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Using DidFail to Analyze Flow of Sensitive Information in Sets of Android Apps

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*presenting

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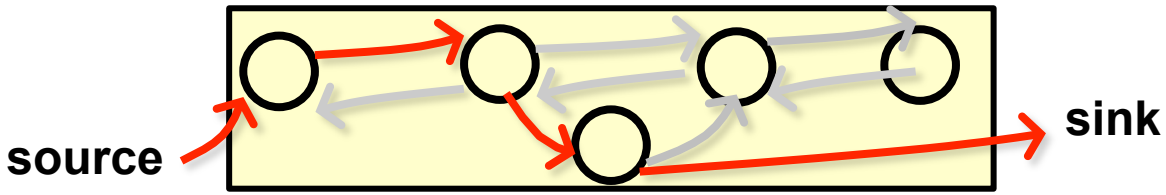
Overview

Problem: Sensitive/private information can be leaked by apps on smartphones.

- Precise detection on Android is made difficult by communication between components of apps.
- Malicious apps could evade detection by collusion or by exploiting a leaky app using *intents* (messages to Android app components) to pass sensitive data.

Goal: Precisely detect undesired flows **across multiple Android components**.

- Remedies if such flows are discovered:
  - At present: Refuse to install app
  - Future work: Block undesired flows



Our Tool *(DidFail)*:

- Input: set of Android apps (APK files)
- Output: list of flows of sensitive information

Major Achievements:

- First published static taint flow analysis for app sets (not just single apps)
- Fast user response: two-phase method uses phase-1 precomputation

Introduction

One billion Android devices (phones and tablets) estimated sold in 2014.[1]

Goal: 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.

[1] **Gartner Report:** http://www.gartner.com/newsroom/id/2665715

Introduction: Android

Android apps have four types of **components**:

- Activities
- 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`")

Introduction

Taint Analysis tracks the flow of sensitive data.

- Can be static or dynamic.
  - Static analysis: Analyze the code *without* running it.
  - Dynamic analysis: Analyze the program by running it.
- Our analysis is static.

Our analysis is built upon existing Android static analyses:

- **FlowDroid** [1]: finds intra-component information flow
- **Epicc** [2]: identifies intent specifications

[1] S. Arzt et al., "FlowDroid: Precise Context, Flow, Field, Object-sensitive and Lifecycle-aware Taint Analysis for Android Apps". ***PLDI*, 2014.**

[2] D. Octeau et al., "Effective inter-component communication mapping in Android with Epicc: An essential step towards holistic security analysis". ***USENIX Security*, 2013.**

Our Contribution

We developed the **DidFail** static analyzer
("Droid Intent Data Flow Analysis for Information Leakage").

- Finds flows of sensitive data across app boundaries.
- Source code available at: (or google "DidFail CERT")

  `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 sets of apps.

Terminology

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

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

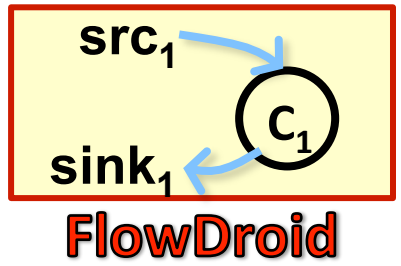
For example,

- **Sources**: Device ID, contacts, photos, location (GPS), intents, etc.
- **Sinks**: Internet, outbound text messages, file system, intents, etc.

Definition. Data is *tainted* if it originated from a (sensitive) source.

Analysis of Android App Sets: Sensitive Dataflow

- If an undesired flow is discovered:
  - User might refuse to install app
  - App store might remove app



Previous tools: taint flow in single component

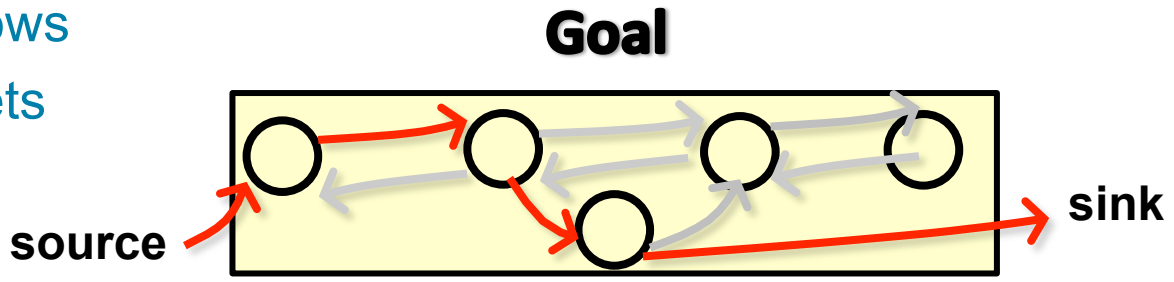
- Intents can be treated as sources/sinks.
- But cannot precisely identify full flows involving multiple components.

Malicious developer strategy:

- Hide from tools by using multiple apps for tainted data flow (launder)
- Colluding apps, or combination leaky app and malicious app

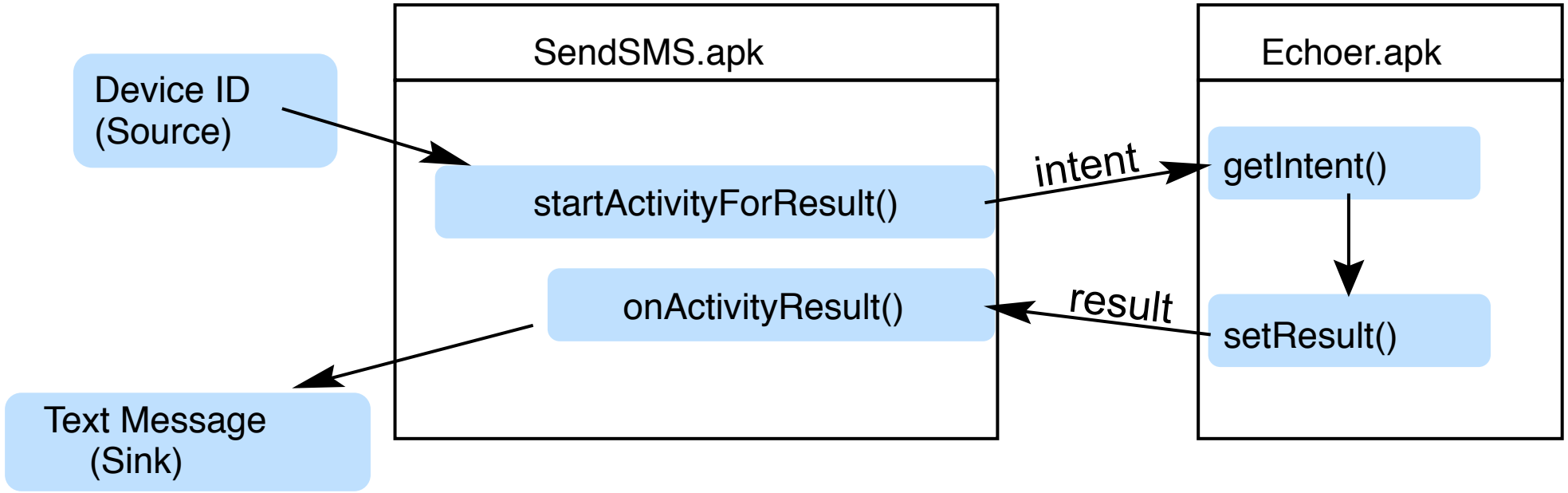
DidFail:

- Defeat multiple-app strategy, detect full tainted flows
- First published static taint flow analysis for app sets
- Fast user response: 2 phases



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*.
- Pre-existing static analysis tools could not precisely detect such inter-app data flows.

