can infer that the JSON object contains some sensitive user ID. Since the JSON object is part of the Web server response, according to the workflow, we can conclude that the response contains sensitive information. Thus the logging operation at line 9 should be reported as a sensitive data disclosure.

Note that even if we recognized that the JSON object at line 28 contains sensitive information, we could not detect the disclosure problem using traditional analysis techniques that try to find forward data flow from source points to sink points. We show the data flow via solid arrows in Fig. 2, starting from retrieving the data from the key-value mapping (line 8). If we treat line 28 as a source point, we cannot get a forward data flow path from the source point to the sink point. Thus the disclosure defect is still missed after we augment traditional techniques with our new sensitive data recognition method.

**BiDText** solves the problem by introducing bi-directional propagation. Instead of propagating tags like tainted and untainted in traditional techniques, our approach uses the constant strings as the tags and propagates both backward and forward. As the dashed arrows in Fig. 2 show, constant text as {"CampaignActivity", "Got data back": "data", "avatar_url", "username", "created_at", "content"}. The first two textual tags are associated with the variable directly at the sink point. Tag "data" is propagated to the variable (at the logging statement) in a forward manner. The remaining texts are propagated to the sink point via a bi-directional manner discussed above.

**BiDText** also associates UI texts to variables. UI often contains texts that also indicate the sensitiveness of data shown on the UI (see [17, 27]). We examine the corresponding layout file to get the texts, add them to the tag set of the related variables and propagate them like the texts found in the code. In the example, we can find several code locations that interact with the UI (e.g., line 33), through which we identify the corresponding layout files to collect UI texts. However, the content of the UI is dynamically created and none of the UI elements holds constant texts. Therefore, no GUI texts are propagated to the sink point in this example.

Next we apply a natural language processing (NLP) technique to the tag set of the sink point to find out if the texts can tell the sensitiveness of the variable dt. Among the collected texts, "username" matches a predefined sensitive keyword. Thus our technique reports a sensitive data disclosure problem for the logging operation at line 9.

### 3. DESIGN

We propose **BiDText**, a static bi-directional text correlation analysis approach, to detect sensitive data disclosures. **BiDText** combines both the bi-directional propagation and the new approach that uses internal constant texts to identify sensitive variables as illustrated in Section 2.

#### 3.1 Language Abstraction

To simplify our discussion, we introduce an abstract language. The language is presented in Fig. 3. We only model the language features that are related to explaining the text correlation analysis and the bi-directional propagation. Others are abstracted away or simplified. As we discussed in Section 2, we leverage the constant texts in the code as well as in the UI to tag variables and determine whether sensitive data is disclosed at sink points. Therefore, constant strings in the code and constant IDs that are associated with UI are of special interest and explicitly modeled in the language. For simplicity, we do not allow constant strings/IDs to appear in complex operations, e.g., binary operations and method calls. For such scenarios, the constant is first assigned to a variable, which is further used in the complex operation. This is similar to how Android apps handle constant values in DEX bytecode. For example, the method call json.getString("username") at line 28 in Fig. 1 is converted to two statements: tmp = "username"; json.getString(tmp).

An invocation to method m(vf) is modeled by two separate statements: call(m,m,vf) passing the actual argument mv to the formal argument vf and v = return(m,vf) returning the value in v in m to v in the caller. The separation allows us clearly model the data flow at the entry and the exit of a method call.

### 3.2 Type System and Bi-directional Propagation

As discussed earlier, we use the constant texts in either the code
or the UI to tag the correlated variables and propagate the tags bidirectionally. We formalize this approach in a type system, i.e., the set of tags associated with a variable is treated as the type of the variable. Since the type is a set, we also call it a type set in this paper. The mappings from variables to their type sets form the context $\Gamma$ of the type system, which is iteratively updated during analysis until a fixed point is reached. For example, at the beginning, $\Gamma$ is empty. Upon a statement $\texttt{tmp = "username"}$, $\Gamma$ is updated to $\{\texttt{tmp : "username"}\}$. At this point, we have $\Gamma \vdash \texttt{tmp} \vdash \{\texttt{username}\}$, which means under context $\Gamma$, variable $\texttt{tmp}$ is typed with set $\{\texttt{username}\}$. In other words, $\Gamma(\texttt{tmp}) = \{\texttt{username}\}$, where $\Gamma(\texttt{tmp})$ evaluates variable $\texttt{tmp}$ in the context to obtain the corresponding set.

When a statement is evaluated, the context may be updated. We use $\Gamma, S \models \Rightarrow \Gamma'$ to indicate that under context $\Gamma$, evaluating statement $S$ updates the context from $\Gamma$ to $\Gamma'$. We use $\Gamma \models [v : T] \Gamma'$ to represent an update to the context. Specifically, if no mapping is found for variable $v$ in context $\Gamma$, the mapping is added into the context. But if there exists some mapping for $v$, the rule substitutes the existing type set for $v$ with the given type set $T$. Multiple mappings can be updated simultaneously, e.g., $\{\texttt{var : T}, \texttt{var'} : T'\} \Gamma$ updates the context for two variables $\texttt{var}$ and $\texttt{var'}$.

