Learning from Ourselves:
Where are we and where can we go in mobile systems security?

Patrick McDaniel, Penn State University
A cautionary tale …
Where are we now ...

• September 23, 2008 - May 26th, 2016
  • 7.67 years
  • 242,179,200 seconds
  • 4,036,320 minutes
  • 67,272 hours
  • 2,803 days
  • 400 weeks and 3 days
• Smartphones: long awaited realization of mobile computing
• Usage model is very different
  • Multi-user single machine to single-user multiple machines
  • Always on, always computing social instrument
  • Enterprise: separate action from geography
• Changing Risk
  • Necessarily contains secrets (financial, personal)
  • Collects sensitive data as a matter of operation
  • Drifts between “unknown” environments
  • Highly malleable development practices, largely unknown developers
Where are we now ...

- We are closing in on a decade of research and use of smartphones.
  - What questions have we asked and what have we learned?
  - What questions should we be asking?

Promise: the next four dissertations will be ....
Three questions
(2009-2011) …
What do applications ask for?

- *Kirin* certifies applications by vetting policies at install-time (relies on *runtime enforcement*)
- Obvious insight: app config and security policy is an upper bound on runtime behavior.
- Kirin is a modified application installer
  - Apps with unsafe policies are rejected

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Studying the (early) Market

- Kirin enforces security invariants at install-time

```plaintext
restrict permission [ACCESS_FINE_LOCATION, INTERNET]
and receive [BOOT_COMPLETE]
```

- Local evaluation of requested permissions, Intent listeners

Evaluate 311* popular Market apps (Jan 2009)

- 5 had both dangerous configuration / functionality (1.6%)
- 5 dangerous configs, but plausible use of permissions (1.6%)

3 apps failed -- (2) An application must not have the PHONE_STATE, RECORD_AUDIO, and INTERNET permissions
What do the applications do?

- **TaintDroid** is performs system-wide taint tracking in the Android platform
  1. **VM Layer**: variable tracking throughout Dalvik VM
  2. **Native Layer**: patches state after native method (JNI)
  3. **Binder IPC Layer**: extends tracking between applications
  4. **Storage Layer**: persistent tracking on files

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Findings

• 15 of the 30 applications shared physical location with an ad server (admob.com, ad.qwapi.com, ads.mobclix.com, data.flurry.com)

• Not trying hard to hide (e.g., AdMob HTTP GET):

  ...&s=a14a4a93f1e4c68&..&t=062A1CB1D476DE85B717D9195A6722A9&d%5Bcoord%5D=47.661227890000006%2C-122.31589477&...

• 7 applications sent device (IMEI) and 2 apps sent phone info (Ph. #, IMSI, ICC-ID) to a remote server without informing the user.
What can the applications do?

- **Static analysis**: look at the possible paths and interaction of data
  - Very, very hard (often undecidable), but community has learned that we can do a lot with small analyses.

- Step 1: decompiler for Android applications (ded)

- Step 2: static source code analysis for both **dangerous functionality** and **vulnerabilities**
  - What data could be exfiltrated from the application?
  - Are developers safely using interfaces?

Studying Application Security

- Decompiled top 1,100 apps from Android market: >21 MLOC
- Queried for security properties using program analysis, followed by manual inspection to understand purpose
- Used several types of analysis to design security properties specific to Android using the Fortify SCA framework

### Analysis for Dangerous Behavior

<table>
<thead>
<tr>
<th>Misuse of Phone Identifiers</th>
<th>Data flow analysis</th>
</tr>
</thead>
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<tr>
<td>Exposure of Physical Location</td>
<td>Data flow analysis</td>
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<td>Semantic analysis</td>
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<tr>
<td>Eavesdropping on Video</td>
<td>Control flow analysis</td>
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<tr>
<td>Eavesdropping on Audio</td>
<td>Structural analysis (+CG)</td>
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<td>Structural analysis</td>
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<td>Havesting Installed Applications</td>
<td>Structural analysis</td>
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</table>

