Android Application Taint Analysis Seminar in Distributed Computing

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M.Sc Computer Science

Introduction to Taint Analysis

- Taint analysis detects flow from ***sensitive data sources*** to ***untrusted sinks***.

Sensitive Data Source

Untrusted Sinks

History of Taint Analysis

- Operating Systems
- Programming Languages
- Web Browsers
- Smart Phones like Android

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Use Case of Taint Analysis

Strengths and Weakness of Taint Analysis

- Strengths
  - **Scales Well**
  - Can find bugs with **high confidence** for certain aspects like Buffer Overflow, SQL Injection Flows etc.

- Weakness
  - **High numbers** of **false positives**.
  - **Security vulnerabilities** such as **authentication(OAuth 2.0)** problems, are very difficult to find automatically
  - Frequently can't find **configuration issues**, since they are not represented in the code.

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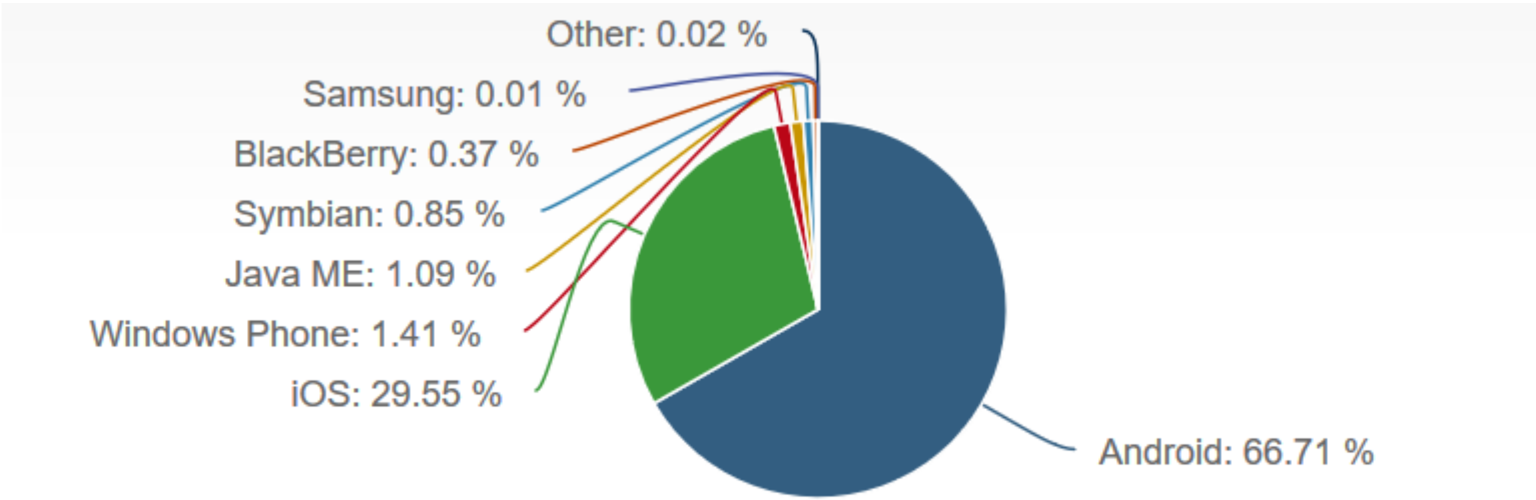
Static V/S Dynamic Taint Analysis

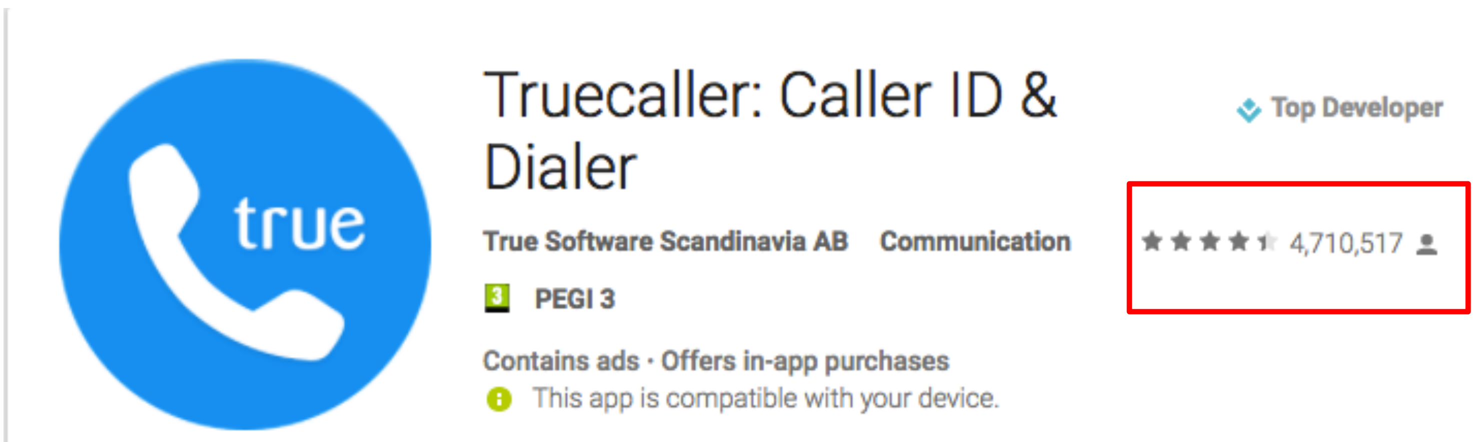
Static Taint Analysis	Dynamic Taint Analysis
Statically analyze source code	Dynamic Debugger Approach
Does not affect the **execution time**	**Slows** the **execution** of the program
Greater Code **Coverage**	Typically **lacks** code **coverage**
Requires **single run** to check complete code	Requires **multiple test runs** to reach appropriate code coverage
Not easily detectable as code is analyzed statically	**Easily detectable** by malicious app and could fool the analyzer

Why Android security is important?



Android has the largest market share and it is very common for the apps to disclose sensitive information on network