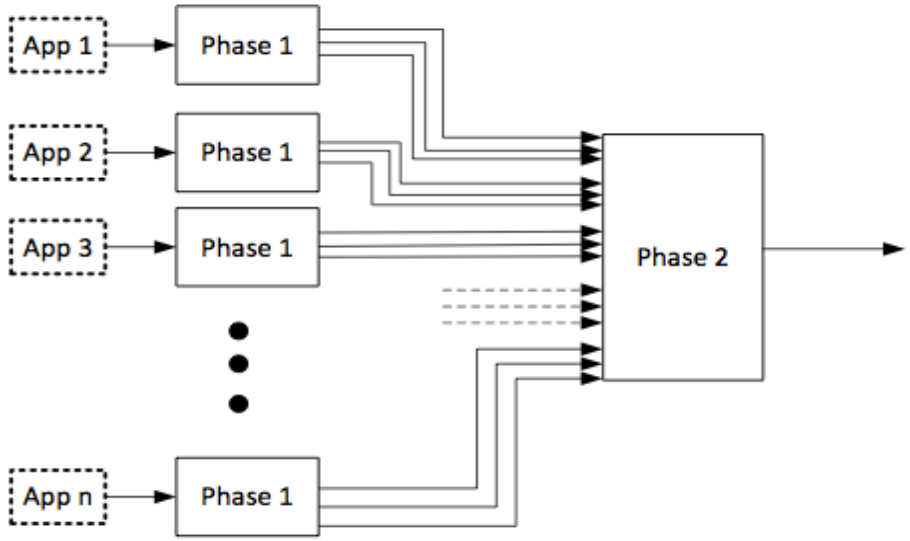
Analysis Design

Phase 1: Each app analyzed once, in isolation.

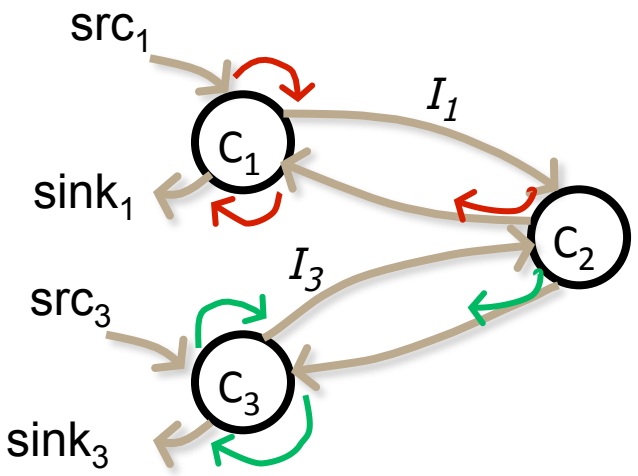
- **FlowDroid:** Finds tainted dataflow from sources to sinks.
  - Received intents are considered sources.
  - Sent intent are considered sinks.
- **Epicc:** Determines properties of intents.
- Each intent-sending call site is labelled with a unique *intent ID*.

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.

C1 = SendSMS

C2 = Echoer

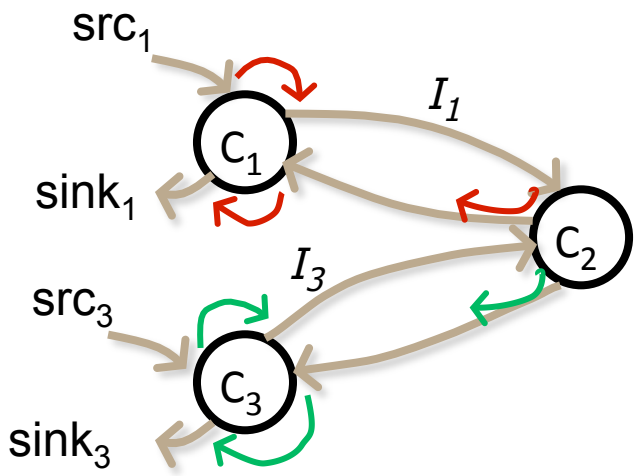
C3 is similar to C1

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.

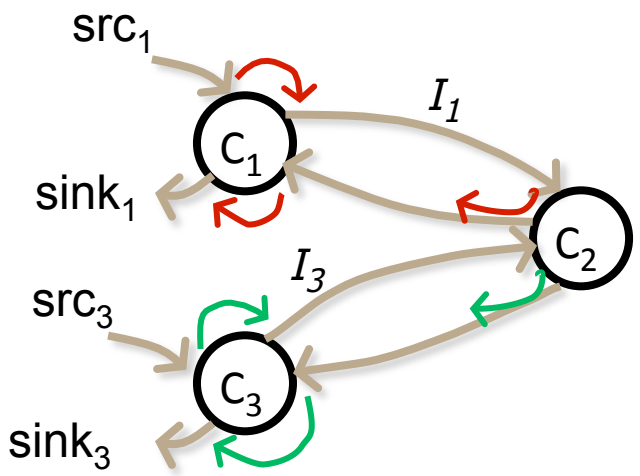
Running Example



Notation:

- "$src \xrightarrow{C} sink$": Flow from src to $sink$ in C.
- "$I(C_{\mathrm{TX}}, C_{\mathrm{RX}}, id)$": 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



$$src_1 \xrightarrow{C_1} I(C_1, C_2, id_1)$$

$$I(C_1, C_2, id_1) \xrightarrow{C_2} R(I(C_1, C_2, id_1))$$

$$R(I(C_1, C_2, id_1)) \xrightarrow{C_1} sink_1$$

$$src_3 \xrightarrow{C_3} I(C_3, C_2, id_3)$$

$$I(C_3, C_2, id_3) \xrightarrow{C_2} R(I(C_3, C_2, id_3))$$

$$R(I(C_3, C_2, id_3)) \xrightarrow{C_3} sink_3$$

Notation:

- "$src \xrightarrow{C} sink$": Flow from src to $sink$ in C.
- "$I(C_{\text{TX}}, C_{\text{RX}}, id)$": 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.

