Android Taint Flow Analysis for App Sets

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*presenting
Motivation

- Detect malicious apps that leak sensitive data.
  - E.g., leak contacts list to marketing company.
  - “All or nothing” permission model.

- Apps can collude to leak data.
  - Evades precise detection if only analyzed individually.

- We build upon FlowDroid.
  - FlowDroid alone handles only intra-component flows.
  - We extend it to handle inter-app flows.
Introduction: Android

- Android apps have four types of **components**: 
  - Activities **(our focus)**
  - Services
  - Content providers
  - Broadcast receivers

- **Intents** are messages to components.
  - Explicit or implicit designation of recipient

- Components declare **intent filters** to receive implicit intents.

- Matched based on properties of intents, e.g.:
  - Action string (e.g., “android.intent.action.VIEW”)
  - Data MIME type (e.g., “image/png”)
Taint Analysis tracks the flow of sensitive data.
  - Can be static analysis or dynamic analysis.
  - Our analysis is static.

We build upon existing Android static analyses:
  - FlowDroid [1]: finds intra-component information flow
  - Epicc [2]: identifies intent specifications


Our Contribution

- We developed a static analyzer called “DidFail” (“Droid Intent Data Flow Analysis for Information Leakage”).
  - Finds flows of sensitive data across app boundaries.
  - Source code and binaries available at: (or google “DidFail SOAP”) http://www.cert.org/secure-coding/tools/didfail.cfm

- Two-phase analysis:
  1. Analyze each app in isolation.
  2. Use the result of Phase-1 analysis to determine inter-app flows.

- We tested our analyzer on two sets of apps.
Terminology

Definition. A source is an external resource (external to the app, not necessarily external to the phone) from which data is read.

Definition. A sink is an external resource to which data is written.

For example,

- **Sources**: Device ID, contacts, photos, current location, etc.
- **Sinks**: Internet, outbound text messages, file system, etc.
Motivating Example

- App *SendSMS.apk* sends an **intent** (a message) to *Echoer.apk*, which sends a **result** back.

  - *SendSMS.apk* tries to launder the taint through *Echoer.apk*.
  - Existing static analysis tools cannot precisely detect such inter-app data flows.
Analysis Design

- **Phase 1**: Each app analyzed once, in isolation.
  - **FlowDroid**: Finds tainted dataflow from sources to sinks.
    - Received intents are considered sources.
    - Sent intent are considered sinks.
  - **Epicc**: Determines properties of intents.
    - Each intent-sending call site is labelled with a unique *intent ID*.

- **Phase 2**: Analyze a set of apps:
  - For each intent **sent** by a component, determine which components can **receive** the intent.
  - Generate & solve taint flow equations.
Running Example

Three components: $C_1$, $C_2$, $C_3$.
- $C_1 = \text{SendSMS}$
- $C_2 = \text{Echoer}$
- $C_3$ is similar to $C_1$

For $i \in \{1, 3\}$:
- $C_i$ sends data from $src_i$ to component $C_2$ via intent $I_i$.
- $C_2$ reads data from intent $I_i$ and echoes it back to $C_i$.
- $C_i$ reads data from the result and writes it to $sink_i$.

- $sink_1$ is tainted with only $src_1$.
- $sink_3$ is tainted with only $src_3$. 
Running Example

Notation:

- “src $\xrightarrow{C} sink$”: Flow from src to sink in C.
- “$I(C_{TX}, C_{RX}, id)$”: Intent from $C_{TX}$ to $C_{RX}$ with ID id.
- “$R(I)$”: Response (result) for intent I.
- “$T(s)$”: Set of sources with which s is tainted.
Running Example

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Running Example

Notation:
- “\( \text{src} \xrightarrow{c} \text{sink} \)”: Flow from \( \text{src} \) to \( \text{sink} \) in \( C \).
- “\( I(C_{\text{TX}}, C_{\text{RX}}, id) \)”: Intent from \( C_{\text{TX}} \) to \( C_{\text{RX}} \) with ID \( id \).
- “\( R(I) \)”: Response (result) for intent \( I \).
- “\( T(s) \)”: Set of sources with which \( s \) is tainted.

Final Sink Taints:
- \( T(\text{sink}_1) = \{\text{src}_1\} \)
- \( T(\text{sink}_3) = \{\text{src}_3\} \)

\[ \begin{align*}
\text{src}_1 & \xrightarrow{c_1} I(C_1, C_2, id_1) \\
I(C_1, C_2, id_1) & \xrightarrow{c_2} R(I(C_1, C_2, id_1)) \\
R(I(C_1, C_2, id_1)) & \xrightarrow{c_1} \text{sink}_1 \\
\text{src}_3 & \xrightarrow{c_3} I(C_3, C_2, id_3) \\
I(C_3, C_2, id_3) & \xrightarrow{c_2} R(I(C_3, C_2, id_3)) \\
R(I(C_3, C_2, id_3)) & \xrightarrow{c_3} \text{sink}_3
\end{align*} \]
Phase 1 Flow Equations

Analyze each component separately.