Some insights about Sensitive Information

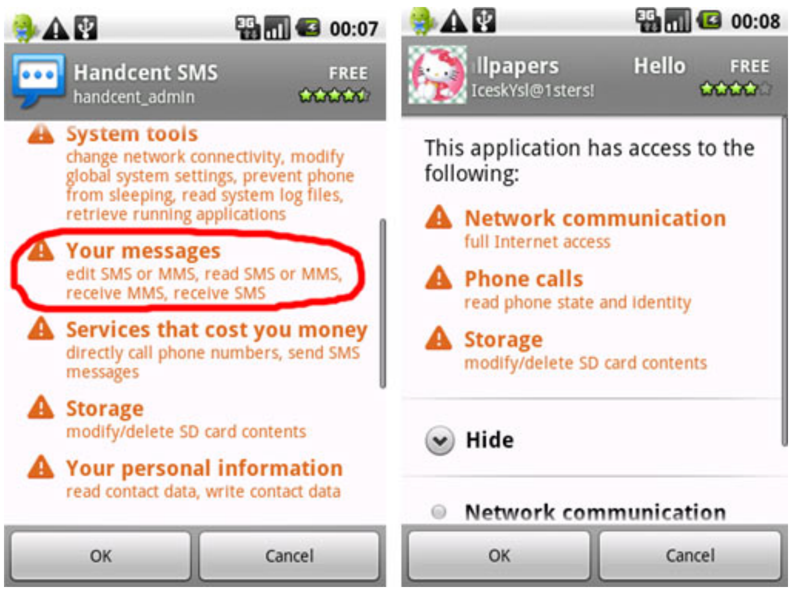


Big Security Flaw

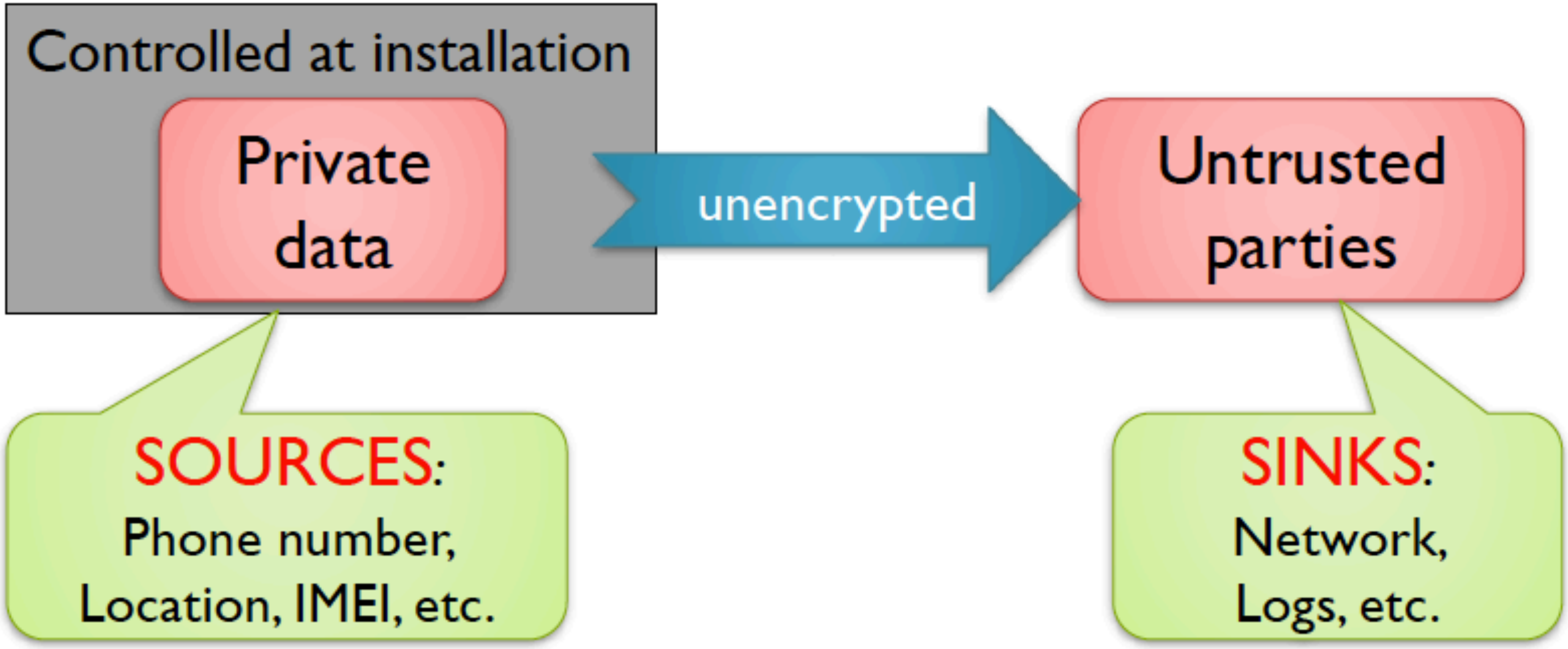
Anyone gaining the IMEI of a device will be able to get Truecaller users' personal information (including phone number, home address, mail box, gender, etc.) and tamper app settings without users' consent, exposing them to malicious phishers

Problem

- Sensitive Data Disclosures
- Leak private data through a dangerously broad set of permissions granted by the users.



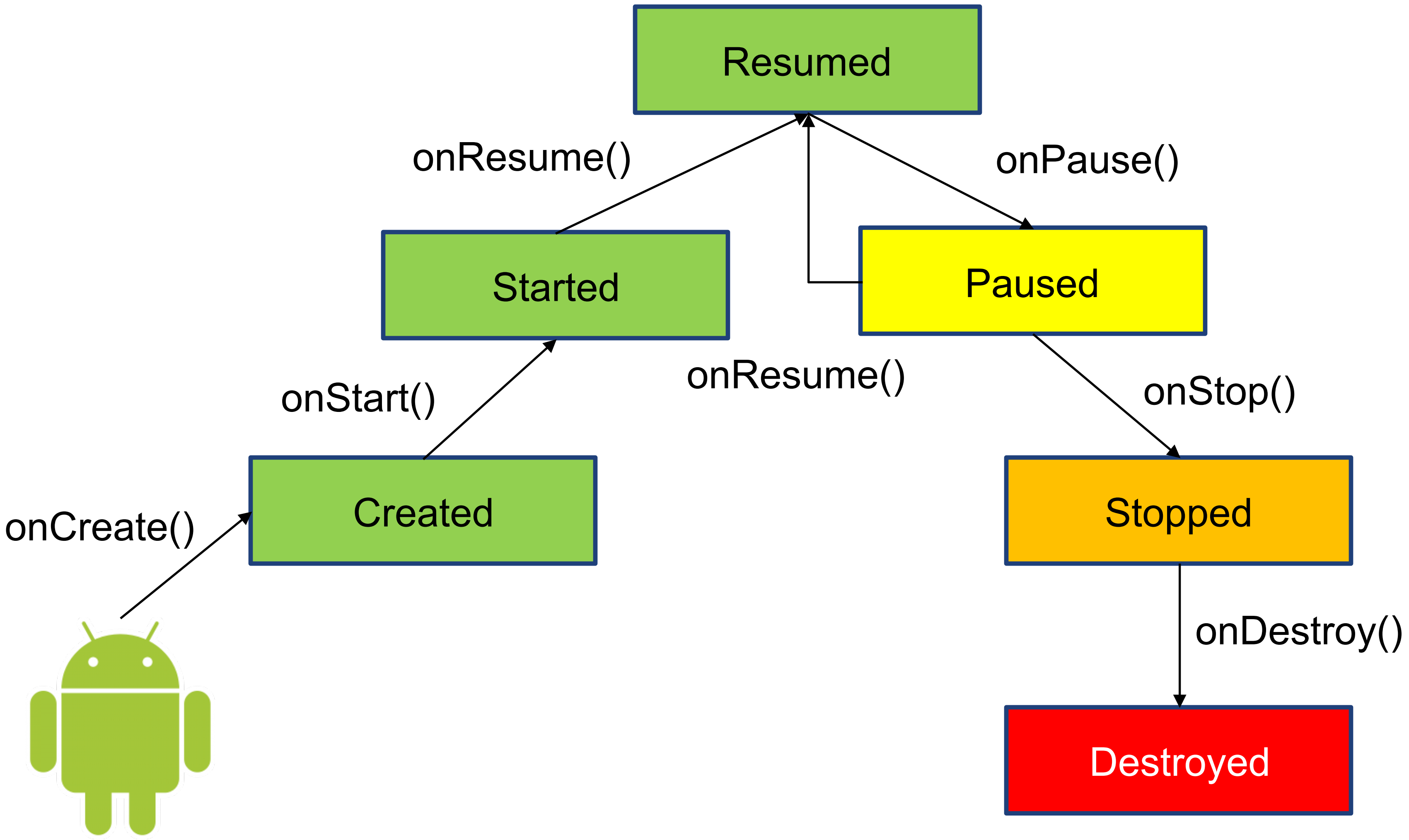
Motivation


Controlled at installation
Private data
unencrypted
Untrusted parties
SOURCES:
Phone number, Location, IMEI, etc.
SINKS:
Network, Logs, etc.

General Problem with Static Analysis on Android Platform

- Abstraction of the Runtime Environment
- Analyzing XML and Manifest files
- Aliasing

Android Lifecycle

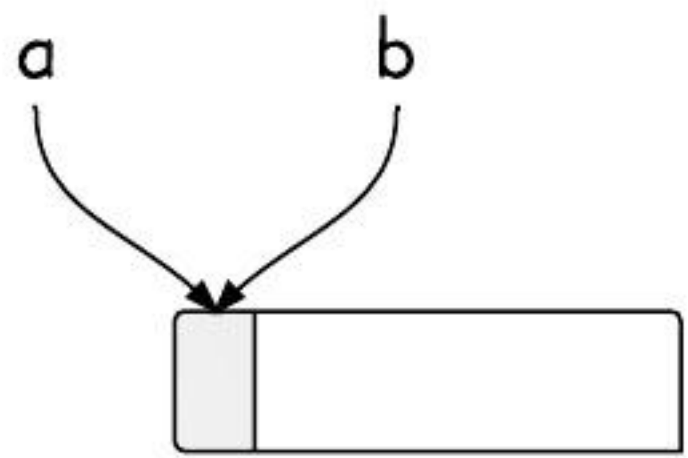


XML and Manifest Files

- Lot of UI Related Stuff is present in Layout XML
- Callbacks are registered in the XML files
- While decompiling code all those XML files are lost

Aliasing

Aliasing describes a situation in which a data location in memory can be accessed through different symbolic names in the program



Outline of Talk

- Flow Droid
- DidFail: “Flow Droid + Epicc”
- DFlow and DInfer

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Flow Droid: Precise Context, Flow, Field, Object-sensitive and Lifecycle aware Taint Analysis for Android Apps

Some basic terminology

Context Sensitivity

```
secret = 1;
public = 2;
s = f ( secret );
x = f ( public );
p = x ;

int f ( int x ) { return x +42; }
```

Some basic terminology

Flow Sensitivity

```
secret = 1;
public = 2;
if secret == 1:
    public = 3;
else:
    public = 4;
```