### Analysis for Vulnerabilities

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<th>Data flow analysis</th>
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<td>Leaking Information to IPC</td>
<td>Control flow analysis</td>
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<tr>
<td>Unprotected Broadcast Receivers</td>
<td>Control flow analysis</td>
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<tr>
<td>Intent Injection Vulnerabilities</td>
<td>Control flow analysis</td>
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<td>Delegation Vulnerabilities</td>
<td>Control flow analysis</td>
</tr>
<tr>
<td>Null Checks on IPC Input</td>
<td>Control flow analysis</td>
</tr>
<tr>
<td>Password Management*</td>
<td>Data flow analysis</td>
</tr>
<tr>
<td>Cryptography Misuse*</td>
<td>Structural analysis</td>
</tr>
<tr>
<td>Injection Vulnerabilities*</td>
<td>Data flow analysis</td>
</tr>
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Phone Identifiers

com.avantar.wny - com/avantar/wny/PhoneStats.java

```java
public String toUrlFormatedString()
{
    StringBuilder $r4;
    if (mURLFormatedParameters == null)
    {
        $r4 = new StringBuilder();
        $r4.append((new StringBuilder("&uuid=")).append(URLEncoder.encode(mUuid)).toString());
        $r4.append((new StringBuilder("&device=")).append(URLEncoder.encode(mModel)).toString());
        $r4.append((new StringBuilder("&platform=")).append(URLEncoder.encode(mOSVersion)).toString());
        $r4.append((new StringBuilder("&ver=")).append(mAppVersion).toString());
        $r4.append((new StringBuilder("&app=")).append(this getAppName()).toString());
        $r4.append("&returnfmt=json");
        mURLFormatedParameters = $r4.toString();
    }

    return mURLFormatedParameters;
}
```
public void onCreate(Bundle r1) {
    ...  
    IMEI = ((TelephonyManager) this.getSystemService("phone")).getDeviceId();
    retailerLookupCmd = (new StringBuilder(String.valueOf(constants.server))).append("identifier=").append(EncodeURL.KREncodeURL(IMEI)).append("&command=retailerlookup&retailername=").toString();
    ...  
}

http://kror.keyringapp.com/service.php

public void run() {
    ...  
    r24 = (TelephonyManager) r21.getSystemService("phone");
    url = (new StringBuilder(String.valueOf(url))).append("&vid=60001001&pid=10010&cid=C1000&uid=").append(r24.getDeviceId()).append("&gid=").append(QC.onfiguration.mGid).append("&msg=").append(QC.onfiguration.getInstance().mPCStat.toMsgString()).toString();
    ...  
}

http://client.qunar.com:80/QSearch
public static String getDeviceId(Context r0) {
    String r1;
    r1 = "";
    label_19: {
        if (deviceId != null) {
            if (r1.equals(deviceId) == false) {
                break label_19;
            }
        }
        if (r0.checkCallingOrSelfPermission("android.permission.READ_PHONE_STATE") == 0) {
            deviceId = ((TelephonyManager) r0.getSystemService("phone")).getSubscriberId();
        }
    } //end label_19:
    ...
51% of the apps included an ad or analytics library (many also had custom functionality)