Bi-directional propagation. When a statement is evaluated, the context may be updated. We use $\Gamma, S \models \Rightarrow \Gamma'$ to indicate that under context $\Gamma$, evaluating statement $S$ updates the context from $\Gamma$ to $\Gamma'$. We use $\Gamma \models [v : T] \Gamma'$ to represent an update to the context. Specifically, if no mapping is found for variable $v$ in context $\Gamma$, the mapping is added into the context. But if there exists some mapping for $v$, the rule substitutes the existing type set for $v$ with the given type set $T$. Multiple mappings can be updated simultaneously, e.g., $\{\texttt{var : T}, \texttt{var'} : T'\} \Gamma$ updates the context for two variables $\texttt{var}$ and $\texttt{var'}$.

Bi-directional propagation rule.

### 3.2.1 Binding Constant Value

As mentioned earlier, we focus on constant texts in the code and the constant Ids that are associated to UI. An assignment of a constant string to a variable adds a new mapping from the variable to a set holding the string to the context. For a constant Id, we need to make sure the Id is indeed a resource Id (e.g., layout Id in Android apps or an Id for a specific UI element). This check is modeled by predicate resource_id(). If the prerequisite satisfies, updating the context is similar to the constant string assignment, except that the type set is the extracted texts from the corresponding UI through function extract_text(). For instance, if the constant Id is associated with a typical login screen, the extracted text set may often be $\{\texttt{Username, Password, Login}\}$.

#### 3.2.2 Propagation for Assignment

Rule Unary-Assignment updates the context for both the LHS and RHS variables with the union of the two separate type sets.

By rule [binary-assignment], we update the variable $\texttt{username}$ with the union of data obtained from the two sources. For a constant Id, we need to check whether there is a sensitive tag (by the operation). Thus, as specified by Rule Binary-Assignment, the propagation is conducted as follows. The type sets of the two RHS variables are unioned and inserted to the type set of the LHS variable. Intuitively, assuming the two RHS variables are $\texttt{v_1}$ and $\texttt{v_2}$, being associated with a sensitive tag does not entail $\texttt{v_2}$ having the same sensitive tag (by the operation). Thus, as specified by Rule Binary-Assignment, the propagation is conducted as follows. The type sets of the RHS variables are unioned and inserted to the type set of the LHS variable. Only the part of the LHS type set that is not in the type set of $\texttt{v_2}$ is propagated to $\texttt{v_2}$ and only the part of the LHS type set that is not in the type set of $\texttt{v_2}$ is propagated to $\texttt{v_1}$. There is a corner case in which the two RHS variables are the same one, e.g., $\texttt{a = b}$ and $\texttt{b = c}$. The updated type set for $\texttt{b}$ is $\Gamma(b) \cup \Gamma(a) = \Gamma(b)$, which is equal to $\Gamma(a) \cup \Gamma(b)$. In other words, this special case behaves the same as a unary assignment. The propagation for $\phi$ statements has the same nature (Rule Phi-Assignment).

We use a real example from an Android app com.mojo.animewallpaper to show how our propagation rule for $\phi$ statements eliminates false alarms. The simplified code snippet is shown in Fig. 5a. If a certain condition satisfies, the device Id is assigned to variable $x$ at line 2. The detail of acquiring the device Id is omitted but even-
if (...) {
  x = getDeviceId(); // x is tagged with "android_id"
} else {
  x = some_random_uuid(); // gen random value for x
  log.d("Random: ", x); // sink
}
use(x);

(a) Simplified code snippet.

android_id
\xrightarrow{\text{src \at \phi}}
x @ 7 = \phi(x @ 2, x @ 4)
\xrightarrow{\text{sink \at 5}} x @ 4

(b) Data flow and type propagation.

Figure 5: Code example and bi-directional propagation for \( \phi \) from app com.mojo.animationwallpaper.

Actually a constant string "android_id" is added to the type set of \( x \). If the condition doesn't satisfy, a random value is generated as the requested Id at line 4 and stored to variable \( x \), which is immediately used at a sink point at line 5. After the branch, variable \( x \), whose value is either the real device Id or a random value, is used elsewhere.

From the perspective of \( \phi \) representation, we know that right before the \( x \) is used at line 7, we have a \( \phi \) statement as \( x @ 7 = \phi(x @ 2, x @ 4) \). The data flow for the several occurrences of \( x \) is described by the solid arrows in Fig. 5b and the propagation relations are shown by dashed arrows.

Consider a naive bi-directional propagation that simply unions all the type sets. During the first iteration, "android_id" is propagated to \( x @ 7 \) via forward propagation. Nothing is backwardly propagated to \( x @ 2 \) or \( x @ 4 \) from \( x @ 7 \). Therefore, at the end of the first iteration, \( \Gamma(x @ 2) = \Gamma(x @ 7) = \{ \text{android_id} \} \) and \( \Gamma(x @ 4) = \emptyset \). Then during the second iteration, if we directly propagate the type set of \( x @ 7 \) to both \( x @ 2 \) and \( x @ 4 \), we would get \( \Gamma(x @ 4) = \{ \text{android_id} \} \), which is later propagated to the sink point at line 5. Thus a sensitive data disclosure is reported which is a false alarm.