Final Sink Taints:

- $T(sink_1) = \{src_1\}$
- $T(sink_3) = \{src_3\}$

Phase-1 Flow Equations

Analyze each component separately.

Phase 1 Flow Equations:

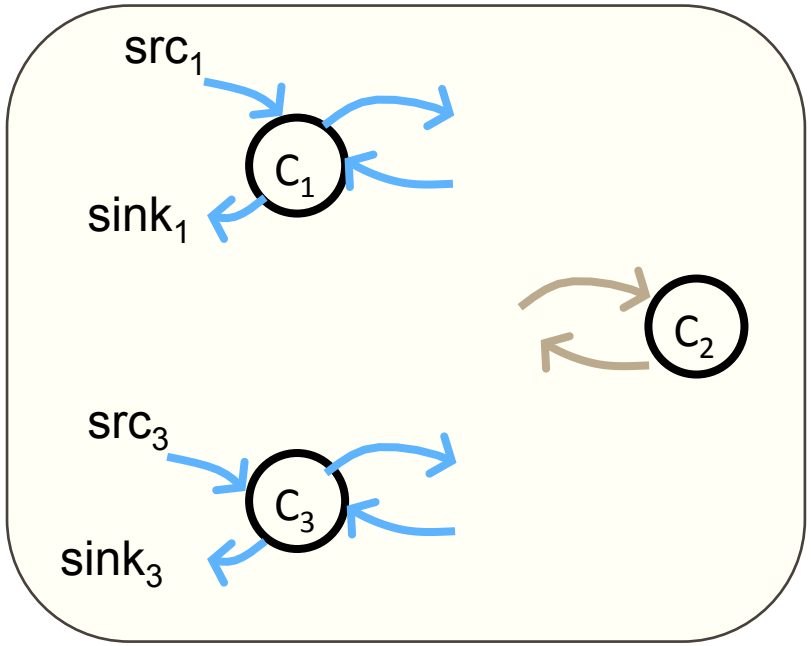
$$src_1 \xrightarrow{C_1} I(C_1, *, id_1)$$

$$R(I(C_1, *, *)) \xrightarrow{C_1} sink_1$$

$$I(*, C_2, *) \xrightarrow{C_2} R(I(*, C_2, *))$$

$$src_3 \xrightarrow{C_3} I(C_3, *, id_3)$$

$$R(I(C_3, *, *)) \xrightarrow{C_3} sink_3$$

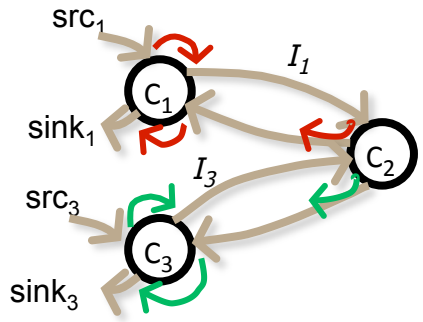


Notation

- "$src \xrightarrow{C} sink$": Flow from src to $sink$ in C.
- "$I(C_{\text{TX}}, C_{\text{RX}}, id)$": 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:

$$src_1 \xrightarrow{C_1} I(C_1, *, id_1)$$

$$R(I(C_1, *, *)) \xrightarrow{C_1} sink_1$$

$$I(*, C_2, *) \xrightarrow{C_2} R(I(*, C_2, *))$$

$$src_3 \xrightarrow{C_3} I(C_3, *, id_3)$$

$$R(I(C_3, *, *)) \xrightarrow{C_3} sink_3$$

Phase 2 Flow Equations:

$$src_1 \xrightarrow{C_1} I(C_1, C_2, id_1)$$

$$R(I(C_1, C_2, id_1)) \xrightarrow{C_1} sink_1$$

$$I(C_1, C_2, id_1) \xrightarrow{C_2} R(I(C_1, C_2, id_1))$$

$$I(C_3, C_2, id_3) \xrightarrow{C_2} R(I(C_3, C_2, id_3))$$

$$src_3 \xrightarrow{C_3} I(C_3, C_2, id_3)$$

$$R(I(C_3, C_2, id_3)) \xrightarrow{C_3} sink_3$$

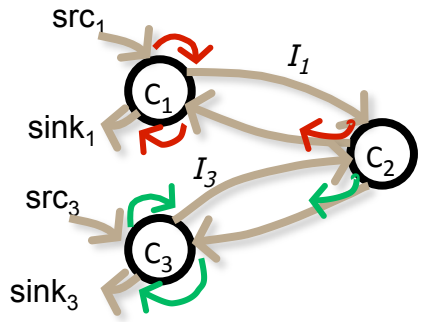
Notation

- "$src \xrightarrow{C} sink$": Flow from src to $sink$ in C.
- "$I(C_{\text{TX}}, C_{\text{RX}}, id)$": Intent from C_{TX} to C_{RX} with ID id.
- "$R(I)$": Response (result) for intent I.

Manifest and Epicc info (not shown) are used to match intent senders and recipients.

Phase-2 Taint Equations

For each flow equation $src \longrightarrow sink$,
generate taint equation $T(src) \subseteq T(sink)$.



Phase 2 Flow Equations:

$$src_1 \xrightarrow{C_1} I(C_1, C_2, id_1)$$

$$R(I(C_1, C_2, id_1)) \xrightarrow{C_1} sink_1$$

$$I(C_1, C_2, id_1) \xrightarrow{C_2} R(I(C_1, C_2, id_1))$$

$$I(C_3, C_2, id_3) \xrightarrow{C_2} R(I(C_3, C_2, id_3))$$

$$src_3 \xrightarrow{C_3} I(C_3, C_2, id_3)$$

$$R(I(C_3, C_2, id_3)) \xrightarrow{C_3} sink_3$$

Phase 2 Taint Equations:

$$T(src_1) \subseteq T(I(C_1, C_2, id_1))$$

$$T(R(I(C_1, C_2, id_1))) \subseteq T(sink_1)$$

$$T(I(C_1, C_2, id_1)) \subseteq T(R(I(C_1, C_2, id_1)))$$

$$T(I(C_3, C_2, id_1)) \subseteq T(R(I(C_3, C_2, id_3)))$$

$$T(src_3) \subseteq T(I(C_3, C_2, id_3))$$

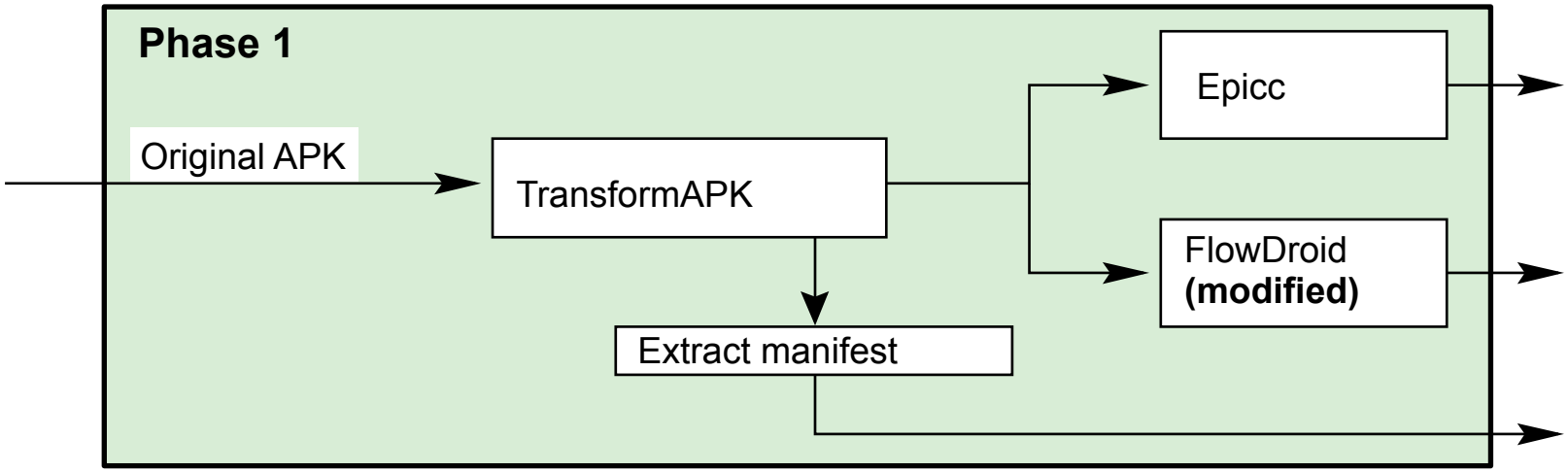
$$T(R(I(C_3, C_2, id_3))) \subseteq T(sink_3)$$

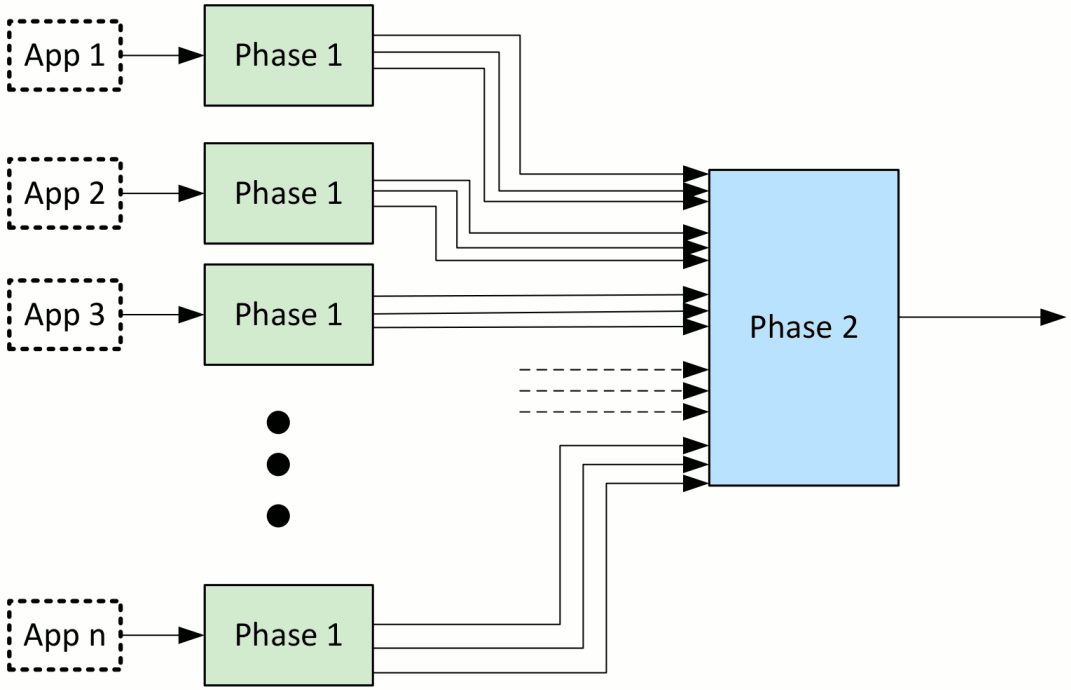
Notation

- "$src \xrightarrow{C} sink$": Flow from src to $sink$ in C.
- "$I(C_{\text{TX}}, C_{\text{RX}}, id)$": 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.

Then, solve.

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



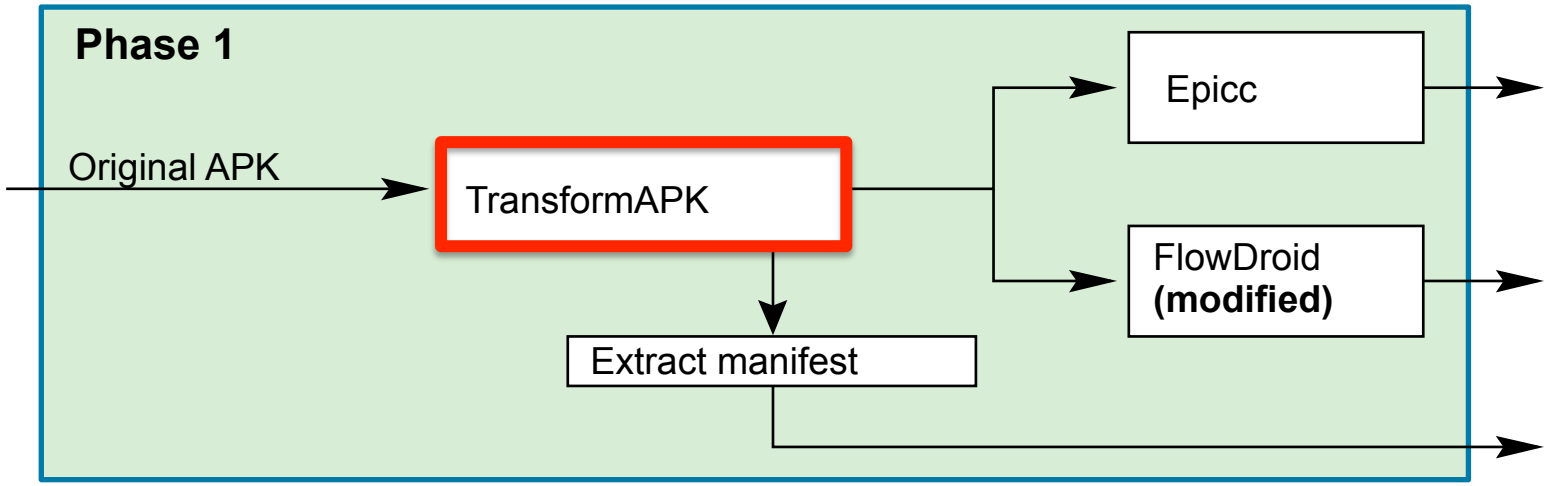


Implementation: Phase 1

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.