A few libraries were used most frequently

Use of phone identifiers and location sometimes configurable by developer

<table>
<thead>
<tr>
<th>Library Path</th>
<th># Apps</th>
<th>Obtains</th>
</tr>
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<tbody>
<tr>
<td>com/admob/android/ads</td>
<td>320</td>
<td>L</td>
</tr>
<tr>
<td>com/google/ads</td>
<td>206</td>
<td>-</td>
</tr>
<tr>
<td>com/flurry/android</td>
<td>98</td>
<td>-</td>
</tr>
<tr>
<td>com/qwapi/adclient/android</td>
<td>74</td>
<td>L, P, E</td>
</tr>
<tr>
<td>com/google/android/apps/analytics</td>
<td>67</td>
<td>-</td>
</tr>
<tr>
<td>com/adwhirl</td>
<td>60</td>
<td>L</td>
</tr>
<tr>
<td>com/mobcliix/android/sdk</td>
<td>58</td>
<td>L, E</td>
</tr>
<tr>
<td>com/mellennial/media/android</td>
<td>52</td>
<td>-</td>
</tr>
<tr>
<td>com/zestadz/android</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>com/admarvel/android/ads</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>com/estsoft/adlocal</td>
<td>8</td>
<td>L</td>
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<tr>
<td>com/adfonic/android</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>com/vdroid/ads</td>
<td>5</td>
<td>L, E</td>
</tr>
<tr>
<td>com/greystripe/android/sdk</td>
<td>4</td>
<td>E</td>
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<tr>
<td>com/medialets</td>
<td>4</td>
<td>L</td>
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<tr>
<td>com/wooboo/adlib_android</td>
<td>4</td>
<td>L, P, I</td>
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<tr>
<td>com/adserver/adview</td>
<td>3</td>
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<tr>
<td>com/tapjoy</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>com/inmobi/androidsdk</td>
<td>2</td>
<td>E</td>
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<tr>
<td>com/apegroup/ad</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>com/casee/adsdk</td>
<td>1</td>
<td>S</td>
</tr>
<tr>
<td>com/webtrents/mobile</td>
<td>1</td>
<td>L, E, S, I</td>
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</table>

1 app has 8 libraries!
• Similar analysis rules as independently verified by Chin et al. [Mobisys 2011]

• Leaking information to IPC - unprotected intent broadcasts are common, occasionally contain sensitive info

• Unprotected broadcast receivers - a few apps receive custom action strings w/out protection (lots of “protected bcasts”)

• Intent injection attacks - 16 apps had potential vulnerabilities

• Delegating control - pending intents are tricky to analyze (notification, alarm, and widget APIs) --- no vulns found

• Null checks on IPC input - 3925 potential null dereferences in 591 apps (53%) --- most were in activity components
Non-app centric work ...
So ... then what?

- The community has been working in concert since the early days trying to sort out not just what applications are doing, but how we deal with this new world of security.

- You can distill the non-app centric work into two areas ...

Thanks to: Octeau, Enck, Porter Felt, Liu, Roesner, ... and hundreds more.
What to do about permissions?
Permissions define security policy ...

- Perhaps no subject has spurred more discussion and research than permissions.
  - Understanding permissions
  - Enhancing permissions

- Perhaps define who can do what to whom and when.
• The existential question: a permission is a statement of a right of an application to use some interface or resource.

Application A can use interface/resource P.

• In a broader sense, a permission is a (non-negotiable) contract between the application and the user about security relevant actions.
Permission problems

• Permissions are presented largely without the context needed to make an informed decision:

  Application A can use interface/resource P (FOR WHAT?).

• Dynamic permissions in Marshmallow start to address context by providing temporal context, but this still lacks the specificity needed.
Permission problems

- Permissions lack the kinds of clear meaning for people to understand what they mean or what the implications are:

  Application A can use interface/resource P (THAT ENCOMPASSES ..) (FOR WHAT?).

- Permission groups start to address context by providing needed semantics (calendar, contacts, location). But …
• The scope of permissions are sometimes too coarse to make informed decisions:

  Application A can use interface/resource
  P(.REFINEMENT) (THAT ENCOMPASSES ..) (FOR WHAT?).

• Consider the calendar permission group. That protects the calendar database, but not controls on the elements of it.
A debate ...

android.permissionINTERNET
• All of these arguments are true, but rely on a particular interpretation of “user”.

• The problem is that there is no one single class of user or uniform set of needs for a permission system.

• The current permission system has NOT failed, it has just failed to address all possible user needs and the same time.
One of the key challenges of the current permission system is that it leads to an emergent security policy.

Each application adds something to the aggregate information flow allowed in the system, and therefore alters the security policy.

**Implication**: Inter-component communication (ICC) analysis is essential to the security of the phone.

**Challenge**: adding a new application may substantially influence security. Therefore security analysis must be a maintenance process, not a certification process.
What about markets?
Markets have changed the software industry.