In contrast, our propagation rule supports the mutual exclusion of the type sets in the two respective branches. Specifically, we only backwardly propagate \( \Gamma(x @ 7) = \Gamma(x @ 2) \), i.e., an empty set, to \( x @ 4 \). At last, the type set of \( x @ 4 \) stays unchanged and the sink point does not observe any sensitive type for the variable. Thus no sensitive data disclosure is reported.

3.2.3 Propagation for Method Calls

Propagation through a method call occurs at passing argument from the caller and returning value from the callee. Therefore, we define two separate rules for these two events. Note that these two rules handle method calls whose implementations are included in the analysis. We also propose a special rule for propagation over API functions, the implementations of which are typically invisible during analysis.

Rules Method-Call-Param and Method-Call-Return union the type sets. A concrete example for rule Method-Call-Param is the instantiation call at line 10 in Fig. 1. The constructor at line 17 is invoked and the value held by variable \( dt \) is passed to variable \( data \). Then constant value "data" associated with \( dt \) is propagated to \( data \) and "username" associated with \( data \) is backwardly propagated to \( dt \).

Rule API-Call does not directly propagate the type sets between parameters and the return value. BidiText relies on the model for the API function for proper propagation. Prior static taint analysis [7, 14] have shown that it is effective to simply propagate from all parameters to the return value and the receiver object (i.e., \( this \) reference in instance method calls). However, this naive approach does not work well in bi-directional propagation. We need to investigate the type correlations for the variables involved in an API call, including all the parameters and the return value.

Some API functions may not support fully bi-directional propagation among the variables. For example, variable \( name \) can be used to type value in statement \( value=\text{HashMap} \cdot \text{get} (\text{name}) \) but not the reverse according to the semantics. Specifically, if \( name \) holds some sensitive constant strings, we can infer that value may hold sensitive information, but not the other way around. If we ignore this reference, after evaluating the statement under context \( \Gamma \), we have \( \Gamma'(name) = \Gamma(name) \) and \( \Gamma'(value) = \Gamma(value) \cup \Gamma(name) \). Many API functions, on the other hand, can be applied with the naive propagation policy, unifying the type sets of all variables. For example, we have \( \Gamma'(ret) = \Gamma(str) = \Gamma(ret) \cup \Gamma(str) \) after evaluating statement \( ret = \text{str.toUpperCase()} \) under context \( \Gamma \). In the rule, the behavior depends on functions \( \text{model_fwd()} \) and \( \text{model_bwd()} \) which define the propagation policies from \( v_a \) to \( v_b \) and from \( v_b \) to \( v_a \), respectively.

We formalized our approach to identifying and bi-directionally propagating constant texts in a type system and developed a set of propagation rules based on our abstract language in Fig. 3. While the rules are general for our language, in practice we need to perform a number of enhancements to the rules to handle real-world language/program features. These enhancements are discussed in next section.

3.3 Practical Enhancements

There are two main practical enhancements to our formal model that are critical to the effectiveness of BidiText.

3.3.1 Check and Alert

It is common in real programs to prompt some alerts to the user or write to the log file if a condition check fails. In this case, we can use the alert/log message to infer what the corresponding variables involved in the condition check may hold. For example, an Android app can alert the user about some previous errors, e.g., some required inputs are missing, by showing a short message on the screen. A typical implementation looks like the following.

```java
if (str == null || str.isEmpty())
Toast.makeText(this, "Please Enter Password", 1);```

We can type variable \( str \) with the constant text "Please Enter Password" and propagate it through the aforementioned rules.

The abstraction and the corresponding propagation rule are shown in Fig. 6. This applies to a set of API functions, called the alert functions.

3.3.2 String Concatenation

String concatenation is common in real-world apps. A concatenation operation may involve both constant values and multiple variables. If we simply union the type sets of all the involved variables and update the variables with resultant type set, we may introduce false positives. Furthermore, the associations between the constant strings (involved in the concatenation) and the variables (involved in the concatenation) also need to be properly identified.
A simple strategy that associates all constant strings to all variables also produces a lot of false positives. For example, building a URL often involves multiple variables, each holding a value as part of the HTTP request. The variables can be either sensitive (e.g., password) or insensitive (e.g., user comment). We need to distinguish the exact types correlated to the variables. Consider the following example, in which a typical URL is constructed.