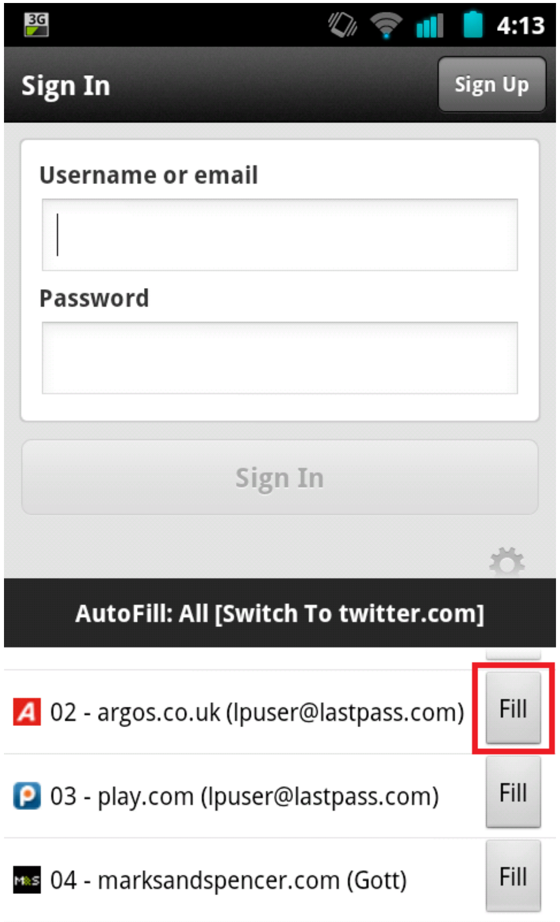
Some basic terminology

Object Sensitivity

```
class A {
    String x;
    void set(String y) {
        this.x = y;
    }
    String get() {
        return this.x
    }
}

class B {
    A a = new A();
    A a1 = new A();
    a.set("secret");
    a1.set("public");
    sendNetwork(a.get());
    sendNetwork(a1.get());
}
```

Some basic terminology

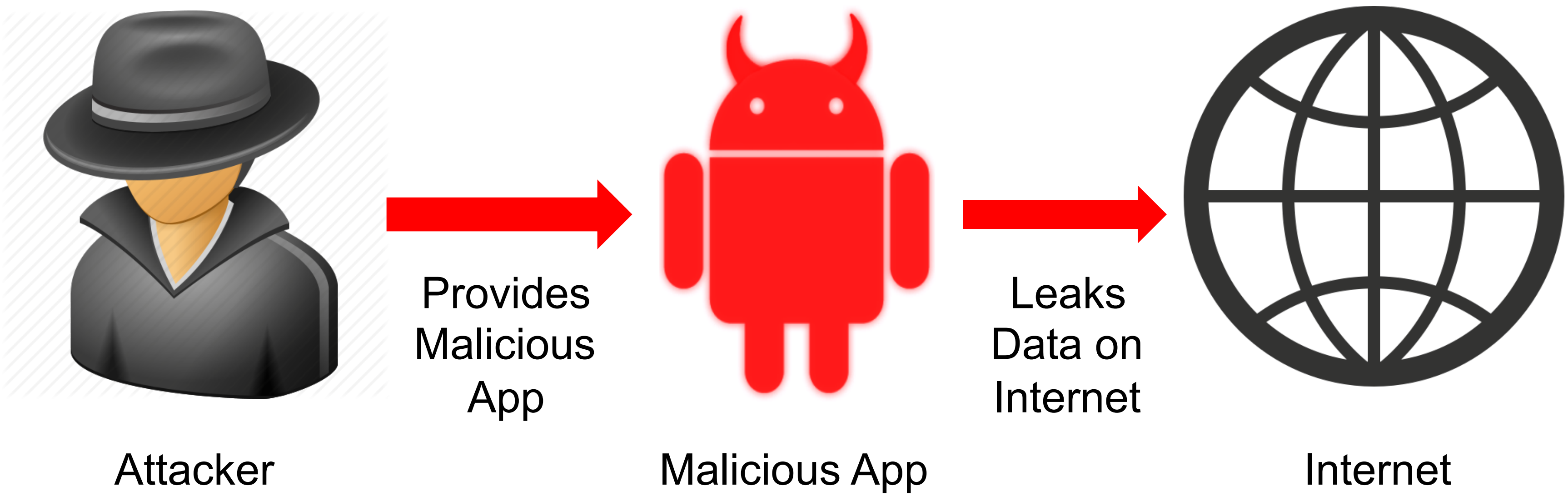
Field Sensitivity



Contributions of FlowDroid

- **FlowDroid** the first fully ***context, field, object and flow-sensitive*** taint analysis
- Considers **Android application lifecycle and UI widgets**, and which features a novel approach
- **DroidBench**, a novel **benchmark suite**
- Ran **FlowDroid** over **500 apps** from Google Play and about **1000 malware apps** from the VirusShare project

Attacker Model



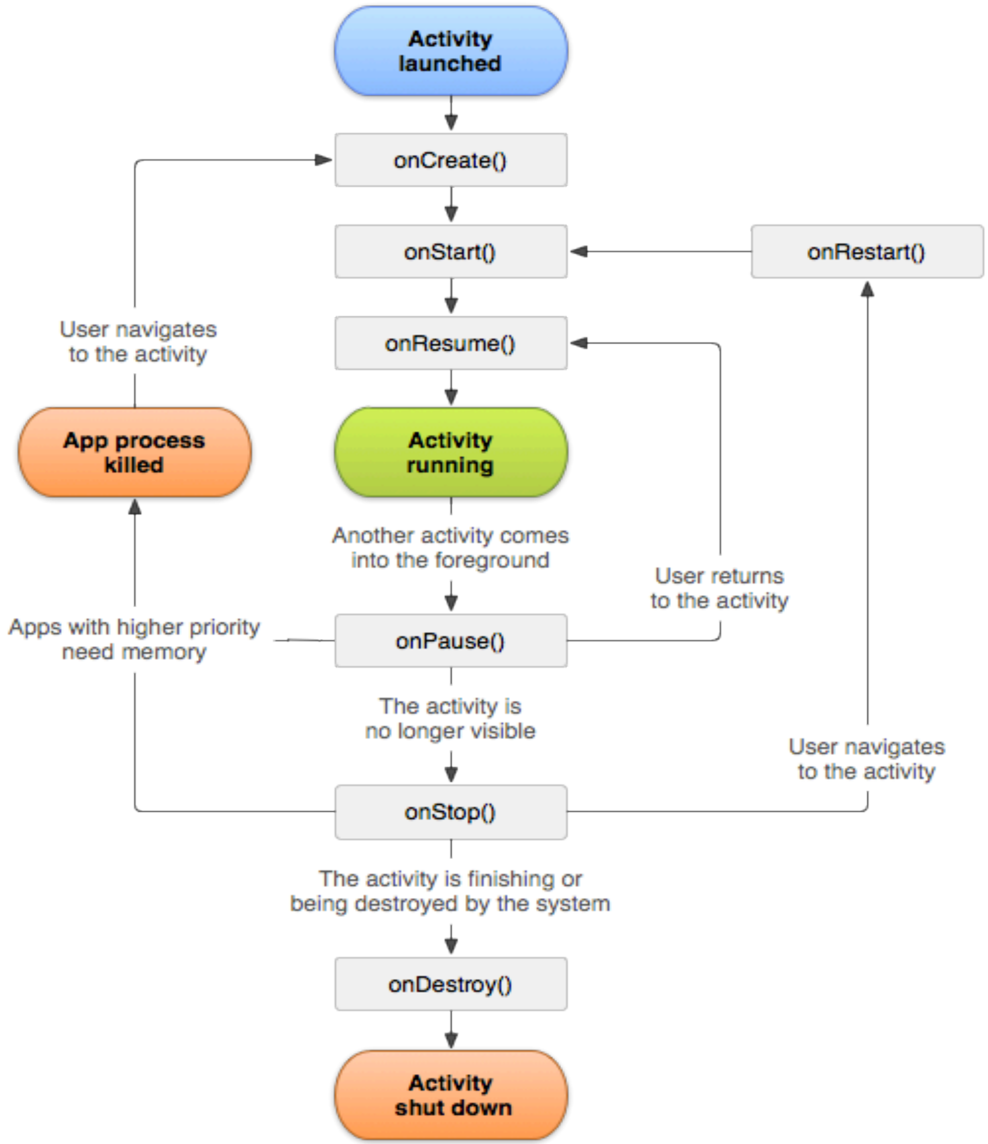
```
public class LeakageApp extends Activity {
    EditText passwordText =
        ( EditText )findViewById(R.id.pwdString);
    String pwd = passwordText . toString ();
}

// Callback method in xml file
public void sendMessage ( View view )
    Password pwd = user . getpwd ();
    String pwdString = pwd . getPassword ();
    String obfPwd = "";
    // must track primitives :
    for( char c : pwdString . toCharArray ())
        obfPwd += c + "_"; // String concat .

    String message = " User : " +
    user . getName () + " | Pwd: " + obfPwd ;
    SmsManager sms = SmsManager . getDefault ();
    sms.sendTextMessage(" +44 020 7321 0905 ",
        25 null , message , null , null );
}
```