- Easy access to consumer market
- Vender channel (30% to market), highly profitable
- Low barrier to entry
  - Android structure and tools are designed to ease barriers and reduce learning curves
  - There to foster innovation (think 2008-ish)
- Fast-always available patching

Trivia: 460,00 distinct developers as of Feb 2016
• Myth: application markets provide security

• Actually, Markets can’t provide security
  • They don’t know what it means (because it is unknowable for any future context)
  • They can evaluate applications for compliance with proper design usage, and identify over malware ... (and they do, but details are sketchy)
  • Even markets could provide security, they could not possibly perform the necessarily expensive analysis for the thousands of applications hitting the market every day

Application markets myths ...

- **Myth**: markets identify developers and provide transparency of how users and data are part of economy
  - You know where you are getting your software from and how your data is used ...
- Actually, Markets don’t and can’t provide transparency
  - Developer environment and run-time economy is a complex collection of hidden, and fluid relationships
    - App developers, libraries providers, third-party networks, add resellers, all have a role in development and execution
    - Monetization is opaque to the user and market.
- Repackaging: a serious consequence
Stepping back …
Future research

• There are two open areas of research that will define the future of research:
  
  • Permissions: how do we define and maintain security policy
  
  • Markets: how do we provide applications to users in a safe way
  
• Put another way: the next 4 dissertations topics …
Open problems:

- Permission structures and definition: how do we design permission systems that can map to the cognitive models of users (usability) while providing for complete, granular and contextually meaningful mediation?

- Separating system and user policy: How do we trade off system defined policy with user defined policy - note that the sweet spot is likely going to be dependent on the application, user, and environment?
• Open problems:

  • *Code provenance*: how can we identify the (a) developers of the application and its parts, (b) identify different parts of the application (app vs. library)

  • *Behavioral disclosure and regulation*: disclose behaviors that have security consequences (SMS premium rate, ad acquisition)
Conclusions
Android security research is often conflated with application security analysis, but it is much larger.

- Access control and the way we define it is essential to the future of security research
- Getting a handle on the applications
Questions?

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• Smartphones: long awaited realization of mobile computing

• Usage model is very different
  • Multi-user single machine to single-user multiple machines
  • Always on, always computing social instrument
  • Enterprise: separate action from geography

• Changing Risk
  • Necessarily contains secrets (financial, personal)
  • Collects sensitive data as a matter of operation
  • Drifts seamlessly between “unknown” environments
  • Highly malleable development practices, largely unknown developers
Rethinking (host) Security

\[
\text{security} \equiv \text{permissions} \times \text{apps} \\
\text{security} \neq \text{users}
\]

- Permissions define capabilities.
- Application markets deliver packaged applications from largely unknown sources.
- Users make permission decisions.
- Applications are run within middleware supported sandboxes provided by the OS.

Note: App markets don’t (and can’t) provide security.

A 8-ish Year Span ...

- Evaluating Android Application Security ....
Permissions granted to applications and never changed

- Permissions allow an application to access a component, API, ..

- Runtime decisions look for assigned permissions (access is granted iff app A assigned perm X at install)

- Permissions levels: normal, dangerous, signature, or system

Example permissions: location, phone IDs, microphone, camera, address book, SMS, application “interfaces”

Aside: Dalvik EXecutables

- Android applications written in Java, compiled to Java bytecode, and translated into DEX bytecode (Dalvik VM)

- We want to work with Java (bc), not DEX bytecode
  - There are a lot of existing program analysis tools for Java
  - We want to see what the developer was doing (i.e., confirmation)

- Non-trivial to retarget back to Java: register vs. stack architecture, constant pools, ambiguous scalar types, null references, etc.
The **ded** (later **dare**) decompiler

- Refers to both the entire process and `.dex` → `.class` retargeting tool

**dare** recovers logic

from application package

- **Retargeting**: type inference, instruction translation, etc
- **Optimization**: use Soot to optimize Java bytecode
- **Decompilation/IR**: standard Java decompilation (Soot) or translate to TyDe IR (typed dex in DARE)

What can the applications do?

- **Static analysis**: look at the possible paths and interaction of data
  - Very, very hard (often undecidable), but community has learned that we can do a lot with small analyses.

- Step 1: decompiler for Android applications (ded)

- Step 2: static source code analysis for both dangerous functionality and vulnerabilities
  - What data could be exfiltrated from the application?
  - Are developers safely using interfaces?