```java
url = "&pwd=" + un + "http://.../login?username=" + p;
```

At the bytecode level, the above statement is converted to:

```java
url = "&pwd=" + un + "http://.../login?username=" + p;
```

Assume the model for API `StringBuilder.append()` entails fully bi-directional propagation, i.e., we propagate the type sets of all involved variables to each other. The constant string "http://.../login?username=" is propagated to `builder0`, `builder1`, `builder2`, and `builder3` and `p`. A later analysis would indicate that both `un` and `p` are associated with the sensitive text "username", which is incorrect for variable `p`. Similarly, "&pwd=" will be propagated to `un`, which causes a false alarm.

However, if we do not allow the propagation from the `StringBuilder` instance (e.g., `builder0`) to the appended variable (e.g., `un`), that is, the red and blue edges are removed from Fig.7, then neither "username" nor "pwd" could be propagated to `un` or `p`. As a result, we cannot infer that these two variables may hold sensitive information.

The expected propagation, according to the semantics of the URL string, is that "username" is propagated to `un`, and "pwd" to `p`, exclusively. We observe that it is impossible to enforce such propagation through API models (e.g., the model for `append()`) as an API call may only represent a local operation that does not have the global view of the concatenated string. To address the problem, we need to analyze the entire concatenated string produced at the end. In our example, we ought to examine the final result associated with `url` in order to associate the appropriate text to variables `un` and `p`. Therefore, we need to enhance our type system with the following string analysis.

Rule `Str-API` in Fig. 8 determines if an API call has a string argument `v_0` with a well-defined format through function `api_w_str()`. For example, new `URL(url)` is such a function as it implies the variable `str` is a string of the url format. If so, the string is of interest. `BtdText` computes an abstract string `E` for `v_0`, which is stored in a string context `Σ` that maps a variable to an abstract string. An abstract string is a regular expression including both constant strings and variables. The abstract string is partitioned by the function `string_partition()` so that the variables in the regular expression are associated with the appropriate texts. For the above example, the rule produces `Γ′ = {un : {username}, p : {pwd}}`. We then combine `Γ′` into the current context `Γ` and further propagate the generated texts. Next, we will first explain how the abstract strings are computed and then the `string_partition()` function.

The rules for computing abstract strings are shown in Fig. 9. The interpretation of the rules is similar to that for our type system. One difference is that we use the string context `Σ` instead of the type context `Γ`. Rule `Str-typ` simply concatenates the two abstract strings of the operands. Rule `Str-Const-Assign` handles the constant string handled when the second operand does not have mapping and the variable itself is concatenated to the resulting string. It is similarly handled when the second operand does not have mapping and the rule is elided. Rule `Str-Const-Assign` handles the constant string assignment.

Rule `Str-If` specifies that for a conditional statement, BtDText computes the string contexts for the true and false branches separately. For any variable that is present in the string context `s`, the resulting abstract string is an alternation of the abstract strings in the branches. Consider the following code snippet.

```java
if (c) str := strcat("&User Id=" + sId); else str := strcat("&session Id=" + sId);
```

The abstract string for variable `str` is ("&User Id=". `sId") ("&session Id=". `sId")

Rule `Str-LOOP-Closure` specifies that for a loop, `BtdText` first computes the string context for the loop body with an empty string context and then aggregates the resulting abstract strings to the original string context. In particular, if the abstract string for a variable `v` also contains `v`, it indicates the resulting string has recursive structure (caused by the loop), `BtdText` hence associates `v` to a kleene closure in the context outside the loop. Tail recursion is similarly handled. Currently, `BtdText` only handles regular languages, which is sufficient for most cases we encountered. Rule `Str-LOOP-Simple` specifies that if there is no recursive structure, the abstract strings are simply copied from the context of the loop body to the context outside the loop. For the following example, `BtdText` produces the abstract string "Output:". "(". for variable `str`.