Password is read and send out via SMS

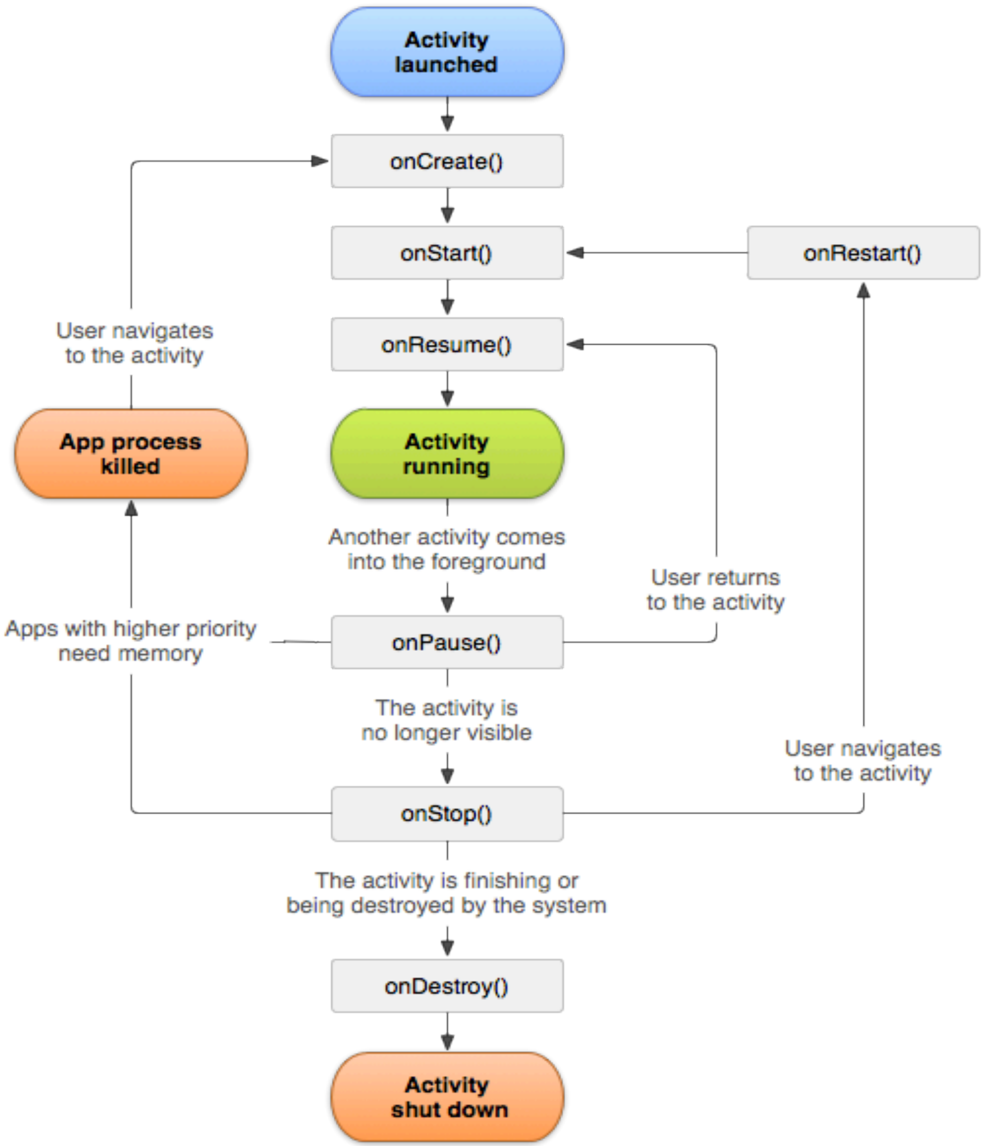
Problems in Static Analysis of Android Apps

- Precise Modeling of Android Lifecycle
- Multiple Entry Points
- Asynchronously executing components
- Callbacks

Problem 1: Precise Modeling of Lifecycle



Problem 2: Multiple Entry Points



Test.java

```java
package com.journaldev.java.examples1;

public class Test {

    public static void main(String args[]) {

        System.out.println("Hello World");

    }
}
```

Problem 3: Asynchronously executing components

Problem 4: Callbacks

- Register callbacks for various purposes like **location update, UI interaction** etc.
- FlowDroid **does not assume any order** on registration of callback
- Callback can be registered in two ways:
  - XML files of an activity and
  - Using well known calls to specific system methods