Decompiled top 1,100 apps from Android market: over 21 MLOC

Queried for security properties using program analysis, followed by manual inspection to understand purpose

Misuse of Phone Identifiers
Data flow analysis

Exposure of Physical Location
Data flow analysis

Abuse of Telephony Services
Semantic analysis

Eavesdropping on Video
Control flow analysis

Eavesdropping on Audio
Structural analysis (+CG)

Botnet Characteristics (Sockets)
Structural analysis

Harvesting Installed Applications
Structural analysis

Leaking Information to Logs
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Leaking Information to IPC
Control flow analysis

Unprotected Broadcast Receivers
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Intent Injection Vulnerabilities
Control flow analysis

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Control flow analysis

Null Checks on IPC Input
Control flow analysis

Password Management*
Data flow analysis

Cryptography Misuse*
Structural analysis

Injection Vulnerabilities*
Data flow analysis

* Included with analysis framework

Also studied inclusion of advertisement and analytics libraries and associated properties
Phone Identifiers

com.avantar.wny - com/avantar/wny/PhoneStats.java

```java
public String toUrlFormatedString()
{
    StringBuilder $r4;
    if (mURLFormatedParameters == null)
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        $r4 = new StringBuilder();
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        $r4.append(((new StringBuilder("&device=")).append(URLEncoder.encode(mModel)).toString()));
        $r4.append(((new StringBuilder("&platform=")).append(URLEncoder.encode(mOSVersion)).toString()));
        $r4.append(((new StringBuilder("&ver=")).append(mAppVersion).toString()));
        $r4.append(((new StringBuilder("&app=")).append(this getAppName()).toString()));
        $r4.append("&returnfmt=json");
        mURLFormatedParameters = $r4.toString();
    }

    return mURLFormatedParameters;
}
```
com.froogloid.kring.google.zxing.client.android - Activity_Router.java (Main Activity)

```java
public void onCreate(Bundle r1) {
    ...
    IMEI = ((TelephonyManager) this.getSystemService("phone")).getDeviceId();
    retailerLookupCmd = (new StringBuilder(String.valueOf(constants.server))).append("identifier=").append(EncodeURL.KREncodeURL(IMEI)).append("&command=retailerlookup&retailername=").toString();
    ...
}
```

http://kror.keyringapp.com/service.php

com.Qunar - net/NetworkTask.java

```java
public void run() {
    ...
    r24 = (TelephonyManager) r21.getSystemService("phone");
    url = (new StringBuilder(String.valueOf(url))).append("&vid=60001001&pid=10010&cid=C1000&uid=").append(r24.getDeviceId()).append("&gid=").append(QConfiguration.mGid).append("&msg=").append(QConfiguration.getInstance().mPCStat.toMsgString()).toString();
    ...
}
```

http://client.qunar.com:80/QSearch
How would you feel about a PII to phone database?
public static String getDeviceId(Context r0) {
    String r1;
    r1 = "";

    label_19:
    {
        if (deviceId != null)
        {
            if (r1.equals(deviceId) == false)
            {
                break label_19;
            }
        }
        if (r0.checkSelfPermission("android.permission.READ_PHONE_STATE") == 0)
        {
            deviceId = ((TelephonyManager) r0.getSystemService("phone")).getSubscriberId();
        }
    } //end label_19:
    ...
}
• 51% of the apps included an ad or analytics library (many also had custom functionality)

New libraries were used most frequently

Use of phone identifiers and location sometimes configurable by developer

1 app has 8 libraries!
• Similar analysis rules as independently verified by Chin et al. [Mobisys 2011]

• *Leaking information to IPC* - unprotected intent broadcasts are common, occasionally contain sensitive info

• *Unprotected broadcast receivers* - a few apps receive custom action strings w/out protection (lots of “protected bcasts”)

• *Intent injection attacks* - 16 apps had potential vulnerabilities

• *Delegating control* - pending intents are tricky to analyze (notification, alarm, and widget APIs) --- no vulns found

• *Null checks on IPC input* - 3925 potential null dereferences in 591 apps (53%) --- most were in activity components
• Application analysis is more challenging because of application execution “life-cycle”
  • E.g., component asynchrony, multiple entry points, system events, callbacks …
• FlowDroid is a static taint analysis system that tracks data flow from sources to sinks
  • Approach: identify all entry points construct a dummy main, perform analysis
• Analysis: 93% recall and 86% precision
  • DroidBench (39 hand crafted applications)
• Market or enterprise level analysis
  • Getting back to the certification model of Kirin

How do applications work on concert?