```java
str := "Output:";
for (...) str := strcat(str, "*");
```

As shown by Rule `Str-API`, the abstract string at an API that specifies the format of the string is partitioned to acquire the texts for the variables within the abstract string. This is done by calling
a string partition(). This function has a number of built-in parsers that can parse the different string formats based on the API name. For example, if the API is URL (), it uses the parser for url. Particularly, the parser searches for symbol “?”, the part after the symbol is parsed by “(^\?=\?=|^\?=\?=\?\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?=\?
5.2 Unification vs. Bi-directional Propagation

In classic type inference, given an assignment statement such as \( z = x + y \) and \( z = \phi(x, y) \), the updated type sets of \( x \), \( y \), and \( z \) are the union of all three original type sets. In Section 3.2.2 (Rules Binary-Assignment and Phi-Assignment in Fig. 4), we mentioned that such a unification based approach may produce a lot of false positives and hence B\(_{\text{IDTEXT}}\) makes use of a bi-directional propagation strategy that avoids propagating type sets between right-hand-side operands (i.e., \( x \) and \( y \) in the example). In this experiment, we want to compare these two propagation strategies.

Due to the lack of ground truth, such a study requires manually inspecting the reported disclosure defects and determining if they are false positives. Among the 2000 apps tested in the pilot study, we selected the first 60 apps whose data disclosure path (i.e., the data flow subgraph that includes the path from the source to the sink and the path that the sensitive text is propagated from its origin to the sink) involves \( \phi \) statements and/or binary operations with the unification based propagation policy. We re-run B\(_{\text{IDTEXT}}\) on the 60 apps with the bi-directional propagation policy and compare the two sets of results.

Among these 60 apps, 42 of them are reported by both the unification policy and the bi-directional policy; 25 of them contains flows only reported by the unification policy. Note that the two do not add up to 60 because some apps have multiple reported disclosures, some being reported by both policies and the others being only reported by the unification policy. We manually studied the 25 cases reported by the unification policy and found that they are all false positives. We have shown one sample false positive in Section 3.2.2.

5.3 Large Scale Evaluation

In this experiment, we use 10,000 apps not covered by the pilot study. The apps have a minimum size of 6.46KB for the APK files and a maximum size of 49.94MB. The average size of the APK files is 9.17MB. Among these apps, there are two that do not contain any DEX bytecode in the APK files. For the remaining apps, the minimum size of the bytecode files (classes.dex) is 452 bytes and the maximum size is 10.32MB. The average size of the bytecode files is 2.53MB.

5.3.1 Results

The total analysis time for the 10,000 apps is 587.6 hours. Fig. 10 presents the distribution of the cumulative analysis time for all the 10,000 apps. We divide the total analysis time into three parts according to how the analysis on an app terminates. As mentioned above, we set the analysis timeout to 20 minutes for each app. In our evaluation, 856 apps (8.56%) time out and the total analysis time account for 49% of the total time consumed for the 10,000 apps. We have 293 other apps of which the analysis ran out of memory. The total time for these apps accounts for 9%. For the remaining 8,852 apps that finished normally take only 42% of the total analysis time. Observe in Fig. 10 that the first 7,500 apps take less than 15% of the total time. Among the 8,852 apps, the minimum analysis time is 0.2 seconds and the maximum time is 1197.4 seconds. The median is 24.9 seconds while the average time is 99.9 seconds. The largest app that terminates normally has the APK size of 49.94MB, and the bytecode size of 10.32MB.

Overall, B\(_{\text{IDTEXT}}\) reports 4,406 apps with sensitive data disclosure problems. We show the analysis time distribution of these apps in Fig. 11. The blue bars show the number of apps that finished within a time period. For instance, 472 apps took more than 5 minutes but less than 10 minutes. We also see that 27 apps timed out in the experiments, although partial results were collected before the analysis terminated. The red line presents the cumulative analysis time: 93.0% of the apps were analyzed within 10 minutes. We can conclude that B\(_{\text{IDTEXT}}\) is efficient to be applied to market-scaled apps.

We also show the breakdown of the 4,406 apps by the sources of data disclosures in Fig. 12a. There are three types of sources: (1) TEXT – constant texts in the code that denote sensitive data; (2) API – sensitive API (recall that B\(_{\text{IDTEXT}}\) also detects data disclosures originating from sensitive APIs by associated artificial texts to the source APIs such as Location.getLatitude()); and (3) UI – constant texts retrieved from user interfaces that denote sensitive data. Observe that the majority of disclosures are/can be detected by the sensitive text labels. Some data disclosure defects can be recognized through multiple sources (e.g., TEXT+API), meaning that there are some (bi-directional) data flow paths from a sensitive API to a sink and from some constant text to the same sink. Consider the following example. The data flow path \( 2 \rightarrow 6 \rightarrow 7 \) denotes a disclosure originating from TEXT (i.e., \texttt{"android_id"}) and the path \( 4 \rightarrow 6 \rightarrow 7 \) denotes a disclosure originating from API (i.e., \texttt{getDeviceId()}).