Brief Implementation Overview of FlowDroid

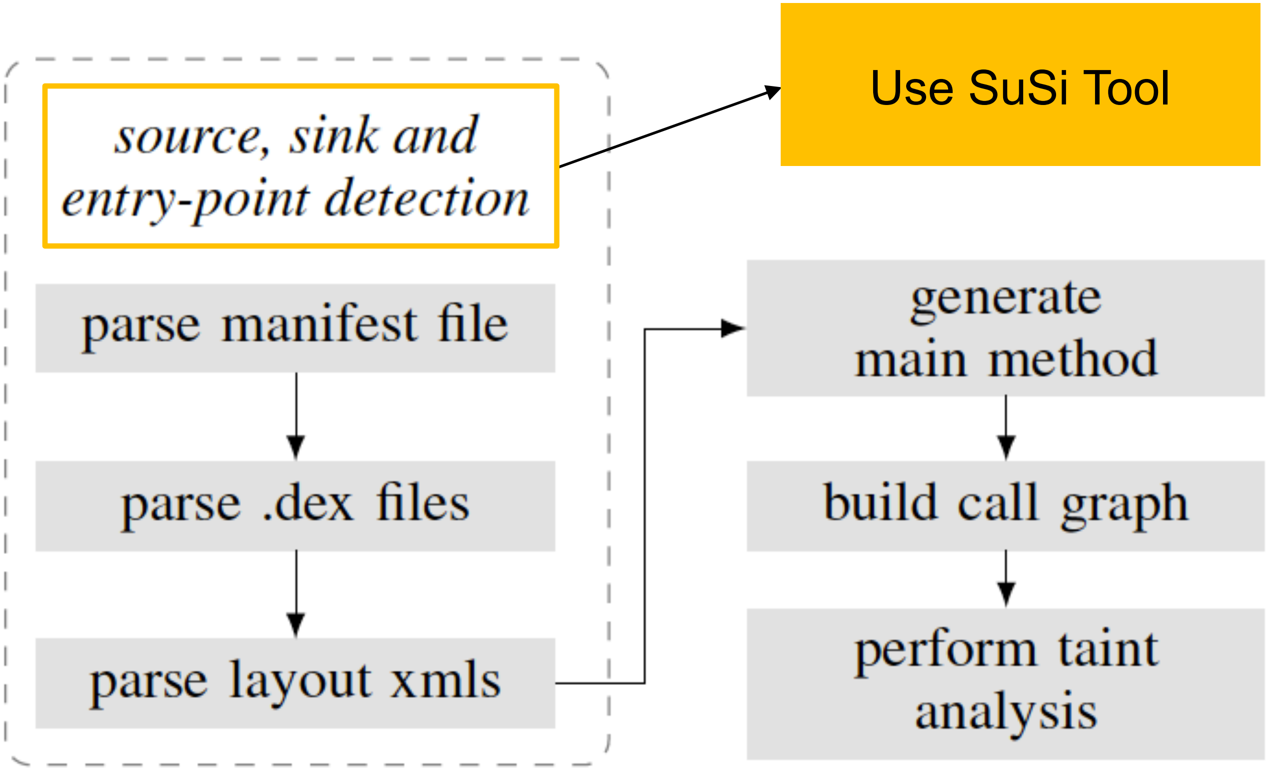


Figure 4: Overview of FLOWDROID

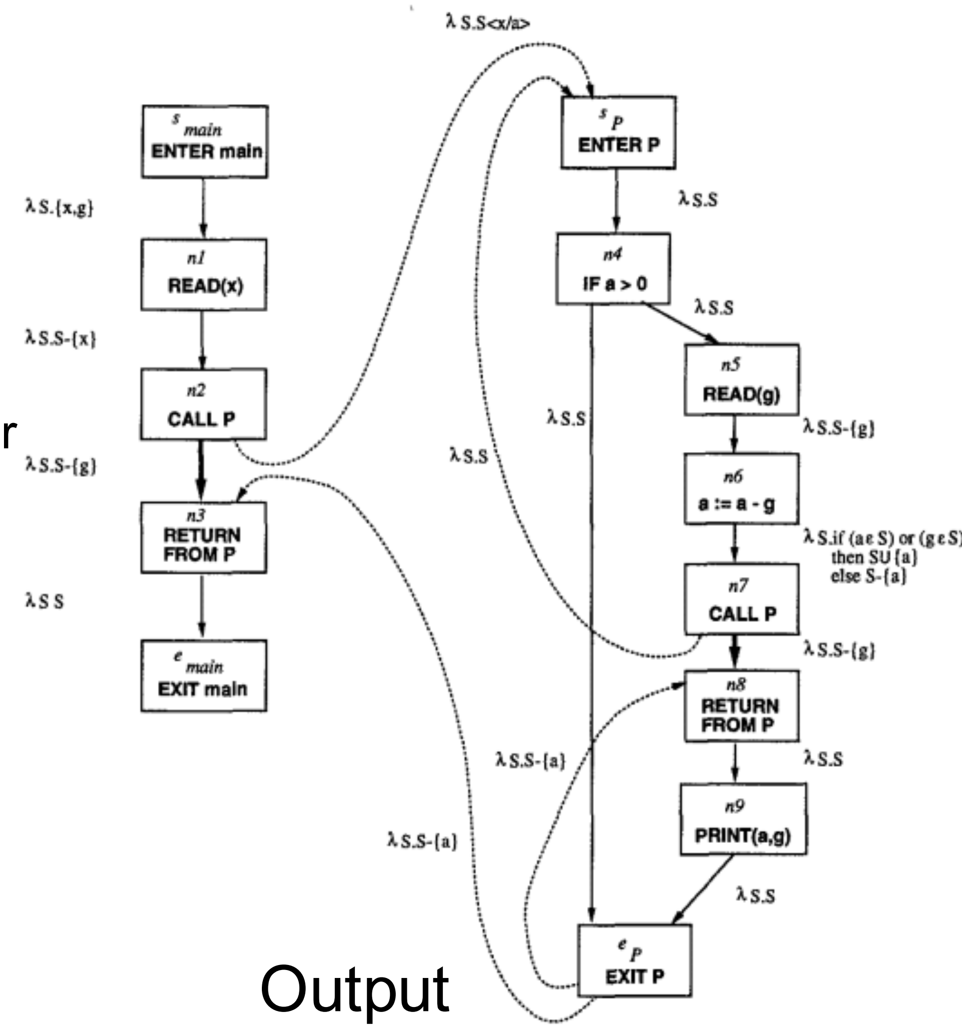
FlowDroid's Approach

- FlowDroid Analysis is based upon **Soot** (Android Code Analyser) and **Heros**(IFDS Solver)
- Build a dummy main method which take care of all the problems mentioned previously.
- Accurate and **efficient alias search** is crucial for **context-sensitivity** in conjunction with field-sensitivity

IFDS Solver

```
declare g: integer

program main
begin
  declare x: integer
  read(x)
  call P (x)
end


procedure P (value a : integer)
begin
  if (a > 0) then
    read(g)
    a := a − g
    call P (a)
    print(a, g)
  fi
end
```

IFDS Solver



Input

Output

Solving Aliasing Problem

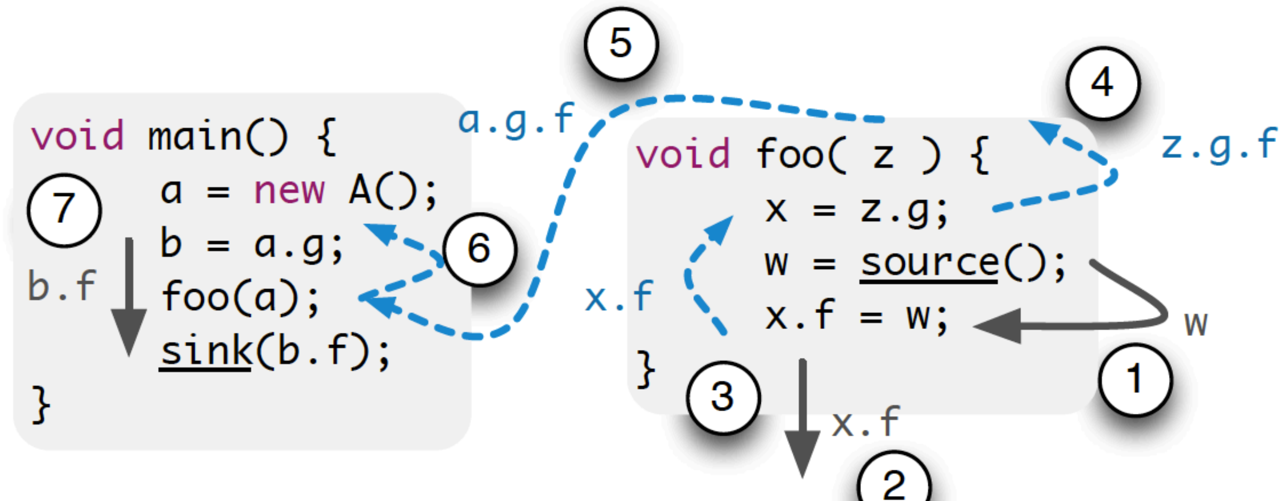


Figure 2: Taint analysis under realistic aliasing

Statements are examined in the reverse order and learn that z.g.f, a.g.f and b.f are aliases of x.f. The sink method takes b.f as input parameter, so there is a source-to-sink connection.

Experimental Evaluation

- How does FlowDroid compare to commercial taint analysis tools for Android in terms of precision and recall?

DroidBench

- Android specific test-suite, keeping in Android specific problems
- 39 hand-crafted Android apps
- Precision of 86% and recall 93% which is much better than AppScan Source and FortifySCA.

Precision = correct warning / (correct warning + false warning)

Recall = correct warning / (correct warning + missed leak)

Cont. Experimental Evaluation

- **Performance on InsecureBank**

InsecureBank is basically a vulnerable App designed to test analysis tools

  - Analysis of App: 31 seconds
  - Detects all 7 data leaks
  - No false positive or false negatives

- **Performance on Real-World Applications**
  - Ran FlowDroid on 500 Google Play apps = no leaks
  - Again ran on 1000 known malware samples from Virus Share project = average 2 leaks

Cont. Experimental Evaluation

- **SecuriBench Micro**

Intended for web-based applications

The number of actual leaks reported (117/121) and false positives (9) gives good results for FlowDroid

Test-case group	TP	FP
Aliasing	11/11	0
Arrays	9/9	6
Basic	58/60	0
Collections	14/14	3
Datastructure	5/5	0
Factory	3/3	0
Inter	14/16	0
Pred	n/a	n/a
Reflection	n/a	n/a
Sanitizer	n/a	n/a
Session	3/3	0
StrongUpdates	0/0	0
Sum	117/121	9

Table 2: SecuriBench Micro test results

Limitations

- Resolves reflective calls only if their arguments are string constants
- Handles arrays imprecisely
- **Cannot detect Inter Application security leaks**
- **Cannot detect network leaks**
- Big Flawed Assumption :

Threads execute in any arbitrary but sequential order and thus does not account for multiple threads

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Android Taint Flow Analysis for App Sets

Motivation

- **Detect malicious apps** that leak sensitive data
  - E.g., leak contact list to marketing company
  - "All or nothing" permission model
- Apps can **collude** to **leak data**
  - Evades precision detection if only analyzed individually
- Build upon **FlowDroid**
  - FlowDroid alone handles only intra-component flows.
  - Extend it to handle inter-app flows