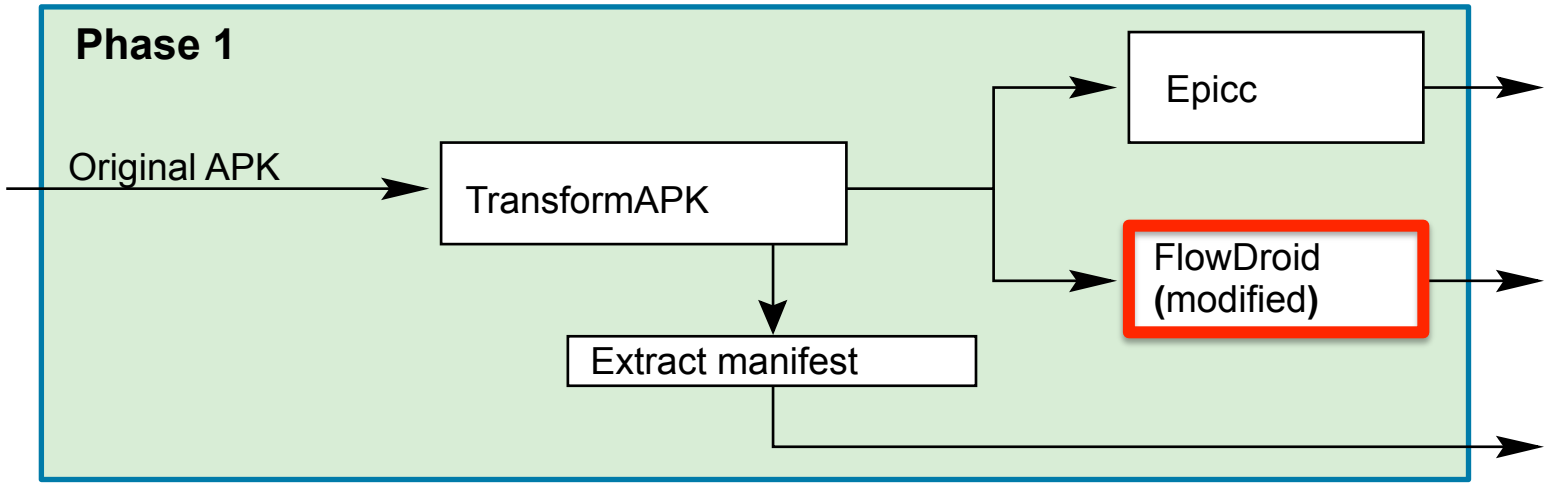
- Problem: Epicc is closed-source. How to make it emit Intent IDs?
- Solution (hack): Add `putExtra` call with Intent ID.



Implementation: Phase 1

FlowDroid Modifications:

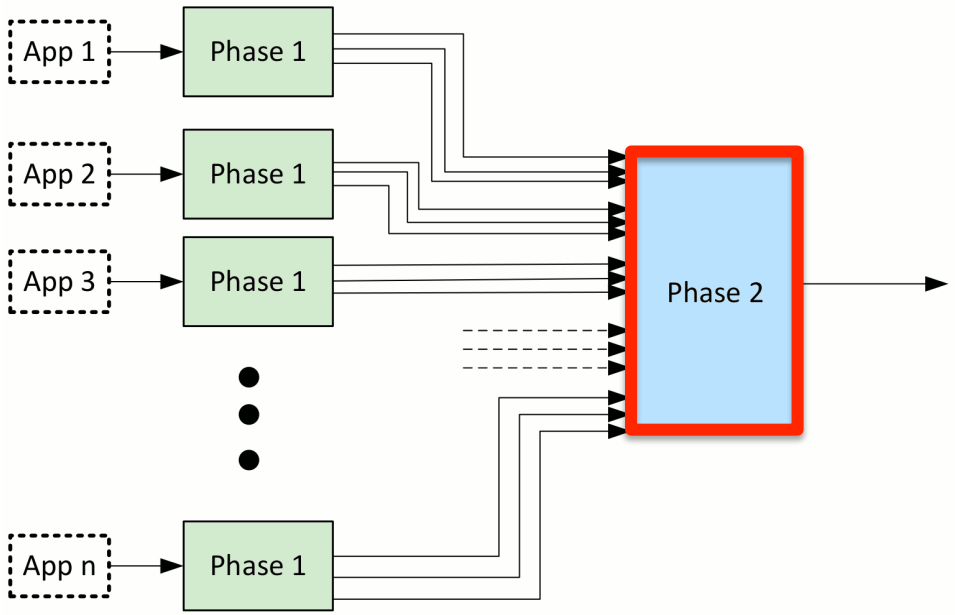
- Extract intent IDs inserted by APK Transformer, and include in output.
- When sink is an intent, identify the sending component.
  - In `base.startActivity`, assume `base` is the sending component.
- For deterministic output: Sort the final list of flows.



Implementation: Phase 2

Phase 2

- Input: 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

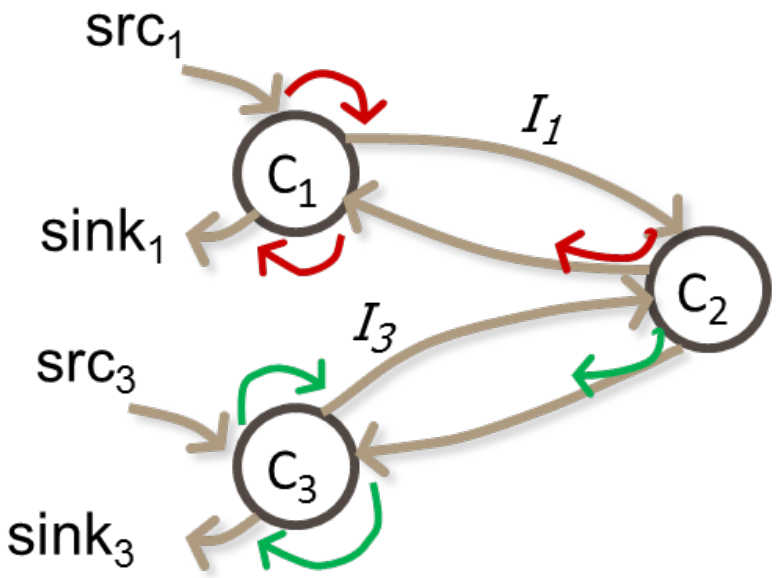
- Reads device ID, passes through Echoer, and leaks it via SMS

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



Flows found by DidFail

- $getDeviceId \xrightarrow{SendSMS} startActivityForResult$
  $getIntent \xrightarrow{Echoer} setResult$
  $onActivityResult \xrightarrow{SendSMS} sendTextMessage$
- $getLastKnownLocation \xrightarrow{WriteFile} startActivityForResult$
  $getIntent \xrightarrow{Echoer} setResult$
  $onActivityResult \xrightarrow{WriteFile} write$

Limitations

Unsoundness

- Inherited from FlowDroid/Epicc
  - Native code, reflection, etc.
- Shared static fields
  - Partially addressed by Jonathan Burket, but with scalability issues
- Implicit flows
- Originally only considered activity intents
  - Students added partial support for services and broadcast receivers.