Phase 1 Flow Equations:

\[ \text{src}_1 \xrightarrow{C_1} I(C_1, *, id_1) \]

\[ R(I(C_1, *, *)) \xrightarrow{C_1} \text{sink}_1 \]

\[ I(*, C_2, *) \xrightarrow{C_2} R(I(*, C_2, *)) \]

\[ \text{src}_3 \xrightarrow{C_3} I(C_3, *, id_3) \]

\[ R(I(C_3, *, *)) \xrightarrow{C_3} \text{sink}_3 \]

Notation

- “src \xrightarrow{C} sink”: Flow from src to sink in C.
- “I(C_{TX}, C_{RX}, id)”: Intent from C_{TX} to C_{RX} with ID id.
- “R(I)”: Response (result) for intent I.
- An asterisk (“*”) indicates an unknown component.
Phase 2 Flow Equations

Instantiate Phase-1 equations for all possible sender/receiver pairs.

**Phase 1 Flow Equations:**

\[
\begin{align*}
src_1 & \xrightarrow{C_1} I(C_1, *, id_1) \\
R(I(C_1, *, *)) & \xrightarrow{C_1} sink_1 \\
I(*, C_2, *) & \xrightarrow{C_2} R(I(*, C_2, *)) \\
src_3 & \xrightarrow{C_3} I(C_3, *, id_3) \\
R(I(C_3, *, *)) & \xrightarrow{C_3} sink_3
\end{align*}
\]

**Phase 2 Flow Equations:**

\[
\begin{align*}
src_1 & \xrightarrow{C_1} I(C_1, C_2, id_1) \\
R(I(C_1, C_2, id_1)) & \xrightarrow{C_1} sink_1 \\
I(C_1, C_2, id_1) & \xrightarrow{C_2} R(I(C_1, C_2, id_1)) \\
I(C_3, C_2, id_3) & \xrightarrow{C_2} R(I(C_3, C_2, id_3)) \\
src_3 & \xrightarrow{C_3} I(C_3, C_2, id_3) \\
R(I(C_3, C_2, id_3)) & \xrightarrow{C_3} sink_3
\end{align*}
\]

**Notation**

- “src \xrightarrow{C} sink”: Flow from src to sink in C.
- “I(C_{TX}, C_{RX}, id)”: Intent from C_{TX} to C_{RX} with ID id.
- “R(I)”: Response (result) for intent I.
Phase 2 Taint Equations

For each flow equation “src → sink”, generate taint equation “T(src) ⊆ T(sink)”.

**Phase 2 Flow Equations:**

\[
\begin{align*}
\text{src}_1 & \xrightarrow{C_1} I(C_1, C_2, id_1) \\
R(I(C_1, C_2, id_1)) & \xrightarrow{C_1} \text{sink}_1 \\
I(C_1, C_2, id_1) & \xrightarrow{C_2} R(I(C_1, C_2, id_1)) \\
I(C_3, C_2, id_3) & \xrightarrow{C_2} R(I(C_3, C_2, id_3)) \\
\text{src}_3 & \xrightarrow{C_3} I(C_3, C_2, id_3) \\
R(I(C_3, C_2, id_3)) & \xrightarrow{C_3} \text{sink}_3
\end{align*}
\]

**Phase 2 Taint Equations:**

\[
\begin{align*}
T(\text{src}_1) & \subseteq T(I(C_1, C_2, id_1)) \\
T(R(I(C_1, C_2, id_1))) & \subseteq T(\text{sink}_1) \\
T(I(C_1, C_2, id_1)) & \subseteq T(R(I(C_1, C_2, id_1))) \\
T(I(C_3, C_2, id_1)) & \subseteq T(R(I(C_3, C_2, id_3))) \\
T(\text{src}_3) & \subseteq T(I(C_3, C_2, id_3)) \\
T(R(I(C_3, C_2, id_3))) & \subseteq T(\text{sink}_3)
\end{align*}
\]

**Notation**

- “\( src \xrightarrow{C} sink \)”: Flow from \( src \) to \( sink \) in \( C \).
- “\( I(C_{TX}, C_{RX}, id) \)”: Intent from \( C_{TX} \) to \( C_{RX} \) with ID \( id \).
- “\( R(I) \)”: Response (result) for intent \( I \).
- “\( T(s) \)”: Set of sources with which \( s \) is tainted.