Quick Recap about Android

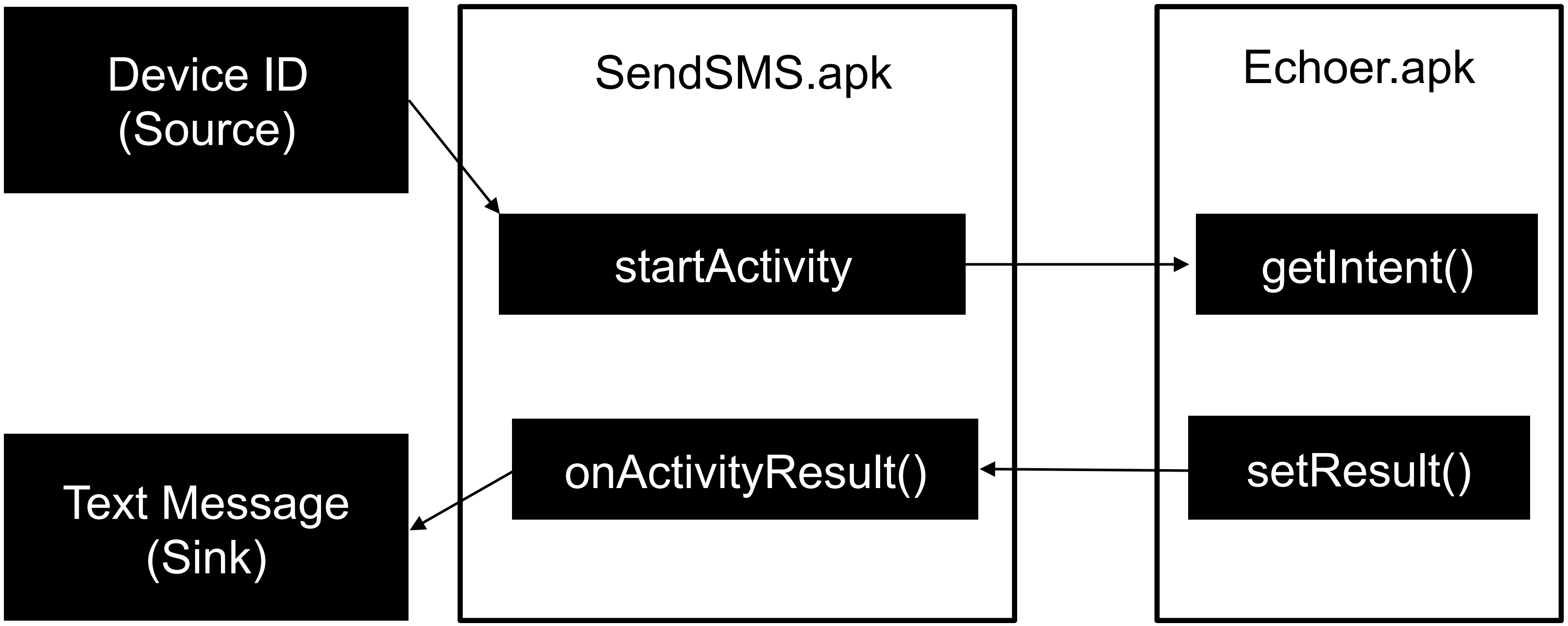
- Android apps have four types of components
  - Activities (main focus)
  - Services
  - Content Providers
  - Broadcast Receivers
- **Intents** are messages to components

Contributions

- Developed a static analyzer called **“DidFail”**
  - Find flows of sensitive data across app boundaries
- Two phase analysis
  - Analyze each app in isolation
  - Use the result of Phase-1 analysis to determine inter-app flows
- Tested analyzer on two set of apps

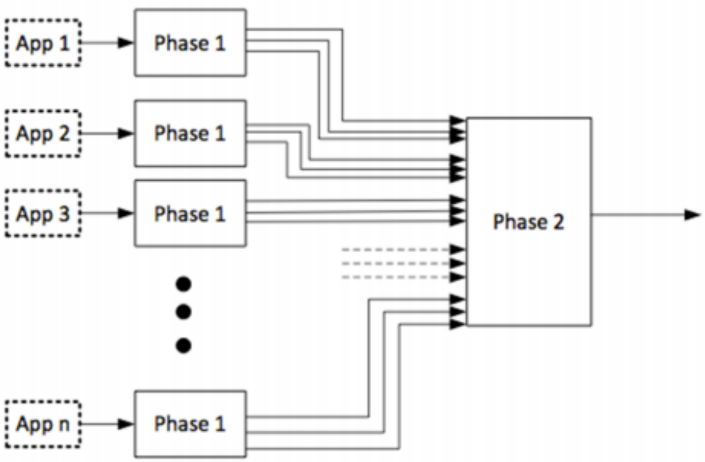
Motivating Example

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



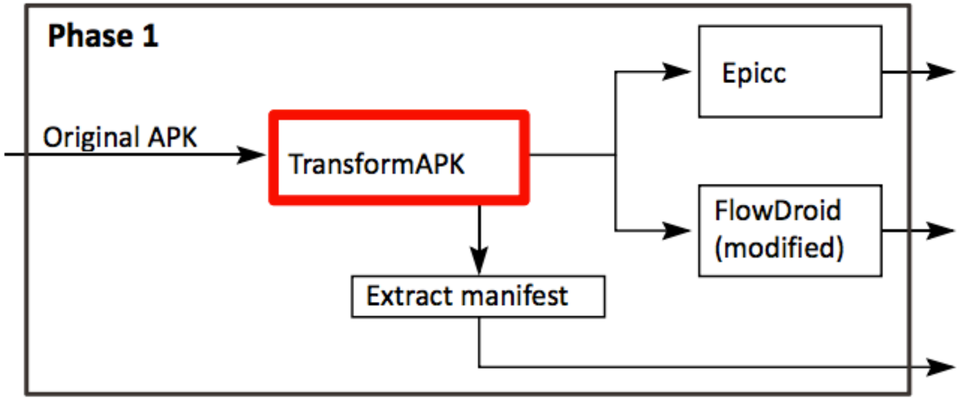
Analysis Design

- **Phase 1:** Each app analyzed once, in isolation
  - Each intent is given a unique 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.



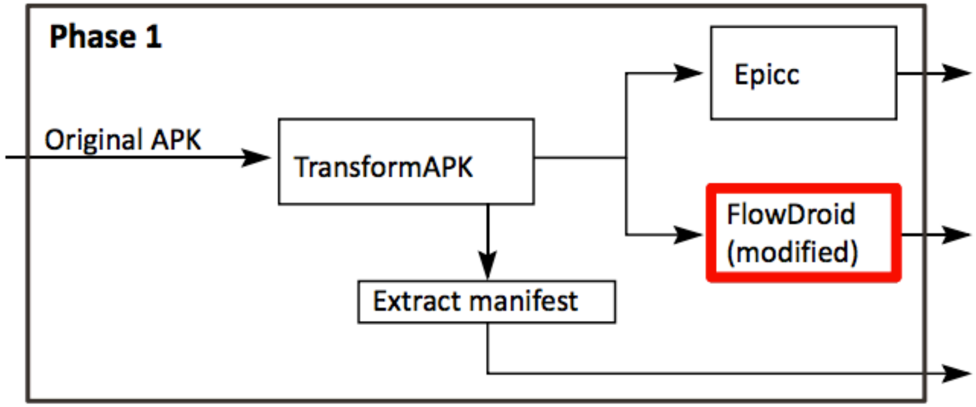
Implementation: Phase 1

- **APK Transformer**
  - Assigns **unique Intent ID** to each call site of intent-sending methods
  - Uses **Soot** to read APK, modify code and write new APK



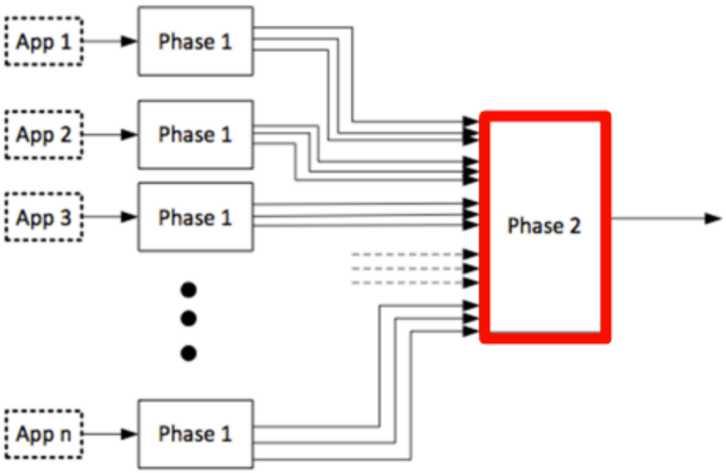
Implementation: Phase 1

- **FlowDroid Modifications**
  - Extract intent IDs inserted by APK Transformer, and include in output.
  - When sink is an intent, identify the sending components



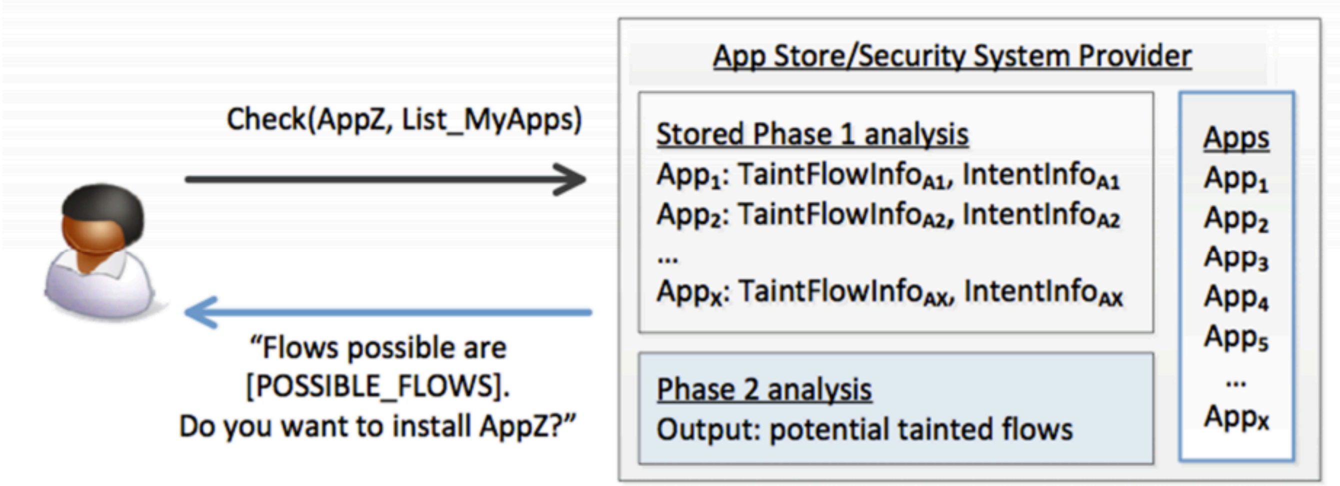
Implementation: Phase 2

- **Phase 2**
  - Take the Phase 1 output
  - Generate and solve the data-flow equations
  - Outputs:
    - Directed graphs indicating information flow between sources, intent, intent results, and sinks
    - **Taintedness** of each sink