```java
if (!fails_to_obtain_imei()) {
    id = Settings.Secure.getString(resolver, "android_id");
} else {
    id = telephonyManager.getDeviceId();
}
json.putString("id", id);
http_sink(json.toString()); // sink
```

The breakdown of the apps by the sink types is shown in Fig. 12b. Note that 64.9% of the reported apps contain disclosures due to logging. Although data disclosure through logging is substantially
mitigated by access control in the latest version of Android, it is still a security concern for legacy Android systems such that most existing works [7, 22, 17] report these disclosures. About 38.3% of the reported apps (16.9% of all the apps evaluated) contain sensitive data disclosures due to non-to nal-sinking sinks. They are serious threats even in the latest Android systems.

Fig. 13 shows how BidText compares with an implementation of the traditional taint tracking technique (tracking disclosures from source APIs through forward data-flow similar to [14]) and SUPOR [17], which is a technique that tracks disclosures from sensitive UI elements (e.g., input boxes) through forward data-flow. BidText always reports a super-set of those reported by the classic tainting and SUPOR. In the figure, the numbers of apps reported by tainting and SUPOR are normalized to those reported by BidText. Observe that they only report 17.5% and 53.9% of those reported by BidText, respectively. Even combining the two can only detect 64.0%. If only taking non-logging disclosures into account, they report 15.3% and 60.4% of those reported by BidText. This attributes to both the new text label correlation analysis and the bi-directional type set propagation strategy.

We present the length distribution of the emitted data disclosure paths for the 4,406 apps in Fig. 14. Though some paths tend to be very long (more than 80 elements), most of them are relatively short. More than 75% of the paths require less than 30 steps from the origination of the sensitive texts to the sink points.

**False Positives and False Negatives.** It is critical to understand the quality of the reported defects. Due to the lack of ground truth, we had to perform manual inspection. Studying the full set of results is infeasible. Hence, we randomly chose 100 reported apps with a uniform size distribution for manual inspection. The results are presented in Table 1.

The columns indicate the sources of the disclosures. Row Total shows the total number of reported apps for each sources. Row Only shows the number of apps that only have reported disclosures falling into one category. The last row shows the number of false positives.

Observe that the 10 false positives are exclusive. Therefore, the false positive rate is 10%. The causes for false positives will be discussed in Section 5.3.3. We do not count the false negatives because we don’t have the ground truth.

Among the 84 apps where disclosures are reported by code text analysis, 62 apps contain paths that can be only detected by our approach via text correlation analysis, i.e., the data used at sink points neither come from any UI inputs nor from traditional source APIs. In other words, 62 of them cannot be detected by classic tainting or SUPOR. This ratio is consistent with that in Fig. 13 for the larger experiment. The other reported disclosures have the sensitive data coming from these two categories of sources. They are reported by both BidText and the existing technique(s). Another interesting finding is that BidText often produces a shorter disclosure path.

A typical scenario is that there is a long data flow path from a UI input element to a sink. However, mid way through the path, the (sensitive) data is put/get to/from some container with a sensitive textual key, which allows BidText to report a shorter path from the put/get operation to the sink. The benefits of shorter paths are two-folded: less human efforts needed for inspection and detecting more disclosures (because the full path from the source points to the sink points might be complicated, involving inter-component communications, such that the tool may fail to traverse the full path).

**5.3.2 Case Studies**

We observe many cases in which sensitive textual keys appear together with data in key-value operations, e.g., constructing a name value pair (e.g., com.gunsound.eddy.fafapro), inserting data into a hash map (e.g., me.tango.fishepic), retrieving/adding data to persistent storage through an instance of SharedPreferences (e.g., com.ifreeindia.sms_mazaau or putting data into a JSON object (e.g., com.mobilegustro.war.battle.airforce). BidText recognizes the sensitiveness of corresponding data via text correlation analysis.

In the following, we show a code snippet adopted from app com.pro.find.differences that discloses sensitive device information to Web servers.

```java
// sink
sink(id);
```

We observe many cases in which sensitive textual keys appear together with data in key-value operations, e.g., constructing a name value pair (e.g., com.gunsound.eddy.fafapro), inserting data into a hash map (e.g., me.tango.fishepic), retrieving/adding data to persistent storage through an instance of SharedPreferences (e.g., com.ifreeindia.sms_mazaau or putting data into a JSON object (e.g., com.mobilegustro.war.battle.airforce). BidText recognizes the sensitiveness of corresponding data via text correlation analysis.

In the following, we show a code snippet adopted from app com.pro.find.differences that discloses sensitive device information to Web servers.

```java
1 void obtainDeviceInfo() {
2 TCore.aid = Settings.Secure.getString(resolver, 
3 "android_id");
4 }
5
6 void connectWebServer() {
7 Map map = new HashMap();
8 map.put("android_id", TCore.aid);
9 String params = convertURLParams(map); // omitted
10 http_sink(params); // sink
11 }
12
13 void safePut(Map map, String k, String v) {
14 map.put(k, v);
15 }
```

The method call at line 2 returns system information based on the given key value. For example, a unique Id for the device is obtained if "android_id" is given as the key. If the key is "enabled_input_methods", the return value contains a list of input methods that are currently enabled. Therefore, the sensitiveness of the return value depends on the key. BidText works by correlating the textual key with the return variable to decide whether a later sink operation involves sensitive data or not.

In the above example, the variable TCore.aid is typed with the constant text "android_id" at line 2, which is later propagated to parameter v of method safePut() at line 10. v is inserted into the hash map at line 11. Note that "android_id" at line 6 is propagated to @7 which is further propagated to the hash map and variable v according to the corresponding API model for propagation. Along the data flow, the constant text is propagated to params@7 that is eventually used at the sink point at line 8. BidText reports the data disclosure.

**5.3.3 False Positives**

One of the 10 false positives is caused by unmodeled API functions. The corresponding code snippet is from app at.zuggabecka.radiofm4.