If \( s \) is a non-intent source, then \( T(s) = \{s\} \).
Phase 1

Original APK → TransformAPK → Extract manifest → Epicc → FlowDroid (modified)

Phase 2

App 1 → Phase 1 → Phase 2

App 2 → Phase 1 → Phase 2

App 3 → Phase 1 → Phase 2

App n → Phase 1 → Phase 2
Implementation: Phase 1

- **APK Transformer**
  - Assigns unique Intent ID to each call site of intent-sending methods.
    - Enables matching intents from the output of FlowDroid and Epicc
  - Uses Soot to read APK, modify code (in Jimple), and write new APK.

- Problem: Epicc is closed-source. How to make it emit Intent IDs?
- Solution (hack): Add `putExtra` call with Intent ID.
Implementation: Phase 1

- **FlowDroid Modifications:**
  - Extract intent IDs inserted by APK Transformer, and include in output.
  - When sink is an intent, identify the sending component.
    - In `base.startActivity`, assume `base` is the sending component. (Soundness?)
  - For deterministic output: Sort the final list of flows.
Implementation: Phase 2

- Phase 2
  - Take the Phase 1 output.
  - Generate and solve the data-flow equations.
  - Output:
    1. Directed graph indicating information flow between sources, intents, intent results, and sinks.
    2. Taintedness of each sink.
Testing DidFail analyzer: App Set 1

- **SendSMS.apk**
  - Reads device ID, passes through Echoer, and leaks it via SMS

- **Echoer.apk**
  - Echoes the data received via an intent

- **WriteFile.apk**
  - Reads physical location (from GPS), passes through Echoer, and writes it to a file

```
- getDeviceId \xrightarrow{\text{SendSMS}} startActivityForResult
- getIntent \xrightarrow{\text{Echoer}} setResult
- onActivityResult \xrightarrow{\text{SendSMS}} sendTextMessage
- getLastKnownLocation \xrightarrow{\text{WriteFile}} startActivityForResult
- getIntent \xrightarrow{\text{Echoer}} setResult
- onActivityResult \xrightarrow{\text{WriteFile}} write
```
Testing DidFail analyzer: App Set 2 (DroidBench)

Int3 = I(IntentSink2.apk, IntentSource1.apk, id3)
Int4 = I(IntentSource1.apk, IntentSink1.apk, id4)
Res8 = R(Int4)
Src15 = getDeviceId
Snk13 = Log.i

Some taint flows:

- \[ \text{Src15} \xrightarrow{\text{IntentSink2}} \text{Int3} \xrightarrow{\text{IntentSource1}} \text{Snk13} \]
- \[ \text{Src15} \xrightarrow{\text{IntentSink2}} \text{Int3} \xrightarrow{\text{IntentSource1}} \text{Int4} \xrightarrow{\text{IntentSink1}} \text{Res8} \xrightarrow{\text{IntentSource1}} \text{Snk13} \]
- \[ \text{Src15} \xrightarrow{\text{IntentSink1}} \text{Res8} \xrightarrow{\text{IntentSource1}} \text{Snk13} \]
Limitations

- **Unsoundness**
  - Inherited from FlowDroid/Epicc
    - Native code, reflection, etc.
  - Shared static fields
  - Implicit flows
  - Currently, only activity intents
  - Bugs

- **Imprecision**
  - Inherited from FlowDroid/Epicc
  - DidFail doesn’t consider permissions when matching intents
  - All intents received by a component are conflated together as a single source
Use of Two-Phase Approach in App Stores

- We envision that the two-phase analysis can be used as follows:
  - An app store runs the phase-1 analysis for each app it has.
  - When the user wants to download a new app, the store runs the phase-2 analysis and indicates new flows.
  - Fast response to user.
DidFail vs IccTA

- IccTA was developed (at roughly the same time as DidFail) by:
  - Li Li, Alexandre Bartel, Jacques Klein, Yves Le Traon (Luxembourg);
  - Steven Arzt, Siegfried Rasthofer, Eric Bodden (EC SPRIDE);
  - Damien Octeau, Patrick McDaniel (Penn State).

- IccTA uses a one-phase analysis
  - IccTA is more precise than DidFail’s two-phase analysis.
  - Two-phase DidFail analysis allows fast 2nd-phase computation.

- Future collaboration between IccTA and DidFail teams?
Conclusion

- We introduced a new analysis that integrates and enhances existing Android app static analyses.

- Demonstrated feasibility by implementing a prototype and testing it.

- Two-phase analysis can be used by app store to provide fast response.

- Future work:
  - Implicit flows
  - Static fields
  - Distinguish different received intents
  - Other data channels (file system, non-activity intents)
  - Etc.
Thank You