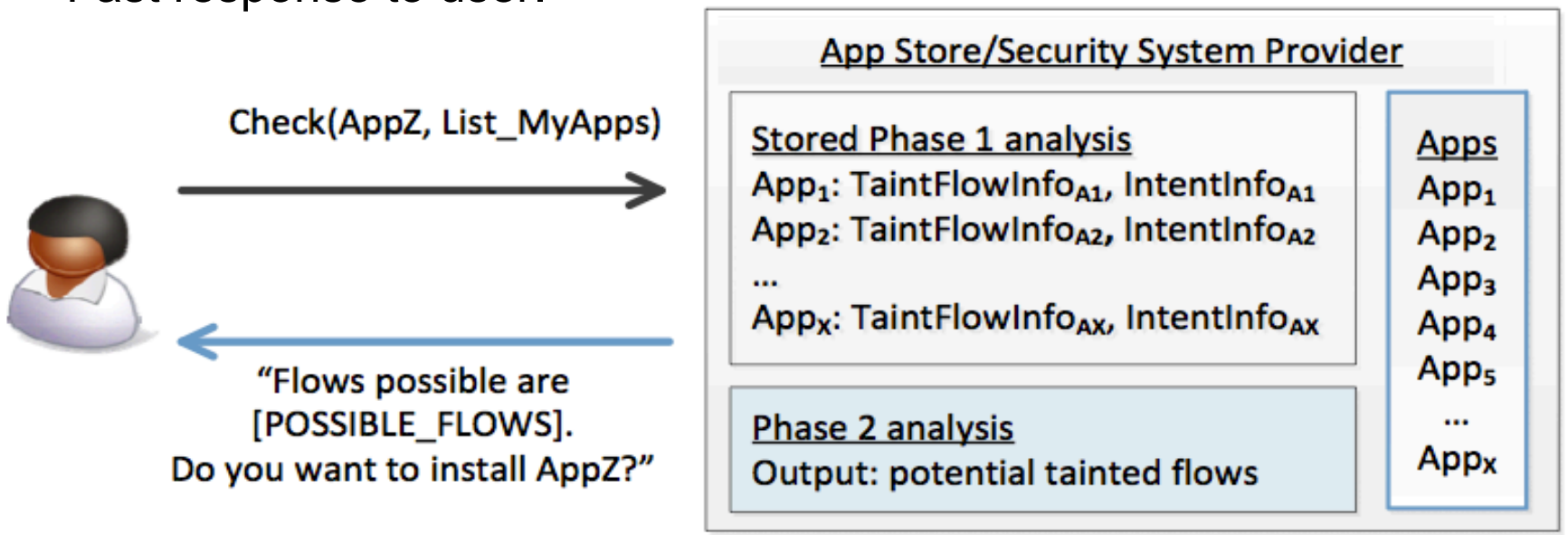
Imprecision

- 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.



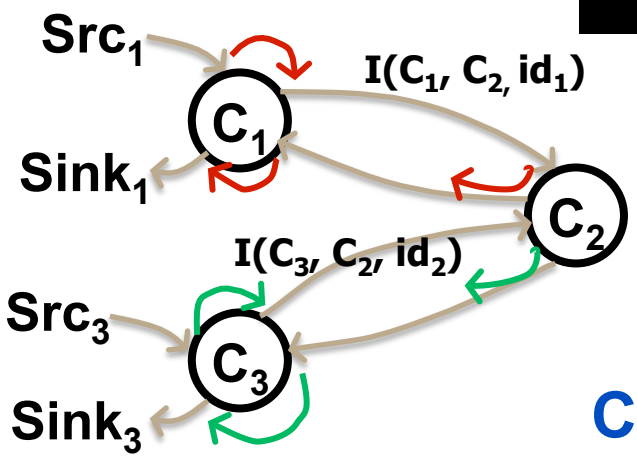
Policy guidance/enforcement, for usability.

Usability: Policies to Determine Allowed Flows

Policies could come from:
- App store
- Security system provider
- Employer
- User option

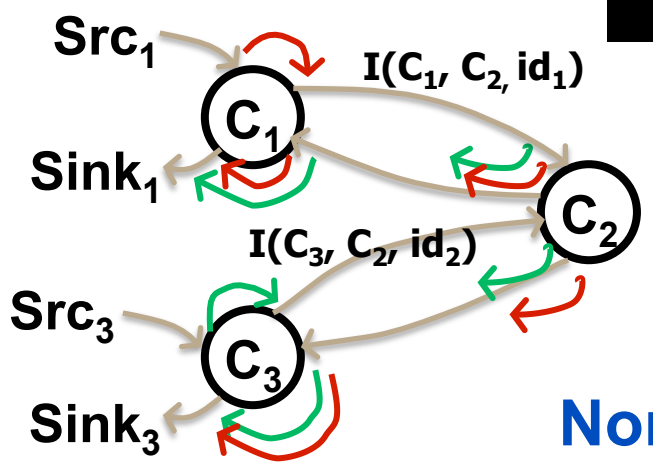
Policy: Prohibit flow from Src_1 to $Sink_3$

Example 1



Compliant

Example 2



Noncompliant

DidFail vs IccTA

IccTA was developed (at roughly the same time as DidFail)

IccTA uses a one-phase analysis

- IccTA is more precise than DidFail's two-phase analysis.
  - More context-sensitive
  - Less overestimation of taints reaching sinks
- Two-phase DidFail analysis allows fast 2nd-phase computation.
  - Pre-computed Phase-1 analysis done ahead of time
  - User doesn't need to wait long for Phase-2 analysis

Typical time for simple apps:

- DidFail: 2 sec (2nd phase)
- IccTA: 30 sec

Working together now! Ongoing collaboration between IccTA and DidFail teams

Analysis of Android App Sets: Sensitive Dataflow

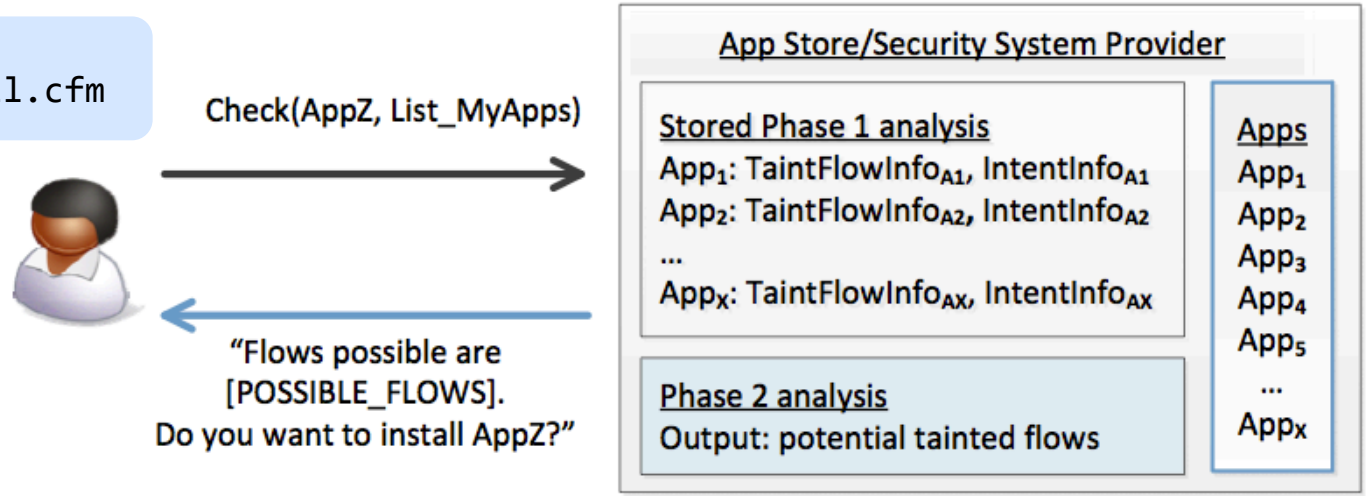
Goal: enforce confidentiality and integrity

Novel Android static dataflow analysis "DidFail" combines precise **single-component taint analysis** (FlowDroid) and **intent analysis** (Epicc).

- Phase 1: Each app analyzed once, in isolation
  - Examine flow of tainted data from sources to sinks (including intents)
  - Examines intent properties to match senders and receivers
- Phase 2: For a particular set of apps
  - Generate taint flow equations
  - Iteratively solve equations
  - **Fast!**

Phase 2 fast because of Phase 1 pre-computation

Source code:
`http://www.cert.org/secure-coding/tools/didfail.cfm`



Installing DidFail

Main DidFail website

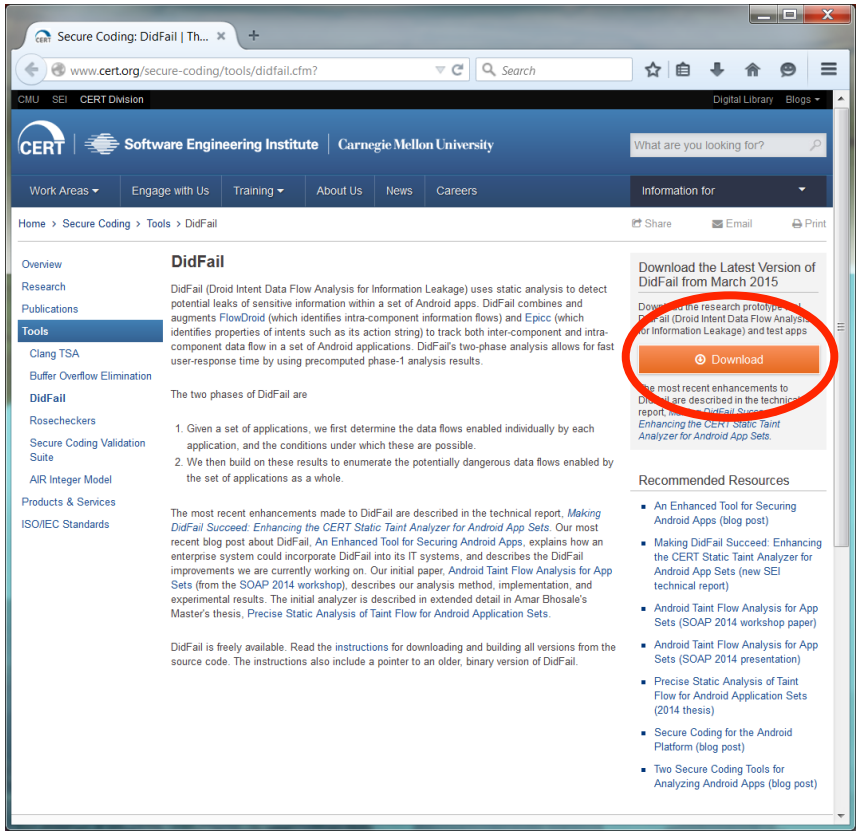
- http://www.cert.org/secure-coding/tools/didfail.cfm

Detailed install instructions are on the download website

- https://www.cs.cmu.edu/~wklieber/didfail/install-latest.html

There are 3 branches

- Static fields (Dec. 2014)
- Services and broadcast receivers (Dec. 2014)
- Improved DEX conversion (Nov. 2014)



Running DidFail

https://www.cs.cmu.edu/~wklieber/didfail/running.html

- To run DidFail (both phases 1 and 2):

```
$ run-didfail.sh OUT_DIR APK_1 ... APK_n
```

- Running just parts of phase 1:
  - The scripts for running parts of Phase 1 independently are available in the latest versions of the three branches in the repository.
  - First, set up environment variables in your Bash shell:

```
$ source paths.local.sh
```

  - Running APK Transformer:

```
$ run-transformer.sh OUT_DIR APK
```

  - Running FlowDroid:

```
$ run-indep-flowdroid.sh OUT_DIR APK
```

  - Running Epicc:

```
$ run-indep-epicc.sh OUT_DIR APK
```

  - Extracting manifest file (to stdout):

```
$ extract-manifest.sh APK
```

- Running Phase 2:

```
$ python taintflows.py phase1_output_files --js jsonfile --gv graphfile
[--quiet]
```

Phase-1 Output from FlowDroid (Echoer Toy App)