Use of Two-Phase Approach in App Stores

- An app store runs the phase-1 analysis for each app it has
- When the user wants to download new app, the stores runs the phase-2 analysis and indicates new flows
- Fast Response to user



Limitations

- **Unsoundness**
  - Inherited from FlowDroid/Epicc
    - Native code, reflection etc
- **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

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Scalable and Precise Taint Analysis For Android

Basic Idea about Type System

A **type system** is a set of rules that assign a property called type to various constructs a computer program consists of, such as variables, expressions, functions or modules.

Main Purpose: Reduce possibilities of bug in computer program

For ex: string a = string b

string a $\neq$ int b

Motivating Example [From DroidBench]

```java
public class Data {
   String f;
   String get() { return f; }
   void set(String p) { f = p; }
}
public class FieldSensitivity3 {
   protected void onCreate(Bundle b) {
      Data dt = new Data();
      …
      String sim = tm.getSimSerialNumber();
      dt.set(sim);
      String sg = dt.get();
      sms.sendTextMessage(…,sg,…); // sink
   }
}
```

Leak!

Solution – DFlow/DroidInfer

```
public class Data {
   String f;
   String get() { return f; }
   void set(String p) { f = p; }
}
public class FieldSensitivit
   protected void onCreate(Bund     b) {
      tainted Data dt = new Da   a();
      tainted String sim =
         tm.getSimSerialNumber()
      dt.set(sim);
      tainted String sg = dt.get   ();
      sms.sendTextMessage(…,sg,…); // sink
   }
}
```

Subtyping:
safe <: tainted

Source: the return value is tainted

Sink: the parameter is safe

Type error!

Contributions

- **DFlow** context sensitive information flow **type system**
- **DroidInfer**: An **inference algorithm** for DFlow
- CFL-Explain: A CFL-reachability algorithm to **explain** type errors
- Implementation and **evaluation**
  - DroidBench, Contagio, Google Play Store

Inference and Checking Framework

- Build **DFlow/DroidInfer** on top of **type inference** and checking framework
- Frameworks infers the “best” typing
  - If inference succeeds, this **verifies the absence of errors**
  - Otherwise, this **reveals errors** in the program

DFlow

- **Type Qualifiers**
  - **tainted**: A variable x is tainted, if there is flow from a sensitive source to x
  - **safe**: A variable x is safe, if there is flow from x to an untrusted sink
  - **poly**: The polymorphic qualifier, is interpreted as tainted in some contexts and as **safe** in other contexts
- **Subtyping hierarchy**:
  - **safe** <: **poly** <: **tainted**

Context Sensitivity (View Adaptation)

Concrete value of **poly** is interpreted by the viewpoint adaptation operation.

```
class Util {
    poly String id(tainted Util this, poly String p) {
        return p;
    }
}
 ...
Util y = new Util();
tainted String src = ...;
safe String sink = ...;
tainted String srcId = y.id10(src);
safe String sinkId = y.id11(sink);
```

Inference Example

```
public class Data {
    {poly, tainted} String f;
    {safe, poly, tainted} String get ({safe, poly, tainted} Data this) {
        return this.f;
    }
    void set({safe, poly, tainted} Data this,
                {safe, poly, tainted} String p) {
        this.f = p;
    }
}

public class FieldSensitivity3 {
    protected void onCreate(Bundle b) {
        {safe, poly, tainted} Data dt = new Data();
        {safe, poly, tainted} String sim =
                    tm.getSerialNumber(); // source
        dt.set(sim);
        {safe, poly, tainted} String sg = dt.get();
        sms.sendTextMessage(..., sg, ...); // sink
    }
}
```

Inference Example

```
public class Data {
    {poly, tainted} String f;
    {safe, poly, tainted} String get ({safe, poly, tainted} Data this) {
        return this.f;
    }
    void set({safe, poly, tainted} Data this,
             {safe, poly, tainted} String p) {
        this.f = p;
    }
}

public class FieldSensitivity3 {
    protected void onCreate(Bundle b) {
        {safe, poly, tainted} Data dt = new Data();
        {            tainted} String sim =
                tm.getSerialNumber(); // source
        dt.set(sim);
        {safe, poly, tainted} String sg = dt.get();
        sms.sendTextMessage(..., sg, ...); // sink
    }
}
```

safe

Inference Example

```
public class Data {
    {poly, tainted} String f;
    {safe, poly, tainted} String get ({safe, poly, tainted} Data this) {
        return this.f;
    }
    void set({safe, poly, tainted} Data this,
            {            tainted} String p) {
        this.f = p;
    }
}

public class FieldSensitivity3 {
    protected void onCreate(Bundle b) {
        {safe, poly, tainted} Data dt = new Data();
        {            tainted} String sim =
                    tm.getSerialNumber(); // source
        dt.set(sim);
        {safe, poly, tainted} String sg = dt.get();
        sms.sendTextMessage(..., sg, ...); // sink
    }
}
```

safe

Inference Example

```
public class Data {
    { tainted} String f;
    { tainted} String get ({ tainted} Data this) {
        return this.f;
    }
    void set({safe, poly, tainted} Data this,
             { tainted} String p) {
        this.f = p;
    }
}

public class FieldSensitivity3 {
    protected void onCreate(Bundle b) {
        {safe, poly, tainted} Data dt = new Data();
        { tainted} String sim =
                   tm.getSerialNumber(); // source
        dt.set(sim);
        {safe, poly, tainted} String sg = dt.get();
        sms.sendTextMessage(..., sg, ...); // sink
    }
}
```

safe

Inference Example

```
public class Data {
    {  tainted} String f;
    {  tainted} String get ({  tainted} Data this) {
        return this.f;
    }
    void set({safe, poly, tainted} Data this,
             {  tainted} String p) {
        this.f = p;
    }
}

public class FieldSensitivity3 {
    protected void onCreate(Bundle b) {
        {safe, poly, tainted} Data dt = new Data();
        {  tainted} String sim =
                tm.getSerialNumber(); // source
        dt.set(sim);
        {  tainted} String sg = dt.get();
        sms.sendTextMessage(..., sg, ...); // sink
    }
}
```

safe

Inference Example

```
public class Data {
    {          tainted} String f;
    {                   tainted} String get ({                   tainted} Data this) {
        return this.f;
    }
    void set({safe, poly, tainted} Data this,
             {                   tainted} String p) {
        this.f = p;
    }
}

public class FieldSensitivity3 {
    protected void onCreate(Bundle b) {
        {safe, poly, tainted} Data dt = new
        {                   tainted} String si
                    tm.getSerialNumber();
        dt.set(sim);
        {                   tainted} String sg = dt.   t();
        sms.sendTextMessage(..., sg, ...); // sink
    }
}
```

safe

Type Error
safe != tainted

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CFL-Explain

- Type Error

$$q \rhd \mathtt{ret}_{\mathtt{getSimSerialNumber}}\ \{\mathsf{tainted}\}\ \texttt{<:}\ \mathtt{sim}\ \{\mathsf{safe}\}$$

- Construct a dependency graph based on CFL-reachability
- Map a type error into a source-sink path in the graph

Android Specific Features

- Libraries
  - Flow through library method
- Multiple Entry Points and Callbacks
  - Connections among callback methods
- Inter-Component Communication (ICC)
  - Explicit or Implicit Intents

Libraries

- Insert annotations into Android Library
  - Source → {tainted} Sink → {safe}

```
public LocationLeak2 extends Activity implements
LocationListener {
        private double latitude;
        protected void onResume() {
            double d = this.latitude;
            Log.d("Latitude", "Latitude: "+ d); // sink
        }
        public void onLocationChanged(Location loc) {
        double lat = loc.getLatitude(); // loc is a source
        this.latitude = lat;
    }
}
```