```java
1 uidx = cursor.getColumnIndex("username");
2 idx = cursor.getColumnIndex("_id");
3 id = cursor.getLong(iidx);
4 sink(id);
```

At line 1, a sensitive keyword "username" is correlated with the receiver object cursor that is related to a database query. Then all uses of cursor propagate the text label to other variables, e.g., the return value of a relevant method call. Thus, id at line 3 is typed
with “username”. Later when it is used at a sink point, BiDText reports a sensitive data disclosure after analyzing the corresponding type set. To remove this false alarm, we can build a model for API Cursor.getColumnIndex(key) to only propagate type set from key to the return value, avoiding propagating to the receiver object. Then in the above code snippet, only variable uidx@1 is typed with “username”. Variable id that appears at the sink point is only typed with “id” which is not considered as a sensitive keyword. Therefore there is no disclosure problem with the model.

All the other nine false positives are caused by incorrect recognition of text, two for code text and seven for UI text.

App com.netcosports.andalpineski contains a text label as “Apps-lang[apps_lng_iso2]” which indicates the language of the app. However, it contains a predefined sensitive keyword “lng” which is mostly used as an abbreviation of “longitude”. Failing to understand the meaning of the text, BiDText incorrectly reports a sensitive data disclosure.

App com.wactiveportsmouthcollege has a UI text of “Pin to desktop” where sensitive keyword “Pin” is used as a verb. Failing to understand it leads to a false positive. All other false positives have similar causes – sensitive keywords in a phrase or sentence do not indicate any sensitive information. Possible solutions for this type of false positives include integrating more advanced NLP techniques with program analysis to understand the meanings of the text.

5.4 Discussion
One limitation of BiDText lies in that the text in code may not be in a generalized format. For example, some developers use “lng” for “longitude” whereas others use “long” for it, which is a more general word in English. If we treat “long” as a sensitive keyword, we can expect many false positives. In addition, developers tend to combine several words (or abbreviations) into a single word, which makes it more difficult to determine whether the correlated data are sensitive or not.

In the future, we plan to improve our approach in the following aspects. The first one is to discover text labels in the names of method calls, if they are not obfuscated, and variable/field names. The second improvement is to consider code comments if source code is available. The third one is to improve the NLP aspect by putting the keywords in their program context. Doing so, we may be able to recognize “long” indeed means longitude.

6. RELATED WORK
A lot of prior research has focused on detecting sensitive data disclosures, either statically or dynamically, for mobile apps [14, 7, 8, 9, 15]. Most of them consider specific APIs as sensitive source points while BiDText analyzes text labels to determine if a variable can hold sensitive data. SUSI [32] gives a comprehensive list of the data sources in Android, but it does not assume the data obtained from the sources must be sensitive. In addition, even if the state-of-the-art static detectors, e.g., FlowDroid [7] and DroidSafe [15], had been enhanced with various ways of determining data sensitiveness, they would likely not be able to detect some sensitive data disclosures reported by BiDText such as our motivating example, where the sensitiveness of the data is determined after the sink point and there is no forward data-flow from the sensitiveness revelation point and the sink point. BiDText, however, leverages bi-directional propagation to address this problem.

Huang et al. developed type-based taint analysis to detect information leaks in Java-based Web applications and Android apps via type inference [19, 20]. They abstract the information flow analysis into a type system and check if any type error occurs. Their technique scales well without using advanced points-to analysis [7, 15]. Their technique still follows the traditional definition of data disclosure, which is a forward data flow path from the source to the sink. In other words, it does not propagate data sensitiveness in a backward fashion. As such, it may not be able to report many disclosures reported by BiDText, including the motivating example. Furthermore, their type system does not leverage text information. Ernst et al. also developed a type-based taint analysis system [11]. Their technique associates a few (security) types such as LOCATION, INTERNET, and SMS to sources and sinks and have a set of predefined policies such as LOCATION can only be compatible, or type-checked, with INTERNET. So if LOCATION reaches a program point with the SMS type, a leak is reported. Their flow analysis is forward whereas BiDText is bi-directional. And BiDText leverages text labels.

SUPOR [17] and UIPicker [27] discover sensitive information on user interfaces through static analysis. However, they essentially belong to the traditional forward data-flow based techniques. AsDroid [18] collects the set of API calls in an event handler and compares the meaning of these API calls with the UI text of the event to detect unwanted/unexpected app behavior. In contrast, BiDText types individual variables in the program with text labels and leverages a type system that allows bi-directional propagation. Researchers also combine code and comment analysis to detect bugs or inconsistencies [35, 36, 37]. We envision comment analysis can leverage our bi-directional type system so that the information in comments can be leveraged to analyze fine-grained and in-depth app behavior. In addition, WHYPER [29] and AutoCog [31] apply NLP techniques to app’s descriptions to obtain a comprehensive view of the app and check if the required permissions are appropriately specified in the descriptions. Besides, [30] and [41] apply NLP techniques on API descriptions or documents to infer method specifications. We can leverage these techniques to automate the generation of API models used in BiDText.

7. CONCLUSION
We propose BiDText, a novel static technique to detect sensitive data disclosures. BiDText identifies text labels appearing in both code and UI, treats them as types, associates them to the corresponding variables, bi-directionally propagates the types through data flow and eventually attributes them to sink points that potentially disclose sensitive information. At the end, the parameters at the sink points have type sets of correlated texts. Textual analysis is applied to the type sets to determine if the variables may hold sensitive data. We implement BiDText and evaluate it on 10,000 apps downloaded from Google Play store. BiDText reports 4,406 apps that have sensitive data disclosure problems including 4,263 apps disclosing sensitive information through logging and 1,688 through non-log channels. Existing techniques can only report 64.0% of cases reported by BiDText. Manual inspection shows the false positive rate is 10%. The overhead of BiDText is reasonable.

8. ACKNOWLEDGEMENTS
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9. ARTIFACT DESCRIPTION
This artifact provides an executable environment of BidTEXT. The goal is to reproduce the results shown in the paper, as well as to let the users be able to apply BidTEXT on Android apps of their interest.

9.1 Where is the artifact?
The source code is publicly available at https://bitbucket.org/hjjandy/toydroid.bidtext. Gradle [3] build is supported. And JDK 7 or newer versions is required to compile the source code. A virtual machine (VM) image with Ubuntu 14.04 can be found at: https://github.com/hjjandy/FSE16-BidText-Artifacts-VM. It is created by Oracle VM VirtualBox [4]. The VM contains the source code, executables and a small set of test apps. It has been tested on Windows 10 and Ubuntu 14.04, but not on MacOs. The users can also download the executables and the test apps at https://github.com/hjjandy/FSE16-BidText-Artifacts. It provides support to execute the tool on both Windows and Linux if Java 7 or newer versions with AMD64 architecture has been installed. Git LFS [2] is required to clone the repository. If the users encounter an IOException when BidTEXT tries to load the parser from englishPCFG.ser.gz, please check if the models of Stanford Parser (“stanford-parser-3.4.1-models.jar”) have been downloaded correctly via Git LFS.

9.2 What are contained?
In the HOME directory of the VM, one file and three folders are related to the artifacts.

File “FSE16-Artifacts-Eval-README” is a detailed description of the artifacts, including how to run the tool and how to understand the results. It also contains some issues that need special attention to run the tool well.

Folder “BidTEXT-Source” contains a full copy of the source code. The users can update it via “git pull”. “BidTEXT-TestApps” contains a portion of Android apps used in the paper. Inside it, there are four special cases, corresponding to the four examples presented in the paper. They are the motivation example (Fig. 1 in Section 2), the example for bi-directional propagation on PHI statement (Fig. 5 in Section 3.2.2), the example of two different types of sources flowing to the same sink (Section 5.3.1) and the case study in Section 5.3.2. Besides, sub-folder “Others” contains the 100 apps used to measure the accuracy of BidTEXT, whose results are presented in Table 1. “BidTEXT-Bin” contains the necessary libraries, configurations and scripts to execute BidTEXT. Note that it is infeasible to host all the apps used in the paper due to the sheer volume of the apps.

9.3 How to run the tool?
In order to apply the tool on an Android app, the user can run it on a terminal under the folder “BidTEXT-Bin”: ./RUN Path_to_APK. The user can also use the four start scripts to perform analysis on the four corresponding cases. For example, ./Motivation is equal to ./RUN $HOME/BidTEXT-TestApps/Motivation/com.buycott.android-22.apk. If the users want to test the 100 apps, just execute ./Eval-100.

Since BidTEXT requires a lot of memory to perform analysis, the user is required to allocate enough memory for the VM when creating a VM in VirtualBox. It should be at least 5GB because the default setting of JVM heap size for running BidTEXT in the VM is 4GB, which is not enough to evaluate all the 100 apps. We suggest 12GB to evaluate the 100 apps. The users can modify “bidtext.prog” to set a larger JVM heap size for BidTEXT.

The non-VM artifacts also contain start scripts (batch files) to allow easy execution of BidTEXT on Windows. The commands and the settings are the same as in the VM.

9.4 How to understand the results?
After analyzing an APK file, BidTEXT generates the results (if reported any) in folder “APK name.bidtext” which is aside the APK file. Each reported sink point has an individual result file named “idx.Sink_Type.txt”, e.g., 384.LOG.txt. The result file contains the sink API and the enclosing method of the sink. For each identified sensitive textual label, surrounded by “********”, the propagation path is listed. Each path element is the String representation of a WALA [6] Statement, an IR used during the analysis. In the following, we show part of the results for the motivation example.

Note that we did some simplification for readability.