3 possible flows to sinks found

```
 3 <flow>
 4 <sink method="&lt;android.util.Log: int i(java.lang.String,java.lang.String)&gt;"></sink>
 5 <source method="&lt;android.app.Activity: android.content.Intent getIntent()&gt;" component="org.cert.echoer.MainActivity">
 6 <in>getDataFromIntent</in>
 7 </source>
 8 <source method="&lt;android.os.Bundle: java.lang.String getString(java.lang.String)&gt;" component="org.cert.echoer.MainActivity">
 9 <in>getDataFromIntent</in>
10 </source>
11 </flow>
12 <flow>
13 <sink method="&lt;android.util.Log: int i(java.lang.String,java.lang.String)&gt;"></sink>
14 <source method="&lt;android.app.Activity: android.content.Intent getIntent()&gt;" component="org.cert.echoer.MainActivity">
15 <in>getDataFromIntent</in>
16 </source>
17 </flow>
18 <flow>
19 <sink method="&lt;android.app.Activity: void setResult(int,android.content.Intent)&gt;" is-intent-result="1" component="org.cert.e
  choer.Button1Listener"></sink>
20 <source method="&lt;android.app.Activity: android.content.Intent getIntent()&gt;" component="org.cert.echoer.MainActivity">
21 <in>getDataFromIntent</in>
22 </source>
23 </flow>
```

Phase-1 Output from FlowDroid: One XML <flow> for Echoer

Phase-1 Output from Epicc (SendSMS Toy App)

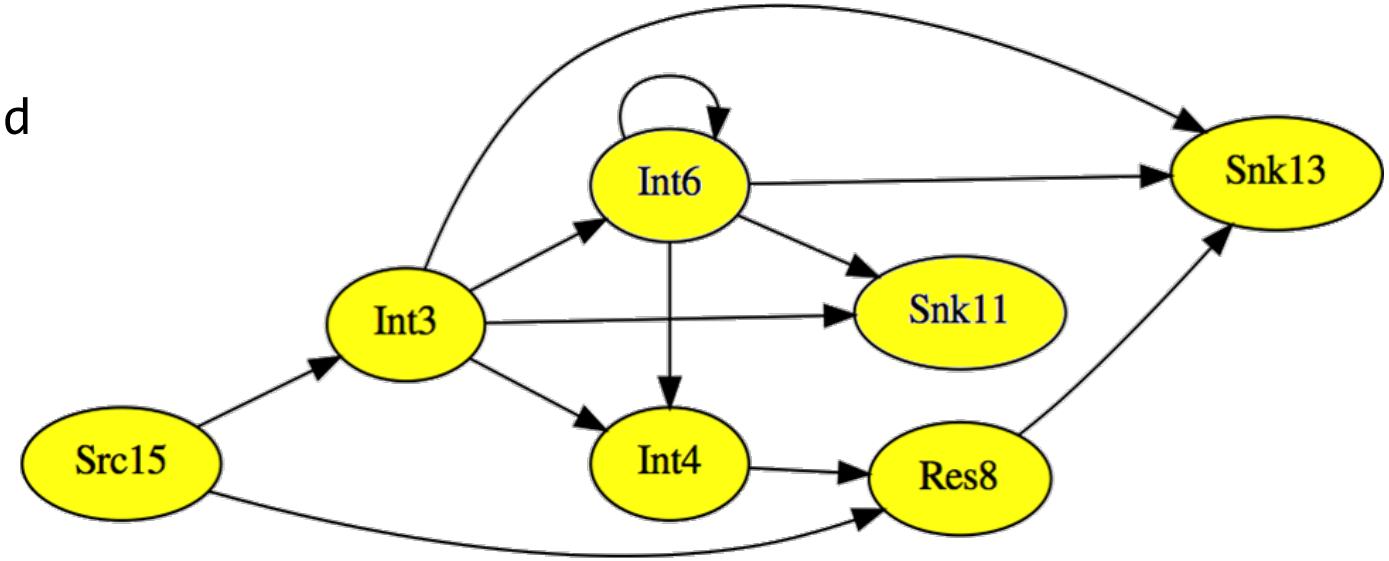
Epicc provides precision about fields in intents sent

```
485 The following ICC values were found:
486   - org/cert/sendsms/Button1Listener/onClick(Landroid/
    view/View;)
487 Intent value: 1 possible value(s):
488 Action: android.intent.action.SEND, Type: text/plain,
    Extras: [newField_6, secret],
```

GraphViz output for DroidBench app set

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

Graph generated using GraphViz.



Some flows:

- $Src15 \xrightarrow{IntentSink2} Int3 \xrightarrow{IntentSource1} Snk13$
- $Src15 \xrightarrow{IntentSink2} Int3 \xrightarrow{IntentSource1} Int4 \xrightarrow{IntentSink1} Res8 \xrightarrow{IntentSource1} Snk13$
- $Src15 \xrightarrow{IntentSink1} Res8 \xrightarrow{IntentSource1} Snk13$

Phase-2 Output: JSON-format (excerpts)

```
{
    "Flows": [
        [
            "Src: <android.telephony.TelephonyManager: java.lang.String getDeviceId()>",
            "org.cert.sendsms",
            "Sink: <android.util.Log: int i(java.lang.String,java.lang.String)>"
        ],
        [
            "Src: <android.telephony.TelephonyManager: java.lang.String getDeviceId()>",
            null,
            "Intent(tx=('org.cert.sendsms', 'MainActivity'),
                   rx=('org.cert.echoer',  'MainActivity'), intent_id='newField_6')"
        ],
        [
            "Intent(tx=('org.cert.sendsms', 'MainActivity'),
                   rx=('org.cert.echoer',  'MainActivity'), intent_id='newField_6')",
            null,
            "Sink: <android.util.Log: int i(java.lang.String,java.lang.String)>"
        ],
    ],
```

Phase-2 Output: JSON-format (excerpts)

```
19.     "Taints": {
20.         "Intent(tx=('org.cert.sendsms', 'MainActivity'),
                    rx=('org.cert.echoer',  'MainActivity'), intent_id='newField_6')":
            [
21.             "Src: <android.telephony.TelephonyManager: java.lang.String getDeviceId()>"
22.         ],
23.         "Sink: <android.telephony.SmsManager:
                    void sendTextMessage(java.lang.String,java.lang.String,java.lang.String,
                                         android.app.PendingIntent, android.app.PendingIntent)>":
            [
24.             "Src: <android.os.Bundle: java.lang.String getString(java.lang.String)>",
25.             "Src: <android.telephony.TelephonyManager: java.lang.String getDeviceId()>"
26.         ],
27.     }
28. }
```

Extracted Manifest XML (excerpts)

ReceiveApp.manifest.xml +

```
<?xml version="1.0" encoding="utf-8"?>
<manifest
    xmlns:android="http://schemas.android.com/apk/res/android"
    android:versionCode="1"
    android:versionName="1.0"
    package="org.cert.ReceiveApp">
```

```
<activity
    android:label="@7F050000"
    android:name="org.cert.ReceiveApp.ReceiveMainActivity">
    <intent-filter>
```

```
<service
    android:name="org.cert.ReceiveApp.ReceiveAppService">
    <intent-filter>
        <action   android:name="custom_action2"> </action>
        <data android:mimeType="text/plain"> </data>
    </intent-filter>
</service>
```

```
</application>
</manifest>
```

18,73 All

For More Information

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