Callbacks

```
public class SmsReceiver extends BroadcastReceiver {
    public void onReceive(Context c, Intent i) {
        for (int i = 0; i < pdusObj.length; i++) {
            SmsMessage msg = SmsMessage.createFromPdu(String secret); // source
            String body = msg.getDisplayMessageBody();
            sb.append(body);
        }
        Intent it = new Intent(c, TaskService.class);
        it.putExtra("data", sb.toString());
        startService(i);
    }
}
public class TaskService extends Service {
    public void onStart(Intent it, int d) {
        HttpClient client = ....getHttpClient();
        HttpPost post = new HttpPost();
        post.setURI(URI.create("http://103.30.7.178/getMotion.htm"));
        Entity e = new UrlEncodedFormEntity(list, "UTF8");
        post.setEntity(e); // sink
    }
}
```

Inter Component Communication (ICC)

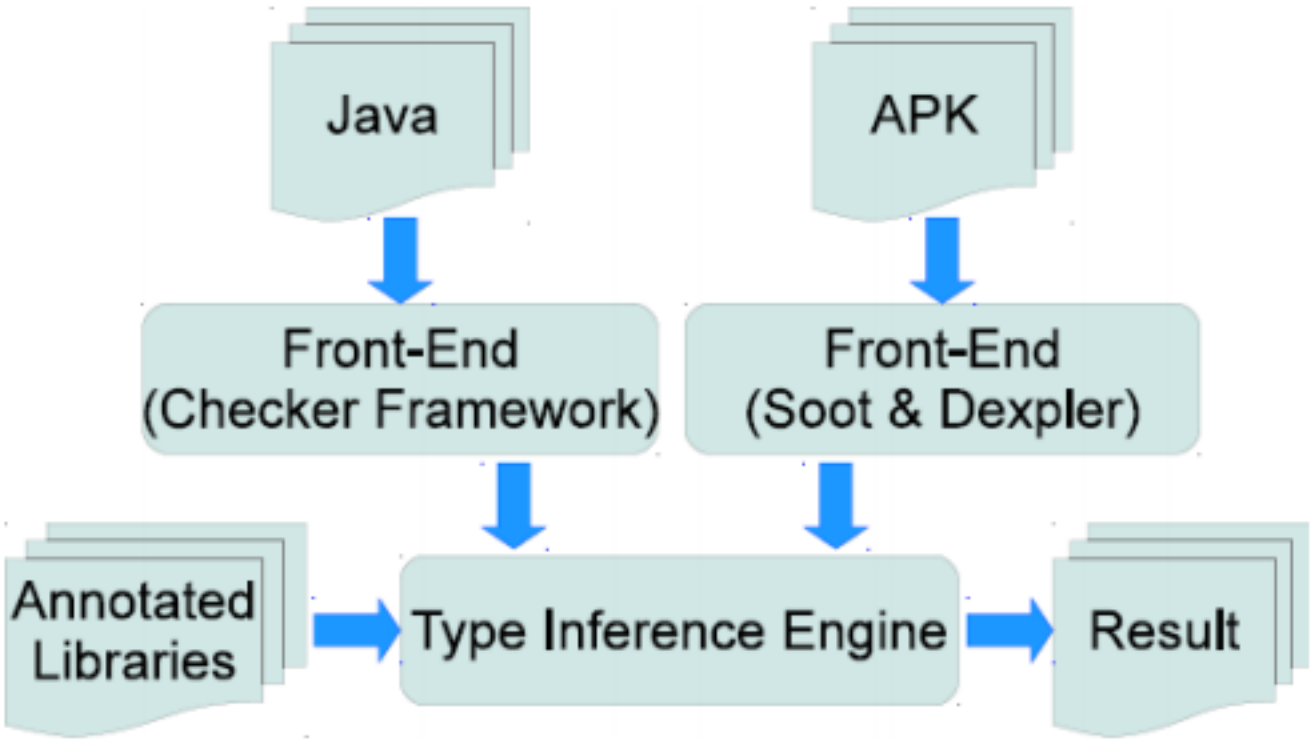
- Android components interact through Intents

- Explicit Intents
  - Have an explicit target component
  - DroidInfer connects them using placeholders

- Implicit Intents
  - Do not have a target component
  - DroidInfer conservatively considers them as sinks

Implementation

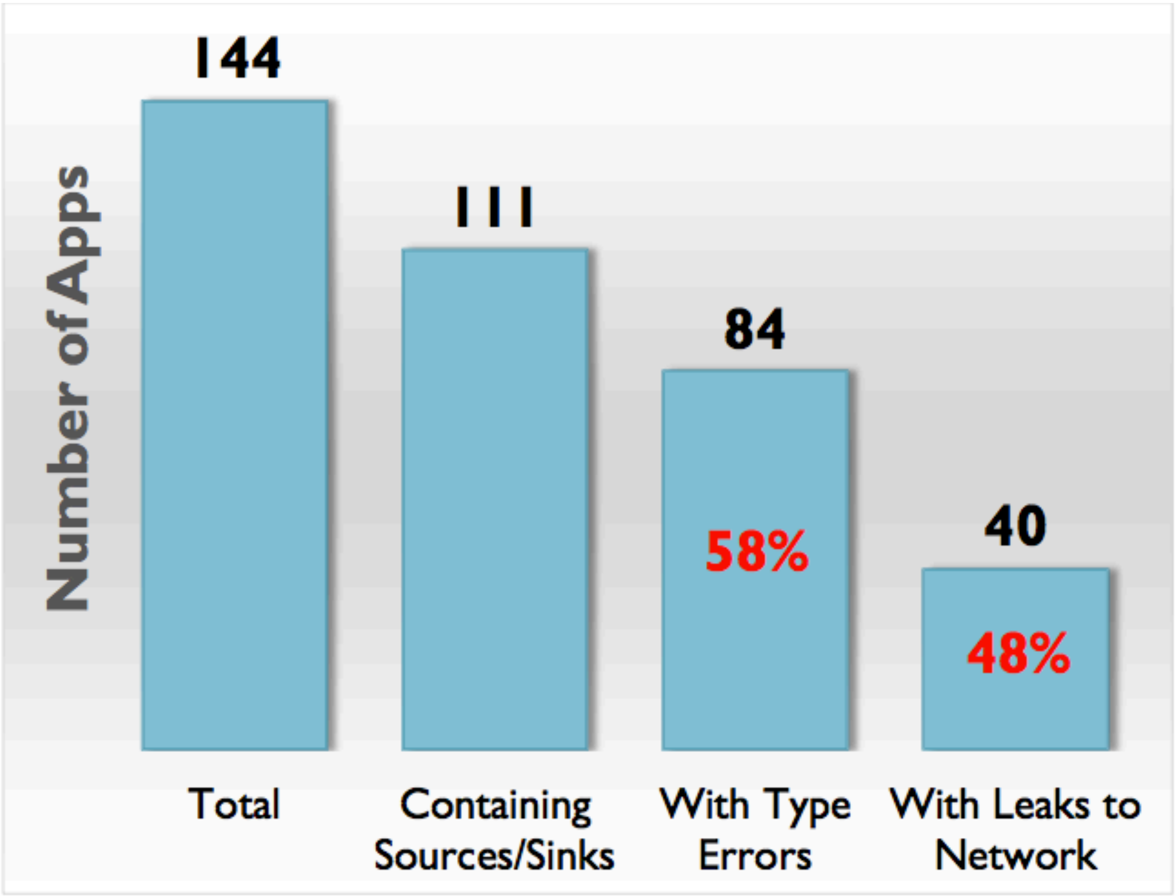
- Built on top of Soot and Dexpler



Evaluation

- DroidBench 1.0
  - Recall: 96%, precision: 79%
- Contagio
  - Detect leaks from 19 out of total 22 apps
- Google Play Store
  - 144 free Android apps (top 30 free apps)
  - Maximal heap size: 2GB
  - Time: 139 sec/app on average
  - False positive rate: 15.7%

Results from Google Play Store



Advantages Dflow over FlowDroid

- FlowDroid is computationally and memory intensive
- FlowDroid only reports log flows in apps and does not report any network flows (which are very important these days)

Conclusions

- DFlow and DroidInfer: context-sensitive information flow type system and inference
- CFL-reachability algorithm to explain type errors
- Effective handling of Android-specific features
- Implementation and evaluation

Current Trends

There has been an active research going in this field after these three pioneer approaches were present both in industry and academia

Amandroid: A Precise and General Inter-component Data Flow Analysis Framework for Security Vetting of Android Apps

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Composite Constant Propagation: Application to Android Inter-Component Communication Analysis

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AppContext: Differentiating Malicious and Benign Mobile App Behaviors Using Context

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Some General Comments

- All of the approaches lack extensive test set.
- Not clear details about the benchmarking machine on which these tools were ran
- Except for DidFail, no one suggested any approach to deploy it or integrate with current Google Play Store
- Implicit assumption about a lot of prior knowledge like IFDS algorithm and CFL problem.


That's all Folks!


Questions?