- **Intents** are used to pass information between apps

- **IPC (intra-) data flows**

- **ICC Analysis**: location of ICC, and data (types, attributes)
  - Soundness: all Intra-Component-Communication (ICC) identified
  - Precision: reduce number of false positives
  - Enable security analysis of ensemble of applications
    - Data flows between components within application
    - Exported flows/interfaces are used by other applications

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Analysis Results

- Epicc builds a model of ICC
  - Reduce to an Interprocedural Distributive Environment (IDE) problem and extract possible Intent values (specifications)
  - Experiment: attempt to recover Intent use in 1200 applications (850 most popular, 350 random applications),
    - Runtime: average 113 seconds per application
- Entry/exit point analysis
  - All attributes known in about 93% of ICC specifications
  - 56,106 exits points
    - 90% were found to have fixed Intent specification
    - 45% have key-value data
  - 29,154 entry points
    - About 95% were found to have single Intent Filter specification
    - 8,566 exported components, 5% protected by permissions
• IC3: Inter-Component Communication Analysis in Android with COAL

• More sophisticated two-phase string analysis using flow graph of constraints on string operations

• Added deeper URI analysis

• Experiment: analyze ICC for 460 apps using IC3 and Epicc

<table>
<thead>
<tr>
<th></th>
<th>Epicc</th>
<th>IC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intents/Filters</td>
<td>69%</td>
<td>86%</td>
</tr>
<tr>
<td>URIs</td>
<td>34%</td>
<td>72%</td>
</tr>
<tr>
<td>Total</td>
<td>66%</td>
<td>85%</td>
</tr>
</tbody>
</table>

Precision: Identified (possible) ICC Flows

Epicc: 120,817
IC3: 26,872

Ongoing: Scaling up analysis …

- Static analysis
  - Epicc/EC2: find all Intent values at message-passing program points
  - Small static analysis imprecisions cause explosion in number of links at large scale
- 600 apps -> 2 million links!
- Two challenges
  - Intent resolution
  - Intent flow ranking

1: Intent Resolution

• Intent resolution - identifying the flows between apps
  • Compute inter-component links in scalable manner
  • Take into account field value regular expressions
  • Our algorithm is based on intersecting sets of Filters that verify several Intent resolution tests
    • Exploits fast matching of constant intent values
  • Runs in time $\Theta(n |E|)$, where $e$ is small constant

• Experiment
  • Match 10,928 applications
  • Runtime: 8,434 seconds (140 min)
2: Intent flow ranking

- Intent flow ranking – determining estimated likelihood of flows being “real” by comparing against known flows
- Idea: Intents are highly predictable
  - For example, displaying a map is done by sending Intent with VIEW action and geo scheme (common to applications)
  - Explicit Intents almost always target components within the same application, but often identified as being inter-application
- Approach
  - Estimate the probability of having a given Intent field combination, given the Intents that are known, i.e., to simplify

\[
P(\text{flow}) = \% \text{ known Intent matching specifications matching Intent filter}
\]

- Intuition: how similar is potential flow to known flows
Preliminary Results

- 10,928 applications, 489,099,606 potential ICC flows
- 111,254 components, 58,480 Intent filters
- 452,984 Intent values (47% explicit, 53% implicit)

Key Results
- 97.3% links $Pr() < 0.1$
- 75% explicit links are tagged as inter-application
- 99.6% of Implicit links are inter-application

Take away: vastly reduces the number of links
Conclusions

• The security community has been analyzing mobile applications for almost a decade now..

  • Research is driven by deep and deeper questions

    • Analysis techniques are getting more sophisticated …

  • Volumes of data are getting larger …

  • Adversarial behavior getting subtler and more costly …

  • Industrial and academic cooperation is very strong …

• Future is bright for research!