```
****username********
2 NORMAL_RET_CALLER:Node: <CampaignActivity$2051, run(V) V> run(V) 66 = invokevirtual JJSONObject, get(String(String): 18, 64
3 NORMAL_RET_CALLER:Node: <CampaignActivity$2051, run(V) V> run(V) 18 = invokevirtual JJSONObject, (int)JJSONObject> 5, 172
```

NORMAL_RET_CALLER is the type of the Statement and “Node” indicates the location of the statement. The numbers are the variables values, distinct for any SSA variables. For example, “66” can be treated as a variable v66, which can only be defined once in the enclosing method. For more details about the representation, please refer to WALA document. The sensitive textual label “username” propagates from line 1, which is a method invocation. Through inspecting the app’s code, we know that the label is a constant string stored in v64 while the JSON object is associated with v18. In the second statement, we see that v18 is the return value of a method call. That means, the two statements constitute a backward propagation. Please refer to Fig. 1 to get a better understanding of the motivation example.

10. REFERENCES
[11] ERNST, M. D., JUST, R., MILLSTEIN, S., DIETL, W., Pernsteiner, S., ROESNER, F., KOSCHER, K., BARROS,


[19] Huang, W., Dong, Y., and Milanova, A. Type-based taint analysis for Java Web applications. In FASE (2014).


